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Dominant diatom species in the Canada Basin in summer 2003, a reported serious melting season

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ABSTRACT. During the second Chinese National Arctic Research Expedition in summer 2003, sea ice cores and the underlying water were sampled from seven stations in the pack ice zone of the Canada Basin and were examined with a phase contrast microscope. A total of 102 and 78 algal species were identified for the ice cores and the underlying water, respectively, ranking in the middle range among the surveys of the Arctic Ocean up to the present despite seasonal variability. The Shannon-Wiener indices ranged from 1.40 to 4.88 with an average of 3.58 ± 0.68. Diatom species, especially pennate species, dominated in all the samples. A large number of algal spores were contained in every layer (abundance percentage $> 1\%$). The microalgal abundances ranged from 1.4×10^4 to 8.73×10^5 cells L^{-1} and the biomass ranged from 0.56 to 89.49 $\mu g\ L^{-1}$. They were correlated with the number of algal species ($P < 0.05$) but not with the diversity index ($P > 0.05$). Ice algal maxima were observed in various layers (bottom, interior and near the surface of the ice floes). The phytoplankton biomass in the ice-water interface was one order of magnitude lower than that in the bottom ice ($P < 0.05$). The species number and the diversity index in water samples, with much less biomass ($P < 0.01$), were comparative with the ice samples ($P > 0.05$). Spatial heterogeneity in both horizontal and vertical directions was the main characteristic of the algal community structure, which was demonstrated by the cluster analysis result and the distribution patterns.

Introduction

Despite the accelerating reduction of Arctic sea ice over the past decades (Budikova 2009), ice algae are usually considered indispensable in biogeochemical cycles in the Arctic Ocean (Gosselin and others 1997; Søreide and others 2006). They used to contribute 4% ∼ 26% of the total primary production in seasonally ice covered waters and more than 50% in the permanently ice covered central Arctic (Gosselin and others 1997; Sakshaug 2004). In a recent study of west Greenland, ice algae were found to contribute 30% of total primary production during the sea ice season and less than 1% annually (Mikkelsen and others 2008). Particulate ice algal production during the transect from the Chukchi Sea to the Nansen Basin via the North Pole in July/August 1994 ranged from 0.5 to 310 mg C m^{-2} day^{-1} and showed maximum rates in the central Arctic Ocean (Gosselin and others 1997). They were major contributors to primary production and algal biomass in the Chukchi and Beaufort Seas during May/June 2002 with significantly higher primary productivity (0.1–23.0 mg C m^{-2} h^{-1}) and pigment content (0.2–304.3 mg pigments m^{-2}) than water column parameters (0.2–1.0 mg pigments m^{-3}; $<$ 0.1–0.4 mg C m^{-2} h^{-1}) (Gradinger 2009). They are also a main food source for sympagic fauna (Werner 1997; Poltermann 2001), which might supply and extend the restricted grazing season for Arctic zooplankton (Michel and others 1996), and serve as food for the benthos as large aggregates when the ice begins to melt in spring (McMahon and others 2006; Renaud and others 2006). Additionally, ice algal communities are a major contributor of the Arctic's biodiversity. For example, at least 251 species were recorded in first year ice from the Chukchi Sea in early June 1998 (Quilfeldt and others 2003).

The central Arctic Ocean now is changing substantially with an expected reduction in ice cover and probable changes of the polar flora and fauna due to global climate change. A reduction in ice thickness of the southern Chukchi Sea was observed of approximately 0.5–1.0m over the past two decades (Shirasawa and others 2009). The ice extent observed in summer 2003 was almost as low as the record low levels of the ice extent in the summer of 2002 since being monitored by satellite from 1979 (Lindsay and Zhang 2005). Annual ice algal production of 2003 at Barrow, Alaska (2.0 g C m^{-2} $year^{-1}$) was lower than three decades ago by a factor of two to three (Lee and others 2008). Changes in species composition were also observed. Unusual coccolithophorid blooms, the more temperate species, occurred since 1997 in the Bering Sea (Iida and others 2002) may replace the previously occurring summer flagellate community (Schumacher and others

2003). *Emiliania huxleyi* was even reported to intrude and dominate the high Arctic Ocean in summer 2003 (Hegseth and Sundfjord 2008). Greater overall primary production was expected in a warmer Arctic with less sea ice and earlier ice melting, and resulted from greater increase in the pelagic production than the reduction in ice algal production (Wassmann and others 2006; Lavoie and others 2008). This was proved by a recent study that the annual Arctic primary production has increased yearly by an average of 27.5 TgC.yr^{-1} since 2003 and by 35 TgC.yr^{-1} between 2006 and 2007 (Arrigo and others 2008). As the ongoing trend persists, the pelagic food web is expected to dominate over a geographically larger area (Bluhm and Gradinger 2008).

Most studies of algal communities in the ice-covered Arctic waters focus on coastal and shelf regions. The Canada Basin (maximum depth $>$ $=$ 3,800 m), the largest and geographically most isolated Arctic basin (Swift and others 1997), is one of the least known areas in the Arctic Ocean (Lee and Whitledge 2005). Our knowledge about the ice algal community in this area is still sparse and can hardly be compared due to different measurements and variable studying seasons. The ice algal biomass of the Canada Basin were measured between 0.4 μg C L^{-1} to 5.3 μg C L^{-1} for the multi-year ice from autumn 1997 to spring 1998, and $<$ 0.1 μg C L^{-1} to 1.7 μg C L^{-1} for the first year ice in autumn and winter of 1997 (Melnikov and others 2002). The annual primary production and new production of phytoplankton in the Canada Basin in 2002 was 5 and 1g C m^{-2} year^{-1}, respectively (Lee and Whitledge 2005). Chl *a* concentration in off-shore pack ice of the Beaufort Gyre ranged from 0.1–1.7 mg Chl *a* m^{-2} in summers 2002 and 2003 which was similar to estimates for multi-year ice of the transpolar drift and $\sim$2 orders of magnitude below coastal fast first year ice estimates (Gradinger and others 2005). Until now, we are still far from having a comprehensive perception of the algal community in the Canada Basin.

Our present research, conducted during the second Chinese National Arctic Expedition (CHINARE-2003) in the late summer of 2003 and based on R/V *Xuelong*, focused on the algal communities in sea ice and the under ice water column in the pack ice zone of the Canada Basin. This information provides baseline data to evaluate future changes in the algal communities driven by changing ice regimes and any loss of the multi-year ice cover (Serreze and others 2003).

Materials and methods

Samples were collected in the Canada Basin of the Arctic Ocean between 11 August and 6 September 2003 (Fig. 1). A MARK II type ice corer (9 cm in inner diameter) was used to collect one ice core each from seven pack ice stations (Table 1; due to loss of the on-the-spot record, the ice cores longer than 1.5 m were considered as multi-year ice). The upper half of each ice core was drilled out first to obtain brine, and the lower half was drilled through later. The whole process for each ice core was completed within 10 minutes. Ice cores were immediately sectioned into 10- or 20- cm segments, transferred into 1-L plastic containers, and then melted in particle free seawater (pre-filtered through 0.2 μm Whatman nuclepore polycarbonate filters to minimise osmotic stress during the melting process) at 4°C in the dark (Garrison and Buck 1986). The underlying water samples were collected with a 2.5 L Niskin type water sampler, directly through the drilled ice holes. At most stations, water samples were only collected in the ice-water interface (0 m depth). For station SI4, water was sampled at 0 and 10 m depths, while 0, 5 and 10 m depth waters were sampled for station SI5. For species identification and cell counts, all the samples were fixed with glutaraldehyde (final concentration 1.5–2%) and stored at 4°C in the dark before analysis.

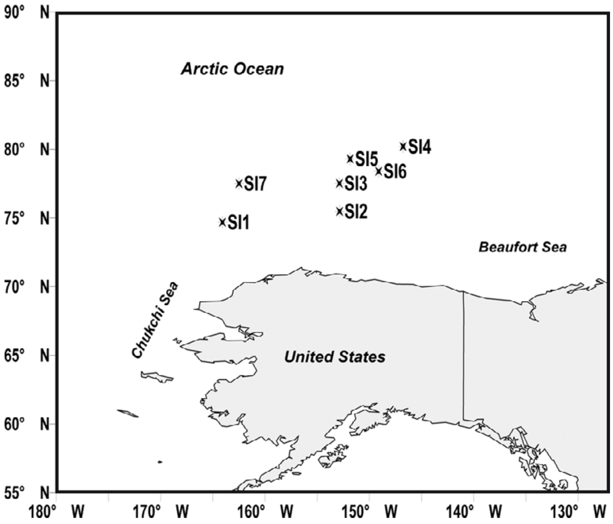


Fig. 1. The investigated area in the Canada Basin of the Arctic Ocean during the second Chinese National Arctic Expedition from 11 August to 6 September 2003.

