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Seasonal change of ice algal and phytoplankton assemblages in the Nella Fjord near Zhongshan Station, East Antarctica

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Abstract The ice algal and phytoplankton assemblages were studied from Nella Fjord near Zhongshan Station, East Antarctica from April 12 to December 30, 1992. Algal blooms occurred about 3 cm thick on the bottom of sea ice in late April and mid November to early December respectively, and a phytoplankton bloom appeared in the underlying surface water in mid December following the spring ice algal bloom. The biomass in ice bottom was 1 to 3 orders of magnitude higher than that of surface water. *Amphiprora kjellmanii*, *Berkeleya* sp., *Navicula glaciei*, *Nitzschia barkelyi*, *N. cylindrus* / *N. curta*, *N. lecointei* and *Nitzschia* sp. were common in the sea ice temporarily or throughout the study period. The biomass in a certain ice segment was decreased gradually and the dominant species were usually succeeded as the season went on. *Nitzschia sublineata* and *Dactyliosolen antarctica* were two seasonal dominant species only observed in underlying water column. The assemblages between bottom of ice and underlying surface water were different except when spring ice algae bloomed. The evidence shows that the ice algal blooms occurred mainly by in situ growth of ice algae, and the phytoplankton bloom was mostly caused by the release of ice algae.
Key words Antarctica, sea ice, ice algae, phytoplankton, biomass, algal composition.

1 Introduction

The sea ice cover is significantly variable in the Antarctic Ocean, and the recent estimate suggests that more than 20% of the total biogenic carbon comes from sea ice (Legendre *et al*. 1992).

The investigations show that two ice algal blooms occur in the bottom of ice throughout the year in the fast ice zone (Hoshiai 1981; Perrin *et al*. 1987; Fiala and Delille 1999). The biomass is relatively lower in autumn bloom, and the chlorophyll *a* concentrations exceed 2000 mg/m^3 in spring bloom (Hoshiai 1981; Spindler *et al*. 1990). The blooms usually occur several centimeters thick on the bottom (McConville and Wetherbee 1983; Perrin *et al*. 1987; Watanabe and Satoh 1987; McMinn *et al*. 1999), and sometimes can be 20 cm on the bottom (Palmisano and Sullivan 1983). The biomass on the ice bottom is at least one magnitude higher than that in underlying surface water (Hoshiai 1981; Palmisano and Sullivan 1983) and chlorophyll *a* concentrations are usually less than 0.1 mg/m^3 under the ice in winter (Marra and Boardman 1984; Satoh *et al*. 1986). Only one chlorophyll *a* concentration peak occurs in the water column under the ice between January and mid February (Fukuchi *et al*. 1984; Satoh *et al*. 1986) with the values of more than 10 mg/m^3 during blooms (Satoh *et al*. 1986). But several peaks are also found (e.g. Krebs 1983; McMinn and Hodson 1993).

Little study has been made on the seasonal changes of algal assemblages within fast ice. Some good records of seasonal succession of dominant species have been found in the fast ice cores near Davis (Scott *et al*. 1994). Grossi and Sullivan (1985) attributed the vertical distribution patterns of ice algae in congelation ice to successive blooms in the water during the ice algal bloom period in austral spring. But the model study suggests that during blooms the ice algae are able to maintain their vertical position relative to the lower congelation ice margin and avoid to be incorporated into the crystal matrix as the ice sheet thickens (Arrigo *et al*. 1993).

The former works show that the ice algae and phytoplankton nearshore may be uncoupling (McConville and Wetherbee 1983; Grossi and Sullivan 1985), but some researches also show that they are related at least during the spring bloom with sea surface covered by sea ice (Krebs 1983). The study in Allis Fjord near Davis Station shows that there are two phytoplankton blooms (i.e. spring and summer blooms), and the phytoplankton communities in spring bloom are from ice algal communities on the ice bottom (McMinn and Hodson 1993). Further study suggests that algal seeding of phytoplankton from fast-ice is not significant (McMinn 1996).

This paper aims through the comparison of chlorophyll *a* concentrations, the abundance and composition of dominant species in the sea ice and underlying water column, at the study of the seasonal changes of ice algae and phytoplankton with reference to their relationship.

