SHORT-TERM VARIATION OF CHEMICAL PROPERTY OF WATER AND MICROPLANKTON COMMUNITY IN THE COASTAL AREA NEAR SYOWA STATION, ANTARCTICA, IN MIDSUMMER OF 1984, I. CHEMICAL PROPERTY INCLUDING CHLOROPHYLL *A*

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Abstract: Variation of chemical porperties and chlorophyll *a* standing stock in the water column below fast ice were monitored in the coastal area north of Syowa Station, Antarctica, for 2 weeks in midsummer of 1984. Because the ice was continuously melting, the surface water was diluted to a greater extent and isolated from underlying waters by a well-defined pycnocline. Nitrate and nitrite were rapidly and completely depleted from the surface water. Silicate was also removed rapidly but remained at a certain level in the latter half of the investigation period. Phosphate and ammonium were apparently replenished probably by excretion of larger animals such as seals. Despite of not a small amount of the nutrients, chlorophyll *a* decreased in the surface water. Excess dilution with ice melted water is likely to be detrimental to most phytoplankters. During these variations in the surface layer, the chlorophyll maximum was formed in the subsurface layer and clearly observed to become definite at shallower depths. The present findings demonstrate that the variations of phytoplankton stocks as well as environmental conditions within a limited period can be very intensive in midsummer.

1. Introduction

It is generally known that seasonal changes of solar radiation, and temperature and stability of water in the upper layer are the major environmental factors governing the variation of microplankton productivity in the polar seas. The stability of water is largely controlled by melting sea ice in summer (GRAN, 1931). The melting ice also plays an important role to seed the water column with microalgae grown in and on the ice (HASLE, 1969). Although low temperature, especially of the Antarctic waters, may suppress phytoplankton productivity (NEORI and HOLM-HANSEN, 1982), it cannot be a significant factor affecting biological seasonality in the permanently ice-covered area; annual variation in temperature, *e.g.*, in the coastal water near Syowa Station, is usually as narrow as $-1.9 \sim -1.4°C$ and $-2.0 \sim -0.8°C$ even in the extreme case (FUKUCHI *et al.*, 1984, 1985). Unlike in the arctoboreal seas in the northern hemisphere, the upper layer is hardly stratified thermally in the Antarctic seas, because there is no prevailing surface current of warm water from the low latitudes. Ice melt only is causative of

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the stabilization of high Antarctic waters.

In the coastal waters near Syowa Station, solar radiation increases from negligibly low value in August to the maximum in late November. The maximum is sustained till early January. The sea ice consequently melts slowly in early stages but most extensively in January (HOSHIAI, 1969a). During these courses, phytoplankton standing crops in the water column below the ice start to increase at the end of November, attain to the maximum in summer, from late December to early February and decrease soon after (HOSHIAI, 1969b; FUKUCHI et al., 1984, 1985). The same seasonal variation had been observed near Mawson (BUNT, 1960). The previous findings indicate that the planktonic phenomenon varies very widely within a short summer.

In this paper we describe the short-term variation in abundances of phytoplankters and other microplankters as well as variation in the environmental conditions in the coastal water near Syowa Station (69°00′S, 39°35′E), which were observed during our limited stay at the station in January 1984. The present part of our paper deals with chemical property of water as an agent in variation of microplankters which will be described in the second part of our studies.

2. Methods and Materials

Water samples were collected from 6 layers with a 5-liter Van Dorn bottle at Station 78 fixed at the location of 36.5 m depth in the Kita-no-ura Cove north of Syowa Station (Fig. 1). Vertical plankton net hauls and digital bathythermograph (DBT) casts from the bottom to the surface were also done. All samplings were carried out every two days during the period from 10 to 24 January 1984. After 24 January the condition of sea ice became insecure.
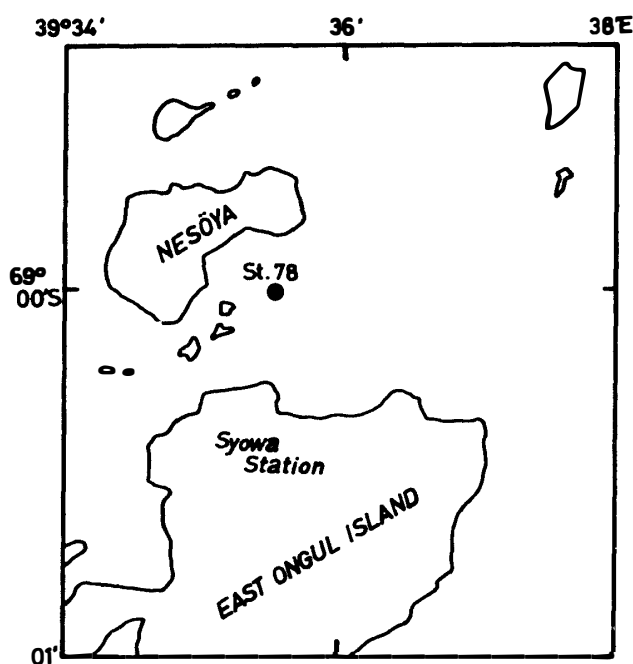

Fig. 1. Location of Stn. 78 in the fast ice covered
Kita-no-ura Cove north of Syowa Station.