Samples were settled according to the methods described by Utermöhl (1958) before counting. Algal cells were counted and identified in a 0.1 ml phytoplankton counting chamber using a Nikon 80i microscope with phase contrast illumination at a magnification of 200–400×. Identification of algal species was based on morphology and cell size (Poulin and Cardinal 1982a; Poulin and Cardinal 1982b; Poulin and Cardinal 1983; Medlin and Hasle 1990; Medlin and Priddle 1990; Hegseth 1992; Legendre and others 1992; Hasle and Syvertsen 1996). At least three horizontal transects across the bottom of the chamber (one in the middle and the other two at the two sides) and 300 cells with intact plasma were counted for each sample. More than 10 algal cells for each taxon were measured and cell numbers were transformed into carbon biomass according to the formula of Menden-Deuer and Lessard (2000). Shannon-Wiener diversity index (Shannon and Wiener 1963) with a $\log_2$ basis and

Table 1. Sampling information of seven ice stations in the Canada Basin during the Second Chinese National Arctic Research Expedition

Ice St. No.	Sampling date (mm/dd/yy)	Location	Ice thickness (cm)
SI1	08/11/03	74°41′11″N, 164°04′28″W	226
SI2	08/13/03	75°28′52″ N, 152°51′18″W	342
SI3	08/20/03	77°30′59″N, 152°52′04″W	150
SI4	08/26/03	80°11′50″N, 146°46′10″W	150
SI5	08/27/03	79°17′36″N, 151°50′49″W	155
SI6	09/02/03	78°23′14″N, 149°06′55″W	181
SI7	09/06/03	77°30′03″N, 162°29′22″W	228

species number were used to measure the biodiversity of the algal communities. SPSS v. 16.0 with the Euclidean distance and the nearest neighbour method was applied to conduct cluster analysis of algal communities, treated as a matrix composed of species and specific abundances, to determine their relationships and similarity. T-test and correlation analysis were included.

Results

Algal species in the ice cores and the underlying water column

102 and 78 algal species were identified in the ice cores (Table 2) and the underlying water column (Table 3) respectively of the seven sea ice stations, with diatoms dominating in both habitats (95 species in ice; 75 species in water). A small fraction ($<$ 1% in total abundance of each sample) was composed of dinoflagellates, chrysophytes and chlorophytes. Many algae could only be identified to genus or higher taxa, such as *Nitzschia* spp. and *Navicula* spp.

The micro-sized ice flora of the Canada Basin was predominately diatoms (Table 2), including *Cylindrotheca closterium*, *Fragilariopsis cylindrus*, *Nitzschia frigida*, *Nitzschia neofrigida*, *Nitzschia polaris*, *Fragilariopsis curta*, *Thalassionema nitzschioides*, *Nitzschia arctica*, *Nitzschia promare*, *Pinnularia quadratarea*, and *Navicula directa* (from most abundant to less abundant) (Fig. 2).

Pennate diatoms also dominated the underlying water column (Table 3), such as *C. closterium*, *F. cylindrus*, *F. curta*, *N. frigida*, *Navicula pelagica*, *N. neofrigida*, *Synedropsis hyperborea*, *Pseudonitzschia delicatissima*, *N. polaris*, *Stauroneis radissonii*, and *N. promore* (from most abundant to less abundant), most of which were also found as the dominant species in the ice cores. All samples contained numbers of *Chaetoceros* spores and unidentified dinoflagellates spores. The algal spores together occupied more than 1% of abundance in all the ice cores and most of the water samples, ranging from 0.48×10^3 cells L^{-1} to 1.48×10^4 cells L^{-1} (Tables 2 and 3).

Algal biomass and abundance

The ice algal biomass ranged from 1.3 to 89.5 μg C L^{-1}, with the lowest value found at 216–226 cm in the ice core from SI1 and the highest in the bottom 10 cm of the ice core from SI4 (Fig. 2). The total biomass of the SI6 ice core was less than other ice cores ($P < 0.01$) (Fig. 2). The algal abundance in the ice cores ranged from 1.40×10^4 to 8.73×10^5 cells L^{-1}, with the minimum abundance located at 216–226 cm in the ice core of SI1 and the maximum at 130–155 cm in the ice core of SI5 (Fig. 3).

The ice algal biomass differed greatly among different stations and within each ice core (Figs. 2, 4a). The ice algal maximal biomass was found at various layers of different stations. Of the seven ice cores, three (SI3, SI4 and SI6) had an ice algal biomass bottom maximum, two (SI1, SI2) had the maximum biomass in the sub-surface segment, one (SI7) had the biomass maximum in the sub-bottom layer, and one (SI5) in the centre.

The algal biomass of all the 10 cm bottom samples was one order of magnitude higher than the underlying 0 m samples (Fig. 4a; $P < 0.05$). The algal biomass in the water column ranged from 0.56 to 7.63 μg C L^{-1}, with the lowest and the highest in the ice-water interface at SI5 and SI3, respectively (Fig. 2). The phytoplankton abundance ranged from 1.4×10^4 to 9.4×10^4 cells L^{-1}, with the minimum and the maximum value found at the ice-water interface of SI7 and SI3, respectively (Fig. 3). A discrepancy in cell volume among different species caused the different samples with maximum ice algal biomass and abundance and minimum phytoplankton biomass and abundance (Figs. 2, 3).

Abundances for each predominant species varied among stations and layers, and the species composition diverged among stations and between ice and water, either (Fig. 3). Abundant cells of *C. closterium*, *F. cylindrus*, *N. frigida*, *N. neofrigida* and the spores were found at every station. Large number of dinoflagellate and *Chaetoceros* spores dominated especially in the near-surface layers of the ice cores, in the water column and in every layers of SI5. They accounted for over 40% in the surface layers in the ice cores of SI5, SI6 and SI7 (Fig. 3).

Biodiversity and composition of the algal community

The number of microalgal species showed indented vertical distribution in every station (Fig. 5) and diverged in the horizontal direction among different stations (Fig. 4b). The Shannon-Wiener index ranged from 1.40

Table 2. Algal abundance ($\times 10^3$ cells L^{-1}) of every species present in the sea ice samples collected from seven ice cores ("_" characterised as the abundance $<$ 10 cells L^{-1} or absent)

