

1 **Late Quaternary sea-ice and sedimentary redox conditions in the eastern Bering Sea –**
2 **implications for ventilation of the mid-depth North Pacific and an Atlantic-Pacific**
3 **seesaw mechanism**

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12 **Highlights:**

- 13 • Extended to seasonal sea ice in the eastern Bering Sea during late MIS 3 and MIS 2
14 • Millennial sea-ice variability across the deglaciation
15 • Glacial sea-ice dynamics respond to atmospheric temperature and circulation changes
16 • During early Heinrich Stadial 1 brine rejection aided to initiate deep convection
17 • Terrestrial carbon input might have caused OMZ expansion during the early Holocene

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22 geochemistry, Bering Sea, NPIW, U/Mn, foraminiferal assemblages

23 **Abstract**

24 On glacial-interglacial and millennial timescales, sea ice is an important player in the
25 circulation and primary productivity of high latitude oceans, affecting regional and global
26 biogeochemical cycling. In the modern North Pacific, brine rejection during sea-ice freezing
27 in the Sea of Okhotsk drives the formation of North Pacific Intermediate Water (NPIW) that
28 ventilates the North Pacific Ocean at 300 m to 1000 m water depth. Glacial intervals of the
29 late Quaternary, however, experienced a deepening of glacial NPIW to at least 2000 m, with
30 the strongest ventilation observed during cold stadial conditions of the last deglaciation.
31 However, the origin of the shifts in NPIW ventilation is poorly understood. Numerical
32 simulations suggest an atmospheric teleconnection between the North Atlantic and the North
33 Pacific, in response to a slowdown or shutdown of the Atlantic meridional overturning
34 circulation. This leads to a build-up of salinity in the North Pacific surface ocean, triggering
35 deep ventilation. Alternatively, increased sea-ice formation in the North Pacific and its
36 marginal seas may have caused strengthened overturning in response to enhanced brine
37 rejection.

38 Here we use a multi-proxy approach to explore sea-ice dynamics, sedimentary redox
39 chemistry, and benthic ecology at Integrated Ocean Drilling Program Site U1343 in the
40 eastern Bering Sea across the last 40 ka. Our results suggest that brine rejection from
41 enhanced sea-ice formation during early Heinrich Stadial 1 locally weakened the halocline,
42 aiding in the initiation of deep overturning. Additionally, deglacial sea-ice retreat likely
43 contributed to increased primary productivity and expansion of mid-depth hypoxia at Site
44 U1343 during interstadials, confirming a vital role of sea ice in the deglacial North Pacific
45 carbon cycle.

46 **1. Introduction**

47 High latitude oceans play a pivotal role in global biogeochemical cycling. Depending on the
48 mode of oceanic circulation and the efficiency of the biological pump, carbon, oxygen, and
49 nutrients are redistributed in these regions, both within the ocean and between the ocean and
50 the atmosphere (Knox and McElroy, 1984; Levitus et al., 1993; Sarmiento et al., 2004, 1988;
51 Sigman et al., 2010; Toggweiler, 1999; Weber et al., 2016). The formation of deep and
52 intermediate water masses at high latitudes ventilates the ocean’s interior, replenishing its O₂
53 reservoir (Shcherbina et al., 2003; Talley, 1993; Toggweiler, 1999). Conversely, Ekman
54 suction (Gargett, 1991; Talley and Talley, 1985) and, in the case of the eastern Bering Sea,
55 eddy formation (Ladd, 2014; Mizobata et al., 2002; Mizobata and Saitoh, 2004), cause
56 upwelling of old, low-O₂, high-nutrient, and CO₂-rich deep waters to the surface ocean. Here
57 the exchange of CO₂ between the ocean and the atmosphere hinges on net primary
58 productivity, fueled by the supply of macronutrients from below and dependent on light and
59 micronutrient availability, and the efficiency of the biological pump. On glacial/interglacial
60 (G/IG) and millennial timescales, the dynamics of the ocean circulation and the biological
61 pump are thus fundamental for the distribution of carbon and oxygen in the ocean interior and
62 the atmosphere. In the Bering Sea, the northernmost marginal sea of the Pacific Ocean, sea-
63 ice dynamics strongly influence the regional circulation and primary productivity, modifying
64 the biogeochemical cycling and influencing sedimentary redox conditions.

65 Large areas of the modern North Pacific surface ocean are characterized as high nutrient low
66 chlorophyll (HNLC) regions with iron representing the limiting micronutrient (Lam and
67 Bishop, 2008; Moore et al., 2001). As such, the North Pacific currently represents a net
68 source of CO₂ to the atmosphere and excess nutrients are re-circulated to lower latitudes
69 (Takahashi et al., 2009, 1997). However, a pronounced spring bloom with high rates of
70 primary productivity is observed along the eastern Bering Sea slope and near the retreating

71 sea-ice edge (Niebauer et al., 1995; Springer et al., 1996). This is due to nutrient upwelling as
72 well as nutrient release and increased stratification of the water column during spring sea-ice
73 melting (Wang et al., 2014). On longer timescales, sea ice also influences primary
74 productivity by affecting light availability in the surface ocean. While extended sea-ice cover,
75 especially during glacial intervals, may reduce light transmission (Frey et al., 2011;
76 Perovich, 2016), sea-ice melting, on the other hand, leads to stratification in the upper water
77 column, shoaling the mixed layer and increasing light availability (Niebauer et al., 1990;
78 Smith, 1987).

79 Sea ice is also a critical control of the regional circulation regime of the North Pacific due to
80 brine rejection during sea-ice freezing. At present, no deep water convection takes place in
81 the North Pacific, where excess precipitation and runoff over evaporation result in low
82 surface salinities and a permanent halocline (Emile-Geay et al., 2003; Warren, 1983).
83 Nevertheless, North Pacific Intermediate Water (NPIW) forms in the mixed water region
84 between the Kuroshio and Oyashio Current east of Japan (Talley, 1993). The Oyashio water
85 obtains its characteristic density from Okhotsk Sea Mode Water, which forms via brine
86 rejection during sea ice freezing over the shelves of the Sea of Okhotsk (Shcherbina et al.,
87 2003; Talley, 1993). Characterized as a salinity minimum and an oxygen maximum following
88 the $26.8 \sigma_{\theta}$ isopycnal surface (Talley, 1993), NPIW can be traced throughout the North
89 Pacific Ocean between approximately 300 m and 1000 m water depth (Fujii et al., 2013) and
90 can be recognized as far south as 20°N in the eastern subtropical Pacific and even further
91 south in the west (Talley, 1993).

92 Proxy reconstructions of past oxygenation, nutrient, temperature, and salinity variability of
93 the intermediate and deep North Pacific suggest a deeper and better ventilated intermediate
94 water mass during the Last Glacial Maximum (LGM, 19-26.5 ka) and stadial periods of the
95 last deglaciation (Heinrich Stadial 1 (HS1, 14.7-18 ka) and Younger Dryas (YD, 11.8-12.8

96 ka)) (Ahagon et al., 2003; Cook et al., 2016; Duplessy et al., 1989; Gong et al., 2019; Jang et
97 al., 2017; Matsumoto et al., 2002; Max et al., 2014; Okazaki et al., 2010, 2012; Rae et al.,
98 2014; Rella et al., 2012; Saenko et al., 2004; Sagawa and Ikehara, 2008). The division
99 between well-ventilated glacial NPIW (GNPIW) and poorly ventilated North Pacific Deep
100 Water (NPDW) has been placed at around 2000 m depth in the North Pacific during the LGM
101 and the early deglaciation (Jaccard and Galbraith, 2013). Studies from the Bering Sea suggest
102 a maximum GNPIW depth of 1000 m to 2000 m during marine isotope stage (MIS) 2 (Cook
103 et al., 2016; Worne et al., 2019), while sediment cores from the Gulf of Alaska indicate
104 potential mixing of well-ventilated waters down to ~3500 m during HS1 (Rae et al., 2014). A
105 vertically expanded intermediate water mass during glacial intervals has the potential to
106 fundamentally alter the North Pacific carbon cycle by reducing the amount of NPDW that is
107 mixed to the surface, thus preventing the release of deeply sequestered carbon (Gong et al.,
108 2019; Gray et al., 2018; Kender et al., 2018; Max et al., 2014). Breakdown of enhanced
109 GNPIW formation and shoaling of NPDW across the last deglaciation, on the other hand,
110 would have increased the upwelling of carbon and nutrients into the photic zone (Gray et al.,
111 2018). The enhanced supply of macronutrients due to shoaling of NPDW likely contributed
112 to peaks in primary productivity observed during warm interstadial periods across the last
113 deglaciation, such as the Bølling-Allerød (BA, 12.8-14.7 ka) and the earliest Holocene,
114 coinciding with widespread mid-depth hypoxia in the North Pacific as seen from laminated
115 sediments (Aiello and Ravelo, 2012; Cook et al., 2005; Expedition 323 Scientists, 2010;
116 Kuehn et al., 2014; Ohkushi et al., 2013; Praetorius et al., 2015; Schlung et al., 2013; Zheng
117 et al., 2000).

118 The LGM and stadial periods of the last deglaciation were marked by a reduced Atlantic
119 meridional overturning circulation (AMOC), while the BA and early Holocene likely
120 experienced a strengthened AMOC (McManus et al., 2004), suggesting an Atlantic-Pacific

121 overturning seesaw. The dynamics of the seesaw and specifically the trigger mechanism for
122 deep convection in the North Pacific, however, remain equivocal. Numerical simulations
123 suggest an atmospheric teleconnection between the North Atlantic and the North Pacific via
124 lower latitudes, affecting the oceanic and atmospheric circulation in the Pacific and leading to
125 a salinity build up in the North Pacific, driving enhanced regional overturning (Chikamoto et
126 al., 2012; Gong et al., 2019; Menviel et al., 2012; Okazaki et al., 2010; Okumura et al., 2009;
127 Wu et al., 2008). Proxy reconstructions, on the other hand, indicate a pivotal role of brine
128 rejection from increased sea-ice formation in the Bering Sea and/or the Sea of Okhotsk, as a
129 mechanism driving enhanced GNPIW ventilation (Cook et al., 2016; Horikawa et al., 2010;
130 Knudson and Ravelo, 2015; Max et al., 2014; Rella et al., 2012). Alternatively, some
131 combination of both the sea ice and atmospheric teleconnection mechanisms might drive the
132 suggested overturning seesaw (Gong et al., 2019).

133 Although there are only a few LGM sea-ice reconstructions in the Bering Sea, previous
134 investigations demonstrate that sea-ice extent in the Bering Sea responds sensitively to
135 climate change on millennial and G/IG timescales (Caissie et al., 2010; Itaki et al., 2012;
136 Méheust et al., 2016, 2018), in line with a potential role of sea ice for GNPIW formation. As
137 of yet, however, no studies have co-investigated the sea-ice history of the Bering Sea in
138 combination with local changes in the biogeochemical cycling, to decipher the mechanisms
139 driving sea-ice variability, the potential of sea ice to trigger enhanced overturning, and its role
140 in the deglacial North Pacific carbon cycle.

141 This study, thus, uses a multi-proxy approach to simultaneously investigate past changes in
142 eastern Bering Sea sea-ice cover and changes in the biogeochemical cycling at Integrated
143 Ocean Drilling Program (IODP) Site U1343 (57°33.4'N, 176°49.0'W; 1953 m) (Figure 1)
144 (Expedition 323 Scientists, 2010) across the last ~40 ka. Sea-ice reconstructions are based on
145 source-specific biomarkers, while past changes in sedimentary redox chemistry are inferred

146 from authigenic foraminiferal U/Ca and U/Mn, in combination with the benthic foraminiferal
147 assemblage. This provides a more complete picture of the late Quaternary sea-ice evolution in
148 the North Pacific and its role for GNPIW formation and primary productivity.

149 **2. Regional oceanography**

150 The modern Bering Sea is characterized by a subarctic water column structure. Above the
151 permanent halocline (100-200 m) a warm surface layer (0-50 m) forms during summer
152 underlain by a cold dichothermal layer (50-200 m), a remnant of winter mixing (Miura et al.,
153 2002; Tanaka and Takahashi, 2005). Cooling and deepening of the thermocline during winter
154 promotes the formation of a winter mixed layer, restricted by the halocline depth (Miura et
155 al., 2002; Tanaka and Takahashi, 2005). While only little is known about the water masses in
156 the mid-depth Bering Sea today, the deep Bering Sea is characterized by NPDW (Coachman
157 et al., 1999; Stabeno et al., 1999), entering through Kamchatka Strait at depth below 2500 m
158 (Coachman et al., 1999; Stabeno et al., 1999) and modified by small amounts of deep water
159 that are formed in situ in the Bering Sea today (Warner and Roden, 1995).

160 The surface circulation in the Bering Sea forms a cyclonic gyre, fed by the inflow of
161 relatively warm and nutrient-rich Alaskan Stream waters through several passes in the
162 Aleutian Arc (Stabeno et al., 1999) (Figure 1). Within the Bering Sea, the cyclonic gyre is
163 composed of the eastward flowing Aleutian North Slope Current (ANSC), the Bering Slope
164 Current (BSC), and the southward flowing East Kamchatka Current (EKC). Main surface
165 outflow occurs through Kamchatka Strait, while some surface water (0.85 Sverdrup)
166 (Coachman, 1993) flows northward on the eastern Bering Sea shelf and into the Arctic Ocean
167 through the 50 m deep Bering Strait. Along the eastern Bering Sea slope, mesoscale eddies
168 form within the BSC, causing upwelling of nutrient-rich deep waters (Ladd et al., 2012;
169 Mizobata et al., 2008, 2002; Mizobata and Saitoh, 2004). Together with the mixing of shelf

170 and basin waters (Hurst et al., 2010; Springer et al., 1996; Tanaka et al., 2012) and nutrient
171 release during spring sea-ice melting (Wang et al., 2014), this fuels one of the most
172 productive ecosystems in the world’s ocean, often termed the ‘Green Belt’ (Springer et al.,
173 1996). High rates of primary productivity ($175\text{-}275\text{ g C m}^{-2}\text{ yr}^{-1}$, (Springer et al., 1996)) and
174 demineralization of sinking organic matter lead to depleted oxygen concentrations in mid-
175 depth waters, forming a pronounced oxygen minimum zone (OMZ) between 600-1000 m
176 (Figure 1) (Expedition 323 Scientists, 2010; Whitledge and Luchin, 1999). Within the core of
177 the OMZ, oxygen concentrations range from $0.43\text{-}1.57\text{ mg L}^{-1}$ ($0.3\text{-}1.1\text{ ml L}^{-1}$) (Whitledge
178 and Luchin, 1999). Beyond the Green Belt, the Bering Sea is largely characterized as a
179 HNLC region, with iron representing the limiting micronutrient (Aguilar-Islas et al., 2007;
180 Leblanc et al., 2005; Springer et al., 1996). However, a pronounced spring phytoplankton
181 bloom can be observed on the eastern shelf, tightly coupled to the northward retreat of sea ice
182 from March/April onwards (Brown and Arrigo, 2013; Niebauer et al., 1995).

183 Seasonal sea ice in the eastern Bering Sea originates in the Chukchi Sea and in polynyas on
184 the southward facing coastlines (Niebauer et al., 1999), with an average winter sea ice and
185 brine formation in Bering Sea polynyas of $10\text{-}12\text{ cm day}^{-1}$ and $0.006\text{-}0.042\text{ Sv}$, respectively
186 (Niebauer et al., 1999). Based on observational data and modelling studies, Cavalieri and
187 Martin (1994) concluded that brines formed on the eastern Bering shelf flow northward
188 across the shelf and into the Arctic Ocean. The maximum extent of sea ice in the eastern
189 Bering Sea is closely coupled to atmospheric and oceanic temperatures together with the
190 predominant direction of winter storm tracks (Rodionov et al., 2007). Typically, the
191 maximum sea-ice extent is reached near the eastern Bering Sea slope during March/April
192 (Figure 1). Recent years, however, have seen a pronounced retreat of the winter sea-ice edge
193 with important implications for the marine ecosystem (Brown et al., 2011; Brown and Arrigo,
194 2013; Grebmeier et al., 2006).

195 3. Materials and methods

196 3.1 IODP Site U1343

197 IODP Site U1343 (57°33.4'N, 176°49.0'W, water depth 1953 m) (Figure 1) was recovered
198 from a topographic high off the eastern Bering Sea slope. In total, five holes were cored (A-
199 E) and a composite depth scale was constructed between 0-270 m core composite depth using
200 cores from holes A, C, and E (Expedition 323 Scientists, 2010). Under modern conditions,
201 the core site is bathed in NPDW, characterized by local bottom water temperatures of 1.9°C,
202 salinities of 34.6, and [O₂] of 1.2 ml L⁻¹ (Garcia et al., 2014; Locarnini et al., 2013; Zweng et
203 al., 2013).

204 The age model is based on benthic foraminifera oxygen isotope ($\delta^{18}\text{O}_b$) stratigraphy (Asahi et
205 al., 2016; Kender et al., 2018; Worne et al., 2019) and correlation to the LR04 stack (Lisiecki
206 and Raymo, 2005). As the $\delta^{18}\text{O}_b$ record at Site U1343 is of relatively low resolution and
207 correlation to the LR04 stack has been performed over multiple G/IG cycles, uncertainty in
208 the chronology, especially when interpreting millennial-scale climate events, needs to be
209 considered. Across the last deglaciation a prominent reduction in mid-depth oxygen
210 concentrations in the North Pacific, related to increased productivity during interstadial
211 conditions, led to the expansion of the mid-depth OMZ in the Bering Sea and preservation of
212 laminated sediments, formed under anoxic conditions between ~800 m and 2100 m (Caissie
213 et al., 2010; Cook et al., 2005; Expedition 323 Scientists, 2010; Gersonde, 2012; Kuehn et al.,
214 2014; Max et al., 2012; Schlung et al., 2013). Previous studies on the north-eastern Bering
215 Sea slope (SO202-18-3/6, HLY02-02-3JPC (Figure 1)) at ~1000 m water depth have dated
216 the base of laminated sediment section to 14.4-14.6 ka and ~11.7 ka, corresponding to the
217 onset of the BA and the early Holocene, respectively (Cook et al., 2005; Kuehn et al., 2014).
218 At Site U1343 the base of the laminated intervals are found at 1.07 m CCSF-A and 2.69 m

219 CCSF-A (Supplementary Figure 1) (Expedition 323 Scientists, 2010). Using the $\delta^{18}\text{O}_b$
220 stratigraphy for Site U1343 recently updated by Worne et al. (2019) this yields ages of 10.5
221 ka and 16.3 ka for the base of the laminations, respectively. Considering that the present day
222 core of the OMZ lies at 800 m water depth (Expedition 323 Scientists, 2010; Whitledge and
223 Luchin, 1999), it seems unlikely that the onset of the laminations at 2000 m water depth
224 would predate those occurring at ~1000 m by ~2 kyr. Using the original $\delta^{18}\text{O}_b$ stratigraphy by
225 Asahi et al. (2016), the base of the laminated intervals at Site U1343 are dated to 10.5 ka and
226 14.7 ka, suggesting that this age model provides a better fit for the LGM-Holocene transition.
227 Thus, we use those age-depth tie points as the base for our chronology (Supplementary
228 Figure 2) (Table 1). Further, we added the bases of the laminations at 1.07 and 2.69 m CCSF-
229 A as additional age-depth tie points using ages of 11.7 ka and 14.5 ka, respectively, based on
230 previous studies from the north-eastern Bering Sea slope (Cook et al., 2005; Kuehn et al.,
231 2014) (Supplementary Figure 2). This approach assumes vertically synchronous expansion of
232 the OMZ between 1000 m and 2000 m at the onset of the BA and the early Holocene. The
233 expansion of the OMZ was most likely caused by the high rates of primary productivity
234 during interstadial phases and subsequent demineralization of organic matter in the water
235 column (Kuehn et al., 2014). This suggests that anoxic conditions associated with the OMZ
236 expansion might have occurred somewhat earlier at the shallower sites. Considering the
237 average sample resolution of our highest resolved dataset (0.5 kyr temporal spacing),
238 however, we assume this temporal discrepancy to be negligible. Further, by applying this
239 chronology, the mass accumulation rate of opal (MAR_{opal}) (Kim et al., 2014) peaks at ~13.5
240 ka at Site U1343 (Supplementary Figure 2) within the BA interval, consistent with similar
241 productivity peaks between ~13 ka and 14.5 ka from numerous other sites in the subarctic
242 North Pacific (Addison et al., 2012; Brunelle et al., 2007, 2010; Caissie et al., 2010; Cook et

243 al., 2005; Gebhardt et al., 2008; Jaccard et al., 2009; Kuehn et al., 2014; Ren et al., 2015;
244 Schlung et al., 2013).

245 Our chronology thus allows us to identify general millennial-scale trends at Site U1343
246 across the last deglaciation, while short-term events (e.g. the YD) and the exact timing of
247 stadial/interstadial boundaries should be considered with more caution.

248 **3.2 Sea-ice biomarker analyses**

249 **3.2.1 Methodology**

250 Reconstructions of past sea-ice extent are based primarily on selected source-specific highly
251 branched isoprenoid (HBI) biomarkers. IP₂₅ (Ice Proxy with 25 carbon atoms) is a mono-
252 unsaturated HBI produced by certain Arctic diatoms living in brine channels at the bottom
253 surface of seasonal sea ice (Belt, 2018; Belt et al., 2007; Brown et al., 2014). Thus, its
254 sedimentary presence provides binary evidence of past seasonal sea ice (Belt, 2018). To
255 complement IP₂₅ data, we co-measured a tri-unsaturated HBI (HBI III), produced by diatoms
256 characteristic of the spring sea-ice edge bloom within the open waters of the marginal ice
257 zone (MIZ) (Belt et al., 2017, 2015; Smik et al., 2016), and used the MAR_{opal} (Kim et al.,
258 2014), as an indicator of primary productivity. We also measured a di-unsaturated HBI (HBI
259 II), which typically co-varies with IP₂₅ in the Arctic (Belt et al., 2007; Brown et al., 2014;
260 Vare et al., 2009), and a range of sterol biomarkers. Sterols are common lipids in cell
261 membranes of eukaryotic organisms, occurring in a range of marine primary producers and in
262 higher plants, which can complicate their use as environmental tracers (Belt and Müller,
263 2013; Volkman, 1986). Nonetheless, diatoms are a common source of brassicasterol and
264 dinosterol in the marine realm (Volkman, 1986; Volkman et al., 1998; Volkman, 2006) and
265 they are routinely applied as indicators of open water productivity (e.g. Berben et al., 2017;
266 Méheust et al., 2013; Müller et al., 2009; Navarro-Rodriguez et al., 2013). Other sterols, such

267 as campesterol and β -sitosterol, on the other hand, are more common in higher plants and are
268 often considered to reflect terrestrial organic matter (Volkman, 1986; Volkman, 2006).

269 **3.2.2 Lipid extraction and analysis**

270 Biomarkers were extracted from ~3 g of freeze-dried homogenized sediments. The samples
271 were freeze dried (-45°C; 0.2 mbar; 48 h) using an Edwards K4 Modulyo freeze drier and a
272 Christ Alpha 1-4 LSC freeze drier at Cardiff and Aarhus University, respectively. Dried
273 samples were homogenized using an agate pestle and mortar. 9-octylheptadec-8-ene (9-OHD)
274 and 5 α -androstan-3 β ol (0.1 μ g each) were used as internal standards for HBI and sterol
275 quantification, respectively. Lipid biomarkers were extracted using two different extraction
276 techniques. A relatively small number of samples (n = 15) were extracted using
277 Dichloromethane (DCM):Methanol (2:1, v/v) as outlined in Belt et al. (2012). Elemental
278 Sulphur was removed from extracts using tetrabutylammonium sulphite (Cabedo-Sanz and
279 Belt, 2015) and lipid classes were separated using silica column chromatography. Apolar
280 lipids (e.g. HBIs) were eluted with hexane, while more polar lipids, including sterols, were
281 eluted using hexane/methyl acetate (1:4; v/v). All other samples (n = 28) were extracted by a
282 saponification-based method (5% Potassium hydroxide (KOH) solution in Methanol:H₂O
283 (9:1, v/v); 70°C; 1 h). After cooling to room temperature, the non-saponifiable lipids were
284 extracted (hexane; 3 x 2 mL), transferred into glass vials, and dried (N₂; 25°C). HBI fractions
285 were further purified using silver-ion chromatography (5:95 AgNO₃:SiO₂). Saturated
286 hydrocarbons were eluted with hexane (1 mL) and HBI fractions then eluted with acetone (2
287 mL). Sterol fractions were derivatised using N,O- Bis(trimethylsilyl)trifluoroacetamide
288 (50 μ L, 70 °C, 1 h) and diluted with 0.5 mL DCM immediately prior to analysis by gas
289 chromatography-mass spectrometry (GC-MS). To check for consistency between the two
290 extraction procedures, five samples (between ~8 ka and ~24 ka) were extracted using both
291 methods and the HBI fractions purified using silver-ion chromatography. The IP₂₅ and HBI

292 III concentrations were comparable between the two methods with an average relative
293 standard deviation (r.s.d.) of 11% and 16% and a significant correlation between the two
294 methods for both IP₂₅ ($R^2 = 0.99$ [0.98; 1], $n = 5$) and HBI III ($R^2 = 0.99$ [0.99; 1], $n = 5$)
295 (Supplementary Figure 3 and 4). As such, we consider the HBI data from both methods to be
296 mutually consistent. In contrast, brassicasterol concentrations were significantly lower with
297 the DCM:Methanol extraction method, likely due to a (variable) percentage of the total
298 extracted sterols remaining in a bound format and thus not readily derivatised using BSTFA.
299 As such, we only report brassicasterol concentrations for samples obtained using the KOH
300 extraction method.

301 All biomarker samples were analyzed at Plymouth University using an Agilent 7890A GC
302 coupled to a 5975 series mass selective detector fitted with an Agilent HP-5ms column. The
303 operating conditions are specified in Belt et al. (2012). The identification of individual lipids
304 was based on their characteristic retention indices and mass spectra (Belt, 2018), while
305 quantification was achieved through comparison of the integrated peak area (PA) of the
306 selected ions (m/z 350 (IP₂₅); 348 (HBI II); 346 (HBI III); 470 (brassicasterol); 458
307 (cholesterol); 382 (campesterol); 396 (β -sitosterol)) with the PA of the respective internal
308 standards (Belt et al., 2012), together with individual instrumental response factors and the
309 mass of sediment extracted (Belt et al., 2012).

310 Semi-quantitative measures of sea-ice extent were determined via the so-called PIP₂₅ index
311 (Müller et al., 2011) and classification tree (CT) methods (Köseoğlu et al., 2018b, 2018a).
312 The latter is based on distributions of a suite of HBIs in surface sediments from the Barents
313 Sea, which has a similar modern sea-ice cycle to the Bering Sea (Köseoğlu et al., 2018a,
314 2018b). CT analysis categorizes sea-ice conditions into marginal (0-10%), intermediate (10-
315 50%), and extensive (>50%) spring sea-ice concentration. PIP₂₅ indices (Equation 1) were
316 calculated for both HBI III (P_{III}IP₂₅) (Smik et al., 2016) and brassicasterol (P_BIP₂₅) (Müller et

317 al., 2011) as counterparts to IP_{25} , with the c-factor (Equation 2) based on the average
318 biomarker concentrations in the analyzed interval.

$$319 \quad PIP_{25} = \frac{[IP_{25}]}{([IP_{25}] + ([phytoplankton\ marker] * c))} \quad (1)$$

$$320 \quad c = \frac{mean [IP_{25}]}{mean [phytoplankton\ marker]} \quad (2)$$

321 **3.3 Geochemical and taxonomic foraminiferal analyses**

322 In total, 27 samples (10 cc) between ~8 ka and ~42 ka with an average resolution of ~1.4 ka
323 were processed for foraminiferal geochemistry and taxonomy. The samples were washed
324 over a 63 μ m sieve and dried over night at 30°C. Benthic and planktonic foraminifera were
325 counted and picked from the 150-250 μ m size fraction.

326 **3.3.1 Authigenic foraminiferal U/Ca and U/Mn**

327 The authigenic U/Ca (aU/Ca) and U/Mn (aU/Mn) of planktonic and benthic foraminifera are
328 sensitive to sedimentary redox conditions, via post-depositional diagenetic processes, and
329 have recently been proposed as proxies for sedimentary redox chemistry (Boiteau et al.,
330 2012; Chen et al., 2017; Gottschalk et al., 2016). At Site U1343 scanning electron
331 microscope images and geochemical analyses of discolored foraminiferal specimens clearly
332 demonstrate authigenic carbonate formation, related to organoclastic sulphate reduction (> 8
333 meters below seafloor (mbsf)) and anaerobic oxidation of methane (~8 mbsf) (Detlef et al.,
334 2020). Compared to primary foraminiferal carbonate, foraminifera-bound authigenic
335 carbonates are enriched in both U and Mn (Detlef et al., 2020), suggesting that U/Ca and
336 U/Mn may be valuable proxies to determine past changes in sedimentary redox chemistry at
337 Site U1343. In the modern ocean uranium behaves conservatively in seawater but is removed
338 from pore waters as U^{4+} under anoxic conditions (Boiteau et al., 2012). Both planktonic and
339 benthic foraminiferal tests act as a low uranium substrate (3-23 nmol/mol) (Boiteau et al.,

2012; Chen et al., 2017; Raitzsch et al., 2011; Russell et al., 2004) and can accumulate
authigenic uranium. As the ionic radius of U^{4+} is similar to that of Ca^{2+} , U^{4+} can be readily
incorporated into authigenic carbonates forming in the sediment during early diagenesis
(Sturchio et al., 1998; Zhao et al., 2016). Sedimentation rates of $34 \pm 11 \text{ cm ka}^{-1}$ (Asahi et al.,
2016) at Site U1343 suggest that authigenic U accumulation is unlikely to be affected by re-
oxidation processes. Manganese, on the other hand, precipitates as Mn^{4+} in sediments under
oxic conditions in the form of Mn-oxides or Mn-carbonates and is re-dissolved into pore
waters as Mn^{2+} under reducing conditions (Froelich et al., 1979). The dissolved Mn^{2+} either
migrates upwards until it reaches the depth of oxygen penetration where it re-precipitates or
is removed from pore waters by the formation of diagenetic carbonates (Froelich et al., 1979;
Pedersen and Price, 1982). Thus, Gottschalk et al. (2016) proposed to normalize authigenic
foraminiferal uranium to manganese (U/Mn) rather than calcium (U/Ca), to avoid species-
specific differences resulting from changes in the surface-to-mass ratio. Recently, however,
Skinner et al. (2019) showed that U and Mn might be incorporated into foraminiferal
authigenic coatings in different ways and caution should be taken when interpreting aU/Mn
alone.

As the abundance of different benthic foraminiferal species varies across the analyzed time
interval, the record of authigenic trace metals is based on multiple species. Authigenic
foraminiferal trace metals were analyzed for the benthic foraminiferal species *Islandiella*
norcrossi (n = 7) and *Uvigerina* spp. (n = 3), and the planktonic foraminiferal species
Neogloboquadrina pachyderma (n = 6), for all samples with sufficient specimens (>80 μg).
We were unable to determine planktonic aU/Mn ratios, as *N. pachyderma* samples were too
small to yield reliable Mn/Ca results (signal-to-noise-ratio < 5). Previous studies suggest that
foraminiferal aU/Ca may be susceptible to changes in the surface-to-mass-ratio of
foraminiferal tests, indicating that aU/Ca is likely species-specific and sensitive to the

365 foraminiferal test size (Gottschalk et al., 2016). To circumvent the effect of test size on
366 authigenic mineral precipitation, both planktonic and benthic foraminifera were picked from
367 a narrow size fraction (150-250 μm). Planktonic aU/Ca was measured exclusively on *N.*
368 *pachyderma*, avoiding any effects of species-specific surface-to-mass ratio on aU/Ca.

369 Analyses of authigenic foraminiferal trace metals typically only require weak chemical
370 cleaning (Gottschalk et al., 2016) to preserve the authigenic geochemical signal. Benthic
371 foraminiferal samples at Site U1343, however, were also analyzed for primary foraminiferal
372 trace metal ratios, such as Mg/Ca, a faithful proxy of bottom water temperatures (e.g. Lea et
373 al., 1999; Nürnberg et al., 1996; Rosenthal et al., 1997). Thus, benthic foraminiferal samples
374 were cleaned according to the Cd-cleaning protocol (Boyle, 1983; Boyle and Keigwin, 1985),
375 consisting of: (i) A clay removal step with repeated rinses in UHQ water and methanol with
376 intervals of ultrasonication, to remove adhered clay particles. (ii) A reductive step in a hot
377 solution of 1200 μl hydrous hydrazine in a citric acid (10 mL)/ammonia (10 mL) buffer for
378 30 minutes, including several intervals of short (~5 seconds) ultrasonication followed by
379 extensive rinsing with UHQ water and a sample transfer to fresh acid-cleaned micro-
380 centrifuge tubes, targeting the removal of oxide coatings. (iii) An oxidative step in a hot
381 solution of alkali (0.1 M NaOH) buffered 1% H_2O_2 to remove remnant organic material. (iiii)
382 A dilute acid leach in 0.001 M HNO_3 to remove remaining contaminants adsorbed to the
383 surface of the foraminifera fragments. Planktonic foraminifera, on the other hand, were
384 cleaned according to the Mg-cleaning protocol (Barker et al., 2003), which omits the
385 reductive step compared to the Cd-cleaning protocol. As, Cd-cleaning is more effective in the
386 removal of authigenic mineral phases compared to Mg-cleaning (Hasenfratz et al., 2017;
387 Pena et al., 2005), Cd-cleaned benthic foraminiferal trace metal ratios can be compared to
388 Mg-cleaned planktonic foraminiferal trace metal ratios to ensure a signal of authigenic origin.

389 Following the chemical cleaning, foraminiferal samples were dissolved in 120 μ L 0.065M
390 HNO₃. All samples were analyzed using a Thermo Element XR High Resolution Inductively
391 Coupled Plasma Mass Spectrometer (ICP-MS) at Cardiff University. Trace metal ratios were
392 quantified using matrix-matched standards and two consistency standards were run at the
393 beginning and end of every sequence. The two consistency standards have U/Ca
394 concentrations of 4.49 nmol/mol and 27.21 nmol/mol, respectively and U/Mn concentrations
395 of 0.16 mmol/mol and 0.14 mmol/mol, respectively. The long-term reproducibility between
396 2015 and 2018 (n = 25) was $\pm 3.03\%$ (relative standard deviation, r.s.d.), $\pm 2.63\%$ (r.s.d.),
397 $\pm 3.11\%$ (r.s.d.), and $\pm 2.26\%$ (r.s.d.) for U/Ca and U/Mn, respectively.

398 **3.3.2 Benthic foraminiferal assemblages**

399 Benthic foraminiferal assemblages in the mid-depth Bering Sea is dominated by calcareous
400 infaunal species, controlled primarily by the supply of organic matter to the sediments
401 (Kender et al., 2019; Kender and Kaminski, 2017; Okazaki et al., 2005; Setoyama and
402 Kaminski, 2015). The dominant species are typically tolerant of high-productivity-low-
403 oxygen conditions, related to the pronounced mid-depth OMZ and export of organic carbon
404 to the sediments, particularly within the Green Belt along the eastern Bering Sea slope
405 (Expedition 323 Scientists, 2010; Kender et al., 2019; Khusid et al., 2006; Setoyama and
406 Kaminski, 2015).