A hydrohole, *ca.* 1 m × 1 m in opening, was bored into the 1.2 m thick fast ice on 10 January. Six water samples were collected from 0, 5, 10, 20, 30 and 36.2 m depths on 10 January, and 0, 2.5, 5, 10, 25 and 36.2 m depths on the other days. Since we used a bucket to sample the surface water, "the surface water" in our studies was the water which had been exposed to air and direct sunlight, not the water just beneath the ice.

From every sample six aliquots were subsampled to determine dissolved oxygen by the Winkler's method with a Metrhom E415-20S titrator, salinity with an AutoLab 601MKIII inductive salinometer, pH with a Denki Kagaku Keiki HG-3 digital pH meter, phytoplankton chlorophyll by the fluorometric method (YENTSCH and MENZEL, 1963), various nutrients including silicate by the molybdenum yellow method, phosphate by the molybdenum blue method, nitrate by modified Morris and Riley method, nitrite using sulphanilamide and N-(1-naphthyl)-ethylenediamine 2 HCl and ammonium by the indophenol method, and microplankton abundance by the Utermöl method. Except the last, these determinations were completed in February 1984. The details of the methods have been described by STRICKLAND and PARSONS (1968) and KISHÔCHÔ (1981) and the results are published in IWANAMI and FUTATSUMACHI (1986) and HAMADA *et al.* (1985).

Since DBT did not work properly after 16 January, a complete thermal profile could not be obtained. The data obtained before 16 January and those on the surface temperature, however, indicate that variation of temperature was negligibly small especially below 5 m depth. The surface temperature increased very slightly from $-1.9°C$ on the first day to $-1.7°C$ on the last day. Little variability of temperature is a characteristic of the area (*cf.* HOSHIAI, 1969b; FUKUCHI *et al.*, 1984, 1985).

3. Results and Discussion

Because salinity of sea ice is as low as 3–6 (HOSHIAI, 1977; WAKATSUCHI, 1981), the water mass of very low salinity is formed just underneath the ice in summer. Such a low salinity water differently affects productivities of different taxa of unicellular algae originated from the ice algae and plankton populations in the underlying layer (BUNT, 1960; BURSA, 1961; GRANT and HORNER, 1976; HSIAO *et al.*, 1977). Consequently, the succession of algal populations should be different between two layers in and under the surface water just beneath the ice (BUNT, 1960; HOSHIAI, 1969b).

The thickness of the surface water largely depends on the extent of hollows on the undersurface of the ice. It may not be very thick owing to a possible vertical mixing by tidal current under the ice, although sometimes it reaches 1 m (ENDO, 1970; WATANABE *et al.*, 1982). Sampling of such a thin layer might be difficult even by SCUBA diving. However, since the ice-melted water accumulates at the surface in a hydrohole, the analogous dilution process of sea water and the following succession of plankton community to those which possibly proceed in an inaccessible layer just beneath the ice can be observed in the surface water in the hole.