Species/Station	SI1	SI2	SI3	SI4	SI5	SI6	SI7
BACILLARIOPHYTA							
Achnanthes taeniata Grunow	0.06	1.38	0.51	–	1.87	0.45	0.54
Actinocyclus curvatulus Janisch	0.06	0.24	0.16	4.01	0.07	0.06	0.97
Amphora proteus Gregory	3.81	0.30	0.55	12.00	0.19	0.62	1.27
Asteromphalus sp.	–	–	0.06	–	–	0.05	–
Attheya septentrionalis (Østrup) Crawford	–	–	–	–	0.05	–	–
Aulacoseira sp.	0.45	0.98	0.04	0.42	3.65	0.69	0.90
Chaetoceros borealis Bailey	0.12	0.05	0.06	–	–	0.04	–
Ch. concavicornis Mangin	–	–	–	–	–	0.01	–
Ch. constrictus Gran	–	0.05	–	–	0.22	0.02	–
Ch. furcellatus Bailey	–	–	–	–	–	0.02	–
Ch. holsaticus Schütt	–	0.11	–	–	0.38	0.07	–
Ch. radicans Schütt	0.66	0.22	0.05	5.18	0.17	0.26	1.08
Ch. socialis Lauder	0.40	–	–	4.14	0.06	0.08	0.15
Chaetoceros sp.	–	0.16	–	–	0.50	1.12	0.10
Chaetoceros spores	3.60	1.07	0.28	7.55	132.30	2.85	1.70
Cocconeis scutellum Ehrenberg	0.36	0.27	0.23	0.69	0.52	0.28	0.33
Coscinodiscus asteromphalus Ehrenberg	–	–	–	–	–	–	0.05
Coscinodiscus concinnus W.Smith	–	0.10	–	–	0.15	–	–
Cylindrotheca closterium (Ehrenberg) Reimann & Lewin	26.64	25.08	9.30	94.69	99.51	5.72	34.39
Diploneis didyma (Ehrenbert) Cleve	–	0.05	–	0.26	–	0.20	0.11
D. litoralis (Donkin) Cleve	1.21	0.92	0.67	3.83	2.99	0.31	0.89
Entomoneis kjellmanii (Cleve) Poulin & Cardinal	0.27	–	–	0.26	0.02	0.05	–
E. paludosa var. *hyperborean* (Grunow) Poulin & Cardinal	0.13	0.36	–	–	0.32	0.09	0.19
Eucampia zodiacus var. *recta* Ehrenberg	0.67	0.11	–	–	–	–	0.11
Fragilaria islandica Lyngbye	4.81	1.47	0.29	15.13	5.38	0.25	3.74
F. striatula Lyngbye	3.91	0.30	0.81	39.25	2.70	0.26	1.02
Fragilariopsis cylindrus (Grunow) Krieger	29.38	8.11	16.00	123.62	29.17	5.73	15.85
F.curta (Van Heurck) Hustedt	11.46	2.99	4.52	83.02	9.03	2.09	7.89
F.oceanica (Cleve) Hasle	6.36	0.90	1.87	23.63	1.16	0.15	2.70
F. rhombica (O'Mera) Hustedt	–	–	0.42	–	–	–	–
Fragilariopsis sp.	0.45	0.44	0.48	3.23	2.14	0.33	0.38
Gomphonema acuminatum Ehrenberg	0.25	0.08	–	2.72	0.05	0.11	0.11
Gyrosigma sp.	0.13	–	–	–	–	–	–
Haslea crucigeroides Hustedt	–	–	–	–	–	–	0.24
Hantzschia weyprechtii Grunow	–	–	–	–	–	0.05	–
Leptocylindrus minimus Gran	2.91	1.35	0.67	83.01	4.70	0.76	1.35
Licmophora sp.	0.12	0.22	–	2.11	0.10	0.11	0.06
Melosira arctica Dickie	0.42	0.41	0.82	20.74	0.52	1.56	1.43
Navicula algida Grunow	0.25	–	0.06	–	0.25	0.02	–
N. directa (Smith) Ralfs	1.64	0.54	0.22	23.62	2.60	0.41	0.62
N. gelida Grun.	0.45	0.04	0.04	1.40	0.05	0.03	0.15
N. glacialis (Cleve) Grunow	0.13	–	0.03	0.91	–	0.05	0.10
N. impexa Hustedt	0.41	0.05	0.11	–	0.20	0.23	0.05
N. kariana Grunow	0.28	0.10	0.04	–	0.27	0.13	0.13
N. lineola Grunow	–	–	0.06	–	0.02	0.02	–
N. lineola var. *perlepida* (Grunow) Cleve	–	0.21	0.11	–	0.06	0.10	0.05
N. novadesipiens Hustedt	–	0.05	0.11	–	0.12	0.08	–
N. pelagica Cleve	2.40	2.56	0.87	4.06	14.12	2.68	4.90
N. cf. *recurvata* Gran	–	–	–	–	–	0.03	–
N. septentrionalis (Grunow) Gran	0.12	–	0.48	–	1.68	0.64	0.87
N. solitaria Cleve	0.46	–	–	–	–	–	–
N. cf. *spicula* (Hickie) Cleve	–	0.05	–	–	0.17	–	–
N. superba var. *subacuta* Gran	0.13	–	–	–	–	–	–
N. transitans Cleve	0.06	0.57	0.17	19.02	0.49	0.52	0.31
N. transitans var. *derasa* (Grunow) Cleve	1.77	0.18	0.25	1.93	0.31	0.05	0.25
N. valida Cleve & Grunow	1.12	0.21	0.53	9.17	0.83	0.34	0.17
N. vanhoeffenii Gran	0.27	1.36	0.31	8.63	4.29	0.13	2.43
Navicula sp.	2.03	1.85	1.35	10.88	3.55	2.47	1.13

Table 2. Continued.

Species/Station	SI1	SI2	SI3	SI4	SI5	SI6	SI7
Nitzschia arctica Cleve	2.87	3.05	3.44	127.83	0.91	0.54	2.50
N. frigida Grunow	15.90	10.06	11.96	274.41	11.0	5.53	9.04
N. grunowii Hasle	0.06	–	0.11	–	0.23	0.05	–
N. laevissima Grunow	–	–	–	–	0.07	–	–
N. longissima Bréb	–	0.04	–	0.59	–	0.06	–
N. neofrigida Medlin	3.49	4.97	5.43	292.83	2.76	1.34	4.30
N. pellucida Grunow	0.54	0.11	0.23	2.72	0.81	0.31	0.12
N. polaris Grunow	5.58	8.25	3.55	271.17	5.24	1.51	2.93
N. promare Medlin	1.99	5.18	0.39	41.89	9.69	1.98	5.71
N. cf. *scabra* Cleve	0.12	–	–	–	–	–	–
N. separanda (Hustedt) Hasle	–	0.16	–	–	0.07	0.14	0.19
N.taeniiformis Hustedt	0.06	–	–	–	–	–	–
N.turgidula Hustedt	–	–	0.17	–	0.19	0.02	0.05
Nitzschia sp.	–	2.53	2.04	2.33	11.16	1.11	2.99
Odontella aurita Agardh	–	–	–	0.26	0.41	0.02	–
Phaeodactylum tricornutum Bohlin	0.22	0.05	–	0.26	–	0.09	0.04
Pinnularia quadratarea (Schmidt) Cleve	4.16	5.84	0.52	5.81	5.91	0.70	3.09
P. quadratarea var. *bicontracta* (Østrup) Heiden	0.72	0.09	0.03	6.20	–	0.15	0.16
P. quadratarea var. *constricta f. interrupta* (Østrup) Heiden	1.58	0.21	0.03	6.34	0.10	0.22	–
P. quadratarea var. *cuneata* (Østrup) Østrup	–	–	–	–	0.08	–	–
P. quadratarea var. *dubia* Heiden	0.22	–	–	–	–	–	–
Pinnularia sp.	–	0.04	–	0.59	0.06	0.02	0.04
Planktoniella sol (Wallich) Schütt	–	–	–	–	–	0.03	–
Pleurosigma sp.	0.36	–	–	–	–	–	0.04
Pseudogomphonema arcticum (Grunow) Medlin	–	0.42	0.06	–	0.05	–	–
Pseudonitzschia delicatissima (Cleve) Heiden	2.43	2.32	0.90	139.81	3.49	0.53	1.25
P. prolongatoides (Hasle) Hasle	–	0.16	–	–	–	0.05	–
P. seriata (Cleve)	0.34	0.66	1.06	90.68	0.62	0.24	1.06
Stauroneis radissonii Poulin & Cardinal	2.42	0.11	0.06	1.29	3.33	0.74	0.82
Synedropsis hyperborean (Grunow) Hasle	3.93	2.01	2.39	19.27	6.55	0.54	1.41
Thalassionema nitzschioides (Grunow) Mereschkowsky	6.97	3.47	2.30	170.93	2.07	1.01	1.51
Thalassiosira angulata (Gregory) Hasle	–	–	–	–	–	0.03	–
T. gravida Cleve	0.28	0.47	0.62	2.39	0.49	0.18	1.12
T. leptopus (Grunow) Hasle & Fryxell	0.36	0.42	0.85	14.08	0.48	0.28	0.39
T. nordenskioeldii Cleve	0.61	0.46	0.39	6.38	1.46	0.21	0.98
Thalassiosira sp.	1.18	–	0.06	0.16	0.30	0.08	0.09
Thalassiothrix sp.	–	–	–	–	0.11	–	–
DINOPHYTA							
Dinophysis sp.	–	–	–	–	0.17	–	–
Gymnodinium sp.	0.67	0.11	0.58	1.30	0.37	0.27	0.56
Protoperidinium spp.	–	–	0.08	0.93	0.37	0.10	0.18
Dinoflagellate spores	10.69	1.83	22.96	81.90	15.39	9.05	14.51
DICTYOCHOPHYTA							
Dictyocha speculum var. *octonarius* (Ehrenberg) Jørgensen	0.06	–	–	–	0.34	0.05	–
Dictyocha sp.	0.51	–	–	–	0.06	0.03	–
CHLOROPHYTA							
Chlorophyta sp.	0.74	0.05	0.42	0.33	0.48	0.28	–

to 4.88 and exhibited similar distribution pattern with less varying extent (STDEV of the Shannon-Wiener indices = 0.68; STDEV of the species numbers = 14.50). They were positively correlated ($r = 0.56$, $P < 0.01$) (Fig. 4b, c, 5). An ice sample of the 10–30-cm ice segment of SI6 had both the highest number of algal species (71 taxa) and the highest Shannon-Wiener index (4.88). The second highest, 70 taxa and 4.78, were for phytoplankton at 0-m depth of SI3. The number of algal species and the diversity index in water samples, with much less biomass ($P < 0.01$) (Figs. 2, 4a), were comparative with the ice samples ($P = 0.45$ and $0.50 > 0.05$) (Fig. 4b, c, 5). Biomass was correlated with species number ($r = 0.27$, $P < 0.05$), but was not correlated with Shannon-Wiener

Table 3. Algal abundance ($\times 10^3$ cells L^{-1}) of every species present in the water samples collected in seven ice stations ("_" characterised as the abundance $<$ 10 cells L^{-1} or absent)