2 Materials and methods

The study was made at station 4 in Nella Fjord near Zhongshan Station (69°22′24″S, 76°22′40″E) from April 12 to December 30, 1992 (He and Chen 1996). The site had 103.5 m in depth.

Ice cores were taken with a 7.6 cm (internal diameter) ice auger, and the covered-snow and ice thicknesses were measured. Water samples were collected with a Kemmerer water bottle of 2.5 litres at 0, 5, 10, 25, 50 m and 100 m depths through the ice hole. The cores were cut into 10 cm segments from the surface to bottom and naturally melted in the dark room at the temperature of 5 – 10℃. The colored segments of ice bottom in the autumn and spring were treated separately.

200 ml of each melted ice-core sample as well as 1 litre of each sea water sample was filtered on a 0.45 μm HA Millipore membrane, then chlorophyll *a* concentrations were measured according to Jeffrey and Humphrey (1975), by using a spectrophotometer after 24 h extraction with 90% acetone in the dark room at − 20℃. The remainder of each sample was concentrated by filtration, preserved within buffered glutaraldehyde (ca. 1.5% final concentrations) and stored in the dark room at 4℃. Algal enumeration was made by phase-contrast method under a Zeiss Axioskop 50 microscope, and species identification was carried out under Zeiss microscope or a HITACHI S-520 scanning electron microscope.

3 Results

Ice cover formed in late March, grew stably and reached the highest thickness of 160 cm in early December, then decreased because of melting of ice bottom. Little covered-snow was observed in most of time with the maximum depth of 30 cm in 15 May (Fig. 1).

