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DISTRIBUTION AND BIOLOGICAL PROPERTIES OF THE ANTARCTIC KRILL *EUPHAUSIA SUPERBA* DANA DURING WINTER WEDDELL GYRE STUDY (WWGS) 1989

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Abstract: Samplings with Bongo net and observations on the krill predators (*e.g.* crabeater seals, Adélie penguins) were conducted for studying distribution and biological properties of the Antarctic krill, *Euphausia superba* in the western Weddell Gyre during the international Winter Weddell Gyre Study in September–October 1989 on board the ice-breaker "Akademik Fedorov". Furciliae and postlarvae were abundant in the vicinity of the frontal zone which divides the waters of the Antarctic Circumpolar Current (ACC) and the Weddell Gyre. The adult krill was obtained only in the marginal ice zone. The presence of crabeater seals indicated the occurrence of the krill also in the areas to the west of Maud Rise where inflow of the Circumpolar Deep Water was recognized. These results confirm the hypothesis that the krill is distributed over the vast periphery of the Weddell Gyre but not in the interior of the western cell of the gyre. The youngest generation consisted of furciliae IV–VI and postlarvae in September. The older krill consisted of the specimens just started to mature. They were feeding (probably on ice algae) and moulting actively.

1. Introduction

Several investigations have been made on the Antarctic krill (*Euphausia superba*) distribution and ecology in winter or early spring in the ice-covered areas (SPIRIDONOV *et al.*, 1985; KAWAGUCHI *et al.*, 1986; O'BRIEN, 1987; DALY and MACAULAY, 1988; MARSCHALL, 1988; HOSIE and STOLP, 1989; BERGSTROM *et al.*, 1990; SIEGEL *et al.*, 1990). But most of them were confined to the ice-edge or near-shore areas. Although SIEGEL *et al.* (1990) conducted their study between the South Shetland and South Orkney Islands with the fine spatial resolution, the conditions of the marginal ice zone prevailed over the large part of the area. Very little is known on the biology of the krill within the ice-massive interior. The aim of this study is to present new data on the krill distribution and biological properties in the inner part of the Weddell Gyre obtained during the international Winter Weddell Gyre Study (WWGS) 1989 in late austral winter of 1989/90.

2. Material and Methods

While conducting part of the international Winter Weddell Gyre Study on board the ice-breaking ship "Akademik Fedorov" in September–October 1989, data on the krill distribution and biology were obtained. Total vertical samplings with Bongo net (0.25 m^2 mouth opening, 300 μm mesh aperture size) down to the depth of 500 or 1000 m were conducted at 42 stations. For detailed information on the hauls see ANONYMOUS (1991). Larval and adult krill were counted and measured (from the tip of the rostrum to the end of the telson). Fresh adult krill from station 93 was investigated for feeding condition (PAVLOV, 1969) and moult stage (BUCHHOLZ, 1982). After preservation in 4% buffered formalin these specimens were investigated for maturity stages, using staging systems of BARGMANN (1945) and MAKAROV (1983). These results can be converted to the simple but widely adopted staging system of MAKAROV and DENYS (1981).

Observations of the krill washed up on the ice during ice-breaking and observations on the krill predators (*e. g.* crabeater seal, *Lobodon carcinophagus*, Adélie penguin, *Pygoscelis adeliae*, snow and antarctic petrels (*Pagodroma* spp., *Thalassoica antarctica*) were conducted from the bridge, and occasionally from the deck in the daytime.

3. Results and Discussion

3.1. *Krill distribution*

The west transect of R/V "Akademik Fedorov" crossed the frontal zone, dividing the Gyre and the waters of the Antarctic Circumpolar Current (ACC), the northern part of the Weddell Gyre and the Gyre interior (Anonymous, 1991; NÖTHIG *et al.*, 1991), the longitudinal transect to the Maud Rise was situated within the zone of the Circumpolar Deep Water (CDW) inflow, and the east transect was situated in the boundary zone between the east and west cells of the Weddell Gyre (BAGRIANTSEV *et al.*, 1989; N. V. BAGRIANTSEV, pers. commun.).