Species/Station	SI1(0m)	SI2(0m)	SI3(0m)	SI4(0m)	SI5(0m)	SI6(0m)	SI7(0m)	SI5(5m)	SI4(10m)	SI5(10m)
BACILLARIOPHYTA										
Achnanthes taeniata Grunow	–	–	4.32	–	–	–	–	–	–	–
Actinocyclus curvatulus Janisch	0.18	–	0.10	0.18	–	–	–	0.10	–	–
Amphora proteus Gregory	0.09	0.16	0.19	0.26	–	0.10	–	0.10	–	–
Aulacoseira sp.	–	–	–	–	–	–	–	0.90	–	–
Chaetoceros borealis Bailey	–	–	0.19	–	–	–	–	0.10	–	–
Ch. constrictus Gran	–	–	0.38	–	–	–	–	–	–	–
Ch. diadema (Ehrenberg) Gran	–	–	0.19	–	–	–	–	–	–	–
Ch. holsaticus Schütt	–	0.08	1.44	–	–	–	0.26	0.10	–	–
Ch. radicans Schütt	0.09	0.16	0.86	–	–	–	0.09	0.40	–	–
Ch. socialis Lauder	–	–	1.06	–	–	–	–	0.20	–	–
Chaetoceros sp.	–	–	0.77	–	–	–	–	0.20	–	–
Chaetoceros spores	0.28	0.32	4.61	0.09	6.72	0.77	0.09	23.10	1.16	5.16
Cocconeis scutellum Ehrenberg	0.09	–	–	0.18	–	–	0.35	0.50	–	–
Coscinodiscus sp.	–	–	–	–	–	–	0.09	–	–	–
Cylindrotheca closterium (Ehrenberg) Reimann & Lewin	2.21	5.68	12.00	0.97	1.68	4.22	0.35	26.30	1.39	5.16
Diploneis litoralis (Donkin) Cleve	0.28	0.08	–	0.09	–	0.10	0.09	0.10	0.23	–
Entomoneis kjellmaniib(Cleve) Poulin & Cardinal	–	–	–	–	–	–	0.09	–	–	–
E. paludosa var. *hyperborean* (Grunow) Poulin & Cardinal	–	–	–	–	–	–	–	0.20	–	–
Eucampia zodiacus var. *recta* Ehrenberg	–	–	–	–	–	0.10	–	–	–	–
Fragilaria islandica Grunow	0.28	0.08	–	0.09	–	0.10	–	0.40	0.23	–
F. striatula Lyngbye	–	0.16	0.67	–	1.2	–	–	–	–	3.44
Fragilariopsis cylindrus (Grunow) Krieger	1.84	4.8	11.33	4.22	2.40	3.65	1.94	5.30	0.93	3.44
F.curt (Van Heurck) Hustedt	2.12	1.04	–	3.52	–	0.86	1.23	1.80	0.23	5.16
F.oceanica (Cleve) Hasle	0.18	0.24	–	0.09	–	–	0.09	0.60	–	–
Fragilariopsis sp.	–	–	1.63	–	–	–	–	0.10	–	–
Gomphonema acuminatum Ehrenberg	–	–	–	0.09	–	–	–	–	–	–
Leptocylindrus minimus Gran	–	–	–	0.44	0.48	0.19	0.79	3.00	–	–
Licmophora sp.	0.18	–	–	–	–	–	0.09	0.20	–	–
Melosira arctica Dickie	0.83	–	0.19	0.35	0.24	–	0.53	0.30	–	–
Navicula algida Grunow	–	–	–	–	–	–	–	–	0.69	–
N. directa (Smith) Ralfs	0.37	0.08	–	0.18	–	–	–	0.10	0.46	–
N. gelida Grunow	–	–	–	–	–	–	–	–	0.23	–
N. impexa Hustedt	–	–	1.25	–	–	–	–	0.20	1.16	–
N. kariana Grunow	–	–	0.19	–	–	–	–	–	–	–
N. kryokonites Cleve	–	–	–	–	–	–	–	–	0.23	–
N. lineola Grunow	–	–	0.19	–	–	–	–	–	–	–
N. lineola var. *perlepida* (Grunow) Cleve	–	–	0.19	–	–	–	–	–	–	–
N. novadesipiens Hustedt	–	–	–	–	–	–	–	0.50	–	–
N. pelagica Cleve	0.09	0.16	6.14	0.62	0.24	0.10	0.26	5.80	–	8.60

Table 3. Continued.

Species/Station	SI1(0m)	SI2(0m)	SI3(0m)	SI4(0m)	SI5(0m)	SI6(0m)	SI7(0m)	SI5(5m)	SI4(10m)	SI5(10m)
N. septentrionalis (Grunow) Gran	0.18	–	–	0.26	–	–	–	0.80	–	–
N. spicula (Hickie) Cleve	–	–	–	–	–	–	–	0.10	–	–
N. transitans Cleve	–	–	0.19	0.09	0.24	–	0.09	–	–	–
N. transitans var. *derasa* (Grunow) Cleve	–	–	0.19	0.09	–	–	–	–	0.23	–
N. valida Cleve & Grunow	0.09	–	–	–	–	–	–	–	–	–
N. vanhoeffenii Gran	–	0.24	1.73	0.26	–	–	–	0.80	0.93	–
Navicula sp.	0.09	0.16	9.12	0.18	–	0.10	0.09	0.40	–	–
Nitzschia arctica Cleve	0.46	0.32	1.15	0.09	0.48	0.58	–	0.30	0.23	–
N. frigida Grunow	0.46	0.40	6.53	1.32	1.20	1.63	0.35	3.70	1.85	–
N. grunowii Hasle	–	–	1.06	–	–	–	–	–	–	–
N. laevissima Grunow	–	–	–	–	–	–	–	0.10	0.23	–
N. longissima Bréb	–	–	–	–	–	–	0.09	–	–	–
N. neofrigida Medlin	0.83	0.64	1.92	0.79	–	1.25	–	0.90	2.08	–
N. polaris Grunow	0.28	0.32	6.24	0.53	–	0.38	0.09	1.00	0.93	–
N. promare Medlin	0.28	0.16	3.74	–	–	0.58	–	5.00	0.46	–
N. separanda (Hustedt) Hasle	–	–	0.10	–	–	–	–	–	–	–
N. turgidula Hustedt	–	–	–	–	–	–	–	–	0.23	–
Nitzschia sp.	–	–	5.57	–	–	–	–	1.60	–	–
Pinnularia quadratarea (Schmidt) Cleve	0.28	0.16	0.48	–	–	0.29	–	1.80	–	–
P. quadratarea var. *bicontracta* (Østrup) Heiden	–	–	–	–	–	0.19	–	–	0.23	–
P. quadratarea var. *constricta f. interrupta* (Østrup) Heiden	–	–	–	–	–	–	–	–	0.23	–
Pinnularia sp.	–	–	–	–	–	0.10	–	–	–	–
Pseudogomphonema arcticum (Grunow) Medlin	–	–	–	–	–	–	–	0.10	–	–
Pseudonitzschia delicatissima (Cleve) Heiden	0.37	0.72	1.06	0.35	0.48	–	–	1.40	1.85	3.44
P. prolongatoides (Hasle) Hasle	–	–	0.10	–	–	–	–	–	–	–
P. seriata (Cleve)	0.18	0.24	0.19	0.18	–	0.10	–	0.20	1.62	–
Stauroneis radissonii Poulin & Cardinal	–	–	0.77	–	0.96	0.19	–	0.20	2.08	–
Synedropsis hyperborean (Grunow) Hasle	2.21	2.64	1.54	0.44	–	0.48	0.09	0.40	0.23	–
Thalassionema nitzschioides (Grunow) Mereschkowsky	0.28	0.32	0.29	0.44	–	0.19	–	1.10	0.69	–
Thalassiosira angulata (Gregory) Hasle	–	–	–	–	–	–	–	–	0.23	–
T. gravida Cleve	–	0.08	0.58	0.18	–	–	0.18	0.30	–	1.72
T. leptopus (Grunow) Hasle & Fryxell	–	–	0.77	0.09	–	–	0.53	0.40	–	–
T. nordenskioeldii Cleve	0.18	–	1.25	–	–	–	0.18	0.50	–	1.72
Thalassiosira sp.	0.09	0.08	0.29	–	–	–	–	–	–	–
Thalassiothrix sp.	–	–	–	–	–	–	–	0.10	–	–
DINOPHYTA										
Gymnodinium sp.	–	0.24	–	0.26	–	0.29	0.09	–	–	–
Dinoflagellate spores	17.85	0.16	1.25	8.80	2.40	0.86	5.90	0.10	0.23	29.24
CHLOROPHYTA										
Chlorophyta sp.	0.09	–	–	–	0.24	–	–	–	–	–