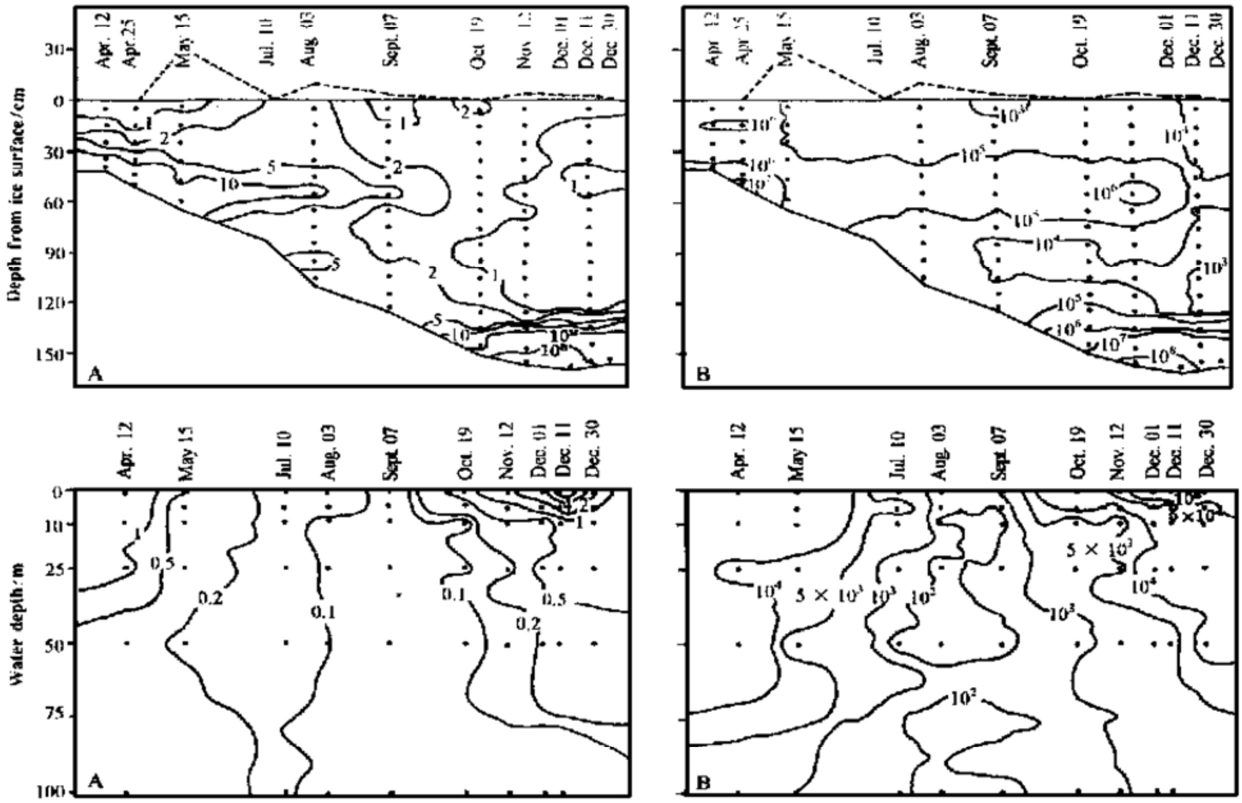

Fig. 1. The profiles showing the seasonal change of chlorophyll *a* concentrations (A: mg/m^3) and algal abundance (B: cells/l) in the sea ice and underlying water column. Dash line refers to depths of covered snow.

Ice algal blooms occurred about 3 cm on the bottom of ice in late April and mid November to early December respectively (Fig. 1). The chlorophyll *a* concentrations within ice decreased gradually and dropped to less than 1 mg/m^3 in mid December. Higher biomass was corresponding to the blooms, with the chlorophyll *a* concentrations as high as 88.3 mg/m^3 or more than 10^3 mg/m^3, and the algal abundance as high as 3.5×10^6 cells/l and 1.56×10^8 cells/l respectively. In August and September, because of the lower values in the ice bottom, the peak values occurred in the interior segment where the autumn ice algal bloom had occurred. In mid December, the abundance dropped to less than 10^4 cell/l in most of upper segments.

In underlying water column the phytoplankton biomass was relatively higher in the upper layer. It decreased obviously after ice was formed, and dropped to less than 0.2 mg/m^3 in July. The lowest values of less than 0.1 mg/m^3 occurred in September in all water layers, and then increased again, especially in the upper layers. Only one bloom was observed in the surface water with the value of 21 mg/m^3 in mid December, about one month later than the beginning of spring ice algal bloom. The vertical variation and seasonal change of algal abundance were very similar to those of chlorophyll *a* concentrations. Seasonal change of biomass in the upper layer of water column was similar to that of ice bottom with the lowest values occurring in the winter and early spring. But chlorophyll *a* concentrations were 1 to 3 orders of magnitude lower than those of ice bottom and the algal abundances were 2 to 3 orders of magnitude lower than those of ice bottom throughout the study period (Fig. 1, Table 1).

Table 1. Seasonal changes in the abundance of main ice algae and the underlying phytoplankton (percent abundance≥1%).

