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Sea ice may be a direct food source for fish

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ABSTRACT
It is recognized that the rich fishery stock in sea-ice regions is supported by the increased zooplankton abundance that follows phytoplankton growth as the ice melts (the 'ice-edge bloom'; Aota, 1993). However, the mechanisms of biological production after the sea ice has melted are unknown. We investigated the abundance and distribution of zooplankton assemblages within the floating sea ice and water column in the seasonal ice zone of the Southern Ocean in the summer of 2013. Within the sea ice, we found Foraminifera, Harpacticoida, *Paralabidocera antarctica* and nauplii, and *Stephos longipes* at high densities (mean: 390×10^3 ind m^{-3}). In contrast, except for foraminiferans, zooplankton was nearly absent in the water column. We propose that, under sea ice and near the ice edge, ice-associated copepods and nauplii are consumed by fish and higher predators as they are released into the water column. Thus, the remarkable depletion of the sea-ice assemblage in the water column might be caused by predation pressure. Here, we propose a role for sea ice as a direct food source for fish.

Key Words
Sea ice, Zooplankton, Direct food source

Introduction

Sea ice is a dominant environmental factor of the marine ecosystem in polar regions. In particular, the seasonal ice zone, which is one of the largest, most dynamic and most productive marine ecosystems on Earth, occupies about 42% of the Southern Ocean (Atkinson, 1998). The seasonal disappearance of sea ice affects the life of marine organisms in the water column. For example, the 'ice-edge bloom', an explosive growth of phytoplankton in the water column around the ice edge, is a widely recognized phenomenon. This bloom leads to increasing zooplankton abundance in the water column, which could, in turn, support the activities of higher predators, such as penguins, birds, seals, and whales (Massom & Stammerjohn, 2010). However, the processes of biological production after sea ice melting are poorly understood because of a paucity of observations.

Zooplankton plays an important role as a link between producers and higher predators in marine ecosystems and, in polar regions, some taxa of zooplankton are known to be distributed specifically within the sea ice (Bradford, 1978; Eicken, 1992). On their release from the sea ice, such assemblages could have direct and indirect effects on biological production. However, at present, even basic data on the abundance and distribution of these assemblages within the sea ice and water column are lacking.

The goal of the present program is to reveal the mechanisms of biological production after sea ice melting in the Polar Regions. In the present study, we examined the abundance and distribution patterns of zooplankton assemblages within the sea ice and in the water column in the seasonal ice zone of the South Polar Region.

Materials and Methods

Environmental measurements

Sea-ice concentration was calculated from daily data obtained from the Advanced Microwave Scanning Radiometer-Earth Observing System (AMSR-E). Sea-ice-free areas were defined as having sea-ice concentrations below 15%. For each station we calculated the number of sea-ice-free days that had elapsed until the sampling day.

Sampling

The survey was conducted during the cruise of the 'Umitaka-maru', a research vessel of the Tokyo University of Marine Science and Technology in the seasonal-ice zone (along a line 110°E and southward from 60°S) from 6–11 January 2013 (Fig. 1). Zooplankton samples were collected in the water column using a closing net (mouth diameter 0.75 m, mesh size 60 μm) at 10 stations. The net was equipped with a flow-meter to estimate the volume of water filtered and was vertically hauled from four layers (0–50, 50–100, 100–200 and 200–500 m). At the ice edge, we selected seven ice floes (approximately 20×20×20 cm^3) that were observed to be colored by algae and simultaneously carried out zooplankton sampling in this region (mesh size 60 μm) from a depth of about 5 m to the surface. Onboard the vessel, the four sea-ice samples were crushed, melted and fixed immediately with buffered 5% formaldehyde in seawater.

Analysis

In the laboratory, zooplankton samples were split using a Motoda box splitter (Motoda, 1959). The samples were identified to the lowest possible taxonomic level (generally species or genus) with a stereomicroscope. Members of the Ostracoda, Polychaeta, Salpa, Foraminifera, Chaetognatha, Medusa, and Euphausiacea were not identified to species level. Individual counts were converted to the number of individuals per 1 m^3 (ind m^{-3}) for each station.

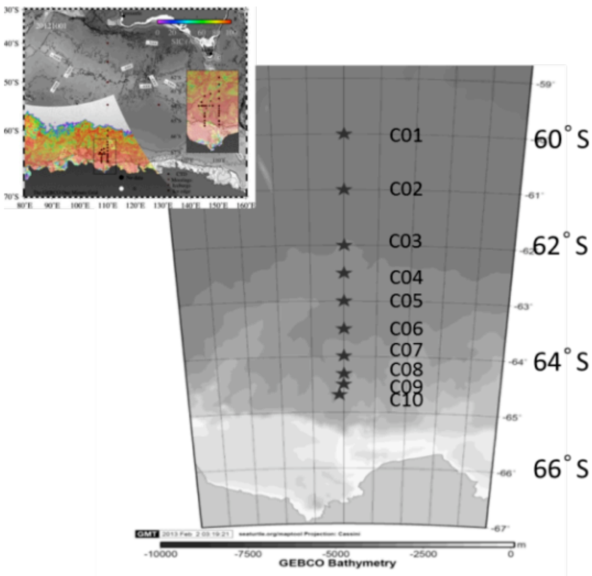

Fig. 1 Map of the study region in the Southern Ocean. Sampling was conducted in the seasonal ice zone (110°E and south of 60°S) in the water column at ten stations and at an ice-edge station. The map at top left shows the sea-ice concentrations in the previous winter.

