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1 **Impacts of unusually light sea-ice cover in winter 2017-2018 on the northern**
2 **Bering Sea marine ecosystem – An introduction**

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5 ABSTRACT

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7 This paper serves as an introduction to the Deep-Sea Research II special issue on the
8 impacts of a severe lack of sea ice in the northern Bering Sea (NBS) in the winter of
9 2017-2018. To complement the papers in this volume, we provide a brief synopsis of the
10 physical oceanography of the NBS, including information on the characteristics of the
11 dominant water masses, and the patterns of sea-ice formation and duration in years past.
12 The 17 papers in this volume provide a series of snapshots of the northern Bering Sea in
13 the spring and summer of 2018, which followed an unusual warming in February 2018
14 and record-breaking low sea-ice concentrations. The lack of ice in spring affected the
15 temperatures and structure of the water column, impacted the timing of the spring
16 bloom, and affected the marine food webs from the amounts and kinds of phytoplankton
17 and zooplankton, to the distribution of fish and the reproduction and survival of marine
18 birds and mammals. As the Arctic and sub-Arctic warm, events like those observed in
19 2018 may well become the norm. If so, we may anticipate major changes in the NBS
20 marine ecosystem and those dependent upon its resources.

21
22 *Keywords:* Climate change, Loss of sea ice, Sub-Arctic seas

24

25 **1. Introduction**

26

27 The winter of 2017-2018 had record low sea-ice cover in the Northern Bering
28 Sea (NBS). Although seven recent publications provide a synopsis of the events leading
29 up to this almost ice-free winter (Stabeno and Bell, 2019; Stabeno et al., 2019; Baker et
30 al., 2020; Thoman et al., 2020) and the follow-on impacts of the lack of sea ice on this
31 sub-Arctic sea (Duffy-Anderson et al., 2019; Danielson et al., 2020; Huntington et al.,
32 2020), many aspects of the ecological changes that were manifested in the spring and
33 summer of 2018 have not been described or evaluated. Thus, the goal of this special
34 volume is to bring together scientists who have been working in the NBS to present
35 what they have learned about the impact of the extraordinarily limited sea-ice cover in
36 winter 2017-2018.

37

38

39 **2. Background**

40

41 The recent warming trend in the Arctic (Box et al., 2019) is expected to change
42 what we have come to expect as a stable annual sea ice pattern. Sea-ice extent for the
43 whole Arctic Ocean has had a negative trend for the past 28 years (1979-2006)
44 (Parkinson and Cavalieri, 2008). In particular, there was a significant reduction in
45 2005-2006 (Comiso, 2006), and then a summer minimum extent was recorded in 2007
46 in the Pacific Arctic region. Change in sea-ice cover induced an increase of primary
47 production of phytoplankton (Arrigo and van Dijken, 2015; Brown et al., 2011; Brown

48 and Arrigo, 2012; Hirawake et al., 2012), and a significant decrease in the size of
49 phytoplankton species present (Fujiwara et al., 2016) in the NBS. At the same time, a
50 northward shift of the marine ecosystems also occurred, and the species composition,
51 structure, and distributions of marine communities changed in the NBS and southern
52 Chukchi Sea (e.g. Fujiwara et al., 2011; Grebmeier et al., 2006a; Landeira et al., 2017;
53 Matsuno et al., 2011; Waga et al., 2019). These changes were even more striking in
54 winter and spring 2018.

55 The NBS is a transition zone between the boreal southeastern Bering Sea and
56 the Chukchi and Beaufort seas, which are both Arctic shelf seas (Sigler et al. 2011) (Fig.
57 1). Not only are there differences in the amount and duration of sea-ice cover and water
58 temperatures across this gradient from the southeastern Bering Sea to the Arctic shelf
59 seas, but also in the kinds and relative abundances of zooplankton, fish, seabird, and
60 marine mammal species. For the purposes of this volume, the southern Boundary of the
61 NBS on the eastern Bering Sea shelf is at about 60°N (Stabeno et al., 2012a). There, a
62 front marks the change from the southeastern Bering Sea system in which the
63 hydrographic stratification derives from a marked temperature difference between the
64 surface layer and the bottom layer and the NBS where the stratification is primarily
65 controlled by salinity differences (Stabeno et al., 2012a; Stabeno and Bell, 2019). The
66 northern limit is the Bering Strait. The NBS has been classified as part of the East
67 Bering Sea Large Marine Ecosystem (LME) (Carlton and Hayden, 1993) and, more
68 recently has been split between the East Bering Sea LME and the Northern
69 Bering-Chukchi Seas LME (<http://www.lmehub.net/#>, visited 7 April 2020; see also a
70 discussion of the close similarity of the Chirikov Basin, NBS and the Chukchi Sea in
71 Sigler et al., 2011).