3.1. *Stability of water*

Figures 2 and 3 show changes in salinity and density of water. Salinity of the surface water rapidly decreased and the water finally turned into freshwater ($S < 1.0$).
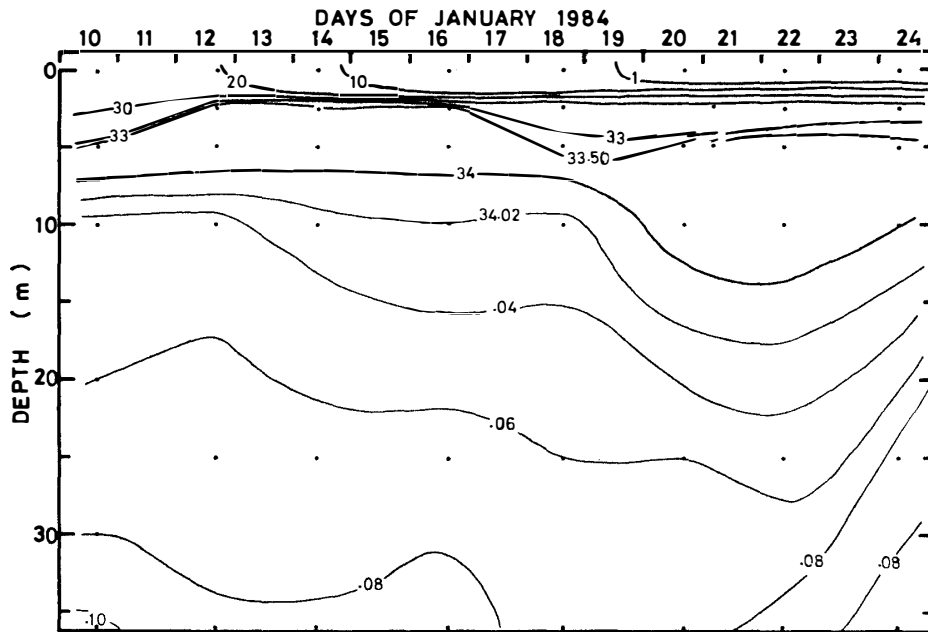
Fig. 2.   Temporal variation of salinity in vertical plane from the surface to near
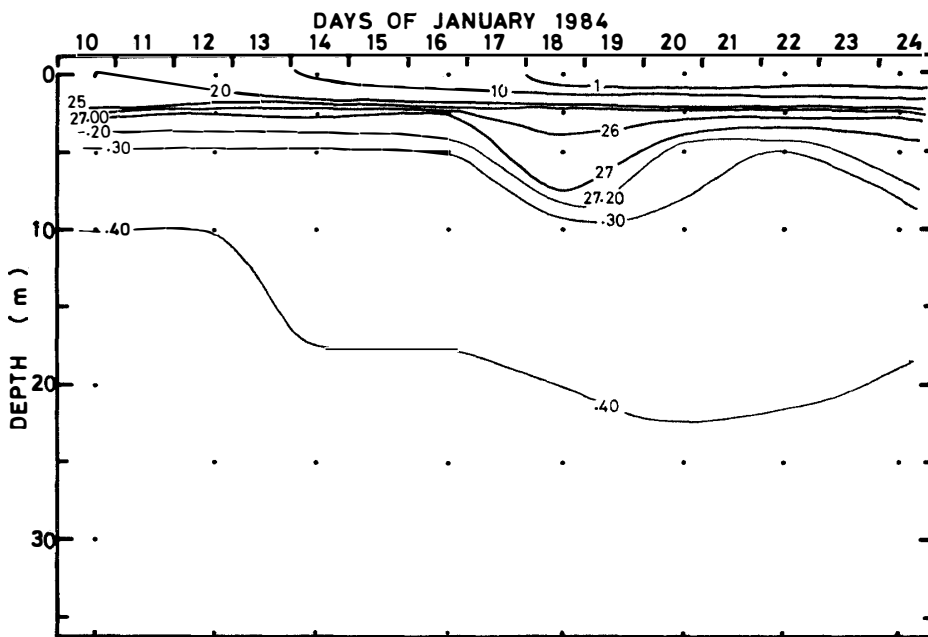bottom observed during the period from 10 to 24 January 1984.

Fig. 3.   Variation of density of sea water, σ_t.

Below 5 m depth, variation in salinity was relatively small with both time and depth, while it tended to decrease slightly in the entire water column in the latter half of the investigation period.

Because vertical change in temperature was little, stability of water depended upon the vertical gradient of salinity.   A pycnocline was formed between 5 and 10 m on 10

and 12 January, and became definite at a shallower depth as ice melted.   The surface water was finally separated from the underlying water.

3.2. Nutrients

Ice melt might not contribute to nutrients of the sea water because the ice contains little nutrients.   Rich nutrients accumulated in the deep layer hardly came up to the surface water due to the well-defined pycnocline.   Therefore, nutrient concentration in the surface water simply decreased with time by dilution with ice-melted water and/or uptake by phytoplankton until abundant bacteria, zooplankton or other animals regenerate the nutrients there.