There were no indications of *E. superba* in the net samples, obtained in the waters north of the frontal zone, dividing the ACC and the Weddell Gyre waters (Figs. 1 and 2). However the krill furciliae were occasionally caught there by the pump, which was used for sampling surface water. In the west transect furciliae and postlarvae constantly occurred between the frontal zone and the ice-edge (Fig. 1), and the highest abundance of them was observed just to the south of the frontal zone (Fig. 2). The only considerable catch of the adult krill was obtained in the marginal ice zone (Fig. 2). The abundance was the same order of magnitude (192.5 ind./1000 m^3 averaged over two rings of Bongo net) as that observed in the closed pack-ice zone of the Scotia Sea in October 1988 (SIEGEL *et al.*, 1990). No krill was caught in the net samples, obtained in the Weddell Gyre interior and over the greater part of the longitudinal transect (Fig. 1). Larvae and postlarvae occasionally occurred in the Maud Rise area and along the east transect. The highest abundance of them in the east was observed close to the ice-edge (183 ind./1000 m^3).

When drifting in the Maud Rise area (6–18 October, 1989) we regularly observed the krill in the artificial holes protected from freezing. Small specimens (approximately 20 mm in length) remained near the water surface, but the larger krill (about 40 mm) swam close to the bottom surface of ice, moving in different directions. Diving there, three swarms of the krill, approximately 1.5 m in the major axis were recorded

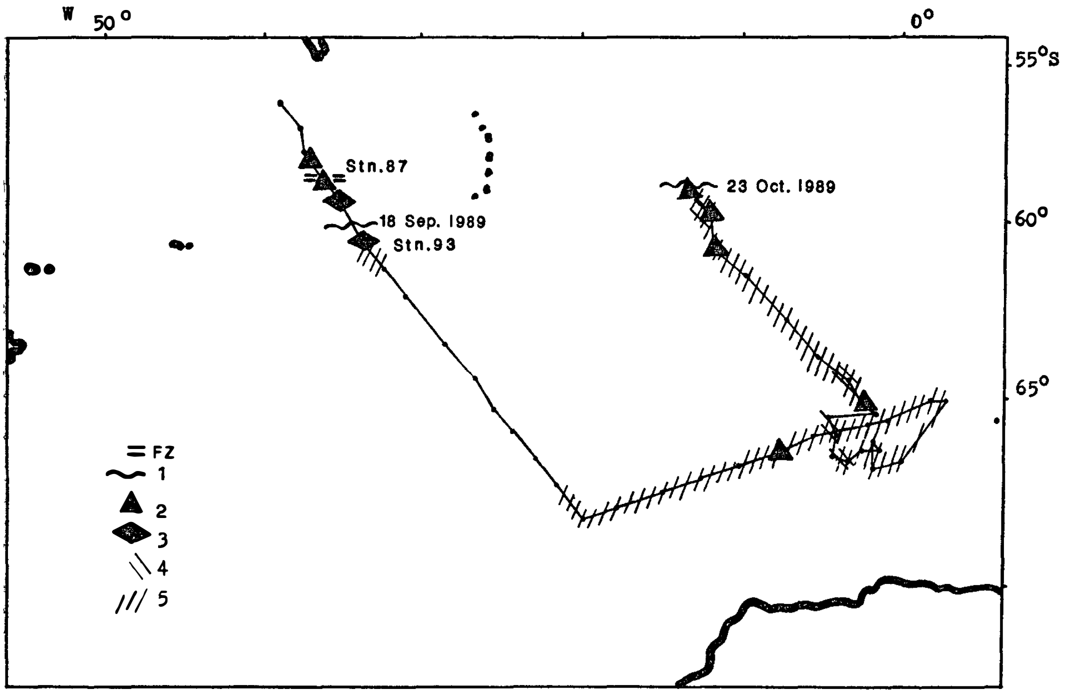

Fig. 1. *Cruise track of R/V "Akademik Fedorov" during Winter Weddell Gyre Study 1989. Positions of net hauls and occurrence of krill* (Euphausia superba) *are also shown. FZ, frontal zone (ACC/Weddell Gyre) position; 1, ice-edge position; 2, occurrence of larval krill in net samples; 3, occurrence of both adult+subadult and larval krill in samples; 4, visual observations of krill on (under) ice; 5, observations of crabeater seals on ice.*