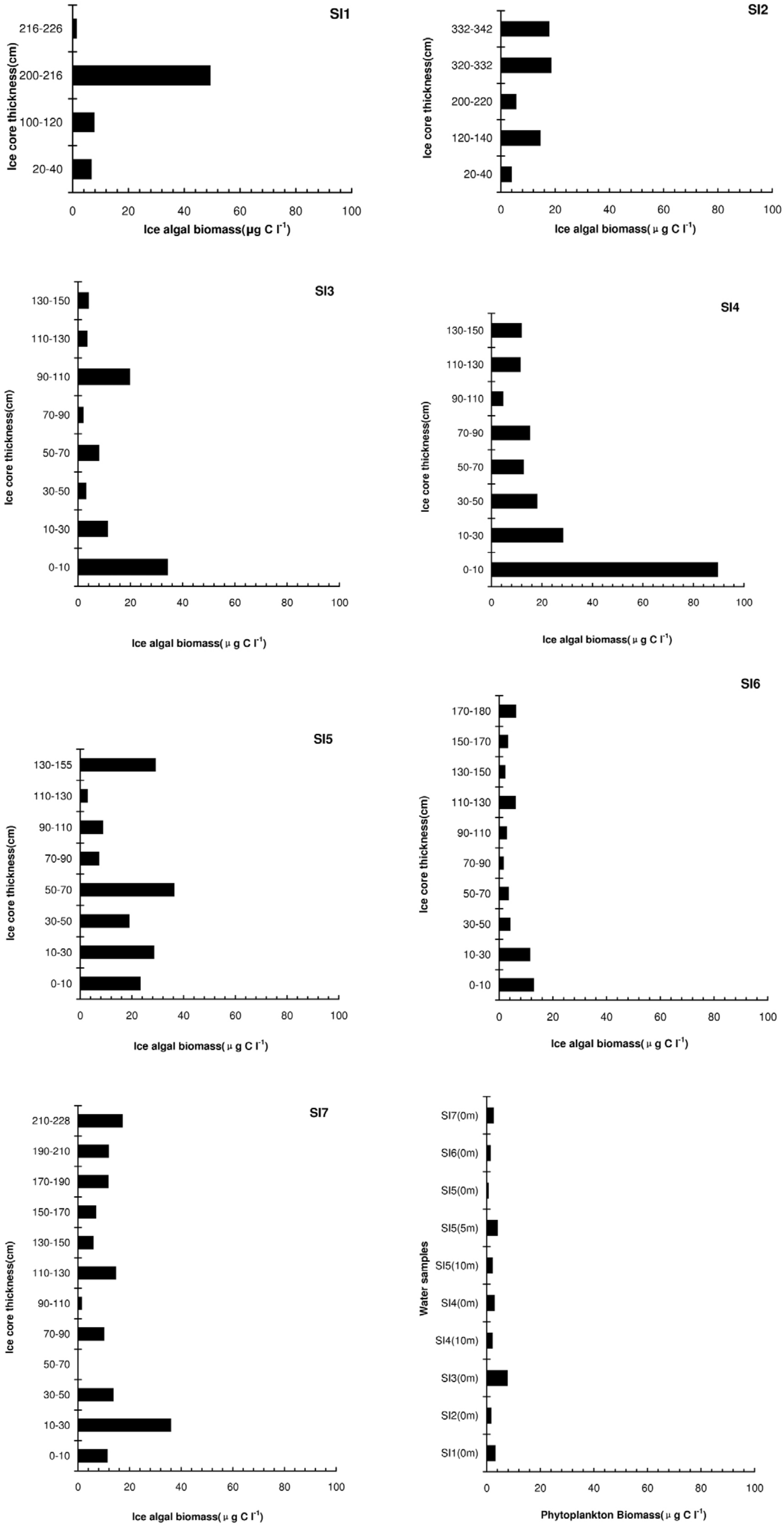


Fig. 2. The vertical distribution of algal biomass in the ice cores and the underlying water.

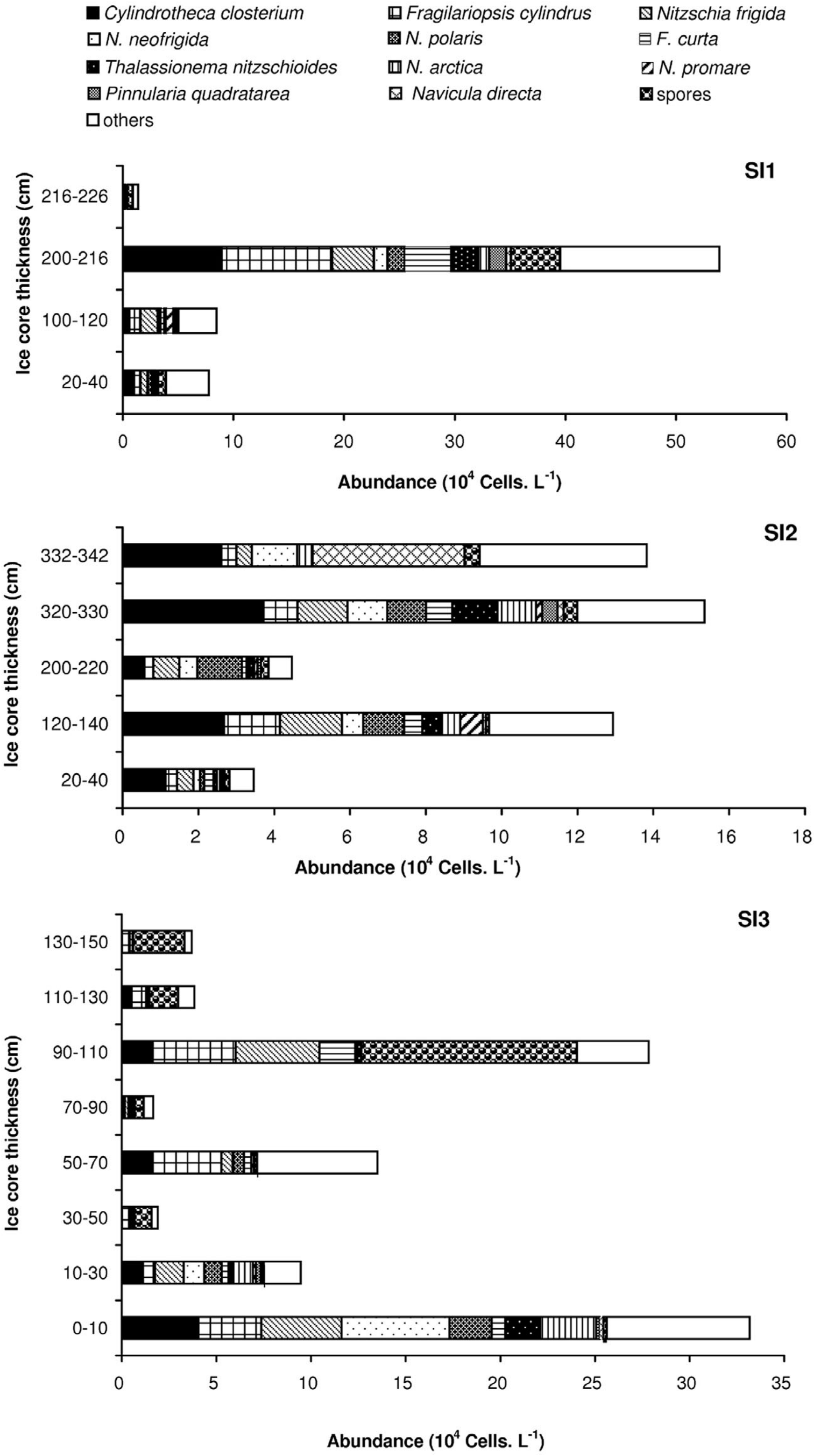
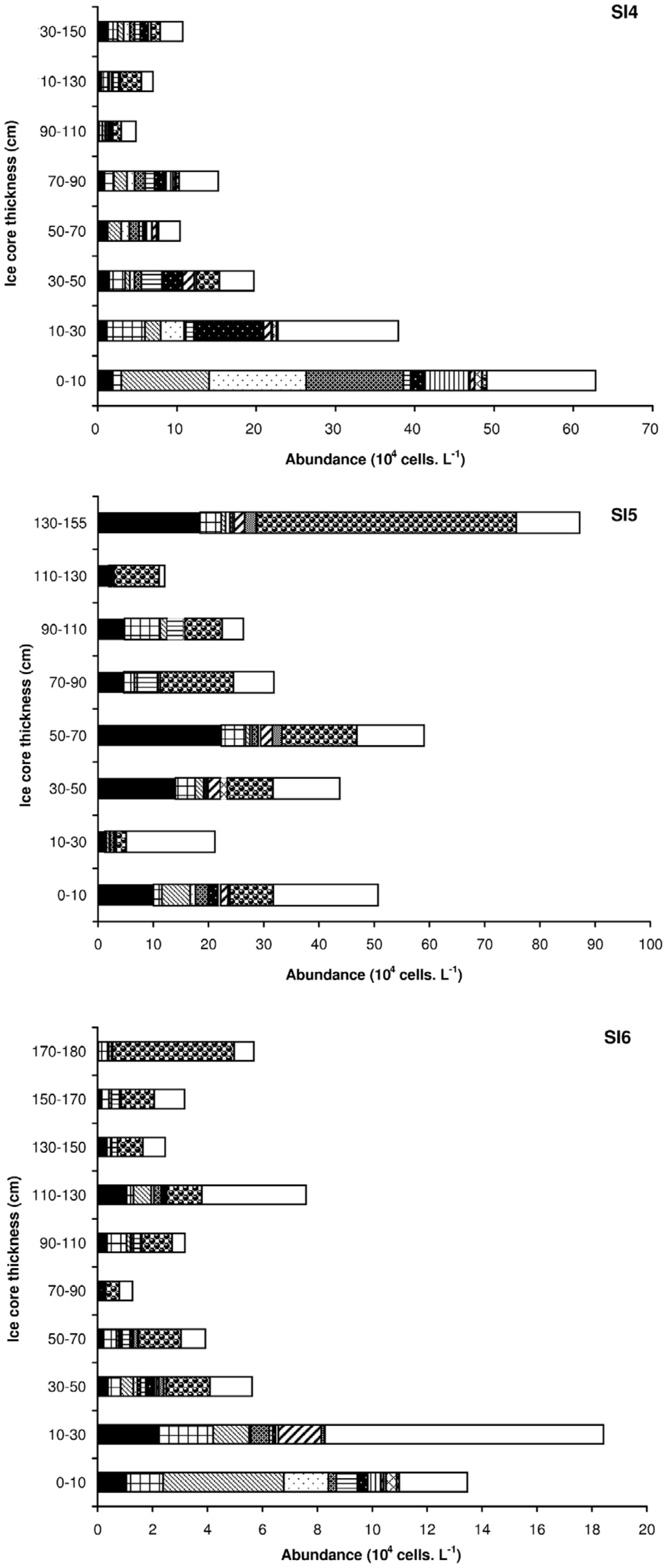


