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

ABSTRACT

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

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

1. Introduction

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

2. Background

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

3. Highlights of papers in this issue

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

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

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

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

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

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

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

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

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

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

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References

- Alexander, V., Niebauer, H.J., 1981. Oceanography of the eastern Bering Sea ice-edge zone in spring. *Limnol. Oceanogr.* 26, 1111–1125.
<https://doi.org/10.4319/lo.1981.26.6.1111>.
- Arrigo, K.R., van Dijken, G.L., 2015. Continued increases in Arctic Ocean primary production. *Prog. Oceanogr.* 136, 60–70.
<https://doi.org/10.1016/j.pocean.2015.05.002>.
- Basyuk, E., Zuenko Y., 2020. Extreme oceanographic conditions in the northwestern Bering Sea in 2017-2018. *Deep-Sea Res. II* (this issue).
- Baier, C.T., Napp, J.M., 2003. Climate-induced variability in *Calanus marshallae* populations. *J. Plankt. Res.* 25, 771-782. <https://doi.org/10.1093/plankt/25.7.771>.
- Baker, M.R., Kivva, K.K., Pisareva, M.N., Watson, J.T., Selivanova, J., 2020. Shifts in the physical environment in the Pacific Arctic and implications for ecological timing and conditions. *Deep-Sea Res. II* 177, 104802.
<https://doi.org/10.1016/j.dsr2.2020.104802>.
- Box, J.E., Colgan, W.T., Christensen, T.R., Schmidt, N.M., Lund, M., Parmentier, F.J.W., Brown, R., et al., 2019. Key indicators of Arctic climate change: 1971-2017. *Environ. Res. Lett.* 14, 045010.
<https://doi.org/10.1088/1748-9326/aafc1b>.
- Boveng, P., Ziel, H., McClintock, B., Cameron, M., 2020. Body condition of phocid seals during a period of rapid environmental change in the Bering Sea and Aleutian Islands, Alaska. *Deep-Sea Res. II* (this issue).
- Brown, Z.W., Arrigo, K.R., 2013. Sea-ice impacts on spring bloom dynamics and net

primary production in the eastern Bering Sea. J. Geophys. Res. 118,

doi:10.1029/2012JC008034.

Brown, Z.W., Arrigo, K.R., 2012. Contrasting trends in sea ice and primary production in the Bering Sea and Arctic Ocean. ICES J. Mar. Sci. 69, 1180–1193.

<https://doi.org/10.1093/icesjms/fss113>.

Brown, Z.W., van Dijken, G.L., Arrigo, K.R., 2011. A reassessment of primary production and environmental change in the Bering Sea. J. Geophys. Res. 116,

doi:10.1029/2010JC006766.

Carleton, R.G., Hayden, B.P., 1993. Marine biogeographic provinces of the Bering, Chukchi and Beaufort Seas. Pp. 175–184 in *Large Marine Ecosystems: Stress, Mitigation and Sustainability*. K. Sherman, L.M. Alexander, and B.D. Gold, eds, AAAS Press, Washington, DC.

Ciannelli L., Bailey, K.M., 2005. Landscape dynamics and resulting species interactions: the cod-capelin system in the southeastern Bering Sea. Mar. Ecol. Prog. Ser. 291, 227-236. <https://doi.org/10.3354/meps291227>.

Comiso, J.C., 2006. Abrupt decline in the Arctic winter sea ice cover. Geophys. Res. Lett. 33, L18504. <https://doi.org/10.1029/2006GL027341>.

Comiso, J.C., 2006. Abrupt decline in the Arctic winter sea ice cover. Geophys. Res. Lett. 33, L18504. <https://doi.org/10.1029/2006GL027341>.

Danielson, S.L., Ahkinga, O., Ashjian, C., et al., 2020. Manifestation and consequences of warming and altered heat fluxes over the Bering and Chukchi Sea continental shelves. Deep-Sea Res. II 177, 104781.

<https://doi.org/10.1016/j.dsr2.2020.104781>.

Danielson, S.L., Eisner, L., Ladd, C., Mordy, C., Sousa, L., Weingartner, T.J., 2017. A comparison between late summer 2012 and 2013 water masses, macronutrients, and phytoplankton standing crops in the northern Bering and Chukchi Seas.