72 Although the NBS, as defined by the LME, includes a portion of the Bering
73 Sea Basin and the shelf along the coast of Siberia, the papers in this volume, with the
74 exception of Baysuk and Zuenko (this issue), focus on the shallow (≤ 170 m) waters
75 over the eastern and northern portion of the NBS shelf, including the Chirikov Basin
76 north of St. Lawrence Island. The region is dominated by three water masses with
77 different characteristics which flow into the Arctic Ocean (Fig. 1) (Woodgate et al.,
78 2012; Danielson et al., 2014; Mueter et al., 2017;). In the west, Anadyr Water, which is
79 rich in nutrients, supports high primary production (Springer and McRoy, 1993;
80 Danielson et al., 2017). In contrast, along the eastern margin of the NBS, Alaska Coastal
81 Water, derived from the Alaska Coastal Current and the inflow of rivers, is fresh and
82 low in nutrients (Stabeno et al., 1995; Weingartner et al., 2005; Woodgate et al., 2006).
83 Between these two water masses is Bering Shelf Water, lower in nutrients than Anadyr
84 Water due to their uptake by primary producers (Grebmeier et al., 2006b). In the
85 Chirikov Basin, fast-flowing Anadyr Water may make rapid excursions to the east,
86 almost to King Island (Fig.1) (e.g. Hunt and Harrison, 1990). Consequently, water
87 masses need to be identified by their salinity characteristics rather than by just their
88 location.

89 Seasonal sea-ice cover is a signature feature of the NBS. Sea-ice forms
90 primarily in latent heat polynyas in the lees of islands and promontories (Pease, 1980),
91 and is blown south by cold arctic winds. In the NBS, the polynyas along the south
92 coasts of St. Lawrence Island (SLI) and the Gulf of Anadyr are some of the largest
93 polynyas in the northern hemisphere (Ohshima et al., 2016). The initial seasonal sea-ice
94 covering of the northern NBS usually has occurred in November - December, and final
95 melt-back in spring typically has occurred in May - June (Stabeno and Bell, 2019).

96 Sea ice plays a major role in physically structuring the NBS and in determining the
97 timing and fate of primary production. Sea-ice formation results in the rejection of salty,
98 cold, dense brine, which sinks to the bottom to form a layer of -1.7°C water (Stabeno
99 and Bell, 2019). Usually, this “cold pool” extends into the southeastern Bering Sea,
100 sometimes as far south as the Alaska Peninsula (Stabeno et al., 2012b; Stabeno and Bell,
101 2019). This cold pool functions as refuge for forage fish that can tolerate colder
102 temperatures than predatory adult pollock and Pacific cod (Wyllie-Echeverria and
103 Wooster, 1998; Ciannelli and Bailey, 2005; Hollowed et al., 2012; Kotwicki and Lauth,
104 2013; Spencer et al., 2016), It is also a barrier for the northward movement of demersal
105 sub-Arctic species, such as Pacific cod and walleye pollock (Mueter and Litzow, 2008;
106 Mueter et al., 2017).

107 In the NBS, ice-melt back usually occurs in late May or early June (Stabeno
108 and Bell, 2019; Thoman et al., 2020). The timing of sea-ice melt-back affects the
109 availability of ice algae to herbivores (Baier and Napp, 2003; Søreide et al., 2010, 2013;
110 Wold, 2011; Dasse et al., 2013; Brown and Arrigo 2013, Hunt et al., in press), as well
111 as the timing of ice-edge blooms (Alexander and Niebauer, 1981). Ice algae released on
112 melt-back may sink to the bottom, ungrazed, thereby fueling the benthic ecosystem, as
113 may also happen with ice-edge blooms (Grebmeier et al., 1988, 1989, 2015; Grebmeier
114 and Mcroy, 1989; Piepenburg, 2005). The melting of the sea-ice also results in a surface
115 layer of low salinity water. The interface of this relatively fresh water with the cold
116 bottom brine layer results in a strong pycnocline that can last through summer, and
117 which supports a sub-surface bloom (Stabeno et al., 2012a).

118 Observations of the unusual conditions in winter 2017-2018 and
119 spring/summer 2018 in the NBS were facilitated by both satellite imagery and

120 shipboard sampling. The US Marine Mammal Laboratory had a cruise to the NBS in
121 2018 for the study of ice-dependent seals (Fig. 2) (Boveng et al., this volume). Ongoing
122 annual spring and fall cruises for ecosystem studies in the NBS south of St. Lawrence Is.
123 have been conducted by the National Oceanic and Atmospheric Administration
124 (NOAA) since the 1990s. As part of the international collaborative research program,
125 the Arctic Challenge for Sustainability (ArCS) project, the Japanese vessel T/S
126 Oshoro-Maru had cruises for oceanographic and ecosystem research in the summers of
127 2017 and 2018 in the NBS (Fig. 3). Cruises of both countries investigated the physical
128 structure with CTDs, as well as nutrients, phytoplankton, primary production,
129 zooplankton, fish and seabirds. In addition, the NOAA Fisheries bottom trawl survey
130 was extended to the NBS in 2018 and 2019 (Fig. 4) because of the discovery in 2017 of
131 large biomasses of both walleye pollock and Pacific cod far to the north of where these
132 species were believed to spend the summer.

