—レビュー—
Review

A Review of the Coastal Marine Ecosystem Research at Syowa Station, Antarctica

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南極昭和基地で実施した沿岸海洋生態系研究

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要旨：国際共同研究 BIOMASS の一環として実施した，昭和基地 (69°00′S, 39°35′E) における沿岸海洋生態系研究の結果を概説した．沿岸海洋生態系の主要構成要素に関する周年情報を得ることを目指した本研究は，1982 年から 1984 年にわたって行われた．植物プランクトン，アイスアルジー，動物プランクトンについて；生産された有機粒子の沈降，分解過程について；ナンキョクオキアミの冬期生存戦略について；底生生物の生態について；幾つかの知見が得られた．ここでは，それらの知見をとりまとめ，紹介した．この過程を通して，沿岸生態系を更に深く理解するためには，未解決のまま残されている問題の研究が必要だとの感を抱くに至った．解決を要すると考えた課題は，SCAR によって現在計画が進められている "Coastal and Shelf Studies in the Ecology of the Antarctic Sea Ice Zone" の枠組みの中で，我が国の研究者が中心となって，取り組むのにふさわしい研究だと考えている．

Abstract: Results of marine biological research on the coastal marine ecosystem in the Syowa Station area (69°00′S, 39°35′E) in conjunction with BIOMASS are reviewed. This research aimed at the collection of year-round information on the basic elements in the ecosystem of the region in the 1982-84 winters. General information on the ecology of bacteria, phytoplankton, ice algae and zooplankton; sinking and decomposing processes of organic particulates produced; overwintering strategy of krill; and ecology of benthos is given. Based on the above investigations, some research topics for a recently proposed international program, "Coastal and Shelf Studies in the Ecology of the Antarctic Sea Ice Zone" were suggested.

1. Introduction

Biological research on the Antarctic coastal marine ecosystem by the Japanese Antarctic Research Expedition (JARE) was conducted in the 1982 to 1984 winters in conjunction with an international project, Biological Investigations of Marine Antarctic Systems and Stocks (BIOMASS) (HOSHIAI *et al*., 1991a). This research was carried out in the coastal fast ice area of Syowa Station (69°00′S, 39°35′E). This shore-based research activity aimed at gathering year-round information on the basic elements of a coastal and ice-covered ecosystem. However, due to the limitation of

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manpower, research activities could cover only part of the elements of the ecosystem.

Acquisition of basic physical, chemical and biological oceanography data was continued for three winters, the number of sites and the frequency of observations were reduced in 1983 and 1984 (FUKUCHI *et al.*, 1985a; WATANABE *et al.*, 1986; MATSUDA *et al.*, 1987a). The main research topics in each season varied depending on the specific research field of the participating biologists, while it was commonly understood among the participants that one of the principal objectives of the project was to obtain year-round information on important elements of the ecosystem. In the first year, 1982, stress was placed on planktonic primary consumers and the routine observation of oceanographic conditions in the research area. In 1983, ecological research on primary producers, phytoplankton and ice algae, was conducted. In the 1984 winter, the ecology of the overwintering krill, *Euphausia superba*, and decomposition process of organic particulates in relation to the cyclic flow of matter were investigated.

The results of the above research and the preliminary knowledge which had been obtained before the BIOMASS period are reviewed below. This paper is intended to be useful as a reference in preparatory discussions for the implementation of an international cooperative research program, Coastal and Shelf Studies on the Ecology of the Antarctic Sea Ice Zone (CS-EASIZ), which has been developed by the Scientific Committee on Antarctic Research (SCAR).

2. Primary Producers

2.1. Phytoplankton

Temporal change of chlorophyll *a* of phytoplankton in the water column under the sea ice was observed at the two sites through winter 1968 (HOSHIAI, 1969a). The standing stock of phytoplankton in terms of chlorophyll *a* varied following the seasonal change of solar radiation with time lags. The minimum was 0.10 mg m^{-2} on September 7, 1968 and the maximum was 59.54 mg m^{-2} on January 29, 1969 at the shallower site (9 m in depth). While the concentration of chlorophyll *a* was extremely low during winter, its gradual increase started in September and the increase became abrupt in December. The maximum value of 11.93 mg m^{-3} in chlorophyll *a* concentration was attained in the near bottom layer of the shallower site. The chlorophyll *a* concentration in the whole water column at the deeper site of 92.5 m remained below 0.50 mg m^{-3} in December.