- 324 Deep-Sea Res. II 135, 7–26. <https://doi.org/10.1016/j.dsr2.2016.05.024>.
- 325 Danielson, S.L., Weingartner, T.J., Hedstrom, K.S., Aagaard, K., Woodgate, R.,
326 Curchitser, E., Stabeno, P.J., 2014. Coupled wind-forced controls of the
327 Bering–Chukchi shelf circulation and the Bering Strait throughflow: Ekman
328 transport, continental shelf waves, and variations of the Pacific–Arctic sea surface
329 height gradient. Prog. Oceanogr. 125, 40–61.
330 <https://doi.org/10.1016/j.pocean.2014.04.006>.
- 331 Daase, M., Falk-Petersen, S., Varpe, Ø., et al., 2013. Timing of reproductive events in the
332 marine copepod *Calanus glacialis*: a pan-Arctic perspective. Can. J. Fish. Aquat.
333 Sci. 70, 871–884. <https://doi.org/10.1139/cjfas-2012-0401>.
- 334 Duffy-Anderson, J.T., Stabeno, P., Andrews, A.G., Cieciel, K., Deary, A., Farley, E.,
335 Fugate, C., et al., 2019. Responses of the Northern Bering Sea and southeastern
336 Bering Sea pelagic ecosystems following record-breaking low winter sea ice.
337 Geophys. Res. Lett. 46, 9833–9842. <https://doi.org/10.1029/2019GL083396>.
- 338 Duffy-Anderson, J.T., Stabeno, P.J., Siddon, E.C., et al., 2017. Return of warm conditions
339 in the southeastern Bering Sea: Phytoplankton – fish. PLoS ONE 12 (6), e0178955.
340 <https://doi.org/10.1371/journal.pone.0178955>.
- 341 Eisner, L., Zuenko, Y., Basyuk, E., Britt, L., Duffy-Anderson, J., Kotwicki, S., Ladd, C.,
342 2020. Environmental impacts on Walleye pollock (*Gadus chalcogrammus*)
343 distribution across the Bering Sea shelf. Deep-Sea Res. II (this issue).
- 344 Fedewa, E.J., Jackson, T.M., Richar, J.I., Gardner, J.L., Litzow, M.A., 2020. Recent
345 shifts in northern Bering Sea snow crab (*Chionoecetes opilio*) size structure and
346 the potential role of climate-mediated range contraction. Deep-Sea Res. II (this
347 issue).

- Fujiwara, A., Hirawake, T., Suzuki, K., Eisner, L., Imai, I., Nishino, S., Kikuchi, T., Saitoh, S.I., 2016. Influence of timing of sea ice retreat on phytoplankton size during marginal ice zone bloom period on the Chukchi and Bering shelves. *Biogeosci.* 13, 115–131. <https://doi.org/10.5194/bg-13-115-2016>.
- Fujiwara, A., Hirawake, T., Suzuki, K., Saitoh, S.I., 2011. Remote sensing of size structure of phytoplankton communities using optical properties of the Chukchi and Bering Sea shelf region. *Biogeosci.* 8, 3567–3580. <https://doi.org/10.5194/bg-8-3567-2011>.
- Fukai, Y., Abe, Y., Matsuno, K., Yamaguchi, A., 2020. Spatial changes in the diatom community of the northern Bering Sea in 2017 and 2018. *Deep-Sea Res. II* (this issue).
- Fukai, Y., Matsuno, K., Fujiwara, A., Yamaguchi, A., 2019. The community composition of diatom resting stages in sediments of the northern Bering Sea in 2017 and 2018: the relationship to the interannual changes in the extent of the sea ice. *Polar Biol.* 42, 1915–1922. <https://doi.org/10.1007/s00300-019-02552-x>.
- Grebmeier, J.M., Mcroy, C.P., 1989. Pelagic-benthic coupling on the shelf of the northern Bering and Chukchi Seas . III. Benthic food supply and carbon cycling. *Mar. Ecol. Prog. Ser.* 53, 79–91.
- Grebmeier, J.M., Bluhm, B.A., Cooper, L.W., Danielson, S.L., Arrigo, K.R., Blanchard, A.L., Clarke, J.T., et al., 2015. Ecosystem characteristics and processes facilitating persistent macrobenthic biomass hotspots and associated benthivory in the Pacific Arctic. *Prog. Oceanogr.* 136, 92–114. <https://doi.org/10.1016/j.pocean.2015.05.006>.
- Grebmeier, J.M., Cooper, L.W., Feder, H.M., Sirenko, B.I., 2006b. Ecosystem

dynamics of the Pacific-influenced Northern Bering and Chukchi Seas in the

Amerasian Arctic. *Prog. Oceanogr.* 71, 331–336.

<https://doi.org/10.1016/j.pocean.2006.10.001>.

Grebmeier, J.M., Feder, H.M., Mcroy, C.P., 1989. Pelagic-benthic coupling on the shelf

of the northern Bering and Chukchi Seas . II. Benthic community structure. *Mar.*

Ecol. Ser. 51, 253–268.

Grebmeier, J.M., Mcroy, C.P., Feder, H.M., 1988. Pelagic-benthic coupling on the shelf

of the northern Bering and Chukchi Seas . I. Food supply source and benthic

biomass. *Mar. Ecol. Ser.* 48, 57–67.

Grebmeier, J.M., Overland, J.E., Moore, S.E., Farley, E. V, Carmack, E.C., Cooper,

L.W., Frey, K.E., et al., 2006a. A major ecosystem shift in the northern Bering Sea.

Science 311, 1461–1464. <https://doi.org/10.1126/science.1121365>.

Hirawake, T., Shinmyo, K., Fujiwara, A., Saitoh, S.-I., 2012. Satellite remote sensing of

primary productivity in the Bering and Chukchi Seas using an absorption-based

approach. *ICES J. Mar. Sci.* 69, 1194–1204.

<https://doi.org/10.1093/icesjms/fss111>.

