Diatom assemblages in the surface water of the Indian Sector of the Antarctic Surface Water in summer of 1999/2000

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Abstract: Abundance and species composition of diatom assemblages in surface water of the Indian Sector of the Antarctic Surface Water of the Southern Ocean were examined using samples gathered during the JARE-41 Cruise of the icebreaker *Shirase* in the summer of 1999/2000. On the westward leg (Leg 1), abundance of the diatom assemblage was geographically rather uniform, while species composition was different geographically in mosaic manner. Dominant species on Leg 1 were the pennate *Pseudo-nitzschia* spp. and the centric *Dactyliosolen tenuijunctus*, *Chaetoceros* sp. cf. *dichaeta* and *Chaetoceros neglectus*. On the eastward leg (Leg 2), abundance and species composition were different east and west of 60˚E. The community to the west was large in abundance and dominated by *D. tenuijunctus*, while that to the east was small and dominated by the pennate *Fragilariopsis* species. These diatom assemblages were grouped into four clusters on Leg 1 and three on Leg 2. Mosaic distribution of the clusters was again evident on Leg 1, while rather simple east-west difference was the case on Leg 2. These geographical variations seem to be affected by local sea ice dynamics.

key words: diatom assemblages, sea ice dynamics, Antarctic Surface Water, cluster analysis, spatial and temporal variations

Introduction

The hydrographic regime in the surface Southern Ocean is controlled by the westward Antarctic Coastal Current in the south and the eastward Antarctic Circumpolar Current in the north. The latter is further demarcated by the Antarctic Convergence at the center into two major water masses, *i.e.*, the Subantarctic Surface Water and the Antarctic Surface Water (Knox, 1994). Because the configuration of these water masses is basically circumpolar, spatial variability in abundance and species composition of phytoplankton assemblages are expected to be large in the latitudinal direction but small in the longitudinal direction (Hart, 1942). Therefore, previous works on phytoplankton distribution in the Southern Ocean have mainly examined the latitudinal variation covering the above-mentioned two water masses (Fukase, 1962; Cassie, 1963; Hasle, 1969; Steyaert, 1973; Jacques *et al.*, 1979; Kopczynska *et al.*, 1986). However, the present study focuses on longitudinal variation in the Antarctic Surface Water. To illustrate the longitudinal variation of diatom assemblage, distribution of

diatom species along east-west cruise tracks through the Indian Sector of the Antarctic Surface Water was analyzed. The effect of sea ice on abundance and species composition of the diatom assemblage is also discussed.

Materials and methods

Sampling was carried out on the cruise tracks of the icebreaker *Shirase* to and from Syowa Station, Antarctica in the summer of 1999/2000 (JARE-41). From 8 to 17 December 1999 samples were taken at 19 stations (Sts. A9–A27) on Leg 1 on the westward track from 53°59.5´S, 109°59.3´E to 64°08.9´S, 39°14.4´E, and from 17 February to 13 March 2000 at 30 stations (Sts. B1–B30) on Leg 2 on the eastward track from 66°45.09´S, 39°00.7´E to 58°52.9´S, 150°00.5´E (Fig. 1). The surface water was sampled at every station by a bucket and poured into a 500 m*l* bottle with 25 m*l* neutralized formalin, and brought back to a land laboratory. In the land laboratory, a 10–25 m*l* aliquot of the fixed sample, depending on the concentrations of chlorophyll *a* of the samples, was settled for at least 24 h in a Utermöhl chamber, and diatom cells were examined and counted under an inverted microscope.

The remaining 200 or 250 m*l* of the sampled water was used for chlorophyll *a* determination. The water was filtered through a GF/F filter and pigments were extracted in N,N-dimethylformamide to determine chlorophyll *a* with a Turner Designs fluorometer on board the *Shirase* (Suzuki and Ishimaru, 1990). The data obtained have just been published in the JARE Data Report 279 (Hirawake and Fukuchi, 2004).

Temperature and salinity of the surface water at each sampling station were read from the continuous records of the shipboard Surface Water Monitoring System (Fukuchi and Hattori, 1987).

In order to examine relationships among stations, cluster analysis based on percent sim-
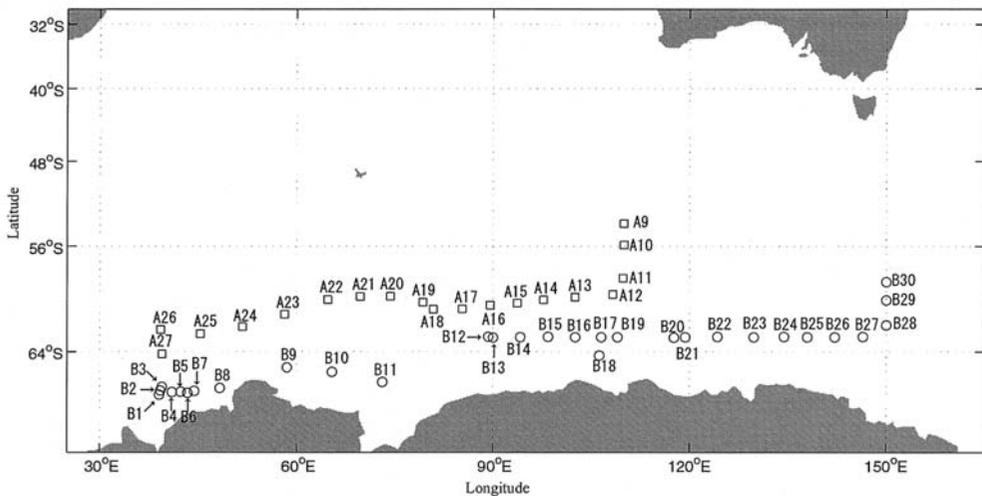

Fig. 1. Location of sampling stations. Stations A9–A27 (Leg 1: □) were occupied on the westward leg during the period from 8 to 17 December 1999, Stations B1–B30 (Leg 2: ○) on the eastward leg from 17 February to 13 March 2000.

ilarity was carried out for both Leg 1 and Leg 2 with BIODIV Version 5.1 (Pensoft, Sofia and Moscow). The similarity between stations was calculated for species composition using the Czekanovski-Dice Sorensen index (Pesenko, 1982), and the weighted average linkage was used for the clustering method (Legendre and Legendre, 1983).