407 Typically, foraminiferal census counts rely on a representative subset of the sample with
408 >300 specimens. However, at Site U1343 the foraminiferal abundance is generally low
409 (Expedition 323 Scientists, 2010) with 0-309 specimens in the 150-250 μ m fraction per
410 sample for the studied interval. We consider all samples with >50 specimens for
411 environmental inferences, which has previously been shown to yield reliable diversity at the
412 Bowers Ridge in the southern Bering Sea (Kender et al., 2019).

413 In addition to the relative abundance of species with strong environmental preferences (e.g.
414 *Bulimina exilis*), we use correspondence analysis (CA) to gain insights into the overall
415 changes in benthic foraminiferal assemblages at Site U1343. CA (using the software PAST
416 (Hammer et al., 2001)) was performed on all samples with >50 specimens. Species that only
417 occurred in very low numbers (<10 specimens for the entire dataset) were grouped and
418 excluded from the CA. CA uses reciprocal averaging to compare the species within a given
419 dataset (Greenacre, 1983), with CA scores characterizing similar faunal traits (e.g. Hammer
420 and Harper, 2006; Kender et al., 2019). The CA axes describe the variance in the dataset,
421 corresponding to the ecological parameter predominantly controlling the abundance of
422 species within the assemblage.

423 **3.4 Statistical analyses**

424 Correlation analyses of time-series data ($n > 10$) was performed in PearsonT3 (Mudelsee,
425 2003), which automatically performs mean detrending and estimates the persistence time of
426 both variables. The reported confidence intervals (CI) for these correlations are students t CIs
427 based on nonparametric bootstrapping (Mudelsee, 2003). For all time-series data with $n < 10$
428 and non-time-series data, correlation analyses were performed in R Studio (R Studio Team,
429 2015) with a 95% significance level. We further calculated a 10-pt moving window
430 correlation for IP_{25} and HBI III, as well as IP_{25} from Site U1343 and IP_{25} from SO202-27-6,
431 in R Studio (R Studio Team, 2015) with CIs based on Monte Carlo simulations ($n = 10,000$)
432 of random variables with the same amount of observations and window width as for the data
433 set.

434 **4. Results**

435 **4.1 Sea ice related biomarkers**

436 **4.1.2 HBI biomarker concentrations in sediments from MIS 3 to MIS 1 at IODP Site**
437 **U1343**

438 HBIs were measured on 43 samples with an average temporal resolution of 0.5 ka between
439 7.8 ka and 25 ka and 2.5 ka between 25 ka and 42.5 ka. IP₂₅ concentrations vary from 0-6.2
440 ng/g sed with the highest concentrations occurring during early MIS 2 at ~25 ka (Figure 2).

441 In general, IP₂₅ is relatively high during MIS 3 and MIS 2 (mean concentration = 3.2 ng/g
442 sed.) and much lower during early MIS 1 (mean concentration = 0.2 ng/g sed.) (Figure 2).

443 HBI II varies between 0 ng/g sed and 29.9 ng/g sed. It follows the IP₂₅ trend with a
444 significant correlation between the two biomarkers ($R^2 = 0.90$ [0.49; 0.98], $n = 43$), as
445 expected given their co-production (Brown et al., 2014). Since HBI II concentrations are
446 higher than those for IP₂₅, its detection in some samples where IP₂₅ could not be quantified
447 (BA and early Holocene) suggests that the latter was likely present, but below the limit of
448 detection and thus in very low concentration.

449 HBI III concentrations vary between 0.4 ng/g sed and 43.5 ng/g sed. and are generally low
450 during MIS 3 and MIS 2 (<3.2 ng/g sed) with local maxima around 16 ka and 21 ka (Figure
451 2). MIS 1 is characterized by an increase in HBI III concentrations at the BA/YD transition
452 up to ~4.5 ng/g sed., followed by a sharp decrease. Starting at ~11 ka HBI III concentrations
453 increase to values of up to 43.5 ng/g sed., an order of magnitude higher than values during
454 MIS 3 and MIS 2 (Figure 2). HBI III and IP₂₅ show a weak negative correlation ($R^2 = -0.35$ [-
455 0.58; -0.06], $n = 43$) for the entire dataset, which is likely influenced by the extreme increase
456 of HBI III during the early Holocene. We thus calculated a 10-pt moving window correlation
457 with 95% and 99% confidence intervals based on Monte Carlo simulations ($n = 10,000$) of
458 random variables with 43 data points and a window width of 10. The running correlation
459 reveals no significant correlation of IP₂₅ and HBI III throughout the analyzed interval

460 (Supplementary Figure 5), consistent with a pronounced seasonal sea-ice cycle in the eastern
461 Bering Sea from late MIS 3 to the early Holocene (Detlef et al., 2018).

462 All HBIs exhibit millennial-scale variability across the last deglaciation (Figure 2). HS1 is
463 marked by an increase in IP₂₅, HBI II, and HBI III. Both IP₂₅ and HBI II demonstrate an early
464 (~17.5 ka) and mid-HS1 peak (~16 ka). HBI III, on the other hand, is characterized by one
465 broad peak during mid-HS1 (~15.3-16.4 ka) (Figure 2), which coincides with the second peak
466 in IP₂₅ and HBI II. Late HS1 (<15.3 ka) sees a rapid decrease in the concentrations of all
467 three HBIs towards the BA. IP₂₅ and HBI II are low throughout the BA, with IP₂₅ below the
468 level of detection. During the YD, both biomarkers increase again, although with lower
469 concentrations compared to the early deglaciation (Figure 2). HBI III is low during the early
470 BA and increases again towards the end, peaking around the BA/YD transition followed by
471 another decrease (Figure 2). The early Holocene is marked by a sharp increase in HBI III yet
472 low IP₂₅ and HBI II concentrations (Figure 2).

473 **4.1.3 Sterol biomarker concentrations in sediments from MIS 3 to MIS 1 at IODP Site** 474 **U1343**

475 We analyzed 28 samples from 7.8 ka to 25 ka with an average temporal resolution of 0.63 ka
476 for their brassicasterol, campesterol, cholesterol, and β -sitosterol content. Sterol
477 concentrations vary between 3.1-23.6 $\mu\text{g/g sed.}$, 2.0-12.3 $\mu\text{g/g sed.}$, 3.2-18.0 $\mu\text{g/g sed.}$, and
478 3.8-19.8 $\mu\text{g/g sed.}$ for brassicasterol, campesterol, cholesterol, and β -sitosterol, respectively
479 (Figure 2). The temporal trend in sterol biomarker concentrations is relatively uniform with
480 small differences between sterols classified as being predominantly marine (brassicasterol
481 and cholesterol) and predominantly terrestrial (campesterol and β -sitosterol). In general,
482 sterol concentrations are low during the LGM, followed by an increase during HS1. The
483 increase in campesterol and β -sitosterol across HS1 is more continuous compared to

484 brassicasterol and cholesterol, suggesting a two-stepped increase (Figure 2). Maximum sterol
485 concentrations occur during the early BA, followed by a decrease into the early Holocene
486 (Figure 2). Across the YD, sterol concentrations were only measured for one sample, thus we
487 cannot draw reliable conclusions for this period. Across the early Holocene, brassicasterol
488 and cholesterol are consistently low, while campesterol and β -sitosterol have a local
489 maximum at the onset of the Holocene (Figure 2).

490 **4.1.4 Semi-quantitative sea-ice reconstructions based on the PIP₂₅ index and** 491 **classification tree analysis**

492 P_{III}IP₂₅ and P_BIP₂₅ vary from 0-0.65 and 0-0.61, respectively, indicating reduced/ice free to
493 seasonal sea-ice conditions in the eastern Bering Sea across the last ~45 ka. P_{III}IP₂₅ is high
494 throughout most of MIS 3 and MIS 2 (~0.3-0.7) with a decrease observed during late HS1
495 (Figure 3). This is followed by low values during MIS 1 with the exception of two data points
496 in the YD (Figure 3). There are no P_BIP₂₅ data beyond 25 ka (see section 4.1.3), but P_BIP₂₅ is
497 generally high during MIS 2 (~0.4-0.6) with a decrease during late HS1 and overall low
498 values throughout MIS 1 apart from one data point that falls into the YD interval (Figure 3).
499 Although P_BIP₂₅ and P_{III}IP₂₅ are highly correlated ($R^2 = 0.94$ [0.88; 0.97], $n = 28$), some
500 differences in the peak values occur during the YD, late HS1, and around 25 ka (Figure 3).

501 According to the CT approach (Köseoğlu et al., 2018b, 2018a), sea-ice conditions in the
502 eastern Bering Sea were generally extensive (i.e. >50% spring sea-ice concentration) during
503 MIS 3 and early MIS 2 (Figure 3). Intermediate sea-ice conditions (i.e. 10-50%)
504 characterized the mid to late MIS 2 with a sporadic return to extensive sea-ice extent during
505 early HS1 and a decrease to marginal ice conditions (i.e. <10%) at the HS1/BA transition
506 (Figure 3). Early MIS 1 is also characterized by marginal sea-ice conditions with two peaks

507 of intermediate sea-ice concentrations during the YD (Figure 3). Thus, the overall trend of the
508 two PIP₂₅ indices and CT results compare well, especially across the deglaciation (Figure 3).

509 **4.2 Authigenic foraminiferal geochemistry**

510 **4.2.1 Authigenic benthic and planktonic foraminiferal U/Ca**

511 Foraminiferal aU/Ca ratios at Site U1343 were determined on 6 *N. pachyderma*, 3 *Uvigerina*
512 spp., and 7 *I. norcrossi* samples between 10.0 ka and 27.2 ka (Figure 4). Planktonic aU/Ca
513 are consistently higher compared to benthic aU/Ca, with an offset of 6.1-12.0 nmol/mol
514 (Figure 4), as a result of more effective removal of authigenic mineral phases during Cd-
515 cleaning.

516 Planktonic foraminiferal aU/Ca ranges from 10.6-48.8 nmol/mol with highest values during
517 the early Holocene (Figure 4). Benthic foraminiferal aU/Ca varies between 4.4 nmol/mol and
518 18.2 nmol/mol. Although foraminiferal U/Ca ratios are low and predominantly within the
519 range expected for primary foraminiferal calcite (<23 nmol/mol (Boiteau et al., 2012; Chen et
520 al., 2017; Raitzsch et al., 2011; Russell et al., 2004)), we argue for an authigenic origin.

521 Previous studies propose that primary foraminiferal U/Ca responds to changes in $\Delta[\text{CO}_3^{2-}]$
522 (Keul et al., 2013; Raitzsch et al., 2011), although recent core-top results by Chen et al.

523 (2017) did not find a significant correlation between benthic foraminiferal U/Ca and
524 carbonate system parameters. Parallel benthic and planktonic aU/Ca ratios, available for 4
525 samples at Site U1343, show a significant positive correlation ($R^2 = 0.98$ [0.28;1], $n = 4$).

526 This, together with previous results on the presence of high U and Mn authigenic carbonates
527 at Site U1343 (Detlef et al., 2020), strongly suggests that the aU/Ca signal was acquired post-
528 depositional when co-deposited benthic and planktonic foraminifera tests were exposed to the
529 same sedimentary redox conditions.

530 The benthic foraminiferal assemblage is characterized by a faunal change associated with the
531 deglaciation. MIS 2 benthic aU/Ca was measured on *I. norcrossi* (4.4-18.2 nmol/mol), while
532 benthic aU/Ca across MIS 1 was measured exclusively on *Uvigerina* spp. (7.1-10.0
533 nmol/mol) (Figure 4). This suggests, that the benthic aU/Ca change associated with the
534 transition from *I. norcrossi* to *Uvigerina* spp. could reflect changes in the species-specific
535 accumulation of authigenic mineral phases (due to differences in the surface-to-mass ratio
536 and/or shell morphology) rather than sedimentary redox changes. Nonetheless, intra-species
537 benthic aU/Ca changes across MIS 2 and MIS 1, respectively, can be interpreted as reflecting
538 relative changes in the sedimentary redox chemistry at Site U1343.

539 There are two episodes of decreased *I. norcrossi* aU/Ca at ~24.7 ka and ~17.4 ka suggesting
540 changes in the sedimentary redox chemistry across MIS 2 (Figure 4). While there is no
541 planktonic aU/Ca data available around 24.7 ka, a contemporaneous decrease in planktonic
542 aU/Ca is observed at ~17.4 ka (Figure 4), substantiating the proposed sedimentary redox
543 changes based on benthic aU/Ca. Across the deglaciation benthic aU/Ca remains relatively
544 constant, however this is associated with the faunal change from *I. norcrossi* to *Uvigerina*
545 spp. Planktonic aU/Ca, on the other hand, demonstrates an increase associated with the
546 deglaciation, suggesting more reducing conditions (Figure 4), in line with the preservation of
547 laminated sediments at Site U1343.

548 **4.2.2 Authigenic benthic foraminiferal U/Mn**

549 Benthic aU/Mn varies between 0.1-0.2 mmol/mol and 0.5-1.2 mmol/mol for *Uvigerina* spp.
550 and *I. norcrossi*, respectively (Figure 4). Across MIS 2 benthic aU/Mn, based on *I. norcrossi*,
551 shows two episodes of decreased ratios around 25 ka and 17.5 ka, corresponding to
552 simultaneous decreases in the benthic aU/Ca ratio and the planktonic aU/Ca ratio at ~17.5 ka
553 (Figure 4). Additionally, *Uvigerina* spp. aU/Mn suggest changes in the sedimentary redox

554 chemistry associated with the YD interval. However, it is unclear how this relates to the
555 changes observed during MIS 2 due to the faunal shift in the benthic foraminiferal
556 assemblage.

557 Although previous studies suggested, that aU/Mn is less susceptible to species-specific
558 changes in the surface-to-mass ratio (Gottschalk et al., 2016), benthic foraminiferal aU/Mn
559 decreases across the deglaciation associated with the shift from *I. norcrossi* to *Uvigerina* spp.,
560 while planktonic aU/Ca increases and the preservation of laminated sediments at Site U1343
561 indicate more reducing conditions (Figure 4, Supplementary Figure 1). There are several
562 potential explanations for the observed discrepancy. Firstly, planktonic aU/Ca and benthic
563 aU/Mn were not measured on the same sample material across MIS 1. Thus, it is possible that
564 both reflect actual changes in the sedimentary redox chemistry with large shifts on relatively
565 short timescales of ~1 ka (Figure 4). On the other hand, benthic aU/Mn may be subject to
566 species-specific effects, similar to benthic aU/Ca. Species-specific effects may result from
567 differences in the accumulation of authigenic carbonates due to differences in the surface-to-
568 mass ratio or shell morphology and/or differences in the partitioning of Mn and U into
569 primary foraminiferal calcite. Both U/Ca and Mn/Ca ratios of benthic foraminifera are within
570 the range expected for primary foraminiferal calcite across the analyzed interval (<23
571 nmol/mol and <50 μ mol/mol for U/Ca and Mn/Ca, respectively (Chen et al., 2017; Raitzsch
572 et al., 2011; Russell et al., 2004)). Even though the co-variance of benthic and planktonic
573 U/Ca ratios strongly supports a signal of predominantly authigenic origin, relatively low
574 U/Ca and Mn/Ca ratios could result in aU/Mn being more susceptible to species-specific
575 differences in the primary trace metal partitioning. Koho et al. (2017), for example,
576 demonstrate differences in the primary foraminiferal Mn/Ca ratio based on the microhabitat
577 preferences of the living organism, with deep infaunal foraminifera having higher Mn/Ca
578 ratios in response to changes in the dissolved Mn concentrations. If microhabitat preferences

579 were the determining factor of foraminiferal Mn/Ca ratios, an average Mn/Ca of 40.6
580 $\mu\text{mol/mol}$ and 11.4 $\mu\text{mol/mol}$ for *Uvigerina* spp. and *I. norcrossi*, respectively would suggest
581 a shallower habitat for *I. norcrossi*. While *Uvigerina* spp. has a proposed habitat depth of 1-2
582 cm within the sediment (Tachikawa and Elderfield, 2002), *I. norcrossi* may be migrating
583 between shallower and deeper layers in search of a preferred microhabitat (Hunt and Corliss,
584 1993; Ishimura et al., 2012; Ivanova et al., 2008), potentially in line with the observed
585 differences in Mn/Ca ratios between the two species. Further, results by Skinner et al. (2019)
586 suggest that Mn and U may be incorporated into authigenic foraminiferal coatings in different
587 ways, with Mn tracking the dissolved pore water Mn concentrations, while U appears to
588 record changes in the U-flux to the sediments, complicating a straightforward application of
589 aU/Mn as a proxy for changes in the sedimentary redox chemistry.

590 Nonetheless, aU/Mn of *I. norcrossi* supports the two intervals of less reducing sedimentary
591 redox conditions across MIS 2 (~17.5 and 25 ka), observed in both benthic and planktonic
592 aU/Ca (Figure 4). Across the deglaciation planktonic aU/Ca seems to provide the most
593 reliable trends in sedimentary redox chemistry changes, as benthic aU/Ca and aU/Mn are
594 likely affected by changes in the assemblage composition and thus subject to species-specific
595 effects (Figure 4).

596 **4.3 Benthic foraminiferal assemblage**

597 At Site U1343 the dominant benthic foraminiferal species are *Elphidium batialis* Saidova
598 (1961), *Uvigerina* spp., *Islandiella norcrossi* (Cushman, 1933), *Bulimina exilis* Brady (1884),
599 *Cassidulinoides parkerianus* (Brady, 1881), *Nonionella labradorica* (Dawson, 1860),
600 *Valvulineria araucana* (D'Orbigny, 1839), and *Globobulimina* spp. (predominantly *G.*
601 *pacifica* Cushman (1927) and *G. affinis* (D'Orbigny, 1839)). When present, *B. exilis* typically
602 occurs in large abundances and dominates the benthic foraminiferal assemblage. *B. exilis* is

603 tolerant to hypoxic conditions and has previously been reported from environments with very
604 high primary productivity and export of labile organic matter to the seafloor (Caralp, 1989;
605 Cauille et al., 2014; Filipsson et al., 2011; Jannink et al., 1998; McKay et al., 2016). During
606 MIS 2 the abundance of *B. exilis* varies between 30-45 % (Figure 4) with two pronounced
607 decreases to 20 % at ~25 ka and 1.5-3 % between ~16.4-17.4 ka (Figure 4). Following the
608 latter decrease the abundance increases to >80 % and then remains high throughout MIS 1
609 compared to MIS 2 (Figure 4).

610 The CA analysis also reveals clear changes in the benthic foraminiferal assemblage across the
611 last glacial interval and the deglaciation. CA axis 1 describes 45 % of the total variance in the
612 dataset, with negative scores for *B. exilis*, *N. labradorica*, and *Uvigerina* spp. (Assemblage 1)
613 and positive scores for *E. batialis*, *N. digitata*, *Globobulimina* spp., and *I. norcrossi*
614 (Assemblage 2) (Supplementary Figure 6). CA axis 2 explains 24 % of the total variance and
615 shows negative correlation with *C. parkerianus*, *V. araucana*, and *I. norcrossi* (Assemblage
616 3) and positive correlation with *E. batialis*, *N. digitata*, and *Uvigerina* spp. (Supplementary
617 Figure 6). Axes 3 explains 12 % of the variance but does not define another meaningful
618 assemblage.

619 MIS 2 is dominated by Assemblage 3, as seen from the negative scores for CA axis 2. The
620 even lower scores during HS1 and Heinrich Stadial 2 (HS2, 24.3-26.5 ka) are driven by an
621 increase in the abundance of *C. parkerianus* (Figure 4). Simultaneously, CA axis 1 increases
622 during HS1 and HS2, driven by a decrease in the abundance of *B. exilis* (Figure 4). Across
623 the deglaciation, Assemblage 1 becomes dominant, as seen from the decrease in scores for
624 CA axis 1 (Figure 4). The increase in the scores for CA axis 2 during the deglaciation is
625 dominated by the occurrence of *Uvigerina* spp., while all other species positively correlated
626 with CA axis 2 remain low.

627 **5. Discussion**

628 **5.1 Sea-ice dynamics in the eastern Bering Sea and the subarctic North Pacific across** 629 **the last ~40 ka**

630 The seasonal extent of sea ice in the modern Bering Sea is governed by the interplay of
631 atmospheric and oceanic forcings (Zhang et al., 2010). While low atmospheric and sea
632 surface temperatures (SST) initiate sea ice formation during winter, prevailing northerly
633 winds over the Bering Sea cause a south-eastward expansion, with the maximum position of
634 the ice edge determined by the SST-induced melting of sea ice (Zhang et al., 2010). Across
635 the last ~ 40 ka, these boundary conditions changed continuously in response to global
636 climate and the transition from a glacial to an interglacial state, affecting the sea-ice
637 concentration in the Bering Sea and the subarctic North Pacific.

638 Biomarker-based sea-ice reconstructions at Site U1343 in the eastern Bering Sea reveal
639 dynamic behavior on G/IG timescales, with an overall decrease in the spring sea-ice
640 concentration between the last glacial maximum (LGM) and the early Holocene and
641 millennial-scale variability across the last deglaciation (Figure 2). Late MIS 3 to LGM
642 conditions are characterized by elevated IP₂₅ concentrations, with maximum values during
643 early MIS 2 (Figure 2). Contemporaneously, HBI III and sterol concentrations are low, in line
644 with the MAR_{opal} at Site U1343 (Kim et al., 2014) (Figure 2), attributed to low primary
645 productivity and no spring sea ice bloom in the vicinity of the core site. In combination with
646 the P_{III}IP₂₅, P_BIP₂₅, and CT results (Figure 3) this suggests extensive seasonal sea ice in the
647 eastern Bering Sea during late MIS 3 and early MIS 2 with a transition towards slightly
648 decreased sea-ice extent around 23 ka (Figure 2, Figure 3). This is corroborated by
649 radiolarian and diatom assemblages in the north-eastern Bering Sea and at the Umnak Plateau
650 (Caissie et al., 2010; Itaki et al., 2012). While the record of diatom assemblages only reaches

651 back to ~22 ka, the abundance of *Actinomma boreale* and *A. leptodermum*, radiolarian
652 species characteristic of extensive to perennial sea ice environments, is highest during early
653 MIS 2, decreasing towards ~23 ka and again at ~21 ka (Figure 5) (Itaki et al., 2012). Thus,
654 throughout the studied interval, the eastern Bering Sea might have experienced the most
655 severe sea-ice conditions during early MIS 2, coinciding with HS2. Additional support for an
656 expanded sea-ice cover during MIS 2 compared to today, comes from sea-ice biomarker
657 studies in the eastern (SO202-27-6) and western (SO202-07-6) North Pacific (Figure 5),
658 demonstrating extended to marginal sea-ice conditions, respectively (Méheust et al., 2018)
659 and the central Sea of Okhotsk (Lo et al., 2018). In contrast, sea ice related diatoms are
660 absent in LGM sediments at the Bowers Ridge (BOW-12A) (Katsuki and Takahashi, 2005),
661 while IRD occurrence is consistently high (GC-11, GC-13) (Gorbarenko et al., 2010),
662 indicating (at least) the occurrence of drift ice in the central southern Bering Sea.

663 As previously mentioned, the sea-ice extent in the Bering Sea is sensitive to the interaction of
664 atmospheric and oceanic forcing mechanisms (Zhang et al., 2010). Reconstructions of SST in
665 the subarctic North Pacific and its marginal seas across the LGM reveal large spatial
666 heterogeneity, with some sites documenting warming from the LGM to the Holocene, while
667 others show no change or even cooling (Caissie et al., 2010; Gebhardt et al., 2008; Gray et
668 al., 2020; Harada et al., 2008, 2006, 2004; Hernández-Almeida et al., 2020; Kiefer and
669 Kienast, 2005; Max et al., 2012; Méheust et al., 2018; Meyer et al., 2016; Praetorius et al.,
670 2020; Riethdorf et al., 2013; Taylor et al., 2014) (Supplementary Figure 8, Supplementary
671 Table 1). This discrepancy can partly be attributed to the varying proxy carriers used as
672 paleothermometers, including microfossil assemblages, planktonic foraminiferal Mg/Ca,
673 alkenone unsaturation indices, and the Tetra Ether indeX (TEX₈₆). Such proxies may be
674 biased towards subsurface vs. surface temperatures, and/or temperatures during the respective
675 bloom seasons, which might have changed across G/IG transitions. Nonetheless, a spatially

676 heterogeneous North Pacific SST development contrasts a region-wide expanded sea-ice
677 cover during the LGM (Supplementary Table 1). A potential mechanism to reconcile this
678 divergence would be an increased sensitivity of sea ice to atmospheric temperatures and
679 circulation, rather than oceanic dynamics.

680 Numerical simulations and proxy reconstructions suggest a strengthening and expansion of
681 the North Pacific subarctic gyre caused by a southward shift of the mid-latitude westerlies
682 and polar easterlies during the LGM in response to the Laurentide ice sheet and atmospheric
683 CO₂ concentrations (Gray et al., 2020; Nagashima et al., 2007). The strengthened wind stress
684 curl over the subarctic North Pacific might have caused enhanced thermodynamic ice growth,
685 as well as increased export of sea ice away from the nucleation sites, in line with the regional-
686 wide increase of sea-ice extent during MIS 2 (Caissie et al., 2010; Itaki et al., 2012; Lo et al.,
687 2018; Méheust et al., 2018). Further, weakening of the oceanic connection between the
688 subarctic North Pacific gyre and the Bering Sea via the Alaskan Stream due to sea level fall
689 and restriction of several Aleutian passes (Caissie et al., 2010; Meyer et al., 2016; Riethdorf
690 et al., 2013), as well as closure of the Bering Strait may have isolated the glacial Bering Sea
691 making it more sensitive to atmospheric rather than oceanic forcing. A strong sensitivity to
692 atmospheric temperatures is supported by the decrease in sea ice extent around ~23 ka
693 (Figure 5). This is contemporaneous with an increase in atmospheric temperatures over
694 Greenland, as suggested by the North Greenland Ice Core Project (NGRIP) $\delta^{18}\text{O}$ curve
695 (Rasmussen et al., 2006; Svensson et al., 2008; Vinther et al., 2006) (Figure 5), indicating
696 close atmospheric coupling between the Bering Sea and the North Atlantic during MIS 2.
697 This decrease, however, is not observed in the eastern and western subarctic Pacific (Méheust
698 et al., 2018) (Figure 5). Although the records are of relatively low resolution, this could
699 indicate that sea-ice extent in the western and eastern North Pacific was additionally
700 modulated by oceanic changes in relation to the subarctic gyre dynamics. Different

701 sensitivities to oceanic and atmospheric forcing between the eastern Bering Sea and eastern
702 North Pacific are further supported by the lack of correlation between IP₂₅ records from these
703 two regions during the LGM, which changes to a significant positive correlation during HS1
704 (Supplementary Figure 7).

705 HS1 is marked by a double peak in IP₂₅ and HBI II in the eastern Bering Sea, also recognized
706 in the eastern North Pacific (Méheust et al., 2018) (Figure 5, Supplementary Figure 7). In the
707 eastern North Pacific, the double peak is associated with an increase in brassicasterol,
708 suggesting more marginal sea-conditions compared to the LGM. Seasonal sea-ice conditions
709 during HS1 are also evident from biomarker records in the western North Pacific (Méheust et
710 al., 2018, 2016) (Figure 5). In the eastern Bering Sea, on the other hand, the collective
711 biomarker data for the early HS1 peak indicate extended seasonal sea ice in line with the
712 P_{III}IP₂₅, P_BIP₂₅, and CT results (Figure 2, Figure 3). This is supported by the re-appearance of
713 the radiolarian species *A. boreale* and *A. leptodermum*, in the north-eastern Bering Sea (Itaki
714 et al., 2012) (Figure 5), characteristic of an extensive sea-ice cover. Further, diatom
715 assemblages at the Umnak Plateau suggest more than 6 months of sea-ice per year during
716 early HS1 (Caissie et al., 2010), in line with biomarker records from the Shirshov Ridge in
717 the western Bering Sea also indicating extensive sea-ice cover (Méheust et al., 2016).

718 Contemporaneous IP₂₅ peaks in the eastern North Pacific and the eastern Bering Sea during
719 HS1 could indicate a more unified forcing in the eastern subarctic Pacific during HS1
720 compared to the LGM (Supplementary Figure 7), although higher resolution records are
721 needed to confirm the observed similarities. As the oceanic connection between the eastern
722 Bering Sea and the eastern North Pacific was still restricted during the early deglaciation
723 (Supplementary Figure 7), one possibility would be a heightened sensitivity to atmospheric
724 temperatures. While NGRIP $\delta^{18}\text{O}$ suggests warming over Greenland during early HS1
725 (Rasmussen et al., 2006; Svensson et al., 2008; Vinther et al., 2006), North Greenland

726 Eemian Ice Drilling (NEEM) $\delta^{18}\text{O}$ (Buizert et al., 2014) and the northern hemisphere
727 temperature stack (Shakun et al., 2012) both indicate atmospheric cooling (Figure 5). Under
728 glacial boundary conditions, NEEM might be more representative of Pacific climate and
729 moisture fluxes, compared to NGRIP (Buizert et al., 2014). Atmospheric cooling during early
730 HS1 is further supported by pollen records from eastern Beringia (150-180°W) (Viau et al.,
731 2008) (Figure 5). Alternatively, flood events from the retreating Cordilleran Ice Sheet, routed
732 into the eastern North Pacific might have caused surface ocean cooling and freshening during
733 the early deglaciation, causing region-wide synchronous sea-ice patterns (Praetorius et al.,
734 2020). However, while a compilation of SST records from the eastern North Pacific suggests
735 cooling during the early HS1 compared to the LGM (Praetorius et al., 2020), available Bering
736 Sea SST records indicate early warming from ~19 ka (Hernández-Almeida et al., 2020;
737 Meyer et al., 2016; Riethdorf et al., 2013), with only transient cooling events (Supplementary
738 Figure 8). Warming SSTs, especially during the summer season (Meyer et al., 2016), at the
739 same time as an increase in the sea-ice extent, might suggest a larger seasonal contrast in the
740 Bering Sea during early HS1 compared to the LGM.

741 Following the interval of enhanced sea-ice cover during early HS1 (~17.5 ka), the second
742 HS1 peak in IP₂₅ is associated with increased HBI III and brassicasterol, suggesting a shift
743 towards MIZ conditions in the eastern Bering Sea around 16.5 ka (Figure 2). This is
744 supported by a more dynamic sea-ice cover at the Umnak Plateau from ~16.7 ka onwards
745 (Caissie et al., 2010) and the disappearance of *A. boreale* and *A. leptodermum* in the northern
746 Bering Sea (Itaki et al., 2012) (Figure 5). From 16 ka onward, a sharp decline in all three HBI
747 biomarkers is observed at Site U1343, contemporaneous with a decrease of IP₂₅ in the eastern
748 North Pacific (Figure 2, Figure 5) (Méheust et al., 2018). At the same time all sterol
749 biomarkers, as well as MAR_{opal}, start to increase rapidly (Figure 2), indicating a northward
750 retreat of the sea-ice margin in the eastern Bering Sea and eastern North Pacific during late

751 HS1. This sea-ice retreat is synchronous with local and northern hemisphere atmospheric
752 warming (Kurek et al., 2009; Shakun et al., 2012; Vialou et al., 2008) and increasing northern
753 hemisphere summer insolation (Figure 5).

754 In contrast, biomarker records from the western Bering Sea and the western North Pacific, as
755 well as in the central Sea of Okhotsk, document continuously extensive sea ice until ~15 ka
756 (Lo et al., 2018; Méheust et al., 2018, 2016) (Figure 5). This suggests an east-west gradient in
757 the late HS1 sea-ice retreat in the subarctic North Pacific. Recently, using planktonic
758 foraminiferal $\delta^{18}\text{O}$ and numerical simulations, Gray et al. (2020) demonstrated an east-west
759 gradient in the deglacial northward migration of the subarctic gyre. From 16.5 ka onwards,
760 northward migration of the gyre boundary is evident in the eastern subarctic Pacific, while
761 the western boundary changes occur between ~12.5-10 ka (Gray et al., 2020). Further, Gong
762 et al. (2019) demonstrate a strengthened Aleutian Low during HS1, which transports cold air
763 masses from East Siberia to the Sea of Okhotsk and the western Bering Sea. Thus, an east-
764 west gradient in deglacial sea-ice dynamics is consistent with atmospheric and oceanic
765 circulation patterns at this time, suggesting colder conditions in the west compared to the east
766 during late HS1. The latter is also observed in a recent compilation of high resolution SST
767 reconstructions, showing colder SSTs in the western North Pacific compared to the east
768 during late HS1 (Praetorius et al., 2020).

769 From ~15 ka, however, sea-ice biomarker records demonstrate a consistent decrease in the
770 Bering Sea and the subarctic North Pacific sea-ice cover (Figure 5) (Méheust et al., 2018,
771 2016); while the record from the central Sea of Okhotsk indicates a transition towards
772 marginal sea-ice conditions (Lo et al., 2018). This is in line with substantial hemisphere-wide
773 atmospheric (Shakun et al., 2012) and region-wide SST warming at the onset of the BA
774 (Caissie et al., 2010; Hernández-Almeida et al., 2020; Max et al., 2012; Méheust et al., 2018;
775 Meyer et al., 2016; Praetorius et al., 2020; Riethdorf et al., 2013) (Supplementary Figure 8).

776 Consistent with warming during the BA, sea-ice biomarker records at Site U1343 suggest
777 predominantly ice-free conditions, with a renewed increase in MIZ sedimentation during the
778 late BA, as indicated by increasing HBI III concentrations (Figure 2). An ice-free
779 environment is further supported by very high sterol concentrations throughout the BA and a
780 peak in MAR_{opal} (Figure 2), attributed to increased primary productivity and increased
781 continental runoff throughout this interval (Supplementary Figure 9). Ice-free conditions in
782 the eastern Bering Sea are consistent with previous biomarker-based sea-ice reconstructions
783 from the western Bering Sea and the subarctic North Pacific (Méheust et al., 2018, 2016),
784 also indicating very low spring sea-ice occurrence during the early and mid-BA (Figure 5).
785 Diatom assemblages at the Umnak Plateau, on the other hand, suggest a shift from near
786 perennial to seasonal sea ice associated with the onset of the BA, while ice-free conditions
787 are not encountered until 11 ka (Caissie et al., 2010). This suggests a discrepancy between
788 biomarker-based and diatom-based sea-ice reconstruction in the deglacial Bering Sea and
789 further research is needed to understand the cause of this disagreement. Nonetheless, diatoms
790 characteristic of high productivity environments seem to dominate the assemblage at the
791 Umnak plateau during the BA (Caissie et al., 2010), indicative of a major environmental shift
792 and reduced ice cover compared to HS1.

793 Following peak BA northern hemisphere warmth at ~13.5 ka, atmospheric temperatures
794 (Shakun et al., 2012) and Bering Sea SSTs (Hernández-Almeida et al., 2020; Max et al.,
795 2012; Méheust et al., 2018; Meyer et al., 2016) decrease into the YD stadial (Figure 5,
796 Supplementary Figure 8). Simultaneously, sea-ice biomarkers increase in the western and
797 eastern Bering Sea (Méheust et al., 2016) (Figure 5). An increase in IP_{25} is also observed in
798 the western North Pacific off Kamchatka, while the Emperor Seamount further to the east
799 remained ice-free during the YD (Méheust et al., 2018). In the central Sea of Okhotsk IP_{25} is
800 slightly lower compared to the BA. In combination with lowered HBI III concentrations,

801 however, this also indicates a renewed sea-ice advance compared to the BA interstadial (Lo
802 et al., 2018). The YD stadial is thus characterized by seasonal sea ice in the Bering Sea, off
803 Kamchatka and in the central Sea of Okhotsk (Lo et al., 2018; Méheust et al., 2018, 2016).
804 MIZ conditions with high HBI III concentrations at Site U1343 (Figure 2), however, suggest
805 that, at least in the eastern Bering Sea, sea ice did not extend as far south as during early HS1.
806 This is in line with sea ice not reaching the Bowers Ridge during the YD stadial (Cook et al.,
807 2005).