Hollowed, A.B., Barbeaux, S.J., Cokelet, E.D., Farley, E., Kotwicki, S., H., Ressler, P.H.,

Spital, C., et al., 2012. Effects of climate variations on pelagic ocean habitats and

their role in structuring forage fish distributions in the Bering Sea. *Deep-Sea Res II*

65–70, 230–250. <https://doi.org/10.1016/j.dsr2.2012.02.008>.

Hunt, Jr., G.L., Yasumiishi, E.M., Eisner, L.B., Stabeno, P.J., Decker, M.B., In Press.

Climate warming and the loss of sea ice: the impact of sea-ice variability on the

southeastern Bering Sea ecosystem. *ICES J. Mar Sci.*

<https://doi.org/10.1093/icesjms/fsaa206>.

- 396 Hunt, Jr., G.L., Harrison, N.M., 1990. Foraging habitat and prey taken by Least Auklets
397 at King Island, Alaska. *Mar. Ecol. Prog. Ser.* 65, 141-150.
- 398 Huntington, H.P., Danielson, S.L., Wiese, F.K., et al., 2020. Evidence suggests potential
399 transformation of the Pacific Arctic ecosystem is underway. *Nature Clim.*
400 Change 10, 342-348. <https://doi.org/10.1038/s41558-020-0695-2>.
- 401 Kikuchi, G., Abe, H., T. Hirawake, T., Sampei, M., 2020. Distinctive spring
402 phytoplankton bloom in the Bering Strait in 2018: A year of historically
403 minimum sea ice extent. *Deep-Sea Res. II* (this issue).
- 404 Kimura, F., Abe, Y., Matsuno, K., Hopcroft, R.R., Yamaguchi, A., 2020. Seasonal
405 changes in zooplankton community and population structure in the northern
406 Bering Sea from June to September 2017. *Deep-Sea Res. II* (this issue).
- 407 Kotwicki, S., Lauth, R.R., 2013. Detecting temporal trends and environmentally-driven
408 changes in the spatial distribution of bottom fishes and crabs on the eastern
409 Bering Sea shelf. *Deep-Sea Res. II* 94, 231–243.
410 <https://doi.org/10.1016/j.dsr2.2013.03.017>.
- 411 Kuletz, K., Cushing, D., Labunski, E., 2020. Distributional shifts among seabird
412 communities of the Northern Bering and Chukchi seas in response to ocean
413 warming during 2017-2019. *Deep-Sea Res. II* (this issue).
- 414 Kuletz, K., Labunski, L., Kaler, R., Parish, J., Jones, T., Burgess, H., Sheffield, G., et al.,
415 2018. Seabird mortality events in 2018 are highest in Beringia Region, in: Siddon,
416 E., and Zador, S. Eds. *Ecosystem Status Report, Eastern Bering Sea*. North Pacific
417 Fishery Management Council, 605 W. 4th Avenue, Suite 306, Anchorage, AK
418 99301.
- 419 Landeira, J.M., Matsuno, K., Yamaguchi, A., Hirawake, T., Kikuchi, T., 2017.

- Abundance, development stage, and size of decapod larvae through the Bering and Chukchi Seas during summer. *Polar Biol.* 40, 1805–1819.
<https://doi.org/10.1007/s00300-017-2103-6>.
- Maekakuchi, M., Matsuno, K., Yamamoto, J., Abe, Y., Yamaguchi, A., 2020. Abundance, horizontal and vertical distribution of epipelagic ctenophores and scyphomedusae in the northern Bering Sea in summer 2017 and 2018: quantification by underwater video imaging analysis. *Deep-Sea Res. II* (this issue).
- Matsuno, K., Yamaguchi, A., Hirawake, T., Imai, I., 2011. Year-to-year changes of the mesozooplankton community in the Chukchi Sea during summers of 1991, 1992 and 2007, 2008. *Polar Biol.* 34, 1349–1360,
<https://doi.org/10.1007/s00300-011-0988-z>.
- Mueter, F.J., Litzow, M., 2008. Sea ice retreat alters the biogeography of the Bering Sea continental shelf. *Ecol. Appl.* 18, 309–20. <https://doi.org/10.1890/07-0564.1>
- Mueter, F.J., Weems, J., Farley, E. V., Sigler, M.F., 2017. Arctic Ecosystem Integrated Survey (Arctic Eis): Marine ecosystem dynamics in the rapidly changing Pacific Arctic Gateway. *Deep-Sea Res. II* 135, 1–6.
<https://doi.org/10.1016/j.dsr2.2016.11.005>.
- Nishio, S., Sasaki, H., Waga, H., Yamamura, O., 2020. Effects of the timing of sea ice retreat on demersal fish assemblages in the northern Bering and Chukchi Seas. *Deep-Sea Res. II* (this issue).
- Nishizawa, B., Yamada, N., Hayashi, H., Wright, C., Kuletz, K.J., Ueno, H., Mukai, T., et al., 2020. Timing of spring sea-ice retreat and summer seabird-prey associations in the northern Bering Sea. *Deep-Sea Res. II* (this issue).
- Ohshima, K.I., Nihashi, S., Iwamoto, K., 2016. Global view of sea-ice production in

polynyas and its linkage to dense/bottom water formation. *Geosci. Lett.* 3, 13.

<https://doi.org/10.1186/s40562-016-0045-4>.