Silicate-Si (Fig. 4):   Time course of depletion of silicate at the surface was typical of the isolated water mass.   A discontinuity layer of silicate developed following the halocline (Fig. 2).   This fact evidently indicates that the ice-melted water could not enrich the sea water and no extensive regenerators of silicate inhabited the surface layer.   Among the higher concentration in the bottom layer which indicates the regeneration at the bottom, a low value was observed on 18 January.   Stocks of the other nutrients were again small there.   This was probably due to temporal consumption by phytoplankton as will be described later.
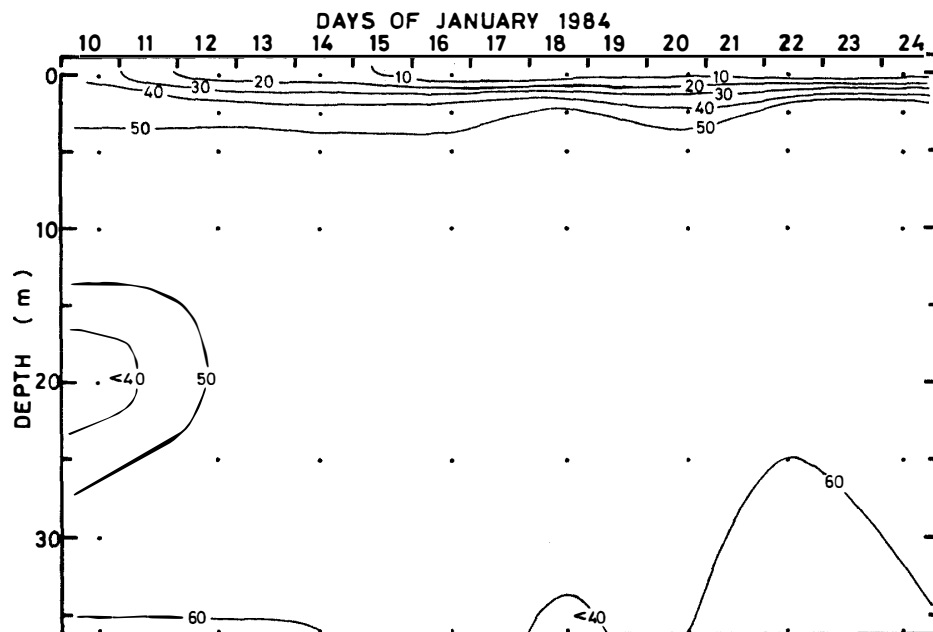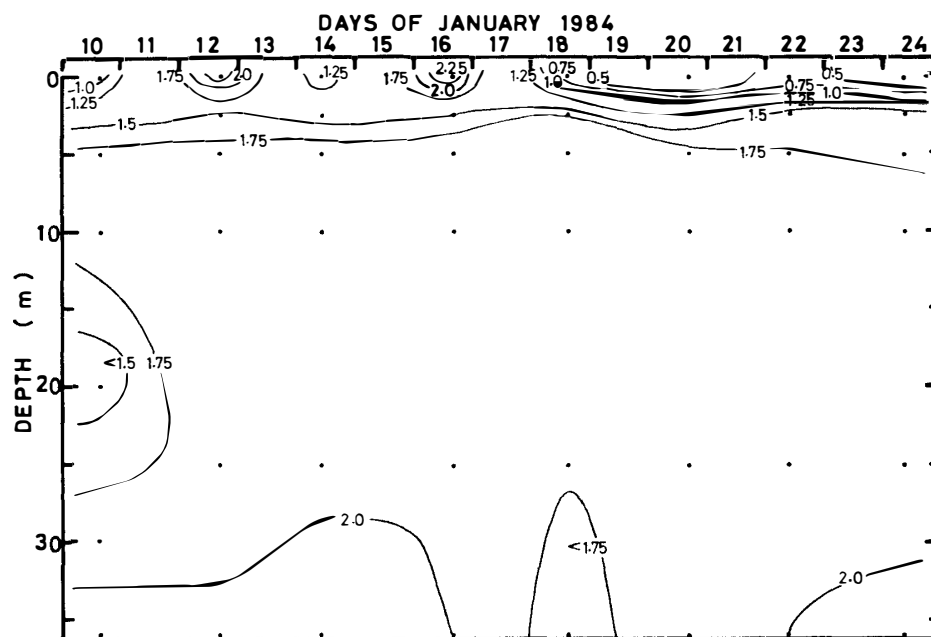

Fig. 4.   Variation of silicate (μg at Si/l).

Phosphate-P (Fig. 5):   Temporal and spatial variation of phosphate in the water column below 5 m depth was identical with that of silicate.   Unlike silicate, however, phosphate varied in mosaic manner in the surface layer; high and low concentrations occurred alternatively.   If we delete the temporally higher values on 12 and 16 January, the background level of phosphate can be seen to decrease from ca. 1 to well less than 0.5 μg at P/l within first 10 days.   The intermittent increases to more than double of

the preceding concentration could not be attributable to the constant regeneration by bacteria or zooplankton but resulted from bulk excretion of large animals. We frequently found pups of the Weddell seal lying on the ice around the hydrohole. Because there were no openings such as tide crack on ice, the pups must have swum in and out through our hydrohole. It was reported by MATSUDA (1963) that they stay on the ice in the daytime but swim under the ice at night.

Fig. 5.   Variation of phosphate (μg at P/l).

Fig. 6.   Variation of nitrate (μg at N/l).   A contour of 55 μg at N/l indicating the maximum is also given.

Nitrate-N (Fig. 6): Depletion of nitrate in the surface water occurred rapidly within first 4 days. While silicate and phosphate remained at a very low but detectable lebel, nitrate was completely removed after 14 January. In the water column below 5 m depth, apparent nitrate consumption was not perceived in the first half. It became perceivable after 18 January but very slightly. Such a very slow consumption in the subsurface layer was also common among silicate and phosphate.