Results

Surface temperature and salinity

Shimazaki and Nakauchi (2002) always detected cold water below 2˚C in the upper 200 m water column at every station by XBT or XCTD deployment, indicating that both Leg 1 and 2 sampled the Antarctic Surface Water that is defined by the presence of water colder than 2˚C in the top 200 m (Belkin and Gordon, 1996).

On Leg 1, the overall surface temperature range was from −0.6 to 2.2˚C, generally high in lower latitudes (Sts. A9–A11), intermediate at eastern Sts. A12–A16 and lowest at the remaining stations (Fig. 2a). Salinity ranged from 33.3 to 33.9: lower values (＜33.7) were recorded at Sts. A15 and A18–A22 and relatively uniform values (33.7–33.9) at the remaining stations (Fig. 2a). Although the stations on Leg 2 were located further south, the overall temperature range was almost the same as that on Leg 1 (−0.5 to 2.2˚C) and colder temperature below 0˚C was rare (Fig. 2b). While irregularity in the geographical trend was apparent
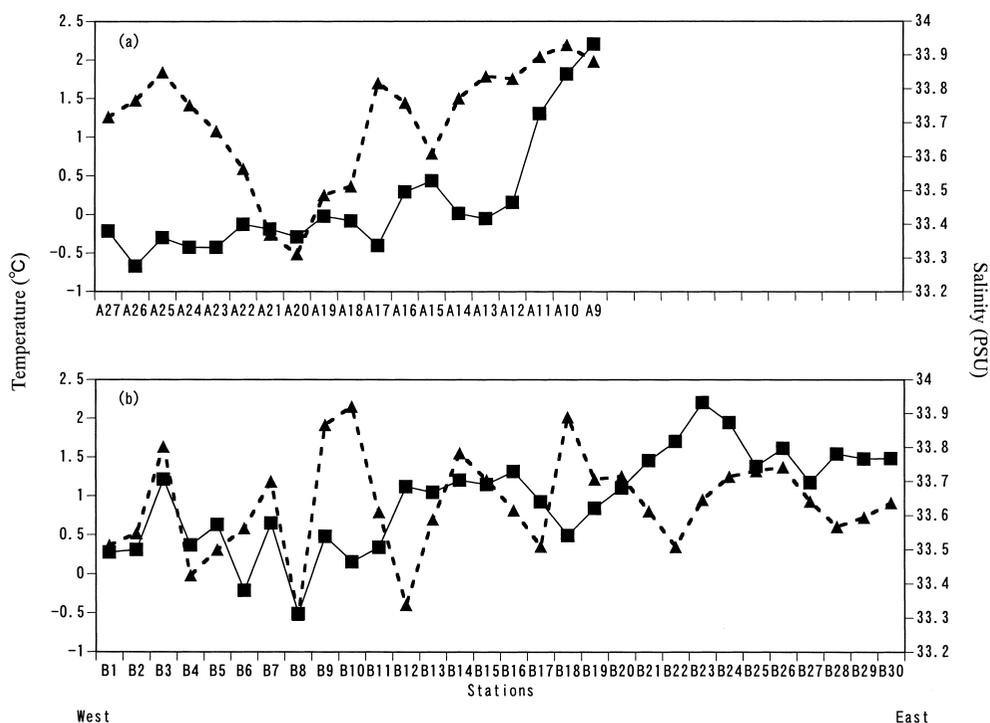

Fig. 2. Horizontal variations of temperature (■: ˚C) and salinity (▲: PSU) on Leg 1 (a) and Leg 2 (b) recorded with the Surface Water Monitoring System on board.

on Leg 2, temperature was generally higher in the east than in the west as seen on Leg 1 (Fig. 2b).

Chlorophyll *a*

On Leg 1, concentration of chlorophyll *a* ranged from 0.14 to 2.93 mg/m³. At Sts. A18–A21 where lower salinity was recorded, the concentration of chlorophyll *a* was higher than 1.5 mg/m³ and the maximum value of 2.93 mg/m³ was observed at St. A18. Higher values than 1.5 mg/m³ were also observed at neighboring Sts. A16 and A17. On the other hand, lower values, less than 0.3 mg/m³, were recorded at Sts. A23 and A24 (Fig. 3a). On Leg 2, chlorophyll *a* ranged from 0.16 to 3.26 mg/m³, being high in the west with several peaks and low in the east. Since stations in the west (Sts. B1–B11) were located in the southern area, this variation was also interpreted as a result of the north-south variation of the chlorophyll *a* concentration that was generally higher in the south than in the north, except for the two northern Sts. B12 and B13, where a marked peak was observed (Fig. 3b).

Abundance of diatom assemblage

The diatom assemblage abundance was rather uniform on Leg 1, being $2.05 \times 10^5 \pm 1.01 \times 10^5$ cells/l on average except for apparently lower abundance than 2×10^4 cells/l at Sts. A23 and A24 (Fig. 4a). On Leg 2, on the return cruise, overall mean abundance (2.37×10^5
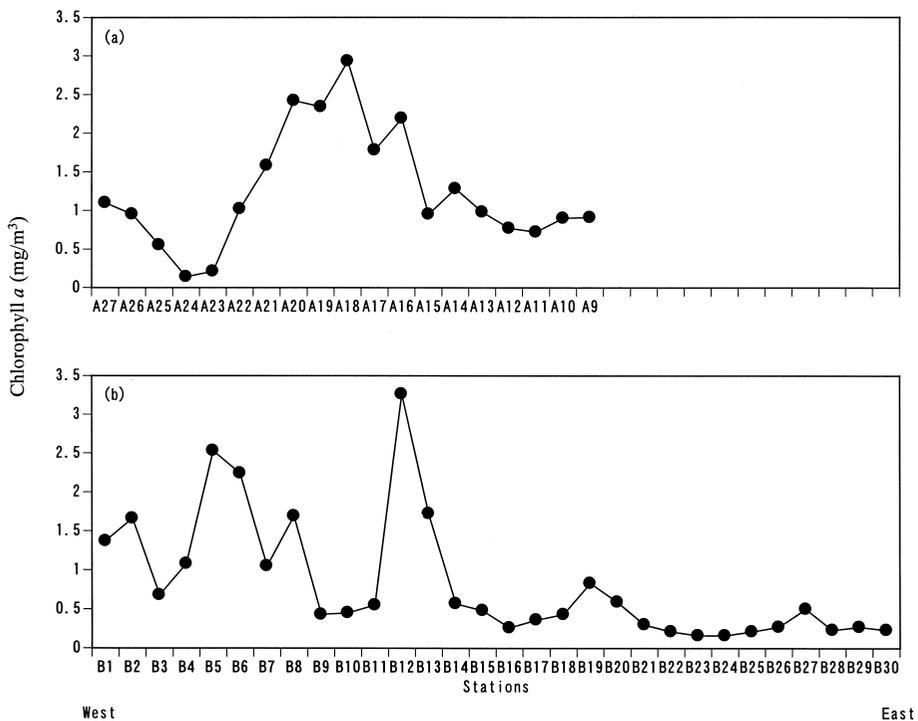

