

VERTICAL FLUX OF ICE ALGAL CELLS DURING THE ICE MELTING AND BREAKING PERIODS IN SAROMA KO LAGOON, HOKKAIDO, JAPAN

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Abstract: The vertical flux of ice algae was determined with a multiple sediment trap at 4 m depth at the central station in Saroma Ko lagoon, Hokkaido, Japan. Collection was done in 5-day intervals from March 1 to April 24, 1994. The sea ice started breaking at the end of that period, from April 10 to 14, 1994 and disappeared completely from the lagoon on April 17, 1994. The average fluxes of CHL_a, PHEO, POC, PON, and BioSi during the melting season of sea ice were 20 ± 6.5 mg CHL_a, 2.0 ± 1.0 mg PHEO, 630 ± 190 mg C, 110 ± 39 mg N, and 490 ± 170 mg Si m⁻² d⁻¹, respectively. The average % loss rates, determined by the ratio of the average vertical flux to the average ice algal production estimated from the standing stock and the growth rate, was calculated as 100% d⁻¹ for CHL_a during the ice melting period. Once the sea ice started breaking and disappeared, they increased by at least 1.5 fold. A relatively high increase was observed for PHEO (2.5 fold) and BioSi (2.3 fold) compared to the lowest increase of CHL_a (1.5 fold). This implies that either the vertical flux of CHL_a has been depressed due to unfavorable physical conditions, such as low salinity produced by a combination of melting sea ice and runoff of fresh water and exposure to high light provided by a disturbed position of broken sea ice, or the vertical flux of BioSi has been accelerated through physical breakage of ice algal cells by heterotrophic grazing and possibly resuspension of PHEO-rich water induced by wind forced mixing, evidenced by a significant increase of PHEO under the ice free water. Wind-forced resuspension should be considered in any study of vertical flux of ice algae when sea ice disappears in shallow water.

1. Introduction

Ice algal communities develop extensively under the bottom surface of sea ice in both the Arctic (GOSSELIN *et al.*, 1990) and Antarctic (GARRISON *et al.*, 1993; SMETACEK *et al.*, 1992). The chlorophyll *a* concentration increases with the growth of sea ice and reaches >300 mg m⁻³ toward the end of the sea ice melting season (ROBINEAU *et al.*, 1996). As long as the daily maximum air temperature is lower than the critical temperature of freezing (-1.33°C) when 24.7 psu is assumed for the winter salinity, the growth of sea ice continues (SQUIE, 1990). When the maximum air temperature becomes higher than that, the sea ice starts melting (HUDIER *et al.*, 1996). Although few ice algal cells are released from the sea ice when the ice is growing, ice algal cells start to be released from sea ice once the sea ice starts melting (MICHEL *et al.*, 1996). When the sea ice breaks, ice algal cells are released into the

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water column. However, during the end of the sea ice melting and breaking period, little study has been conducted without disturbance of the sea ice structure because of logistic problems. A multiple sediment trap can overcome this problem since the traps can be placed when the sea ice structure is solid and the traps continue to collect the ice algal cells during and immediately after the sea ice breaking period.

Ice algal cells go through different physical environments once they are released into the water column (SHIRASAWA *et al.*, 1993). They are forced to change their biochemical compositions during those processes particularly in coastal water with runoff (TAGUCHI *et al.*, 1996). The change in the biochemical composition of ice algae can be followed with a multiple sediment trap. If the trap collects ice algal cells effectively, the analysis of particles collected by the trap can provide the vertical flux and biochemical characteristics of ice algae prior to sedimentation to deeper layers. Therefore, in the present study, the following two hypotheses will be tested (1) the increasing vertical flux of PHEO compared to the vertical flux of CHL_a can indicate the increase of grazing pressure in a brine channel or undersurface of the ice (BUCK *et al.*, 1990), and (2) constant C:N ratio and BioSi:[CHL_a + PHEO] ratio of sedimented particles can suggest the stable biochemical composition of ice algae during the melting period, and change in biochemical characteristics immediately after the sea ice breaking period can reflect resuspension of materials sedimented in the bottom layer in shallow water.