808 The early Holocene is characterized by ice-free conditions in the Bering Sea, the subarctic
809 North Pacific, and the central Sea of Okhotsk, with a mid-Holocene increase in IP₂₅
810 accumulation observed in the northern and western Bering Sea after ~10 ka (Figure 5)
811 (Caissie et al., 2010; Itaki et al., 2012; Lo et al., 2018; Méheust et al., 2016, 2018). Diatom
812 assemblages at the Umnak Plateau also suggest ice-free conditions during the early Holocene
813 (Caissie et al., 2010). This is consistent with substantial environmental changes in the Bering
814 Sea during the early Holocene, corresponding to a widespread regional warming (Elias et al.,
815 1996; Kaufman et al., 2004) in response to maximum northern hemisphere summer insolation
816 (Kaufman et al., 2004). Further, deglacial sea level rise resulted in the flooding of the Bering
817 Land Bridge around 11 ka (Jakobsson et al., 2017) and enhanced influence of warm and
818 nutrient-rich Alaskan Stream waters in the eastern Bering Sea (Caissie et al., 2010). While
819 the MAR_{opal}, cholesterol, and brassicasterol are relatively low during the early Holocene,
820 campesterol and β -sitosterol peak following the YD/Holocene transition (Figure 2).

821 Contemporaneously, the abundance of radiolarian species, indicative of melt-water discharge
822 spike in the northern Bering Sea (Itaki et al., 2012), suggesting increased continental runoff
823 and input of terrestrial organic matter (Supplementary Figure 9).

824 From ~11 ka onwards, HBI III values at Site U1343 increase by orders of magnitude, yet the
825 IP₂₅, HBI II and brassicasterol concentrations remain low, indicating absence of MIZ

826 sedimentation at Site U1343. Similar biomarker patterns have been observed in sediment
827 cores from the Barents Sea and the Norwegian Sea (Belt et al., 2015; Berben et al., 2017;
828 Xiao et al., 2017), with absent IP₂₅ and increased HBI III from 9.9-8.0 ka and 11.2-9.3 ka,
829 respectively (Belt et al., 2015). This was attributed to enhanced warm Atlantic Water inflow
830 resulting in increased productivity. In the eastern Bering Sea, we suggest that the steep
831 increase in HBI III is most likely related to warming and enhanced nutrient concentrations
832 during the early Holocene. At the Umnak Plateau the abundance of *Rhizosolenia hebetata*, a
833 known producer of HBI III (Belt et al., 2017), increases from 9 ka onwards, together with
834 increased occurrence of *Neodenticula seminae*, a species characteristic of the Alaskan Stream
835 (Caissie et al., 2010). Species of the genus *Rhizosolenia* are often associated with oceanic
836 fronts (Oksman et al., 2019), regions of enhanced nutrient supply. Thus, strengthened inflow
837 of warm, nutrient-rich Alaskan Stream waters into the eastern Bering Sea potentially created
838 an environment especially suitable for HBI III producing diatoms.

839 **5.2 Ventilation changes in the eastern Bering Sea over the last ~30 ka and the role of sea** 840 **ice for glacial NPIW formation**

841 Under modern conditions, deep water masses are formed in the North Atlantic and the
842 Southern Ocean, while in the North Pacific, a permanent halocline (Emile-Geay et al., 2003;
843 Warren, 1983) impedes the formation of deep water masses. Instead, intermediate water
844 forms via brine rejection during sea-ice freezing in the Sea of Okhotsk (Shcherbina et al.,
845 2003; Talley, 1993). Numerous proxy studies and numerical simulations indicate that
846 intermediate depths of the North Pacific experienced enhanced ventilation during the LGM
847 (GNPIW) and especially during stadial periods of the last deglaciation (Ahagon et al., 2003;
848 Cook et al., 2016; Cook and Keigwin, 2015; Duplessy et al., 1989; Gong et al., 2019; Jaccard
849 and Galbraith, 2013; Jang et al., 2017; Keigwin, 1998; Knudson and Ravelo, 2015;
850 Matsumoto et al., 2002; Max et al., 2014; Okazaki et al., 2010, 2012; Ovsepyan et al., 2017;

851 Rae et al., 2014; Saenko et al., 2004; Sagawa and Ikehara, 2008; Worne et al., 2019; Zou et
852 al., 2020) (Supplementary Table 1). This suggests an Atlantic-Pacific overturning seesaw
853 with increased Pacific meridional overturning circulation (PMOC) at times of a reduced
854 AMOC (McManus et al., 2004). Improved ventilation of the glacial North Pacific from
855 GNPIW is widely recorded to depth of up to ~2000 m, while HS1 might have experienced
856 enhanced ventilation up to >3000 m (Okazaki et al., 2010; Rae et al., 2014). This is in
857 contrast to NPDW, which was characterized by reduced oxygen concentrations during the
858 LGM (Jaccard et al., 2009), likely a result of changes in the preformed to regenerated nutrient
859 ratio, facilitating deep ocean carbon storage (Galbraith et al., 2007; Jaccard et al., 2009).
860 Across the deglaciation, during the BA and the early Holocene, these trends were reversed.
861 NPDW experienced improved ventilation (Galbraith et al., 2007), while the mid-depth North
862 Pacific was marked by widespread anoxia (Aiello and Ravelo, 2012; Cook et al., 2005;
863 Expedition 323 Scientists, 2010; Kuehn et al., 2014; Ovsepyan et al., 2017; Pelto et al., 2018;
864 Rella et al., 2012).

865 At ~2000 m water depth, Site U1343 is located at the proposed boundary of GNPIW and
866 NPDW, making it ideal to study past changes in North Pacific ventilation. However, the
867 records of benthic foraminiferal assemblages, planktonic and benthic aU/Ca, and benthic
868 aU/Mn are of relatively low resolution due to low foraminiferal abundance in the sediments.
869 The most robust features are two distinct events of less reducing conditions at ~17.5 ka and
870 ~25 ka, marked by decreased aU/Ca, aU/Mn, and a lower abundance of hypoxia-tolerant
871 benthic foraminiferal species from Assemblage 1, including *B. exilis* (Supplementary Figure
872 6, Figure 4). Further, planktonic aU/Ca and the benthic foraminiferal assemblage suggest
873 more reducing conditions associated with the BA and the early Holocene, characterized by
874 elevated planktonic aU/Ca and a dominance of *B. exilis* in sediments at Site U1343 (Figure
875 4).

876 The two events of less reducing conditions at ~17.5 ka and ~25 ka, correspond to early HS1
877 and late HS2, respectively (Figure 6). As there are no changes in the MAR_{opal} , representing
878 first order changes in primary productivity, during these intervals (Figure 6), the two events
879 are interpreted to reflect increased bottom water oxygenation. Two primary reasons have
880 been identified for enhanced bottom water oxygen concentrations: (i) enhanced ventilation
881 (via lateral or vertical water mass exchange) or (ii) the release of carbon from the deep ocean.
882 Volumetrically, the deep North Pacific represents the largest reservoir of carbon in the
883 world's deep ocean. Thus, a release of carbon from the North Pacific abyss should result in
884 increased atmospheric CO_2 concentrations and/or increased primary productivity, capturing
885 the released carbon. Atmospheric CO_2 , however, does not increase significantly until 17 ka
886 (Bereiter et al., 2015) and subarctic North Pacific primary productivity remains low until ~16
887 ka (Brunelle et al., 2010, 2007; Cook et al., 2005; Kim et al., 2014; Kohfeld and Chase, 2011;
888 Lam et al., 2013; Max et al., 2012; Okazaki et al., 2005). Further, NPDW ventilation does not
889 increase on a region-wide scale until the onset of the BA (Galbraith et al., 2007; Jaccard et
890 al., 2009; Jaccard and Galbraith, 2012; Lund et al., 2011), suggesting that deep ocean carbon
891 release did not drive the increased sedimentary oxygenation at 25 ka and 17.5 ka in the
892 eastern Bering Sea. Instead, we attribute improved ventilation via expansion of GNPIW as
893 the cause for the enhanced oxygenation of sediments at Site U1343 during late HS2 and early
894 HS1.

895 As research has primarily focused on the deglacial history of North Pacific ventilation, few
896 records reach as far back as HS2. However, there is evidence for improved ventilation in the
897 Okinawa Trough at 703 m water depth, attributed to enhanced formation and ventilation of
898 GNPIW (Zou et al., 2020). Further, records of oxic benthic foraminiferal abundance peak
899 around 25 ka in a sediment core from 1300 m water depth off Japan (Shibahara et al., 2007)
900 as well as at 500-600 m water depth in the Santa Barbara Basin (Cannariato and Kennett,

901 1999; Ohkushi et al., 2013). Under modern conditions, these sites are from the distal reaches
902 of NPIW, however records of foraminiferal carbon isotopes ($\delta^{13}\text{C}$) suggest that GNPIW
903 extended further south under glacial boundary conditions (Max et al., 2017). In contrast,
904 more proximal records of $\delta^{13}\text{C}$ from the mid-depth Bering Sea (600-1000 m) do not show a
905 clear signal of improved ventilation during HS2 (Max et al., 2017; Rella et al., 2012) (Figure
906 6). As the age model at Site U1343 is more uncertain at the lower end of the record, further
907 research is needed to confirm the exact timing and duration of the proposed deep ventilation
908 event.

909 The second ventilation event at 17.5 ka during early HS1 coincides with the onset of
910 widespread improved ventilation in the mid-depth Bering Sea and Sea of Okhotsk
911 (Gorbarenko et al., 2010; Max et al., 2014; Rella et al., 2012) (Figure 6), and precedes a deep
912 ventilation event to >3000 m water depth observed in the Gulf of Alaska by ~500 years (Rae
913 et al., 2014). Evidence for improved ventilation at ~17.5 ka is also available from the wider
914 North Pacific region off Japan (978-2700 m) (Ahagon et al., 2003; Ohkouchi et al., 1994;
915 Zou et al., 2020) and off California and Baja California (500-600 m) (Cannariato and
916 Kennett, 1999; Ohkushi et al., 2013; Tetard et al., 2017).

917 Compared to shallower records from the northern and western Bering Sea (975-1000 m),
918 where improved ventilation is sustained until 16 ka and 15 ka, respectively (Max et al., 2014;
919 Rella et al., 2012), the ventilation event at U1343 seems to be of relatively short duration,
920 indicating a pulse of enhanced GNPIW formation to 2000 m water depth in the eastern
921 Bering Sea during early HS1 (Figure 6). Increased North Pacific overturning during HS1 is
922 further supported by records of carbon cycle dynamics. From 17.5 ka onwards, diatom-bound
923 nitrogen isotopes ($\delta^{15}\text{N}$) suggest a decrease in the nutrient utilization in the Bering Sea
924 (Brunelle et al., 2010, 2007) and North Pacific surface ocean CO_2 partial pressure (pCO_2)
925 shows a transient increase during early HS1 (Gray et al., 2018) (Figure 6). This is attributed

926 to increased mixing of nutrient and CO₂-rich deep water to the surface at the onset of deep
927 overturning during HS1. Subsequently, deepening of the relatively warm and fresh GNPIW
928 intensified the deep ocean stratification, preventing further upwelling of NPDW until the
929 breakdown of GNPIW formation at the HS1/BA transition (Gong et al., 2019; Gray et al.,
930 2018). While nutrient utilization decreases from 17.5 ka (Figure 6), primary productivity in
931 the subarctic North Pacific remains low until 16 ka (Brunelle et al., 2010, 2007; Cook et al.,
932 2005; Kim et al., 2014; Kohfeld and Chase, 2011; Lam et al., 2013; Max et al., 2012;
933 Okazaki et al., 2005; Riethdorf et al., 2016), which can be attributed to light limitation in
934 response to seasonal sea-ice cover and a deepened mixed layer due to enhanced GNPIW
935 formation.

936 Improved ventilation of the mid-depth North Pacific during HS1, observed in numerous
937 studies from the subarctic to the subtropics (Ahagon et al., 2003; Cannariato and Kennett,
938 1999; Cook et al., 2016; Duplessy et al., 1989; Gorbarenko et al., 2010; Max et al., 2014;
939 Ohkushi et al., 2013; Rae et al., 2014; Rella et al., 2012; Sagawa and Ikehara, 2008;
940 Shibahara et al., 2007; Tetard et al., 2017; Zou et al., 2020) (Supplementary Table 1), is in
941 line with increased overturning in the North Pacific at times of a reduced AMOC. The
942 reasons for a stronger PMOC, however, are still under debate. Several numerical simulations
943 suggest prominent changes in the atmospheric circulation over the subtropical and subarctic
944 North Pacific in response to reduced northward heat transport in the Atlantic during an
945 AMOC-off mode (Chikamoto et al., 2012; Gong et al., 2019; Menviel et al., 2012; Okazaki et
946 al., 2010; Okumura et al., 2009; Wu et al., 2008). These changes include a southward shift in
947 the Intertropical Convergence Zone (ITCZ) (Chikamoto et al., 2012; Okumura et al., 2009;
948 Wu et al., 2008), stronger midlatitude westerlies (Gong et al., 2019; Okumura et al., 2009),
949 and a strengthened Aleutian Low over the subarctic North Pacific (Chikamoto et al., 2012;
950 Gong et al., 2019; Okumura et al., 2009). A stronger Aleutian Low results in colder, drier

951 East Siberian air masses over the western Bering Sea and Sea of Okhotsk reducing the net
952 precipitation in this region (Gong et al., 2019). Additionally, strengthened atmospheric
953 circulation would lead to a spin up of the subarctic North Pacific gyre with enhanced Ekman
954 suction and increased meridional transport of saline subtropical waters to the subarctic North
955 Pacific (Chikamoto et al., 2012; Gong et al., 2019; Gray et al., 2020; Menviel et al., 2012;
956 Okazaki et al., 2010; Okumura et al., 2009). In combination, these processes might act to
957 increase the North Pacific surface ocean salinity (SSS), which could weaken the permanent
958 halocline, initiating thermohaline overturning. A positive overturning-salinity feedback might
959 then aid to sustain high SSS in the North Pacific (Chikamoto et al., 2012; Gong et al., 2019;
960 Max et al., 2014). Along with increased meridional transport, several models suggest an
961 enhanced northward heat transport in the Pacific in response to increased overturning
962 (Chikamoto et al., 2012; Gong et al., 2019; Menviel et al., 2012; Okazaki et al., 2010). In
963 contrast, studies of foraminiferal $\delta^{18}\text{O}$ and ϵNd in the Bering Sea suggest a pivotal role of
964 brine rejection during sea-ice freezing for enhanced GNPIW formation (Cook et al., 2016;
965 Horikawa et al., 2010; Knudson and Ravelo, 2015).

966 Both deep ventilation events, as recognized at Site U1343, correspond to times of increased
967 sea-ice extent in the eastern Bering Sea (Figure 6). Especially during early HS1, warming
968 Bering Sea summer SSTs (Meyer et al., 2016) in combination with increased sea-ice extent
969 suggest a stronger seasonal contrast, likely associated with intensified new ice growth and
970 brine rejection. Brine rejection during early HS1 and late HS2 is also supported by the $\delta^{18}\text{O}_b$
971 at Site U1343 (Asahi et al., 2016). During sea-ice freezing, brine rejection leads to an
972 increase in surface water salinity without significantly fractionating surface water $\delta^{18}\text{O}$
973 (Brennan et al., 2013), transporting the low surface water $\delta^{18}\text{O}$ signature to greater depth,
974 resulting in a negative offset of local benthic $\delta^{18}\text{O}$ from the global benthic $\delta^{18}\text{O}$ stack (LR04)
975 (Knudson and Ravelo, 2015; Lisiecki and Raymo, 2005). Even though $\delta^{18}\text{O}_b$ at Site U1343 is

976 of relatively low resolution, negative offsets from the LR04 stack can be observed across
977 both ventilation events, albeit of lower amplitude compared to IODP Site U1342 at 800 m
978 water depth in the southern Bering Sea (Figure 6) (Knudson and Ravelo, 2015). The
979 difference between $\delta^{18}\text{O}_b$ at Site U1343 and the shallower Site U1342 (~800 m), as well as
980 the similarities between U1343 $\delta^{18}\text{O}_b$ and the LR04 stack, however, suggest that NPDW
981 remained the predominant water mass at ~2000 m in the eastern Bering Sea during MIS 2,
982 with entrainment of GNPIW restricted to the two deep ventilation events during HS1 and
983 HS2.

984 This indicates that while the LGM in the Bering Sea, in line with glacial intervals of the last
985 1.2 Ma, may have experienced enhanced GNPIW ventilation to depth of ~1000 m (Cook et
986 al., 2016; Knudson and Ravelo, 2015; Rella et al., 2012), deep convection to at least 2000 m
987 was restricted to HS1 and potentially also HS2 (Figure 7). We propose that during early HS1
988 increased brine rejection locally weakened the halocline by promoting downward transport of
989 low salinity surface waters and upward mixing of higher salinity intermediate waters (Figure
990 7). Thus, enhanced sea-ice formation during early HS1 in the Bering Sea and the subarctic
991 North Pacific might have helped to ‘kick start’ deep convection, in line with the observed
992 pulse of improved ventilation at 2000 m water depth in the eastern Bering Sea (Figure 6). The
993 subsequent northward retreat of the sea-ice margin in the eastern Bering Sea and eastern
994 North Pacific from ~16 ka onwards (Figure 5), however, suggests that while sea ice likely
995 aided in the initiation of deep convection, other mechanisms might have been more important
996 in sustaining increased ventilation until the onset of the BA. These mechanisms might include
997 a positive salinity-circulation feedback, transporting high salinity subtropical waters to the
998 North Pacific, decreased precipitation over the North Pacific, and/or increased upwelling of
999 high salinity surface waters in the subarctic gyre due to intensified Ekman suction
1000 (Chikamoto et al., 2012; Gong et al., 2019; Gray et al., 2020; Max et al., 2014; Menviel et al.,

1001 2012; Okazaki et al., 2010; Okumura et al., 2009). Alternatively, sustained brine rejection in
1002 the western Bering Sea and Sea of Okhotsk, in line with a later sea-ice demise (~15 ka) in
1003 this region (Figure 5) (Lo et al., 2018; Méheust et al., 2018, 2016), might have
1004 driven/contributed to enhanced North Pacific overturning during late HS1 (Gong et al.,
1005 2019).

1006 An increased sea-ice cover during times of an intensified PMOC conflicts with results
1007 suggesting enhanced northward heat transport in response to PMOC strengthening
1008 (Chikamoto et al., 2012; Gong et al., 2019; Gray et al., 2020; Menviel et al., 2012; Okazaki et
1009 al., 2010). As mentioned in section 5.1, the increase in sea-ice extent during early HS1 is
1010 most likely a response to either atmospheric cooling (Kurek et al., 2009; Shakun et al., 2012;
1011 Viau et al., 2008) and/or meltwater runoff from the retreating Cordilleran Ice Sheet
1012 (Praetorius et al., 2020). If the former was the case, atmospheric cooling might have masked
1013 any significant increase in northward heat transport, as suggested in a recent modelling study
1014 (Gong et al., 2019). In contrast, a sea-ice increase in response to surface freshening is
1015 difficult to reconcile with the enhanced ventilation of the mid-depth North Pacific during
1016 HS1, unless brine rejection was able to compensate for the freshwater-induced halocline
1017 strengthening. In this case, input of cold freshwater might have compensated for increased
1018 northward heat transport, allowing for an extended sea-ice cover. Future modelling studies
1019 might be able to explore this relationship further.

1020 From 16 ka onwards primary productivity increases on a North Pacific wide scale (Brunelle
1021 et al., 2010, 2007; Cook et al., 2005; Kim et al., 2014; Kohfeld and Chase, 2011; Lam et al.,
1022 2013; Max et al., 2012; Okazaki et al., 2005; Riethdorf et al., 2016). At Site U1343, rising
1023 primary productivity is recorded by a steep increase in MAR_{opal} (Kim et al., 2014) and sterol
1024 biomarkers from 16 ka, peaking during the early BA interstadial (Figure 2). As the timing
1025 corresponds to the onset of sea-ice decline (Figure 2), increased primary productivity was

1026 likely a result of alleviation of light limitation due to diminishing sea-ice cover, and a
1027 shallower mixed layer, promoted by sea-ice melting inducing surface ocean stratification. At
1028 the HS1/BA transition, subarctic North Pacific surface ocean pCO₂ increased rapidly above
1029 atmospheric CO₂ concentrations at the time (Figure 6), indicating outgassing of CO₂ from the
1030 North Pacific (Gray et al., 2018). Gray et al. (2018) suggest that increased surface ocean
1031 pCO₂ resulted from the breakdown of GNPIW formation following the resumption of the
1032 AMOC (McManus et al., 2004) resulting in upwelling of NPDW, due to enhanced Ekman
1033 suction in the subarctic gyre as a result of the remnant Laurentide Ice Sheet. Enhanced
1034 upwelling of NPDW during the BA would have flushed deeply sequestered CO₂ and nutrients
1035 from the abyss to the surface, in line with signs of improved NPDW ventilation (Galbraith et
1036 al., 2007) and increased primary productivity in the North Pacific (Brunelle et al., 2010,
1037 2007; Cook et al., 2005; Kim et al., 2014; Kohfeld and Chase, 2011; Lam et al., 2013; Max et
1038 al., 2012; Riethdorf et al., 2016).

1039 Contemporaneously, planktonic aU/Ca and benthic foraminiferal assemblages at Site U1343
1040 record reduced sedimentary oxygenation across the BA and the early Holocene (Figure 6).
1041 While the last glacial interval was dominated by Assemblage 3, predominately composed of
1042 phytodetrivore species (Kender et al. 2019), the BA and the early Holocene are dominated
1043 by Assemblage 1 (Figure 6). The latter is composed of species adapted to low oxygen
1044 conditions and very high export of organic carbon to the seafloor (Kender et al., 2019;
1045 Okazaki et al., 2005; Piña-Ochoa et al., 2010; Schumacher et al., 2007; Sen Gupta and
1046 Machain-Castillo, 1993), dominated by *B. exilis* (Figure 6). Decreased oxygenation is in line
1047 with the preservation of laminations in sediment core U1343 (Expedition 323 Scientists,
1048 2010) (Supplementary Figure 1) and numerous other cores from the mid-depth Bering Sea
1049 (Aiello and Ravelo, 2012; Cook et al., 2005; Expedition 323 Scientists, 2010; Kuehn et al.,
1050 2014; Pelto et al., 2018; Schlung et al., 2013) and across the North Pacific (Crusius et al.,

1051 2004; Ikehara et al., 2006; Praetorius et al., 2015; Zheng et al., 2000). Laminated sediments
1052 during the BA and the early Holocene suggest that waters with $[O_2] < 5 \mu\text{mol/kg}$ (Moffitt et
1053 al., 2015) intersected the sediment-water interface, bearing witness of a substantial
1054 intensification and expansion of the mid-depth OMZ throughout these intervals (Kuehn et al.,
1055 2014). During the BA, OMZ expansion was most likely attributed to enhanced respiration of
1056 organic carbon in the ocean interior due to increased export productivity (Figure 2), fueled by
1057 upwelling of nutrient-rich NPDW and increased mixed layer stratification as a result of
1058 warming atmospheric temperatures and enhanced meltwater discharge (Gray et al., 2018;
1059 Itaki et al., 2012; Kuehn et al., 2014; Ren et al., 2015) (Figure 7). Additionally, the
1060 breakdown of GNPIW formation likely contributed to reduced ventilation of the mid-depth
1061 North Pacific (Gray et al., 2018). During the early Holocene, on the other hand, sterol
1062 biomarkers and MAR_{opal} at Site U1343 indicate relatively lower in situ primary productivity
1063 compared to the BA (Figure 2). Instead, sterol biomarkers suggest enhanced input of
1064 terrestrial organic carbon due to sea level rise and increased meltwater discharge (Itaki et al.,
1065 2012; Spratt and Lisiecki, 2016) (Supplementary Figure 9) as the primary cause for OMZ
1066 expansion in the eastern Bering Sea.

1067 **6. Conclusions**

- 1068 1. MIS 3 and MIS 2 were characterized by seasonal to extended seasonal sea-ice
1069 concentration in the eastern Bering Sea, with the most severe sea-ice conditions
1070 occurring during early MIS 2.
- 1071 2. Across the deglaciation, sea-ice dynamics in the eastern Bering Sea demonstrate
1072 millennial-scale variability. HS1 was marked by an initial intensification of sea-ice
1073 conditions around 17.5 ka, followed by a transition to MIZ conditions around 16.5 ka
1074 and a rapid northward retreat of the sea ice margin at the HS1/BA transition. The BA

1075 and early Holocene were characterized by primarily ice-free conditions in the eastern
1076 Bering Sea, separated by a return of MIZ conditions during the YD.

1077 3. The timing of sea-ice changes in the eastern Bering Sea, as well as its oceanic
1078 isolation due to glacial sea-level fall, suggest that sea ice was most sensitive to
1079 atmospheric forcing during MIS 3 and MIS 2. Across the deglaciation, the effects of
1080 oceanic forcing likely strengthened in response to sea level rise and subarctic gyre
1081 dynamics.

1082 4. During late HS2 (~25 ka) and early HS1 (~17.5 ka), foraminiferal assemblages and
1083 authigenic trace metals, suggest pulses of improved ventilation at Site U1343,
1084 corresponding to times of enhanced sea-ice cover. Especially during early HS1, we
1085 propose that enhanced sea-ice formation aided in the initiation of deep overturning by
1086 locally weakening the halocline. The subsequent retreat of the sea-ice margin however
1087 indicates that other mechanisms, such as a positive circulation salinity feedback,
1088 and/or sea ice in the western Bering Sea/Sea of Okhotsk were more important to
1089 sustain deep overturning during HS1. As the age model becomes more uncertain
1090 towards the lower end of the record, additional research is needed, but the similarities
1091 between the events at 17.5 ka and 25 ka, suggest that deep ventilation initiated by sea-
1092 ice formation may have been a recurrent feature of Heinrich events in the North
1093 Pacific.

1094 5. The dominance of the high productivity, hypoxia-tolerant benthic foraminiferal
1095 species *B. exilis* during the BA and the early Holocene, is in line with the preservation
1096 of laminations and OMZ expansion in the eastern Bering Sea. During the BA, high
1097 concentrations of all sterol biomarkers and MAR_{opal} , indicate that an increase in in
1098 situ primary productivity in combination with influx of terrestrial organic carbon
1099 drove down mid-depth oxygen concentrations. During the early Holocene, however,

1100 terrestrial sterol biomarkers dominate, suggesting that organic carbon from meltwater
1101 runoff and sea level rise might have been the dominant driver of OMZ expansion at
1102 this time.

1103

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1111

1112 **Research data**

1113 Supporting data are can be accessed under the following link
1114 <https://www.pangaea.de/tok/ba8f0a1a1a09bf6c18c671b20a9d4319b2d11b3b> (please note that
1115 this is a preliminary link for reviewers only, which will expire after 100 days and will be
1116 updated upon acceptance of the manuscript).

1117 **References**

- 1118 Addison, J.A., Finney, B.P., Dean, W.E., Davies, M.H., Mix, A.C., Stoner, J.S., Jaeger, J.M., 2012.
1119 Productivity and sedimentary $\delta^{15}\text{N}$ variability for the last 17,000 years along the northern Gulf
1120 of Alaska continental slope. *Paleoceanography* 27. <https://doi.org/10.1029/2011PA002161>
- 1121 Aguilar-Islas, A.M., Hurst, M.P., Buck, K.N., Sohst, B., Smith, G.J., Lohan, M.C., Bruland, K.W.,
1122 2007. Micro- and macronutrients in the southeastern Bering Sea: Insight into iron-replete and
1123 iron-depleted regimes. *Prog. Oceanogr.* 73, 99–126.
1124 <https://doi.org/10.1016/J.POCEAN.2006.12.002>
- 1125 Ahagon, N., Ohkushi, K., Uchida, M., Mishima, T., 2003. Mid-depth circulation in the northwest
1126 Pacific during the last deglaciation: Evidence from foraminiferal radiocarbon ages. *Geophys.*
1127 *Res. Lett.* 30, 2097. <https://doi.org/10.1029/2003GL018287>
- 1128 Aiello, I.W., Ravelo, A.C., 2012. Evolution of marine sedimentation in the Bering Sea since the
1129 Pliocene. *Geosphere* 8, 1231–1253. <https://doi.org/10.1130/GES00710.1>
- 1130 Asahi, H., Kender, S., Ikehara, M., Sakamoto, T., Takahashi, K., Ravelo, A.C., Alvarez Zarikian,
1131 C.A., Khim, B.K., Leng, M.J., 2016. Orbital-scale benthic foraminiferal oxygen isotope
1132 stratigraphy at the northern Bering Sea Slope Site U1343 (IODP Expedition 323) and its
1133 Pleistocene paleoceanographic significance. *Deep Sea Res. Part II Top. Stud. Oceanogr.* 125–
1134 126, 66–83. <https://doi.org/10.1016/J.DSR2.2014.01.004>
- 1135 Barker, S., Greaves, M., Elderfield, H., 2003. A study of cleaning procedures used for foraminiferal
1136 Mg/Ca paleothermometry. *Geochemistry, Geophys. Geosystems* 4, 8407.
1137 <https://doi.org/10.1029/2003GC000559>
- 1138 Belt, S.T., 2018. Source-specific biomarkers as proxies for Arctic and Antarctic sea ice. *Org.*
1139 *Geochem.* 125, 277–298. <https://doi.org/10.1016/J.ORGGEOCHEM.2018.10.002>
- 1140 Belt, S.T., Brown, T.A., Rodriguez, A.N., Sanz, P.C., Tonkin, A., Ingle, R., 2012. A reproducible
1141 method for the extraction, identification and quantification of the Arctic sea ice proxy IP25 from
1142 marine sediments. *Anal. Methods* 4, 705. <https://doi.org/10.1039/c2ay05728j>
- 1143 Belt, S.T., Brown, T.A., Smik, L., Taterek, A., Wiktor, J., Stowasser, G., Assmy, P., Allen, C.S.,
1144 Husum, K., 2017. Identification of C25 highly branched isoprenoid (HBI) alkenes in diatoms of
1145 the genus *Rhizosolenia* in polar and sub-polar marine phytoplankton. *Org. Geochem.* 110, 65–
1146 72. <https://doi.org/10.1016/J.ORGGEOCHEM.2017.05.007>
- 1147 Belt, S.T., Cabedo-Sanz, P., Smik, L., Navarro-Rodriguez, A., Berben, S.M.P., Knies, J., Husum, K.,
1148 2015. Identification of paleo Arctic winter sea ice limits and the marginal ice zone: Optimised
1149 biomarker-based reconstructions of late Quaternary Arctic sea ice. *Earth Planet. Sci. Lett.* 431,
1150 127–139. <https://doi.org/10.1016/J.EPSL.2015.09.020>
- 1151 Belt, S.T., Massé, G., Rowland, S.J., Poulin, M., Michel, C., LeBlanc, B., 2007. A novel chemical
1152 fossil of palaeo sea ice: IP25. *Org. Geochem.* 38, 16–27.
1153 <https://doi.org/10.1016/J.ORGGEOCHEM.2006.09.013>
- 1154 Belt, S.T., Müller, J., 2013. The Arctic sea ice biomarker IP25: a review of current understanding,
1155 recommendations for future research and applications in palaeo sea ice reconstructions. *Quat.*
1156 *Sci. Rev.* 79, 9–25. <https://doi.org/10.1016/j.quascirev.2012.12.001>
- 1157 Berben, S.M.P., Husum, K., Navarro-Rodriguez, A., Belt, S.T., Aagaard-Sørensen, S., 2017. Semi-
1158 quantitative reconstruction of early to late Holocene spring and summer sea ice conditions in the
1159 northern Barents Sea. *J. Quat. Sci.* 32, 587–603. <https://doi.org/10.1002/jqs.2953>
- 1160 Bereiter, B., Eggleston, S., Schmitt, J., Nehrbass-Ahles, C., Stocker, T.F., Fischer, H., Kipfstuhl, S.,
1161 Chappellaz, J., 2015. Revision of the EPICA Dome C CO₂ record from 800 to 600 kyr before
1162 present. *Geophys. Res. Lett.* 42, 542–549. <https://doi.org/10.1002/2014GL061957>

- 1163 Boiteau, R., Greaves, M., Elderfield, H., 2012. Authigenic uranium in foraminiferal coatings: A proxy
1164 for ocean redox chemistry. *Paleoceanography* 27, PA3227.
1165 <https://doi.org/10.1029/2012PA002335>
- 1166 Boyer, T.P., Antonov, J.I., Baranova, O.K., Coleman, C., Garcia, H.E., Grodsky, A., Johnson, D.R.,
1167 Locarnini, R., Mishonov, A. V, O'Brien, T.D., Paver, C.R., Reagan, J.R., Seidov, D., Smolyar, I.
1168 V, Zweng, M.M., Sullivan, K.D., 2013. WORLD OCEAN DATABASE 2013, NOAA Atlas
1169 NESDIS 72. Sydney Levitus, Ed.; Alexey Mishonoc, Tech. Ed. NOAA Atlas, 209 pp.
1170 <https://doi.org/10.7289/V5NZ85MT>
- 1171 Boyle, E.A., 1983. Manganese carbonate overgrowths on foraminifera tests. *Geochim. Cosmochim.*
1172 *Acta* 47, 1815–1819. [https://doi.org/10.1016/0016-7037\(83\)90029-7](https://doi.org/10.1016/0016-7037(83)90029-7)
- 1173 Boyle, E.A., Keigwin, L.D., 1985. Comparison of Atlantic and Pacific paleochemical records for the
1174 last 215,000 years: changes in deep ocean circulation and chemical inventories. *Earth Planet.*
1175 *Sci. Lett.* 76, 135–150. [https://doi.org/10.1016/0012-821X\(85\)90154-2](https://doi.org/10.1016/0012-821X(85)90154-2)
- 1176 Brady, H.B., 1884. Report on the Foraminifera dredged by H.M.S. Challenger during the Years 1873-
1177 1876. Rep. Sci. Results Voyag. H.M.S. Chall. Dur. years 1873–76. *Zool.* 9 (part 22, 1–814).
- 1178 Brady, H.B., 1881. Notes on some of the Reticularian Rhizopoda of the "Challenger" Expedition. Part
1179 III. *Q. J. Microsc. Sci.* 21, 31–71.
- 1180 Brennan, C.E., Meissner, K.J., Eby, M., Hillaire-Marcel, C., Weaver, A.J., 2013. Impact of sea ice
1181 variability on the oxygen isotope content of seawater under glacial and interglacial conditions.
1182 *Paleoceanography* 28, 388–400. <https://doi.org/10.1002/palo.20036>
- 1183 Brown, T.A., Belt, S.T., Tatarek, A., Mundy, C.J., 2014. Source identification of the Arctic sea ice
1184 proxy IP25. *Nat. Commun.* 5, 4197. <https://doi.org/10.1038/ncomms5197>
- 1185 Brown, Z.W., Arrigo, K.R., 2013. Sea ice impacts on spring bloom dynamics and net primary
1186 production in the Eastern Bering Sea. *J. Geophys. Res. Ocean.* 118, 43–62.
1187 <https://doi.org/10.1029/2012JC008034>
- 1188 Brown, Z.W., van Dijken, G.L., Arrigo, K.R., 2011. A reassessment of primary production and
1189 environmental change in the Bering Sea. *J. Geophys. Res.* 116, C08014.
1190 <https://doi.org/10.1029/2010JC006766>
- 1191 Brunelle, B.G., Sigman, D.M., Cook, M.S., Keigwin, L.D., Haug, G.H., Plessen, B., Schettler, G.,
1192 Jaccard, S.L., 2007. Evidence from diatom-bound nitrogen isotopes for subarctic Pacific
1193 stratification during the last ice age and a link to North Pacific denitrification changes.
1194 *Paleoceanography* 22, n/a-n/a. <https://doi.org/10.1029/2005PA001205>
- 1195 Brunelle, B.G., Sigman, D.M., Jaccard, S.L., Keigwin, L.D., Plessen, B., Schettler, G., Cook, M.S.,
1196 Haug, G.H., 2010. Glacial/interglacial changes in nutrient supply and stratification in the
1197 western subarctic North Pacific since the penultimate glacial maximum. *Quat. Sci. Rev.* 29,
1198 2579–2590. <https://doi.org/10.1016/J.QUASCIREV.2010.03.010>
- 1199 Buizert, C., Gkinis, V., Severinghaus, J.P., He, F., Lecavalier, B.S., Kindler, P., Leuenberger, M.,
1200 Carlson, A.E., Vinther, B., Masson-Delmotte, V., White, J.W.C., Liu, Z., Otto-Bliesner, B.,
1201 Brook, E.J., 2014. Greenland temperature response to climate forcing during the last
1202 deglaciation. *Science* (80-.). 345, 1177–1180. <https://doi.org/10.1126/science.1254961>
- 1203 Cabedo-Sanz, P., Belt, S.T., 2015. Identification and characterisation of a novel mono-unsaturated
1204 highly branched isoprenoid (HBI) alkene in ancient Arctic sediments. *Org. Geochem.* 81, 34–39.
1205 <https://doi.org/10.1016/J.ORGGEOCHEM.2015.01.009>
- 1206 Caissie, B.E., Brigham-Grette, J., Lawrence, K.T., Herbert, T.D., Cook, M.S., 2010. Last Glacial
1207 Maximum to Holocene sea surface conditions at Umnak Plateau, Bering Sea, as inferred from
1208 diatom, alkenone, and stable isotope records. *Paleoceanography* 25.

