



First record of the larvae of tanner crab *Chionoecetes bairdi* in the Chukchi Sea: A future northward expansion in the Arctic?



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ABSTRACT

In the Bering Sea, warming and reduction of summer sea-ice cover are driving species ranges towards the Arctic. Tanner crab, *Chionoecetes bairdi*, is a commercially important species in the SE Bering Sea with a northerly range margin in 62°N. In this paper, using plankton samples collected in the Pacific sub-Arctic/Arctic sector during summer, we report for the first time the presence of larval stages (zoea II) of *C. bairdi* far from its northern limit of the distribution, in the south of St. Lawrence Island during 1991, and even crossing the Bering Strait into the Chukchi Sea during 1992. We suggest that the long planktonic phase (3–5 months), in combination with the oceanographic circulation, may facilitate eventual long-distance transport.

1. Introduction

Global warming is driving population-level alterations, including changes in phenology and northward shift in species distribution, that modifies the ecosystem functioning (Pinsky et al., 2013). The impact is already visible in the poles, where it is particularly striking, because of the sensitivity of ecosystems to sea-ice retreat (Doney et al., 2012). In the Pacific sub-Arctic/Arctic sector such responses in the pelagic ecosystem include the increase in jellyfish biomass (Brodeur et al., 1999), and northward shift in grey whale feeding grounds in Bering Sea (Moore et al., 2003), as well as the increase in the abundance of Pacific copepods in the Chukchi Sea (Nelson et al., 2014) and its reproductive success (Matsuno et al., 2015). In the benthic ecosystems these changes are also noticeable. For instance, the increase of clams in the Chukchi Sea (Sirenko and Gagaev, 2007), the abundance declines of Arctic amphipods in the Chirikov Basin (Moore et al., 2003), and the northward contraction of cod and snow crab distribution (Orensanz et al., 1998; Bluhm et al., 2009). Similar changes have been reported in Antarctica, where for example, large populations of king crabs have invaded deep-water, continental-slope environments (Aronson et al., 2007), modifying the abundance and distribution of native benthic invertebrate (Smith et al., 2017).

If water temperature is one of the main factors limiting the distribution of Pacific species to the north, one might expect range expansion of many species as warming continues. One candidate for this expansion is the tanner crab, *Chionoecetes bairdi*, that distributes along

the outer continental shelf of the Bering Sea, at depths > 100 m, and far north as 62°N (Fig. 1) (Slizkin, 1990). In the southeastern Bering Sea, tanner crabs sustain a historical lucrative fishery. Overfishing has forced to close the stock several times since 1985 and the landings have never again reached those levels. In season 2015/2016 the catches accounted a total of 8909 t; however, the Alaska Department of Fish and Game determined that mature female tanner crab biomass did not meet their criteria for opening a fishery and the stock was closed again in 2016/2017 (NPFMC, 2017). Therefore, changes in the spatial distribution of the stocks as a response to the warming in the area, could be an added problem for the fisheries sustainability.

Here we report for the first time the presence of larval stages of *C. bairdi* in Chukchi Sea, that proves the dispersal capacity of this species to the north, far from the adult populations in the Bering Sea. Our ability to predict future northern expansions should be of paramount interest for the fishery resource management.

2. Materials and methods

Sampling cruises were conducted onboard T.S. *Oshoro-Maru* in the Pacific sub-Arctic/Arctic sector from the southeastern Bering Sea to Chukchi Sea during the summers of 1991 (25 June–31 July, $n = 60$) and 1992 (28 June–31 July, $n = 64$). Sea ice extent data were obtained from the National Snow and Ice Data Center (Fetterer et al., 2017). Zooplankton samples were collected by the vertical tow of a North Pacific Standard net (NORPAC net, 45 cm mouth diameter, 0.335 mm