Sampling data	Apr. 12		May 15		Aug. 02		Sep. 07		Oct. 19		Nov. 12		Dec. 11	
	ice	water	ice	water	ice	water	ice	water	ice	water	ice	water	ice	water
Abundance of ice-water interface (10^5 cells/l)	13.6	0.257	11.4	0.169	0.459	0.00109	0.816	0.00902	72.6	0.360	2010	0.593	212	5.63
Integrated abundance* (10^8 cells/l)	9.09	9.63	1.71	4.23	1.22	0.00525	1.72	0.0244	9.88	2.24	71.0	2.74	18.8	16.1
Bacillariophyta	Percent abundance(%)													
Actinocyclus actinochilus (Ehr.) Simonsen	−	+	+	1.1	+	8.2	+	+	+	+	+	+	+	+
Amphiprora kjellmanii Cleve	−	−	1.3	−	+	−	+	+	1.0	47.3	69.9	67.2	26.0	81.4
Amphiprora sp.	−	−	+	−	+	4.2	−	+	−	−	−	−	−	−
Berkeleya sp.	−	−	−	−	−	+	+	2.5	−	−	4.3	1.0	22.6	+
Biddulphic striata Karsten	+	4.8	+	11.6	+	3.2	−	−	+	+	−	+	−	−
Coscinodiscus debilis Cleve	−	1.0	−	−	−	−	−	−	−	−	−	−	−	−
C. oculus-iridis Ehr.	−	+	−	1.2	−	+	+	+	+	−	+	+	+	−
Coscinodiscus spp.	+	4.3	+	5.0	−	11.4	+	+	−	+	+	+	+	+
Dactyliosolen antarctica Castr.	−	−	+	37.0	+	−	−	−	−	−	−	−	−	−
Eucampia antarctica Mang.	+	1.0	+	2.8	−	+	−	−	+	+	−	+	+	+
Navicula directa W. Smith	+	1.3	+	+	+	−	+	−	−	+	+	+	+	−
Nav. graciei V.H.	2.7	−	+	−	11.0	−	3.4	−	7.6	12.1	6.2	8.3	10.3	8.0
Nitzschia barkleyi Hust.	1.1	20.7	3.1	7.0	3.3	5.0	1.6	−	1.1	5.3	+	8.5	+	+
N. cylindrus (Grun.) Halse and *N. curta* (V.H.) Halse	25.9	40.2	16.7	15.1	7.4	34.0	8.5	32.4	76.9	15.8	3.6	10.5	+	2.8
N. lecointei V.H.	65.0	3.5	73.7	10.5	62.0	+	79.7	61.9	11.4	7.6	5.0	+	40.2	+
N. lineata (Casatr.) Halse	−	5.1	+	−	−	−	+	−	+	+	−	+	+	−
N. turgiduloides Halse	+	+	+	−	+	4.3	−	−	+	2.2	+	−	−	+
N. sublineata (Hust.) Halse	+	3.5	+	+	−	−	+	+	+	1.7	+	+	+	−
N. ritscheri (Hust.) Halse	+	+	−	+	−	3.3	+	−	+	+	+	1.7	+	−
Nitzschia sp.	+	+	4.1	+	8.9	13.0	5.6	−	1.0	+	+	+	+	+
R. alata cf. *graillima* (Cleve) Gran.	−	2.2	+	+	−	+	−	−	+	−	−	−	+	−
R. alata cf. *indica* (Peragallo) Gran.	−	+	−	1.2	−	−	+	−	+	−	+	−	+	−
Thallasiosira sp.	+	1.5	+	−	−	+	−	−	−	−	+	+	+	−
Pryyophyta														
Protoperidinium antarcticum (Sch.) Balech	+	+	+	−	+	6.3	+	+	+	+	+	−	+	−
Chrysophyta														
Distephanus speculum (Ehr.) Haeck.	+	1.8	−	+	−	−	+	−	+	+	−	+	+	−
Total percent abundance (%)	94.7	90.9	98.9	92.5	92.6	92.9	98.8	96.8	99.0	92.0	89.0	97.2	99.1	92.2

* : The abundance of water column is integrated value from 0 to 50 m; (−): None; (+): Less than 1%.

The dominant algal species and their percent abundance in per square meter are summarized in Table 1. *Amphiprora kjellmanii*, *Berkeleya* sp., *Navicula glaciei*, *Nitzschia barkelyi*, *N. cylindrus* / *N. curta*, *N. lecointei* and *Nitzschia* sp. were the most abundant species in ice, which occupied 89.0% to 99.1% of the total integrated abundance. Among them, *N. lecointei* was predominant from April to September, and *N. cylindrus* was also common during this period. In October, the percent abundance of *N. cylindrus* exceeded that of *N. lecointei*. The dominant species in November was *A. kjellmanii* because of the ice algal bloom and *A. kjellmanii*, *N. lecointei*, *Berkeleya* sp. and *Nav. glaciei* were common in mid December.

Fig. 2 shows that *N. lecointei* was predominated in sea ice, especially in the segment of 30 − 70 cm below ice surface, where it accounts for more than 40% of the cell numbers until late spring. But succession occurred seasonally in most ice segments. For