Fig. 3. Horizontal variation of the surface chlorophyll *a* (mg/m³) on Leg 1 (a) and Leg 2 (b) determined by fluorometric method on board.
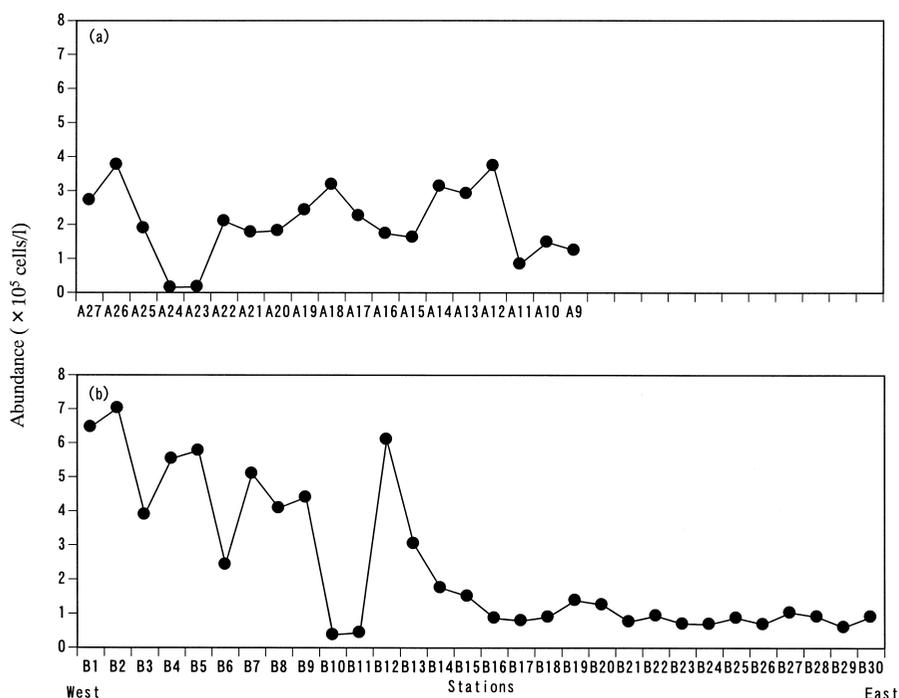
Fig. 4. Horizontal variations of diatom assemblages in abundance ($\times 10^5$ cells/l) on Leg 1 (a) and Leg 2 (b).

cells/l) was at the same level as on Leg 1 but was more variable (SD: $\pm 2.10 \times 10^5$ cells/l) with the geographical trend being low in the east and high in the west (Fig. 4b). At southern Sts. B1–B11 in the west, while some lower values were observed, the general level was high, with the highest value of 7.02×10^5 cells/l at St. B2. In the east or in the north, the abundance was uniformly low ($<2 \times 10^5$ cells/l), except for Sts. B12 and B13, where the chlorophyll a concentration was also high. At the latter two stations, the abundance reached 3.04–6.10×10^5 cells/ l (Fig. 4b).

Distribution of dominant species

     Figures 5 and 6 show the abundances of seven dominant species and two dominant groups, which occupied more than 10% of the total diatom abundance at any one or more stations on Leg 1 or Leg 2. The combined abundance of them (centric diatoms *Chaetoceros dichaeta*, *Chaetoceros neglectus*, *Chaetoceros* sp. cf. *curvisetus*, *Chaetoceros* sp. cf. *dichaeta*, *Corethron criophilum* and *Dactyliosolen tenuijunctus*, and pennate diatoms *Fragilariopsis kerguelensis*, *Fragilariopsis* spp. and *Pseudo-nitzschia* spp.) accounted for 59.5–92.7% and 65.9–94.5% of the total abundances of the diatom assemblages at each station on Legs 1 and 2, respectively.

