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Comparison of the seasonal variability in abundance of the copepod *Pseudocalanus newmani* in Lagoon Notoro-ko and a coastal area of the southwestern Okhotsk Sea

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ABSTRACT

Replacement of the warm water of the Soya Warm Current (SWC) and the cold water of the East Sakhalin Current (ESC) occurs seasonally along the coast of the southwestern Okhotsk Sea, and sea ice covers the surface during winter. *Pseudocalanus newmani* is one of the dominant copepods in coastal waters of the northern hemisphere. To better understand the population dynamics of the copepod *P. newmani* in coastal areas of the southwestern Okhotsk Sea, this study compared the seasonal variation in *P. newmani* abundance in Lagoon Notoro-ko and a coastal area of the Okhotsk Sea with regard to developmental stage. We sampled *P. newmani* in the lagoon, including during the ice cover season, and the coastal waters. *Pseudocalanus newmani* was abundant at both sites in spring. During summer–fall, adults disappeared from the populations at both sites, whereas the early developmental stages were abundant and dominated the population. Total length of adult females decreased toward summer at both sites. *Pseudocalanus newmani* abundance in the lagoon increased in early winter, and larger females were found in the populations at both sites. These phenomena at both sites corresponded with seasonal variation in water temperature caused by seasonal water-mass replacement and sea ice.

1. Introduction

Pseudocalanus newmani is found in subarctic to temperate seas, including the northwestern Atlantic Ocean (Bucklin et al., 1998; McLaren et al., 1989), the northeastern Pacific Ocean (Frost and Bollens, 1992), and the northwestern Pacific Ocean, which includes the seas surrounding Japan in the most southern part of the species' range (Mori, 1964; Frost, 1989; Yamaguchi et al., 1998; Hopcroft and Kosobokova, 2009). *Pseudocalanus newmani* mainly occurs in relatively shallower waters to depths of 100 m (Sazhin and Vinogradov, 1979; Yamaguchi and Shiga, 1997; Yamaguchi et al., 1998). Previous studies conducted in the northeastern Atlantic Ocean and northwestern Pacific Ocean indicated that this species produces three or four generations per year (McLaren et al., 1989; Yamaguchi and Shiga, 1997). The species displays lower growth and a reduction in size in both regions in response to lower chlorophyll-*a* (Chl-*a*) concentrations and higher water temperatures during summer (McLaren et al., 1989; Yamaguchi and Shiga, 1997; Yamaguchi et al., 1998; Arima et al., 2015). In a laboratory experiment, starvation tolerance decreased in copepods maintained at 10 °C than in those kept at 5 °C (Tsuda, 1994). Other studies reported that production of this species is negatively affected by its habit of feeding on diatoms as a sole prey item (Lee et al., 2003; Halsband-Lenk et al., 2005). Ecological information on *P. newmani* has accumulated since 1989 when this species was first described by Frost (1989). However, its seasonal population dynamics in response to seasonal changes in oceanographic conditions are not fully understood, particularly in the early copepodite stages.

In coastal areas of the southwestern Okhotsk Sea, the Soya Warm Current (SWC), originating from the subtropical Kuroshio Current, flows southward along the east coast of Hokkaido, Japan during warm seasons, and current velocity increases from spring to fall (Aota, 1979). The SWC is characterized by high temperatures (7–20 °C) and high salinities (≥ 33.6) (Takizawa, 1982). The Okhotsk Sea has a large-scale cyclonic circulation (Ohshima et al., 2002). The typical boreal East Sakhalin Current (ESC), characterized by low water temperatures (< 7 °C) and low salinities (< 32.0) (Takizawa, 1982), flows southward along the east coast of Sakhalin Island, reaching the east coast of Hokkaido in winter (Ohshima et al., 2002). The ESC and southward

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winds carry drift ice formed in the coastal polynya of the northern Okhotsk Sea to the east coast of Hokkaido where it covers the surface along the coast in winter. Thus, it is difficult to conduct oceanographic surveys in the coastal area water column of the southwestern Okhotsk Sea during winter because ice covers the surface. Therefore, biological information about this area is particularly scarce.

In the present study, we focused on Lagoon Notoro-ko as a sampling site. Approximately 35 km in circumference, with a total area of 58.4 km^2, Lagoon Notoro-ko is connected to the Okhotsk Sea by a man-made channel (up to 324 m wide and 13 m deep); freshwater inflows from rivers are minimal. The lagoon's water mass is largely exchanged by tides, with similar hydrodynamics inside and outside the lagoon as along the southwestern coast of the Okhotsk Sea (Kurata and Nishihama, 1987; Asami et al., 1995; Nishino et al., 2014a, b). Sea ice (first-year ice) covers the lagoon's surface during winter, and ice algae grow on the undersurface of the sea ice (Asami et al., 1995; Nishino et al., 2015, 2016). It is possible to conduct oceanographic surveys on the ice throughout an entire year when the sea ice is formed.

Pseudocalanus newmani could play an important role in the material cycling and energy flow of marine ecosystems in the southwestern Okhotsk Sea (Seki and Shimizu, 1997, 1998). For example, it is a main prey item of chum salmon *Oncorhynchus keta* juveniles found along this coastline during April–July (Seki and Shimizu, 1997, 1998). Information on the population dynamics of *P. newmani* is also vital for estimating the large-scale salmon fishery in Japan. Previous studies during ice-free seasons in Lagoon Notoro-ko reported that the appearance of *P. newmani* corresponded with the distribution of water masses originating from the ESC, and the disappearance of the species in summer and fall corresponded with the SWC, both inside the lagoon (Kitamura et al., 2014; Nakagawa et al., 2015) and along the coast of the southwestern Okhotsk Sea (Nakagawa et al., 2016). However, those studies seem to have under-estimated the early copepodite stages because the mesh aperture size (335 μm) used was too large to collect small copepodites and may have primarily captured adults.