- 1209 <https://doi.org/10.1029/2008PA001671>
- 1210 Cannariato, K.G., Kennett, J.P., 1999. Climatically related millennial-scale fluctuations in strength of
1211 California margin oxygen-minimum zone during the past 60 k.y., *Geology*. *GeoScienceWorld*.
1212 [https://doi.org/10.1130/0091-7613\(1999\)027<0975:CRMSFI>2.3.CO;2](https://doi.org/10.1130/0091-7613(1999)027<0975:CRMSFI>2.3.CO;2)
- 1213 Caralp, M.H., 1989. Abundance of *Bulimina exilis* and *Melonis barleeanum*: Relationship to the
1214 quality of marine organic matter. *Geo-Marine Lett.* 9, 37–43.
1215 <https://doi.org/10.1007/BF02262816>
- 1216 Cauille, C., Koho, K.A., Mojtahid, M., Reichart, G.J., Jorissen, F.J., 2014. Live (Rose Bengal stained)
1217 foraminiferal faunas from the northern Arabian Sea: Faunal succession within and below the
1218 OMZ. *Biogeosciences* 11, 1155–1175. <https://doi.org/10.5194/bg-11-1155-2014>
- 1219 Cavalieri, D.J., Martin, S., 1994. The contribution of Alaskan, Siberian, and Canadian coastal
1220 polynyas to the cold halocline layer of the Arctic Ocean. *J. Geophys. Res.* 99, 18343.
1221 <https://doi.org/10.1029/94JC01169>
- 1222 Chen, P., Yu, J., Jin, Z., 2017. An evaluation of benthic foraminiferal U/Ca and U/Mn proxies for
1223 deep ocean carbonate chemistry and redox conditions. *Geochemistry, Geophys. Geosystems* 18,
1224 617–630. <https://doi.org/10.1002/2016GC006730>
- 1225 Chikamoto, M.O., Menviel, L., Abe-Ouchi, A., Ohgaito, R., Timmermann, A., Okazaki, Y., Oka, A.,
1226 Mouchet, A., 2012. Variability in North Pacific intermediate and deep water ventilation during
1227 Heinrich events in two coupled climate models. *Deep Sea Res. Part II Top. Stud. Oceanogr.* 61–
1228 64, 114–126. <https://doi.org/10.1016/J.DSR2.2011.12.002>
- 1229 Coachman, L.K., 1993. On the flow field in the Chirikov Basin. *Cont. Shelf Res.* 13, 481–508.
1230 [https://doi.org/10.1016/0278-4343\(93\)90092-C](https://doi.org/10.1016/0278-4343(93)90092-C)
- 1231 Coachman, L.K., Whitley, T.E., Goering, J.J., 1999. Silica in Bering Sea Deep and Bottom Water,
1232 Dynamics o. ed. University of Alaska Sea Grant, Fairbanks.
- 1233 Cook, M.S., Keigwin, L.D., 2015. Radiocarbon profiles of the NW Pacific from the LGM and
1234 deglaciation: Evaluating ventilation metrics and the effect of uncertain surface reservoir ages.
1235 *Paleoceanography* 30, 174–195. <https://doi.org/10.1002/2014PA002649>
- 1236 Cook, M.S., Keigwin, L.D., Sancetta, C.A., 2005. The deglacial history of surface and intermediate
1237 water of the Bering Sea. *Deep Sea Res. Part II Top. Stud. Oceanogr.* 52, 2163–2173.
1238 <https://doi.org/10.1016/J.DSR2.2005.07.004>
- 1239 Cook, M.S., Ravelo, A.C., Mix, A., Nesbitt, I.M., Miller, N. V., 2016. Tracing subarctic Pacific water
1240 masses with benthic foraminiferal stable isotopes during the LGM and late Pleistocene. *Deep*
1241 *Sea Res. Part II Top. Stud. Oceanogr.* 125–126, 84–95.
1242 <https://doi.org/10.1016/J.DSR2.2016.02.006>
- 1243 Crusius, J., Pedersen, T.F., Kienast, S., Keigwin, L., Labeyrie, L., 2004. Influence of northwest
1244 Pacific productivity on North Pacific Intermediate Water oxygen concentrations during the
1245 Bølling-Ållerød interval (14.7-12.9 ka). *Geology* 32, 633–636. <https://doi.org/10.1130/G20508.1>
- 1246 Cushman, J.A., 1933. New Arctic Foraminifera collected by Capt. R. A. Bartlett from Fox Basin and
1247 off the northeast coast of Greenland (with two plates). *Smithson. Misc. Collect.* 89, 1–8.
- 1248 Cushman, J.A., 1927. An outline of a re-classification of the Foraminifera. *Contrib. from Cushman*
1249 *Lab. Foraminifer. Res.* 3.
- 1250 D’Orbigny, A., 1839. *Foraminifères*. Paris.
- 1251 Dawson, J.W., 1860. Notice of Tertiary fossils from Labrador, Maine, etc., and remarks on the
1252 climate of Canada in the newer Pliocene or Pleistocene period. *Can. Nat. Geol. Montr.* 5, 188–
1253 200.

- 1254 Detlef, H., Belt, S.T., Sosdian, S.M., Smik, L., Lear, C.H., Hall, I.R., Cabedo-Sanz, P., Husum, K.,
1255 Kender, S., 2018. Sea ice dynamics across the Mid-Pleistocene transition in the Bering Sea. *Nat.*
1256 *Commun.* 9, 941. <https://doi.org/10.1038/s41467-018-02845-5>
- 1257 Detlef, H., Sosdian, S.M., Kender, S., Lear, C.H., Hall, I.R., 2020. Multi-elemental composition of
1258 authigenic carbonates in benthic foraminifera from the eastern Bering Sea continental margin
1259 (International Ocean Discovery Program Site U1343). *Geochim. Cosmochim. Acta* 268, 1–21.
1260 <https://doi.org/10.1016/j.gca.2019.09.025>
- 1261 Duplessy, J.-C., Arnold, M., Bard, E., Juillet-Leclerc, A., Kallel, N., Labeyrie, L., 1989. AMS 14C
1262 Study of Transient Events and of the Ventilation Rate of the Pacific Intermediate Water During
1263 the Last Deglaciation. *Radiocarbon* 31, 493–502.
- 1264 Elias, S.A., Short, S.K., Nelson, C.H., Birks, H.H., 1996. Life and times of the Bering land bridge.
1265 *Nature* 382, 60–63. <https://doi.org/10.1038/382060a0>
- 1266 Emile-Geay, J., Cane, M.A., Naik, N., Seager, R., Clement, A.C., Geen, A. van, 2003. Warren
1267 revisited: Atmospheric freshwater fluxes and “Why is no deep water formed in the North
1268 Pacific.” *J. Geophys. Res.* 108, 3178. <https://doi.org/10.1029/2001JC001058>
- 1269 Expedition 323 Scientists, 2010. Bering Sea paleoceanography: Pliocene-Pleistocene
1270 paleoceanography and climate history of the Bering Sea. *IODP Prelim. Rep.* 323.
1271 <https://doi.org/10.2204/iodp.pr.323.2010>
- 1272 Fetterer, F.K., Meier, W.N., Savoie, M., Windnagel, A.K., 2017. Sea Ice Index, Version 3 | National
1273 Snow and Ice Data Center updated daily.
- 1274 Filipsson, H.L., Romero, O.E., Stuut, J.-B.W., Donner, B., 2011. Relationships between primary
1275 productivity and bottom-water oxygenation off northwest Africa during the last deglaciation. *J.*
1276 *Quat. Sci.* 26, 448–456. <https://doi.org/10.1002/jqs.1473>
- 1277 Frey, K.E., Perovich, D.K., Light, B., 2011. The spatial distribution of solar radiation under a melting
1278 Arctic sea ice cover. *Geophys. Res. Lett.* 38, n/a-n/a. <https://doi.org/10.1029/2011GL049421>
- 1279 Froelich, P.N., Klinkhammer, G.P., Bender, M.L., Luedtke, N.A., Heath, G.R., Cullen, D., Dauphin,
1280 P., Hammond, D., Hartman, B., Maynard, V., 1979. Early oxidation of organic matter in pelagic
1281 sediments of the eastern equatorial Atlantic: suboxic diagenesis. *Geochim. Cosmochim. Acta* 43,
1282 1075–1090. [https://doi.org/10.1016/0016-7037\(79\)90095-4](https://doi.org/10.1016/0016-7037(79)90095-4)
- 1283 Fujii, Y., Nakano, T., Usui, N., Matsumoto, S., Tsujino, H., Kamachi, M., 2013. Pathways of the
1284 North Pacific Intermediate Water identified through the tangent linear and adjoint models of an
1285 ocean general circulation model. *J. Geophys. Res. Ocean.* 118, 2035–2051.
1286 <https://doi.org/10.1002/jgrc.20094>
- 1287 Galbraith, E.D., Jaccard, S.L., Pedersen, T.F., Sigman, D.M., Haug, G.H., Cook, M., Southon, J.R.,
1288 Francois, R., 2007. Carbon dioxide release from the North Pacific abyss during the last
1289 deglaciation. *Nature* 449, 890–893. <https://doi.org/10.1038/nature06227>
- 1290 Garcia, H.E., Locarnini, R.A., Boyer, T.P., Antonov, J.I., Baranova, O.K., Zweng, M.M., Reagan,
1291 J.R., Johnson, D.R., 2014. World Ocean Atlas 2013, Volume 3: Dissolved Oxygen, Apparent
1292 Oxygen Utilization, and Oxygen Saturation. NOAA Atlas NESDIS 75.
- 1293 Gargett, A.E., 1991. Physical processes and the maintenance of nutrient-rich euphotic zones. *Limnol.*
1294 *Oceanogr.* 36, 1527–1545. <https://doi.org/10.4319/lo.1991.36.8.1527>
- 1295 Gebhardt, H., Sarnthein, M., Grootes, P.M., Kiefer, T., Kuehn, H., Schmieder, F., Röhl, U., 2008.
1296 Paleonutrient and productivity records from the subarctic North Pacific for Pleistocene glacial
1297 terminations I to V. *Paleoceanography* 23, n/a-n/a. <https://doi.org/10.1029/2007PA001513>
- 1298 Gersonde, R., 2012. The expedition of the research vessel “Sonne” to the subpolar North Pacific and

- 1299 the Bering Sea in 2009 (SO202-INOPEX). *Berichte zur Polar- und Meeresforsch. = Reports*
1300 *polar Mar. Res.* 643, 323.
- 1301 Gong, X., Lembke-Jene, L., Lohmann, G., Knorr, G., Tiedemann, R., Zou, J.J., Shi, X.F., 2019.
1302 Enhanced North Pacific deep-ocean stratification by stronger intermediate water formation
1303 during Heinrich Stadial 1. *Nat. Commun.* 10, 656. <https://doi.org/10.1038/s41467-019-08606-2>
- 1304 Gorbarenko, S.A., Wang, P., Wang, R., Cheng, X., 2010. Orbital and suborbital environmental
1305 changes in the southern Bering Sea during the last 50 kyr. *Palaeogeogr. Palaeoclimatol.*
1306 *Palaeoecol.* 286, 97–106. <https://doi.org/10.1016/j.palaeo.2009.12.014>
- 1307 Gottschalk, J., Skinner, L.C., Lippold, J., Vogel, H., Frank, N., Jaccard, S.L., Waelbroeck, C., 2016.
1308 Biological and physical controls in the Southern Ocean on past millennial-scale atmospheric
1309 CO₂ changes. *Nat. Commun.* 7, 11539. <https://doi.org/10.1038/ncomms11539>
- 1310 Gray, W.R., Rae, J.W.B., Wills, R.C.J., Shevenell, A.E., Taylor, B., Burke, A., Foster, G.L., Lear,
1311 C.H., 2018. Deglacial upwelling, productivity and CO₂ outgassing in the North Pacific Ocean.
1312 *Nat. Geosci.* 11, 340–344. <https://doi.org/10.1038/s41561-018-0108-6>
- 1313 Gray, W.R., Wills, R.C.J., Rae, J.W.B., Burke, A., Ivanovic, R.F., Roberts, W.H.G., Ferreira, D.,
1314 Valdes, P.J., 2020. Wind-Driven Evolution of the North Pacific Subpolar Gyre Over the Last
1315 Deglaciation. *Geophys. Res. Lett.* 47. <https://doi.org/10.1029/2019GL086328>
- 1316 Grebmeier, J.M., Overland, J.E., Moore, S.E., Farley, E. V., Carmack, E.C., Cooper, L.W., Frey, K.E.,
1317 Helle, J.H., McLaughlin, F.A., McNutt, S.L., 2006. A major ecosystem shift in the northern
1318 Bering Sea. *Science* 311, 1461–4. <https://doi.org/10.1126/science.1121365>
- 1319 Greenacre, M., 1983. *Theory and Applications of Corresponding Analysis.*
- 1320 Hammer, D.A.T., Ryan, P.D., Hammer, Ø., Harper, D.A.T., 2001. *Past: Paleontological Statistics*
1321 *Software Package for Education and Data Analysis, Palaeontologia Electronica.*
- 1322 Hammer, Ø., Harper, D.A.T., 2006. *Paleontological data analysis.* Blackwell Pub.
- 1323 Harada, N., Ahagon, N., Sakamoto, T., Uchida, M., Ikehara, M., Shibata, Y., 2006. Rapid fluctuation
1324 of alkenone temperature in the southwestern Okhotsk Sea during the past 120 ky. *Glob. Planet.*
1325 *Change* 53, 29–46. <https://doi.org/10.1016/j.gloplacha.2006.01.010>
- 1326 Harada, N., Ahagon, N., Uchida, M., Murayama, M., 2004. Northward and southward migrations of
1327 frontal zones during the past 40 kyr in the Kuroshio-Oyashio transition area. *Geochemistry,*
1328 *Geophys. Geosystems* 5, n/a-n/a. <https://doi.org/10.1029/2004GC000740>
- 1329 Harada, N., Sato, M., Sakamoto, T., 2008. Freshwater impacts recorded in tetraunsaturated alkenones
1330 and alkenone sea surface temperatures from the Okhotsk Sea across millennial-scale cycles.
1331 *Paleoceanography* 23, n/a-n/a. <https://doi.org/10.1029/2006PA001410>
- 1332 Hasenfratz, A.P., Martínez-García, A., Jaccard, S.L., Vance, D., Wälle, M., Greaves, M., Haug, G.H.,
1333 2017. Determination of the Mg/Mn ratio in foraminiferal coatings: An approach to correct
1334 Mg/Ca temperatures for Mn-rich contaminant phases. *Earth Planet. Sci. Lett.* 457, 335–347.
1335 <https://doi.org/10.1016/J.EPSL.2016.10.004>
- 1336 Hernández-Almeida, I., Boltovskoy, D., Kruglikova, S.B., Cortese, G., 2020. A new radiolarian
1337 transfer function for the Pacific Ocean and application to fossil records: Assessing potential and
1338 limitations for the last glacial-interglacial cycle. *Glob. Planet. Change* 190, 103186.
1339 <https://doi.org/10.1016/j.gloplacha.2020.103186>
- 1340 Horikawa, K., Asahara, Y., Yamamoto, K., Okazaki, Y., 2010. Intermediate water formation in the
1341 Bering Sea during glacial periods: Evidence from neodymium isotope ratios. *Geology* 38, 435–
1342 438. <https://doi.org/10.1130/G30225.1>
- 1343 Hunt, A.S., Corliss, B.H., 1993. *Distribution and microhabitats of living (stained) benthic*

- 1344 foraminifera from the Canadian Arctic Archipelago. *Mar. Micropaleontol.* 20, 321–345.
1345 [https://doi.org/10.1016/0377-8398\(93\)90041-U](https://doi.org/10.1016/0377-8398(93)90041-U)
- 1346 Hurst, M.P., Aguilar-Islas, A.M., Bruland, K.W., 2010. Iron in the southeastern Bering Sea: Elevated
1347 leachable particulate Fe in shelf bottom waters as an important source for surface waters. *Cont.*
1348 *Shelf Res.* 30, 467–480. <https://doi.org/10.1016/J.CSR.2010.01.001>
- 1349 Ikehara, K., Ohkushi, K., Shibahara, A., Hoshiba, M., 2006. Change of bottom water conditions at
1350 intermediate depths of the Oyashio region, NW Pacific over the past 20,000 yrs. *Glob. Planet.*
1351 *Change* 53, 78–91. <https://doi.org/10.1016/j.gloplacha.2006.01.011>
- 1352 Ishimura, T., Tsunogai, U., Hasegawa, S., Nakagawa, F., Oi, T., Kitazato, H., Suga, H., Toyofuku, T.,
1353 2012. Variation in stable carbon and oxygen isotopes of individual benthic foraminifera: tracers
1354 for quantifying the vital effect. *Biogeosciences Discuss.* 9, 6191–6218.
1355 <https://doi.org/10.5194/bgd-9-6191-2012>
- 1356 Itaki, T., Kim, S., Rella, S.F., Uchida, M., Tada, R., Khim, B.K., 2012. Millennial-scale variations of
1357 late Pleistocene radiolarian assemblages in the Bering Sea related to environments in shallow
1358 and deep waters. *Deep. Res. Part II Top. Stud. Oceanogr.* 61–64, 127–144.
1359 <https://doi.org/10.1016/j.dsr2.2011.03.002>
- 1360 Ivanova, E. V., Ovsepyan, E.A., Risebrobakken, B., Vetrov, A.A., 2008. DOWNCORE
1361 DISTRIBUTION OF LIVING CALCAREOUS FORAMINIFERA AND STABLE ISOTOPES
1362 IN THE WESTERN BARENTS SEA. *J. Foraminifer. Res.* 38, 337–356.
1363 <https://doi.org/10.2113/gsjfr.38.4.337>
- 1364 Jaccard, S.L., Galbraith, E.D., 2013. Direct ventilation of the North Pacific did not reach the deep
1365 ocean during the last deglaciation. *Geophys. Res. Lett.* 40, 199–203.
1366 <https://doi.org/10.1029/2012GL054118>
- 1367 Jaccard, S.L., Galbraith, E.D., 2012. Large climate-driven changes of oceanic oxygen concentrations
1368 during the last deglaciation. *Nat. Geosci.* 5, 151–156. <https://doi.org/10.1038/ngeo1352>
- 1369 Jaccard, S.L., Galbraith, E.D., Sigman, D.M., Haug, G.H., Francois, R., Pedersen, T.F., Dulski, P.,
1370 Thierstein, H.R., 2009. Subarctic Pacific evidence for a glacial deepening of the oceanic respired
1371 carbon pool. *Earth Planet. Sci. Lett.* 277, 156–165. <https://doi.org/10.1016/J.EPSL.2008.10.017>
- 1372 Jakobsson, M., Pearce, C., Cronin, T.M., Backman, J., Anderson, L.G., Barrientos, N., Björk, G.,
1373 Coxall, H., de Boer, A., Mayer, L.A., Mörrh, C.-M., Nilsson, J., Rattray, J.E., Stranne, C.,
1374 Semiletov, I., O'Regan, M., 2017. Post-glacial flooding of the Bering Land Bridge
1375 dated to 11 cal ka BP based on new geophysical and sediment records. *Clim. Past* 13, 991–1005.
1376 <https://doi.org/10.5194/cp-13-991-2017>
- 1377 Jang, K., Huh, Y., Han, Y., 2017. Authigenic Nd isotope record of North Pacific Intermediate Water
1378 formation and boundary exchange on the Bering Slope. *Quat. Sci. Rev.* 156, 150–163.
1379 <https://doi.org/10.1016/J.QUASCIREV.2016.11.032>
- 1380 Jannink, N.T., Zachariasse, W.J., Van der Zwaan, G.J., 1998. Living (Rose Bengal stained) benthic
1381 foraminifera from the Pakistan continental margin (northern Arabian Sea). *Deep Sea Res. Part I*
1382 *Oceanogr. Res. Pap.* 45, 1483–1513. [https://doi.org/10.1016/S0967-0637\(98\)00027-2](https://doi.org/10.1016/S0967-0637(98)00027-2)
- 1383 Katsuki, K., Takahashi, K., 2005. Diatoms as paleoenvironmental proxies for seasonal productivity,
1384 sea-ice and surface circulation in the Bering Sea during the late Quaternary. *Deep Sea Res. Part*
1385 *II Top. Stud. Oceanogr.* 52, 2110–2130. <https://doi.org/10.1016/J.DSR2.2005.07.001>
- 1386 Kaufman, D., Ager, T., Anderson, N., Anderson, P., Andrews, J., Bartlein, P., Brubaker, L.,
1387 Coats, L., Cwynar, L., Duvall, M., Dyke, A., Edwards, M., Eisner, W., Gajewski, K.,
1388 Geirsdóttir, A., Hu, F., Jennings, A., Kaplan, M., Kerwin, M., Lozhkin, A., MacDonald, G.,
1389 Miller, G., Mock, C., Oswald, W., Otto-Bliesner, B., Porinchu, D., Rühland, K., Smol, J.,

- 1390 Steig, E., Wolfe, B., 2004. Holocene thermal maximum in the western Arctic (0–180°W). *Quat.*
1391 *Sci. Rev.* 23, 529–560. <https://doi.org/10.1016/J.QUASCIREV.2003.09.007>
- 1392 Keigwin, L.D., 1998. Glacial-age hydrography of the far northwest Pacific Ocean. *Paleoceanography*
1393 13, 323–339. <https://doi.org/10.1029/98PA00874>
- 1394 Kender, S., Aturamu, A., Zalasiewicz, J., Kaminski, M.A., Williams, M., 2019. Benthic foraminifera
1395 indicate Glacial North Pacific Intermediate Water and reduced primary productivity over
1396 Bowers Ridge, Bering Sea, since the Mid-Brunhes Transition. *J. Micropalaeontology* 38, 177–
1397 187. <https://doi.org/10.5194/jm-38-177-2019>
- 1398 Kender, S., Kaminski, M.A., 2017. Modern deep-water agglutinated foraminifera from IODP
1399 Expedition 323, Bering Sea: ecological and taxonomic implications. *J. Micropalaeontology*
1400 *jmpaleo2016-026*. <https://doi.org/10.1144/jmpaleo2016-026>
- 1401 Kender, S., Ravelo, A.C., Worne, S., Swann, G.E.A., Leng, M.J., Asahi, H., Becker, J., Detlef, H.,
1402 Aiello, I.W., Andreasen, D., Hall, I.R., 2018. Closure of the Bering Strait caused Mid-
1403 Pleistocene Transition cooling. *Nat. Commun.* 9, 5386. <https://doi.org/10.1038/s41467-018-07828-0>
- 1405 Keul, N., Langer, G., de Nooijer, L.J., Nehrke, G., Reichart, G.-J., Bijma, J., 2013. Incorporation of
1406 uranium in benthic foraminiferal calcite reflects seawater carbonate ion concentration.
1407 *Geochemistry, Geophys. Geosystems* 14, 102–111. <https://doi.org/10.1029/2012GC004330>
- 1408 Khusid, T.A., Basov, I.A., Gorbarenko, S.A., Chekhovskaya, M.P., 2006. Benthic foraminifera in
1409 upper Quaternary sediments of the southern Bering Sea: Distribution and paleoceanographic
1410 interpretations. *Stratigr. Geol. Correl.* 14, 538–548. <https://doi.org/10.1134/S0869593806050066>
- 1411 Kiefer, T., Kienast, M., 2005. Patterns of deglacial warming in the Pacific Ocean: a review with
1412 emphasis on the time interval of Heinrich event 1. *Quat. Sci. Rev.* 24, 1063–1081.
1413 <https://doi.org/10.1016/J.QUASCIREV.2004.02.021>
- 1414 Kim, S., Takahashi, K., Khim, B.-K., Kanematsu, Y., Asahi, H., Ravelo, A.C., 2014. Biogenic opal
1415 production changes during the Mid-Pleistocene Transition in the Bering Sea (IODP Expedition
1416 323 Site U1343). *Quat. Res.* 81, 151–157. <https://doi.org/10.1016/J.YQRES.2013.10.001>
- 1417 Knox, F., McElroy, M.B., 1984. Changes in atmospheric CO₂: Influence of the marine biota at high
1418 latitude. *J. Geophys. Res.* 89, 4629. <https://doi.org/10.1029/JD089iD03p04629>
- 1419 Knudson, K.P., Ravelo, A.C., 2015. North Pacific Intermediate Water circulation enhanced by the
1420 closure of the Bering Strait. *Paleoceanography* 30, 1287–1304.
1421 <https://doi.org/10.1002/2015PA002840>
- 1422 Kohfeld, K.E., Chase, Z., 2011. Controls on deglacial changes in biogenic fluxes in the North Pacific
1423 Ocean. *Quat. Sci. Rev.* 30, 3350–3363. <https://doi.org/10.1016/J.QUASCIREV.2011.08.007>
- 1424 Koho, K.A., de Nooijer, L.J., Fontanier, C., Toyofuku, T., Kazumasa, O., Kitazato, H., Reichart, G.-
1425 J., 2017. Benthic foraminiferal Mn/Ca ratios reflect microhabitat preferences. *Biogeosciences*
1426 *Discuss.* 1–22. <https://doi.org/10.5194/bg-2016-547>
- 1427 Köseoğlu, D., Belt, S.T., Husum, K., Knies, J., 2018a. An assessment of biomarker-based multivariate
1428 classification methods versus the PIP25 index for paleo Arctic sea ice reconstruction. *Org.*
1429 *Geochem.* 125, 82–94. <https://doi.org/10.1016/J.ORGGEOCHEM.2018.08.014>
- 1430 Köseoğlu, D., Belt, S.T., Smik, L., Yao, H., Panieri, G., Knies, J., 2018b. Complementary biomarker-
1431 based methods for characterising Arctic sea ice conditions: A case study comparison between
1432 multivariate analysis and the PIP25 index. *Geochim. Cosmochim. Acta* 222, 406–420.
1433 <https://doi.org/10.1016/J.GCA.2017.11.001>
- 1434 Kuehn, H., Lembke-Jene, L., Gersonde, R., Esper, O., Lamy, F., Arz, H., Kuhn, G., Tiedemann, R.,

- 1435 2014. Laminated sediments in the Bering Sea reveal atmospheric teleconnections to Greenland
1436 climate on millennial to decadal timescales during the last deglaciation. *Clim. Past* 10, 2215–
1437 2236. <https://doi.org/10.5194/cp-10-2215-2014>
- 1438 Kurek, J., Cwynar, L.C., Ager, T.A., Abbott, M.B., Edwards, M.E., 2009. Late Quaternary
1439 paleoclimate of western Alaska inferred from fossil chironomids and its relation to vegetation
1440 histories. *Quat. Sci. Rev.* 28, 799–811. <https://doi.org/10.1016/j.quascirev.2008.12.001>
- 1441 Ladd, C., 2014. Seasonal and interannual variability of the Bering Slope Current. *Deep Sea Res. Part*
1442 *II Top. Stud. Oceanogr.* 109, 5–13. <https://doi.org/10.1016/J.DSR2.2013.12.005>
- 1443 Ladd, C., Stabeno, P.J., O’Hern, J.E., 2012. Observations of a Pribilof eddy. *Deep Sea Res. Part I*
1444 *Oceanogr. Res. Pap.* 66, 67–76. <https://doi.org/10.1016/J.DSR.2012.04.003>
- 1445 Lam, P.J., Bishop, J.K.B., 2008. The continental margin is a key source of iron to the HNLC North
1446 Pacific Ocean. *Geophys. Res. Lett.* 35, L07608. <https://doi.org/10.1029/2008GL033294>
- 1447 Lam, P.J., Robinson, L.F., Blusztajn, J., Li, C., Cook, M.S., McManus, J.F., Keigwin, L.D., 2013.
1448 Transient stratification as the cause of the North Pacific productivity spike during deglaciation.
1449 *Nat. Geosci.* 6, 622–626. <https://doi.org/10.1038/ngeo1873>
- 1450 Lea, D.W., Mashiotto, T.A., Spero, H.J., 1999. Controls on magnesium and strontium uptake in
1451 planktonic foraminifera determined by live culturing. *Geochim. Cosmochim. Acta* 63, 2369–
1452 2379. [https://doi.org/10.1016/S0016-7037\(99\)00197-0](https://doi.org/10.1016/S0016-7037(99)00197-0)
- 1453 Leblanc, K., Hare, C.E., Boyd, P.W., Bruland, K.W., Sohst, B., Pickmere, S., Lohan, M.C., Buck, K.,
1454 Ellwood, M., Hutchins, D.A., 2005. Fe and Zn effects on the Si cycle and diatom community
1455 structure in two contrasting high and low-silicate HNLC areas. *Deep Sea Res. Part I Oceanogr.*
1456 *Res. Pap.* 52, 1842–1864. <https://doi.org/10.1016/J.DSR.2005.06.005>
- 1457 Levitus, S., Conkright, M.E., Reid, J.L., Najjar, R.G., Mantyla, A., 1993. Distribution of nitrate,
1458 phosphate and silicate in the world oceans. *Prog. Oceanogr.* 31, 245–273.
1459 [https://doi.org/10.1016/0079-6611\(93\)90003-V](https://doi.org/10.1016/0079-6611(93)90003-V)
- 1460 Lisiecki, L.E., Raymo, M.E., 2005. A Pliocene-Pleistocene stack of 57 globally distributed benthic δ
1461 ^{18}O records. *Paleoceanography* 20, n/a-n/a. <https://doi.org/10.1029/2004PA001071>
- 1462 Lo, L., Belt, S.T., Lattaud, J., Friedrich, T., Zeeden, C., Schouten, S., Smik, L., Timmermann, A.,
1463 Cabedo-Sanz, P., Huang, J.-J., Zhou, L., Ou, T.-H., Chang, Y.-P., Wang, L.-C., Chou, Y.-M.,
1464 Shen, C.-C., Chen, M.-T., Wei, K.-Y., Song, S.-R., Fang, T.-H., Gorbarenko, S.A., Wang, W.-
1465 L., Lee, T.-Q., Elderfield, H., Hodell, D.A., 2018. Precession and atmospheric CO₂ modulated
1466 variability of sea ice in the central Okhotsk Sea since 130,000 years ago. *Earth Planet. Sci. Lett.*
1467 488, 36–45. <https://doi.org/10.1016/J.EPSL.2018.02.005>
- 1468 Locarnini, R.A., Mishonov, A.V., Antonov, J.I., Boyer, T.P., Garcia, H.E., Baranova, O.K., Zweng,
1469 M.M., Paver, C.R., Reagan, J.R., Johnson, D.R., Hamilton, M., Seidov, D., 2013. *World Ocean*
1470 *Atlas 2013, Volume 1: Temperature*. NOAA Atlas NESDIS 73.
- 1471 Lund, D.C., Mix, A.C., Southon, J., 2011. Increased ventilation age of the deep northeast Pacific
1472 Ocean during the last deglaciation. *Nat. Geosci.* 4, 771–774. <https://doi.org/10.1038/ngeo1272>
- 1473 Matsumoto, K., Oba, T., Lynch-Stieglitz, J., Yamamoto, H., 2002. Interior hydrography and
1474 circulation of the glacial Pacific Ocean. *Quat. Sci. Rev.* 21, 1693–1704.
1475 [https://doi.org/10.1016/S0277-3791\(01\)00142-1](https://doi.org/10.1016/S0277-3791(01)00142-1)
- 1476 Max, L., Lembke-Jene, L., Riethdorf, J.-R., Tiedemann, R., Nürnberg, D., Kühn, H., Mackensen, A.,
1477 2014. Pulses of enhanced North Pacific Intermediate Water ventilation from the Okhotsk Sea
1478 and Bering Sea during the last deglaciation. *Clim. Past* 10, 591–605. <https://doi.org/10.5194/cp-10-591-2014>