Nitrite-N (Fig. 7): Vertical distribution and temporal variation of nitrite were quite different from those of the preceding three elements. The most characteristic feature was the development and shift of the maximum layer with time. While the maximum was observed at the surface on 10 January, after the nitrate was depleted in the surface layer (after 14 January) the maximum of nitrite occurred at 5-10 m depth and then shifted above and developed at 2.5 m depth in the latter half of the investigation period.
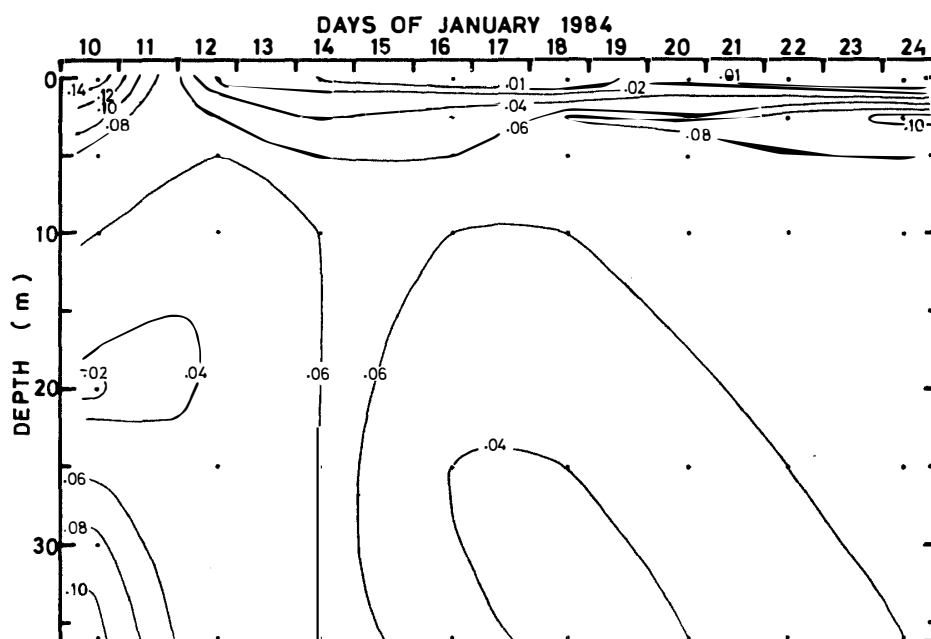

Fig. 7.   Variation of nitrite (μg at N/l).

In the sea areas where nitrate in the surface layer is depleted, nitrite concentration tends to increase in the subsurface layer where nitrate supplied constantly from the deeper layer is reduced by phytoplankton. Such a maximum is formed in the lower part of the active photosynthetic layer (WADA, 1984). Therefore, the developmental course of nitrite maximum just mentioned above indicates the temporal variation of the vertical position of the main photosynthetic layer in the present area. It can be supposed that a broad photosynthetic layer existed between the surface and 10 m depth on 14–16 January and then the sharp photosynthetic maximum was formed within a thin layer between the surface and the 2.5 m depth from 18 January onward. Although we missed the layer, chlorophyll and oxygen distribution to be described later would support this.

Ammonium-N (Fig. 8): Temporal variation of ammonium in the surface water which was probably agitated by excretion of seals as observed in phosphate was abrupt and inconsistent. Although the background concentration increased with depth in phosphate, that of ammonium generally decreased downwards. The largest stock in one cubic meter of the surface water (5.7 mg at N) on 16 January exceeded 66% of integrated stocks throughout the water column below 2.5 m depth (8.5 mg at N/m²). Equivalent value in phosphate was less than 4%. This fact suggests that excreta
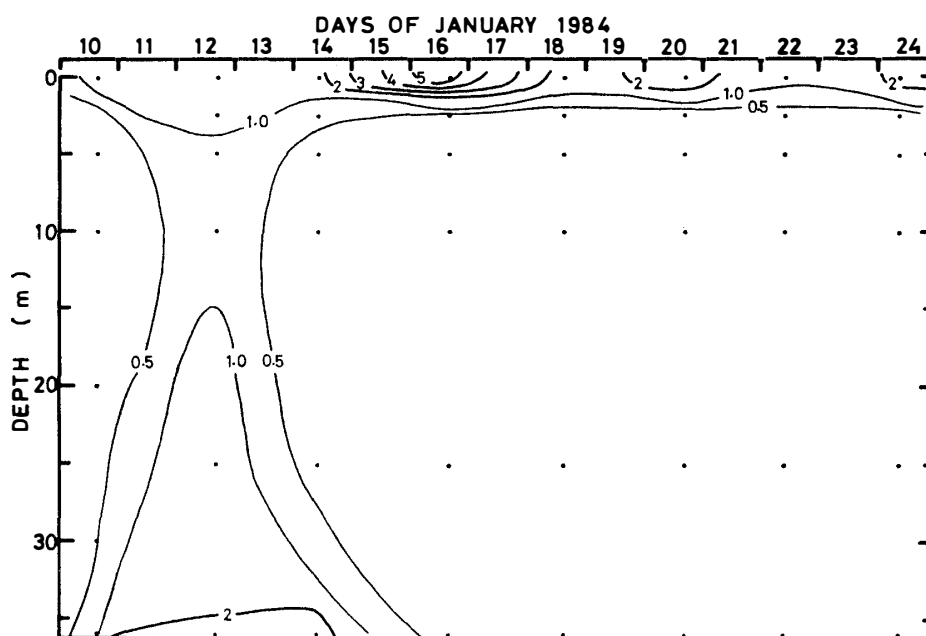