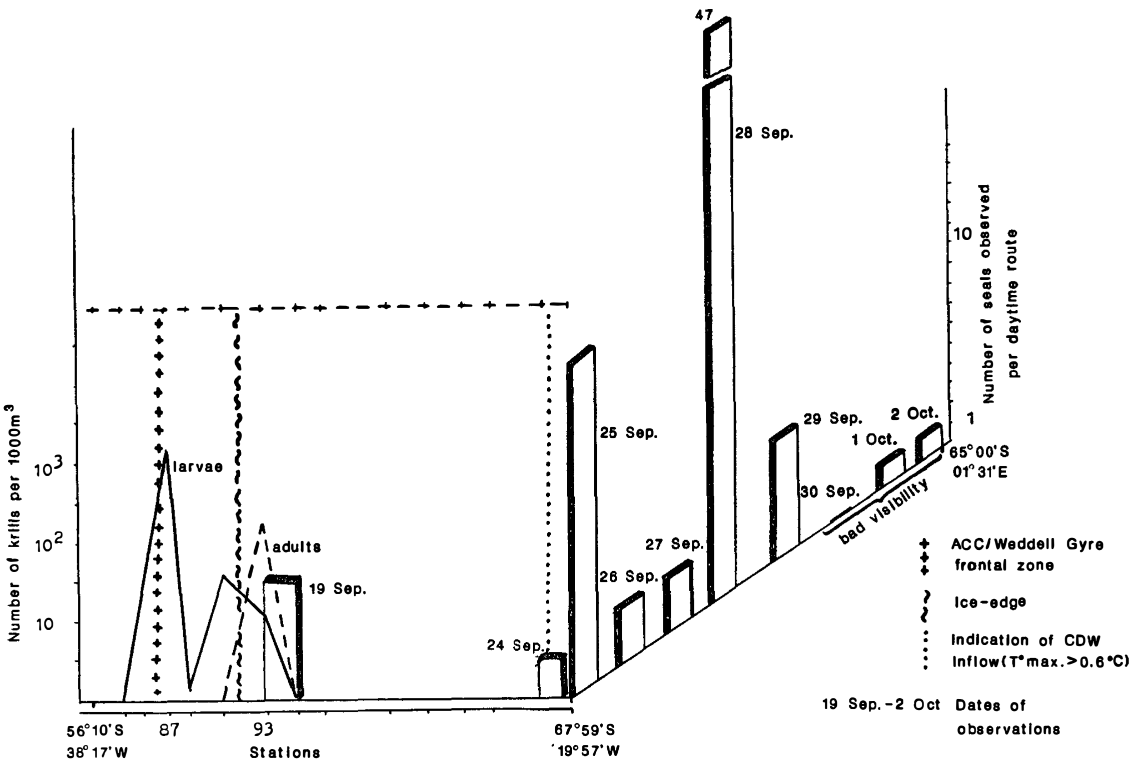

Fig. 2. *Abundance of krill (line graphs) and crabeater seals observed by naked eye (bar diagrams) along the west and longitudinal transect of R/V "Akademik Fedorov".*

(A. Mayer, pers. commun.). In the east transect, the krill was sometimes observed washed up on the ice (Fig. 1). However, such sights of the krill on the ice were rare in our cruise unlike during R/V "Polarstern" transect along the 0° meridian (Anonymous, 1987).

Since the krill is known to be associated with the undersurface of the ice in winter–early spring (O'Brien, 1987; Marschall, 1988, Bergstrom *et al.*, 1990), it can be expected that net sampling is an unadequate method for assessing *E. superba* distribution. One can obtain data on the distribution of the krill indirectly by analyzing the distribution of its predators. It was successfully used in the case of whales (Mackintosh, 1973; Ichii, 1990). The crabeater seal is known to feed predominately on the krill, whereas the percentages of other food items are negligible (Øristland, 1977). So the presence of the crabeater seals on the ice indicates the presence of the krill (Fig. 1). The seals were moderately abundant in the inner ice-edge zone, but when the ship entered the zone of heavy pack ice drifting from the western Weddell Sea, no seals were observed. There were no seals also further south, in the Weddell Gyre interior (Figs. 1 and 2). It was doubtfully related to the availability of open water, since there were enough leads in the central part of the west transect. The seals were recorded again when the first indications of the CDW inflow were noted, and then the seals occurred regularly in the area of the Maud Rise influenced by the CDW inflow. The seals were constantly observed also along the east transect (Fig. 1).