- 1480 Max, L., Riethdorf, J.-R., Tiedemann, R., Smirnova, M., Lembke-Jene, L., Fahl, K., Nürnberg, D.,
1481 Matul, A., Mollenhauer, G., 2012. Sea surface temperature variability and sea-ice extent in the
1482 subarctic northwest Pacific during the past 15,000 years. *Paleoceanography* 27, n/a-n/a.
1483 <https://doi.org/10.1029/2012PA002292>
- 1484 Max, L., Rippert, N., Lembke-Jene, L., Mackensen, A., Nürnberg, D., Tiedemann, R., 2017. Evidence
1485 for enhanced convection of North Pacific Intermediate Water to the low-latitude Pacific under
1486 glacial conditions. *Paleoceanography* 32, 41–55. <https://doi.org/10.1002/2016PA002994>
- 1487 McKay, C.L., Filipsson, H.L., Romero, O.E., Stuut, J.-B.W., Björck, S., 2016. The interplay between
1488 the surface and bottom water environment within the Benguela Upwelling System over the last
1489 70 ka. *Paleoceanography* 31, 266–285. <https://doi.org/10.1002/2015PA002792>
- 1490 McManus, J.F., Francois, R., Gherardi, J.-M., Keigwin, L.D., Brown-Leger, S., 2004. Collapse and
1491 rapid resumption of Atlantic meridional circulation linked to deglacial climate changes. *Nature*
1492 428, 834–837. <https://doi.org/10.1038/nature02494>
- 1493 Méheust, M., Fahl, K., Stein, R., 2013. Variability in modern sea surface temperature, sea ice and
1494 terrigenous input in the sub-polar North Pacific and Bering Sea: Reconstruction from biomarker
1495 data. *Org. Geochem.* 57, 54–64. <https://doi.org/10.1016/J.ORGGEOCHEM.2013.01.008>
- 1496 Méheust, M., Stein, R., Fahl, K., Gersonde, R., 2018. Sea-ice variability in the subarctic North Pacific
1497 and adjacent Bering Sea during the past 25 ka: new insights from IP25 and Uk'37 proxy records.
1498 *arktos* 4, 8. <https://doi.org/10.1007/s41063-018-0043-1>
- 1499 Méheust, M., Stein, R., Fahl, K., Max, L., Riethdorf, J.-R., 2016. High-resolution IP25-based
1500 reconstruction of sea-ice variability in the western North Pacific and Bering Sea during the past
1501 18,000 years. *Geo-Marine Lett.* 36, 101–111. <https://doi.org/10.1007/s00367-015-0432-4>
- 1502 Menviel, L., Timmermann, A., Elison Timm, O., Mouchet, A., Abe-Ouchi, A., Chikamoto, M.O.,
1503 Harada, N., Ohgaito, R., Okazaki, Y., 2012. Removing the North Pacific halocline: Effects on
1504 global climate, ocean circulation and the carbon cycle. *Deep Sea Res. Part II Top. Stud.*
1505 *Oceanogr.* 61–64, 106–113. <https://doi.org/10.1016/J.DSR2.2011.03.005>
- 1506 Meyer, V.D., Max, L., Hefter, J., Tiedemann, R., Mollenhauer, G., 2016. Glacial-to-Holocene
1507 evolution of sea surface temperature and surface circulation in the subarctic northwest Pacific
1508 and the Western Bering Sea. *Paleoceanography* 31, 916–927.
1509 <https://doi.org/10.1002/2015PA002877>
- 1510 Miura, T., Suga, T., Hanawa, K., 2002. Winter Mixed Layer and Formation of Dichothermal Water in
1511 the Bering Sea. *J. Oceanogr.* 58, 815–823. <https://doi.org/10.1023/A:1022871112946>
- 1512 Mizobata, K., Saitoh, S., 2004. Variability of Bering Sea eddies and primary productivity along the
1513 shelf edge during 1998–2000 using satellite multisensor remote sensing. *J. Mar. Syst.* 50, 101–
1514 111. <https://doi.org/10.1016/J.JMARSYS.2003.09.014>
- 1515 Mizobata, K., Saitoh, S., Wang, J., 2008. Interannual variability of summer biochemical enhancement
1516 in relation to mesoscale eddies at the shelf break in the vicinity of the Pribilof Islands, Bering
1517 Sea. *Deep Sea Res. Part II Top. Stud. Oceanogr.* 55, 1717–1728.
1518 <https://doi.org/10.1016/J.DSR2.2008.03.002>
- 1519 Mizobata, K., Saitoh, S.I., Shiimoto, A., Miyamura, T., Shiga, N., Imai, K., Toratani, M., Kajiwara,
1520 Y., Sasaoka, K., 2002. Bering Sea cyclonic and anticyclonic eddies observed during summer
1521 2000 and 2001. *Prog. Oceanogr.* 55, 65–75. [https://doi.org/10.1016/S0079-6611\(02\)00070-8](https://doi.org/10.1016/S0079-6611(02)00070-8)
- 1522 Moffitt, S.E., Moffitt, R.A., Sauthoff, W., Davis, C. V., Hewett, K., Hill, T.M., 2015.
1523 *Paleoceanographic Insights on Recent Oxygen Minimum Zone Expansion: Lessons for Modern*
1524 *Oceanography*. *PLoS One* 10, e0115246. <https://doi.org/10.1371/journal.pone.0115246>
- 1525 Moore, J.K., Doney, S.C., Glover, D.M., Fung, I.Y., 2001. Iron cycling and nutrient-limitation

- 1526 patterns in surface waters of the World Ocean. *Deep Sea Res. Part II Top. Stud. Oceanogr.* 49,
1527 463–507. [https://doi.org/10.1016/S0967-0645\(01\)00109-6](https://doi.org/10.1016/S0967-0645(01)00109-6)
- 1528 Mudelsee, M., 2003. Estimating Pearson's Correlation Coefficient with Bootstrap Confidence Interval
1529 from Serially Dependent Time Series. *Math. Geol.* 35, 651–665.
1530 <https://doi.org/10.1023/B:MATG.0000002982.52104.02>
- 1531 Müller, J., Massé, G., Stein, R., Belt, S.T., 2009. Variability of sea-ice conditions in the Fram Strait
1532 over the past 30,000 years. *Nat. Geosci.* 2, 772–776. <https://doi.org/10.1038/ngeo665>
- 1533 Müller, J., Wagner, A., Fahl, K., Stein, R., Prange, M., Lohmann, G., 2011. Towards quantitative sea
1534 ice reconstructions in the northern North Atlantic: A combined biomarker and numerical
1535 modelling approach. *Earth Planet. Sci. Lett.* 306, 137–148.
1536 <https://doi.org/10.1016/J.EPSL.2011.04.011>
- 1537 Nagashima, K., Tada, R., Matsui, H., Irino, T., Tani, A., Toyoda, S., 2007. Orbital- and millennial-
1538 scale variations in Asian dust transport path to the Japan Sea. *Palaeogeogr. Palaeoclimatol.*
1539 *Palaeoecol.* 247, 144–161. <https://doi.org/10.1016/j.palaeo.2006.11.027>
- 1540 Navarro-Rodriguez, A., Belt, S.T., Knies, J., Brown, T.A., 2013. Mapping recent sea ice conditions in
1541 the Barents Sea using the proxy biomarker IP25: implications for palaeo sea ice reconstructions.
1542 *Quat. Sci. Rev.* 79, 26–39. <https://doi.org/10.1016/J.QUASCIREV.2012.11.025>
- 1543 Niebauer, H.J., Alexander, V., Henrichs, S., 1990. Physical and biological oceanographic interaction
1544 in the spring bloom at the Bering Sea marginal ice edge zone. *J. Geophys. Res.* 95, 22229.
1545 <https://doi.org/10.1029/JC095iC12p22229>
- 1546 Niebauer, H.J., Alexander, V., Henrichs, S.M., 1995. A time-series study of the spring bloom at the
1547 Bering Sea ice edge I. Physical processes, chlorophyll and nutrient chemistry. *Cont. Shelf Res.*
1548 15, 1859–1877. [https://doi.org/10.1016/0278-4343\(94\)00097-7](https://doi.org/10.1016/0278-4343(94)00097-7)
- 1549 Niebauer, H.J., Bond, N.A., Yakunin, L.P., Plotnikov, V.V., 1999. An Update on the Climatology and
1550 Sea Ice of the Bering Sea, Dynamics o. ed. Alaskan Sea Grant College Report No. AK-SG-99-
1551 03.
- 1552 Nürnberg, D., Bijma, J., Hemleben, C., 1996. Assessing the reliability of magnesium in foraminiferal
1553 calcite as a proxy for water mass temperatures. *Geochim. Cosmochim. Acta* 60, 803–814.
1554 [https://doi.org/10.1016/0016-7037\(95\)00446-7](https://doi.org/10.1016/0016-7037(95)00446-7)
- 1555 Ohkouchi, N., Kawahata, H., Murayama, M., Okada, M., Nakamura, T., Taira, A., 1994. Was deep
1556 water formed in the North Pacific during the Late Quaternary? Cadmium evidence from the
1557 Northwest Pacific. *Earth Planet. Sci. Lett.* 124, 185–194. [https://doi.org/10.1016/0012-821X\(94\)00082-4](https://doi.org/10.1016/0012-821X(94)00082-4)
- 1559 Ohkushi, K., Kennett, J.P., Zeleski, C.M., Moffitt, S.E., Hill, T.M., Robert, C., Beaufort, L., Behl,
1560 R.J., 2013. Quantified intermediate water oxygenation history of the NE Pacific: A new benthic
1561 foraminiferal record from Santa Barbara basin. *Paleoceanography* 28, 453–467.
1562 <https://doi.org/10.1002/palo.20043>
- 1563 Okazaki, Y., Sagawa, T., Asahi, H., Horikawa, K., Onodera, J., 2012. Ventilation changes in the
1564 western North Pacific since the last glacial period. *Clim. Past* 8, 17–24.
1565 <https://doi.org/10.5194/cp-8-17-2012>
- 1566 Okazaki, Y., Takahashi, K., Asahi, H., Katsuki, K., Hori, J., Yasuda, H., Sagawa, Y., Tokuyama, H.,
1567 2005. Productivity changes in the Bering Sea during the late Quaternary. *Deep Sea Res. Part II*
1568 *Top. Stud. Oceanogr.* 52, 2150–2162. <https://doi.org/10.1016/J.DSR2.2005.07.003>
- 1569 Okazaki, Y., Timmermann, A., Menviel, L., Harada, N., Abe-Ouchi, A., Chikamoto, M.O., Mouchet,
1570 A., Asahi, H., 2010. Deepwater formation in the North Pacific during the Last Glacial
1571 Termination. *Science* 329, 200–4. <https://doi.org/10.1126/science.1190612>

- 1572 Oksman, M., Juggins, S., Miettinen, A., Witkowski, A., Weckström, K., 2019. The biogeography and
1573 ecology of common diatom species in the northern North Atlantic, and their implications for
1574 paleoceanographic reconstructions. *Mar. Micropaleontol.* 148, 1–28.
1575 <https://doi.org/10.1016/J.MARMICRO.2019.02.002>
- 1576 Okumura, Y.M., Deser, C., Hu, A., Timmermann, A., Xie, S.-P., Okumura, Y.M., Deser, C., Hu, A.,
1577 Timmermann, A., Xie, S.-P., 2009. North Pacific Climate Response to Freshwater Forcing in the
1578 Subarctic North Atlantic: Oceanic and Atmospheric Pathways. *J. Clim.* 22, 1424–1445.
1579 <https://doi.org/10.1175/2008JCLI2511.1>
- 1580 Ovsepyan, E.A., Ivanova, E.V., Lembke-Jene, L., Max, L., Tiedemann, R., Nürnberg, D., 2017.
1581 Penultimate and last glacial oceanographic variations in the Bering Sea on millennial timescales:
1582 Links to North Atlantic climate. *Quat. Sci. Rev.* 163, 135–151.
1583 <https://doi.org/10.1016/J.QUASCIREV.2017.03.012>
- 1584 Pedersen, T.F., Price, N.B., 1982. The geochemistry of manganese carbonate in Panama Basin
1585 sediments. *Geochim. Cosmochim. Acta* 46, 59–68. [https://doi.org/10.1016/0016-](https://doi.org/10.1016/0016-7037(82)90290-3)
1586 [7037\(82\)90290-3](https://doi.org/10.1016/0016-7037(82)90290-3)
- 1587 Pelto, B.M., Caissie, B.E., Petsch, S.T., Brigham-Grette, J., 2018. Oceanographic and Climatic
1588 Change in the Bering Sea, Last Glacial Maximum to Holocene. *Paleoceanogr. Paleoclimatology*
1589 *33*, 93–111. <https://doi.org/10.1002/2017PA003265>
- 1590 Pena, L.D., Calvo, E., Cacho, I., Eggins, S., Pelejero, C., 2005. Identification and removal of Mn-Mg-
1591 rich contaminant phases on foraminiferal tests: Implications for Mg/Ca past temperature
1592 reconstructions. *Geochemistry, Geophys. Geosystems* 6, Q09P02.
1593 <https://doi.org/10.1029/2005GC000930>
- 1594 Perovich, D.K., 2016. Sea ice and sunlight, in: *Sea Ice*. John Wiley & Sons, Ltd, Chichester, UK, pp.
1595 110–137. <https://doi.org/10.1002/9781118778371.ch4>
- 1596 Piña-Ochoa, E., Høglund, S., Geslin, E., Cedhagen, T., Revsbech, N.P., Nielsen, L.P., Schweizer,
1597 M., Jorissen, F., Rysgaard, S., Risgaard-Petersen, N., 2010. Widespread occurrence of nitrate
1598 storage and denitrification among Foraminifera and Gromiida. *Proc. Natl. Acad. Sci. U. S. A.*
1599 *107*, 1148–1153. <https://doi.org/10.1073/pnas.0908440107>
- 1600 Praetorius, S.K., Condron, A., Mix, A.C., Walczak, M.H., McKay, J.L., Du, J., 2020. The role of
1601 Northeast Pacific meltwater events in deglacial climate change. *Sci. Adv.* 6, eaay2915.
1602 <https://doi.org/10.1126/sciadv.aay2915>
- 1603 Praetorius, S.K., Mix, A.C., Walczak, M.H., Wolhowe, M.D., Addison, J.A., Prahl, F.G., 2015. North
1604 Pacific deglacial hypoxic events linked to abrupt ocean warming. *Nature* 527, 362–366.
1605 <https://doi.org/10.1038/nature15753>
- 1606 R Studio Team, 2015. *R Studio: Integrated Development for R*.
- 1607 Rae, J.W.B., Sarnthein, M., Foster, G.L., Ridgwell, A., Grootes, P.M., Elliott, T., 2014. Deep water
1608 formation in the North Pacific and deglacial CO₂ rise. *Paleoceanography* 29, 645–667.
1609 <https://doi.org/10.1002/2013PA002570>
- 1610 Raitzsch, M., Kuhnert, H., Hathorne, E.C., Groeneveld, J., Bickert, T., 2011. U/Ca in benthic
1611 foraminifers: A proxy for the deep-sea carbonate saturation. *Geochemistry, Geophys.*
1612 *Geosystems* 12, Q06019. <https://doi.org/10.1029/2010GC003344>
- 1613 Rasmussen, S.O., Andersen, K.K., Svensson, A.M., Steffensen, J.P., Vinther, B.M., Clausen, H.B.,
1614 Siggaard-Andersen, M.-L., Johnsen, S.J., Larsen, L.B., Dahl-Jensen, D., Bigler, M.,
1615 Röthlisberger, R., Fischer, H., Goto-Azuma, K., Hansson, M.E., Ruth, U., 2006. A new
1616 Greenland ice core chronology for the last glacial termination. *J. Geophys. Res.* 111, D06102.
1617 <https://doi.org/10.1029/2005JD006079>

- 1618 Rella, S.F., Tada, R., Nagashima, K., Ikehara, M., Itaki, T., Ohkushi, K., Sakamoto, T., Harada, N.,
1619 Uchida, M., 2012. Abrupt changes of intermediate water properties on the northeastern slope of
1620 the Bering Sea during the last glacial and deglacial period. *Paleoceanography* 27, n/a-n/a.
1621 <https://doi.org/10.1029/2011PA002205>
- 1622 Ren, H., Studer, A.S., Serno, S., Sigman, D.M., Winckler, G., Anderson, R.F., Oleynik, S., Gersonde,
1623 R., Haug, G.H., 2015. Glacial-to-interglacial changes in nitrate supply and consumption in the
1624 subarctic North Pacific from microfossil-bound N isotopes at two trophic levels.
1625 *Paleoceanography* 30, 1217–1232. <https://doi.org/10.1002/2014PA002765>
- 1626 Riethdorf, J.-R., Max, L., Nürnberg, D., Lembke-Jene, L., Tiedemann, R., 2013. Deglacial
1627 development of (sub) sea surface temperature and salinity in the subarctic northwest Pacific:
1628 Implications for upper-ocean stratification. *Paleoceanography* 28, 91–104.
1629 <https://doi.org/10.1002/palo.20014>
- 1630 Riethdorf, J.-R., Thibodeau, B., Ikehara, M., Nürnberg, D., Max, L., Tiedemann, R., Yokoyama, Y.,
1631 2016. Surface nitrate utilization in the Bering sea since 180 ka BP: Insight from sedimentary
1632 nitrogen isotopes. *Deep Sea Res. Part II Top. Stud. Oceanogr.* 125–126, 163–176.
1633 <https://doi.org/10.1016/J.DSR2.2015.03.007>
- 1634 Rodionov, S.N., Bond, N.A., Overland, J.E., 2007. The Aleutian Low, storm tracks, and winter
1635 climate variability in the Bering Sea. *Deep Sea Res. Part II Top. Stud. Oceanogr.* 54, 2560–
1636 2577. <https://doi.org/10.1016/J.DSR2.2007.08.002>
- 1637 Rosenthal, Y., Boyle, E.A., Slowey, N., 1997. Temperature control on the incorporation of
1638 magnesium, strontium, fluorine, and cadmium into benthic foraminiferal shells from Little
1639 Bahama Bank: Prospects for thermocline paleoceanography. *Geochim. Cosmochim. Acta* 61,
1640 3633–3643. [https://doi.org/10.1016/S0016-7037\(97\)00181-6](https://doi.org/10.1016/S0016-7037(97)00181-6)
- 1641 Russell, A.D., Hönisch, B., Spero, H.J., Lea, D.W., 2004. Effects of seawater carbonate ion
1642 concentration and temperature on shell U, Mg, and Sr in cultured planktonic foraminifera.
1643 *Geochim. Cosmochim. Acta* 68, 4347–4361. <https://doi.org/10.1016/J.GCA.2004.03.013>
- 1644 Saenko, O.A., Schmittner, A., Weaver, A.J., Saenko, O.A., Schmittner, A., Weaver, A.J., 2004. The
1645 Atlantic–Pacific Seesaw. *J. Clim.* 17, 2033–2038. [https://doi.org/10.1175/1520-0442\(2004\)017<2033:TAS>2.0.CO;2](https://doi.org/10.1175/1520-0442(2004)017<2033:TAS>2.0.CO;2)
- 1647 Sagawa, T., Ikehara, K., 2008. Intermediate water ventilation change in the subarctic northwest
1648 Pacific during the last deglaciation. *Geophys. Res. Lett.* 35, L24702.
1649 <https://doi.org/10.1029/2008GL035133>
- 1650 Saidova, K.M., 1961. Ecology of foraminifera and paleogeography of the USSR FAR Eastern seas and
1651 the Northwestern Pacific: *Ekologiya foraminifer i paleogeografiya dalnevostochnih morei*
1652 *SSSR i severo-zapadnoi chasti Tihogo okeana.* Nauka 221.
- 1653 Sarmiento, J.L., Gruber, N., Brzezinski, M.A., Dunne, J.P., 2004. High-latitude controls of
1654 thermocline nutrients and low latitude biological productivity. *Nature* 427, 56–60.
1655 <https://doi.org/10.1038/nature02127>
- 1656 Sarmiento, J.L., Toggweiler, J.R., Najjar, R., Webb, D.J., Jenkins, W.J., Wunsch, C., Elderfield, H.,
1657 Whitfield, M., Minster, J.-F., 1988. Ocean Carbon-Cycle Dynamics and Atmospheric pFormula
1658 [and Discussion]. *Philos. Trans. R. Soc. A Math. Phys. Eng. Sci.* 325, 3–21.
1659 <https://doi.org/10.1098/rsta.1988.0039>
- 1660 Schlitzer, R., 2016. Ocean Data View.
- 1661 Schlung, S.A., Christina Ravelo, A., Aiello, I.W., Andreasen, D.H., Cook, M.S., Drake, M., Dyez,
1662 K.A., Guilderson, T.P., Lariviere, J.P., Stroynowski, Z., Takahashi, K., 2013. Millennial-scale
1663 climate change and intermediate water circulation in the Bering Sea from 90 ka: A high-

- 1664 resolution record from IODP Site U1340. *Paleoceanography* 28, 54–67.
1665 <https://doi.org/10.1029/2012PA002365>
- 1666 Schumacher, S., Jorissen, F.J., Dissard, D., Larkin, K.E., Gooday, A.J., 2007. Live (Rose Bengal
1667 stained) and dead benthic foraminifera from the oxygen minimum zone of the Pakistan
1668 continental margin (Arabian Sea). *Mar. Micropaleontol.* 62, 45–73.
1669 <https://doi.org/10.1016/j.marmicro.2006.07.004>
- 1670 Sen Gupta, B.K., Machain-Castillo, M.L., 1993. Benthic foraminifera in oxygen-poor habitats. *Mar.*
1671 *Micropaleontol.* 20, 183–201. [https://doi.org/10.1016/0377-8398\(93\)90032-S](https://doi.org/10.1016/0377-8398(93)90032-S)
- 1672 Setoyama, E., Kaminski, M., 2015. Neogene Benthic Foraminifera from the southern Bering Sea
1673 (IODP Expedition 323). *Palaeontol. Electron.* <https://doi.org/10.26879/462>
- 1674 Shakun, J.D., Clark, P.U., He, F., Marcott, S.A., Mix, A.C., Liu, Z., Otto-Bliesner, B., Schmittner, A.,
1675 Bard, E., 2012. Global warming preceded by increasing carbon dioxide concentrations during
1676 the last deglaciation. *Nature* 484, 49–54. <https://doi.org/10.1038/nature10915>
- 1677 Shcherbina, A.Y., Talley, L.D., Rudnick, D.L., 2003. Direct observations of North Pacific ventilation:
1678 brine rejection in the Okhotsk Sea. *Science* 302, 1952–5.
1679 <https://doi.org/10.1126/science.1088692>
- 1680 Shibahara, A., Ohkushi, K., Kennett, J.P., Ikehara, K., 2007. Late Quaternary changes in intermediate
1681 water oxygenation and oxygen minimum zone, northern Japan: A benthic foraminiferal
1682 perspective. *Paleoceanography* 22, n/a-n/a. <https://doi.org/10.1029/2005PA001234>
- 1683 Sigman, D.M., Hain, M.P., Haug, G.H., 2010. The polar ocean and glacial cycles in atmospheric CO₂
1684 concentration. *Nature* 466, 47–55. <https://doi.org/10.1038/nature09149>
- 1685 Skinner, L.C., Sadekov, A., Brandon, M., Greaves, M., Plancherel, Y., de la Fuente, M., Gottschalk,
1686 J., Souanef-Ureta, S., Sevilgen, D.S., Scrivner, A.E., 2019. Rare Earth Elements in early-
1687 diagenetic foraminifer ‘coatings’: Pore-water controls and potential palaeoceanographic
1688 applications. *Geochim. Cosmochim. Acta* 245, 118–132.
1689 <https://doi.org/10.1016/J.GCA.2018.10.027>
- 1690 Smik, L., Cabedo-Sanz, P., Belt, S.T., 2016. Semi-quantitative estimates of paleo Arctic sea ice
1691 concentration based on source-specific highly branched isoprenoid alkenes: A further
1692 development of the PIP25 index. *Org. Geochem.* 92, 63–69.
1693 <https://doi.org/10.1016/J.ORGGEOCHEM.2015.12.007>
- 1694 Smith, W.O., 1987. Phytoplankton dynamics in marginal ice zones, in: Barnes, H., Barnes, M. (Eds.),
1695 *Oceanography and Marine Biology: An Annual Review Vol. 25*. Aberdeen University Press.
- 1696 Spratt, R.M., Lisiecki, L.E., 2016. A Late Pleistocene sea level stack. *Clim. Past* 12, 1079–1092.
1697 <https://doi.org/10.5194/cp-12-1079-2016>
- 1698 Springer, A.M., McRoy, P.C., Flint, M. V., 1996. The Bering Sea Green Belt: shelf-edge processes
1699 and ecosystem production. *Fish. Oceanogr.* 5, 205–223. <https://doi.org/10.1111/j.1365-2419.1996.tb00118.x>
- 1701 Stabeno, P.J., Schumacher, J.D., Ohtani, K., 1999. The physical oceanography of the Bering Sea, in:
1702 *Dynamics of the Bering Sea: A Summary of Physical, Chemical, and Biological Characteristics,*
1703 *and a Synopsis of Research on the Bering Sea.* Alaskan Sea Grant College Report No. AK-SG-
1704 99-03, pp. 1–28.
- 1705 Sturchio, N.C., Antonio, M.R., Soderholm, L., Sutton, S.R., Brannon, J.C., 1998. Tetravalent uranium
1706 in calcite. *Science* 281, 971–3. <https://doi.org/10.1126/SCIENCE.281.5379.971>
- 1707 Svensson, A., Andersen, K.K., Bigler, M., Clausen, H.B., Dahl-Jensen, D., Davies, S.M., Johnsen,
1708 S.J., Muscheler, R., Parrenin, F., Rasmussen, S.O., Röthlisberger, R., Seierstad, I., Steffensen,

- 1709 J.P., Vinther, B.M., 2008. A 60 000 year Greenland stratigraphic ice core chronology. *Clim. Past*
1710 4, 47–57. <https://doi.org/10.5194/cp-4-47-2008>
- 1711 Tachikawa, K., Elderfield, H., 2002. Microhabitat effects on Cd/Ca and $\delta^{13}\text{C}$ of benthic foraminifera.
1712 *Earth Planet. Sci. Lett.* 202, 607–624. [https://doi.org/10.1016/S0012-821X\(02\)00796-3](https://doi.org/10.1016/S0012-821X(02)00796-3)
- 1713 Takahashi, T., Feely, R.A., Weiss, R.F., Wanninkhof, R.H., Chipman, D.W., Sutherland, S.C.,
1714 Takahashi, T.T., 1997. Global air-sea flux of CO_2 : An estimate based on measurements of sea-
1715 air pCO_2 difference. *Proc. Natl. Acad. Sci.* 94, 8292–8299.
- 1716 Takahashi, T., Sutherland, S.C., Wanninkhof, R., Sweeney, C., Feely, R.A., Chipman, D.W., Hales,
1717 B., Friederich, G., Chavez, F., Sabine, C., Watson, A., Bakker, D.C.E., Schuster, U.,
1718 Yoshikawa-Inoue, H., Ishii, M., Midorikawa, T., Nojiri, Y., Körtzinger, A., Steinhoff, T.,
1719 Hoppema, M., Olafsson, J., Arnarson, T.S., Johannessen, T., Olsen, A., Bellerby, R., Wong,
1720 C.S., Delille, B., Bates, N.R., de Baar, H.J.W., 2009. Climatological mean and decadal change in
1721 surface ocean pCO_2 , and net sea–air CO_2 flux over the global oceans. *Deep Sea Res. Part II*
1722 *Top. Stud. Oceanogr.* 56, 554–577. <https://doi.org/10.1016/J.DSR2.2008.12.009>
- 1723 Talley, L.D., 1993. Distribution and Formation of North Pacific Intermediate Water. *J. Phys.*
1724 *Oceanogr.* 23, 517–537. [https://doi.org/10.1175/1520-](https://doi.org/10.1175/1520-0485(1993)023<0517:DAFONP>2.0.CO;2)
1725 [0485\(1993\)023<0517:DAFONP>2.0.CO;2](https://doi.org/10.1175/1520-0485(1993)023<0517:DAFONP>2.0.CO;2)
- 1726 Talley, L.D., Talley, L.D., 1985. Ventilation of the Subtropical North Pacific: The Shallow Salinity
1727 Minimum. *J. Phys. Oceanogr.* 15, 633–649. [https://doi.org/10.1175/1520-](https://doi.org/10.1175/1520-0485(1985)015<0633:VOTSNP>2.0.CO;2)
1728 [0485\(1985\)015<0633:VOTSNP>2.0.CO;2](https://doi.org/10.1175/1520-0485(1985)015<0633:VOTSNP>2.0.CO;2)
- 1729 Tanaka, S., Takahashi, K., 2005. Late Quaternary paleoceanographic changes in the Bering Sea and
1730 the western subarctic Pacific based on radiolarian assemblages. *Deep Sea Res. Part II Top. Stud.*
1731 *Oceanogr.* 52, 2131–2149. <https://doi.org/10.1016/J.DSR2.2005.07.002>
- 1732 Tanaka, T., Yasuda, I., Kuma, K., Nishioka, J., 2012. Vertical turbulent iron flux sustains the Green
1733 Belt along the shelf break in the southeastern Bering Sea. *Geophys. Res. Lett.* 39, L08603.
1734 <https://doi.org/10.1029/2012GL051164>
- 1735 Taylor, M.A., Hendy, I.L., Pak, D.K., 2014. Deglacial ocean warming and marine margin retreat of
1736 the Cordilleran Ice Sheet in the North Pacific Ocean. *Earth Planet. Sci. Lett.* 403, 89–98.
1737 <https://doi.org/10.1016/j.epsl.2014.06.026>
- 1738 Tetard, M., Licari, L., Beaufort, L., 2017. Oxygen history off Baja California over the last 80 kyr: A
1739 new foraminiferal-based record. *Paleoceanography* 32, 246–264.
1740 <https://doi.org/10.1002/2016PA003034>
- 1741 The PALE Beringian Working Group, 1999. Paleoenvironmental Atlas of Beringia Presented in
1742 Electronic Form. *Quat. Res.* 52, 270–271. <https://doi.org/10.1006/qres.1999.2073>
- 1743 Toggweiler, J.R., 1999. Variation of atmospheric CO_2 by ventilation of the ocean's deepest water.
1744 *Paleoceanography* 14, 571–588. <https://doi.org/10.1029/1999PA900033>
- 1745 Vare, L.L., Massé, G., Gregory, T.R., Smart, C.W., Belt, S.T., 2009. Sea ice variations in the central
1746 Canadian Arctic Archipelago during the Holocene. *Quat. Sci. Rev.* 28, 1354–1366.
1747 <https://doi.org/10.1016/j.quascirev.2009.01.013>
- 1748 Viau, A.E., Gajewski, K., Sawada, M.C., Bunbury, J., 2008. Low- and high-frequency climate
1749 variability in eastern Beringia during the past 25 000 years. *Can. J. Earth Sci.* 45, 1435–1453.
1750 <https://doi.org/10.1139/E08-036>
- 1751 Vinther, B.M., Clausen, H.B., Johnsen, S.J., Rasmussen, S.O., Andersen, K.K., Buchardt, S.L., Dahl-
1752 Jensen, D., Seierstad, I.K., Siggaard-Andersen, M.-L., Steffensen, J.P., Svensson, A., Olsen, J.,
1753 Heinemeier, J., 2006. A synchronized dating of three Greenland ice cores throughout the
1754 Holocene. *J. Geophys. Res.* 111, D13102. <https://doi.org/10.1029/2005JD006921>

- 1755 Volkman, J.K., 1986. A review of sterol markers for marine and terrigenous organic matter. *Org.*
1756 *Geochem.* 9, 83–99. [https://doi.org/10.1016/0146-6380\(86\)90089-6](https://doi.org/10.1016/0146-6380(86)90089-6)
- 1757 Volkman, J.K., Barrett, S.M., Blackburn, S.I., Mansour, M.P., Sikes, E.L., Gelin, F., 1998. Microalgal
1758 biomarkers: A review of recent research developments. *Org. Geochem.* 29, 1163–1179.
1759 [https://doi.org/10.1016/S0146-6380\(98\)00062-X](https://doi.org/10.1016/S0146-6380(98)00062-X)
- 1760 Volkman, J.K., 2006. Lipid Markers for Marine Organic Matter, in: Volkman, J.K. (Ed.), *Marine*
1761 *Organic Matter: Biomarkers, Isotopes and DNA*. Springer Berlin Heidelberg, Berlin,
1762 Heidelberg.
- 1763 Wang, S., Bailey, D., Lindsay, K., Moore, J.K., Holland, M., 2014. Impact of sea ice on the marine
1764 iron cycle and phytoplankton productivity. *Biogeosciences* 11, 4713–4731.
1765 <https://doi.org/10.5194/bg-11-4713-2014>
- 1766 Warner, M.J., Roden, G.I., 1995. Chlorofluorocarbon evidence for recent ventilation of the deep
1767 Bering Sea. *Nature* 373, 409–412. <https://doi.org/10.1038/373409a0>
- 1768 Warren, B.A., 1983. Why is no deep water formed in the North Pacific? *J. Mar. Res.* 41, 327–347.
1769 <https://doi.org/10.1357/002224083788520207>
- 1770 Weber, T., Cram, J.A., Leung, S.W., DeVries, T., Deutsch, C., 2016. Deep ocean nutrients imply
1771 large latitudinal variation in particle transfer efficiency. *Proc. Natl. Acad. Sci. U. S. A.* 113,
1772 8606–11. <https://doi.org/10.1073/pnas.1604414113>
- 1773 Whitlege, T.E., Luchin, V.A., 1999. Summary of Chemical Distributions and Dynamics in the
1774 Bering Sea, in: Loughlin, T.R., Othani, K. (Eds.), *Dynamics of the Bering Sea*. University of
1775 Alaska Sea Grant.
- 1776 Worne, S., Kender, S., Swann, G.E.A., Leng, M.J., Ravelo, A.C., 2019. Coupled climate and subarctic
1777 Pacific nutrient upwelling over the last 850,000 years. *Earth Planet. Sci. Lett.* 522, 87–97.
1778 <https://doi.org/10.1016/j.epsl.2019.06.028>
- 1779 Wu, L., Li, C., Yang, C., Xie, S.P., 2008. Global teleconnections in response to a shutdown of the
1780 Atlantic meridional overturning circulation. *J. Clim.* 21, 3002–3019.
1781 <https://doi.org/10.1175/2007JCLI1858.1>
- 1782 Xiao, X., Zhao, M., Knudsen, K.L., Sha, L., Eiríksson, J., Gudmundsdóttir, E., Jiang, H., Guo, Z.,
1783 2017. Deglacial and Holocene sea–ice variability north of Iceland and response to ocean
1784 circulation changes. *Earth Planet. Sci. Lett.* 472, 14–24.
1785 <https://doi.org/10.1016/J.EPSL.2017.05.006>
- 1786 Zhang, J., Woodgate, R., Moritz, R., 2010. Sea ice response to atmospheric and oceanic forcing in the
1787 bering sea. *J. Phys. Oceanogr.* 40, 1729–1747. <https://doi.org/10.1175/2010JPO4323.1>
- 1788 Zhao, M.-Y., Zheng, Y.-F., Zhao, Y.-Y., 2016. Seeking a geochemical identifier for authigenic
1789 carbonate. *Nat. Commun.* 7, 10885. <https://doi.org/10.1038/ncomms10885>
- 1790 Zheng, Y., van Geen, A., Anderson, R.F., Gardner, J. V., Dean, W.E., 2000. Intensification of the
1791 Northeast Pacific oxygen minimum zone during the Bölling-Alleröd Warm Period.
1792 *Paleoceanography* 15, 528–536. <https://doi.org/10.1029/1999PA000473>
- 1793 Zou, J., Shi, X., Zhu, A., Kandasamy, S., Gong, X., Lembke-Jene, L., Chen, M.-T., Wu, Y., Ge, S.,
1794 Liu, Y., Xue, X., Lohmann, G., Tiedemann, R., 2020. Millennial-scale variations in sedimentary
1795 oxygenation in the western subtropical North Pacific and its links to North Atlantic climate.
1796 *Clim. Past* 16, 387–407. <https://doi.org/10.5194/cp-16-387-2020>
- 1797 Zweng, M.M., Reagan, J.R., Antonov, J.I., Locarnini, R.A., Mishonov, A.V., Boyer, T.P., Garcia,
1798 H.E., Baranova, O.K., Johnson, D.R., Seidov, D., Biddle, M.M., 2013. *World Ocean Atlas 2013*,
1799 Volume 2: Salinity. NOAA Atlas NESDIS 74.

1801 **Table captions**

1802

1803 **Table 1.** Age-depth tie points for the late Quaternary chronology of IODP Site U1343.