Saroma Ko lagoon is located on the northeast coast of Hokkaido and connected through two channels to the Sea of Okhotsk (Fig. 1). Due to its shallow depth (14 m of average depth), the annual primary production by phytoplankton is as high as 790 gC m⁻² y⁻¹ (FUJI, 1975). The water has been heavily utilized for the aquaculture of scallops and oysters for more than 5 decades (OHARA and MARU, 1967; KONDOH, 1960). The high primary production may support a high biomass of benthic animals such as scallops and oysters (FUJI, 1979). However, this estimate is based on measurements conducted during the ice free period. Although a sporadic determination of ice algal primary production is available during the melting period (SATOH *et al.*, 1989a,b), few data are available for the primary production by ice algae during the ice breaking periods due to logistic problems.

MICHEL *et al.* (1996) determined the vertical flux of the ice algal community during the ice melting period in the eastern basin of Saroma Ko lagoon. Assuming a ice melting period of 65 days and ice algal carbon:chlorophyll *a* ratio of 30, their estimate of total vertical flux was 2.1 gC m⁻² [65 days]⁻¹, which was 0.27% of 790 gC m⁻² y⁻¹. Although the contribution of ice algal primary production was small compared to that of phytoplankton during the ice-free period, the ice algal primary production was almost the sole source of organic matters during the ice-covered period. The significance of primary production by ice algae has been recognized without successful direct observations, particularly during the end of the melting season in Saroma Ko lagoon (KUDOH, 1993). However, the recent development of a multiple sediment trap can provide equivalent information on primary production since the vertical flux of carbon has been considered as a new production in the open ocean (DUGDALE and GOERING, 1967). Strictly speaking, the vertical flux of ice algae is a product of new and regenerated production in the sea ice community (HARRISON