Ohshima, K.I., Tamaru, N., Kashiwase, H., Nihashi, S., Nakata, K., Iwamoto, K., 2020.

Estimation of sea ice production in the Bering Sea from AMSR-E and AMSR2

data, with special emphasis on the Anadyr polynya. *J. Geophys. Res. Ocean.* 125,

e2019JC016023. <https://doi.org/10.1029/2019JC016023>.

Parkinson, C.L., Cavalieri, D.J., 2008. Arctic sea ice variability and trends, 1979-2006.

J. Geophys. Res. 113, C07003. <https://doi.org/10.1029/2007JC004558>.

Pease, C.H. 1980. Eastern Bering sea ice processes. *Monthly Weather Review* 108,

2015–2023.

[http://dx.doi.org/10.1175/1520-0493\(1980\)108<2015:EBSIP>2.0.CO;2](http://dx.doi.org/10.1175/1520-0493(1980)108<2015:EBSIP>2.0.CO;2).

Piepenburg, D., 2005. Recent research on Arctic benthos: common notions need to be

revised. *Polar Biol.* 28, 733–755. <https://doi.org/10.1007/s00300-005-0013-5>.

Romano, M., Renner, H., Kuletz, K., Parrish, J., Jones, T., Burgess, H., Cushing, D.,

Causey, D., 2020. Die-offs, reproductive failure, and changing at-sea abundance of

murres in the Bering and Chukchi Seas in 2018. *Deep-Sea Res. II* (this issue).

Siddon, E. Zador, S., and Hunt, Jr., G.L., 2020. **Climate perturbations resulted in**

ecological responses to minimal sea ice in the northern Bering Sea. *Deep-Sea Res.*

II (this issue).

Siddon, E., Zador, S., Aydin, K., 2018. Ecosystem Assessment, in Siddon, E., and

Zador, S. Eds. Ecosystem Status Report, Eastern Bering Sea. North Pacific Fishery

Management Council, 605 W. 4th Avenue, Suite 306, Anchorage, AK 99301, pp.

3-9.

Sigler, M.F., Renner, M., Danielson, S.L., Eisner, L.B., Lauth, R.R., Kuletz, K.J.,

- Logerwell, E., Hunt, Jr., G.L., 2011. Fluxes, fins, and feathers: Relationships among the Bering, Chukchi, and Beaufort Seas in a time of climate change. *Oceanogra.* 24(3), 112-127. <https://doi.org/10.5670/oceanog.2011.77>.
- Søreide, J.E., Carroll, M.L., Hop, H., et al., 2013. Sympagic-pelagic-benthic coupling in Arctic and Atlantic waters around Svalbard revealed by stable isotopic and fatty acid tracers. *Mar. Biol. Res.* 9 (9), 831-850. <https://doi.org/10.1080/17451000.2013.775457>.
- Søreide, J.E., Leu, E., Berge, J., Graeve, M., Falk-Petersen, S., 2010. Timing in blooms, algal food quality and *Calanus glacialis* reproduction and growth in a changing Arctic. *Glob. Change Biol.* 16, 3154–3163. <https://doi.org/10.1111/j.1365-2486.2010.02175.x>.
- Spencer PD, Holsman KK, Zador S, et al. (2016) Modelling spatially dependent predation mortality of eastern Bering Sea walleye pollock, and its implications for stock dynamics under future climate scenarios. *ICES J. Mar. Sci.* 73, 1330-1342. <https://doi.org/10.1093/icesjms/fsw040>.
- Springer, A.M., McRoy, C.P., 1993. The paradox of pelagic food webs in the northern Bering Sea—III. Patterns of primary production. *Cont. Shelf Res.* 13, 575–599. [https://doi.org/10.1016/0278-4343\(93\)90095-f](https://doi.org/10.1016/0278-4343(93)90095-f).
- Stabeno, P.J., Bell, S.W., Bond, N.A., Kimmel, D.G., Mordy, C.W., Sullivan, M.E., 2019. Distributed Biological Observatory Region 1: Physics, chemistry and plankton in the northern Bering Sea. *Deep-Sea Res. II* 162, 8–21. <https://doi.org/10.1016/j.dsr2.2018.11.006>.
- Stabeno, P.J., Bell, S.W., 2019. Extreme conditions in the Bering Sea (2017–2018): Record-breaking low sea-ice extent. *Geophys. Res. Lett.* 46, 8952–8959.

<https://doi.org/10.1029/2019GL083816>.

Stabeno, P.J., Farley Jr., E.V., Kachel, N.B., et al., 2012a. A comparison of the physics of the northern and southern shelves of the eastern Bering Sea and some implications for the ecosystem. *Deep-Sea Res. II* 65–70, 14–30.

<https://doi.org/10.1016/j.dsr2.2012.02.019>.

Stabeno, P.J., Kachel, N.B., Moore, S.E., Napp, J.M., Sigler, M., Yamaguchi, A., Zerbini, A.N., 2012b. Comparison of warm and cold years on the southeastern Bering Sea shelf and some implications for the ecosystem. *Deep-Sea Res. II* 65–70, 31–45. <https://doi.org/10.1016/j.dsr2.2012.02.020>.