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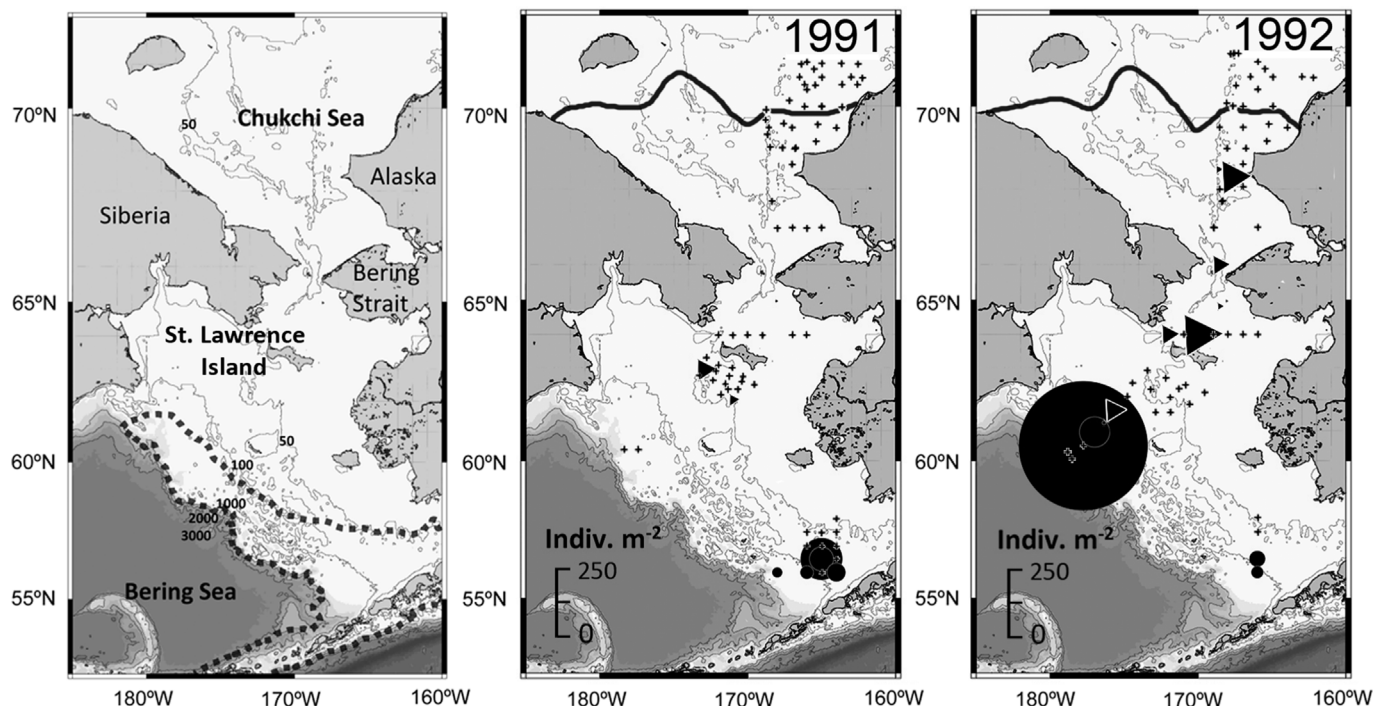


Fig. 1. Location of the distribution limit of crab adults of *Chionoectes bairdi* in the Bering Sea (dotted line). Horizontal distribution of the abundance (indiv. m⁻²) of *C. bairdi* larvae during 1991 and 1992. Symbols indicate the proportional abundance value at each station. Circle: < 62°N, inside north distribution limit; triangle: > 62°N, outside north distribution limit; crosses: no catch. Scale indicate the diameter of circles and side of triangles. Solid line shows sea ice extent.

mesh; Motoda, 1957) from 150 m depth or near the bottom (where the depth was shallower than 150 m) to the surface. The net was equipped with a flowmeter in the mouth, estimating the volume of water filtered. Samples were immediately preserved with 5% buffered formalin. Once in the laboratory, decapod larvae were sorted and quantified. Larvae of *Chionoectes* spp. were grouped using the guide given by Shanks (2001), and by Kornienko and Korn (2009). After that, the larval stage and species-level identification of *C. bairdi* was determined using taxonomic descriptions of its larval morphology (Haynes, 1973, 1981; Jewett and Haight, 1977). Larval abundance was expressed per square meter (indiv. m⁻²).