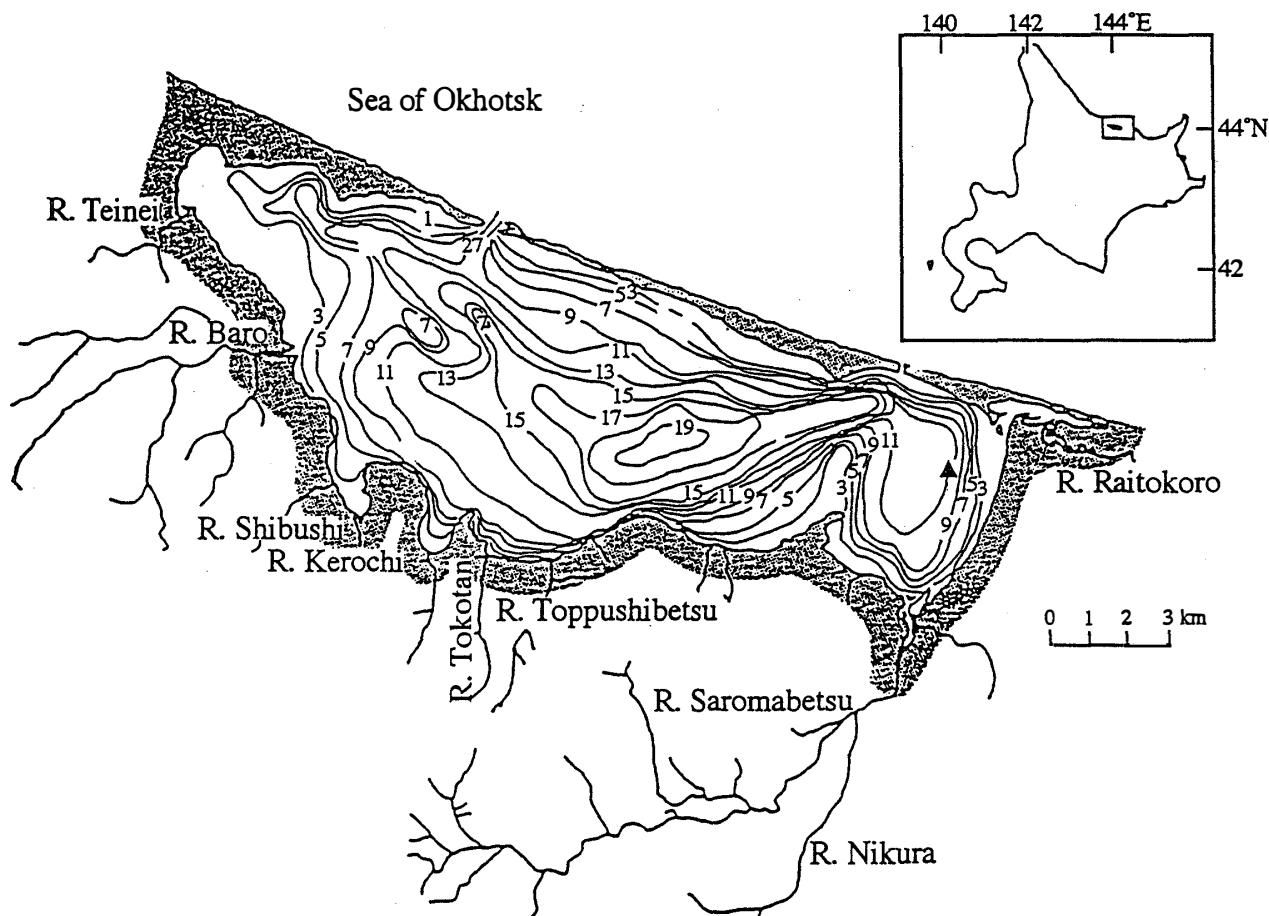


Fig. 1. Map of locations of experimental station E for the sediment trap (indicated by triangle) for the sediment trap and current meter in Saroma Ko lagoon, Hokkaido, Japan.

et al., 1990; TAGUCHI *et al.*, 1996), and ice algal cells are subsequently supplied to the water column as new production. In the present study we will test the two hypotheses mentioned above based on the determination of vertical flux observed by multiple sediment traps.

2. Materials and Methods

The vertical flux of ice algae was determined with a Nichiyu-Giken multiple sediment trap Model T-12S at the central station E (Fig. 1). Prior to deployment, 420 g NaCl dissolved in 3.8 l of distilled water was placed in 12 cylinders (3.8 l in volume) with baffles (1.5×1.5 cm) at the mouth to prevent the entry of at least the larger swimming animals and to ensure that there would be little resuspension of particles once collected within the cylinder. The multiple sediment trap was placed at 4 m over a 9 m-deep bottom through a hole on February 27, 1994. The location of the trap was 5 m from the hole to avoid any disturbance caused by digging the hole. The duration of collection was 5 days between March 1 and April 24, 1994 (Table 1). This period was chosen to monitor short-term events during the melting and breaking season. The ice core samples were collected at station E every 3 days from February 23 to March

Table 1. Date of collection, 5 day flux of CHLa, PHEO, POC, PON, BioSi ($\text{mg m}^{-2}5\text{d}^{-1}$) determined with a multiple sediment trap at the central station in Saroma Ko lagoon, Hokkaido, Japan.

Date	CHLa	PHEO	POC	PON	BioSi
March 1 to 6	55	0.27	1900	350	1200
March 6 to 11	85	4.9	2500	420	2000
March 11 to 16	150	14	3200	530	3100
March 16 to 21	120	12	2600	400	2400
March 21 to 26	58	6.4	2000	280	1300
March 26 to 31	96	12	3500	590	2500
March 31 to April 5	130	17	4800	870	3800
April 5 to 10	110	12	4000	740	3100
April 10 to 15	100	10	3600	640	2500
April 15 to 20	140	22	5100	830	4600
April 20 to 25	170	27	6700	990	6400