Fig. 8.   Variation of ammonium (μg at N/l).
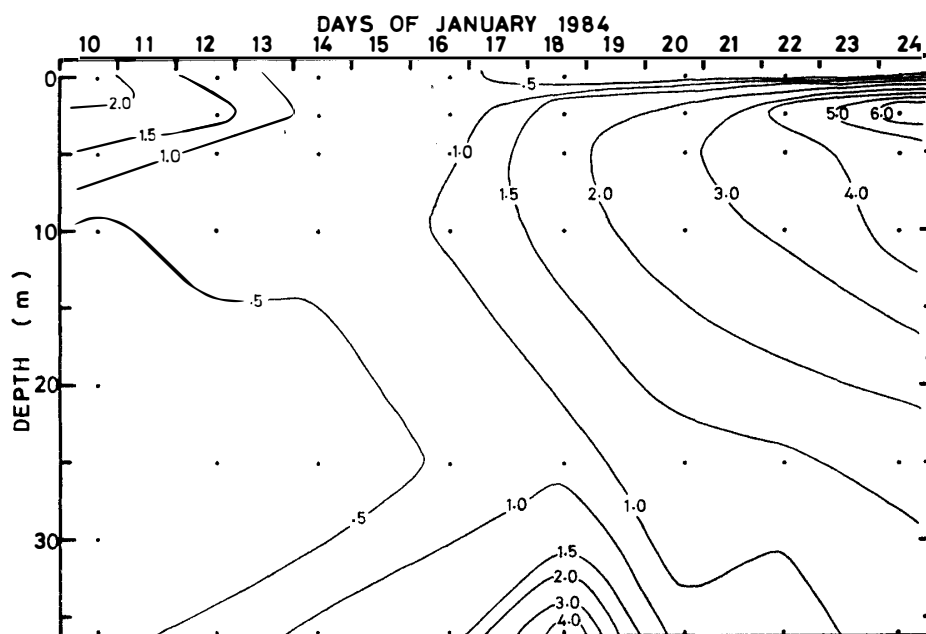

Fig. 9.   Variation of chlorophyll a (μg/l).

of large animals such as seals and penguins can be a main source of ammonium in the Antarctic coastal waters.

Chlorophyll *a* (Fig. 9): On the first day the maximum value of chlorophyll concentration was observed at the surface. This was possibly due to microalgae released from the undersurface of sea ice which was cut and removed to open the hydrohole. Colonies of microalgae were actually found on the ice removed from the hole. This maximum value (2.29 μg Chl. *a*/*l*) then simply decreased with time to less than 0.2 μg/*l* in the surface water. During this course the maximum layer shifted from the surface to 5–10 m layer on 12–20 January and finally settled at 2.5 m depth, while other maxima occurred in the bottom layer on 14–18 January. The contours in the first half of the investigation period suggest that the latter maxima had been formed partly by phytoplankton which sunk from the surface layer.

An exemplary developmental process of the subsurface maximum layer of chlorophyll can be seen in the latter half of the investigation period. On 16 January an inconspicuous maximum appeared at 10 m and turned into a perceptible but broad maximum on 18 January. Thereafter, concentration of chlorophyll increased in the water column below 2.5 m but decreased in the surface water on the one side, and the subsurface maximum tended to develop into a thinner layer at the shallower depth on the other side. On the last day the striking maximum was defined in the lower part of the pycnocline (*cf.* Fig. 3). Such a vertical position of the subsurface maximum (lower part of pycnocline) has been observed commonly over the oligotrophic sea areas where nutrients in the upper layer are easily depleted and a few schemes of its developmental process were argued (*e.g.*, STEELE and YENTSCH, 1960; ANDERSON, 1969; SAIJO *et al.*, 1969; VINOGRADOV *et al.*, 1970). In this investigation it is most likely that phytoplankton formed the maximum in a pycnocline defined well at the shallower depth where the light condition was more preferable, avoiding nutrient-poor surface water and poorly lighted deeper layers. The present observed process shows some similarities to the schemes proposed by ANDERSON (1969) and VINOGRADOV *et al.* (1970). This will be discussed in the subsequent paper with data on species composition of the phytoplankton populations.

Important, from the viewpoint of this paper, is the fact that an almost complete developmental course of subsurface maximum of chlorophyll can be observed within only two weeks. This fact evidently describes the abruptness of the summer plankton phenomena in the high Antarctic seas. Integrated chlorophyll stocks throughout the whole water column also increased rapidly from 20.5 to 103.8 mg Chl. *a*/m^2 within two weeks. One must pay careful attention when he evaluates the plankton productivity in those seas from the data obtained in a limited period.