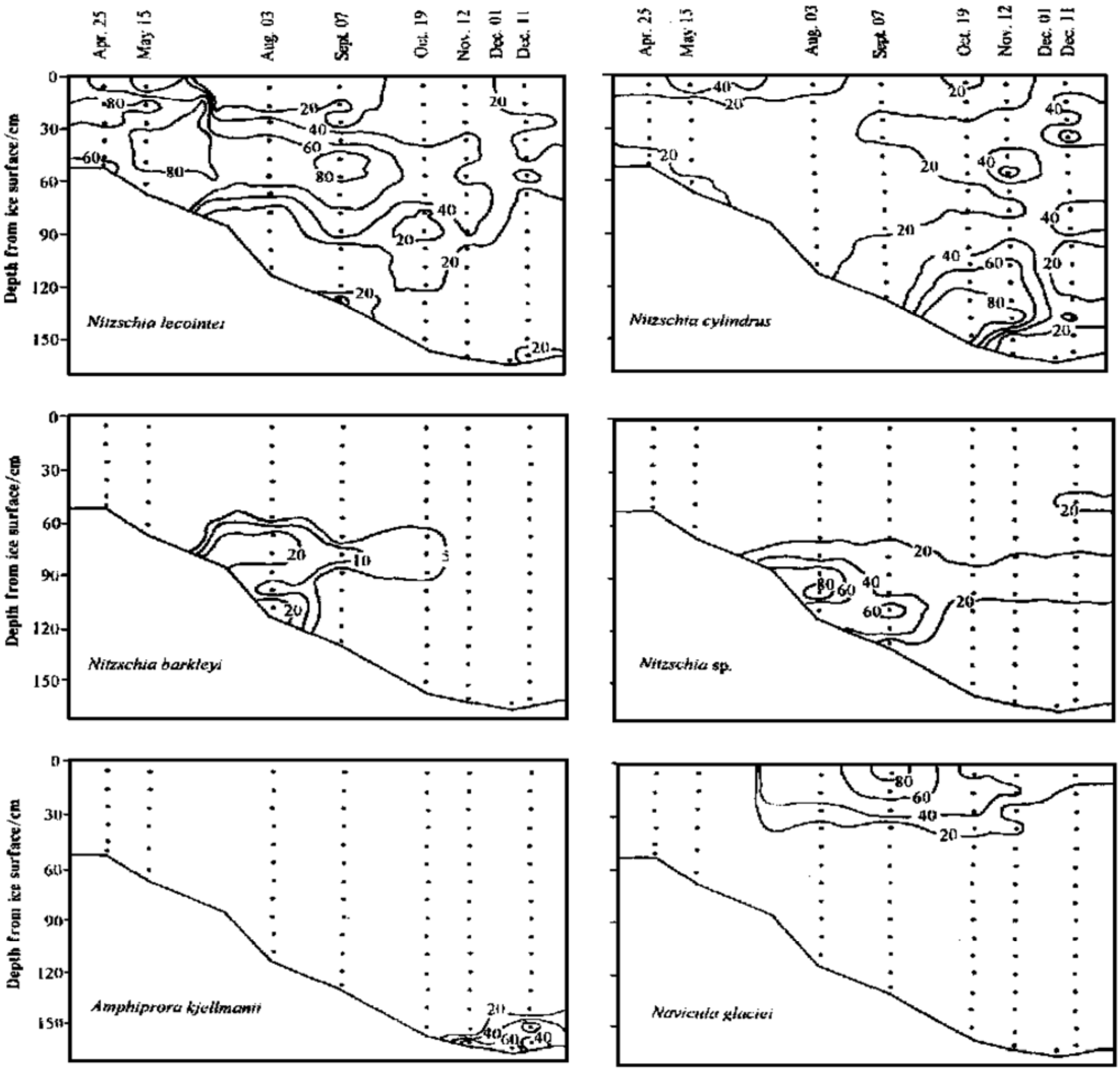

Fig. 2. The profiles showing the abundance of dominant algal species in the ice column.

instance, in the upper 30 cm of ice column, the dominant species *Nitzschia lecointei* and *N. cylindrus* / *N. curta* were succeeded by Nav. *glaciei* after August. The segment of 70 – 100 cm was formed in austral winter, and *Nitzschia* sp. was a dominant species, but *N. lecointei* and *N. cylindrus*/ *N. curta* also became dominant in spring. *Nitzschia* sp. was the dominant species when the 100 – 120 cm segment was formed, but it was replaced by *N. cylindrus*/ *N. curta* in late spring.