14, 1994, with a CRREL core sampler (RAND and MELLOR, 1985). The bottom 3 cm of the ice core was sliced and thawed at room temperature. Subsamples from this thawed water were filtered onto a glass fiber filter type GF/F and stored in 100% acetone at -20°C for the chlorophyll pigment analysis. The traps were recovered from the R/V MICHISHIO MARU on April 26, 1994 when the water surface was free of sea ice. Once traps were returned to the laboratory on shore, the contents of each cylinder were transferred to containers to measure the volume. The contents were divided with a modified Folsom splitter. The first aliquot was filtered onto a glass fiber filter type GF/F and stored in 100% acetone for the chlorophyll pigment analysis. The second aliquot was filtered onto a glass fiber filter type GF/F precombusted at 500°C for 4 hrs for the analysis of POC and PON. The third aliquot was filtered onto a membrane filter with a pore size of $0.2 \mu\text{m}$ for the analysis of biogenic silica.

Water temperature and salinity was determined with an ALEC electromagnetic current meter model ACM-8M at station E (Fig. 1). CHLa and PHEO were analyzed on a Turner Design fluorometer model 10 with the method recommended by HOLM-HANSEN *et al.* (1965). POC and PON were analyzed on a Yanaco CHN analyzer model MT-5T. BioSi was determined on a Bran+Luebbe autoanalyzer model TRAAS 800 with the method of PAASCHE (1980).

3. Results

Water temperature and current speeds showed a distinct seasonal variation (Fig. 2). The temperature reached -1.7°C on January 6, 1994 when ice started developing at the sea surface. During a steady increase of temperature three short-term sudden increases of temperature were observed on February 3, March 7, and April 3, 1994. They were related to the increase of air temperature (SHIRASAWA, unpublished data). The standing crop of CHLa in the bottom 3 cm of sea ice from February 23 to March 14, 1994 changed from 0.44 to 1.2 mg m^{-2} . The vertical flux of CHLa generally increased with season with two peaks during March 11–15 and March

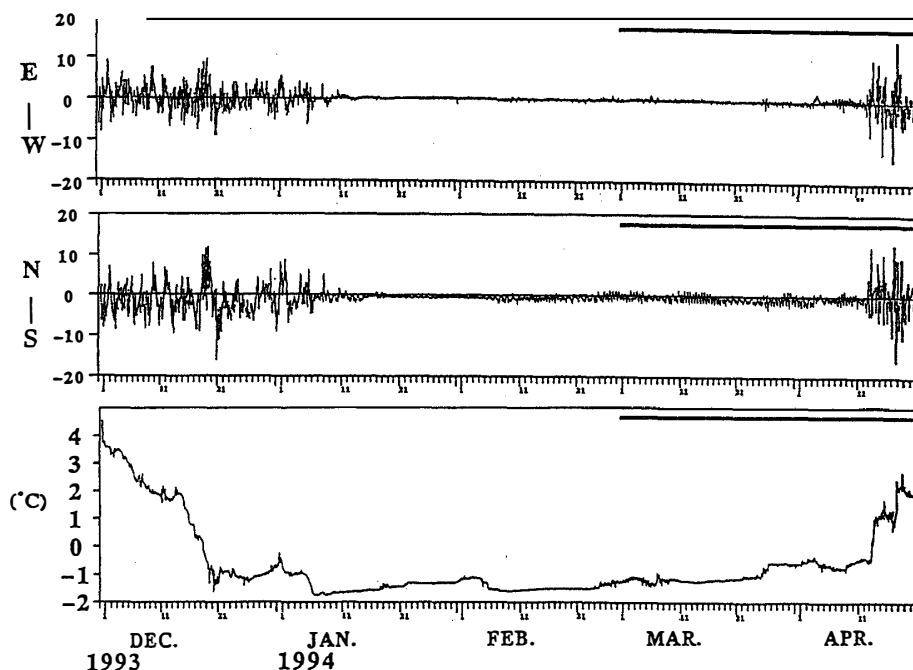


Fig. 2. Seasonal changes of current speeds of East–West and North–South directions and water temperature at 4 m depth at the station E during the period from December 1, 1993 to April 22, 1994.