     Leg 1: Distribution of the *Pseudo-nitzschia* spp. group was comparatively uniform except for lower abundance at Sts. A23–A24 (Fig. 5a). This group occupied a high proportion (*ca*. 20%) of the total diatom assemblage at every station on Leg 1 and was the most
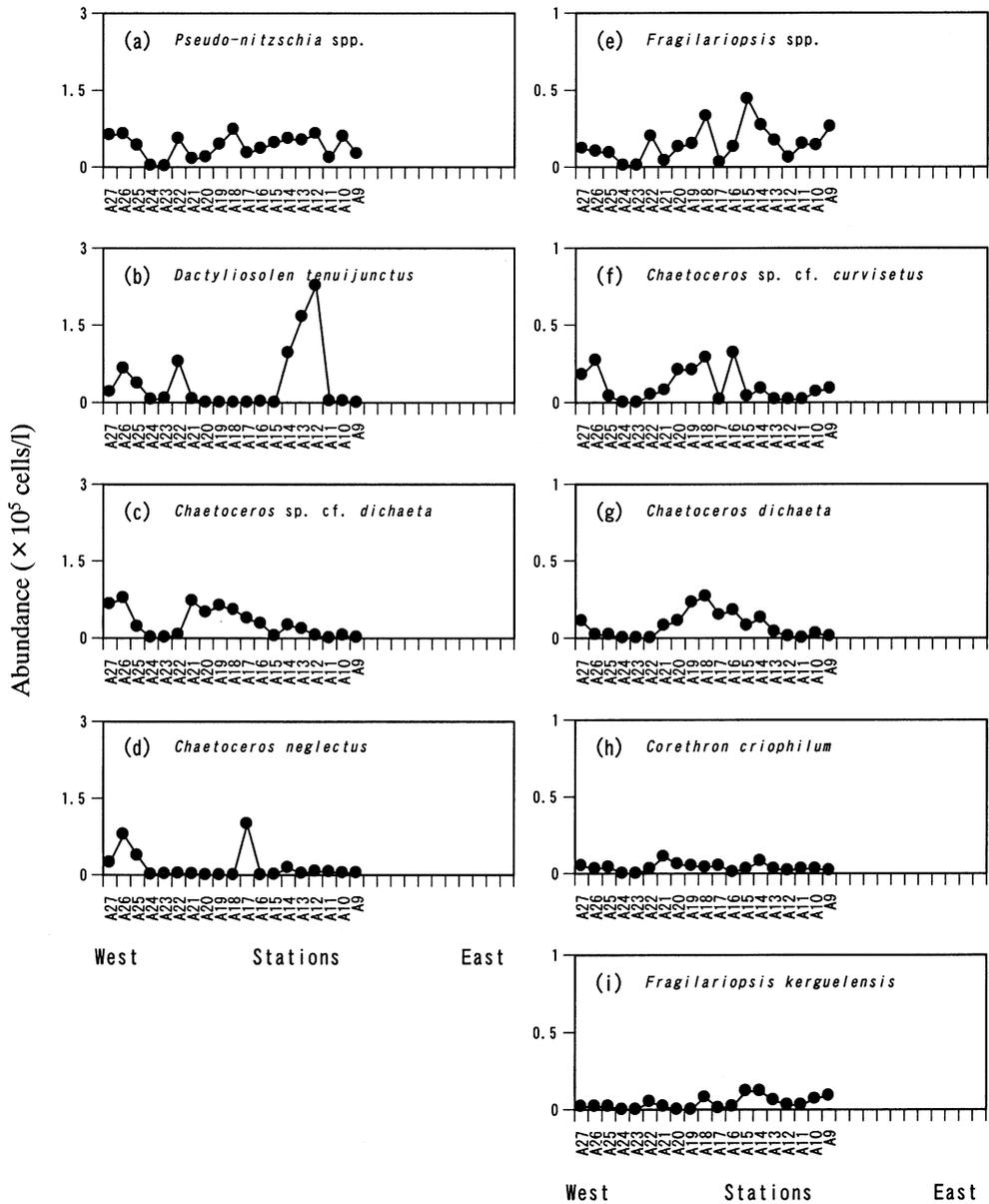
Fig. 5. Horizontal variation in abundance of dominant species and groups of diatoms ($\times 10^5$ cells/l) on Leg 1. Dominant species/groups were defined as those which occupied 10% or more of the total abundance of the assemblages at any one station. (a) *Pseudo-nitzschia* spp., (b) *Dactyliosolen tenuijunctus*, (c) *Chaetoceros* sp. cf. *dichaeta*, (d) *Chaetoceros neglectus*, (e) *Fragilariopsis* spp., (f) *Chaetoceros* sp. cf. *curvisetus*, (g) *Chaetoceros dichaeta*, (h) *Corethron criophilum* and (i) *Fragilariopsis kerguelensis*. Note that the scale of abundance is not uniform throughout the graphs.
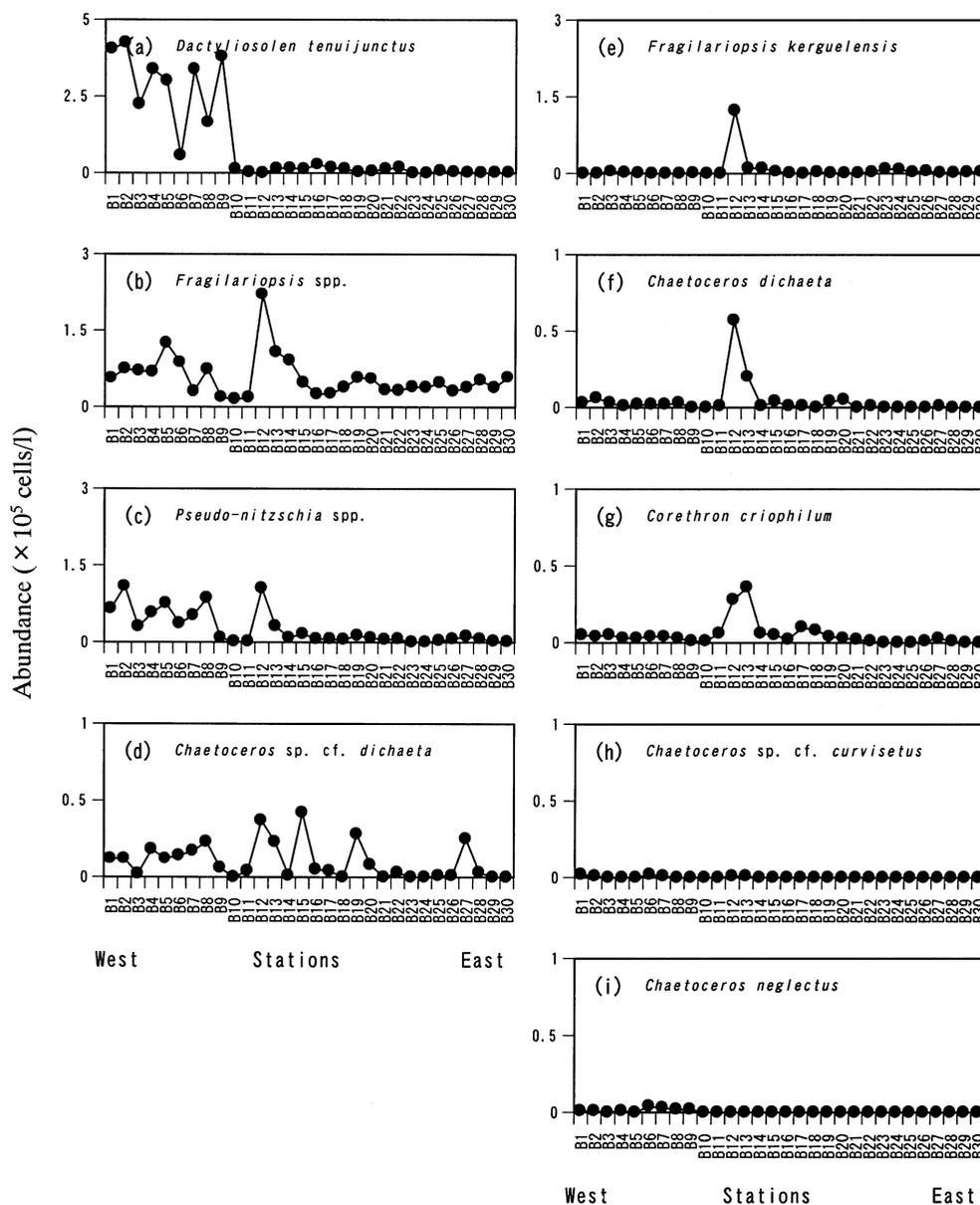
Fig. 6. As in Fig. 5 but on Leg 2. (a) *Dactyliosolen tenuijunctus*, (b) *Fragilariopsis* spp., (c) *Pseudo-nitzschia* spp., (d) *Chaetoceros* sp. cf. *dichaeta*, (e) *Fragilariopsis kerguelensis*, (f) *Chaetoceros dichaeta*, (g) *Corethron criophilum*, (h) *Chaetoceros* sp. cf. *curvisetus* and (i) *Chaetoceros neglectus*.

