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Variability of the fauna within drifting sea ice floes in the seasonal ice zone of the Southern Ocean during the austral summer

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ABSTRACT

Sea ice covering the seasonal ice zone in the Southern Ocean contains micro-organisms (sea ice biota). Studies of sea ice biota have mostly been conducted on the land-fast ice and large ice floes, despite most sea ice in the Southern Ocean being seasonal and drifting ice types. We sampled 17 drifting sea ice floes in the marginal ice zone off Adélie Land, East Antarctica, in January 2013 and 2014. We found high densities of copepods such as Harpacticoida species (18,787 ± 50,647 inds.m^{-3}), *Paralabidocera antarctica* (1773 ± 6370) and their nauplii (69,943 ± 149,607), as well as foraminiferans (193,869 ± 408,721) within ice. Variability in the animal assemblages among the different ice floes was observed. Cluster analysis of samples based on the assemblage of sea ice fauna revealed two major groups, which were divided by the year of the sampling, and were dominated by harpacticoid nauplii and foraminiferans, respectively. Sea ice trajectory and drifting duration estimated from satellite data were different for both years, although the origin of the sea ice was in the same bay. This study suggests that the variability of fauna among sea ice floes may reflect the continuance period of ice formation and the trajectory from where they originated.

1. Introduction

The presence of sea ice is one of core elements of marine ecosystems in the polar regions. At its maximum extent, the sea ice covers 5% of the northern hemisphere and 8% of the southern hemisphere, accounting for approximately 67% of the Earth's permanent ice cover (Horner et al., 1992). In the southern hemisphere, the seasonal ice zone occupies a vast area of the Southern Ocean, reaching to 42% of the whole ocean (Atkinson, 1998). The noticeable seasonal variation, from $>18.5 \times 10^6$ km^2 ice cover at its maximum extent in late winter to $<3.1 \times 10^6$ km^2 by the end of summer (Parkinson and Cavalieri, 2012), characterises the ecosystem in the Southern Ocean.

Sea ice provides an important habitat for micro-organisms, which contribute significantly to the productivity of the Southern Ocean (Eicken, 1992). The ice contains unique animals, typically small copepods such as *Drescheriella glacialis* (Harpacticoida), *Paralabidocera antarctica* (Calanoida), and *Stephos longipes* (Calanoida), radiolarians and foraminiferans (Bradford, 1978). The life cycles of these organisms are obligatorily associated with the ice (Dahms et al., 1990; Tanimura et al., 1996; Swadling, 2001). Some small copepods of the *Oithona* and *Oncaea* are occasionally found in sea ice (Bradford, 1978), although they don't have as strong an association with sea ice compared to above species (Arndt and Swadling, 2006; Swadling, 2014 and references therein).

Current knowledge of sea ice biota is mostly derived from land-fast ice and large ice floes, despite most sea ice in the Southern Ocean being drifting type of different sizes (Heil and Allison, 1999). These drifting ice floes are formed in open water, such as in coastal polynyas, and then are transported to open water by currents and the wind. The biological characteristics of each sea ice floe are likely influenced by its history, when and where it was formed, and its journey track.

During sea ice melting in the summer, animals living in the

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seasonal ice are released into the water column. Although little is known about their fates after leaving the ice (Bradford, 1978; Bluhm et al., 2010), these animals likely affect productivity in the water column both directly and indirectly. In fact, animals generally found in the sea ice frequently occur in the surface waters of the marginal ice zone (Kiko et al., 2008; Ojima et al., 2013; Takahashi et al., 2016; Wallis et al., 2016).

The sea ice fauna possibly form an important component of the food web in the water column from spring to summer near the edge of the sea ice and under it. In fast-ice areas, ice-associated copepod nauplii of *Paralabidocera antarctica* are abundant in the stomach contents of ice-associated notothenid fish *Pagothenia borchgrevinki* (Hoshiai and Tanimura, 1981; Hoshiai et al., 1989). Moteki et al., 2017(this issue) suggested that the myctophid fish *Electrona antarctica*, which has a wide geographical range and large biomass in the Southern Ocean, reproduces under sea ice or in the vicinity of the ice edge. Sea ice may provide nursery places for newly hatched larvae of this myctophid fish. In the seasonal ice zone of the Southern Ocean, seasonal sea ice clearly plays an important role in supplying food, either directly or indirectly, to the ecosystem even after melting.

The fauna contained in the sea ice is considered an essential component to our understanding of the link between sea ice and the water column in the Southern Ocean ecosystem. However, fundamental knowledge is currently lacking on the abundance and distribution of the fauna in drifting sea ice floes in the seasonal ice zone. This study examined the animal assemblages in drifting sea ice floes in the vicinity of the sea ice edge. We discuss the reasons underlying the variation in sea ice fauna based on the trajectories of sea ice estimated from satellite data.