31–April 4 (Fig. 3A). Those two periods corresponded to an increase of water temperature (Fig. 2). The minimum flux of CHLa was $11 \text{ mg CHLa m}^{-2} \text{ d}^{-1}$ from March 1 to 5 and the maximum flux of CHLa was $31 \text{ mg CHLa m}^{-2} \text{ d}^{-1}$ from April 20 to 24. The vertical flux of PHEO also showed a change similar to that of CHLa with extremely low flux from March 1 to 5 while the maximum flux of PHEO was $5.5 \text{ mg PHEO m}^{-2} \text{ d}^{-1}$ from April 20–24 (Fig. 3B). The vertical fluxes of POC and PON showed similar seasonal changes (Fig. 3C and D). The minimum flux of POC was $390 \text{ mg C m}^{-2} \text{ d}^{-1}$ from March 1 to 5 while the maximum flux of POC was $1300 \text{ mg C m}^{-2} \text{ d}^{-1}$ from April 20 to 24. The minimum flux of PON was $56 \text{ mg N m}^{-2} \text{ d}^{-1}$ March 21 to 25 while the maximum flux of PON was $200 \text{ mg N m}^{-2} \text{ d}^{-1}$ from March 20 to 24. The seasonal change of BioSi was similar to that of POC. The minimum flux of BioSi was $240 \text{ mg BioSi m}^{-2} \text{ d}^{-1}$ from March 1 to 5 while the maximum flux of BioSi was $1300 \text{ mg BioSi m}^{-2} \text{ d}^{-1}$ from 20 to 24 (Fig. 3E).

4. Discussion

The average standing stock of ice algal chlorophyll *a* was 5 mg CHLa m^{-2} in 1994 (KUDOH, personal communication). Highly concentrated chlorophyll *a* was always observed immediately below the bottom of sea ice, and as high as $200 \text{ mg CHLa m}^{-3}$ was observed (KUDOH, personal communication). When the maximum growth rate of ice algae and phytoplankton was assumed as one doubling per day (KUDOH, personal communication), more than $20 \text{ mg CHLa m}^{-2} \text{ d}^{-1}$ was estimated for the *in situ* production in the underlying layer immediately below the sea ice assumed to be 10 cm

