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Ecology of newly formed sea ice in the Weddell Sea, Antarctica Ⅰ. chlorophyll *a* and nutrients

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Abstract Textural composition, chlorophyll *a* and nutrients (phosphate, nitrate and silicate) of newly formed sea ice from the Weddell Sea, Antarctica, were analyzed during austral autumn in 1992. Frazil ice, congelation ice and mixed frazil/congelation ice were the main textural types. Mean concentrations of chlorophyll *a* and nutrients in sea ice were varied considerably with ice texture. High chlorophyll *a* occurred mostly in ice floes consisting predominantly or mainly of frazil ice. Nutrients showed an inverse relationship being significantly lower in frazil ice than in congelation ice. Similar observations were made for one year old sea ice.
Key words sea ice, chlorophyll *a*, nutrients, Antarctica.

1 Introduction

The importance of sea ice in the Antarctic marine ecosystem and biogeochemical processes has been emphasized in recent years (Legendre *et al*. 1992; Wang and Dieckmann 1993). Much work has been done on ecological studies on sea ice, particularly pack ice covering a vast area of the Southern Ocean (Garrison and Buck 1987; Spindler *et al*. 1990), since late of 1980's. Many of these studies have concentrated on the microbiota and the communities in sea ice. These are mostly carried out in austral spring and summer. As temperatures rise, ice floes begin to melt and disintegrate. Thus, destruction of ice texture must result in changes of ice ecology, including its physical and chemical properties. Therefore, it is necessary to investigate ice formation, its ecological structure and changes of environmental conditions, in particularly during seasons of new ice growth. This should be available to understand the pysical and chemical properties of sea ice, and the mechanism of ice community formation. This paper reports the results from sduties of ice textural composition, chlorophyll *a* and nutrients (phosphate, nitrate and silicate) of newly formed sea ice in the Weddell Sea, Antarctica.

2 Materials and Methods

(1) The investigation was carried out in the area of north-east Weddell Sea (67°～70°S, 4°～12°W) by POLARSTERN in the voyage "ANX/3" in March～May 1992. 22 ice stations were visited in 5 sections from the pack ice region down to the fast ice region (Fig. 1). Ice samples were collected from 9 stations. Two or three ice cores were taken at each ice station, and ice cores were cut up into sections at an interval of 10 cm and stored in polyethylenejars at −20℃ in the dark. Sea water samples were collected at the same time.