Results

At the three most southern sample stations, only about ten days had elapsed from sea-ice melting but the number of ice-free days increased progressively toward the north and, at the two most northern stations, sixty days had elapsed since the melt.

In the floating sea-ice samples, we identified high densities of Foraminifera, Harpacticoida, *Paralabidocera antarctica* and their nauplii, and *Stephos longipes* (mean total density 390×10^3 ± 9×10^3 ind m^{-3}) (Fig. 2). In contrast, except for Foraminifera, zooplankton was in remarkably low abundance in the water column (max. 970 ind m^{-3} at the sea ice edge) and the composition of this zooplankton assemblage was quite different from that of the sea ice (Fig. 2). The density of Foraminifera at the surface decreased progressively toward the north (i.e., with time since the sea-ice retreat) although it was a dominant component of all samples. In particular, foraminiferans were highly abundant near the ice edge (max. 94% of the total zooplankton assemblage). One species of Foraminifera, *Neogloboquadrina pachyderma*, was dominant in both environments.

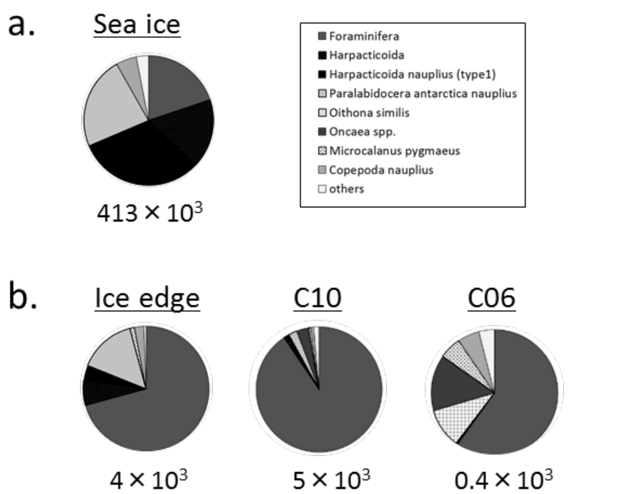

Fig. 2 Abundance (ind m^{-3}) and composition (%) of zooplankton within the sea ice (a) and water column (b).

Discussion

Understanding of ecosystems in the sea-ice regions has been a missing part of the puzzle in polar science. The present research is one of few studies that attempt to assess the distribution of zooplankton within the sea ice and in the water column after the melt in the seasonal-ice zone of the Southern Ocean.

Our data show that, except for foraminiferans, the sea-ice assemblage in the water column almost disappeared. The life cycles of the harpacticoid, *Drescheriella glacialis* and calanoid *Paralabidocera antarctica* are known to be strongly associated with the sea ice (Swadling, 2001; Tanimura et al., 1996) but extension of their distributions into the open ocean have rarely been recorded. Therefore, it seems unlikely that they could adapt to a purely planktonic life in the water column.

At present, the explanation for their low abundance in the water column is unclear. Conceivably, their numbers could be reduced by horizontal spreading or sedimentation. Here we suggest an alternative possibility of predation pressure by fish.

In the fast-ice region, *P. antarctica* nauplii were reported to be consumed by an ice-associated fish, the nototheniid *Pagothenia borchgrevinki* (Hoshai & Tanimura, 1981; Hoshiai et al., 1989). Another widely distributed fish *Electrona antarctica* that has a high biomass in the Southern Ocean is believed to lay its eggs under the sea ice or in the vicinity of the ice edge (Moteki et al., 2013). The mouth size of the fry of this fish is less than 1 mm and their swimming capability is weak. As the nauplii of ice-associated copepods have body sizes below 1 mm and are weak swimmers, they could be preferred food items for these fish.

The traditional view is that biological production at the sea-ice edge originates from growth of phytoplankton as the sea ice retreats. However, the present study shows that zooplankton are already abundant within the sea ice and that they may be released into the water column during melting. It is, therefore possible that high predators such as fish are able to feed directly on plankton as it is released into the water column. That is, fish in the sea-ice regions are fed by a mechanism that does not depend on the ice-edge bloom. Thus, the sea ice might play an important role in supplying food directly to fish in the ecosystem.

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