dominant component at Sts. A9–A11, A15–A16, A18 and A25. In contrast to *Pseudo-nitzschia* spp., *Dactyliosolen tenuijunctus* was highly variable in abundance (Fig. 5b). Its extremely high abundance was observed at Sts. A12–A14, especially at St. A12, where this species occupied the largest proportion (60.8%: 2.27×10^5 cells/l) of the entire diatom

assemblage. Its dominancy was also high at Sts. A22–A24 (37.6–45.8%) and at Sts. A25–A26 (*ca.* 20%). *Chaetoceros* sp. cf. *dichaeta* was distributed unevenly and generally increased from east to west. However, since the abundance was low at the western Sts. A22–A25, two peaks of the abundance appeared at the middle and westernmost stations, especially at Sts. A19–A21 and A26–A27, where it was the most dominant species among the entire diatom assemblage (Fig. 5c). *Chaetoceros neglectus* was again highly variable in abundance as were *D. tenuijunctus*. Its peak was observed at St. A17, where its dominancy reached 44.1% of the assemblage. This species was also abundant at Sts. A25–A27 but very low at the rest of the stations (Fig. 5d).

Fragilariopsis spp., *Chaetoceros* sp. cf. *curvisetus* and *Chaetoceros dichaeta* occupied relatively high proportions following the highly dominant four species described above. These three were generally abundant at middle stations, while westward extension of the higher abundance was different among the three. *Fragilariopsis* spp. was also abundant at the easternmost station and *Chaetoceros* sp. cf. *curvisetus* also at the westernmost stations (Figs. 5e–5g). *Fragilariopsis* spp. attained its maximum abundance (4.40×10^4 cells/*l*) at St. A15 where their dominancy was 27.0% of the entire diatom assemblage (Fig. 5e). *Chaetoceros* sp. cf. *curvisetus* and *C. dichaeta* attained their maxima at St. A16 (3.20×10^4 cells/*l*) and St. A18 (2.65×10^4 cells/*l*), respectively (Figs. 5f and 5g). *Corethron criophilum* also tended to increase at the middle stations as were the three preceding species/groups, its absolute abundance was low ($< 1.1 \times 10^4$ cells/*l*) (Fig. 5h). *Fragilariopsis kerguelensis*, though its abundance was not very high, clearly increased from west to east (Fig. 5i).

Leg 2: The most important species/groups in abundance on Leg 2 were *Dactyliosolen tenuijunctus* and *Fragilariopsis* species. The former largely dominated west of 60˚E or south of 65˚S (Sts. B1–B9) but was low in the east. It contributed to 23.1–86.2% of the total diatom abundance at Sts. B1–B9. Its maximum abundance (4.23×10^5 cells/*l*) recorded at St. B2 was the maximum value among all species/groups observed during this study (Fig. 6a). Absolute abundance of *Fragilariopsis* spp. was generally high at the western and middle stations with a maximum of 2.21×10^5 cells/*l* at middle St. B12 (Fig. 6b). It was also abundant in the east.

Pseudo-nitzschia spp. was often the secondary or tertiary dominant component on Leg 2. Its distribution was similar to that of *Dactyliosolen tenuijunctus*, being dominant in the west, while also abundant at St. B12 (Fig. 6c). *Chaetoceros* sp. cf. *dichaeta* was generally abundant in the west, while several peaks comparable to or higher than those in the west were observed in the east. Especially at Sts. B15, B19 and B27, where its peaks were observed, it occupied a high proportion (19.9–27.6%) of the diatom assemblage following *Fragilariopsis* species.

Fragilariopsis kerguelensis, *Chaetoceros dichaeta* and *Corethron criophilum* were particularly abundant at and around middle Sts. B12 and B13 and uniformly low at the remaining stations (Figs. 6e–6g). Their maxima were 1.23×10^5 cells/*l*, equivalent to 20.1% of the entire assemblage, at St. B12 for *F. kerguelensis* (Fig. 6e), 5.66×10^4 cells/*l* (9.2%) for *C. dichaeta* (Fig. 6f) and 2.84×10^4 cells/*l* (4.6%) for *C. criophilum* at St. B13 (Fig. 6g). *Chaetoceros* sp. cf. *curvisetus* and *Chaetoceros neglectus* occurred mainly at the eastern stations, but their abundances were very low (Figs. 6h and 6i).

Indicator species
    Some indicator species, which occur or form a peak abundance in association with par-

ticular environments such as fronts and sea ice, have been observed in the Antarctic Surface Water. Among them, the following four species were found in this study (Fig. 7): the pennates *Pseudo-nitzschia heimii* and *Amphiprora* spp., and the centrics *Eucampia antarctica* and *Odontella weissflogii*.