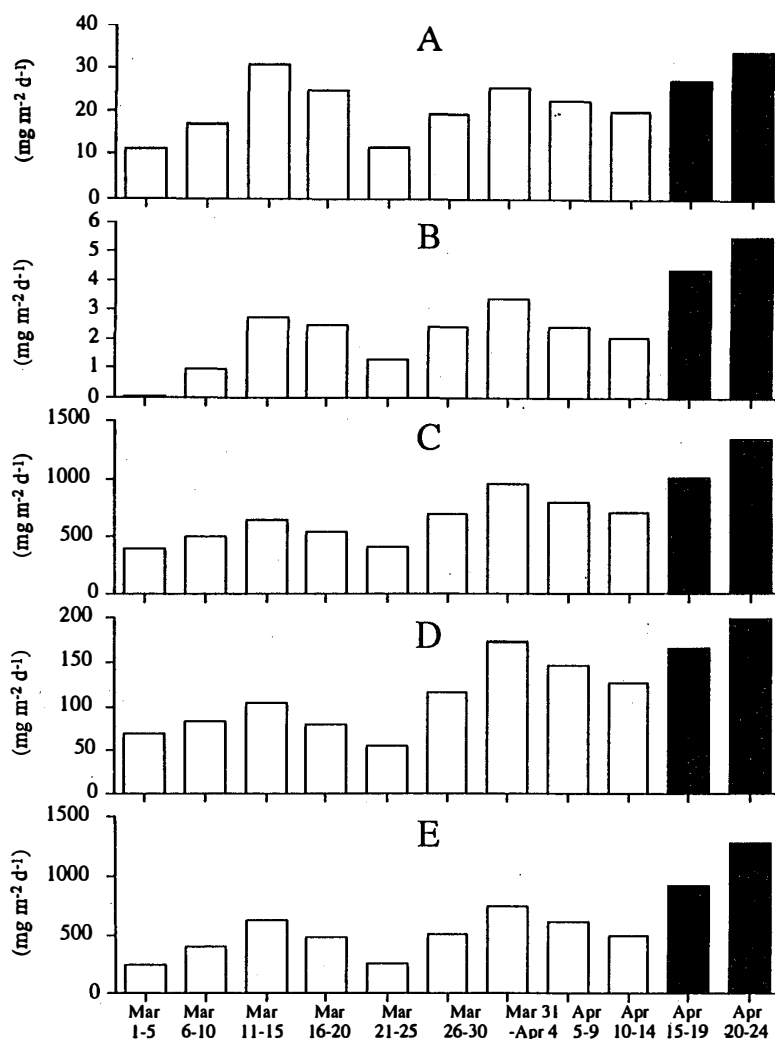


Fig. 3. Seasonal variations in vertical flux of CHLa (A), PHEO (B), POC (C), PON (D), and BioSi (E) at the station E during the period from March 1 to April 24, 1994. Shaded bars indicate the ice breaking period and the ice free period.

in depth. This may suggest that newly produced ice algal chlorophyll *a* is collected into the sediment trap. When the % loss rate is calculated as a ratio of vertically transferred particles to newly produced particles, the % loss rate of ice algae would be almost 100% throughout the season in the present study. However, future study is needed to confirm the present hypothesis.

PHEO are the degradation products of CHLa (CURRIE, 1961). When the sea ice grows, the ice algal population also grows with little PHEO production (ROBINEAU *et al.*, 1996). Toward the end of the ice season, microbial communities developed in brine channels and subsequently PHEO were accumulated in the brine channels due to the grazing activity by heterotrophs (BUCK *et al.*, 1990). The concentration of PHEO in the brine channels increased with season and reached $>10 \text{ mg m}^{-3}$ in Saroma Ko lagoon (ROBINEAU *et al.*, 1996). A relatively high concentration of PHEO was observed in the sediment trap during the melting period in Saroma Ko lagoon (MICHEL *et al.*, 1996), who reported the maximum value of $4.0 \text{ mg PHEO m}^{-2} \text{ d}^{-1}$.