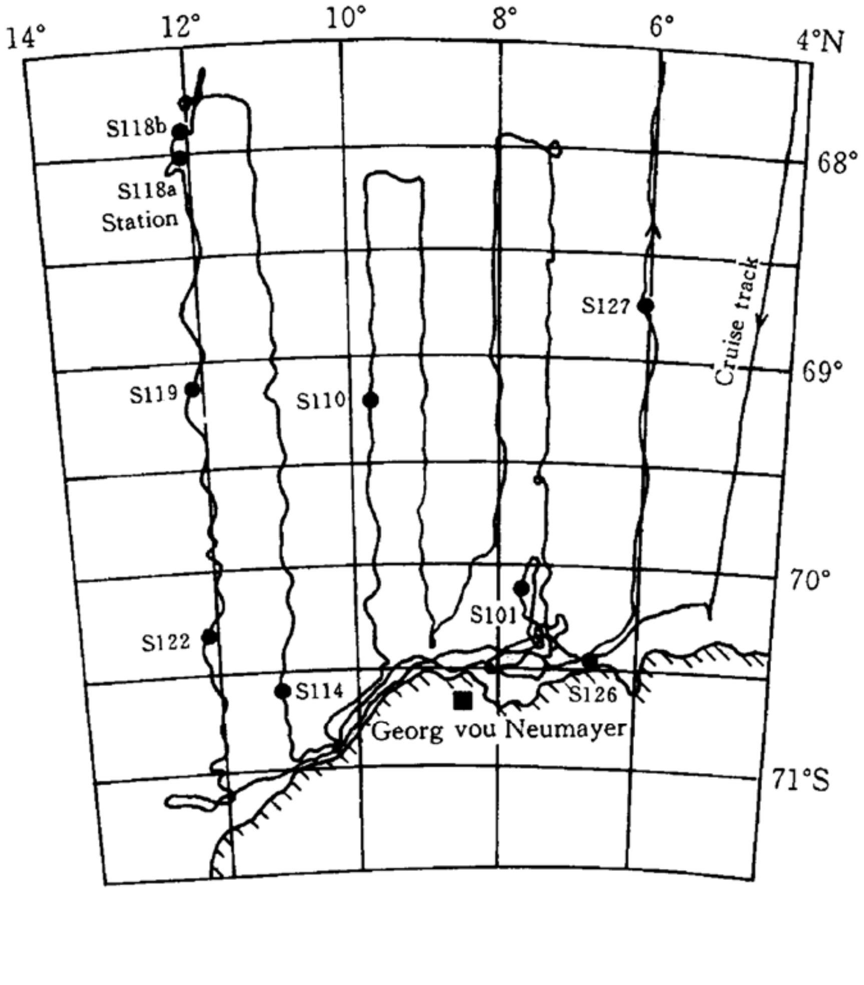

Fig. 1. Cruise track of 92 ANT/X3 and the ice stations.

(2) Ice samples were melted using 1:3 volume of ice sample and filtered sea water. Chlorophyll *a* in sea water and melted ice samples were measured using Turner Design Fluorometer (Parsons *et al*. 1984). Before measuring, samples were filtered through GF/F filters, which were then immediately homogenized in 10 ml of 90% Acetone, and centrifuged.

(3) Nutrient (NH_4、NO_3、NO_2、PO_4 and SiO_2) were analysed by autoanalyzer after the methods of Parsons *et al*. (1984).

(4) Sea ice structure was analysed according to Lange (1990).

3 Results and discussion

3.1 Environmental condition within sea ice

During the period of the cruise, air temperature ranged between −6.2℃ and −23.6℃. Lowest daily temperatures dropped from −9.8 at the biginning to −23.6℃ in the end. The efficiency of attenuation on temperature by surface snow layer was (−0.48±0.22) ℃/cm (if snow density is neglected, to see Table 1). The snow thickness could restrict photosynthesis of microalgae, particularly in the upper of ice.

Table 1. Relationship between the temperature of ice surface and snow cover on it

Ice station	Snow thickness/cm	Tss. /℃	Tsb. /℃	Tice/℃	Tv/℃·cm^{-1}
S101	3.5	−6.1	−5.4	−4.5	0.20
S114	5.0	−13.5	−9.4	−4.8	0.82
S118a	0.0	−6.8	−6.2	−4.6	-
S119	0.0	−15.6	−13.8	−10.9	-
S127	11.5	−8.1	−3.3	−2.7	0.44
S126	19.0	−14.4	−5.5	−4.5	0.47
S122	3.0	−7.6	−6.2	−6.0	0.47

Tss.: temperature on snow surface; Tsb.: temperature at snow bottom; Tice: temperature in the top 10 cm of ice; Tv: mean variate of temperature in ice.

3.2 Ice textural properties, distribution of salinity and temperature in sea ice

Figure 2 shows vertical distribution of temperature and salinity in ice at stations sampled. The decline in temperature is related to ice thickness. The temperature of