133 The winter of 2017-2108 differed from the climatology in several ways
134 (Stabeno and Belll, 2019). In 2017 sea-ice cover began to form in late November, and
135 melt back, driven by strong southerly winds, began in February, with the region mostly
136 ice-free by mid- to late-March (Stabeno and Bell, 2019). The sea-ice producion in the
137 Anadyr polynya was also the lowest during the winter of 2017-2018 (Oshima et al.,
138 2020). Not much is known about the ecological impacts of the late formation of sea-ice
139 cover in the fall of 2017, but the very early retreat of sea ice in winter and spring of
140 2018 resulted a reduction in the availability of ice algae, an absence of a strong ice edge
141 bloom, and a delay of a spring bloom until the water column became stratified by solar
142 warming (Duffy-Anderson et al., 2019; Kikuchi et al., this issue).

143 The early melt-back of sea ice in Wnter 2018 resulted in a number of impacts

144 on the marine ecosystem of the NBS that manifested themselves in summer 2018
145 (Duffy-Anderson et al., 2019; Huntington et al., 2020). These were not necessarily
146 spatially uniform in distribution. For instance, ocean color satellite records show that
147 there was significant change in the timing of the phytoplankton bloom in 2018 relative
148 to the climatology south of St. Lawrence Island, with two bloom peaks and higher
149 concentrations in 2018; there was only a small difference between the satellite records
150 in 2018 and the climatology in the Chirikov Basin north of St. Lawrence Is. (Fig. 5). In
151 contrast, ocean sampling from cruises to the NBS showed spring integrated chlorophyll
152 levels were < 10% of what had been found previously (Duffy-Anderson et al., 2017).

153 Cell counts of diatom resting stages in the sediment south of St Lawrence Is.
154 found a shift in species composition, with the phytoplankton *Thalassiosira* spp.
155 dominating in 2018, as contrasted with ice algae *Fragilariopsis* or *Fossula* spp. that
156 dominated in 2017 (Fukai et al., 2019). Diatom resting stages were 10-100 times higher
157 in 2018 compared to those in 2017. As might be expected under warmer conditions,
158 small copepods were more abundant in 2018 than in earlier years with more sea ice, and
159 large copepods were scarce (Duffy-Anderson et al., 2019). And, in the absence of a cold
160 pool, in 2018 approximately 50% of the estimated eastern Bering Sea Pacific cod
161 biomass was found in the NBS during the NOAA Fisheries bottom trawl surveys
162 (Siddon et al., 2018). Marine birds and mammals were also negatively impacted, with
163 die offs of birds and seals reported from the NBS (e.g. Kuletz et al., 2018, this issue;
164 Siddon et al., 2018; Huntington et al., 2020; Boveng et al., this issue; Romano et al., this
165 issue; Will et al., this issue b).

166 The responses of the NBS marine ecosystem to sea-ice reduction in 2018 have
167 not yet been sufficiently reported. This special issue gathered papers with topics on

168 recent changes in oceanographic environments and changes/responses of phytoplankton,
169 zooplankton, fish, crabs and seabirds in the NBS, particularly with respect to the
170 unusually light sea-ice cover found in 2018. We expect that most of papers here will
171 contribute to projections of how the marine ecosystem in the NBS may respond to
172 future warming and loss of sea-ice cover.

173

174

175 **3. Highlights of papers in this issue**

176

177 Throughout this issue, many papers provide data and insights about the
178 physical oceanography of the NBS. Of these, two papers focus on the physical
179 oceanography of the NBS. One, by Basyuk and Zuenko (this issue), concentrates on the
180 western Bering Sea and provides new data on the temperature and salinity structure of
181 the Gulf of Anadyr in 2017 and 2018. The other, by Ueno et al. (this issue) explores the
182 strength and mechanisms of water column stratification in the NBS in 2017 and 2018.
183 They show that stratification was generally weaker in summer 2018, and that the
184 relative importance of temperature and salinity varied by water mass.

185 Lower trophic levels were represented by four papers, two of which focused on
186 phytoplankton (Kikuchi et al., this issue; Fukai et al., this issue) and two on zooplankton
187 (Kimura et al., this issue; Maekakuchi et al., this issue). Kikuchi et al. (this issue)
188 examine how the timing of sea-ice retreat affected the timing of the spring bloom, while
189 Fukai et al. (this issue) provide a comparison of the diatom and dinoflagellate
190 communities of the NBS in 2017 and 2018, by water mass. Of the papers on
191 zooplankton, Kimura et al. (this issue) provide an examination of monthly changes in

192 the zooplankton community and population structure from June 2017 through
193 September 2017, and show that there were significant differences in the zooplankton
194 present depending on the month sampled. This information has important implications
195 for those wishing to compare zooplankton from one year to another. Using underwater
196 video imaging, Maekakuchi et al. (this issue) show how gelatinous zooplankton varied
197 by water mass, depth and year in 2017 and 2018. In 2018, numbers were lower, possibly
198 because of a reduced availability of prey.