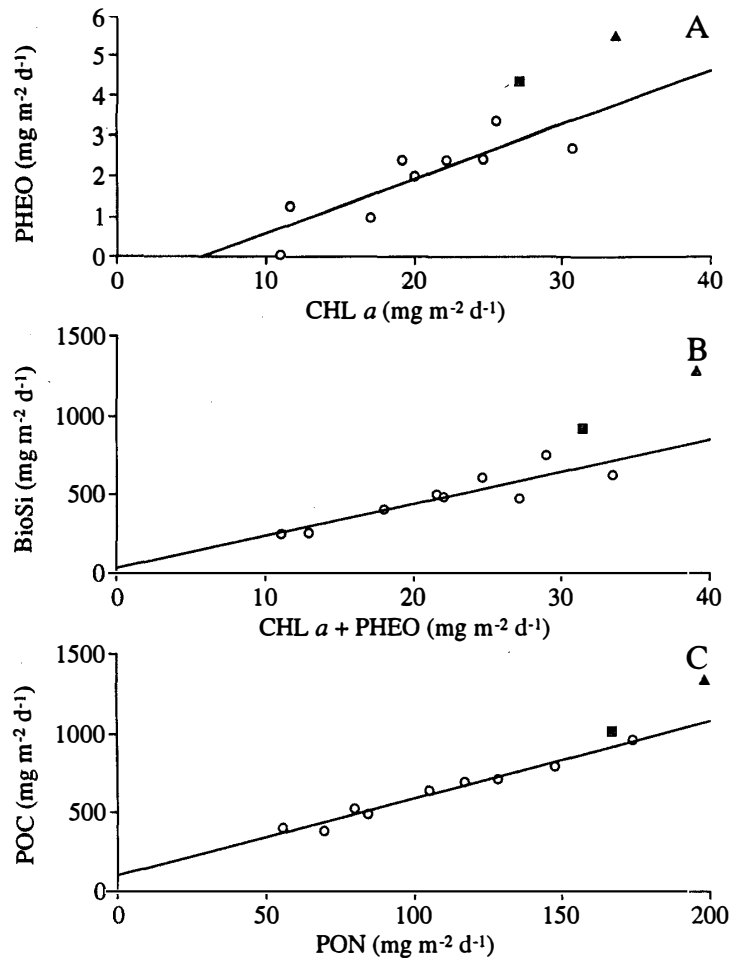


Fig. 4. Relationship between CHL a and PHEO (A), PON and POC (B), and CHL a +PHEO and BioSi (C) from March 1 to April 24, 1994. Squares and triangles indicate April 15 to 19 and April 20 to 24, which correspond to the sea ice breaking period and the ice free period, respectively.

The results of the present study indicate significant increase of PHEO with CHL a , $\text{PHEO} = -0.74 + 0.13 \text{ CHL}a$ with $r^2 = 0.73$, before the ice breaking (Fig. 4A). However, the two values observed immediately after the ice breaking period are different from the linear relation obtained during the ice melting period. This indicates significant production of PHEO compared to CHL a after the ice breaking period. The increased flux of PHEO may be caused by the following two possible reasons. (1) Grazing activity of zooplankton is evidenced by the pigment-poor water compared to BioSi during the ice free period (Fig. 4B). Since zooplankton do not assimilate BioSi but CHL a , a deviation from the significant relationship, $\text{BioSi} = 36 + 20 [\text{CHL}a + \text{PHEO}]$ with $r^2 = 0.80$, indicates the occurrence of grazing activity (CONOVER *et al.*, 1986). (2) Resuspension of PHEO-rich water from the bottom layer is induced by wind-forced mixing under ice-free water. A northerly wind ($>15 \text{ m s}^{-1}$) due to a low pressure system prevailed during the ice breaking period in 1994 around Saroma Ko lagoon (FUJIYOSHI, personal communication), and possibly induced vertical mixing of the entire water column due to the shallow depth. The possible resuspension of particles sedimented at the bottom layer is also evidenced in