Dissolved oxygen (Figs. 10 and 11): Dissolved oxygen decreased with time at the surface where nutrient depletion and consequent decline of chlorophyll stocks gradually progressed. Since salinity was also gradually diluted, degree of saturation of measured oxygen rapidly decreased, *i.e.*, from over 100% on 10–12 January down to less than 60% on the last day. The oxygen-maximum layer shifted from the surface to 5 m depth on 16 January and then settled at 2.5 m depth. In the latter half of the investigation period, the oxygen content of underlying waters also increased. These temporal variations were coincident with those of chlorophyll *a* (Fig. 9).
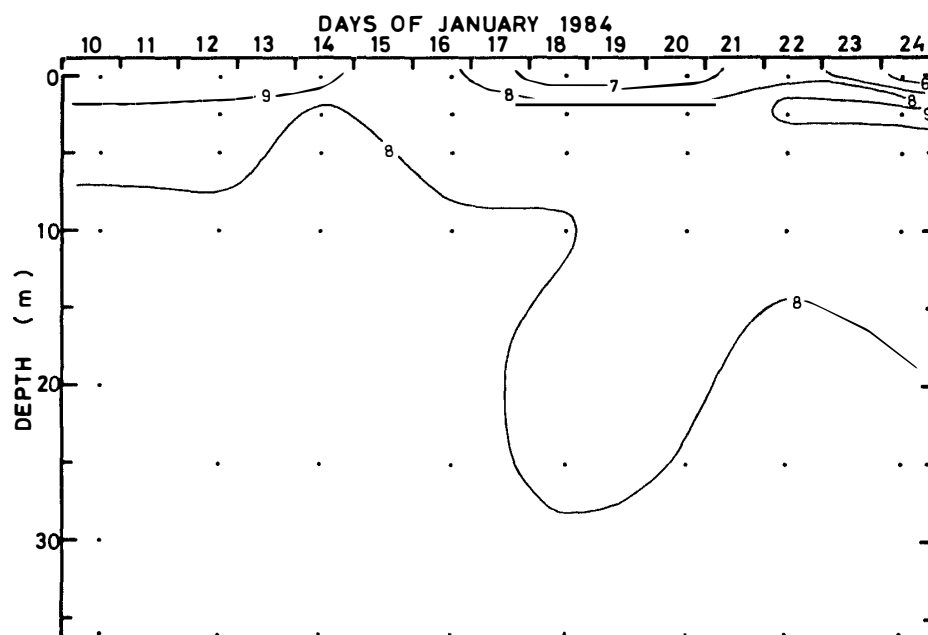
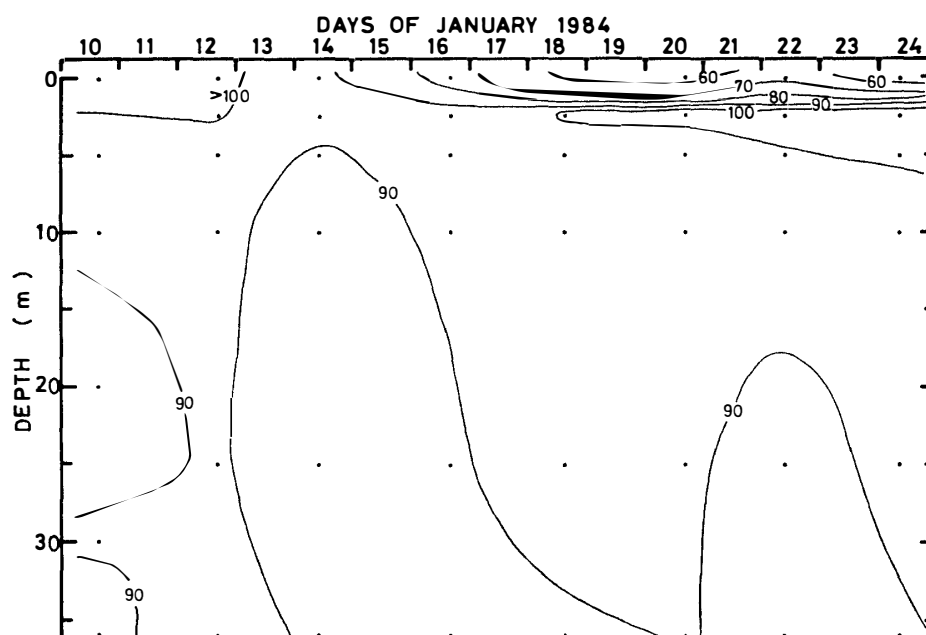Fig. 10.   Variation in concentration of dissolved oxygen (ml O_2/l).

Fig. 11.   Variation in saturation of oxygen (%).