Pseudo-nitzschia heimii is reported to occur in the vicinity of the Antarctic Convergence (Manguin, 1960; Hasle, 1969; Gomi, 2003). In the present study, this species occurred at only four stations (Sts. A9–A11 and A15) located at lower latitudes in the east on Leg 1 (Fig. 7a). *P. heimii* was absent from all stations on Leg 2 except for St. B27, where its abundance was apparently lower than on Leg 1 (Fig. 7e).
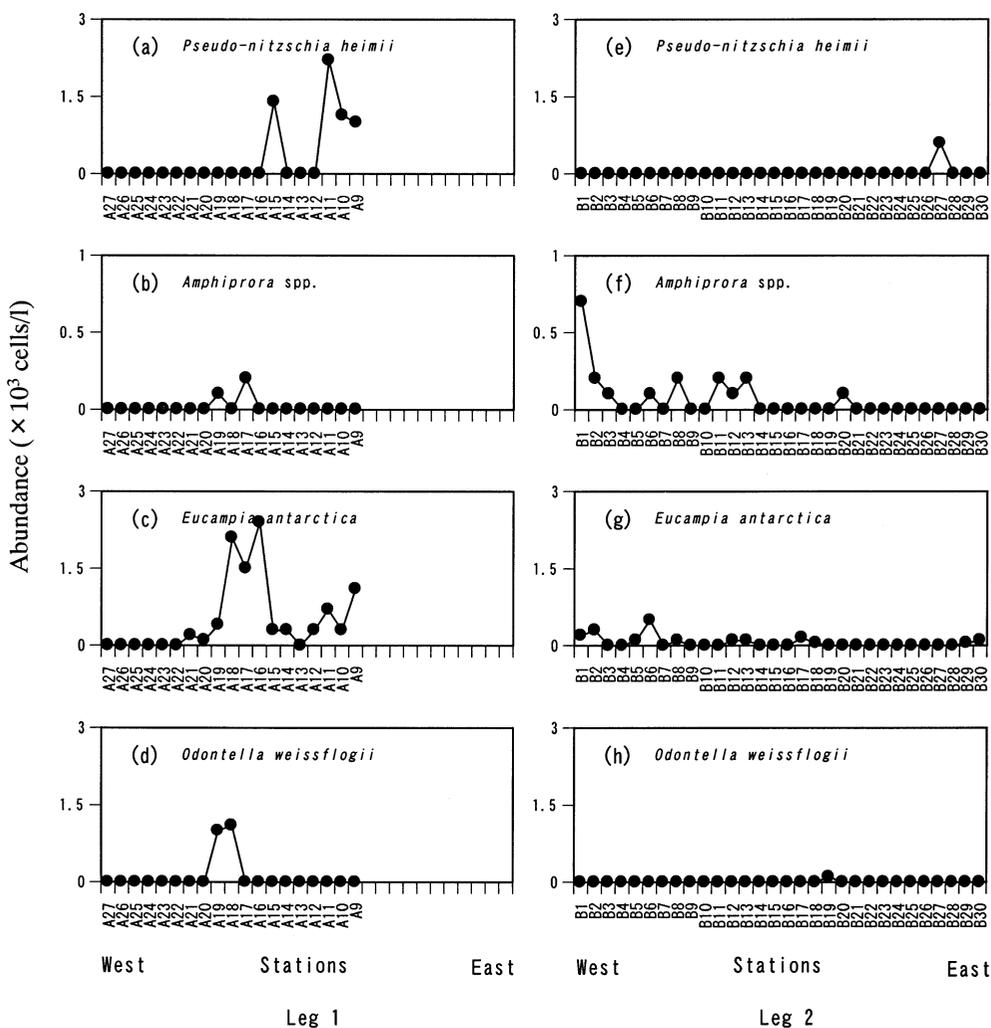

Fig. 7. Horizontal variations in abundance of indicator species ($\times 10^3$ cells/*l*) on Leg 1 (a–d) and Leg 2 (e–h). (a and e) *Pseudo-nitzschia heimii*, (b and f) *Amphiprora* spp., (c and g) *Eucampia antarctica* and (d and h) *Odontella weissflogii*. Note that the scale of abundance is not uniform throughout the graphs.

Amphiprora spp., *Eucampia antarctica* and *Odontella weissflogii* are known as ice-associated species (Palmisano and Garrison, 1993). High abundances of these three were found at middle stations on Leg 1; *Amphiprora* spp. occurred in high abundance at Sts. A17 and A19 (Fig. 7b), *E. antarctica* at Sts. A16–A18 (Fig. 7c) and *O. weissflogii* at Sts. A18–A19 (Fig. 7d). On Leg 2, *Amphiprora* spp. occurred mostly at the western stations, especially those located in higher latitudes. It was also abundant at the middle Sts. B12–B13 in lower latitudes (Fig. 7f), where peaks of most dominant species were observed (Fig. 6). *E. antarctica* occurred in a similar manner to *Amphiprora* spp. but also at the northernmost St. B30 (Fig. 7g). Occurrence of *O. weissflogii* was limited at the middle St. B19 (Fig. 7h).

Discussion

Data on species composition at every station were subjected to cluster analysis to identify geographic separation and configuration of the diatom assemblages. As a result, four clusters were detected on Leg 1 and three on Leg 2 (Figs. 8a and 8b).