199 Three papers focused on pelagic and demersal fishes and one on snow crab.
200 Nishio et al. (this issue) analyzed demersal fish community structure and environmental
201 factors in summers between 1990 and 2018. They show that the timing of sea-ice retreat
202 and bottom water temperature were important factors for the densities of Arctic and
203 boreal fish species, respectively. Eisner et al. (this issue) compiled data of distribution
204 of walleye pollock in the Bering Sea including the northwest region (e.g. Gulf of
205 Anadyr). They revealed that a northward movement of adult walleye pollock occurred
206 in the Bering Sea during the warm years of 2017-219, and that exchange of fish
207 occurred between the eastern and western sides of the NBS. Yasumiishi et al. (this
208 issue) investigated the influence of water temperature on the distribution and abundance
209 of small pelagic fishes in the eastern Bering Sea. The responses to warming differed
210 among the species. For example, the distribution and biomass of juvenile sockeye
211 salmon, which is the most commercially important species of the species studied,
212 nonlinearly covaried with temperature, but it was most responsive to warming. Fedewa
213 et al. (this issue) investigated the distribution of snow crab in relation to bottom
214 temperatures for the period 1988-2019 in the eastern Bering Sea, and for the recent
215 years in the northern Bering Sea. They suggest that changes in distribution and

216 population size of snow crab in the EBS and NBS have been driven by climate change.

217 Six papers in this issue presented recent changes in top marine predators; five
218 of them concentrated on seabirds and one on seals. Nishizawa et al. (this issue) reported
219 both densities of foraging seabirds and prey biomass in 2018 were lower than those in
220 2018. Will et al. (this issue, a) examined the correlation between seabird predators and
221 their prey; they found that the bird distributions were less tightly correlated with prey
222 distributions when prey were scarce. Will et al. (this issue, b) revealed that thick-billed
223 murre (*Uria lomvia*) were the species most affected by the die-off of seabirds that
224 occurred on the St. Lawrence Island in 2018, and that food shortage was not a sufficient
225 explanation for the die-off. They found evidence that suggests that additional cause of
226 this event may have been avian influenza. Romano et al. (this issue) also surveyed
227 thick-billed murre in the colonies in the EBS and eastern Chukchi sea in summer of
228 2018 and reported that reproductive failure observed in the nearly all colonies,
229 especially those of murre. Kuletz et al. (this issue) focused on the change in seabird
230 abundance and habitat comparing the recent three warm years (2017–2019) with before
231 (2007-2016). They found that total seabird density declined for the NBS as a whole, but
232 within that area, there was an increase in the Chirikov Basin. Although piscivorous
233 murre declined throughout the NBS, planktivorous auklets increased in the Chirikov
234 Basin, possibly due to desertion of their breeding colonies. The overall picture for
235 seabirds was not a good one.

236 There was one paper on marine mammals, by Boveng et al. (this issue), on
237 ice-dependent seals and harbor seals (*Phoca vitulina richardii*). Because of the
238 melt-back of sea ice in the NBS, the ice edge, such as it was, was far from the shelf
239 edge where ribbon seals (*Histiophoca fasciata*) normally would give birth to and feed

240 their pups. Female ribbon seals had poor body condition in 2018, and many were
241 apparently absent from the eastern NBS. Those pups that were present had poor body
242 condition, as was also true of spotted seal (*Phoca largha*) pups. Boveng et al. (this
243 issue) discuss the implications of these and other findings for the future of
244 ice-dependent seals in a warming NBS.

245 The final paper in the special issue by Siddon et al. (this issue) provides an
246 integrated view of the papers in the special issue and how they relate to the broader
247 literature on climate warming in the NBS. A theme that runs through many of the papers
248 is that major sectors of the NBS ecosystem had reduced productivity in the warm year
249 of 2018 with early sea-ice retreat. Large diatoms were less abundant as was also true of
250 large, lipid-rich crustacean zooplankton., as were apparently forage fish that depended
251 on zooplankton in the upper water column. Small epibenthic fishes were less affected.
252 The impact of the decline in upper water column productivity was seen to extend
253 through several levels of the food web, including gelatinous zooplankton and seabirds.
254 Species of planktivorous seabirds that nest on the islands of the NBS largely failed in their
255 reproductive efforts, and some species suffered major mortality. Likewise, there was a
256 significant die-off of migrant shearwaters, that annually come to the Bering Sea to feed
257 on euphausiids during the austral winter. Perhaps related to lesser impacts on the
258 benthic food webs, large numbers of walleye pollock, Pacific cod and snow crab had
259 moved north from the southeastern Bering Sea.