A well organized observations of the phytoplankton standing stock with water temperature, salinity, nutrient salts, pH and dissolved oxygen were routinely carried out for three years from 1982 to 1984 (FUKUCHI *et al.*, 1984, 1985a; SATOH *et al.*, 1986; MATSUDA *et al.*, 1987a). Results of these observations showed a peak of phytoplankton biomass between January and March. The value of standing stock, however, varied from year to year.

Horizontal and vertical distribution of chlorophyll *a* concentration was uneven. Maximum concentration of chlorophyll *a* was 11.30 $\mu g\ l^{-1}$ in the 5 m layer of St. 3 on January 27, 1983 (FUKUCHI *et al.*, 1984) and 12.96 $\mu g\ l^{-1}$ in the surface (0 m) layer of St. 1 on March 12, 1984 (MATSUDA *et al.*, 1987a). In general, the higher concentration of chlorophyll *a* appeared in the subsurface layer in areas shallower than 50 m in depth. Correlation between high chlorophyll *a* concentration and high water temperature with low salinity was suggested (FUKUCHI *et al.*, 1984). Increase of pH and dissolved oxygen contents and decrease of nutrients, all of which are generally ascribed to the results of photosynthetic activity of phytoplankton, were frequently observed (HOSHIAI, 1969a; MATSUDA *et al.*, 1987a).

SATOH *et al.* (1991) estimated annual production of phytoplankton to be 17 gC m^{-2} in this region. Seasonal succession in species composition was examined in 1983; it was found that *Phaeocystis pouchetii* dominated the phytoplankton community in the summer bloom (WATANABE unpublished).

2.2. Ice algae

Almost-year-round observations of ice algae, one of the important primary producers in the polar oceans other than phytoplankton, were carried out in 1967, 1970 and 1983 and a short-term observation was done in the 1982 spring-summer. Through the above observations, it was concluded that extreme growth of ice algae occurred two times a year in both autumn and spring-summer at the bottom of seasonal sea ice in the fast ice area of Syowa (HOSHIAI, 1969b, 1981; WATANABE and SATOH, 1987). Close relationship between ice algal chlorophyll *a* and chlorinity of sea ice was observed (HOSHIAI, 1969b, 1981). An inverse relation of the development of bottom community of sea ice to the snow depth on the sea ice was observed in spring-summer (HOSHIAI, 1985; WATANABE *et al.*, 1990). Occurrence and seasonal change of ice algal communities comprising not only bottom community but also surface community and interior community were observed in the fast ice area in terms of chlorophyll *a* and species composition. The standing crop of ice algae attained 125 mg m^{-2} in Kita-no-seto Strait in mid-November 1983 (WATANABE and SATOH, 1987; WATANABE *et al.*, 1990). Productivity of ice algae was measured in the 1983-84 spring-summer (SATOH and WATANABE, 1988). Based on the results of this measurement and solar radiation data, 3.5 gC m^{-2} annual production of ice algae was estimated (SATOH *et al.*, 1991).

Positive correlation between chlorophyll *a* concentration and diatom cell numbers was observed in the bottom and surface communities. *Amphiprora kufferathii, Nitzschia curta, N. cylindrus, N. lecointei, N. obliquecostata, N. sublineata, N. turgiduloides* and *Pleurosigma directum* appeared abundantly in the bottom community (WATANABE *et al.*, 1990). Siliceous cysts of 29 different morphological shapes were discovered from both sea ice and water column (TAKAHASHI *et al.*, 1986). This finding provided data to develop the taxonomy of marine chrysophytes (BOOTH and MARCHANT, 1987).

Strands of ice algae suspended from the undersurface of sea ice were investigated (WATANABE, 1988). Strands, consisting mainly of such pennate diatoms as *Amphiprora kufferathii, Berkeleya rutilans, Nitzschia lecointei, N. stellata, N. turgiduloides* and others, were 10-15 cm in length in early November and grew to 50-60 cm by early December.

2.3. Macroalgae

Although three kinds of red-alga, *Phyllophora antarctica, Phycodrys antarctica* and unidentified red-alga, borne on the back of the sea urchin, *Sterechinus neumayeri*, were commonly collected, their distribution and life cycle in the field remain to be observed.