Cluster abundance on Leg 1 was highest for Cluster W2 and lowest for Cluster W4. The primary and secondary leading species of each of four clusters were *Pseudo-nitzschia* spp. and *Fragilariopsis* spp. in Cluster W1, *Dactyliosolen tenuijunctus* and *Pseudo-nitzschia* spp. in Cluster W2, *Chaetoceros* sp. cf. *dichaeta* and *Pseudo-nitzschia* spp. in Cluster W3 and *D. tenuijunctus* and *Pseudo-nitzschia* spp. in Cluster W4 (Table 1a). Cluster W1 occurred at northern Sts. A9–A11 and A15 (Fig. 9a). The former three stations were in the so-called Permanently Open Ocean Zone (POOZ), while all the rest of the stations were in the Seasonal
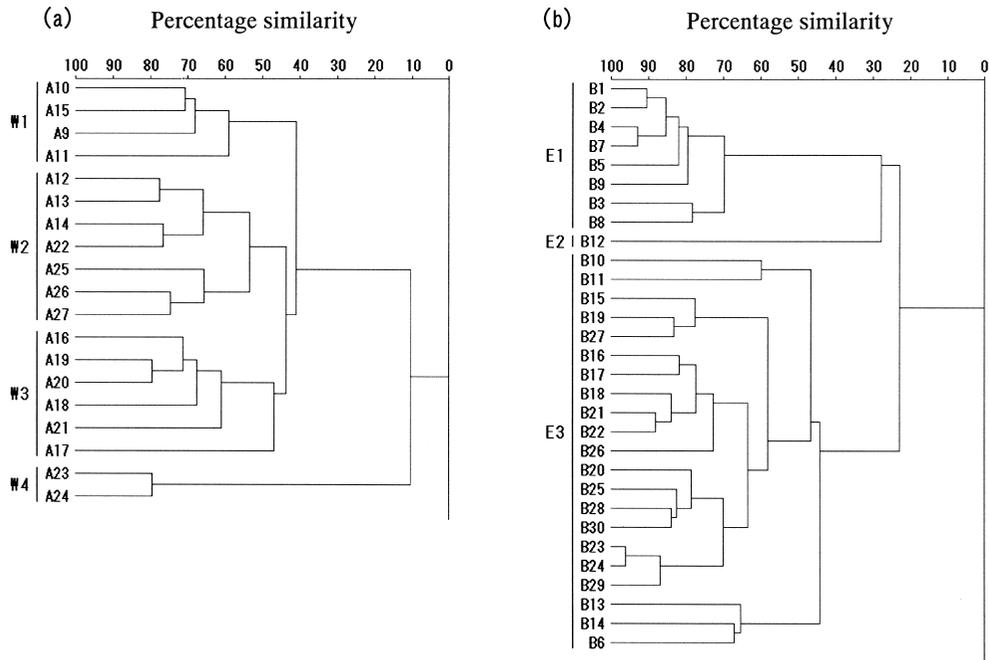

Fig. 8. Dendrograms showing the clusters of diatom assemblages on Leg 1 (a) and Leg 2 (b).

Table 1. Mean abundances of each cluster and dominant species/group ($\times 10^3$ cells/l) in each cluster derived by a cluster analysis for Leg 1 (a) and Leg 2 (b).

(a)

Cluster	W1	W2	W3	W4
Number of stations	4	7	6	2
Mean of total abundance	130.2	289.3	220.2	15.8
Chaetoceros dichaeta	2.9	4.8	16.7	0.0
Chaetoceros neglectus	3.9	24.1	17.0	1.4
Chaetoceros sp. cf. *curvisetus*	5.7	9.4	18.6	0.0
Chaetoceros sp. cf. *dichaeta*	2.4	31.4	50.9	1.0
Corethron criophilum	2.5	3.8	5.2	0.4
Dactyliosolen tenuijunctus	1.6	98.8	1.4	6.7
Fragilariopsis kerguelensis	7.7	4.6	2.0	0.0
Fragilariopsis spp.	25.0	14.5	13.5	0.7
Pseudo-nitzschia spp.	38.8	56.4	35.8	2.5

(b)

Cluster	E1	E2	E3
Number of stations	8	1	21
Mean total diatom abundance	528.1	610.1	108.9
Chaetoceros dichaeta	2.3	56.6	1.9
Chaetoceros neglectus	1.2	0.0	0.1
Chaetoceros sp. cf. *curvisetus*	0.6	1.1	0.1
Chaetoceros sp. cf. *dichaeta*	12.7	36.6	7.7
Corethron criophilum	3.5	28.4	4.4
Dactyliosolen tenuijunctus	321.2	0.1	10.8
Fragilariopsis kerguelensis	0.9	123.2	3.3
Fragilariopsis spp.	64.2	221.0	46.2
Pseudo-nitzschia spp.	60.3	105.4	8.3

Ice Zone (SIZ) (Tréguer and Jacques, 1992). Fiala *et al.* (1998) found that the structure of the phytoplankton community was different between POOZ and SIZ. Thus, Cluster W1 can be recognized to be representative of the POOZ.

On the other hand, the SIZ was occupied by all four clusters in a mosaic manner regardless of latitude (Fig. 9a). Cluster W1 occurred at St. A15 where temperature was relatively high. At the same station, a high abundance of *Pseudo-nitzschia heimii* (Fig. 7a), indicating the Antarctic Convergence or the northern limit of the Antarctic Surface Water, was recorded, as at northern Sts. A9–A11 located in the POOZ (Fig. 7a). These suggest that southward intrusion of POOZ water into the SIZ occurred around St. A15.