260 It is our hope that the papers in this special issue provide a useful overview of
261 the major elements of the ecosystem responses to the marine heatwave of 2017-2019
262 that impacted the NBS ecosystem. Our efforts will have been successful if the papers
263 are well used and catalyze the development of new ideas and research.

264

265

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267

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275

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277

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555 Figure Captions:

556 Fig. 1. The Northern Bering Sea region with major water currents and water masses.

557 Figure courtesy of Seth Danielson, University of Alaska, Fairbanks

558

559 Fig. 2. Shift in areas occupied by ice seal studies in 2014, 2016 and 2018. Due to
560 dramatically reduced ice extent, ice seal sampling and tagging in 2018 was conducted
561 far to the northeast of previous, similar studies

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563 Fig. 3. Map of CTD stations (2017- red circles and 2018- blue circles) for the T/S
564 Oshoro-maru cruises. Bounding boxes indicate regions north and south of St. Lawrence
565 Island used to calculate sea ice coverage and chl. *a* concentrations as shown in Fig. 5.

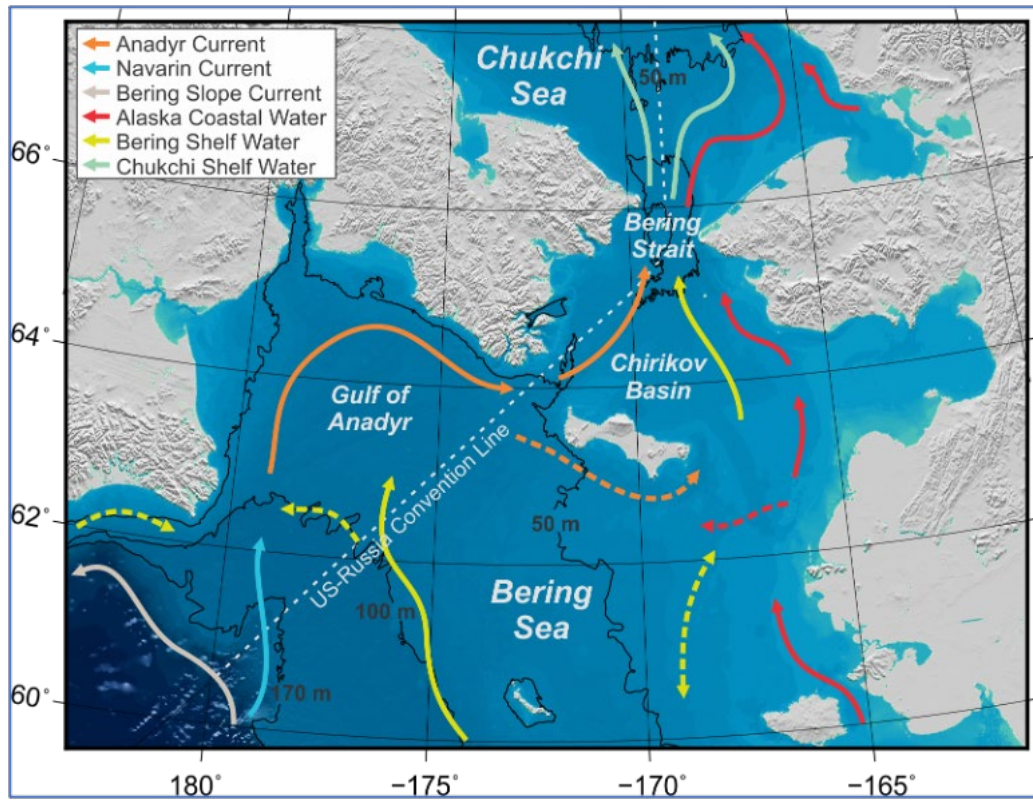
566

567 Fig. 4. Map of stations occupied by NOAA spring, summer and autumn NOAA
568 cruises showing bottom temperatures and station locations. Modified from Duffy
569 -Anderson et al., 2019, with permission.

570

571 Fig. 5. Areal mean ice cover (blue) and chl. *a* concentration (red) to the north (top) and
572 south (bottom) of St Lawrence Island. Solid and dashed lines indicate data in 2018 and
573 climatology for the period 2003-2016. Sea-ice coverage was calculated using daily
574 sea-ice concentration of the AMSR-2/GCOM-W1. 8-days composited data of the
575 MODIS/Aqua was used for chl. *a* concentration. Algorithm of chl. *a* estimation is the
576 GSM model. These datasets are the same as those used in Kikuchi et al. (this volume).
577 Areas for which averages were calculated are shown in Fig. 3.