1804

1805 **Figure captions**

1806

1807 **Figure 1.** Map of the Bering Sea (top) and annual mean oxygen concentrations (Boyer et al.,
1808 2013) along a north (A) south (B) transect in the central Bering Sea (bottom) drawn with
1809 Ocean Data View (Schlitzer, 2016) (Bathymetry from ‘The GEBCO_2014 Grid, version
1810 20141103, <http://www.gebco.net>’). IODP Site U1343 is indicated with a red dot, additional
1811 core locations discussed in the text are marked with yellow dots. The map shows the surface
1812 ocean circulation (dark blue), including the Alaskan Stream, the Aleutian North Slope
1813 Current (ANSC), the Bering Slope Current (BSC), and the East Kamchatka Current (EKC).
1814 The maximum winter sea ice extent between 1981 and 2010 is indicated as an orange dashed
1815 line (Fetterer et al., 2017) and the last glacial maximum (LGM) coastline is shown in purple
1816 (The PALE Beringian Working Group, 1999).

1817

1818 **Figure 2.** Biomarker results from IODP Site U1343. (A) MAR_{opal} at Site U1343 (light grey)
1819 (Kim et al., 2014); (B) Marine sterol biomarkers cholesterol (red) and brassicasterol (orange);
1820 (C) terrestrial sterol biomarker campesterol (purple) and β -sitosterol (yellow); (D) HBI III
1821 (green); and (E) IP_{25} (dark blue) together with HBI II (light blue circles). Note the break in
1822 the HBI III axis. The grey shaded vertical bars indicate the YD, HS1, and HS2.

1823

1824 **Figure 3.** Semi-quantitative sea ice results. (A) Classification tree results (pink) indicating
1825 marginal (0-10%), intermediate (10-50%), and extensive (>50%) sea-ice conditions. (B)
1826 $P_{III}IP_{25}$ (orange) and $P_{B}IP_{25}$ (yellow), with PIP_{25} values of zero indicating no sea ice and
1827 values of one being characteristic of perennial sea-ice conditions. The grey shaded vertical
1828 bars indicate the YD, HS1, and HS2.

1829

1830 **Figure 4.** Results of sedimentary redox chemistry proxies. (A) Scores of the benthic
1831 foraminiferal assemblage correspondence analysis axis 1 (blue) and 2 (yellow); (B) Relative
1832 abundance of the benthic foraminifera *Bulimina exilis* (red); (C) U/Ca (open circles) of *N.*
1833 *pachyderma* (orange), *I. norcrossi* (red), and *Uvigerina* spp. (purple). The shaded areas
1834 indicate the 2σ envelope. (D) U/Mn (open diamonds) of *I. norcrossi* (red) and *Uvigerina* spp.
1835 (purple). The shaded areas indicate the 2σ envelope. The grey shaded vertical bars indicate
1836 the YD, HS1, and HS2.

1837

1838 **Figure 5.** A compilation of sea-ice reconstructions discussed in this manuscript. (A) IP_{25}
1839 concentrations at SO202-18-6 (Méheust et al., 2018); (B) The abundance of *A. boreale* plus
1840 *A. leptodermum* at PC-23A (Itaki et al., 2012); (C) IP_{25} concentrations at SO201-2-114
1841 (Méheust et al., 2016); (D) IP_{25} concentrations at U1343 (blue) (this study); (E) IP_{25}
1842 concentrations at SO201-2-77 (Méheust et al., 2016); (F) IP_{25} concentrations at SO201-2-12
1843 (Méheust et al., 2016); (G) IP_{25} concentrations at SO202-27-6 (Méheust et al., 2018); (H)
1844 IP_{25} concentrations at SO202-07-06 (Méheust et al., 2018); (I) Northern Hemisphere
1845 temperature stack (black) including a 1σ error envelope (Shakun et al., 2012) and Eastern

1846 Beringia (150-180°W) atmospheric temperature stacks from 60-65°N and 65-70°N (light
1847 grey) based on pollen records (Viau et al., 2008); (J) July insolation at 65°N (black) and
1848 NGRIP (light grey) and NEEM (medium grey) $\delta^{18}\text{O}$ on the GICC05 time scale (Buizert et al.,
1849 2014; Rasmussen et al., 2006; Svensson et al., 2008; Vinther et al., 2006).

1850

1851 **Figure 6.** A compilation of ventilation and carbon cycle records discussed in this manuscript
1852 in combination with regional and global climate records. (A) HBI III (green) at Site U1343
1853 (this study); (B) IP₂₅ (dark blue) together with HBI II (light blue circles) (this study); (C)
1854 North Pacific pCO₂ at MD01-2416 (Gray et al., 2018); (D) Diatom-bound $\delta^{15}\text{N}$ at JPC17
1855 (Brunelle et al., 2007); (E) Benthic foraminiferal $\delta^{13}\text{C}$ at MR06-04-PC23A (medium grey)
1856 (Rella et al., 2012), SO201-2-85KL (dark grey), and SO201-2-101KL (light grey) (Max et al.,
1857 2014); (F) Intermediate water ventilation ages in the Bering Sea and the Sea of Okhotsk
1858 (Max et al., 2014); (G) Scores of the benthic foraminiferal assemblage correspondence
1859 analysis axis 1 (blue) and 2 (yellow) and the relative abundance of the benthic foraminifera
1860 *Bulimina exilis* (red) at Site U1343; (H) U/Ca of *N. pachyderma* (orange), *I. norcrossi* (red),
1861 and *Uvigerina* spp. (purple) at Site U1343; (I) MAR_{opal} at Site U1343 (Kim et al., 2014); (J)
1862 Benthic foraminiferal $\delta^{18}\text{O}$ at IODP Site U1342 (light grey) (Knudson and Ravelo, 2015),
1863 Site U1343 (black) (Asahi et al., 2016), and the LR04 stack (grey) (Lisiecki and Raymo,
1864 2005); (K) NGRIP $\delta^{18}\text{O}$ on the GICC05 time scale (Rasmussen et al., 2006; Svensson et al.,
1865 2008; Vinther et al., 2006), and the Northern Hemisphere temperature stack including a 1 σ
1866 error envelope (Shakun et al., 2012).

1867

1868 **Figure 7.** Simplified schematic of the deglacial sea-ice dynamics, intermediate water
1869 ventilation, and biogeochemical cycling in the eastern Bering Sea. The schematic was
1870 produced using features from the IAN symbol library (Courtesy of the Integration and
1871 Application Network, University of Maryland Center for Environmental Science
1872 (ian.umces.edu/symbols/)). (A) The LGM (17.5-24 ka) was characterized by a seasonal sea-
1873 cover, reduced upwelling of NPDW, and an expanded GNPIW resulting from enhanced brine
1874 rejection. GNPIW, however, did not reach to depth of 2000 m. (B) Early HS1 (16.5-17.5 ka)
1875 was characterized by an enhanced seasonal sea-ice cover, in response to atmospheric cooling.
1876 Increased sea-ice formation lead to enhanced brine rejection and increased GNPIW formation
1877 and ventilation compared to the LGM, which in turn caused modest up-mixing of nutrients,
1878 as well as a deepening of the mixed layer resulting in light limitation of primary producers.
1879 (C) The BA (12.8-14.7 ka) is marked by a reduced sea-ice cover due to atmospheric
1880 warming, enhanced NPDW upwelling, increased primary productivity, and pronounced mid-
1881 depth hypoxia causing the preservation of laminations along the eastern Bering Sea slope.

1882

Table 1.

Depth (m CCSF-A)	Age (ka)	Reference
0.01	7.6	Asahi et al. (2016)
1.07	11.7	Correlation to SO202-18-6/3 and HLY02-02-3JPC (Cook et al., 2005; Kuehn et al., 2014)
2.69	14.5	Correlation to SO202-18-6/3 and HLY02-02-3JPC (Cook et al., 2005; Kuehn et al., 2014)
3.86	17.8	Asahi et al. (2016)
7.71	33.02	Asahi et al. (2016)
11.56	48.2	Asahi et al. (2016)

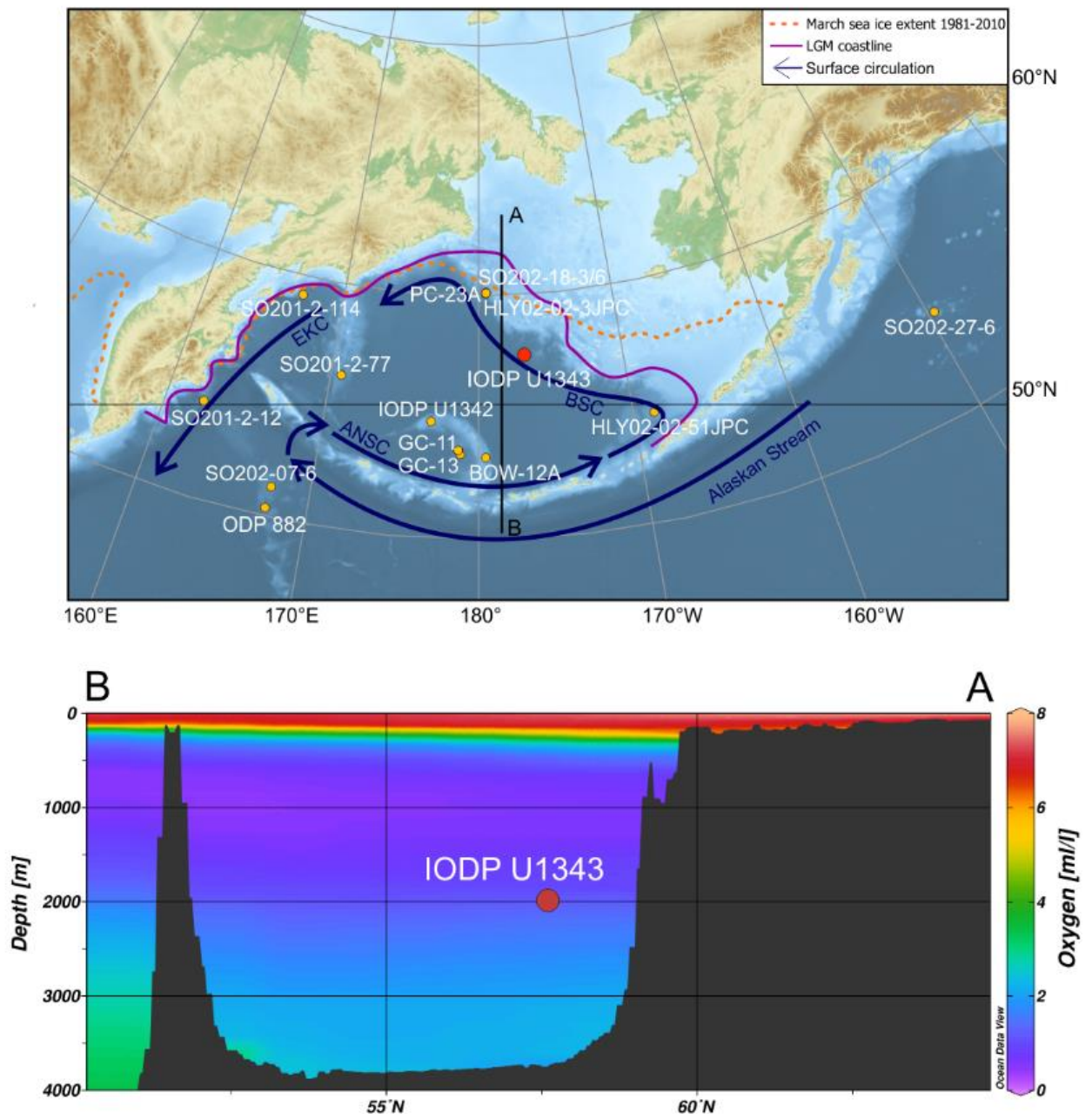


Figure 1.

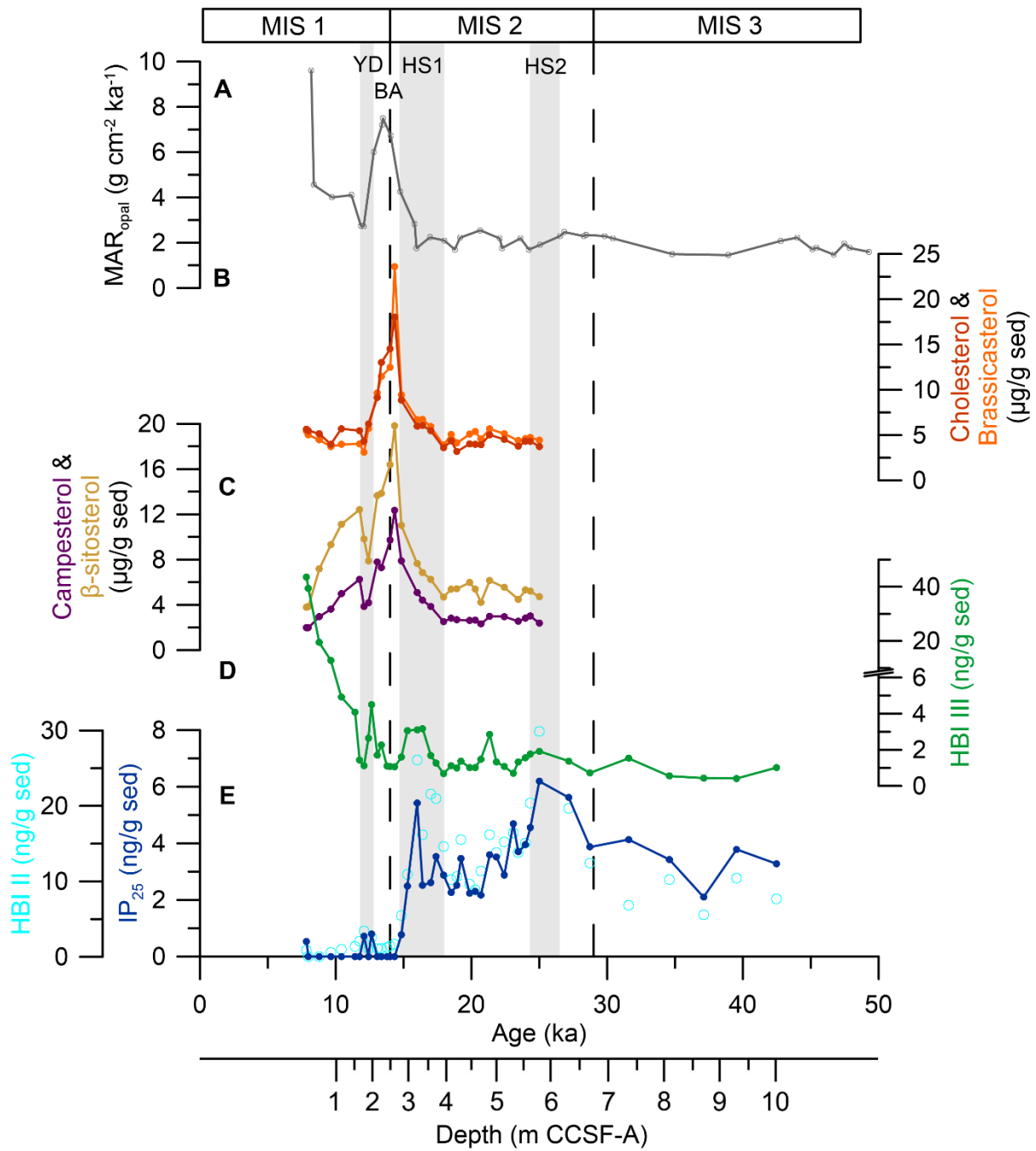


Figure 2.

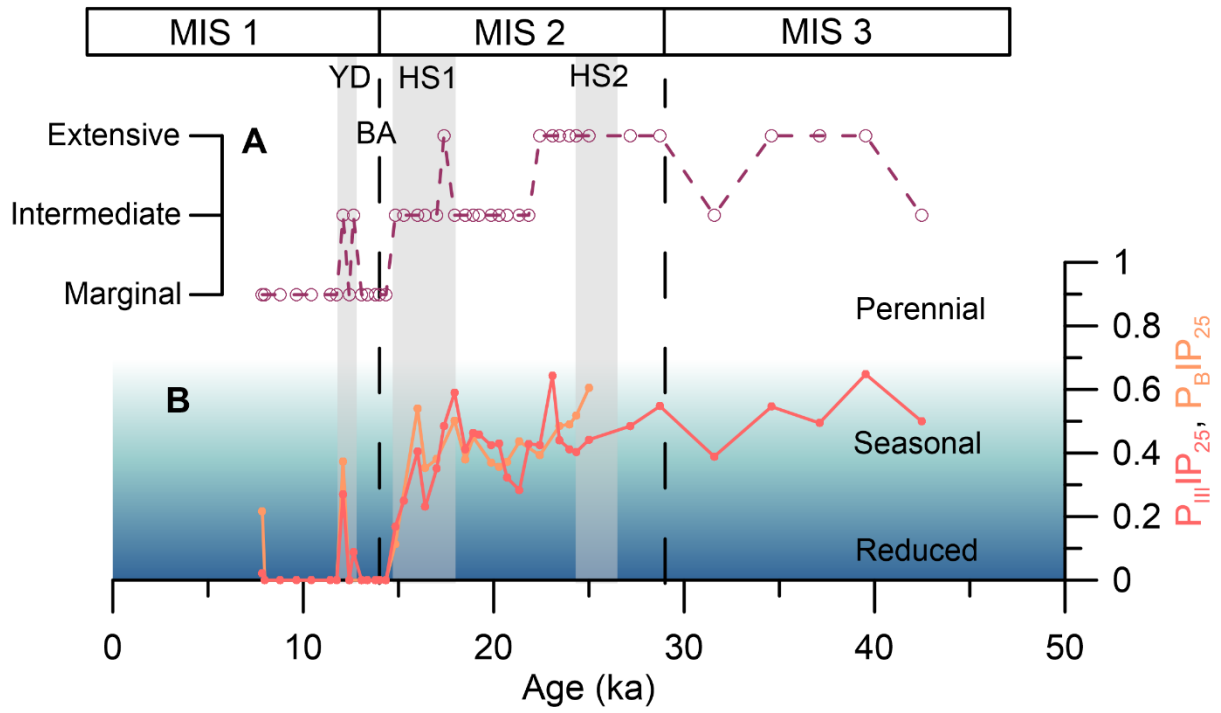


Figure 3.

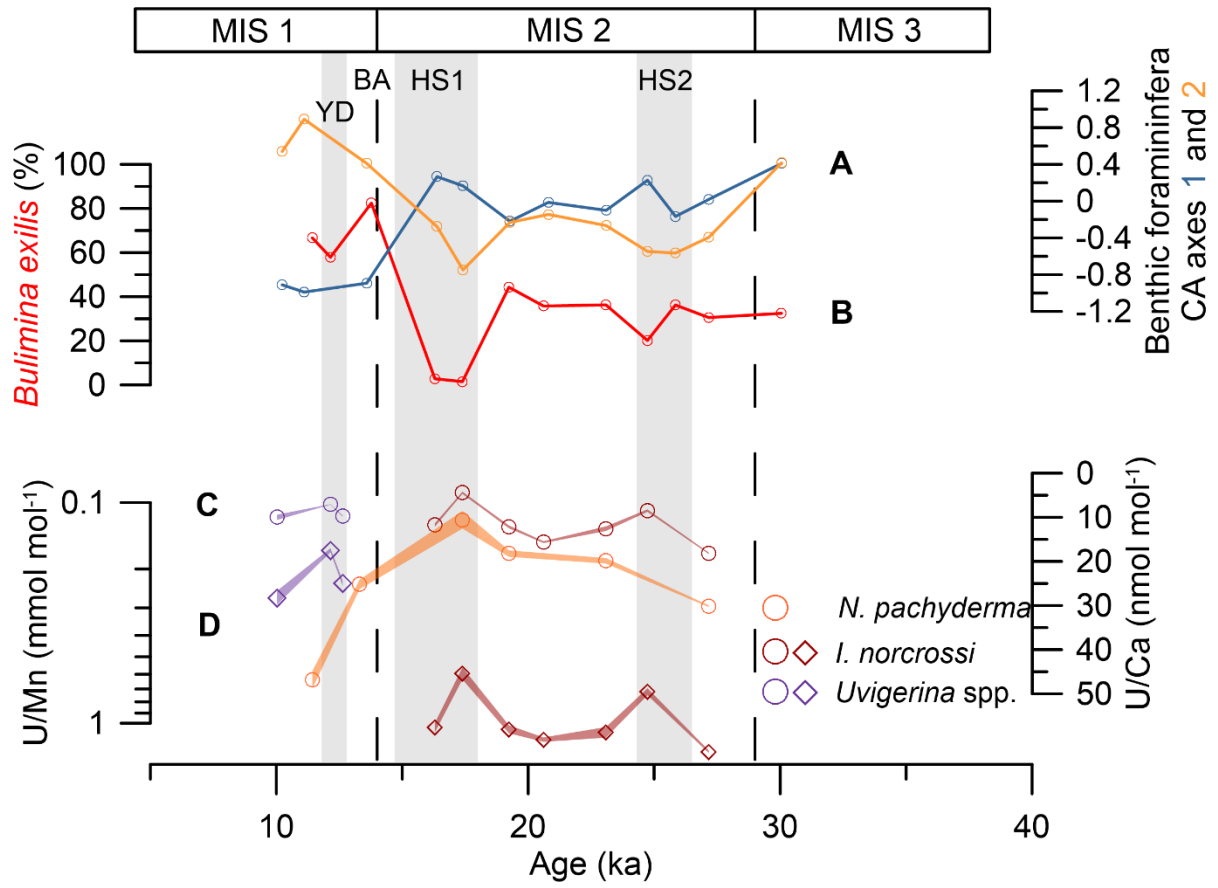


Figure 4.

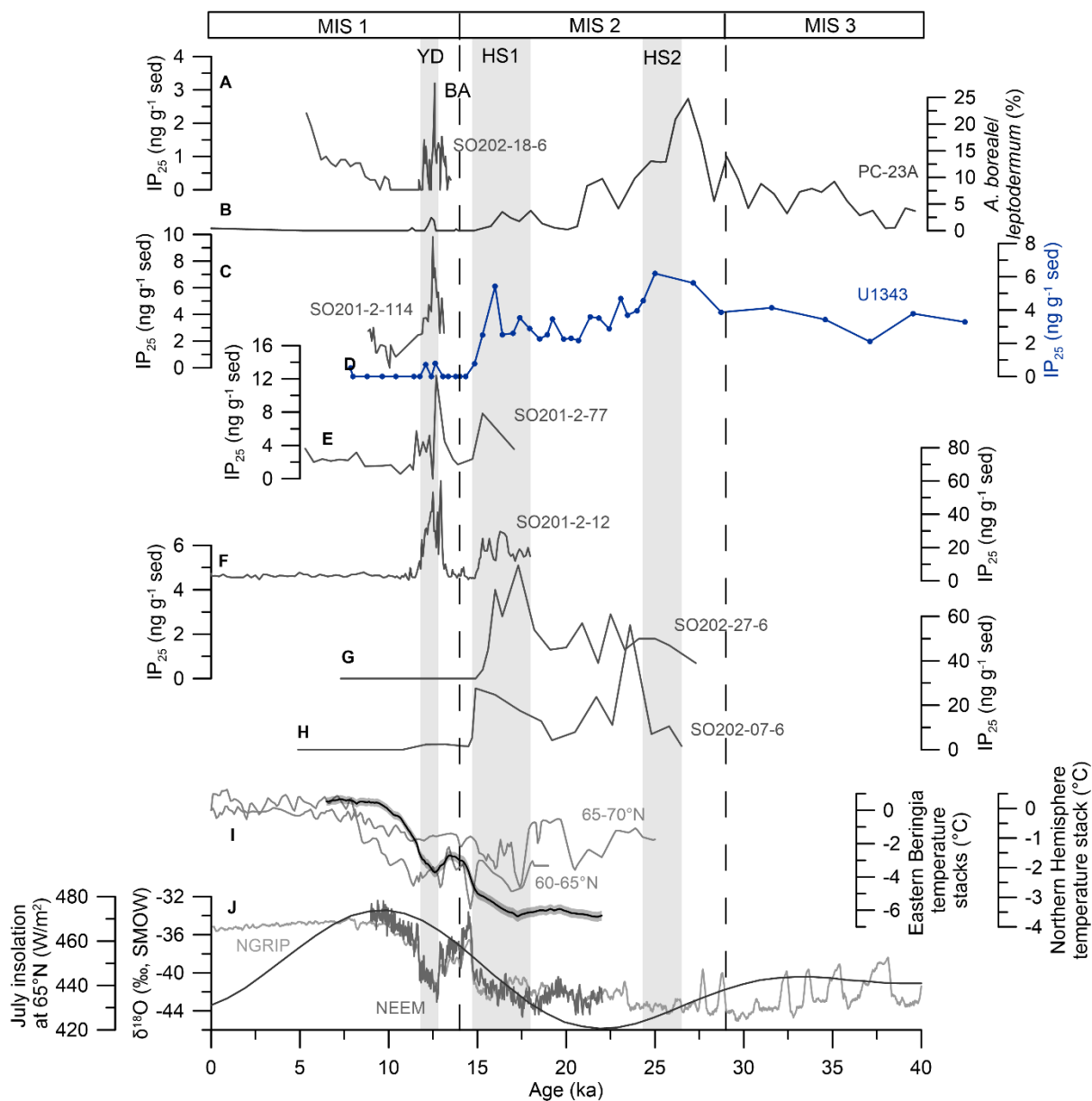


Figure 5.

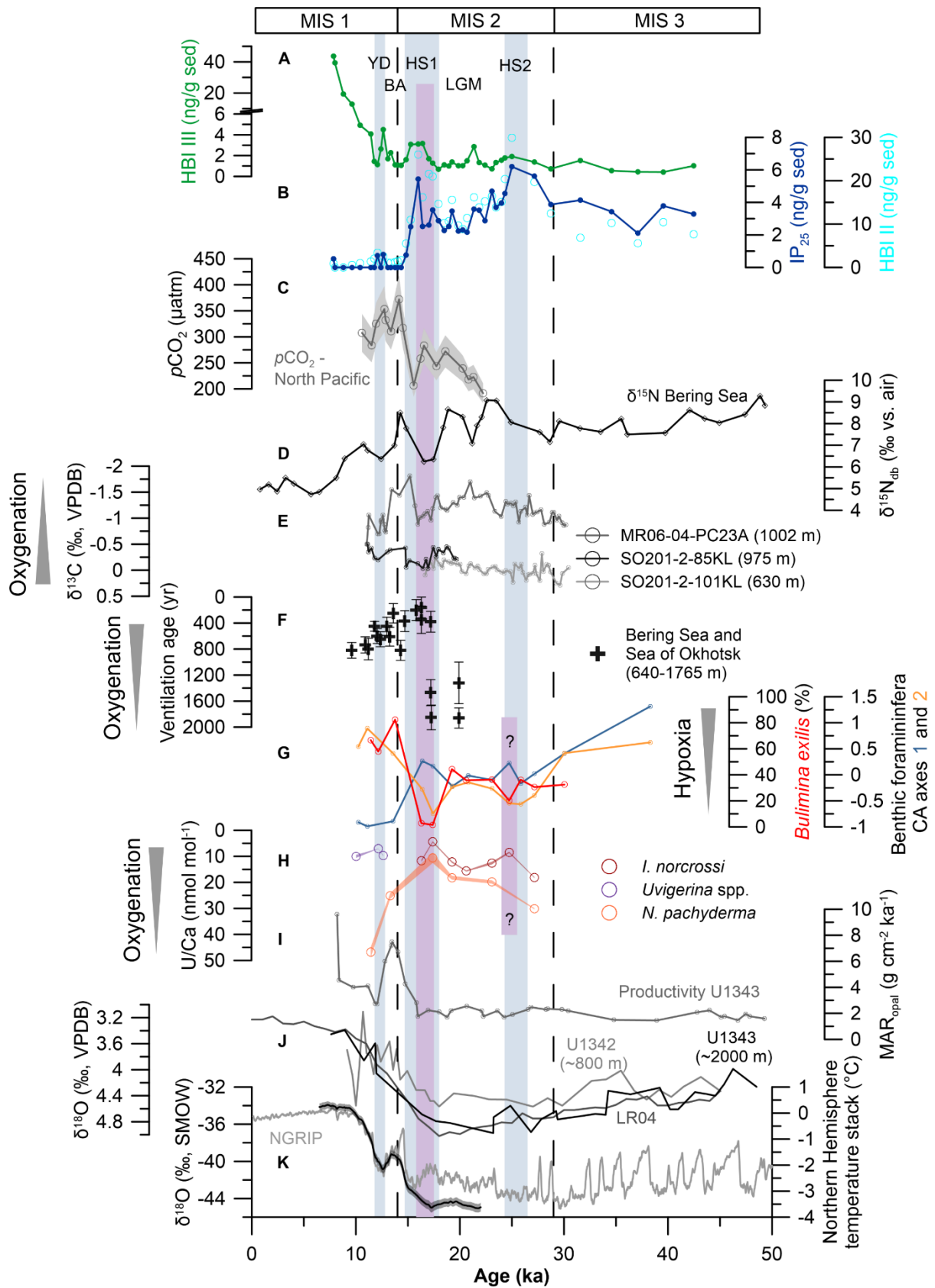


Figure 6.

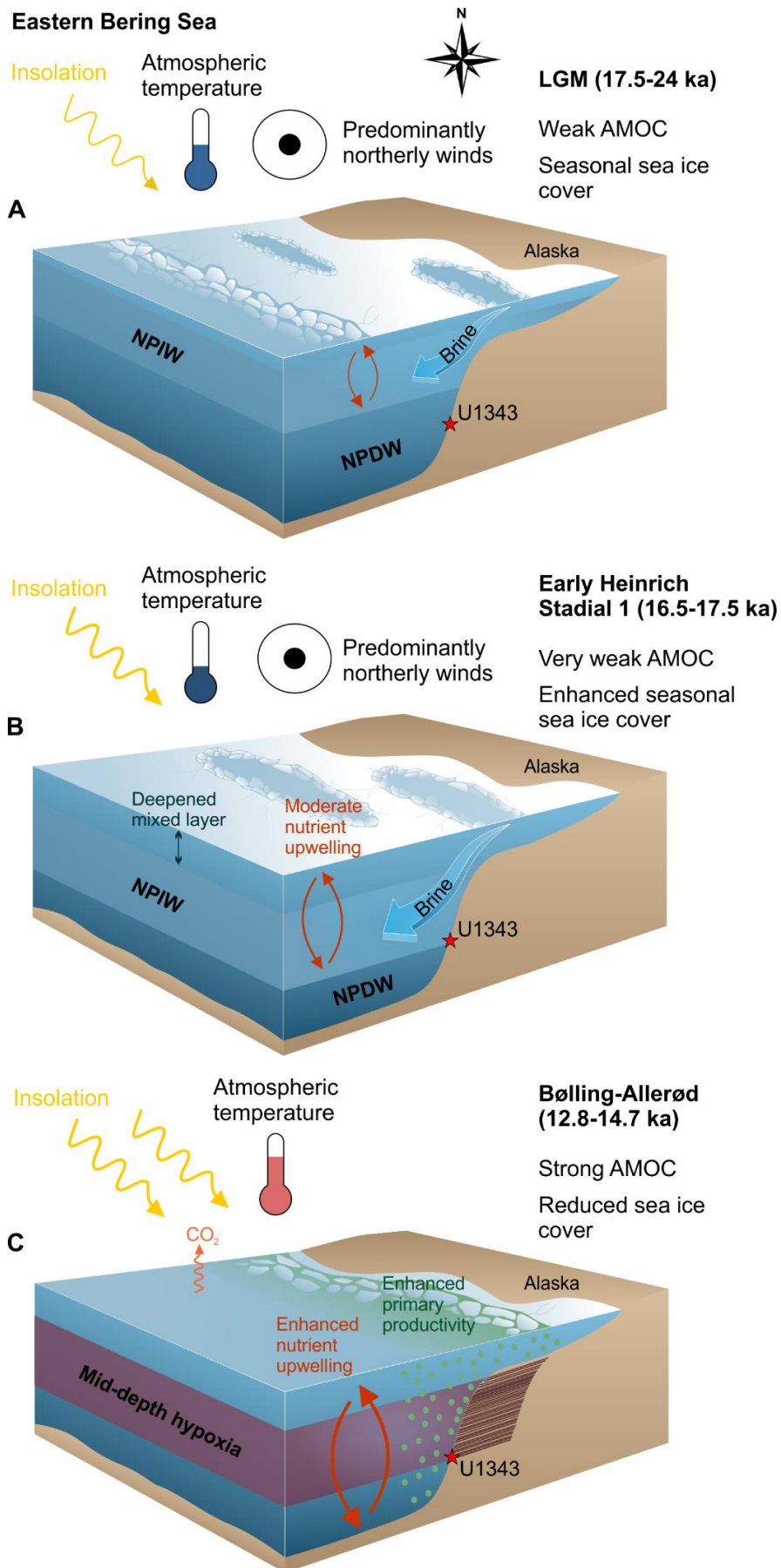
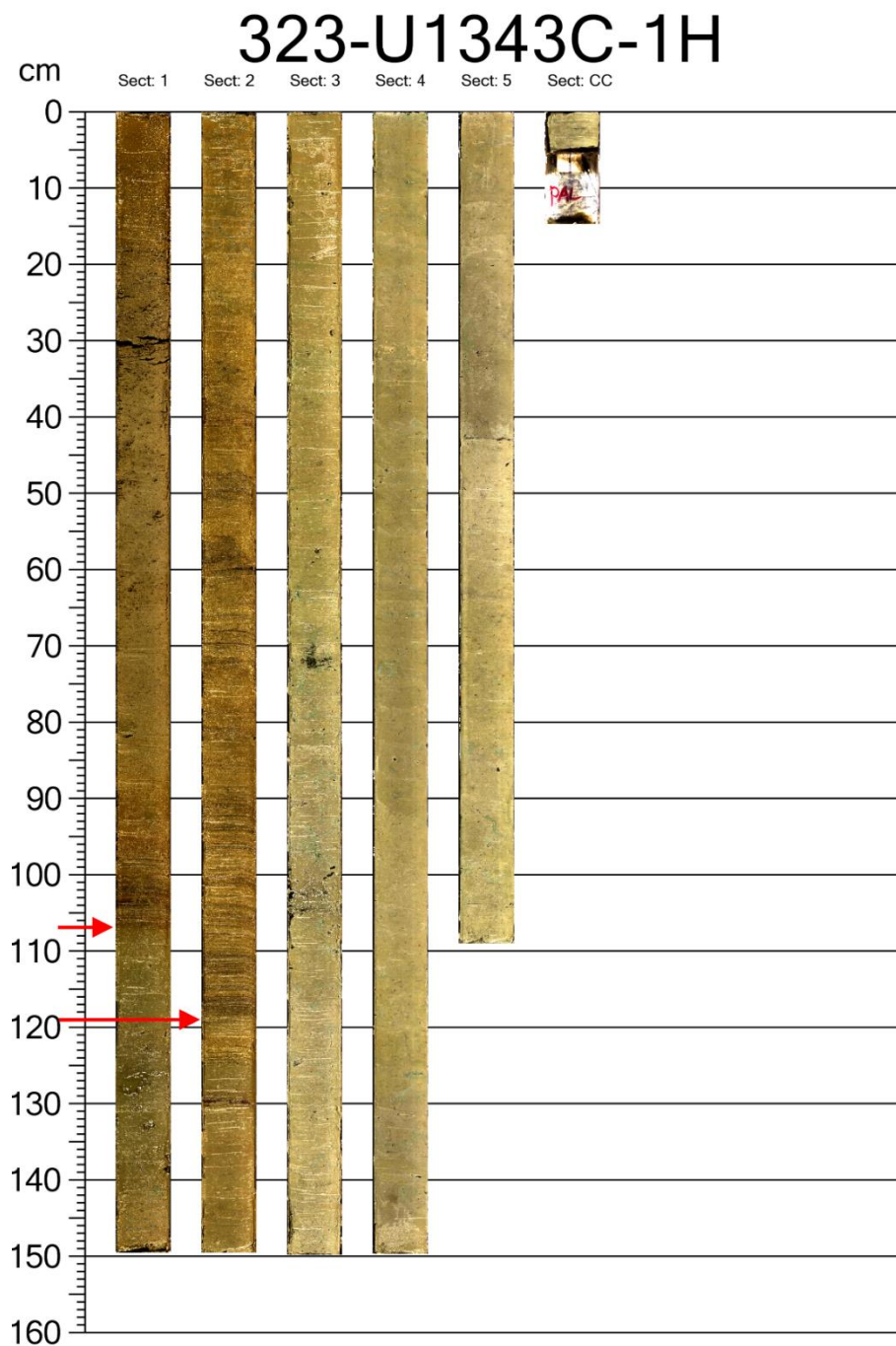
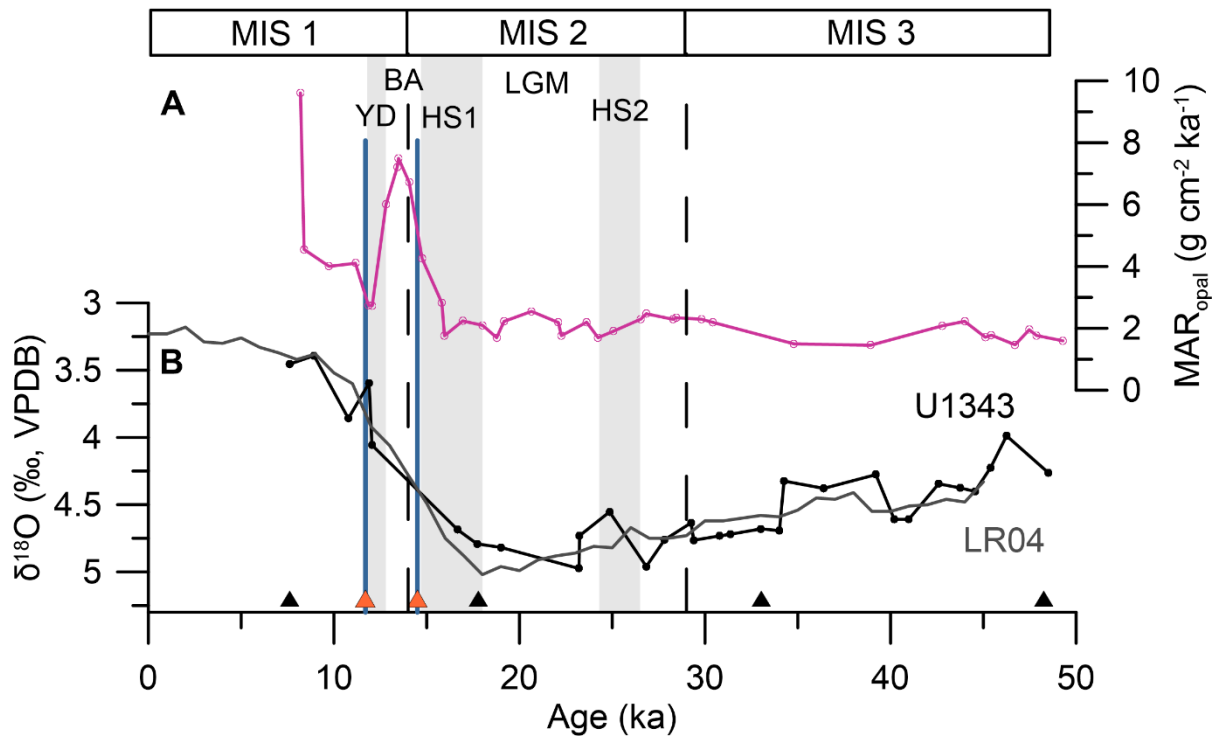


Figure 7.