3. Results and discussion

3.1. Diagnostic morphological features

The larvae reported here from plankton samples collected around St. Lawrence Island and Chukchi Sea, far from their natal population (see following subsection), were identified as *C. bairdi*. These larvae were in stage II zoeae, and their morphology were characterized by the presence of eyes stalked, supraorbital spines, six plumose natatory setae on the exopod of first and second maxilliped pairs, abdomen six-segmented with pleopod buds on 2–5 abdominal somites, and four pairs of inner setae on the telson (Shanks, 2001) (Fig. 2). Even though larval morphology of *C. bairdi* is very similar to those oregoniid larvae that co-exist in the south-east Bering Sea, they are readily separable from each other. Thus, the presence of distinct protuberances posterior to the dorsal spine in *C. bairdi* larvae, is useful to distinguish them from larvae belonging to the genera *Hyas* and *Oregonia* (Hart, 1960; Haynes, 1981). *C. bairdi* is also characterized by the presence of well-developed, posterolateral spines on the abdominal somites 3–5. Those on third and fourth somites extend beyond posterior margin of adjacent somites to about midpoint of fifth and sixth somites, respectively. In addition, it shows lateral processes (knobs) on the second and third abdominal somites, that are also present in *C. opilio* larvae. To distinguish zoea II larvae of *C. bairdi* from *C. opilio* it was useful to check the length of the

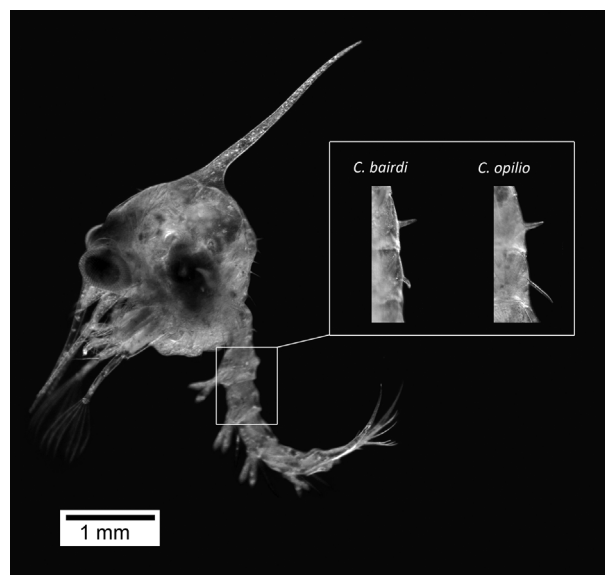


Fig. 2. Photograph of the zoea II of *Chionoectes bairdi* collected in the Chukchi Sea. A zoom of the second and third abdominal somites is given to show differences in curvature of the lateral process between *C. bairdi* and *C. opilio*.

curved lateral process of the third abdominal somite. Thus, it reaches posterior margin of the abdominal somite of *C. opilio*, but, in *C. bairdi* they are markedly shorter (Fig. 2) (Haynes, 1981).

Zoeae II of *C. bairdi* are large larvae, with a length of 6.0–6.5 mm from the tip of rostrum to the tip of dorsal spine (Haynes, 1981; Shanks, 2001), which is well within the size range observed in the analyzed larvae (5.8–6.3 mm). Larval size has been used as a key character to distinguish *C. bairdi* from other sibling species like *C. opilio* and *Hyas* spp., but recent studies have demonstrated that thermal variability of maternal habitat for egg incubation can reflect differences in embryonic (Webb et al., 2006) and larval size (Landeira et al., 2017; Ouellet and

Sainte-Marie, 2017). Considering this, we did not use larval size for species identification.