Among other krill predators Adélie penguins were the most abundant. They were seen on the ice (sometimes in large groups, up to 200 birds) in the marginal ice zone, and, in smaller numbers, in the zone of the CDW inflow, but they were virtually absent in the Weddell Gyre interior. Only young Emperor penguins (*Aptenodites forsteri*), diet of which does not include the krill as the principal component, are found in the central part of the gyre. Another bird species sometimes observed foraging in leads in the gyre interior in the west transect was Antarctic petrel. This species feeds on a variety of organisms, whereas Snow petrel, which is predominately the krill-eater, was observed only once there but more frequently in all other parts of the area.

The distributional pattern of the krill observed may be summarized as follows: The zone of highest abundance of the krill was associated with the northern border of the Weddell Gyre. The distribution of the krill within the main body of the gyre was quite uneven. The krill proved to occur in close association with the undersurface of the ice in the areas influenced more or less by the CDW inflow (N. V. Bagriantsev, pers. commun.). The region of the east transect may be also considered as the boundary region between two cells of the Weddell Gyre circulation (Bagriantsev *et al.*, 1989). The presence of the krill there is proved not only by our observations but also by observations during R/V "Polarstern" expedition in August 1986, when the krill was constantly observed washed up on the ice along 0°E (Anonymous, 1987). But the central zone of the largest, western cell of the Weddell Gyre was apparently devoid of the krill in winter.

Siegel *et al.* (1990) found moderate abundance of the krill in the dense pack-ice zone in the north-western Weddell Sea as south as 63°S in early spring. This is considerably further south of the ice-edge than in our case. But the area investigated by them corresponds rather to the northern zone of the gyre (NÖTHIG *et al.*, 1991). DALY and MACAULAY (1988) investigated the northern part of the Weddell Gyre between 41° and 36°W in November–December and found that the krill regularly occurred over a distance up to 80–90 miles from the ice-edge, but the southernmost net samples (approximately at 63°S) did not reveal the presence of *E. superba*. Other winter records are related to the Southern Weddell Sea where *E. superba* occurred mostly in the northeast of Halley Bay, although it could penetrate further southwestward (MARSCHALL, 1988). However, two summer surveys indicate scarcity of this species in the southern Weddell Sea shelf (SIEGEL, 1983; PIATKOWSKI, 1987).

Summer observations in the Weddell Gyre interior are limited. Very few "Discovery" samples were obtained in the Weddell Gyre south of 63°S and west of 20°W. But it is remarkable that the krill is not found there (MARR, 1962). Searching transect of the trawler "Evrica" along 27°W (60°–68°S) gave no indication of the krill south of 63°S (A. V. NEELOV, pers. commun.). However, Japanese investigators found large biomass of krill along 20°W between 60° and 65°S (ENDO *et al.*, 1986). This area, not covered by this study, is influenced by the so-called South-Sandwich meander, the strong inflow of the CDW (BAGRIANTSEV *et al.*, 1989; DANILOV *et al.*, 1990).

Therefore, it is likely that the krill occupies only those areas within the Weddell Gyre, where some mixing with the modified ACC waters takes place. Previously SIEGEL (1986) suggested that the principal area within the Weddell Gyre inhabited by the krill is the periphery of the gyre, but this periphery includes the northern part of the Gyre, its smaller east cell, the South Sandwich meander, the zone of the CDW inflow to the east and west off the Maud Rise and the Antarctic Coastal current. The krill is likely brought from the latter two systems to the southern Weddell shelf and interior of the west cell of the gyre. There are some reasons for its population does not persist there. First, larvae of *E. superba* cannot develop even if the spawning occurs in these waters. Krill eggs sink down to the CDW, but the thermal characteristics of corresponding layers in the shelf area (below 0°C) and in the gyre interior (up to 0.4°C; NÖTHIG *et al.*, 1991) are too low for normal embryonic development of *E. superba*, as ROSS and QUETIN's (1986) results indicate. Furthermore, the period of the phytoplankton vegetation there may be too short for subsequent successful development of the larvae of such late spawner as the krill (BARGMANN, 1945; MAKAROV, 1983; MENSHENINA, 1991). Secondly, while overwintering, adult krill tend to feed on ice-algae in the areas of thin ice with numerous leads. Large ice floes with smooth undersurface are almost devoid of the krill (MARSCHALL, 1988; BERGSTROM *et al.*, 1990). But there are such floes that predominate in the Weddell Gyre interior, although a number of leads are still formed there. So, adult krill brought to these waters may tend to leave them. This process in turn may result in the concentration of the krill in the marginal ice zone. The east cell of the gyre may be also an unsuitable environment for the krill reproduction, but since this area is surrounded by the waters carrying *E. superba*, repopulation of it with the krill likely takes place frequently.