3. Primary Consumers

3.1. Zooplankton

Seasonal change of zooplankton abundance was observed in 1982. Copepods, chaetognaths and ostracods constituted major components of the zooplankton community; the abundance of these three groups became high between June and September (FUKUCHI *et al.*, 1985b). Copepods numerically dominated the zooplankton community through the year (FUKUCHI *et al.*, 1985b; TANIMURA *et al.*, 1986). Eleven species of copepods except for Harpacticoida were identified: *Calanus propinquus, Ctenocalanus vanus, Microcalanus pygmaeus, Euchaeta* sp., *Scolecithricella glacialis, Metridia gerlachei, Oithona frigida, Oithona similis* and *Oncaea curvata* (oceanic components); *Paralabidocera antarctica* and *Stephos longipes* (neritic components). The number of copepods increased from spring to summer and decreased in autumn. After this decreased it increased again with the progress of season, reaching a peak of 5×10^3 ind m^{-3} in midwinter. Thereafter it decreased gradually toward early spring. *Oithona similis* and *Oncaea curvata* dominated the winter community; *Paralabidocera antarctica* dominated the summer community (TANIMURA *et al.*, 1986).

3.2. Ice associated copepods

Paralabidocera antarctica and three species of Harpacticoid copepods appeared at the sea bottom continuously through the winter. The maximum abundance of copepods was 21.8×10^4 ind m^{-2} in September 1975 (HOSHIAI and TANIMURA, 1986).

Winter survival of *Paralabidocera antarctica* was closely related to the sea ice as habitat and to the ice algae as food (HOSHIAI, 1981; HOSHIAI and TANIMURA, 1986; HOSHIAI *et al.*, 1987). Nauplius larvae of this copepod appeared in the bottom layer of fast ice in autumn when ice algae formed a dense assemblage there. Feeding on ice algae, nauplii grew to the copepodite stage V by the beginning of summer. Nauplii of *P. antarctica* constituted the main components of winter diet of young of a nototheniid fish, *Pagothenia borchgrevinkii*, along with *O. similis* and *O. curvata* (HOSHIAI *et al.*, 1991b). In mid-November, Copepodit V and adult stages of *P. antarctica* began to shift their habitat from the sea ice-water interface to the water in which the enhancement of phytoplankton had begun. This removal was completed in December (HOSHIAI and TANIMURA, 1986). However, the distribution of grown *P. antarctica* was limited to the top layer of the water column (FUKUCHI and SASAKI, 1981). In February, adult *P. antarctica* disappeared from the water column (TANIMURA *et al.*, 1984; HOSHIAI and TANIMURA, 1986).

3.3. Krill

An ecological study of the wintering krill, *Euphausia superba* was done in 1983. Krill were collected with a light-trap in the near bottom layer of the water column in the dark winter (KAWAGUCHI *et al*., 1986b). The observation of stomach fullness and the color of stomach contents along with the collection data indicated that the krill changed their habitat from pelagic to bentho-pelagic during the dark season to subsist on detritus on the sea floor. The lowering of oxygen consumption rate in winter was experimentally observed together with C/N ratio and growth of krill. These seemed to be adaptive strategies to survive in the food deficient condition (KAWAGUCHI *et al*., 1986a).

4. Decomposers

4.1. Heterotrophic microorganisms

The seasonal change of heterotrophic bacterial number in the water column was investigated from May 1983 to January 1984 (SATOH *et al*., 1989). The number of bacteria was less than 1.0 cfu ml^{-1} in winter but began to increase in October and reached a maximum value of 2.4×10^2 cfu ml^{-1} in December. The positive relation between bacterial number and the amount of particulated organic carbon which was assumed to be derived from ice algae was observed. Vibrionaceans, which composed the bacterial community in September together with *Pseudomonas-Alcaligenes, Acinelobacter-Moraxella* and Gram-positive bacteria, disappeared in December. Disappearance of Vibrionaceas was ascribed to the extreme increase of phytoplankton in the water column. In addition, taxonomical and ecological investigations of heterotrophic microflagellates were carried out. Four species of *Paraphysomonas* (Chrysophyceae) including two new species were discovered in both sea ice and the water column (TAKAHASHI, 1987).

4.2. Decomposition of organic matter

The seasonal change of quality and quantity of suspended and sinking organic particles was investigated in relation to primary production in both sea ice and the water column (MATSUDA *et al*., 1987b). The quantity of particulate organic carbon flux was large (136 mgC $m^{-2}day^{-1}$) in summer but extremely small (1.5 mgC m^{-2} day^{-1}) in winter. A similar trend was observed in the particulate organic nitrogen and particulate phosphorous. More drastic seasonal variation of chlorophyll *a* than paticulated organic carbon was observed by the sediment trap experiment (4500 μg $m^{-2}day^{-1}$ in summer and 3 μg $m^{-2}day^{-1}$ in winter). The proportion of chlorophyll *a* to the total organic carbon in the sinking particles was high from November to February and also higher than that in the suspended particles. Based on the above findings, MATSUDA *et al*. (1990) concluded that a considerable part of ice algae and/or phytoplankton was directly transferred to the sea floor in the spring-summer season. A close relationship between the blooming of diatoms and organic particles collected with a moored sediment trap was observed in Breid Bay (70°12′S, 24°19′E) in the 1985–86 summer (FUKUCHI *et al*., 1988; HANDA *et al*., 1992).