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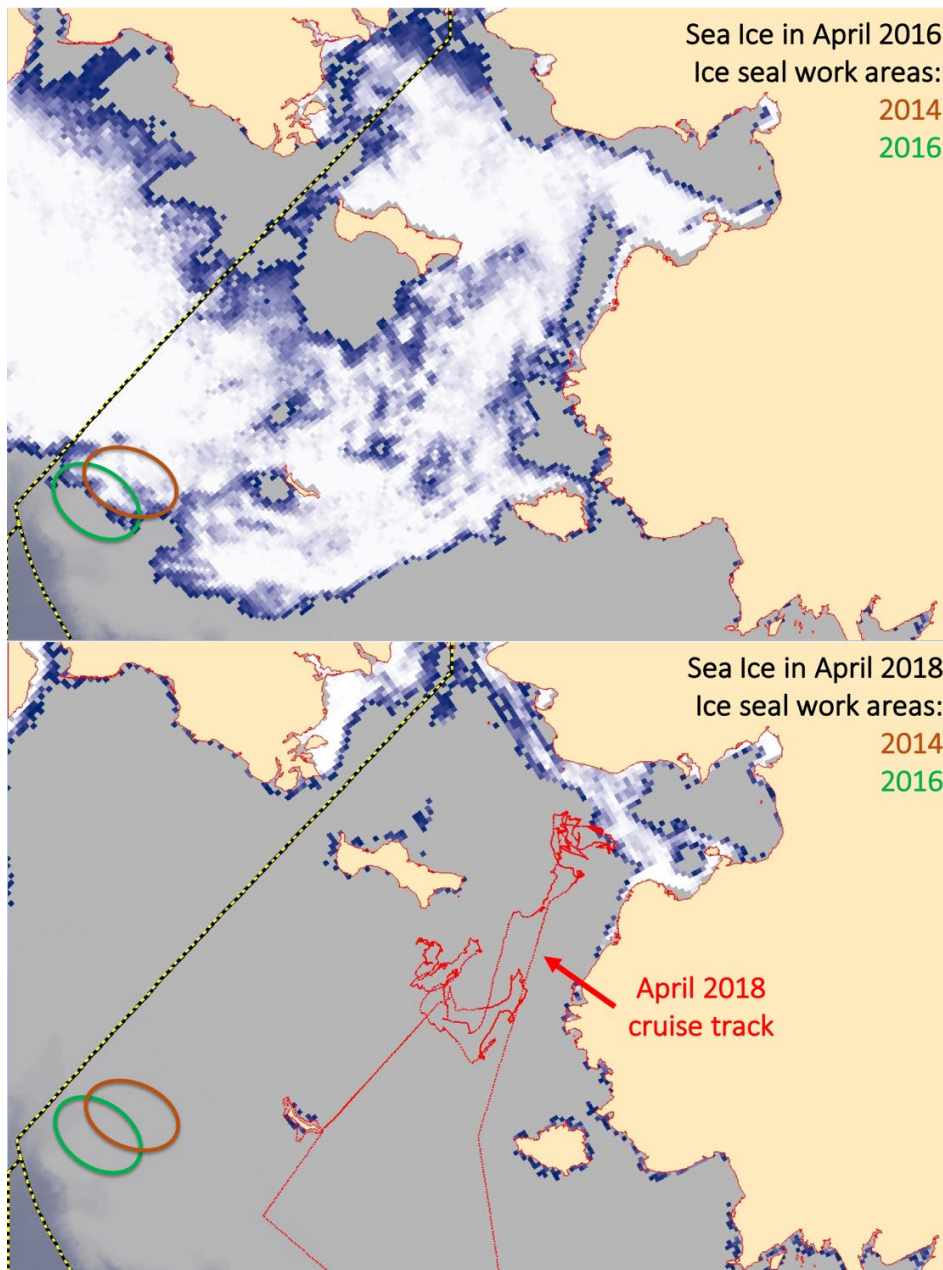
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592 Fig. 2