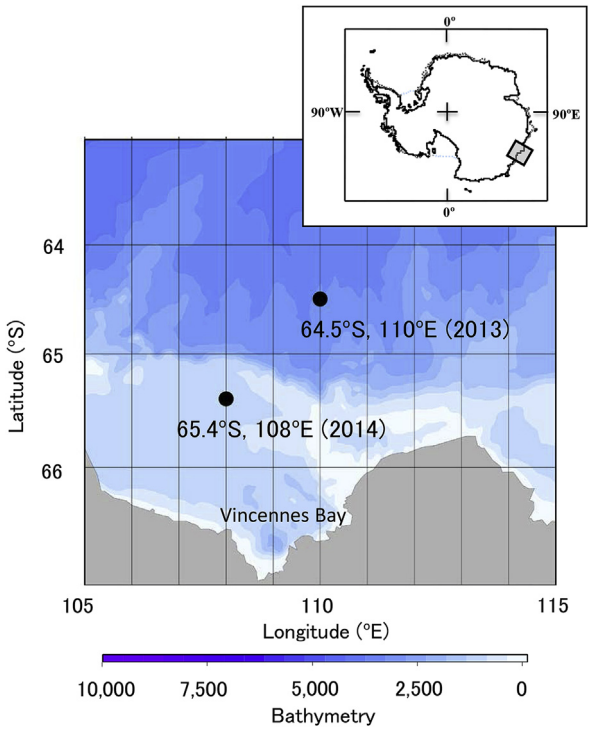

Fig. 1. Sampling stations off Vincennes Bay in the Indian Ocean sector in 2013 and 2014.

2. Materials and methods

Six sea ice floes were sampled at 64.5°S, 110°E on 11 January 2013 during a research voyage by the training vessel (TV) *Umitaka-maru* of the Tokyo University of Marine Science and Technology. A further 11 floes were sampled at 65.4°S, 108°E on 26 January 2014 by the same ship (Fig. 1). All floes were collected in the vicinity of the ice edge (sea ice concentration: <15% of the sea surface).

All samples were stored in the ship freezer at about −20 °C until they were melted in filtered seawater (using a Whatman GF/F glass microfiber filter) to avoid osmotic stress, in the laboratory of the National Institute of Polar Research (NIPR). Thereafter, the samples were concentrated using a 20 μm mesh net to focus on over "micro-zooplankton" (≧20 μm) in the water column and were fixed with borax-buffered formalin seawater (~5% v/v). The average volume of the melted sea ice was $7.23 \pm 4.84 \times 10^{-3}$ m^3 in 2013 and $1.75 \pm 1.28 \times 10^{-3}$ m^3 in 2014.

The samples were divided into eight subsamples using a Motoda box splitter (Motoda, 1959). All of the organisms were identified to the lowest possible taxonomic level (generally the species or the genus level) under a stereomicroscope. Individual counts were converted into the number of individuals per 1 m^3 melted sea ice volume. Density data were log-transformed (log [x+1]) to reduce any bias from highly abundant taxa. A similarity matrix was constructed from the abundance data using the Bray-Curtis similarity index (Field et al., 1982). Group average linkage was performed to group the samples based on similarities between the samples. Statistical analyses were conducted using PRIMER v6 (Clarke and Gorley, 2006). Sampling points were confirmed as being located within the seasonal ice zone, based on satellite images released by the Arctic Data Archive System (ADS) at the NIPR, which also includes the data on the Antarctic.

Trajectories of the sea ice were obtained based on calculations using satellite images from the Advanced Microwave Scanning Radiometer 2 (AMSR2) onboard the GCOM-W satellite.

3. Results

A total of 12 species/taxa including copepods and foraminifera, radiolarians, and ciliate protists were identified from the 17 samples (Table 1). Densities ranged from 3667 to 1,356,316 individuals m^{-3} (291,943 ± 441,830 inds.m^{-3}) with the lowest value in sample 8_14 and greatest value in sample 3_14 in all the floes of both two years (Fig. 2).

Copepods were present in all samples, including adults/copepodites and nauplii of *Paralabidocera antarctica*, *Stephos longipes*, and harpacticoid copepods (Figs. 2 and 3). In sample 5_13, *P. antarctica* and harpacticoid adults/copepodites and the nauplii accounted for 99% of organismal density (235,349 inds.m^{-3}). In both years, harpacticoid adults/copepodites and *P. antarctica* nauplii were present, although harpacticoid nauplii were present only in a few samples from 2014. Cyclopoid copepods such as *Oithona similis* and *Oncaea* spp. occurred only in 2014, while *Stephos longipes* was present only in 2013.

Foraminifera were also highly dominant, particularly in 2014, and accounted for 99.7% of organismal density, with the maximum present in sample 3_14 (1,352,105 inds.m^{-3}) (Figs. 2 and 3). *Neogloboquadrina pachyderma* was dominant (97.4% of foraminiferan density) in the samples from 2013 (Ojima et al., unpublished data).

Cluster analysis divided the samples into two groups and an outlier (sample 1_14), with 45.7% similarity (Fig. 4). The groups were divided by sampling year, although samples 5_14 and 8_14 were placed in group *b* whereas all other samples were from

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