Despite of surprisingly large biomasses of the benthic animals in this area (NAKA-JIMA et al., 1982; HAMADA et al., 1986), oxygen concentration in the bottom layer was not low, exceeding 7.33 ml O_2/l or 87% in saturation. Low ammonium content of the bottom water in general was also contradictory. Vertical distribution of other nutrients and chlorophyll a did not indicate active mixing of the bottom water with overlying waters. These imply that the oxygen consumed by thriving benthic animals

was compensated with photosynthesis *in situ* to a certain extent. The absolute size of chlorophyll stocks in the bottom layer was significantly large (Fig. 9). Ammonium excreted by the animals might be rapidly and directly uptaken by microalgae in the layer (*cf.* HARRIS, 1959) prior to nitrate uptake (*cf.* LEHMAN *et al.*, 1975). If so, accumulation of ammonium and nitrite would not occur. The same can be possible when benthic macrophytes flourish and/or metabolic activity of benthic animals is very low. Biomass of the macrophytes was small in this area (HAMADA *et al.*, 1986), and instead of them diatom colonies had been found on the bottom (WATANABE *et al.*, 1982; and *cf.* GRUZOV, 1977). We have no sufficient information about the activity of the animals so far, while it can be reasonably supposed that their activity is suppressed by low temperature.

3.3. Short-term variation of chemical properties of the surface water

For the reason mentioned above (p. 3), we can estimate the possible factors controlling nutrient levels, which govern within the layer of low salinity water just beneath the ice, from the observed data in the surface water in the hydrohole. Table 1 shows time courses of dilution of salinity and variation of nutrients and chlorophyll *a* in the surface water. Because the salt content of sea ice is very small (HOSHIAI, 1977; WAKATSUCHI, 1981), percentage of salinity value observed on any particular day to the initial value (on 10 January) indicates the degree of dilution of sea water with ice-melted water. By comparing the percentage of nutrients, which was computed in the same manner, with this dilution index, net consumption of nutrients can be known. When the percentage of nutrients was lower than the dilution index, significant consumption was revealed. When the reverse was the case, excess input of nutrients was suggested. Dilution of salinity proceeded daily until the decline of salinity ceased on 20 January at 0.6–0.9 or *ca.* 3% in dilution index. These values might indicate an equilibrium level between the dilution/consumption and the diffusive input from the underlying layer. Decreases of silicate, nitrate and nitrite during 10–12 January were very rapid as compared with dilution of salinity and hence indicate active consumption in

Table 1. Variation of chemical properties of the surface water during 10–24 January 1984. Figures in parentheses denote the relative level of the observed values to the initial value on the 1st day (10/I) in %.

Day	10/I	12/I	14/I	16/I	18/I	20/I	22/I	24/I
Salinity	25.356	20.712 (81.7)	12.048 (47.5)	3.646 (14.4)	1.273 (5.0)	0.786 (3.1)	0.642 (2.5)	0.932 (3.7)
Silicate-Si (μg at/l)	38	13 (34.2)	14 (36.8)	6 (15.8)	3 (7.9)	5 (13.2)	3 (7.9)	2 (5.3)
Phosphate-P (μg at/l)	0.91	2.28 (251)	1.17 (129)	2.35 (258)	0.54 (59.3)	0.37 (40.7)	0.57 (62.6)	0.39 (42.9)
Nitrate-N (μg at/l)	13	2 (15.4)	0	0	0	0	0	0
Nitrite-N (μg at/l)	0.15	0.02 (13.3)	0.00	0.00	0.00	0.02 (13.3)	0.00	0.00
Ammonium-N (μg at/l)	0.2	1.9 (950)	1.5 (750)	5.7 (2850)	1.5 (750)	2.5 (1250)	1.2 (600)	2.1 (1050)
Chlorophyll *a* (μg/l)	2.289	1.343 (58.7)	0.698 (30.5)	0.595 (26.0)	0.224 (9.8)	0.116 (5.1)	0.169 (7.4)	0.278 (12.1)

the period.   After that, although the level of residual silicate varied in parallel with the dilution index, nitrate and nitrite were completely removed.   In ammonium an input probably due to excretion of Weddell seals always surpassed consumption and dilution.   Nevertheless, ammonium was not accumulated, and neither was nitrite. This suggests that ammonium excreted had been uptaken constantly by phytoplankton. Mode of variation in phosphate was intermediate of those elements described above; while consumption or dilution became apparent in the latter half of the investigation period, the residual amount was still large.   Temporal input of phosphate was also demonstrated as in ammonium.   Consequently, phosphorous and nitrogen stocks fluctuated largely.

As a whole, shortage of phosphorus and nitrogen sources did not occur, while the level of silicate seems to have been insufficient in the latter half of the investigation period.   Such a condition should not always be unfavorable at least to phytoplankters other than diatoms and silicoflagellates.   However, extensive dilution with ice-melted water might be detrimental to most marine phytoplankters.   It is most likely that the extensive dilution, instead of nutrient depletion, was responsible for lowering the chlorophyll stocks in the surface water.   Species succession of phytoplankton community in the surface water as well as in the underlying layer will be described and discussed in the second part.

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