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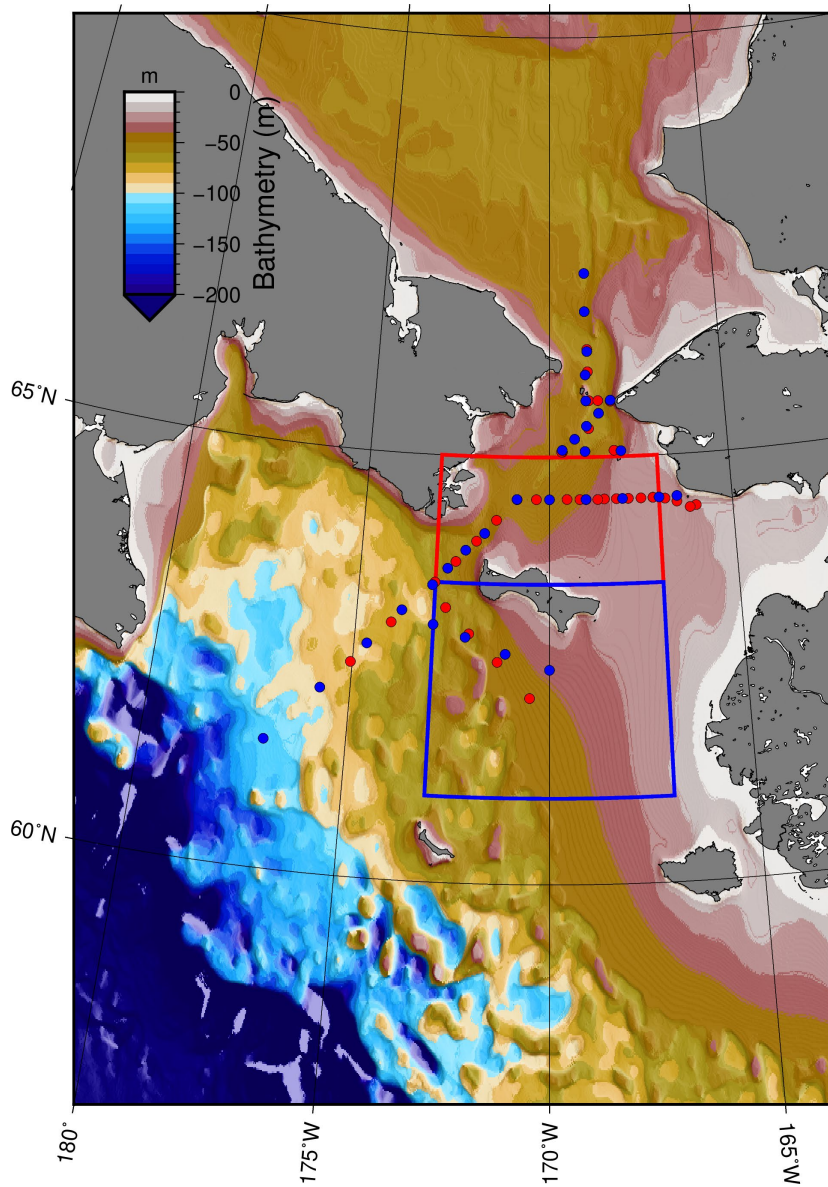
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599 Boveng, Marine Mammal Laboratory, NOAA Alaska Fisheries Science Center.

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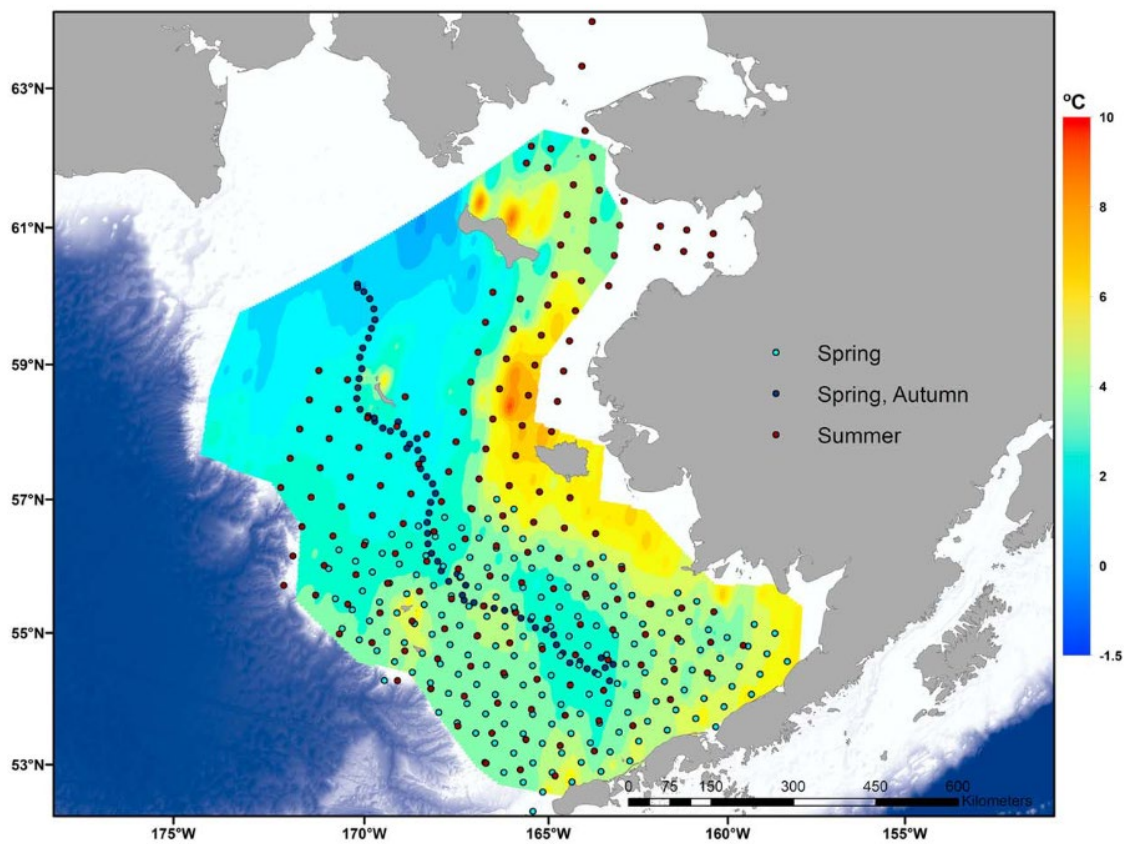
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605 Fig. 3. Map of CTD stations for the cruises of T/S Oshoro-maru. Red and Blue circles show stations
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608 water depth (m).