Stabeno, P.J., Reed, R.K., Schumacher, J.D., 1995. The Alaska Coastal Current: Continuity of transport and forcing. *J. Geophys. Res.* 100, 2477–2485.

<https://doi.org/10.1029/94JC02842>.

Thoman, Jr., R.L., Bhattt, U.S., Bieniek, P.A., Schneider, B.T., Brubaker, M.L., Danielson, S. L., et al., 2020. The record low Bering Sea ice extent in 2018: context, impacts, and assessment of the role of anthropogenic climate change. *Bull. Amer. Meteorol. Soc.* 101, S53-S58. <https://doi.org/10.1175/BAMS-D-19-0175.1>.

Ueno, H., Komatsu, M., Ji, Z., et al., 2020. Stratification in the northern Bering Sea in early summer of 2017 and 2018. *Deep-Sea Res. II* (this issue).

Waga, H., Hirawake, T., Fujiwara, A., Grebmeier, J.M., Saitoh, S.I., 2019. Impact of spatiotemporal variability in phytoplankton size structure on benthic macrofaunal distribution in the Pacific Arctic. *Deep-Sea Res. II* 162, 114–126.

<https://doi.org/10.1016/j.dsr2.2018.10.008>.

Weingartner, T.J., S.L. Danielson, and T.C. Royer. 2005. Freshwater variability and predictability in the Alaska Coastal Current. *Deep-Sea Res. II* 52, 169–191.

<https://doi.org/10.1016/j.dsr2.2004.09.030>.

Will, A., Takahashi, A., Thiebot, J-B., Martinez, A., Kitaiskaia, E., Britt, L., Nichol, D., et al., 2020a. The breeding seabird community reveals that recent sea ice loss in the Pacific Arctic does not benefit piscivores and is detrimental to planktivores.

Deep-Sea Res II (this issue).

Will, A., Thiebot, J-B., Hon, Ip., Shoogukwruk, P., Annogiyuk, M., Takahashi, A., Shearn-Bochsler, V., et al., 2020b. Investigation of the 2018 thick-billed murre (*Uria lomvia*) die-off on St. Lawrence Island rules out food shortage as the cause..

Deep-Sea Res. II (this issue).

Wold, A., Darnis, G., Søreide, J.E., et al., 2011. Life strategy and diet of *Calanus glacialis* during the winter-spring transition in Amundsen Gulf, south-eastern Beaufort Sea. Polar Biol 34, 1929-1946.

<https://doi.org/10.1007/s00300-011-1062-6>.

Woodgate, R.A., Aagaard, K., Weingartner, T.J., 2006. Interannual changes in the Bering Strait fluxes of volume, heat and freshwater between 1991 and 2004. Geophys. Res. Lett. 33, L15609. <https://doi.org/10.1029/2006GL026931>.

Woodgate, R. a., Weingartner, T.J., Lindsay, R., 2012. Observed increases in Bering Strait oceanic fluxes from the Pacific to the Arctic from 2001 to 2011 and their impacts on the Arctic Ocean water column. Geophys. Res. Lett. 39, L24603.

<https://doi.org/10.1029/2012GL054092>.

Wyllie-Echeverria, T., Wooster, W.S., 1998. Year-to-year variations in Bering Sea ice cover and some consequences for fish distributions. Fish. Oceanogr. 7, 159–170. <https://doi.org/10.1046/j.1365-2419.1998.00058.x>.

Yasumiishi, E.M., Cieciel, K., Andrews, A.G., Murphy, J., Dimond, J.A., 2020.

Climate-related changes in the biomass and distribution of small pelagic fishes in
the eastern Bering Sea during late summer, 2002-2018. Deep-Sea Res. II (this
issue).

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Figure Captions:

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

Figure courtesy of Seth Danielson, University of Alaska, Fairbanks

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

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

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

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

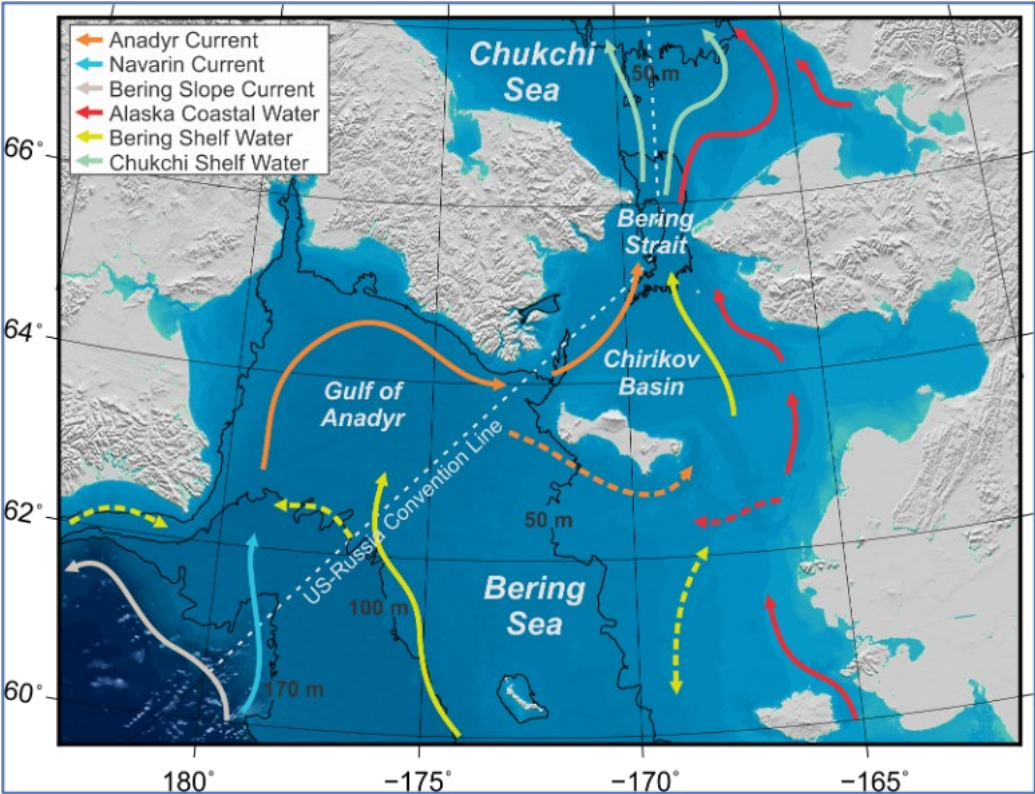


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Fig. 2

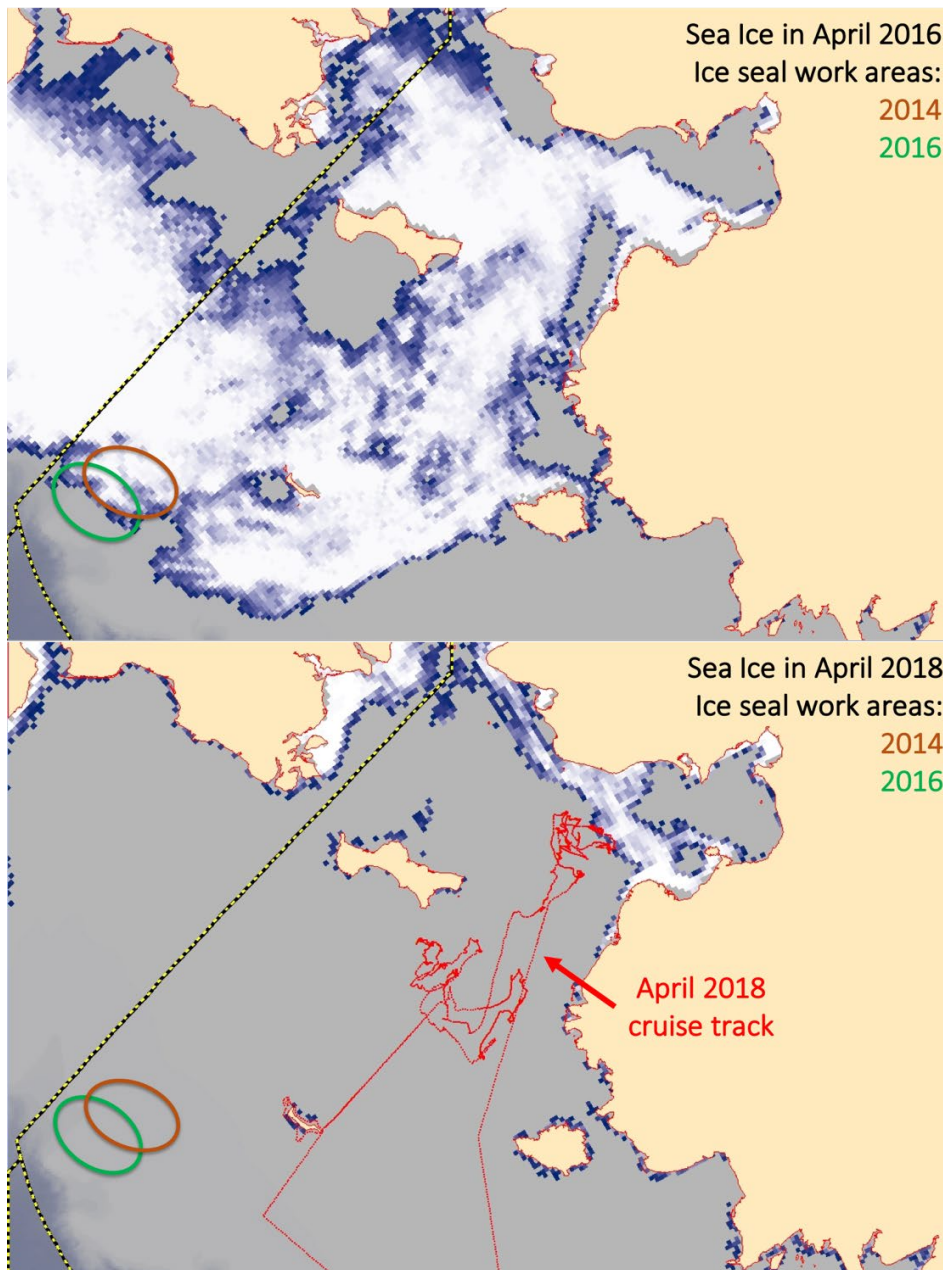


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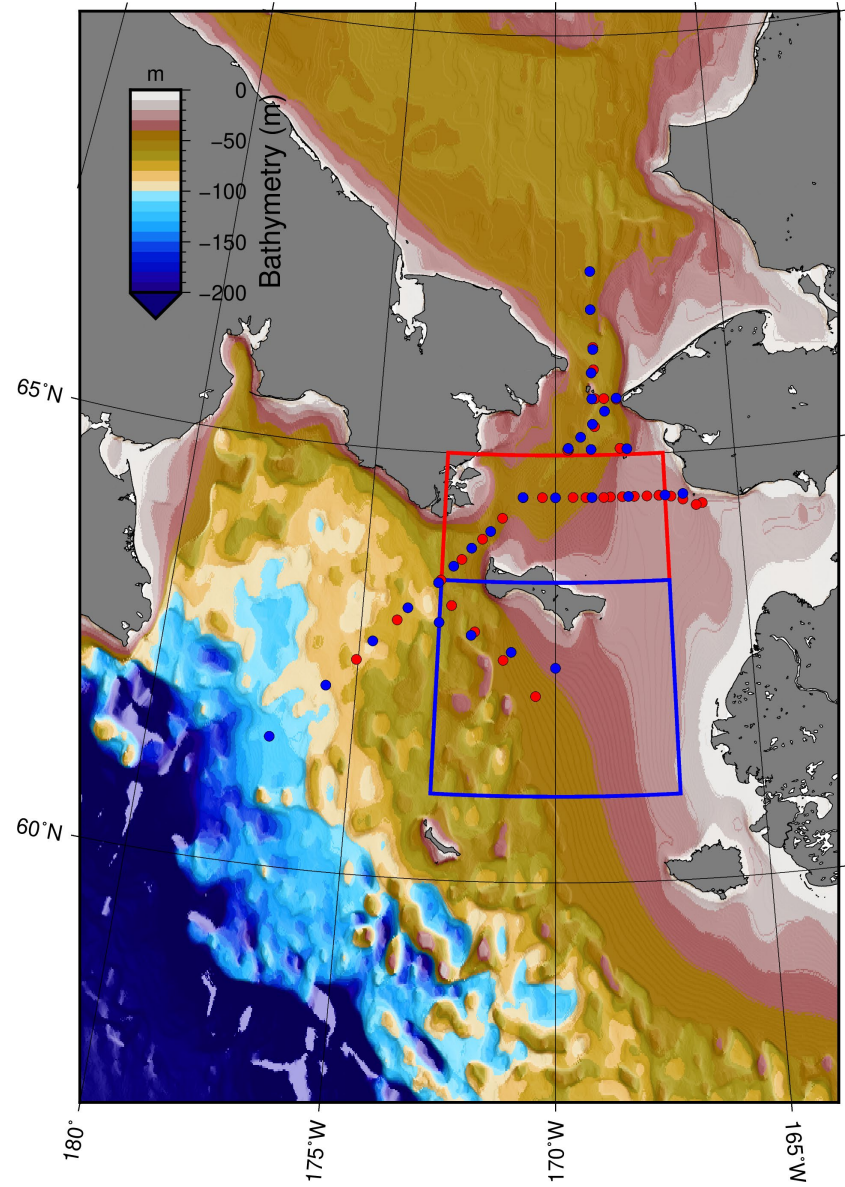