3.2. Larval distribution

Larval abundance of *C. bairdi* showed distinct distribution patterns throughout the study area (Fig. 1). During 1991 cruise, mean abundance were 10.6 larvae·m⁻², and 66% of larvae were in zoea I stage. The larval distribution during this period showed that the abundances were concentrated in the southeastern Bering Sea, and at the south of St. Lawrence Island, around 500 km far from the northern limit of the distribution of *C. bairdi*, where all the larvae were in zoea II stage. In 1992, the larvae showed higher abundance, with a mean value of 20.6 larvae·m⁻², and 95% of them were in zoea II stage. Most of the larvae were concentrated in the northern edge of the distribution limit of this species, but interestingly, zoeae II were observed even more to the north, crossing the Bering Strait, and arriving localities at 68°N in the Chukchi Sea. Mean larval abundance reported here for early summers of 1991 and 1992 are higher than those observed by Landeira et al. (2017) for 2007 (6.6 larvae·m⁻²) and 2008 (3.4 larvae·m⁻²) but notably lower compared with the abundances reported by Incze et al. (1987) for the same season in 1978 (21.2–119.5 larvae·m⁻²), 1979 (128.1 larvae·m⁻²), 1980 (74.1–63.0 larvae·m⁻²), and 1981 (52.2–225.3 larvae·m⁻²). However, we cannot relate the larval abundance information with the decline of the adult populations in the area due to overfishing (Orensanz et al., 1998) since these data were not collected over the same sampling area. Since information derived from larval dynamics is rather useful to understand the oscillations in recruitment of tanner crabs, it is desirable to implement plankton samplings in parallel with the ongoing trawling monitoring for stock evaluation (NPFMC, 2017).

Interestingly, larvae of *C. bairdi* were recorded in the Chukchi Sea for the first time, during the summer of 1992. The long planktonic larval duration of about 90 days (Strathmann, 1987) may facilitate long-distance transport. Larvae of snow crab *C. opilio* also spend long periods as plankton, about 3–4 months, to complete their development (Yamamoto et al., 2014). According to biophysical transport models (Parada et al., 2010), this larval trait, in combination with the prevailing northward current (Clement et al., 2005), allows *C. opilio* larvae to disperse throughout the Alaskan waters, which moreover enables the gene flow and population connectivity (Albrecht et al., 2014). Considering the similarities between the larval traits of both species, it is quite possible that eventual northward transport of *C. bairdi* from the Bering Sea to Chukchi Sea also occur, as we observed. However, recent trawling surveys have not detected the presence of adults in the Chukchi Sea (Bluhm et al., 2009; Grebmeier et al., 2015) suggesting that these larval transfers have been abortive. It is difficult to discern why these larvae apparently have not succeeded to establish populations farther to the north. Temperature conditions may have been a limiting factor, but it seems that have no direct effect on larval survival during the planktonic phase and settlement of *C. bairdi* (Rosenkranz et al., 2001). In this sense, lower post settlement survival has been reported under bottom temperature < 2 °C, around the cold pool of the middle shelf of Bering Sea (Ryer et al., 2016). In the Chukchi Sea, these conditions of low temperature seem unfavorable for the establishment of *C. bairdi* populations. However, in the shelf, depth above 50 m, of the southeast and northeast Chukchi Sea, bottom temperature is generally greater than 2 °C from July to October (Grebmeier et al., 2015), when the settlement takes place. In these regions of Chukchi Sea, temperature conditions would lead to eventual recruitments of *C. bairdi* postlarvae. On the other hand, temperature can play an indirect effect on the survival. That is because lower temperature reduces the metabolic activity and prolongs the duration of both zoeal stages in the plankton, and postlarval stages after settlement (Rosenkranz et al., 2001). Consequently, the longer duration of these early life stages extends the exposure to predators, increasing significantly the mortality. In fact, the

vulnerability to predators is normally very high at these early life stages. For instance, it has been reported that demersal fish like cod can consume up to 90% of new recruits of *C. bairdi* annually in the Bering Sea (Livingston, 1989).

Current scenario of earlier and longer periods of sea-ice retreatment increases the inflow of Pacific Ocean water and Bering Shelf water into the Chukchi Sea (Shimada et al., 2006). It should favor the northward larval transport of non-native species, as has been observed for other planktonic species, such as the copepods *Eucalanus bungii*, *Metridia pacifica*, *Neocalanus cristatus*, and *N. fleminger* (Nelson et al., 2014; Matsuno et al., 2015). Despite the reduction of sea ice extent in summer was significantly higher during 2007–2008 than in 1991–1992 (Comiso et al., 2017), Landeira et al. (2017) did not find any *C. bairdi* larvae crossing the Bering Strait. It can sound contradictory, but it is reasonable to think that, even if the larvae were not found, they could also be present. The low abundance in the plankton might have prevented us to detect the larvae during 2007 and 2008.