The algal assemblages in the water column were different from those in the ice (Fig. 3). Fig. 3 and Table 1 show that *N. lecointei* is not common in the water column, and the percent abundance is less than 5% in the surface water in April and May when the percent abundance are more than 60% in most of ice segments. *Nitzschia sublineata* and *Dactyliosolen antarctica* were two seasonal dominant species found in water column (Fig. 3). The former became dominant in the upper layer of water column instead of *A. kjellmanii* at the end of December, and the latter was common in May and July in the upper water column. There are no apparent similarity in the algal species composition between in bottom of ice and in underlying surface water except when ice algae bloomed

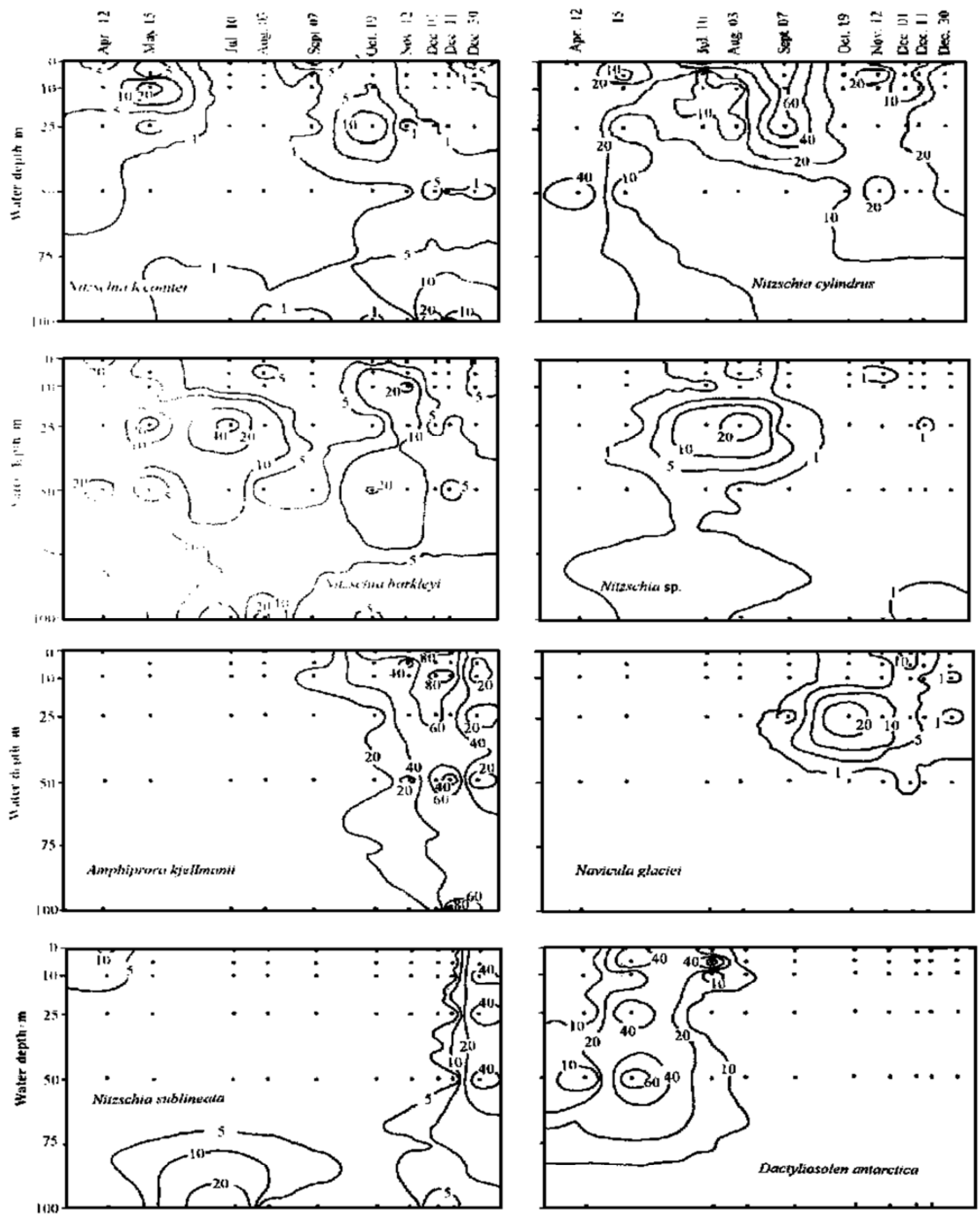

Fig. 3. The profiles showing the abundance of dominant ice algal species in the underlying water column.

in the bottom ice between mid November and early December when *A. kjellmanii* amounted to more than 75% of algal abundance in the ice–water interface (Fig. 4).