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610 Fig. 4



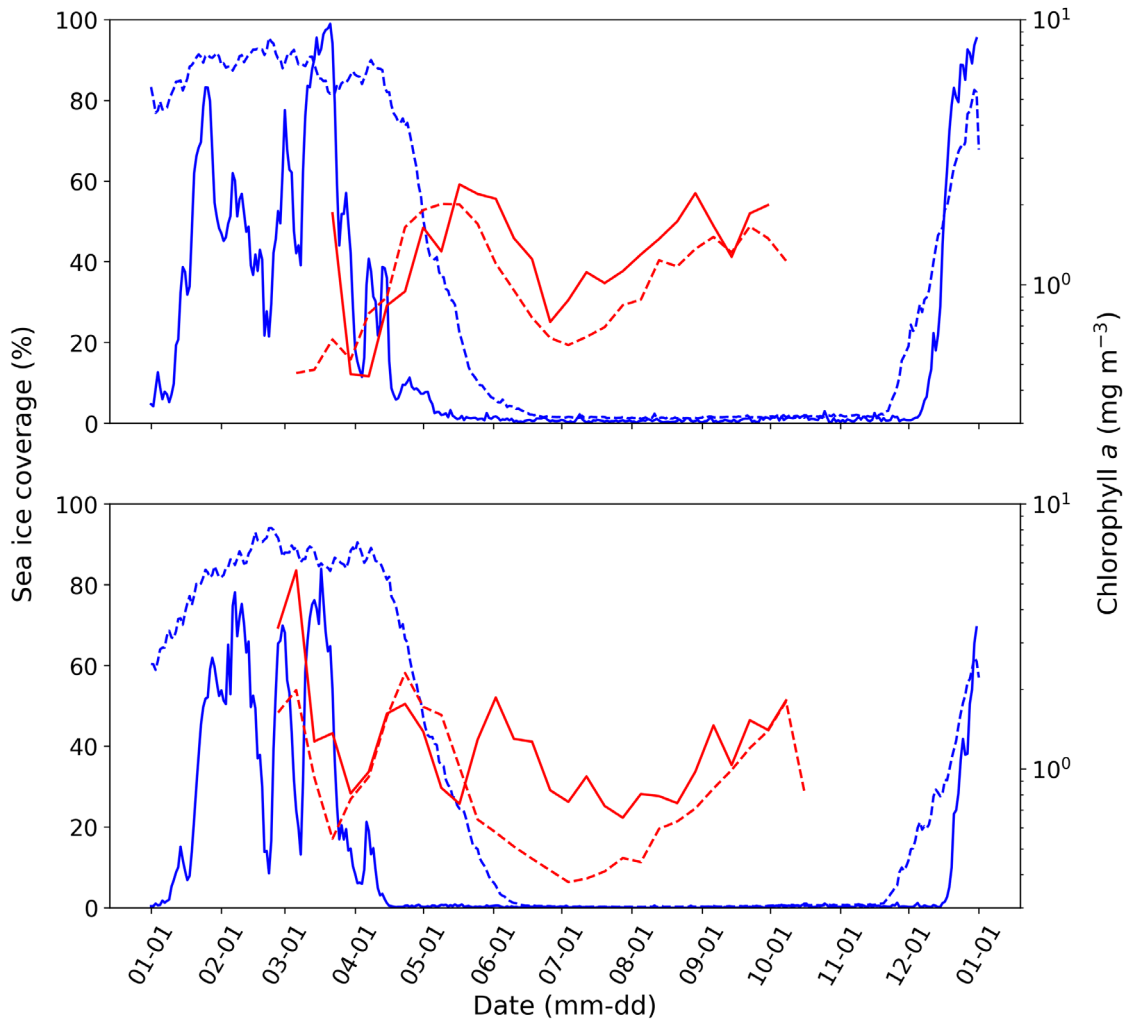
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