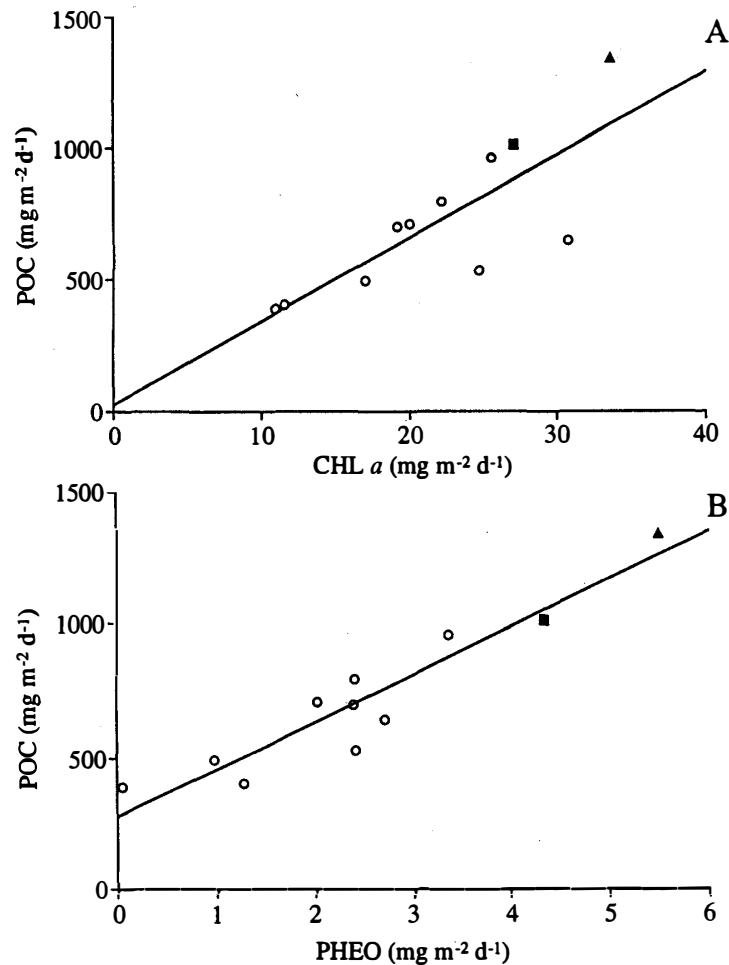


Fig. 5. Relationship between CHL a and POC (A) and PHEO and POC (B) during the period from March 1 to April 24, 1994. See Fig. 4 for symbols.

POC-rich water compared to PON during the ice free period since a significant relationship, $POC = 110 + 4.8 \text{ PON}$ with $r^2 = 0.97$, is obtained for the rest of the period (Fig. 4C).

Assuming that the ice algal C:CHL a ratio in the brine channels and undersurface of sea ice is 20 (TAGUCHI, unpublished data), the increase of C:CHL a ratio obtained from the particles in the sediment trap suggests destruction of CHL a due to either some microbial activity or grazing activity during sedimentation from the surface to 4 m depth (AZAM *et al.*, 1983; MICHAELS and SILVER, 1988). Those biological processes may occur consistently. The significant relationship, $POC = 30 + 32 \text{ CHL}a$ with $r^2 = 0.63$ (Fig. 5A), may indicate that the physiological condition of ice algal cells does not change even after the disappearance of sea ice. Analysis of PHEO and POC indicates a significant relationship, $POC = 280 + 180 \text{ PHEO}$ with $r^2 = 0.88$, observed during the entire period (Fig. 5B). The observation made even after the ice breaking period indicates that PHEO-rich water resuspended from the bottom layer has a similar relationship between PHEO and POC to that during the ice melting period.

Assuming no vertical flux of ice algae during the growth season of sea ice, the duration of the sea ice melting period can be estimated to be 69 days in 1994 from

January 21 to February 6 and from February 25 to April 19 (Fig. 1). The total amount of ice algae released from the sea ice is $1.4 \text{ g CHLa m}^{-2} [69 \text{ days}]^{-1}$, which can be converted to $28 \text{ gC m}^{-2} [69 \text{ days}]^{-1}$ assuming a C:CHLa ratio of 20. This estimate is more than 10 times higher than the estimate made by MICHEL *et al.* (1996). This difference could be related to the depth of sediment trap which was 7.5 m in MICHEL *et al.* (1996) and 4.0 m in the present study. The depth dependent difference may confirm the validity of possible microbial activity or grazing activity during the sedimentation (AZAM *et al.*, 1983; MICHAELS and SILVER, 1988). Although the ice algae utilize nitrate predominantly during the growth season of sea ice and ammonium predominantly during the melting sea ice season (HARRISON *et al.*, 1990), the supply of ice algal cells from the sea ice to the underlying water column can be considered as new production for the ice-covered water.

Not only did the vertical flux of particles increase significantly, but also qualitative characteristics of particles are changed when the sea ice disappears from shallow water such as Saroma Ko lagoon. The increase of vertical flux was obviously provided by the release of the ice algal community from the sea ice. Possible causes for the change in qualitative characteristics are a combination of the seasonal northerly wind which prevailed at the end of the ice season and the shallow water with high abundance of benthic organisms. The consequence of those combination is a resuspension of particles which accumulated and were modified partially by the benthic organisms at the bottom during the ice-covered period. The resuspension process should be considered in studying the vertical flux of particles in seasonally ice-covered shallow water.

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