Mikaelyan and Belyaeva (1995) reported that the carbon : chlorophyll *a* ratio is high when *Dactyliosolen* dominates the phytoplankton community, because the relative volume of chloroplasts in a cell is small in *Dactyliosolen*. They suggested that, in contrast to the generally known trend of increasing chlorophyll content in a cell under low light irradiance (Eppley and Renger, 1974), high irradiance is necessary for development of the Antarctic *Dactyliosolen*. Massive occurrences of *Dactyliosolen* in Antarctic waters reported in summer (Kopczynska *et al.*, 1986, 1995). Thus, Cluster W2 was likely formed in the areas where irradiance had been high.
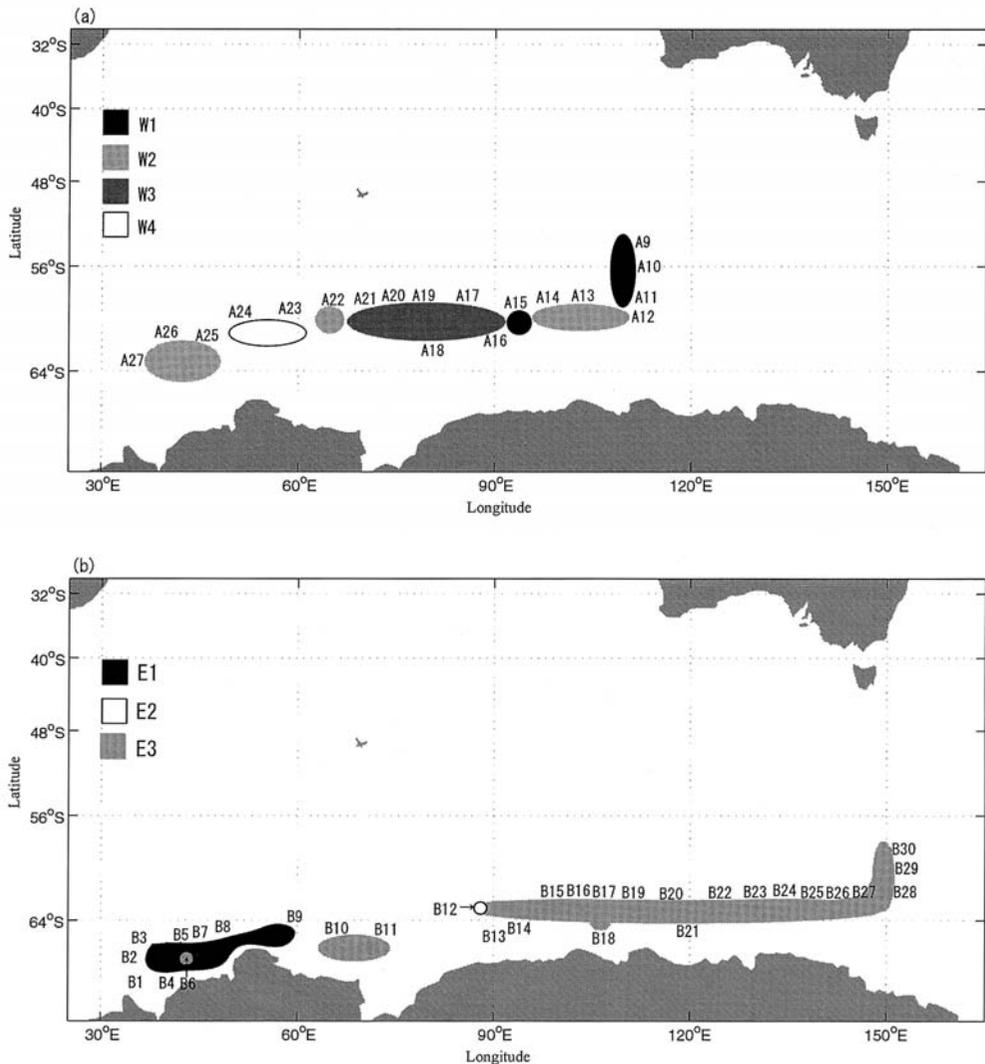
Fig. 9. Geographical distributions of the clusters on Leg 1 (a) and Leg 2 (b).

The mosaic manner of occurrence of Clusters on Leg 1 in the present investigation indi-
cates regional variability of light conditions within the SIZ. Such variability within an area
may be caused by local sea ice dynamics. Ice melt increases light penetration into the water
column and vertical stability of the water column, which keeps phytoplankton in the upper
part of the column where irradiance is high (Knox, 1994). Sea ice gradually disappeared from
Leg 1 from mid-November to mid-December, and the speed and pattern of ice retreat were
different locally (U.S. National Ice Center, http://www.natice.noaa.gov/home.htm). In the
area between 90°E and 110°E, where ice had already disappeared and Sts. A12–A14 were
taken, Cluster W2 was found. In contrast, lower salinity and/or high abundance of ice-asso-

ciated species (*Amphiprora* spp., *Eucampia antarctica* and *Odontella weissflogii*) at Sts. A16–A22 (Fig. 2a and Figs. 7b–d) indicate recent ice melt which, in turn, indicates adaptation of the phytoplankton assemblage to low light. The cluster found there, except at St. A22, was Cluster W3.

The sampling area west of 90˚E where sea ice persisted late was the sea area around Kerguelen Plateau. It has been reported that northward deflection of the surface current is induced by Kerguelen Plateau (Deacon, 1983; Sparrow *et al.*, 1996). Therefore, sea ice might be transported further north in this area by this surface current. Thus, regional differentiation of sea ice dynamics might have resulted from the different direction of the surface current.

On Leg 2, Cluster E3 was smallest in abundance and dominated by *Fragilariopsis* species. Cluster E1 and Cluster E2 were approximately the same in abundance but dominated by different species. Cluster E1 was largely dominated by *Dactyliosolen tenuijunctus*, while Cluster E2 was dominated by *Fragilariopsis kerguelensis*, *Fragilariopsis* spp. and *Pseudo-nitzschia* spp. (Table 1b).

The border between Clusters E1 and E3 was basically at 60˚E. Cluster E1 occurred in the west and Cluster E3 in the east, while the latter was also found at a station (B6) in the west (Fig. 9b). These clusters were demarcated by not only longitude but also latitude. Cluster E1 occurred exclusively at higher latitudes south of 65˚S, while Cluster E3 was distributed widely in lower latitudes north of 63˚S (Fig. 9b). In February and March, when the samplings on Leg 2 were carried out, the ice edge retreated to the southernmost area of the Indian Ocean Sector (U.S. National Ice Center, http://www.natice.noaa.gov/home.htm). Thus, it may be reasonable to assume that Cluster E1 has a close affinity with the ice edge. With distance from the ice edge, vertical stability induced by ice melt water is degraded by lateral flow and increased vertical mixing (Sullivan *et al.*, 1988). Furthermore, since it is suggested that bioavailable iron, which limits phytoplankton growth in summer in the Southern Ocean (Martin *et al.*, 1990), is released from the melting ice to the water column (Sedwick and DiTullio, 1997), the availability of iron would also be weakened with distance from the ice edge. Thus, abundance and species composition of diatom assemblages would geographically vary with distance from the ice edge. *Fragilariopsis* spp. has been known to grow under vertically turbulent condition (Samyshev, 1991; El-Sayed and Fryxell, 1993). The pennate diatoms are reported to grow better even under limited Fe environment in the equatorial Pacific (Fryxell and Kaczmarska, 1994; Erdner and Anderson, 1999). These are likely the cause of the dominance of *Fragilariopsis* spp. (Table 1b) in Cluster E3 that was formed in lower latitudes.

In summary, geographical variation of species composition observed on Leg 1 was likely caused by diversified light conditions due to local sea ice dynamics even on a section transversing through similar latitudes. On the other hand, the geographical variability was small on Leg 2 that was sampled well after the sea ice melted. These indicate that the local sea ice dynamics are the prominent factor determining geographical variability in abundance and structure of the phytoplankton assemblage in the Antarctic Surface Water.

Acknowledgments

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