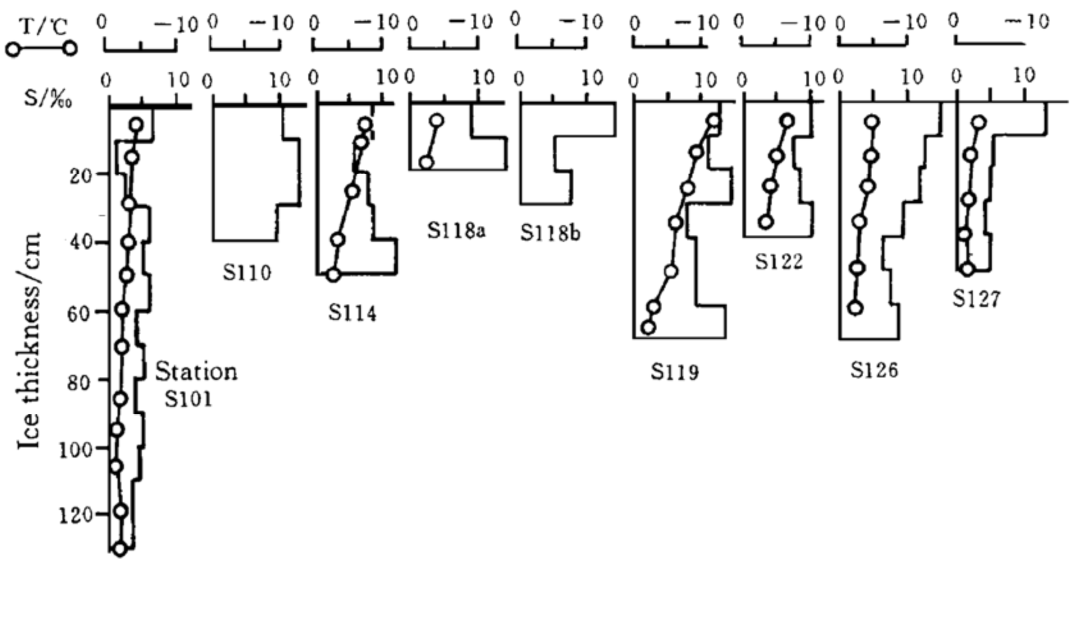

Fig. 2. Vertical distribution of temperature and salinity in sea ice of different stations.

ice surface is related to thickness of snow cover (sea Table 1). Temperature at the bottom of the ice was close to sea water temprature (-1.9 ± 0.1)℃. Salinity changes did not follow ice thickness. The salinity is usualy lower in old ice than that in newly formed ice. Mean salinity in one year old ice was 4.3 ‰, while it was >9 ‰ in newly formed ice. Dieckmann *et al.* (1991) reported that the young sea ice cores were distinguished from "old sea ice" cores from the Weddell Sea in winter, and that the high mean salinity of young ice was >8 ‰. This is in agreement with our results in the following seasons. Figure 3 shows the textural composition of sea ice from different ice cores. Frazil ice, columnar ice and mixed frazil/columnar were the three main textural types in most ice cores. Platelet ice was another textural type of ice, which was not common in this study. Physical processes of sea ice formation and the textural characteristics have been described by Clarke and Ackley (1984), Richter-Menge and Ackley (1990) and Lange (1990). It is explained simply here. Under an unstable (dynamic state) sea condition, many individual ice crystal in sea water occur as frazil ice (<1 mm). These ice crystals then cohere together and become granual ice (> 1 mm); under calm sea condition, the ice crystals congelate and grow with column shape. Thus, in the open sea, the ice forming is mostly under unstable condition and it mainly shows textural type of granular ice, such as the ice in station S118b, which was in north edge of pack ice, and that in S114, which located at a polynya open water. In comparison with this, the sea water near coast or iceself was in more stable situation. Here, ice floes stretch easier and become larger fast ice, which has main textural type of columnar ice, such as the ice in station S126. In mixed type, usualy the ice crystals texture alternatively bears frazil ice and congelation ice, such as in pack ice S110 and S122 (Fig. 3).

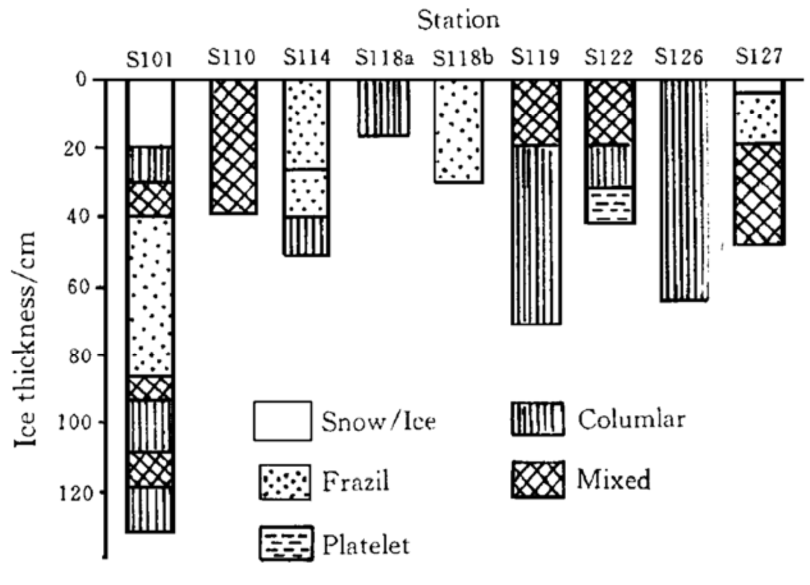

Fig. 3. Textural composition of seaice in the Weddell Sea, Antarctica.