4. Conclusion

Recent alterations in the timing of sea ice formation and retreat, along with increasing seawater temperatures, are driving changes in species composition and northward faunal range expansions (Grebmeier, 2012). For instance, in *C. opilio*, the northward contraction of its populations has been already documented in both Pacific (Bluhm et al., 2009) and Atlantic (Alvsvåg et al., 2009) sectors of the sub-Arctic/Arctic regions. Therefore, if the environmental changes continue, it is likely that the larval survival and the permanent establishment of *C. bairdi* populations expand its northern distribution limit and unpredictably modify the species interaction in the Arctic benthic ecosystems. The hypothetical geographical redistribution of the fishing grounds, would change the access and thereby harvesting opportunities for the crab fleet. As a result, it would have a great impact on the economy of the regions that rely most on this resource, a challenge for the management at international level (Jansen et al., 2016).

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References

- Albrecht, G.T., Valentin, A.E., Hundertmark, K.J., Hardy, S.M., 2014. Panmixia in Alaskan populations of the snow crab *Chionoecetes opilio* (Malacostraca: Decapoda) in the Bering, Chukchi, and Beaufort Seas. *J. Crust. Biol.* 34, 31–39.
- Alvsvåg, J., Agnalt, A.-L., Jørstad, K.E., 2009. Evidence for a permanent establishment of the snow crab (*Chionoecetes opilio*) in the Barents Sea. *Biol. Invasions* 11, 587–595.
- Aronson, R.B., Thatje, S., Clarke, A., Peck, L.S., Blake, D.B., Wigla, C.D., Seibel, B.A., 2007. Climate change and invisibility of the Antarctic benthos. *Annu. Rev. Ecol. Evol. Syst.* 38, 129–154.
- Bluhm, B.A., Iken, K., Hardy, S.M., Sirenko, B.I., Holladay, B.A., 2009. Community structure of epibenthic megafauna in the Chukchi Sea. *Aquat. Biol.* 7, 269–293.
- Brodeur, R.D., Mills, C.E., Overland, J.E., Walters, G.E., Schumacher, J.D., 1999. Evidence for a substantial increase in gelatinous zooplankton in the Bering Sea, with possible links to climate change. *Fish. Oceanogr.* 8, 296–306.
- Clement, J.L., Maslowski, W., Cooper, L.W., Grebmeier, J.M., Walczowski, W., 2005. Ocean circulation and exchanges through the northern Bering Sea: 1979–2001 model results. *Deep-Sea Res.* II 52, 3509–3540.
- Comiso, J.C., Meier, W.N., Gersten, R., 2017. Variability and trends in the Arctic sea ice cover: results from different techniques. *J. Geophys. Res. Oceans* 122, 6883–6900.
- Doney, S.C., Ruckelshaus, M., Duffy, J.E., Barry, J.P., Chan, F., English, C.A., Galindo, H.M., Grebmeier, J.M., Hollowed, A.B., Knowlton, N., Polovina, J., Rabalais, N.N., Sydeman, W.J., Talley, L.D., 2012. Climate change impacts on marine ecosystems. *Annu. Rev. Mar. Sci.* 4, 11–37.
- Fetterer, F., Knowles, K., Meier, W., Savoie, M., Windnagel, A.K., 2017. Updated Daily Sea Ice Index, Version 3. NSIDC: National Snow and Ice Data Center, Boulder, Colorado USA. <https://doi.org/10.7265/N5K072F8> (accessed: 23 January 2018).