Previous studies in the Hudson Bay of northeastern Canada (Runge et al., 1991) and at Lagoon Saroma-ko off the southwestern coast of the Okhotsk Sea (Saito and Hattori, 1997) show that members of the genus *Pseudocalanus*, including *P. newmani* and *P. minutus*, actively feed on ice algae found on the undersurface of sea ice and on phytoplankton in the water column under the sea ice. It has also been suggested that a habit of feeding on ice algae and phytoplankton contributes to increases these populations of *Pseudocalanus* after the sea ice melts (Runge et al., 1991).

In the present study, we collected *P. newmani* with a plankton net and a finer mesh size (100 μm) in Lagoon Notoro-ko and a coastal area of the southwestern Okhotsk Sea, and compared the seasonal variation of *P. newmani* abundance in the lagoon to a coastal area of the southwestern Okhotsk Sea, with respect to the species' developmental stage to better understand the population dynamics of *P. newmani* in coastal areas of the southwestern Okhotsk Sea.

2. Materials and methods

2.1. Study site

Sampling and monitoring were carried out at two locations to compare copepods and oceanographic conditions inside and outside the lagoon. At St. A in the deepest part of Lagoon Notoro-ko (21-m water depth; 44°3′2.1″N, 144°9′38.8″E) sampling was conducted once or twice per month during ice-free periods and three or four times per month during ice-cover periods, from February 2013 to December 2014 (Fig. 1). The sampling point at St. B was set off the lagoon (60-m water depth; 44°8′57.0″N, 144°14′48.0″E) (Fig. 1), during the ice-free period from April to November 2014. Sampling was conducted at 9:00–16:00 during ice-free periods (April–December) and at 10:00–14:00 during ice-cover periods (February–March).

2.2. Sampling

Vertical profiles of water temperature and salinity were recorded with a Compact CTD (JFE Advantech, Nishinomiya, Japan) at St. A and with a Compact STD (Alec Electronics, Nishinomiya, Japan) at St. B. Water samples for the Chl-*a* analysis were obtained using a Van Dorn water sampler at five depths (0, 5, 10, 15, and 18 m) at St. A and at six depths (0, 5, 15, 25, 35, and 55 m) at St. B.

During the ice-cover periods at St. A (February–March in 2013 and 2014), 7-cm diameter ice cores were removed using a manual ice auger to determine Chl-*a* of ice algae found on the undersurface of the sea ice. A 5-cm bottom section of the core was cut away using a handsaw and stored in a container until analysis. After sampling the ice cores at St. A, CTD observations and water and net sampling were performed through a 40-cm square hole.

Zooplankton were collected by vertical haul of a NORPAC net (100 μm mesh size, 45-cm diameter, 180-cm length) from a depth of 15 m at St. A and a depth of 50 m at St. B. The net was towed by hand at 0.5 $m\,s^{-1}$. We collected zooplankton through the opening in the sea ice using a ring net at St. A (100 μm mesh size, 30-cm diameter, 100-cm length). The net was towed by hand at 0.5 $m\,s^{-1}$. The zooplankton samples were preserved in 5% (v/v) buffered seawater formalin. The volume of water filtered by the NORPAC net was calculated using a flow meter attached to the net. A 100% water-filtering efficiency was assumed for the ice-cover period.

2.3. Analysis of samples

A 100–500-mL subsample taken from each water depth at both stations was filtered through a Whatman Grade GF/F filter (GE Healthcare Sciences, Pittsburgh, PA, USA). Chl-*a* on the filter was extracted with 7 ml *N,N*-dimethylformamide, and fluorescence was determined according to the method of Welschmeyer (1994) using a 10-AU Fluorometer (Turner Designs, San Jose, CA, USA). The collected ice cores were melted in their containers and placed in a water bath at room temperature. The containers were not shielded from light during melting of the ice core. The container cut out 32.8% of the photosynthetically active radiation. Water volume of each ice core was measured, and the melted water was filtered through a GF/F filter. Chl-*a* on the filter was analyzed using the same procedure as used for the water samples. An integrated mean concentration was calculated for each sampling date from the integrated water column concentration divided by the maximum collecting depth (St. A: 18 m, St. B: 55 m). The monthly averages of the water column and ice algae were calculated. Integrated mean water temperature and salinity values were obtained using the above calculation.

Zooplankton samples were divided into subsamples (from 1/2 to 1/32 aliquots) using a Motoda box-splitter (Motoda, 1959), depending on copepod abundance of at least 200 individuals in the sample, and were sorted into each taxonomic group under a SZX16 stereomicroscope (Olympus, Tokyo, Japan). *Pseudocalanus newmani* was sorted from a subsample and classified by copepodite developmental stage (C1–C6), while C1–C4 stages of *Pseudocalanus* copepodites were judged as *P. newmani* because *P. minutus* was quite low in abundance in Lagoon Notoro-ko in previous studies (Kitamura et al., 2014; Nakagawa et al., 2015). Stage C6 (adults) was further divided into males and females. C6 females obtained in 2014 were checked for the presence/absence of eggs, and individual copepods were counted. Total length (TL) of stage C6 females was measured with an ocular micrometer under the stereomicroscope with a precision of 100 μm. The monthly average value was used in the data analysis of zooplankton and *P. newmani* abundance, as well as the size frequency of C6 females.

2.4. Statistical analyses

Statistical analyses were applied to monthly averaged data using