The ice thickness is generally parallel to ice age. The older ice underwent variative sea conditions, mostly has thicker size and mixed with more complicated ice types. The ice core from station S101, for example, was 135 cm in thickness, with four different ice types. However, single type could be commonly seen in the ice developed shortly or younger ice, which usually have less thickness, such as in ice floes S114、S118.

3. 3 Chlorophyll a

The distribution of chlorophyll *a* in ice cores from 9 stations are shown in Fig. 4. The mean highest value was 24. 94 μg/L in S101, it was >10 μg/L in S110、S114、S118b、S122 and S127. The mean lowest value was 1. 04 μg/L and 0. 69 μg/L in S118a and S126 respectively. This indicates clearly that chlorophyll *a* in old ice was higher than in young ice. For instance, the total chlorophyll *a* concentration in one year old ice from S101 was 1. 9～36. 2 times higher than other ice cores of newly formed ice. It was also higher in newly formed pack ice cores than in young fast ice cores (S126). Figure 4 shows the vertical distribution of chlorophyll *a* in ice cores from different stations. Values of chlorophyll *a* were generally lower in both top and bottom ice layers. The highest value in one year old ice (S101) appeared in the middle (50～100 cm) of the ice core. This high concentration may have developed during the last spring and summer seasons at the time of the phytoplankton bloom. In contrast, the highest values in new ice are usually in the middle-lower part.

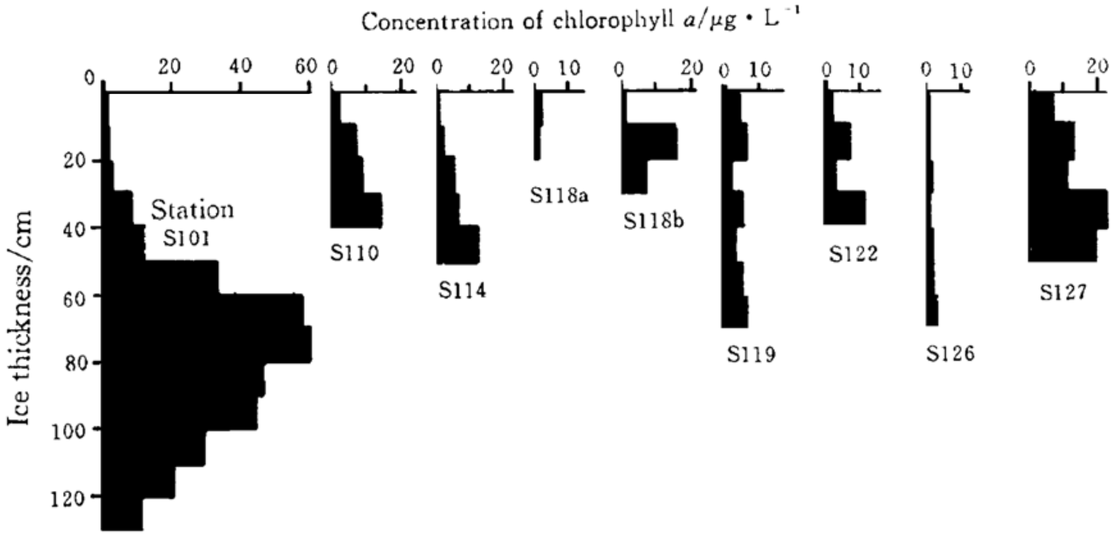

Fig. 4. Vertical distribution of chlorophyll *a* in sea ice from the Weddell Sea.