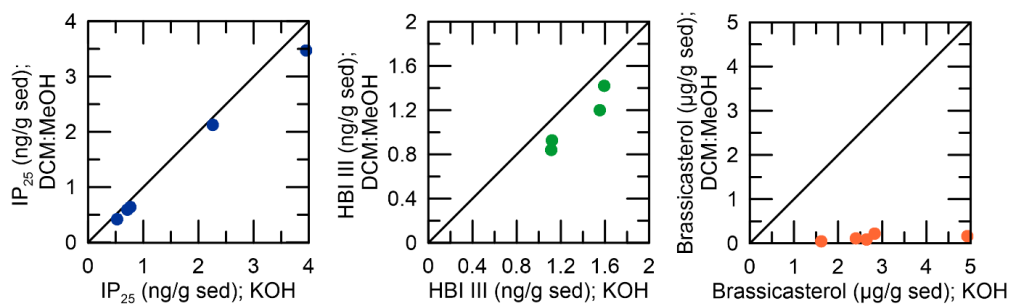
Supplementary Material: ‘Late Quaternary sea-ice and sedimentary redox conditions in the eastern Bering Sea – implications for ventilation of the mid-depth North Pacific and an Atlantic-Pacific seesaw mechanism’



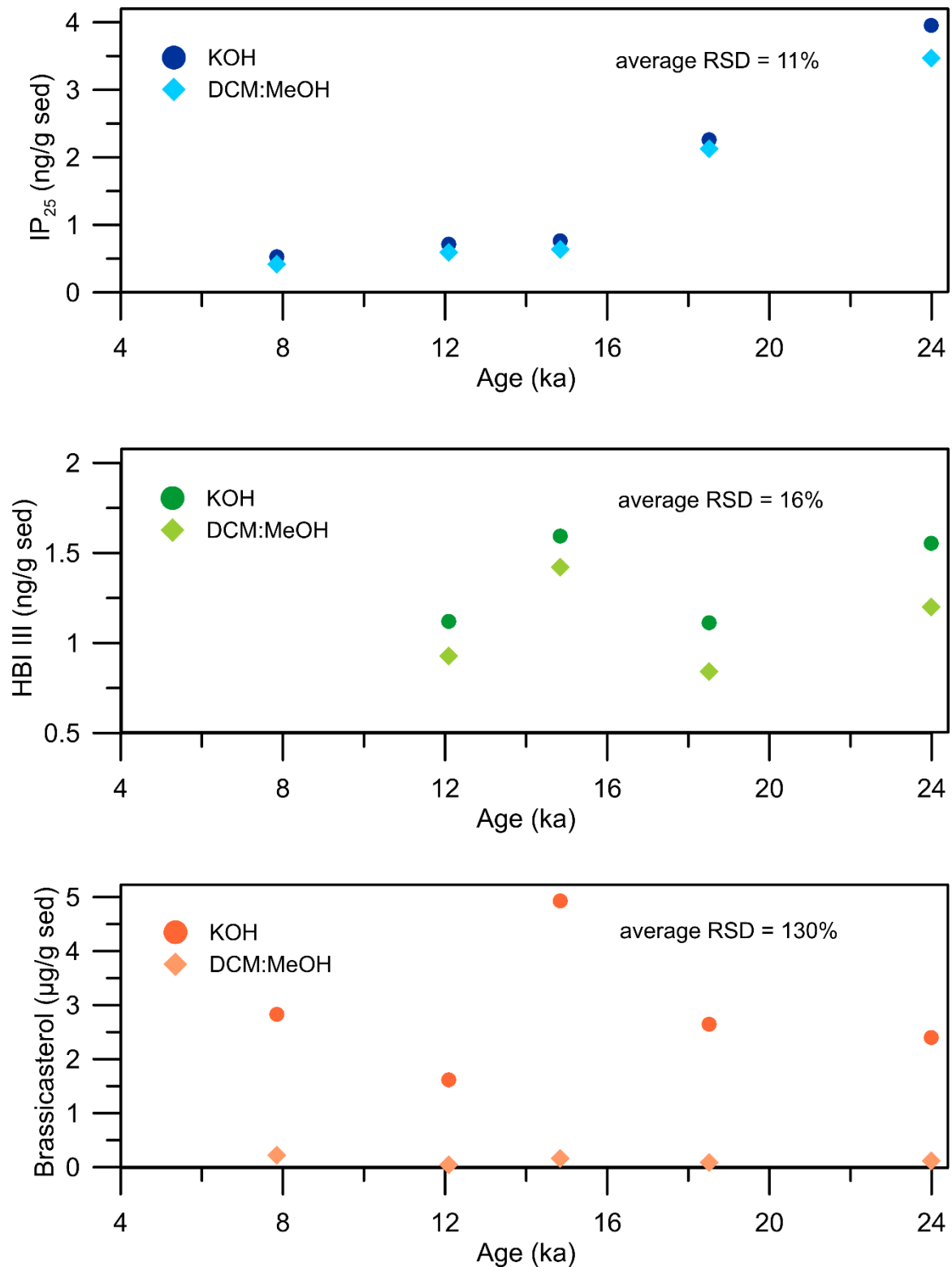
Supplementary Figure 1. Core photo of U1343C-1H from web.iodp.tamu.edu/LORE/, tonal range adjusted to enhance the brightness and contrast. The red arrows indicate the base of the laminated sediment sections (Expedition 323 Scientists, 2010).



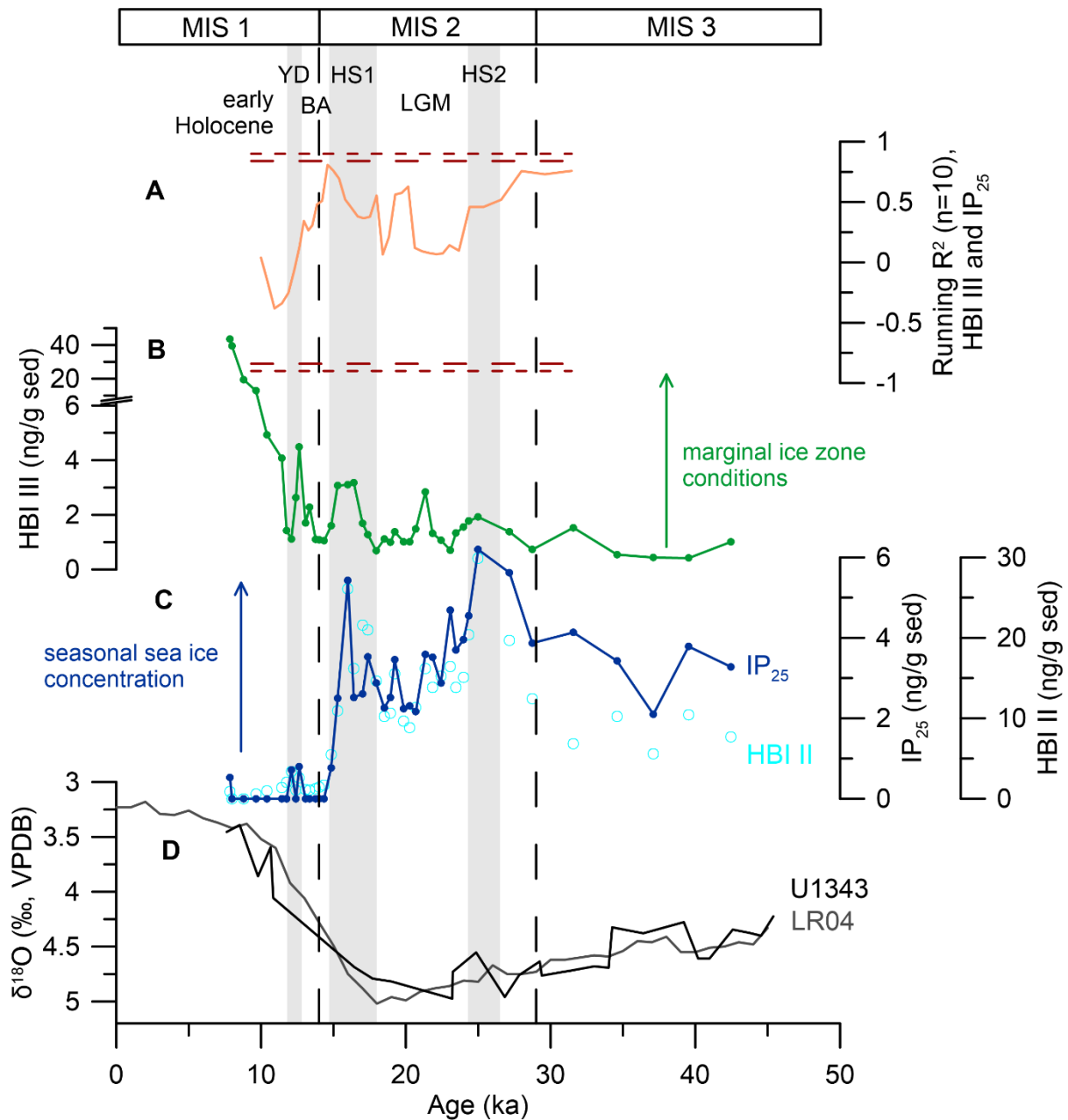
Supplementary Figure 2. (A) MAR_{opal} (Kim et al., 2014) (pink) at Site U1343. (B) $\delta^{18}O_b$ (black) at Site U1343 (Asahi et al., 2016) together with the LR04 stack (grey) (Lisiecki and Raymo, 2005). The bases of the laminated intervals are marked by blue vertical lines (Expedition 323 Scientists, 2010). The triangles at the bottom represent the age-depth tie points: The black triangles are tie points based on $\delta^{18}O_b$ stratigraphy (Asahi et al., 2016) and the orange triangles represent the age-depth tie point based on the correlation of the onset of the BA and early Holocene sediment laminations at Site U1343 with sites HLY02-02-3JPC (60°07.67'N, 180°33.49'E, 1132 m water depth) and SO202-18-3/6 (60°07.60'N, 179°26.64'W, 1109 m water depth) (Cook et al., 2005; Kuehn et al., 2014).



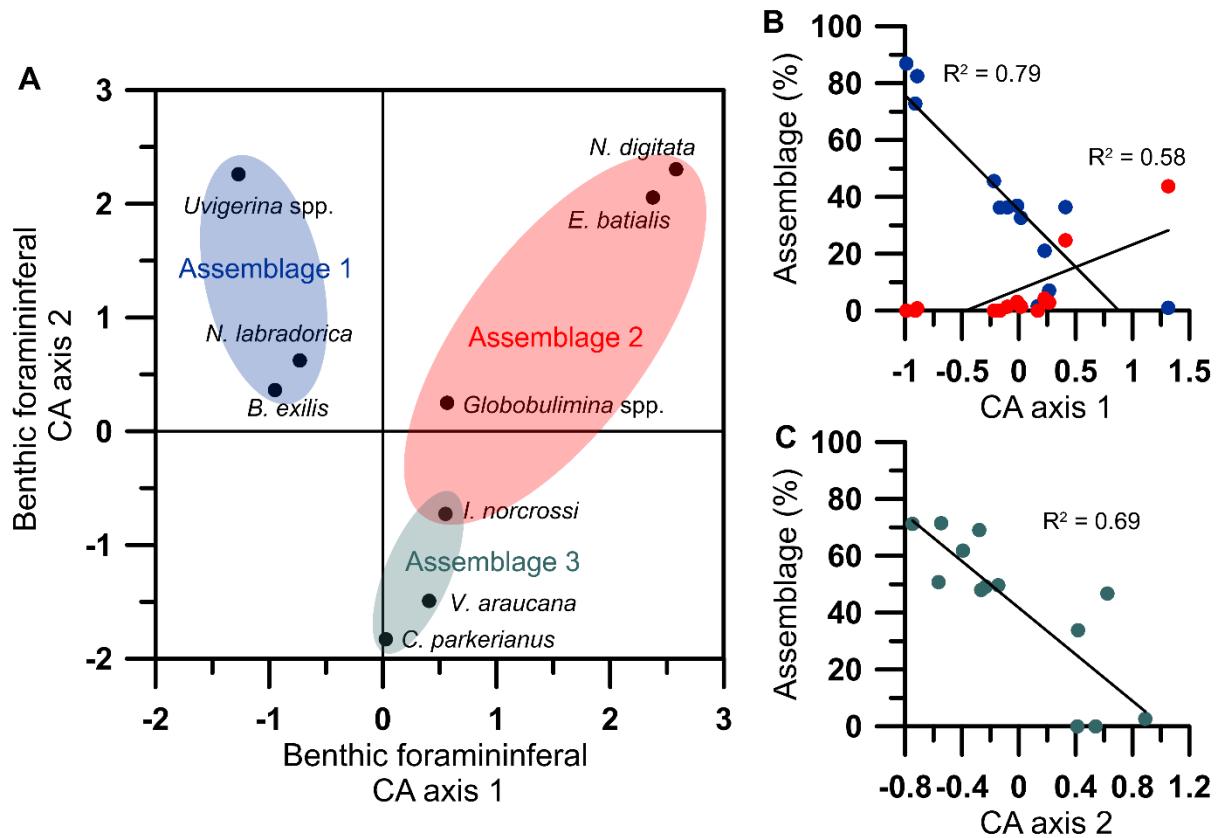
Supplementary Figure 3. Comparison of biomarker results from samples extracted with DCM:Methanol (x-axis) and KOH (y-axis), respectively. Both IP₂₅ (blue) and HBI III (green) show only a minor offset between the two methods, while brassicasterol (orange) is significantly higher in samples extracted with KOH.



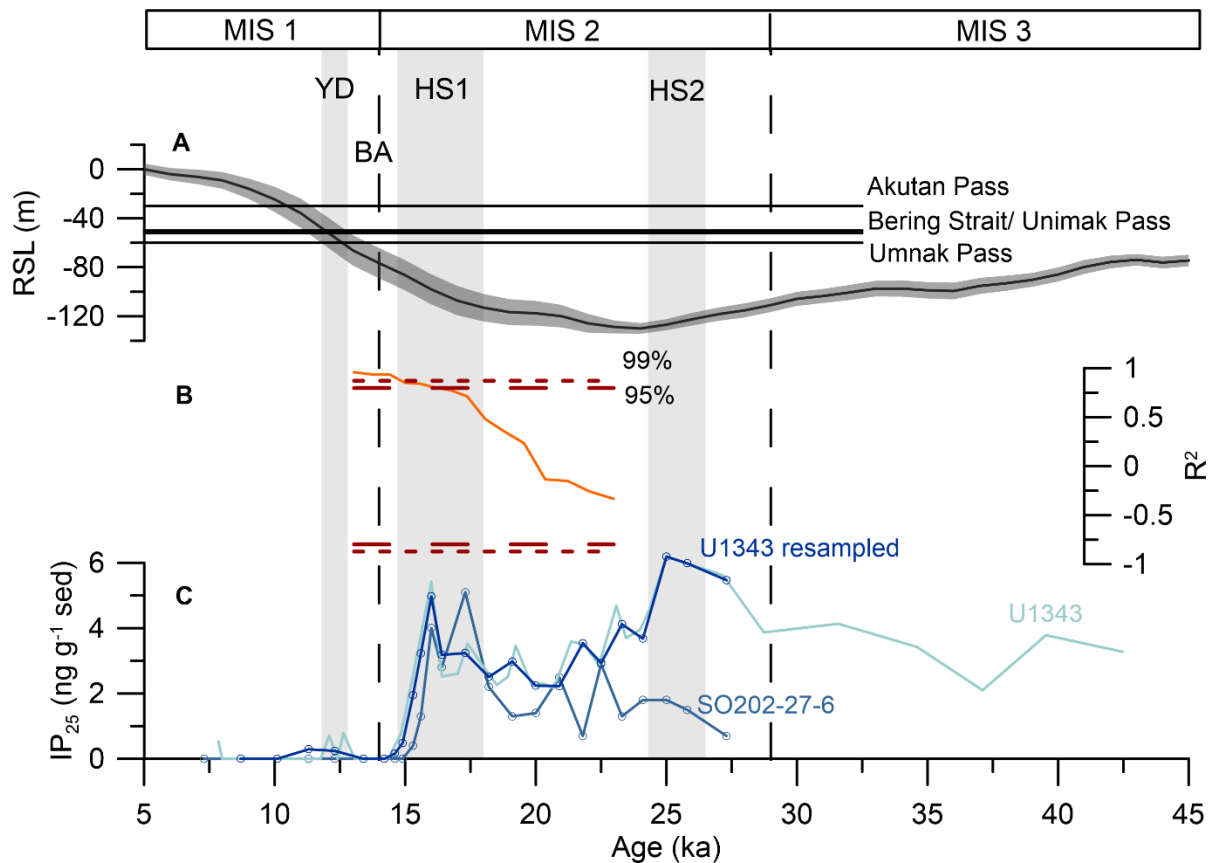
Supplementary Figure 4. Comparison of sea ice biomarkers extracted using DCM:Methanol and KOH against age. The biomarker trends are the same, while there are small offsets between the methods for HBIs (IP₂₅ in blue, HBI III in green) and a large offset for brassicasterol (orange).



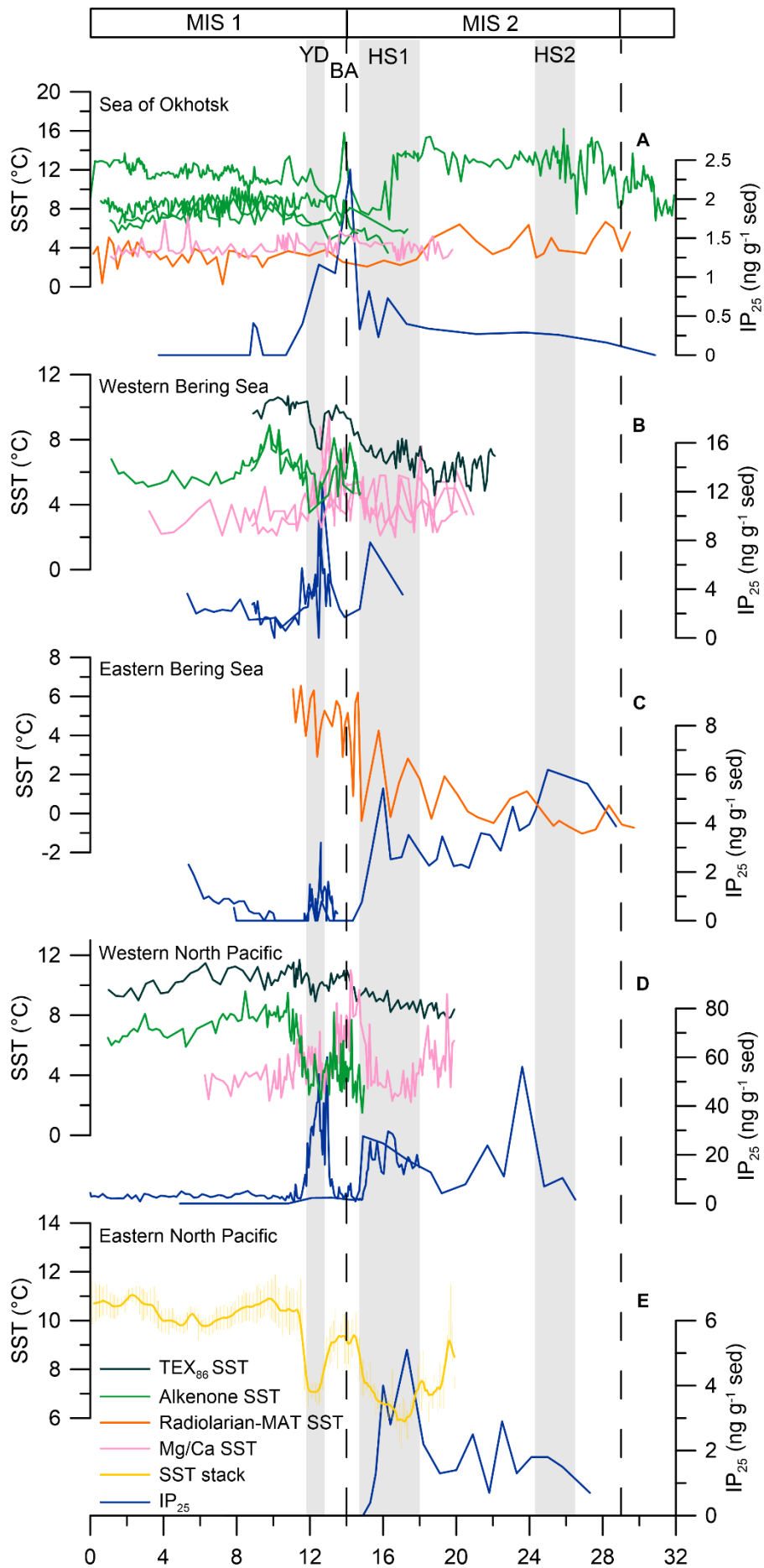
Supplementary Figure 5. (A) 10-pt moving window correlation of IP₂₅ and HBI III (orange) including the 95% (long red dashed line) and 99% (short red dashed line) confidence interval; (B) HBI III (green) at Site U1343; (C) IP₂₅ (dark blue) and HBI II (light blue circles) at Site U1343; (D) δ¹⁸O_b at Site U1343 (black) together with the LR04 stack (grey). The grey shaded areas indicate HS2, HS1, and the YD.



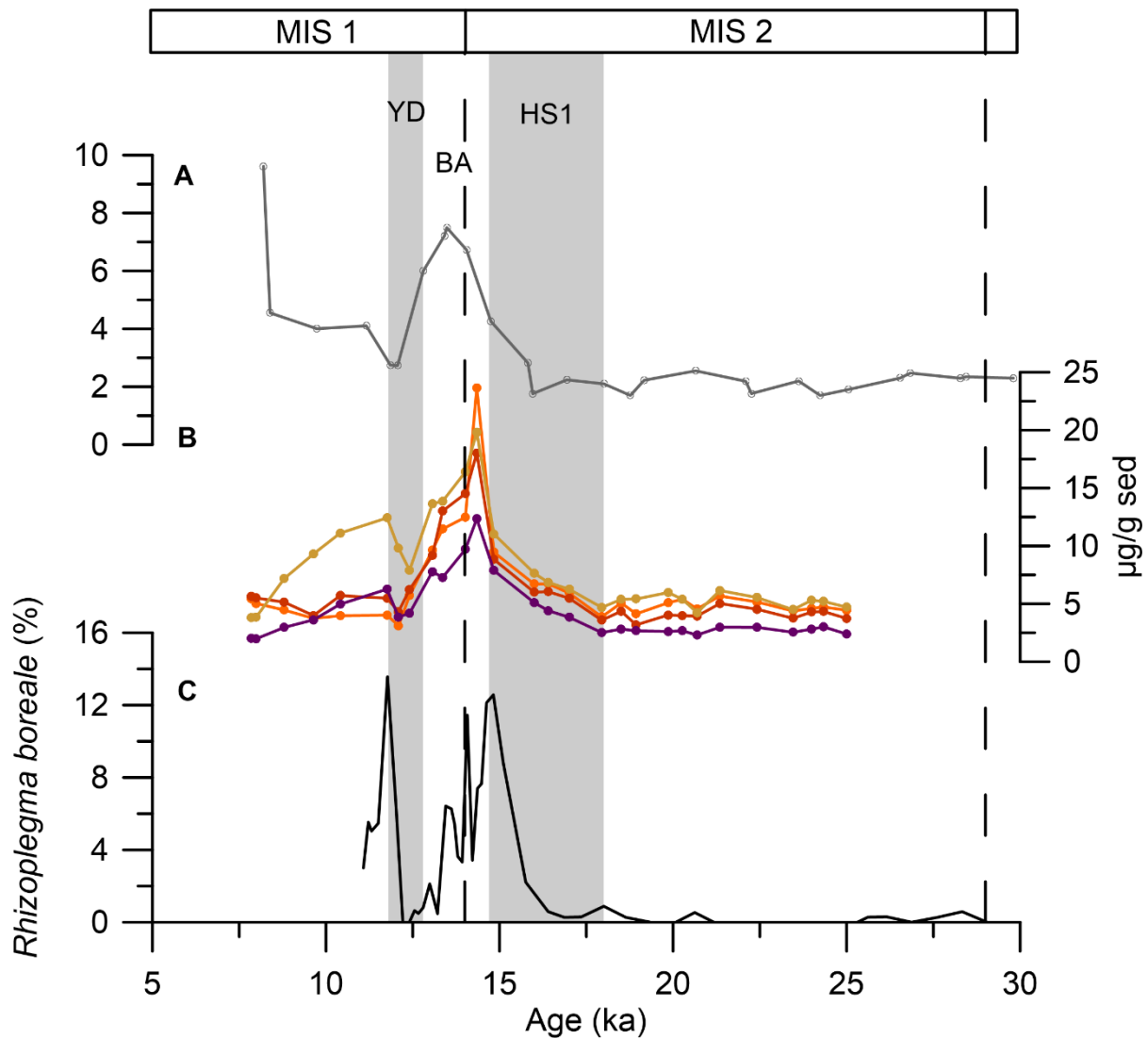
Supplementary Figure 6. (A) Correspondence analysis (CA) of the benthic foraminiferal assemblage data from Site U1343 with samples >50 specimens and for species with >10 individuals in total. The ovals indicate the foraminifera species included in Assemblage 1 (blue), 2 (red) and 3 (green). (B) CA axis 1 scores against the percentage counts of Assemblage 1 (blue) and assemblage 2 (red). (C) CA axis 2 scores against the percentage counts of Assemblage 3 (green).



Supplementary Figure 7. (A) Relative sea level stack including a 2σ error envelope (Spratt and Lisiecki, 2016) and the depth of several eastern Aleutian Passes and the Bering Strait; (B) 10-pt moving window correlation of IP₂₅ at SO202-27-6 and re-sampled IP₂₅ at Site U1343 including the 95% (long red dashed line) and 99% (short red dashed line) confidence interval; (C) IP₂₅ at SO202-27-6 (medium blue), Site U1343 (light blue) and re-sampled IP₂₅ at Site U1343 (navy blue).



Supplementary Figure 8. Compilation of SST and IP₂₅ records from the North Pacific. SST reconstructions are based on planktonic foraminiferal Mg/Ca (pink), TEX₈₆ (dark green), alkenones (green), and radiolarian modern analogue technique (MAT) (orange). **(A)** SST records (Harada et al., 2006, 2004; Hernández-Almeida et al., 2020; Max et al., 2012; Riethdorf et al., 2013) and IP₂₅ (Lo et al., 2018) from the Sea of Okhotsk; **(B)** SST records (Max et al., 2012; Meyer et al., 2016; Riethdorf et al., 2013) and IP₂₅ (Méheust et al., 2016) from the western Bering Sea; **(C)** SST records (Hernández-Almeida et al., 2020) and IP₂₅ (this study, Méheust et al., 2018) from the eastern Bering Sea; **(D)** SST records (Max et al., 2012; Meyer et al., 2016; Riethdorf et al., 2013) and IP₂₅ (Méheust et al., 2018) from the western North Pacific; **(E)** SST stack including the standard error of the mean (Praetorius et al., 2020) and IP₂₅ (Méheust et al., 2018) from the eastern North Pacific.



Supplementary Figure 9. (A) MARopal at Site U1343 (Kim et al., 2014); (B) Concentrations of brassicasterol (orange), cholesterol (red), campesterol (purple), and β -sitosterol (yellow) at Site U1343; (C) Relative concentration of the radiolarian species *Rhizoplegma boreale* at site PC-23A in the northern Bering Sea, indicative of meltwater runoff (Itaki et al., 2012).

Supplementary Table 1. Synthesis of sea ice, SST, oceanic circulation, ventilation, primary productivity, atmospheric temperature and atmospheric circulation dynamics in the Bering Sea and the North Pacific during the LGM, HS1, the BA, the YD, and the early Holocene.