4 Discussion

The texture analysis of sea ice suggests that sea ice grows downward only, and frazil ice occurs only on the top 4.5 cm throughout the study period (He *et al*. 1998). So for

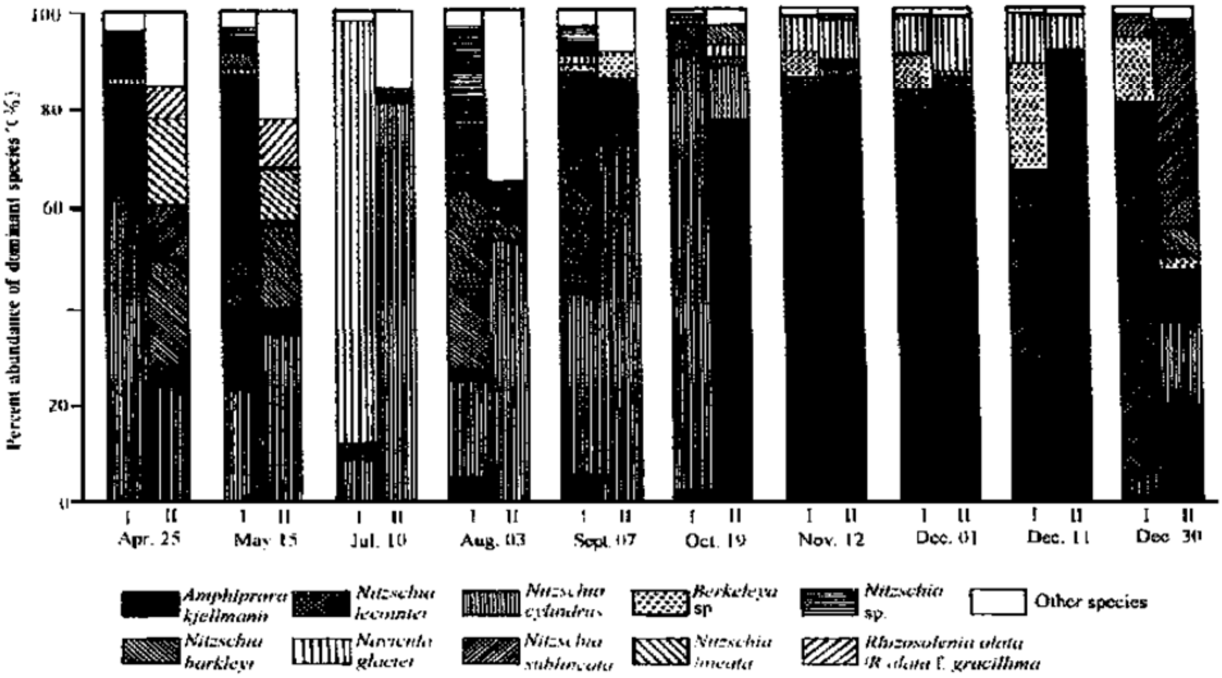

Fig. 4. Comparison of species composition(•) on the bottom of ice and (••) in the underlying surface water.

a certain ice segment, its depth from ice surface was constant and we could know the changes of biomass and algal composition in a certain ice segment through the comparison of data obtained in different months.

Ice algal blooms occurred in the ice bottom in Nella Fjord in autumn and spring respectively, similar to that reported from other fast ice zones (Hoshiai 1981; Perrin *et al*. 1987; Fiala and Delille 1999). The dominant species during spring bloom are similar with those near Davis and *A. kjellmanii* is a predominant species (Archer *et al*. 1996; McMinn and Ashworth 1998; McMinn *et al*. 1999). Chlorophyll *a* concentrations in a certain ice segment decreased gradually (Fig. 1), suggesting that the microhabitat in the interior sea ice was disadvantageous to the ice algal growth with the increase of ice thickness, even in austral spring. It was different from that in pack ice where the environmental conditions were not as hard as those in fast ice zone and algal activity remained even during winter (Dieckmann *et al*. 1991).