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Fig. 4

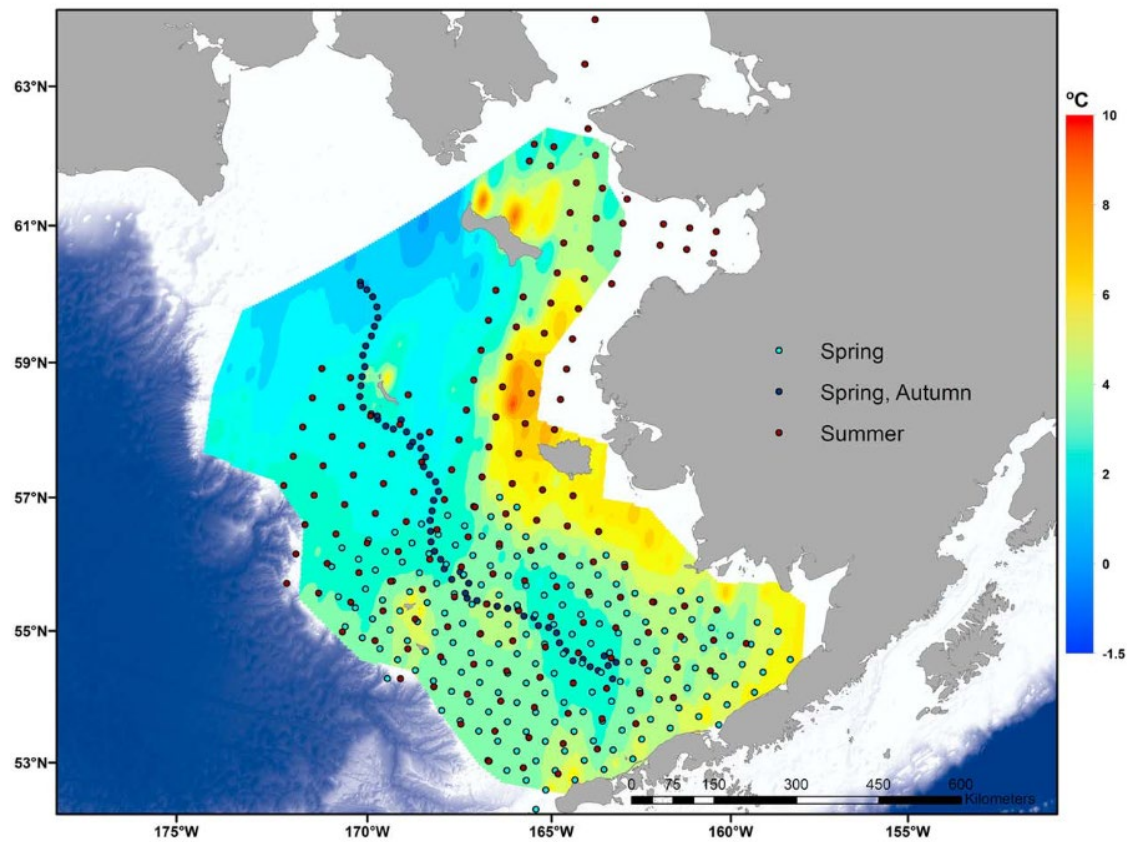


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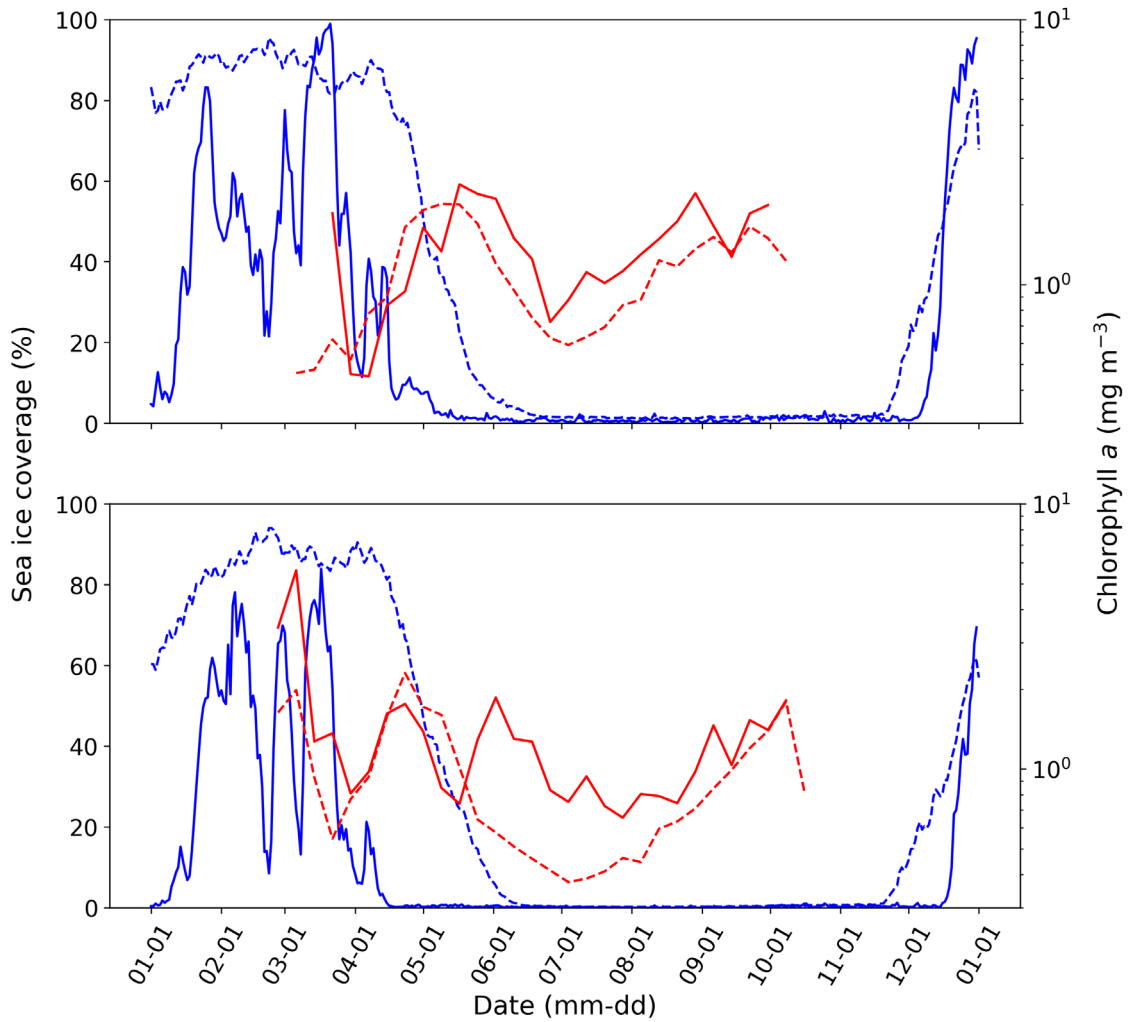


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