Fig. 3. For caption see next page.



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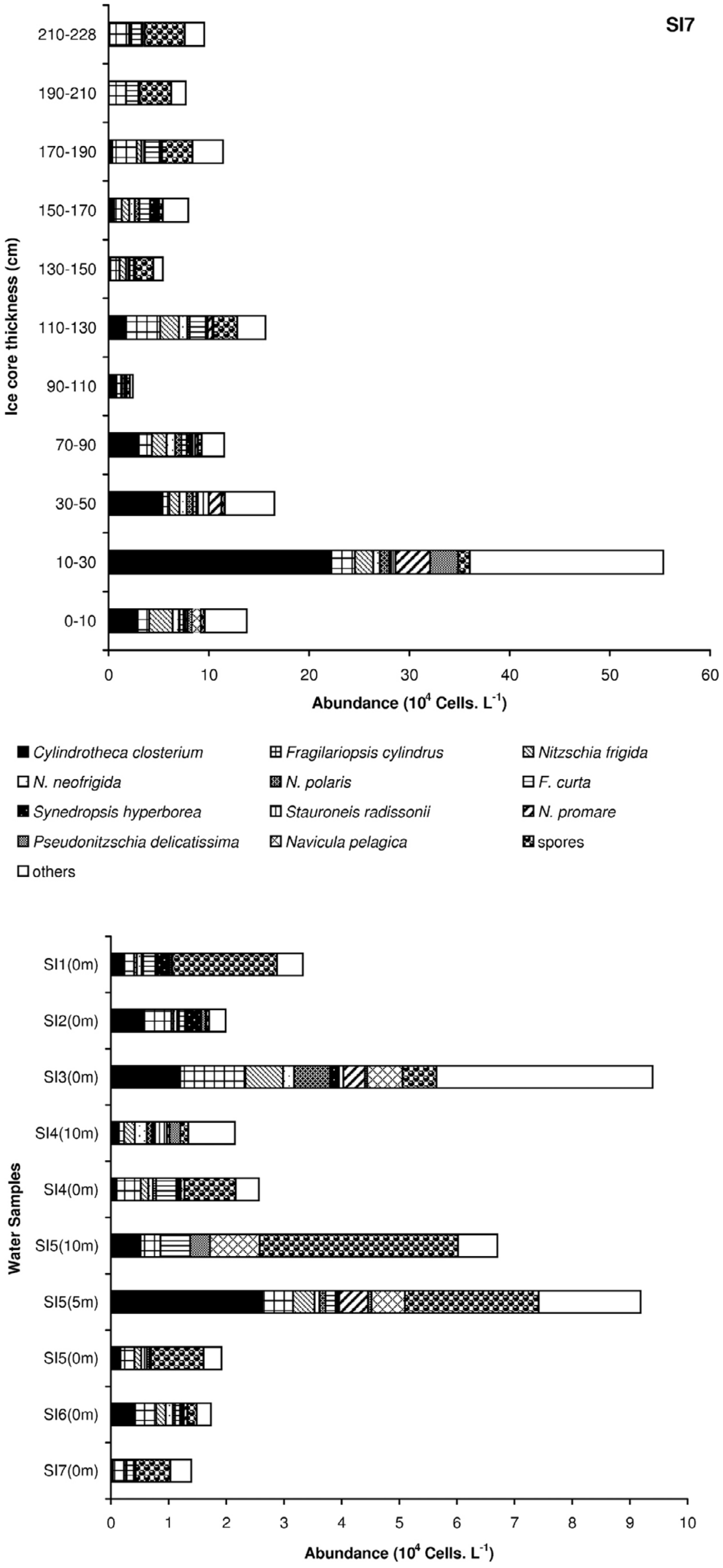

Fig. 3. The vertical distribution of total algal abundances containing that of the dominant species in the ice cores and the underlying water.

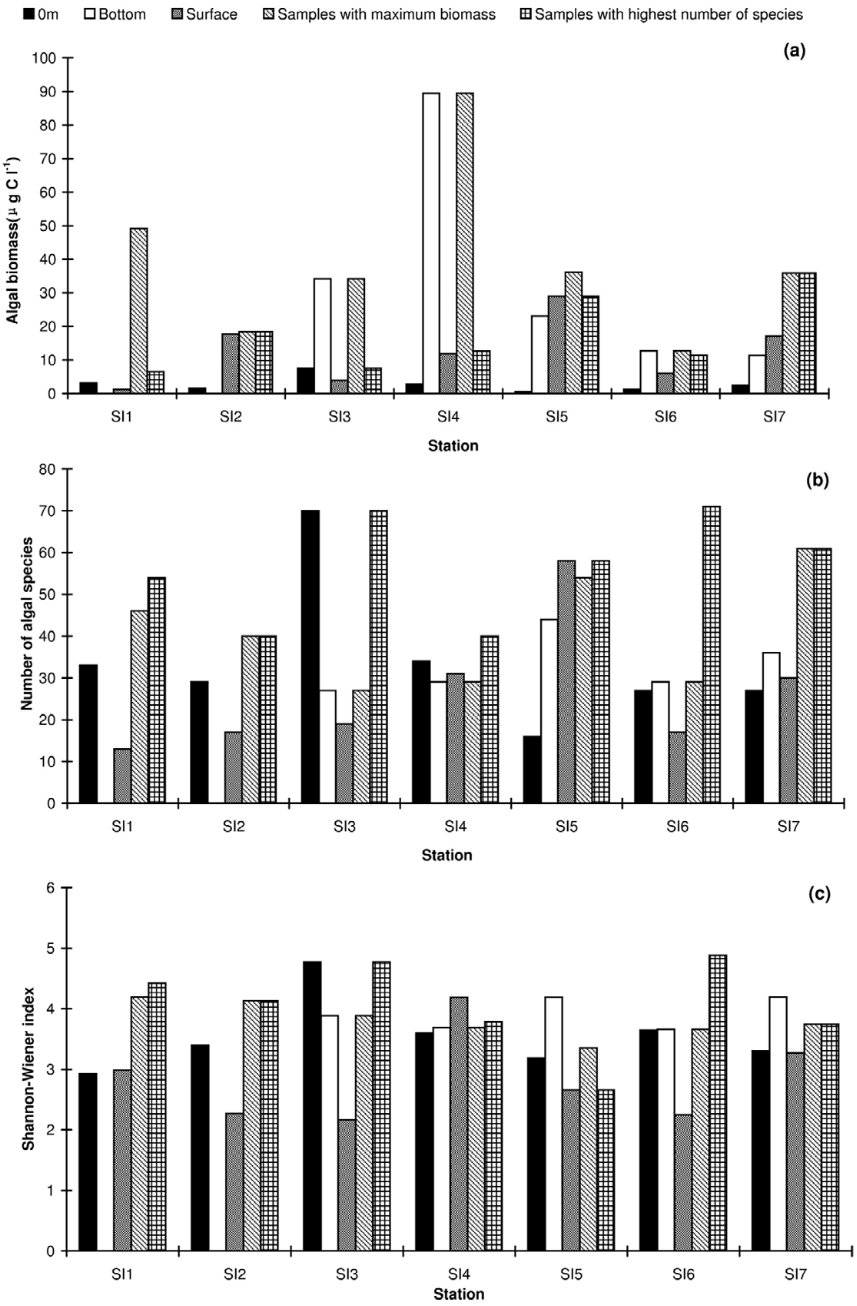

Fig. 4. The horizontal distribution of (a) algal biomass (b) number of algal species and (c) Shannon-Wiener index at 0-m depth of the water column, the bottom and surface layers of the ice cores, and the layers with maximum biomass and species number.

index ($r = 0.059$, $P > 0.05$). So did abundances ($r = 0.41$, $P < 0.01$ and $r = -0.024$, $P > 0.05$, respectively) (Fig. 6).