Concentrations of chlorophyll *a* in different texture of young and old ice cores are listed in Table 2. It is clear that the concentration of chlorophyll *a* in frazil ice are higher than in congelation ice, it is 1. 9 times as high as in congelation in the young sea ice, and 2. 6 times in the old sea ice. In mixed ice, the concentration of chlorophyll *a* is 8. 27 μg/L in the young ice, higher than in young frazil ice, and it is 25. 96 μg/L in the old sea ice, which is lower than in the old frazil ice. In comparison with the old and young ice, the chlorophyll *a* in the old frazil ice is 7 times higher, and 5 times higher in the old congelation ice. Total concentration (frazil+mixed+congelation) in the old ice is 4.8 times as high as in the young ice.

Table 2. Concentration of chlorophyll *a* (μg/L) in different textual types of sea ice

		Frazil	Mixed	Congelation	Mean
New ice	Mean value	5.86	8.27	3.17	5.48
	Standard deviation	4.84	7.67	3.85	4.24
	Range	0.59～15.5	0.37～23.89	0.05～13.21	0.69～13.3
	Samples n	9	12	16	8
Old ice	Mean value	41.44	25.96	16.02	26.50
	Standard deviation	20.05	-	11.10	-
	Range	11.03～59.89	-	2.34～28.29	-
	Samples n	5	-	4	-

Frazil ice develops as suspended crystals in turbulent sea waters, and because of its surface properties, particles in the water column adhere to the crystals. Garrison and Buck (1989) explained the harvesting of algae (mainly diatoms) and other materials. So that the ice floes formed in open water, such as S101, S110, S118b and S127, have more frazil and mixed frazil/columnar and there have higher concentrations of chlorophyll *a* (Fig. 2, 3). In contrast, ice from S118a, S119 and S126, formed under calm sea conditions, has more columnar ice with lower concentrations of chlorophyll *a* (Garrison *et al.* 1983). Thus, the content of chlorophyll *a* is related to physical characteristics (states) of the sea. In newly formed young ice, the concentration of chlorophyll *a* depends on its concentrations of the water column, where it is low (0.061 μg/L mean value in 0～1 m depth in this study).

Cell abundance and algal growth season are important in determining the concentration of chlorophyll *a* in sea ice. Hoshiai (1985) measured the contents of chlorophyll *a* in the sea ice near the Syowa Station in different seasons, he believed that an increase of algae cells occurred in spring-autumn period. Ice algae development in autumn was limited by an increased growth of sea ice. In other hand, in pack ice floes, the contents of chlorophyll *a* in sea ice are not directly related to the contents of chlorophyll *a* in water column, where the ice is located, because of the current and ice drift. In Figure 5, for example, the range of the concentration of chlorophyll *a* from the ice cores is 1.04～57.49 μg/L. As compared with this, it has small range of 0.11～0.22 μg/L, except in S126 (it is lowest, 0.06 μg/L), which is located in large area of fast ice, where the photosynthesis was weakened both in ice and water column, because of the thick ice covered largely and long.

3.4 Nutrients

Figure 6 shows the vertical distribution of nutrients (SiO_2, $NO_2+NO_3+NH_3$ and PO_4) in sea ice cores. Mean concentration of silicate (3.06 μmol/L) and nitrate (2.61 μmol/L) was lower in one year old ice (S101) than in newly formed ice (6.25～17.2 μmol/L and 2.93～9.58 μmol/L respectively), excepting phosphate (0.28 μmol/L), which varied considerably. Higher nutrients area occured in the middle to downward part of the old ice, and in the middle to upward part of young ice except S114.