The decomposition process of suspended and sinking organic particles was experimentally investigated. Degradation of chlorophyll *a* to phaeopigments progressed fast in about one month and was followed by gradual degradation of phaeopigments in the sinking particles at −1.5° in the dark. The rate of time serial change of particulate organic carbon, particulate organic nitrogen and particulate phosphorus in the experiment along with results of chlorophyll *a* indicated that the rate of *in situ* decomposition of particulate organic matter under fast ice was comparable to that at moderate temperature (MATSUDA *et al*., 1986).

5. Benthos

Information on necrophagous and carnivorous animals including demersal fish had been collected by bait trap sampling (NAITO and IWAMI, 1982; NUMANAMI *et al*., 1984). A tagging experiment was done to determine the growth and migration pattern of *Trematomus bernacchii* (KAWAGUCHI *et al*., 1989).

Observations of benthic fauna were done by the SCUBA diving in the shallow water. While there appeared such sedentary animals as sponge, tube-dwelling annelids and ascidians with a sea urchin, *Sterechinus neumayeri* and a star fish, *Odontaster validus* below 5 m in depth, small and motile animals were distributed in the shallower part. Exceptionally, dense populations of an antarctic scallop, *Adamussium colbecki* were found in the shallower zone in the Nisi-no-ura Cove (NAKAJIMA, 1982).

Inspections with a remote-controlled vehicle equipped with a television camera were made at selected sites (HAMADA *et al*., 1986). Although the remote-observation could cover only limited areas, biomass of epifaunal megabenthos was estimated as 400–3000 g m^{-2} (NUMANAMI *et al*., 1986).

6. Concluding Remarks

Our knowledge of the marine ecosystem in the Syowa Station area increased remarkably through BIOMASS related research in 1982–84. One of the most important characteristics of the JARE's ecosystem research is that it was conducted through a whole winter. In spite of efforts of biologists who carried out field work, however, several research topics remain to be studied due to limitation of manpower and to bad sea ice conditions in summer in which activity of organisms is high. Among them, I think that following items are essential to improve our present understanding of the structure and dynamics of the coastal ecosystem, which also may constitute a major part of programs planned in CS-EASIZ.

1) An outline of seasonal sequence and spatial distribution of phytoplankton standing stocks has been clarified. According to the research described above, the distribution of phytoplankton was patchy in summer. However, the process and mechanism of patch formation and decay are unclear. Such biological studies as the production rate of phytoplankton and grazing rate of zooplankton together with

oceanographical studies of water movement on a fine scale are needed to explain patch formation processes. Simultaneous data acquisition with moored systems equipped with appropriate instruments and deployed at selected locations may be effective for this purpose.

2) The occurrence, distribution and seasonal variation of ice algae in terms of chlorophyll *a* have been clarified. The autumnal blooming of ice algae at the bottom of sea ice is a common event; ice algae seem to function as the primary producers during the season in which phytoplankton extremely are reduced in the water column. However, knowledge of the ecology and physiology of the autumnal ice algae are insufficient in comparison with those of the spring-summer algae. Detailed research in this field is needed.

3) As for zooplankton, one of the questions to be studied is the mechanism of winter increase of zooplankton, particularly copepods. The relations of copepods to physical oceanographical conditions and food availability of harviborous species should be studied. Ecology of chaetognaths and ostracods also remains to be examined.

4) Further field observations on wintering strategy of krill and other micronekton as well as experimental research in the laboratory are needed to fill the gaps in the knowledge of their life cycle. Krill and micronekton play an important role in ecosystem function as the major food organisms of higher trophic animals.

5) Information on the benthos in the Syowa Station area is less than in well-surveyed coastal regions such as McMurdo Sound. General survey of benthic communities including meiofauna and physiological studies of common species should be done to acquire basic information on the benthos. Quantitative and qualitative studies of sinking organic particles as food of benthos are important in relation to the energy budget of the benthic community. In this regard, attention should be paid to the productivity of benthic micro- and macro-algae.

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