It was commonly suggested that the frazil ice could enclose phytoplankton during its formation (Weeks and Ackley 1982; Garrison *et al*. 1989; Grossmann and Glertz 1993), but congelation ice will remove the algae following the saline ejection (Clark and Ackley 1984). The analysis of sea ice structure suggests that the autumn ice algal bloom occur in the congelation ice (He *et al*. 1998). Moreover, the physical accumulation of field wave action (Ackermann *et al*. 1994) must be low because the algal compositions in the ice bottom and water surface are very different in austral autumn (Fig. 4). *Nitzschia lecointei*, a predominant species in the ice column in autumn, was not abundant in water column of 0 – 50 m (Table 1). So the ice algal bloom in autumn should occur mainly through algal growth in situ. The obvious similarity of dominant species compositions between ice bottom and underlying surface water was observed only during spring ice algal bloom (Fig. 4), *A. kjellmanii* makes up more than 80% of the total algal abundance, the abundance in the ice bottom is more than 3 orders of magnitude higher than those in the water surface (Table 1), and this species also appeared earlier in the ice bottom than in surface water (Fig. 4), suggesting that spring ice algal bloom occurred through algal growth *in situ* and the algal assemblage in the surface water might be influenced deeply by ice algal assemblage.

Grossi and Sullivan (1985) suggested that the vertical distribution pattern of ice algae in the congelation ice links to the continuous algal blooms in the ice-water interface during spring bloom period. Although some good seasonal successive records have been found in the fast ice cores near Davis (Scott *et al*. 1994). the study in the Nella Fjord shows that the species succession occurs in the same ice segments following the change of season, so the records may also change (Fig. 2). Although some dominant species, such as *Nitzschia lecointei* in segment of 30 – 70 cm below the ice surface, could remain throughout the study period. But with the changes of the environmental factors, succession occurred not only in bottom assemblage, but also in most of the interior assemblages (Fig. 2).

Three phytoplankton blooms were found in the nearshore of Arthur Harbor near Palmer Station between November 1972 and March 1973 (Krebs 1983), two blooms occurred in the Allis Fjord near Davis Station (McMinn and Hodson 1993). But only one bloom occurred in the water column under sea ice near Soywa Station between January and mid February caused by the covering of sea ice during the year (Fukuchi *et al*. 1984; Satoh *et al*. 1986). The results in the Nella Fjord show that a bloom occurred in the water surface under sea ice in mid December, and another bloom occurred in February when the covered-ice broke out (unpublished data). So there were at least two blooms occurring in the water column near Zhongshan Station, similar to that in the Allis Fjord (McMinn and Hodson 1993).

The effects of seeding of ice algae in pack ice zone may be depending on the community patterns (Kuosa *et al*. 1992). So ice algae may play an important role in seeding (Michel *et al*. 1993) or only some of the ice algal species could seed in water column (Scharek 1991), or even no inoculation occurs (Riebesell *et al*. 1991). But in the nearshore fast ice zones, it was suggested that the role of typical ice algal communities to the phytoplankton was ignorible (McConville and Wetherbee 1983; Palmisano and Sullivan 1983). Although sometimes spring phytoplankton bloom in the water surface was closely related to the ice algae at least before the ice broke out (Krebs 1983; McMinn and Hodson 1993), algae released from the ice bottom would removed from the water column quickly (McMinn 1996). The result in the Nella Fjord also shows that the seeding of ice algae to phytoplankton bloom is not obvious. The seasonal change of nutrient concentrations in the underlying surface water shows that they decreased and the integrated chlorophyll *a* in 0 – 50 m water column increased obviously (He *et al*. 1996), suggesting that *in situ* growth may occur. But calculation from Table 1 shows that during the ice algal bloom and phytoplankton bloom, decrease of *A. kjellmanii* abundance in the ice column is 3 times more than the increase of this species in the water column. So the phytoplankton bloom may be caused by the release of ice algae. At the end of December, the dominant species in water column was replaced by *N. sublineata* (Fig. 3), which also proves that the seeding of ice algae to phytoplankton bloom is not significant. There were large amounts of *A. kjellmanii* in the sediments in the Nella Fjord (McMinn 1994), suggesting that the algal sedimentation should be significant during this period.

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