3.2. Krill composition

The youngest group of krill in September was represented by furciliae IV to postlarvae, the furcilia VI with the length 10 mm was the dominant stage (Fig. 3) (see

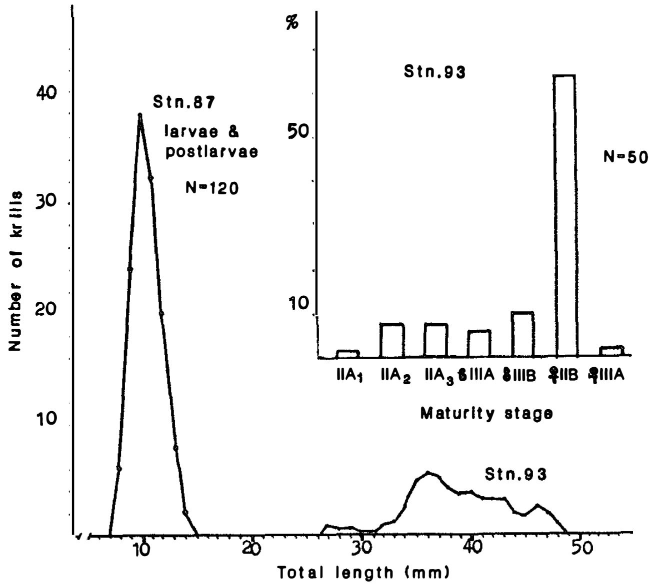

Fig. 3. Length and maturity stage composition of krill in the northern part of the Weddell Gyre. Maturity stages are given according to MAKAROV *and* DENYS *(1981).*

Table 1. Maturity stage composition of the adult and subadult krill (Euphausia superba) *in the marginal ice zone ("Akademik Fedorov" Station 93, September 19, 1989). Maturity stages are given according to* BARGMANN *(1945): C, D and* MAKAROV *(1983): 1–6.*

Length group	Females				Males					
	2 (C)	2 (D)	3a (D)	*n*	1–2	3	4	5	6	*n*
TL<39 mm	42%	58%	—	24	54%	27%	9%	10%	—	11
TL>39 mm	—	67%	33%	9	—	—	17%	33%	50%	6
Total	30%	64%	6%	33	34%	18%	12%	18%	18%	17

also MENSHENINA, 1992). At least two size groups can be identified in the larger krill: one group with the modal length of 36 mm and the other including krill mostly larger than 40 mm (Fig. 3). Both groups consisted of at least sub-adult krill. In particular, larger males carried spermathophores in their ejaculatory ducts (stages 4 and 5 after MAKAROV (1983). Most of the females were in early stages of the vitellogenesis, but their thelyca were in rather advanced stages (Table 1, Fig. 3).

The presence of overwintering larvae in early spring is well-known (MARR, 1962). Our data proves that they can be as young as the furciliae IV. However, no larvae were reported for North-West Weddell Sea in November 1988 (SIEGEL *et al.*, 1990). Instead, the group of the juveniles less than 30 mm in length were recorded in the east of the Bransfield Strait (SIEGEL *et al.*, 1990). In the inner marginal ice zone SIEGEL *et al.* (1990) reported sub-adult and adult krill (cluster 2a) very similar in composition to our sample. Thus, the krill inhabiting the northern Weddell Gyre zone (or the Weddell Drift—MARR (1962), MACKINTOSH (1972)) is probably characterized by certain growth parameters (*e. g.* slower growth rates than those observed in krill in the ACC waters, as MACKINTOSH (1972) and MAKAROV (1980) pointed out).