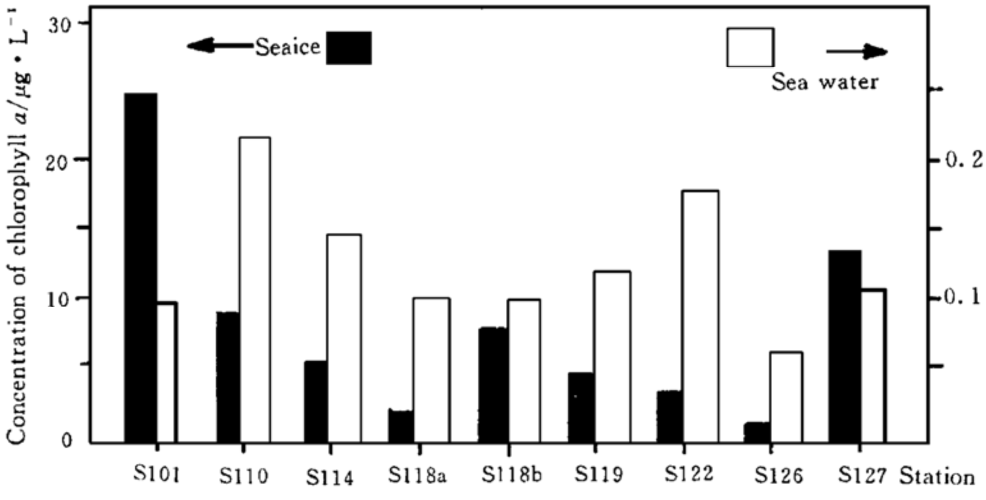

Fig. 5. Concentration of chlorophyll *a* in the ice and sea water.

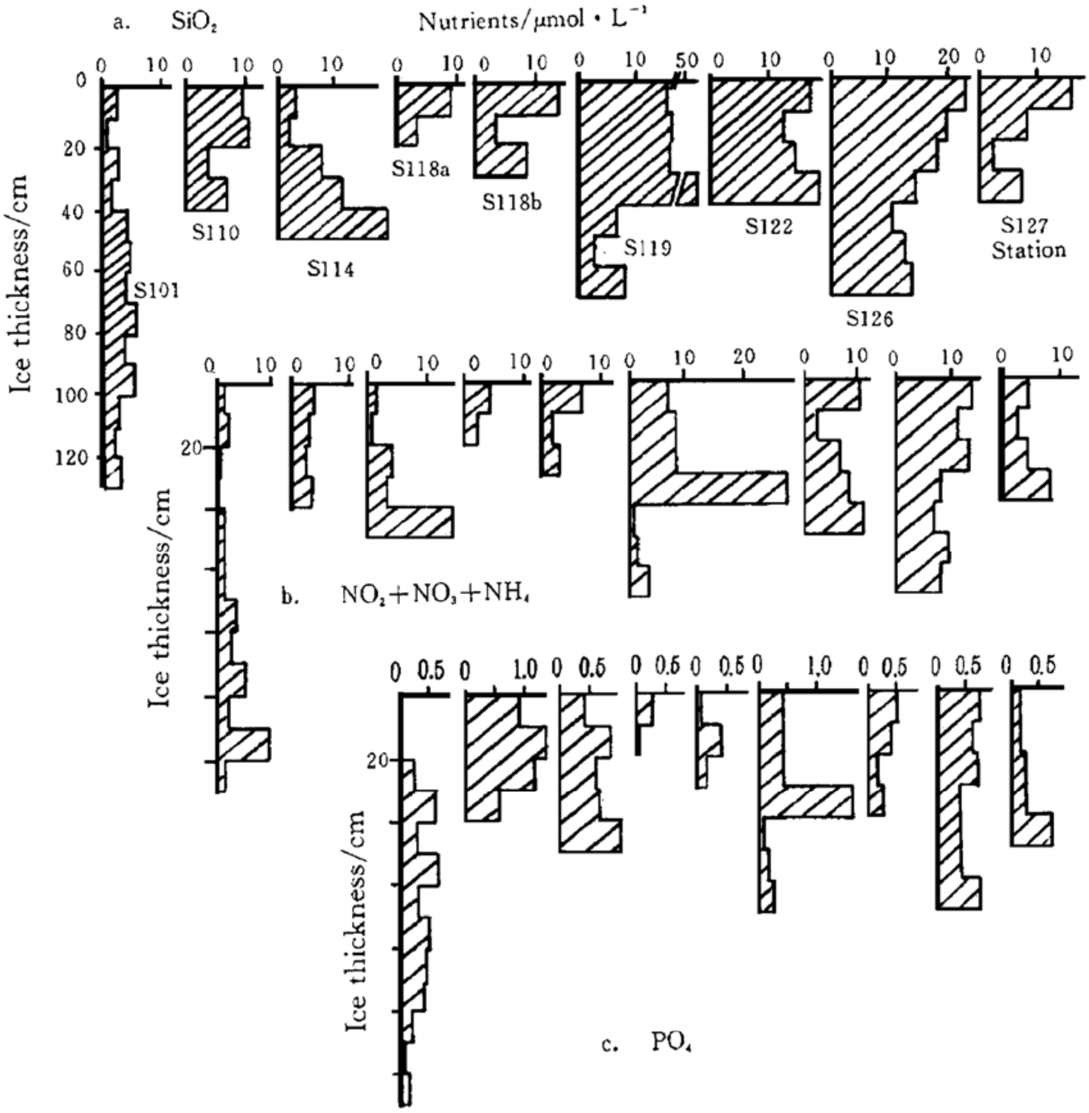

Fig. 6. Vertical distribution of nutrients in the sea ice from the Weddell Sea.