- Grebmeier, J.M., 2012. Shifting patterns of life in the Pacific Arctic and sub-Arctic Seas. *Ann. Rev. Mar. Sci.* 4, 63–78.
- Grebmeier, J.M., Bluhm, B.A., Cooper, L.W., Danielson, S.L., Arrigo, K.R., Blanchard, A.L., Clarke, J.T., Day, R.H., Frey, K.E., Gradinger, R.R., Kedra, M., Konar, B., Kuletz, K.J., Lee, S.H., Lovvorn, J.R., Norcross, B.L., Okkonen, S.R., 2015. Ecosystem characteristics and processes facilitating persistent macrobenthic biomass hotspots and associated benthivory in the Pacific Arctic. *Prog. Oceanogr.* 136, 92–114.
- Haynes, E., 1973. Descriptions of prezoae and stage I zoeae of *Chionoecetes bairdi* and *C. opilio* (Oxyrhyncha, Oregoniinae). *Fish. Bull.* 71, 769–775.
- Haynes, E., 1981. Description of stage II zoeae of snow crab, *Chionoecetes bairdi*, (Oxyrhyncha, Majidae) from plankton of Lower Cook Inlet, Alaska. *Fish. Bull.* 79, 177–182.
- Hart, J.F.L., 1960. The larval development of British Columbia Brachyura. II. Majidae, subfamily Oregoniinae. *Can. J. Zool.* 38, 539–546.
- Ince, L., Armstrong, D.A., Smith, S., 1987. Abundance of larval tanner crabs (*Chionoecetes* spp.) in relation to adult females and regional oceanography of the southeastern Bering Sea. *Can. J. Fish. Aquat. Sci.* 44, 1143–1156.
- Jansen, T., Post, S., Kristiansen, T., Óskarsson, G.J., Boje, J., MacKenzie, B.R., Broberg, M., Siegstad, H., 2016. Ocean warming expands habitat of a rich natural resource and benefits a national economy. *Ecol. Appl.* 26, 2021–2032.
- Jewett, S.C., Haight, R.E., 1977. Description of the megalopa of snow crab *Chionoecetes bairdi* (Majidae, subfamily Oregoniinae). *Fish. Bull.* 75, 459–463.
- Kornienko, E.S., Korn, O.M., 2009. Illustrated key for the identification of brachyuran zoeal stages (Crustacea: Decapoda) in the plankton of Peter the Great Bay (Sea of Japan). *J. Mar. Biol. Assoc. U. K.* 89, 379–386.
- 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.
- Livingston, P.A., 1989. Interannual trends in Pacific cod, *Gadus macrocephalus*, predation on three commercially important crab species in the eastern Bering Sea. *Fish. Bull.* 87, 807–827.
- Matsuno, K., Yamaguchi, A., Hirawake, T., Nishino, S., Inoue, J., Kikuchi, T., 2015. Reproductive success of Pacific copepods in the Arctic Ocean and the possibility of changes in the Arctic ecosystem. *Polar Biol.* 38, 1075–1079.
- Moore, S.E., Grebmeier, J.M., Davies, J.R., 2003. Gray whale distribution relative to forage habitat in the northern Bering Sea: current conditions and retrospective summary. *Can. J. Zool.* 81, 734–742.
- Motoda, S., 1957. North Pacific standard plankton net. *Inf. Bull. Planktol. Jpn* 4, 13–15.
- Nelson, R.J., Ashjian, C.J., Bluhm, B.A., Conlan, K.E., Gradinger, R.R., Grebmeier, J.M., Hill, V.J., Hopcroft, R.R., Hunt, B.P.V., Joo, H.M., Kirchman, D.L., Kosobokova, K.N., Lee, S.H., Li, W.K.W., Lovejoy, C., Poulin, M., Sherr, E., Young, K.V., 2014. Biodiversity and biogeography of the lower trophic taxa of the Pacific Arctic region: sensitivities to climate change. In: Grebmeier, J.M., Maslowski, W. (Eds.), *The Pacific Arctic Region, Ecosystem Status and Trends in a Rapidly Changing Environment*. Springer, Dordrecht, pp. 269–336.
- NPFC, 2017. Stock Assessment and Fishery Evaluation Report for the King and Tanner Crab Fisheries of the Bering Sea and Aleutian Islands Regions. North Pacific Fisheries Management Council, Anchorage. AK.