Males of *E. superba* were shown to complete their maturation early in the season,

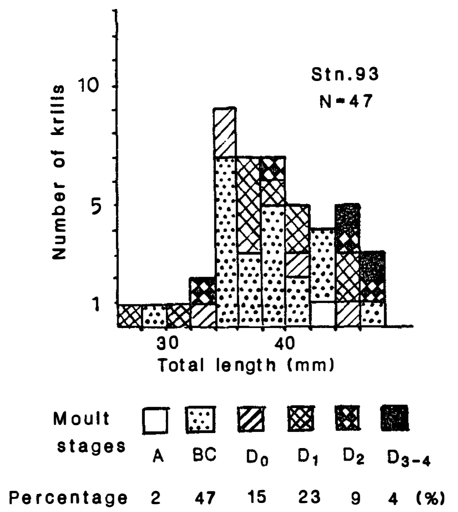

Fig. 4. Moult stage composition vs. length of the adult and subadult krill collected at Station 93 in the marginal ice zone.

often before ice retreating (BARGMANN, 1945; MAKAROV, 1983; SPIRIDONOV *et al.*, 1985; HOSIE and STOLP, 1989). However, in September 1989 only 36% of the males were mature (Table 1), and in October–November 1988 no such specimens were observed within the ice-covered waters (SIEGEL *et al.*, 1990). No doubt, the variability, both spatial and temporal, in the maturation rates of krill males is considerable. CUZIN-ROUDY (1987) concludes that the oogenesis in *E. superba* completes before the winter rest of the gonads and the vitellogenesis starts in the next reproductive season. The latter process has begun as early as in September. Comparison of early-spring data on maturity stages of the krill living in the ice-free waters (MAKAROV, 1983) with our observations shows no principal differences. The phase of the reproductive cycle of *E. superba* was approximately the same in the Weddell Drift and off the South Georgia in September.

Moult stage composition in the adult krill is demonstrated in Fig. 4. About half of the specimens were intermoult (BC stage). There were some late premoult (D3–4) and just moulted (A) individuals. There were no significant differences in the ratio of intermoult+premoult/postmoult krill of different size (2 mm interval) classes (KOLMOGOROV test, $K(\lambda)=0.885$, $p<0.05$). NICOL and STOLP (1990) estimated a duration of the intermoult phase to be up to 44% of the whole moult cycle in actively moulting group of krill. It is likely that the percentage of intermoult animals in the actively moulting wild population would not exceed considerably this value. This percentage is significantly higher (as high as 70%) in particular in dense krill concentrations in autumn, where some decrease in moult rates of the krill probably takes place (SPIRIDONOV, 1991). However, in the marginal ice zone, as our data indicate, moult activity of the krill is not depressed.

Most of the adult krill specimens collected in the marginal ice zone were feeding intensively when they were caught. A few individuals possessing empty alimentary tracts (Fig. 5) were in the stage of just moulted or late premoult. The majority of the krill have full stomachs but only partly filled intestines (Fig. 5). This means that

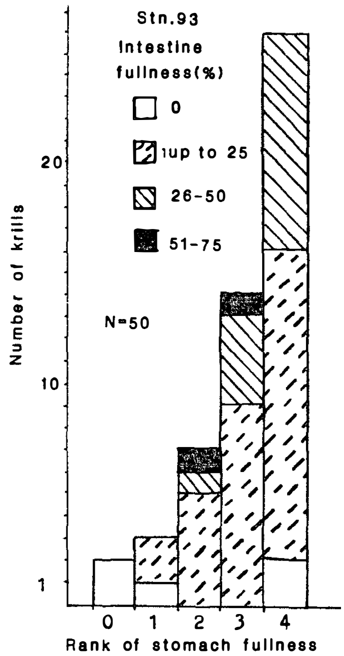

Fig. 5. Feeding state of the adult and subadult krill collected at Station 93 assessed according PAVLOV (1969).

their feeding activity was close to a maximum at the time of sampling (at the sunrise). Although the composition of the food was not examined, these specimens probably fed on ice-algae, as several authors showed (O'BRIEN, 1987; MARSCHALL, 1988; BERGSTROM *et al.*, 1990), since the phytoplankton in the water column was very scarce.

It may be concluded that when inhabiting the Weddell Drift in the vicinity of the marginal ice zone in winter, the krill is provided with feeding conditions allowing normal moulting and starting the maturation. Further investigations are required to answer the questions: 1) Does active moulting of the krill under ice provide growth rates comparable with those observed in the krill feeding on the spring phytoplankton? 2) What maturity stage can be reached in the krill living in ice habitats?

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