The cluster analysis result displayed the heterogeneity of the algal community concerning the species composition and the specific abundances (Fig. 7). Among 60 samples, there were 29 samples classified into the primary group, including nearly all of the water samples except two (one collected from SI5 at 5m and the other from the ice-water interface of SI3), which had been characterised by higher species richness and algal biomass than other water samples and were clustered into the secondary group. Most of the algal communities near and at the sea ice surface were also grouped into this assemblage. None of the ice algal communities in the bottom 10 cm shared a same category and none of a single ice core had all its sub-samples clustered into one group (Fig. 7).

Discussion

Diatoms, especially pennate diatoms dominated in the microalgal community in the sea ice and the underlying water in the Canada Basin at the end of the summer 2003. 102 algal species were found in this study, of which 95 species were diatom, confirming that ice algal community

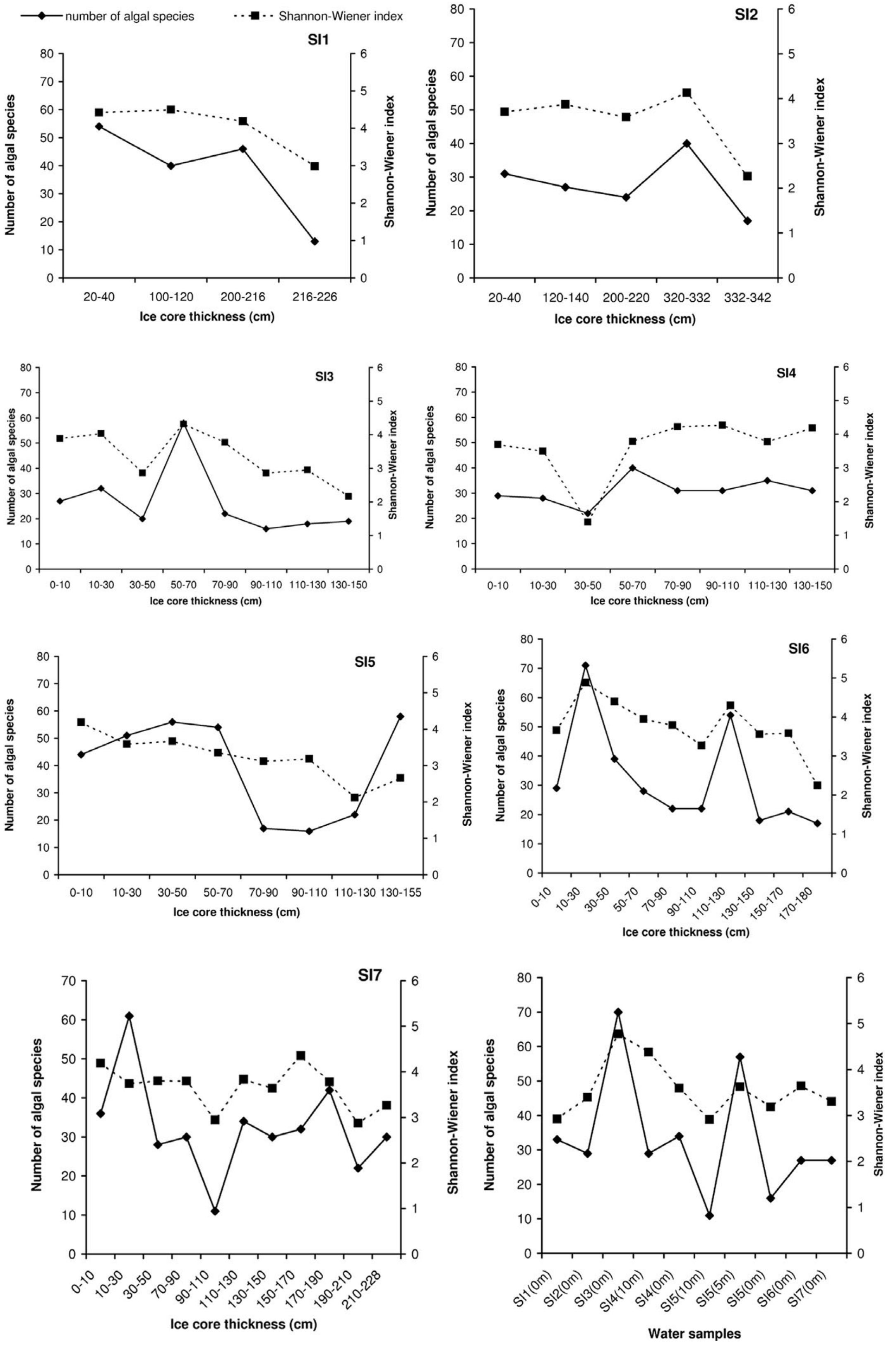

Fig. 5. The vertical distribution of the number of algal species and the Shannon-Wiener indices in the ice cores and the underlying water.

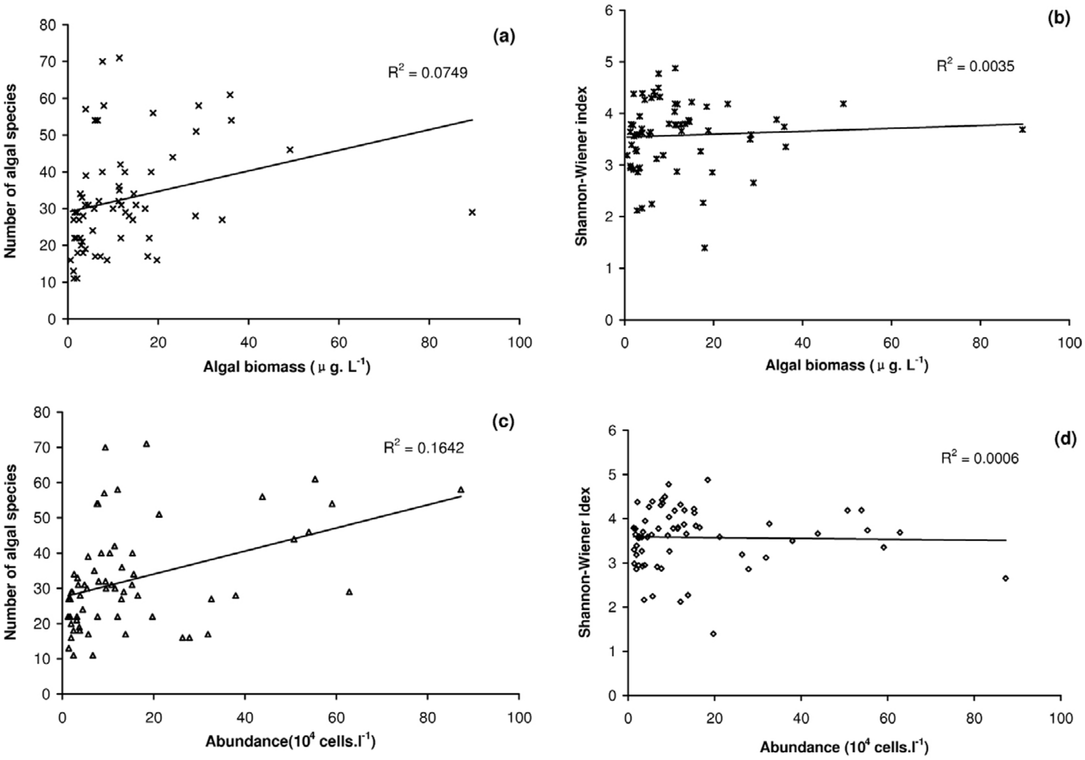

Fig. 6. (a) Correlation of biomass with number of algal species, (b) correlation of biomass with Shannon-Wiener index, (c) correlation of abundances with number of algal species and (d) correlation of abundances with Shannon-Wiener index.

was an important component of the Arctic's biodiversity and diatom was the most important contributor in terms of abundance, productivity and number of species (Melnikov and others 2002; Quilfeldt and others 2003). Flagellates were also reported to substantially contribute to the structure and dynamics of the ice biota community (Ikävalko and Gradinger 1997; Thomsen and Ikävalko 1997), which may be under-represented in this study since they were difficult to see in the count samples and their cells were fragile to fixatives because of lacking a hard shell. The total number of algal species in this study ranked in the middle among the investigations up to now of the Arctic Ocean including coastal areas despite seasonal variability (Quilfeldt and others 2003), with the average Shannon-Wiener index of 3.58 ± 0.68. The correlation coefficient between abundances and species numbers in the Chukchi Sea (Quillfeldt and others 2003) ($r = 0.83$, $P < 0.01$), one of the few papers listing ice algal species by layer, was higher than our result ($r = 0.41$, $P < 0.01$). The irrelevance between the diversity index and biomass (or abundance) and the relevance between the number of algal species and biomass (or abundance) indicated the unevenness of the microalgal community.