- Orensanz, J.M., Armstrong, J., Armstrong, D., Hilborn, R., 1998. Crustacean resources are vulnerable to serial depletion - the multifaceted decline of crab and shrimp fisheries in the Greater Gulf of Alaska. *Rev. Fish Biol. Fish.* 176, 117–176.
- Ouellet, P., Sainte-Marie, B., 2017. Vertical distribution of snow crab (*Chionoecetes opilio*) pelagic stages in the Gulf of St. Lawrence (Canada) and effect of temperature on development and survival. *ICES J. Mar. Sci.* <http://dx.doi.org/10.1093/icesjms/lsx169>.
- Parada, C., Armstrong, D.A., Ernst, B., Hincley, S., Orensanz, J.M., 2010. Spatial dynamics of snow crab (*Chionoecetes opilio*) in the eastern Bering Sea - putting together the pieces of the puzzle. *Bull. Mar. Sci.* 86, 413–437.
- Pinsky, M.L., Worm, B., Fogarty, M.J., Sarmiento, J.L., Levin, S.A., 2013. Marine taxa track local climate velocities. *Science* 341, 1239–1242.
- Rosenkranz, G.E., Tyler, V., Kruse, G.H., 2001. Effects of water temperature and wind on year-class success of Tanner crabs in Bristol Bay, Alaska. *Fish. Oceanogr.* 10, 1–12.
- Ryer, C.H., Ottmar, M., Spencer, M., Anderson, J.D., Cooper, D., 2016. Temperature-dependent growth of early juvenile southern Tanner crab *Chionoecetes bairdi*: implications for cold pool effects and climate change in the southeastern Bering Sea. *J. Shellfish Res.* 35, 259–267.
- Shanks, A.L., 2001. An Identification Guide to the Larval Marine Invertebrates of the Pacific Northwest. Oregon State University Press, Corvallis.
- Shimada, K., Kamoshida, T., Itoh, M., Nishino, S., Carmack, E., McLaughlin, F., Zimmermann, S., Proshutinsky, A., 2006. Pacific Ocean inflow: influence on catastrophic reduction of sea ice cover in the Arctic Ocean. *Geophys. Res. Lett.* 33, L08605. <http://dx.doi.org/10.1029/2005GL025624>.
- Sirenko, B.I., Gagaev, S.Y., 2007. Unusual abundance of macrobenthos and biological invasions in the Chukchi Sea. *Russ. J. Mar. Biol.* 33, 355–364.
- Slizkin, A.G., 1990. Tanner crabs (*Chionoecetes opilio*, *C. bairdi*) of the Northwest Pacific: distribution, biological peculiarities, and population structure. In: *Proceedings of the International Symposium on King and Tanner Crabs*. University of Alaska Fairbanks, pp. 27–33 Alaska Sea Grant Report 90-04.
- Smith, K.E., Aronson, R.B., Steffel, B.V., Amsler, M.O., Thatje, S., Singh, H., Anderson, J., Brothers, C.J., Brown, A., Ellis, D.S., Havenhand, J.N., James, W.R., Moksnes, P.-O., Randolph, A.W., Sayre-McCord, T., McClintock, J.B., 2017. Climate change and the threat of novel marine predators in Antarctica. *Ecosphere* 8, e02017. <http://dx.doi.org/10.1002/ecs2.2017>.
- Strathmann, M.F., 1987. *Reproduction and Development of Marine Invertebrates of the Northern Pacific Coast*. University of Washington Press, Seattle.
- Webb, J.B., Eckert, G.L., Shirley, T.C., Tamone, S.L., 2006. Changes in zoeae of the snow crab, *Chionoecetes opilio*, with variation in incubation temperature. *J. Exp. Mar. Biol. Ecol.* 339, 96–103.
- Yamamoto, T., Yamada, T., Fujimoto, H., Hamasaki, K., 2014. Effects of temperature on snow crab (*Chionoecetes opilio*) larval survival and development under laboratory conditions. *J. Shellfish Res.* 33, 19–24.