Climate Parameter	Region		Early Holocene (~8-11.8 ka)	YD (11.8-12.8 ka)	BA (12.8-14.7 ka)	HS1 (14.7-18 ka)	LGM (19-26.5 ka)	References
Sea ice	Bering Sea	Western	Ice free to marginal sea-ice conditions	Marginal to extended seasonal sea-ice cover, sharp decline in sea-ice extent at the YD/Holocene boundary	Ice free to marginal sea-ice conditions during the early BA, followed by an increase in sea-ice extent prior to the BA/YD boundary	Extended seasonal sea-ice cover, decline of the sea-ice cover from 15 ka onward	No records	Caissie et al., 2010; Itaki et al., 2012; Méheust et al., 2018, 2016, this study
		Eastern				Extended seasonal sea-ice cover during early HS1, followed by a transition to MIZ conditions (16.5 ka) and a northward retreat of the sea-ice margin from 16 ka	Intermediate seasonal sea-ice cover	
	Subarctic North Pacific	Western	Ice free conditions	Reduced to extended seasonal sea-ice cover	Ice free conditions	Marginal to extended sea-ice cover, decline of the sea-ice cover from 15 ka	Reduced to marginal seasonal sea-ice cover	
		Eastern		Ice free conditions	Ice free to reduced seasonal sea-ice conditions	Marginal to extended sea-ice cover, decline of the sea-ice cover from 16 ka	Extended seasonal sea-ice cover	

Sea surface (SST) and subsurface temperatures	Bering Sea	Western	Reconstruction based on alkenones and TEX ₈₆ suggest early Holocene SST warming, planktonic foraminiferal Mg/Ca suggests subsurface cooling	Planktonic foraminiferal Mg/Ca suggest relatively constant subsurface temperatures with minimal cooling, alkenone and TEX ₈₆ records indicate SST cooling	Substantial region-wide SST warming recorded at the HS1/BA boundary, independent of the applied temperature proxy. SST and subsurface cooling into the YD interval.	Planktonic foraminiferal Mg/Ca suggest constant subsurface temperatures with minimal cooling, TEX ₈₆ indicates transient SST cooling during early HS1 followed by warming	Planktonic foraminiferal Mg/Ca suggest relatively mild LGM subsurface temperatures, TEX ₈₆ records indicate substantial SST warming since the LGM and warming summer SSTs from ~19 ka	Caissie et al., 2010; Gray et al., 2018; Hernández-Almeida et al., 2020; Meyer et al., 2016; Praetorius et al., 2020 and references therein; Riethdorf et al., 2013; Harada et al., 2012; Kiefer and Kienast, 2005; Kienast and McKay, 2001; Sarnthein et al., 2006
		Eastern	No records	Relatively constant SSTs based on radiolarian assemblages with potential early YD cooling and warming at the YD/Holocene boundary		Radiolarian assemblages suggest variable SSTs with overall warming trend	Radiolarian assemblages suggest colder LGM SSTs compared to the early Holocene, early deglacial warming spikes in SST from ~20 ka	
	Subarctic North Pacific	Western	Reconstruction based on alkenones and TEX ₈₆ suggest early Holocene SST warming, planktonic foraminiferal Mg/Ca suggests subsurface cooling	Planktonic foraminiferal Mg/Ca suggest early YD subsurface cooling, TEX ₈₆ and alkenone records indicate SST cooling		Planktonic foraminiferal Mg/Ca indicate cooling subsurface temperatures, while TEX ₈₆ SSTs remain stable	TEX ₈₆ , alkenone SSTs, and planktonic foraminiferal Mg/Ca suggest relatively mild LGM SST and subsurface temperatures	
		Eastern	SST stack indicates rapid warming until ~11 ka, followed by relatively stable Holocene SSTs	SST stack suggests substantial cooling		SST stack suggests cooling during early HS1, followed by warming from ~16.5 ka	Planktonic foraminiferal Mg/Ca suggest relatively mild LGM subsurface temperatures	

Oceanic Surface circulation	Bering Sea	Western	Complete flooding of the Bering Sea shelf and Bering Strait, enhanced Alaskan Stream inflow into the Bering Sea, strengthening of the Bering Sea surface circulation	Marine transgression, onset of flooding of eastern Aleutian passes and Bering Sea shelf	Reduced inflow of Alaskan Stream waters through eastern Aleutian Passes, closed Bering Strait	Reduced inflow of Alaskan Stream waters through eastern Aleutian Passes and a closed Bering Strait. The strength of the Bering Slope Current (BSC) depends on the Alaskan Stream inflow to the Bering Sea, thus the BSC was likely weaker. A weaker BSC would also result in less eddy upwelling activity along the eastern slope.	Caissie et al., 2010; Jakobsson et al., 2017; Mann and Hamilton, 1995; Meyer et al., 2016; Pico et al., 2020; Tanaka and Takahashi, 2005; Pelto et al., 2018	
		Eastern						
	Subarctic North Pacific	Western	Modern subpolar gyre (SPG) boundaries, reduced influence of the Alaskan Stream in the western subarctic Pacific	Northward migration of the western SPG boundary from 12.5 ka	Less zonal SPG extending further south in the west	Northward migration of the eastern SPG boundary from 16.5 ka	Wind-driven strengthening and southward expansion of the SPG, enhanced Alaskan Stream influence in the west	Gray et al., 2020; Meyer et al., 2016; Riethdorf et al., 2013
		Eastern						
Primary productivity, nutrients, and $p\text{CO}_2$	Bering Sea	Western	Increased primary productivity and enhanced input of terrestrial organic carbon (eastern Bering Sea) during the Preboreal (10.7-11.7 ka), followed by reduction in productivity	Renewed decrease in primary productivity, albeit of lower extent compared to the LGM	High primary and export productivity and enhanced input of terrestrial organic carbon	Initial deglacial weakening of nutrient utilization from 17.5 ka, increase in primary productivity from ~16 ka	Overall low primary productivity and enhanced nutrient utilization	Brunelle et al., 2010, 2007; Caissie et al., 2010; Cook et al., 2005; Crusius et al., 2004; Gebhardt et al., 2008; Gorbarenko et al., 2005; Gray et al., 2018; Kim et al., 2014; Kohfeld and Chase, 2011; Lam et al., 2013; Max et al., 2012; Okazaki et al., 2005; Pelto et al., 2018; Riethdorf et al., 2016
		Eastern						
	Subarctic North Pacific	Western	Increased primary productivity compared to the LGM, but reduced compared to the BA	High primary and export productivity, rapid increase in surface ocean $p\text{CO}_2$ and CO_2 outgassing	Early HS1 increase in surface ocean $p\text{CO}_2$, initial decrease in nutrient utilization, increase in primary productivity from ~16-15 ka			
		Eastern						

Ventilation, (G)NPIW formation, and OMZ dynamics	Bering Sea	Western	Expansion and strengthening of the mid-depth OMZ and preservation of laminated sediments during the Preboreal period (10.7-11.7 ka) followed by a decrease in mid-depth hypoxia and cessation of laminated sediments	Improved ventilation to depth of at least ~1500 m	Break-down of GNPIW formation, expansion and strengthening of the mid-depth OMZ and preservation of laminated sediments due to enhanced respiration of organic carbon	Improved ventilation to depth of at least 2000 m during early HS1 and to 1000 m during remaining HS1	Improved ventilation to depth of 1000 m	Ahagon, 2003; Aiello and Ravelo, 2012; Cannariato and Kennett, 1999; Chikamoto et al., 2012; Cook et al., 2016, 2005; Cook and Keigwin, 2015; Crusius et al., 2004; Duplessy et al., 1989; Expedition 323 Scientists, 2010; Gong et al., 2019; Gorbarenko et al., 2010; Gray et al., 2018; Ikehara et al., 2006; Jaccard and Galbraith, 2013; Jang et al., 2017; Keigwin, 1998; Knudson and Ravelo, 2015; Kuehn et al., 2014; Matsumoto et al., 2002; Max et al., 2014; Menviel et al., 2012; Ohkouchi et al., 1994; Ohkushi et al., 2013; Okazaki et al., 2012, 2010; Okumura et al., 2009; Ovsepyan et al., 2017; Pelto et al., 2018; Praetorius et al., 2015; Rae et al., 2014; Rella et al., 2012; Saenko et al., 2004; Sagawa and Ikehara, 2008; Schlung et al., 2013; Shibahara et al., 2007; Tetard et al., 2017; Worme et al., 2019; Wu et al., 2008; Zheng et al., 2000; Zou et al., 2020
		Eastern						
	Subarctic North Pacific	Western	Decrease in the ventilation of the mid-depth North Pacific	Improved ventilation to depth of ~1500 m	Break-down of GNPIW formation and improved ventilation of NPDW, enhanced upwelling of nutrient-, CO ₂ -rich NPDW, widespread mid-depth hypoxia and preservation of laminated sediments	Enhanced GNPIW formation and improved ventilation to depth of 2000 m	GNPIW formation and improved ventilation to depth of 2000 m, reduced oxygenation of NPDW	
		Eastern		Potentially enhanced overturning but of lower extent compared to HS1		Enhanced GNPIW formation and improved ventilation to depth of 3600 m		

Atmospheric temperatures	Bering Sea	Western	Northern hemisphere-wide warming	Northern hemisphere cooling during the early YD, followed by consistent warming into the early Holocene	Enhanced rate of northern hemisphere warming, peak BA northern hemisphere warmth at ~13.5 ka followed by cooling into the YD interval	Early HS1 cooling in Beringia and the northern hemisphere, overall warming during the second half of HS1	Northern hemisphere temperatures were colder by 3-3.5 °C during the LGM compared to the early Holocene	Buizert et al., 2014; Kurek et al., 2009; Rasmussen et al., 2006; Shakun et al., 2012; Svensson et al., 2008; Viau et al., 2008; Vinther et al., 2006
		Eastern						
	Subarctic North Pacific	Western						
		Eastern						
Atmospheric circulation	Bering Sea	Western	Establishment of modern positions of polar easterlies and mid-latitude westerlies	Northward shift of the westerlies in the western North Pacific from 12.5 ka	Less zonal jet stream, weakened atmospheric circulation compared to HS1, but enhanced compared to the Holocene due to the remnant Laurentide Ice Sheet	Strengthened Aleutian Low bringing cold air masses to the western Bering Sea and western North Pacific, northward migration of the westerlies in the eastern North Pacific from 16.5 ka	Southward shift of the mid-latitude westerlies and polar easterlies, enhanced wind stress curl over the subarctic North Pacific	Gong et al., 2019; Gray et al., 2020, 2018; Nagashima et al., 2007; Yanase and Abe-Ouchi, 2007
		Eastern						
	Subarctic North Pacific	Western						
		Eastern						

Supplementary References

- Ahagon, N., Ohkushi, K., Uchida, M., Mishima, T., 2003. Mid-depth circulation in the northwest Pacific during the last deglaciation: Evidence from foraminiferal radiocarbon ages. *Geophys. Res. Lett.* 30, 2097. <https://doi.org/10.1029/2003GL018287>
- Aiello, I.W., Ravelo, A.C., 2012. Evolution of marine sedimentation in the Bering Sea since the Pliocene. *Geosphere* 8, 1231–1253. <https://doi.org/10.1130/GES00710.1>
- Asahi, H., Kender, S., Ikehara, M., Sakamoto, T., Takahashi, K., Ravelo, A.C., Alvarez Zarikian, C.A., Khim, B.K., Leng, M.J., 2016. Orbital-scale benthic foraminiferal oxygen isotope stratigraphy at the northern Bering Sea Slope Site U1343 (IODP Expedition 323) and its Pleistocene paleoceanographic significance. *Deep Sea Res. Part II Top. Stud. Oceanogr.* 125–126, 66–83. <https://doi.org/10.1016/J.DSR2.2014.01.004>
- Brunelle, B.G., Sigman, D.M., Cook, M.S., Keigwin, L.D., Haug, G.H., Plessen, B., Schettler, G., Jaccard, S.L., 2007. Evidence from diatom-bound nitrogen isotopes for subarctic Pacific stratification during the last ice age and a link to North Pacific denitrification changes. *Paleoceanography* 22, n/a-n/a. <https://doi.org/10.1029/2005PA001205>
- Brunelle, B.G., Sigman, D.M., Jaccard, S.L., Keigwin, L.D., Plessen, B., Schettler, G., Cook, M.S., Haug, G.H., 2010. Glacial/interglacial changes in nutrient supply and stratification in the western subarctic North Pacific since the penultimate glacial maximum. *Quat. Sci. Rev.* 29, 2579–2590. <https://doi.org/10.1016/J.QUASCIREV.2010.03.010>
- Buizert, C., Gkinis, V., Severinghaus, J.P., He, F., Lecavalier, B.S., Kindler, P., Leuenberger, M., Carlson, A.E., Vinther, B., Masson-Delmotte, V., White, J.W.C., Liu, Z., Otto-Bliesner, B., Brook, E.J., 2014. Greenland temperature response to climate forcing during the last deglaciation. *Science (80-.)*. 345, 1177–1180. <https://doi.org/10.1126/science.1254961>
- Caissie, B.E., Brigham-Grette, J., Lawrence, K.T., Herbert, T.D., Cook, M.S., 2010. Last Glacial Maximum to Holocene sea surface conditions at Umnak Plateau, Bering Sea, as inferred from diatom, alkenone, and stable isotope records. *Paleoceanography* 25. <https://doi.org/10.1029/2008PA001671>
- Cannariato, K.G., Kennett, J.P., 1999. Climatically related millennial-scale fluctuations in strength of California margin oxygen-minimum zone during the past 60 k.y., *Geology*. GeoScienceWorld. [https://doi.org/10.1130/0091-7613\(1999\)027<0975:CRMSFI>2.3.CO;2](https://doi.org/10.1130/0091-7613(1999)027<0975:CRMSFI>2.3.CO;2)
- Chikamoto, M.O., Menviel, L., Abe-Ouchi, A., Ohgaito, R., Timmermann, A., Okazaki, Y., Oka, A., Mouchet, A., 2012. Variability in North Pacific intermediate and deep water ventilation during Heinrich events in two coupled climate models. *Deep Sea Res. Part II Top. Stud. Oceanogr.* 61–64, 114–126. <https://doi.org/10.1016/J.DSR2.2011.12.002>
- Cook, M.S., Keigwin, L.D., 2015. Radiocarbon profiles of the NW Pacific from the LGM and deglaciation: Evaluating ventilation metrics and the effect of uncertain surface reservoir ages. *Paleoceanography* 30, 174–195. <https://doi.org/10.1002/2014PA002649>
- Cook, M.S., Keigwin, L.D., Sancetta, C.A., 2005. The deglacial history of surface and intermediate water of the Bering Sea. *Deep Sea Res. Part II Top. Stud. Oceanogr.* 52, 2163–2173. <https://doi.org/10.1016/J.DSR2.2005.07.004>

- Cook, M.S., Ravelo, A.C., Mix, A., Nesbitt, I.M., Miller, N. V., 2016. Tracing subarctic Pacific water masses with benthic foraminiferal stable isotopes during the LGM and late Pleistocene. *Deep Sea Res. Part II Top. Stud. Oceanogr.* 125–126, 84–95. <https://doi.org/10.1016/J.DSR2.2016.02.006>
- Crusius, J., Pedersen, T.F., Kienast, S., Keigwin, L., Labeyrie, L., 2004. Influence of northwest Pacific productivity on North Pacific Intermediate Water oxygen concentrations during the Bølling-Ållerød interval (14.7-12.9 ka). *Geology* 32, 633–636. <https://doi.org/10.1130/G20508.1>
- Duplessy, J.-C., Arnold, M., Bard, E., Juillet-Leclerc, A., Kallel, N., Labeyrie, L., 1989. AMS 14C Study of Transient Events and of the Ventilation Rate of the Pacific Intermediate Water During the Last Deglaciation. *Radiocarbon* 31, 493–502.
- Expedition 323 Scientists, 2010. Bering Sea paleoceanography: Pliocene-Pleistocene paleoceanography and climate history of the Bering Sea. *IODP Prelim. Rep.* 323. <https://doi.org/10.2204/iodp.pr.323.2010>
- Gebhardt, H., Sarnthein, M., Grootes, P.M., Kiefer, T., Kuehn, H., Schmieder, F., Röhl, U., 2008. Paleonutrient and productivity records from the subarctic North Pacific for Pleistocene glacial terminations I to V. *Paleoceanography* 23, n/a-n/a. <https://doi.org/10.1029/2007PA001513>
- Gong, X., Lembke-Jene, L., Lohmann, G., Knorr, G., Tiedemann, R., Zou, J.J., Shi, X.F., 2019. Enhanced North Pacific deep-ocean stratification by stronger intermediate water formation during Heinrich Stadial 1. *Nat. Commun.* 10, 656. <https://doi.org/10.1038/s41467-019-08606-2>
- Gorbarenko, S.A., Basov, I.A., Chekhovskaya, M.P., Southon, J., Khusid, T.A., Artemova, A. V., 2005. Orbital and millennium scale environmental changes in the southern Bering Sea during the last glacial-Holocene: Geochemical and paleontological evidence. *Deep. Res. Part II Top. Stud. Oceanogr.* 52, 2174–2185. <https://doi.org/10.1016/j.dsr2.2005.08.005>
- Gorbarenko, S.A., Wang, P., Wang, R., Cheng, X., 2010. Orbital and suborbital environmental changes in the southern Bering Sea during the last 50 kyr. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 286, 97–106. <https://doi.org/10.1016/j.palaeo.2009.12.014>
- Gray, W.R., Rae, J.W.B., Wills, R.C.J., Shevenell, A.E., Taylor, B., Burke, A., Foster, G.L., Lear, C.H., 2018. Deglacial upwelling, productivity and CO₂ outgassing in the North Pacific Ocean. *Nat. Geosci.* 11, 340–344. <https://doi.org/10.1038/s41561-018-0108-6>
- Gray, W.R., Wills, R.C.J., Rae, J.W.B., Burke, A., Ivanovic, R.F., Roberts, W.H.G., Ferreira, D., Valdes, P.J., 2020. Wind-Driven Evolution of the North Pacific Subpolar Gyre Over the Last Deglaciation. *Geophys. Res. Lett.* 47. <https://doi.org/10.1029/2019GL086328>
- Harada, N., Ahagon, N., Sakamoto, T., Uchida, M., Ikehara, M., Shibata, Y., 2006. Rapid fluctuation of alkenone temperature in the southwestern Okhotsk Sea during the past 120 ky. *Glob. Planet. Change* 53, 29–46. <https://doi.org/10.1016/j.gloplacha.2006.01.010>
- Harada, N., Ahagon, N., Uchida, M., Murayama, M., 2004. Northward and southward migrations of frontal zones during the past 40 kyr in the Kuroshio-Oyashio transition area. *Geochemistry, Geophys. Geosystems* 5, n/a-n/a. <https://doi.org/10.1029/2004GC000740>

- Harada, N., Sato, M., Seki, O., Timmermann, A., Moossen, H., Bendle, J., Nakamura, Y., Kimoto, K., Okazaki, Y., Nagashima, K., Gorbarenko, S.A., Ijiri, A., Nakatsuka, T., Menviel, L., Chikamoto, M.O., Abe-Ouchi, A., Schouten, S., 2012. Sea surface temperature changes in the Okhotsk Sea and adjacent North Pacific during the last glacial maximum and deglaciation. *Deep. Res. Part II Top. Stud. Oceanogr.* 61–64, 93–105. <https://doi.org/10.1016/j.dsr2.2011.12.007>
- Hernández-Almeida, I., Boltovskoy, D., Kruglikova, S.B., Cortese, G., 2020. A new radiolarian transfer function for the Pacific Ocean and application to fossil records: Assessing potential and limitations for the last glacial-interglacial cycle. *Glob. Planet. Change* 190, 103186. <https://doi.org/10.1016/j.gloplacha.2020.103186>
- Ikehara, K., Ohkushi, K., Shibahara, A., Hoshiba, M., 2006. Change of bottom water conditions at intermediate depths of the Oyashio region, NW Pacific over the past 20,000 yrs. *Glob. Planet. Change* 53, 78–91. <https://doi.org/10.1016/j.gloplacha.2006.01.011>
- Itaki, T., Kim, S., Rella, S.F., Uchida, M., Tada, R., Khim, B.K., 2012. Millennial-scale variations of late Pleistocene radiolarian assemblages in the Bering Sea related to environments in shallow and deep waters. *Deep. Res. Part II Top. Stud. Oceanogr.* 61–64, 127–144. <https://doi.org/10.1016/j.dsr2.2011.03.002>
- Jaccard, S.L., Galbraith, E.D., 2013. Direct ventilation of the North Pacific did not reach the deep ocean during the last deglaciation. *Geophys. Res. Lett.* 40, 199–203. <https://doi.org/10.1029/2012GL054118>
- Jakobsson, M., Pearce, C., Cronin, T.M., Backman, J., Anderson, L.G., Barrientos, N., Björk, G., Coxall, H., de Boer, A., Mayer, L.A., Mörth, C.-M., Nilsson, J., Rattray, J.E., Stranne, C., Semiletov, I., O’Regan, M., 2017. Post-glacial flooding of the Bering Land Bridge dated to 11 cal ka BP based on new geophysical and sediment records. *Clim. Past* 13, 991–1005. <https://doi.org/10.5194/cp-13-991-2017>
- Jang, K., Huh, Y., Han, Y., 2017. Authigenic Nd isotope record of North Pacific Intermediate Water formation and boundary exchange on the Bering Slope. *Quat. Sci. Rev.* 156, 150–163. <https://doi.org/10.1016/j.quascirev.2016.11.032>
- Keigwin, L.D., 1998. Glacial-age hydrography of the far northwest Pacific Ocean. *Paleoceanography* 13, 323–339. <https://doi.org/10.1029/98PA00874>
- Kiefer, T., Kienast, M., 2005. Patterns of deglacial warming in the Pacific Ocean: a review with emphasis on the time interval of Heinrich event 1. *Quat. Sci. Rev.* 24, 1063–1081. <https://doi.org/10.1016/J.QUASCIREV.2004.02.021>
- Kienast, S.S., McKay, J.L., 2001. Sea surface temperatures in the subarctic northeast Pacific reflect millennial-scale climate oscillations during the last 16 kyrs. *Geophys. Res. Lett.* 28, 1563–1566. <https://doi.org/10.1029/2000GL012543>
- Kim, S., Takahashi, K., Khim, B.-K., Kanematsu, Y., Asahi, H., Ravelo, A.C., 2014. Biogenic opal production changes during the Mid-Pleistocene Transition in the Bering Sea (IODP Expedition 323 Site U1343). *Quat. Res.* 81, 151–157. <https://doi.org/10.1016/J.YQRES.2013.10.001>
- Knudson, K.P., Ravelo, A.C., 2015. North Pacific Intermediate Water circulation enhanced by the closure of the Bering Strait. *Paleoceanography* 30, 1287–1304. <https://doi.org/10.1002/2015PA002840>

- Kohfeld, K.E., Chase, Z., 2011. Controls on deglacial changes in biogenic fluxes in the North Pacific Ocean. *Quat. Sci. Rev.* 30, 3350–3363. <https://doi.org/10.1016/J.QUASCIREV.2011.08.007>
- Kuehn, H., Lembke-Jene, L., Gersonde, R., Esper, O., Lamy, F., Arz, H., Kuhn, G., Tiedemann, R., 2014. Laminated sediments in the Bering Sea reveal atmospheric teleconnections to Greenland climate on millennial to decadal timescales during the last deglaciation. *Clim. Past* 10, 2215–2236. <https://doi.org/10.5194/cp-10-2215-2014>
- Kurek, J., Cwynar, L.C., Ager, T.A., Abbott, M.B., Edwards, M.E., 2009. Late Quaternary paleoclimate of western Alaska inferred from fossil chironomids and its relation to vegetation histories. *Quat. Sci. Rev.* 28, 799–811. <https://doi.org/10.1016/j.quascirev.2008.12.001>
- Lam, P.J., Robinson, L.F., Blusztajn, J., Li, C., Cook, M.S., McManus, J.F., Keigwin, L.D., 2013. Transient stratification as the cause of the North Pacific productivity spike during deglaciation. *Nat. Geosci.* 6, 622–626. <https://doi.org/10.1038/ngeo1873>
- Lisiecki, L.E., Raymo, M.E., 2005. A Pliocene-Pleistocene stack of 57 globally distributed benthic $\delta^{18}\text{O}$ records. *Paleoceanography* 20, n/a-n/a. <https://doi.org/10.1029/2004PA001071>
- Lo, L., Belt, S.T., Lattaud, J., Friedrich, T., Zeeden, C., Schouten, S., Smik, L., Timmermann, A., Cabedo-Sanz, P., Huang, J.-J., Zhou, L., Ou, T.-H., Chang, Y.-P., Wang, L.-C., Chou, Y.-M., Shen, C.-C., Chen, M.-T., Wei, K.-Y., Song, S.-R., Fang, T.-H., Gorbarenko, S.A., Wang, W.-L., Lee, T.-Q., Elderfield, H., Hodell, D.A., 2018. Precession and atmospheric CO₂ modulated variability of sea ice in the central Okhotsk Sea since 130,000 years ago. *Earth Planet. Sci. Lett.* 488, 36–45. <https://doi.org/10.1016/J.EPSL.2018.02.005>
- Mann, D.H., Hamilton, T.D., 1995. Late Pleistocene and Holocene paleoenvironments of the North Pacific coast. *Quat. Sci. Rev.* 14, 449–471. [https://doi.org/10.1016/0277-3791\(95\)00016-I](https://doi.org/10.1016/0277-3791(95)00016-I)
- Matsumoto, K., Oba, T., Lynch-Stieglitz, J., Yamamoto, H., 2002. Interior hydrography and circulation of the glacial Pacific Ocean. *Quat. Sci. Rev.* 21, 1693–1704. [https://doi.org/10.1016/S0277-3791\(01\)00142-1](https://doi.org/10.1016/S0277-3791(01)00142-1)
- Max, L., Lembke-Jene, L., Riethdorf, J.-R., Tiedemann, R., Nürnberg, D., Kühn, H., Mackensen, A., 2014. Pulses of enhanced North Pacific Intermediate Water ventilation from the Okhotsk Sea and Bering Sea during the last deglaciation. *Clim. Past* 10, 591–605. <https://doi.org/10.5194/cp-10-591-2014>
- Max, L., Riethdorf, J.-R., Tiedemann, R., Smirnova, M., Lembke-Jene, L., Fahl, K., Nürnberg, D., Matul, A., Mollenhauer, G., 2012. Sea surface temperature variability and sea-ice extent in the subarctic northwest Pacific during the past 15,000 years. *Paleoceanography* 27, n/a-n/a. <https://doi.org/10.1029/2012PA002292>
- Méheust, M., Stein, R., Fahl, K., Gersonde, R., 2018. Sea-ice variability in the subarctic North Pacific and adjacent Bering Sea during the past 25 ka: new insights from IP25 and Uk'37 proxy records. *arktos* 4, 8. <https://doi.org/10.1007/s41063-018-0043-1>
- Méheust, M., Stein, R., Fahl, K., Max, L., Riethdorf, J.-R., 2016. High-resolution IP25-based reconstruction of sea-ice variability in the western North Pacific and Bering Sea during the past 18,000 years. *Geo-Marine Lett.* 36, 101–111. <https://doi.org/10.1007/s00367->

015-0432-4

- Menviel, L., Timmermann, A., Elison Timm, O., Mouchet, A., Abe-Ouchi, A., Chikamoto, M.O., Harada, N., Ohgaito, R., Okazaki, Y., 2012. Removing the North Pacific halocline: Effects on global climate, ocean circulation and the carbon cycle. *Deep. Res. Part II Top. Stud. Oceanogr.* 61–64, 106–113. <https://doi.org/10.1016/j.dsr2.2011.03.005>
- Meyer, V.D., Max, L., Hefter, J., Tiedemann, R., Mollenhauer, G., 2016. Glacial-to-Holocene evolution of sea surface temperature and surface circulation in the subarctic northwest Pacific and the Western Bering Sea. *Paleoceanography* 31, 916–927. <https://doi.org/10.1002/2015PA002877>
- Nagashima, K., Tada, R., Matsui, H., Irino, T., Tani, A., Toyoda, S., 2007. Orbital- and millennial-scale variations in Asian dust transport path to the Japan Sea. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 247, 144–161. <https://doi.org/10.1016/j.palaeo.2006.11.027>
- Ohkouchi, N., Kawahata, H., Murayama, M., Okada, M., Nakamura, T., Taira, A., 1994. Was deep water formed in the North Pacific during the Late Quaternary? Cadmium evidence from the Northwest Pacific. *Earth Planet. Sci. Lett.* 124, 185–194. [https://doi.org/10.1016/0012-821X\(94\)00082-4](https://doi.org/10.1016/0012-821X(94)00082-4)
- Ohkushi, K., Kennett, J.P., Zeleski, C.M., Moffitt, S.E., Hill, T.M., Robert, C., Beaufort, L., Behl, R.J., 2013. Quantified intermediate water oxygenation history of the NE Pacific: A new benthic foraminiferal record from Santa Barbara basin. *Paleoceanography* 28, 453–467. <https://doi.org/10.1002/palo.20043>
- Okazaki, Y., Sagawa, T., Asahi, H., Horikawa, K., Onodera, J., 2012. Ventilation changes in the western North Pacific since the last glacial period. *Clim. Past* 8, 17–24. <https://doi.org/10.5194/cp-8-17-2012>
- Okazaki, Y., Takahashi, K., Asahi, H., Katsuki, K., Hori, J., Yasuda, H., Sagawa, Y., Tokuyama, H., 2005. Productivity changes in the Bering Sea during the late Quaternary. *Deep Sea Res. Part II Top. Stud. Oceanogr.* 52, 2150–2162. <https://doi.org/10.1016/J.DSR2.2005.07.003>
- Okazaki, Y., Timmermann, A., Menviel, L., Harada, N., Abe-Ouchi, A., Chikamoto, M.O., Mouchet, A., Asahi, H., 2010. Deepwater formation in the North Pacific during the Last Glacial Termination. *Science* 329, 200–4. <https://doi.org/10.1126/science.1190612>
- Okumura, Y.M., Deser, C., Hu, A., Timmermann, A., Xie, S.-P., Okumura, Y.M., Deser, C., Hu, A., Timmermann, A., Xie, S.-P., 2009. North Pacific Climate Response to Freshwater Forcing in the Subarctic North Atlantic: Oceanic and Atmospheric Pathways. *J. Clim.* 22, 1424–1445. <https://doi.org/10.1175/2008JCLI2511.1>
- Ovsepyan, E.A., Ivanova, E.V., Lembke-Jene, L., Max, L., Tiedemann, R., Nürnberg, D., 2017. Penultimate and last glacial oceanographic variations in the Bering Sea on millennial timescales: Links to North Atlantic climate. *Quat. Sci. Rev.* 163, 135–151. <https://doi.org/10.1016/J.QUASCIREV.2017.03.012>
- Pelto, B.M., Caissie, B.E., Petsch, S.T., Brigham-Grette, J., 2018. Oceanographic and Climatic Change in the Bering Sea, Last Glacial Maximum to Holocene. *Paleoceanogr. Paleoclimatology* 33, 93–111. <https://doi.org/10.1002/2017PA003265>
- Pico, T., Mitrovica, J.X., Mix, A.C., 2020. Sea level fingerprinting of the Bering Strait flooding history detects the source of the Younger Dryas climate event. *Sci. Adv.* 6,

eaay2935. <https://doi.org/10.1126/sciadv.aay2935>

- Praetorius, S.K., Condron, A., Mix, A.C., Walczak, M.H., McKay, J.L., Du, J., 2020. The role of Northeast Pacific meltwater events in deglacial climate change. *Sci. Adv.* 6, eaay2915. <https://doi.org/10.1126/sciadv.aay2915>
- Praetorius, S.K., Mix, A.C., Walczak, M.H., Wolhowe, M.D., Addison, J.A., Prahl, F.G., 2015. North Pacific deglacial hypoxic events linked to abrupt ocean warming. *Nature* 527, 362–366. <https://doi.org/10.1038/nature15753>
- Rae, J.W.B., Sarnthein, M., Foster, G.L., Ridgwell, A., Grootes, P.M., Elliott, T., 2014. Deep water formation in the North Pacific and deglacial CO₂ rise. *Paleoceanography* 29, 645–667. <https://doi.org/10.1002/2013PA002570>
- Rasmussen, S.O., Andersen, K.K., Svensson, A.M., Steffensen, J.P., Vinther, B.M., Clausen, H.B., Siggaard-Andersen, M.-L., Johnsen, S.J., Larsen, L.B., Dahl-Jensen, D., Bigler, M., Röthlisberger, R., Fischer, H., Goto-Azuma, K., Hansson, M.E., Ruth, U., 2006. A new Greenland ice core chronology for the last glacial termination. *J. Geophys. Res.* 111, D06102. <https://doi.org/10.1029/2005JD006079>
- Rella, S.F., Tada, R., Nagashima, K., Ikehara, M., Itaki, T., Ohkushi, K., Sakamoto, T., Harada, N., Uchida, M., 2012. Abrupt changes of intermediate water properties on the northeastern slope of the Bering Sea during the last glacial and deglacial period. *Paleoceanography* 27, n/a-n/a. <https://doi.org/10.1029/2011PA002205>
- Riethdorf, J.-R., Max, L., Nürnberg, D., Lembke-Jene, L., Tiedemann, R., 2013. Deglacial development of (sub) sea surface temperature and salinity in the subarctic northwest Pacific: Implications for upper-ocean stratification. *Paleoceanography* 28, 91–104. <https://doi.org/10.1002/palo.20014>
- Riethdorf, J.-R., Thibodeau, B., Ikehara, M., Nürnberg, D., Max, L., Tiedemann, R., Yokoyama, Y., 2016. Surface nitrate utilization in the Bering sea since 180 ka BP: Insight from sedimentary nitrogen isotopes. *Deep Sea Res. Part II Top. Stud. Oceanogr.* 125–126, 163–176. <https://doi.org/10.1016/J.DSR2.2015.03.007>
- Saenko, O.A., Schmittner, A., Weaver, A.J., Saenko, O.A., Schmittner, A., Weaver, A.J., 2004. The Atlantic–Pacific Seesaw. *J. Clim.* 17, 2033–2038. [https://doi.org/10.1175/1520-0442\(2004\)017<2033:TAS>2.0.CO;2](https://doi.org/10.1175/1520-0442(2004)017<2033:TAS>2.0.CO;2)
- Sagawa, T., Ikehara, K., 2008. Intermediate water ventilation change in the subarctic northwest Pacific during the last deglaciation. *Geophys. Res. Lett.* 35, L24702. <https://doi.org/10.1029/2008GL035133>
- Sarnthein, M., Kiefer, T., Grootes, P.M., Elderfield, H., Erlenkeuser, H., 2006. Warmings in the far northwestern Pacific promoted pre-Clovis immigration to America during Heinrich event 1. *Geology* 34, 141. <https://doi.org/10.1130/G22200.1>
- Schlung, S.A., Christina Ravelo, A., Aiello, I.W., Andreasen, D.H., Cook, M.S., Drake, M., Dyez, K.A., Guilderson, T.P., Lariviere, J.P., Stroynowski, Z., Takahashi, K., 2013. Millennial-scale climate change and intermediate water circulation in the Bering Sea from 90 ka: A high-resolution record from IODP Site U1340. *Paleoceanography* 28, 54–67. <https://doi.org/10.1029/2012PA002365>
- Shakun, J.D., Clark, P.U., He, F., Marcott, S.A., Mix, A.C., Liu, Z., Otto-Bliesner, B., Schmittner, A., Bard, E., 2012. Global warming preceded by increasing carbon dioxide

- concentrations during the last deglaciation. *Nature* 484, 49–54.
<https://doi.org/10.1038/nature10915>
- Shibahara, A., Ohkushi, K., Kennett, J.P., Ikehara, K., 2007. Late Quaternary changes in intermediate water oxygenation and oxygen minimum zone, northern Japan: A benthic foraminiferal perspective. *Paleoceanography* 22, n/a-n/a.
<https://doi.org/10.1029/2005PA001234>
- Spratt, R.M., Lisiecki, L.E., 2016. A Late Pleistocene sea level stack. *Clim. Past* 12, 1079–1092. <https://doi.org/10.5194/cp-12-1079-2016>
- Svensson, A., Andersen, K.K., Bigler, M., Clausen, H.B., Dahl-Jensen, D., Davies, S.M., Johnsen, S.J., Muscheler, R., Parrenin, F., Rasmussen, S.O., Röthlisberger, R., Seierstad, I., Steffensen, J.P., Vinther, B.M., 2008. A 60 000 year Greenland stratigraphic ice core chronology. *Clim. Past* 4, 47–57. <https://doi.org/10.5194/cp-4-47-2008>
- Tanaka, S., Takahashi, K., 2005. Late Quaternary paleoceanographic changes in the Bering Sea and the western subarctic Pacific based on radiolarian assemblages. *Deep Sea Res. Part II Top. Stud. Oceanogr.* 52, 2131–2149.
<https://doi.org/10.1016/J.DSR2.2005.07.002>
- Tetard, M., Licari, L., Beaufort, L., 2017. Oxygen history off Baja California over the last 80 kyr: A new foraminiferal-based record. *Paleoceanography* 32, 246–264.
<https://doi.org/10.1002/2016PA003034>
- Viau, A.E., Gajewski, K., Sawada, M.C., Bunbury, J., 2008. Low- and high-frequency climate variability in eastern Beringia during the past 25 000 years. *Can. J. Earth Sci.* 45, 1435–1453. <https://doi.org/10.1139/E08-036>
- Vinther, B.M., Clausen, H.B., Johnsen, S.J., Rasmussen, S.O., Andersen, K.K., Buchardt, S.L., Dahl-Jensen, D., Seierstad, I.K., Siggaard-Andersen, M.-L., Steffensen, J.P., Svensson, A., Olsen, J., Heinemeier, J., 2006. A synchronized dating of three Greenland ice cores throughout the Holocene. *J. Geophys. Res.* 111, D13102.
<https://doi.org/10.1029/2005JD006921>
- Worne, S., Kender, S., Swann, G.E.A., Leng, M.J., Ravelo, A.C., 2019. Coupled climate and subarctic Pacific nutrient upwelling over the last 850,000 years. *Earth Planet. Sci. Lett.* 522, 87–97. <https://doi.org/10.1016/j.epsl.2019.06.028>
- Wu, L., Li, C., Yang, C., Xie, S.P., 2008. Global teleconnections in response to a shutdown of the Atlantic meridional overturning circulation. *J. Clim.* 21, 3002–3019.
<https://doi.org/10.1175/2007JCLI1858.1>
- Yanase, W., Abe-Ouchi, A., 2007. The LGM surface climate and atmospheric circulation over East Asia and the North Pacific in the PMIP2 coupled model simulations. *Clim. Past* 3, 439–451. <https://doi.org/10.5194/cp-3-439-2007>
- Zheng, Y., van Geen, A., Anderson, R.F., Gardner, J. V., Dean, W.E., 2000. Intensification of the Northeast Pacific oxygen minimum zone during the Bölling-Alleröd Warm Period. *Paleoceanography* 15, 528–536. <https://doi.org/10.1029/1999PA000473>
- Zou, J., Shi, X., Zhu, A., Kandasamy, S., Gong, X., Lembke-Jene, L., Chen, M.-T., Wu, Y., Ge, S., Liu, Y., Xue, X., Lohmann, G., Tiedemann, R., 2020. Millennial-scale variations in sedimentary oxygenation in the western subtropical North Pacific and its links to North Atlantic climate. *Clim. Past* 16, 387–407. <https://doi.org/10.5194/cp-16-387-2020>