Table 3 shows concentration of nutrients in different textural types of old and young sea ice. In newly formed ice, evidently, the concentration of three main nutrients (Si, N and P) in frazil ice are much lower than that in congelation ice (less than mean value 11.06 μmol/L); Nitrate and, particularly, silicate in congelation ice are higher. The nutrient seems to be more complex in the old ice (Table 3). Concentrations of silicate and phosphate are markedly higher in frazil ice than that in congelation ice, and higher than the mean values (3.06 μmol/L and 0.28 μmol/L), but nitrate is lower (2.04 μmol/L< 2.61 μmol/L); However, nitrate in congelation ice is higher (3.3 μmol/L), and more than that in frazil ice (2.3 μmol/L). In mixed frazil/columnar ice, the values of silicate and nitrate are close to the mean values, but phosphate is lower. As compared with old ice, whatever the textural types the sea ice may be, the concentrations of three main nutrients are higher in newly formed ice.

Table 3. Concentration of nutrients (μmol/L) in different textural types of sea ice

		Frazil	Mixed	Congelation	Mean
New ice	Si	8.32	9.97	15.5	11.06
	N	3.38	5.27	8.49	5.56
	P	0.4	1.05	0.52	0.59
Old ice	Si	4.16	3.25	2.3	3.06
	N	2.04	2.89	3.3	2.61
	P	0.43	0.05	0.10	0.28

3.5 Chlorophyll a and nutrients

Previous studies have verified that the distribution and quantities of nutrients in sea ice are affected by physical properties of ice, as well as by metabolic activity within ice (Cota *et al.* 1990; Dieckmann *et al.* 1991). Dieckmann *et al.* (1991) reported that the changes in the nutrient concentrations are attributed to an increase in biological activity as the season progresses. In old ice, the nutrients are higher and sometimes exhausted. Algae in ice may cause fluctuation in silicate. Comparing the chlorophyll *a* (Fig. 4) with the nutrients (Fig. 6), the highest chlorophyll *a* (indicating highest biomass) corresponds to the lowest nutrients in station S101. Conversely, higher values of silicate appear in stations (Fig. 6a) with lower chlorophyll *a* , such as in S126、S122、S119 and S118a, in which the nutrients, particularly the silicate have not been exhausted. Higher silicate values mostly correspond with congelation ice (Fig. 3 and Table 3). Nitrate and phosphate show a similar tendency (Fig. 6b, 6c). These findings agree with results from the Weddell Sea by Dieckmann *et al.* (1991).

Figure 4 and Figure 6, also show that the higher values of chlorophyll *a* in newly formed ice appear mainly at the bottom. However, the distribution of lower values of nutrients is not paralleled, and the higher values may appear in the uppart of the ice (Fig. 6). This may indicate that nutrients are exhaused by the activity of algae and are complemented from sea water as well.

4 Conclusion

(1) Biological properties and structure of sea ice are dependent on ice type and

texture, which are related to the season of ice formation and development. Usually, more algae are found in the ice which has more frazil or mixed frazil/columnar ice, and more algae there are in the elder ice.

(2) Chemical charecteristics of sea ice are dependent mainly on the situation in sea water during ice formation and development. Because of the exhausting of nutrients in the ice by microorganisms, an inverse relationship develops between chrolophyll *a* and nutrients.

(3) In newly formed ice, growth of microorganisms is limited by a short season. Thus, the chlorophyll *a* and nutrients are basically similar to those in the sea; in the bottom or near ice bottom, particularly in newly formed ice, consumption of nutrients and it's complement from sea water may coexist on both because of exchange processes between ice and sea water.

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