Most of the dominant species found in this study were characteristic ice algal species in the Arctic Ocean, including *N. frigida*, *N. neofrigida*, *F. cylindrus*, *N. promare*, *F. oceanica*, *N. pelagica* (Melnikov and others 2002; Quilfeldt and others 2003; Wassmann and others 2006; McMinn and others 2008). *Navicula* spp., *Nitzschia* spp., *Fragilariopsis* spp., and *Pseudonitzschia* spp., the most frequently documented pennate genera in the Arctic pack ice (Quillfeldt 1997), also contributed to a great fraction of the algae in this study (> 1% of total abundance in most samples). The existence of *Chaetoceros* spp., *Thalassiosira* spp., which are considered true planktonic forms (Gran 1904), with abundant *Chaetoceros* spores in the ice samples signaled the ocean origin of the sea ice in the Canada Basin (Quilfeldt and others 2003). The appearance of the great number of spores should be attributable to the common survival mechanism for algae in the absence of light (Eilertsen and others 1995), and could be a good strategy for the formation of a new bloom. Most of the spores here came from dinoflagellates and *Chaetoceros* spp., which were found to form resting spores regularly (Wassmann and others 2006). The species composition of the algal spores was in accordance with the general algal species renewal in the Arctic sea ice. One example was the sea ice algal community in Kobbefjord, West Greenland dominated by flagellates in December-February, followed by *C. simplex* in March and pennate diatoms in May (Mikkelsen and others 2008).

Our survey, from 11 August to 6 September, was at the end of summer melting and the beginning of autumn freeze-up for the high Arctic, since sea ice starts to melt

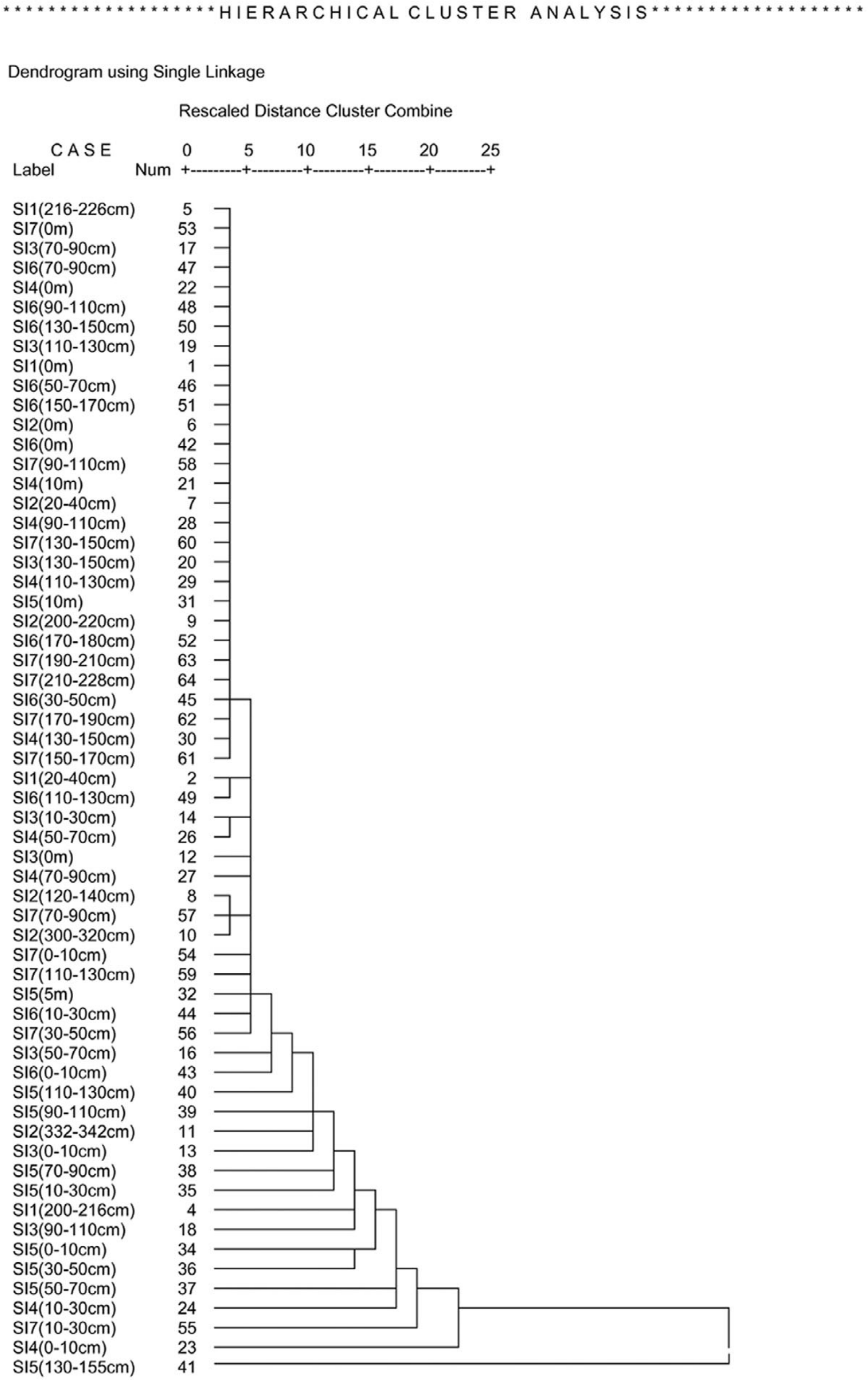

Fig. 7. Dendrogram based on similarity among algal communities concerning species composition and specific abundances.

when the underlying water temperature is over -1.7 °C and ends by August in the Arctic (Andersen and others 2004). Due to the reported severe melting in the Arctic in 2003 summer (Lindsay and Zhang 2005; Arrigo and others 2008; Shirasawa and others 2009), the prevailing amount of pennate diatoms in the water samples of the present study should be mostly released from the sea ice. Besides, their existence indicates the possible effect of ice algal inocula in the Arctic summer. For example, *N. frigida*, one of the dominant species, can remain in plankton for some time after being released from sea ice (Syvertsen 1991).

Compared to Melnikov and others (2002) we observed higher values for ice algal biomass (89.49 μg C l^{-1} compared to 19 μg C l^{-1}) and more species. This discrepancy seems to be puzzling here due to the lack of some environmental knowledge like concentrations of nutrient, although the seasonal change might partly account for it. With similar algal species and much lower algal biomass than the above ice samples, the algae in the under-ice water was probably limited by lack of nutrients in the central Arctic since the deep water of the Canada Basin experiences very slow exchange and tidal currents (Kowalik and Proshutinsky 1994).

The maximum ice algal biomass of each ice core in the Canada Basin of 2003 summer was found in various parts of the ice cores, either at the bottom, near the bottom, in the centre, or near the surface. Algae in the Arctic pack ice are more distributed throughout the ice during winter, becoming concentrated in the bottom sections in spring, and continuing to grow and accumulate in the bottom layer in summer (Quilfeldt and others 2003). This was also the case in the Canada Basin in 1997–1998 (Melnikov and others 2002). Although many studies concentrated on the bottom communities of summer Arctic sea ice algae, more attention was paid to the internal maxima (Gradinger 1999; Quilfeldt and others 2003). Our findings agree with the proposal by Gradinger (1999) that all layers of the sea ice must be studied to avoid underestimation of algal biomass and production.

The cluster analysis result indicated most of the algal communities near or at the ice surface were more similar to the phytoplankton communities than other ice algal communities. The result reflected the spatial heterogeneity of the sea ice algal communities concerning their species composition and specific abundances, which was shown by the distribution patterns of biomass, abundances, number of species and diversity index too. The spatial heterogeneity was found to be characteristic of the sea ice algae in the Arctic Ocean (Gosselin and others 1997; Rysgaard and others 2001) and is partly due to the variable horizontal and vertical structure of pack ice arising from the continual movement and shifting (Andersen 1989). Variable salinity and nutrient concentrations in brine were also responsible for this characteristic, which need to be studied more finely than the currently and broadly used cutting and melting method. In addition, light, the main factor limiting primary production in the Arctic, was another possible interacting cause and was mostly correlated with ice thickness and snow depths (Lazzara and others 2007).

As over-melting of sea ice carried on in 2003 summer in the Canada Basin of the Arctic Ocean indicated by low salinity throughout the whole ice core and the dominance of bacteria and heterotrophic flagellates in the microbial food web (He and others 2005), our survey investigated in detail the composition, biomass and structure of microalgal communities through seven ice cores and the underlying water columns in the pack ice zone, which supplements our limited knowledge in the central Arctic Ocean and provides a background of the sea ice algal communities as the global climate change maintains.

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