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CHANGES IN THE FATTY ACID COMPOSITION OF SINKING PARTICLES DURING A PHYTOPLANKTON BLOOM IN THE AUSTRAL SUMMER IN BREID BAY, ANTARCTICA

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Abstract: Vertical fluxes of fatty acids were measured in sinking particles collected using a time-series sediment trap in Breid Bay, Antarctica during the austral summer from December 1985 to February 1986. Major components of fatty acids indicated that the sinking organic matter was mainly derived from diatoms and the contribution of zooplankton to the sinking particles was small. Temporal variation in fatty acid fluxes indicated changes in the abundance and the growth activity of diatom communities in overlying waters during the observations. Ratios of unsaturated fatty acids to saturated fatty acids in the sinking particles increased in the exponential growth phase of the overlying diatom bloom as inferred from changes in the organic carbon and Chl *a* content of sinking particles which reached their peak and started decreasing thereafter. Relative abundance of 20:5 in total fatty acids increased in the peak fluxes of the sinking particles. Our results suggest that the increase of sinking fluxes during the observations was due to the accumulation of the diatom population, of which growth was induced by some favorable environmental conditions in the surface water.

1. Introduction

In the coastal zone of Antarctica, phytoplankton blooms of extremely high production occur for a few months during the austral summer (BUNT and LEE, 1970). These blooms are generally dominated by sea ice-algae and floating diatoms (KNOX, 1990) which sink rapidly to the bottom as a result of aggregation and flocculation as the bloom progresses. Vertical fluxes of particulate matter can therefore be extensive in the coastal areas of the Antarctica during the austral summer (WEFER *et al.*, 1988), and are an important source of energy for organisms under the ice during the rest of the year (MATSUDA *et al.*, 1990; KARL *et al.*, 1991).

Several early studies have documented chemical and biological characteristics of sinking particles collected in phytoplankton blooms (HANDA *et al.*, 1992; LOHRENZ *et al.*, 1992; HONJO and MANGANINI, 1993). The general consensus is that sinking particles following a bloom have fresh organic matter which is similar to cellular organic matter of phytoplankton in the surface water. The freshness of organic matter is greater when sedimentation rates of particulate matter become higher as a result of aggregation and flocculation of phytoplankton (SMETACEK, 1985; ALLDREDGE and

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GOTSCHALK, 1989). Therefore, duirng phytoplankton blooms, changes of not only primary productivity, but also the physiological condition of the phytoplankton, can be recorded on the basis of the magnitude of vertical flux of organic carbon as well as the chemical composition of the sinking particles. HANDA *et al.* (1992) for instance were able to establish distinct growth stages of an overlying phytoplankton bloom from changes in the carbohydrate content or their stable carbon and nitrogen isotope ratios of sinking particles in Breid Bay, Antarctica.

Fatty acids have been used as indices of source materials of sinking particles at the surface (GOUTX and SALIOT, 1980; WAKEHAM *et al.*, 1980, 1984; MATSUEDA *et al.*, 1986; MARTY *et al.*, 1994). Fatty acid composition in particular can provide valuable information on not only the source of organic materials but also the physiological status of phytoplankton during their bloom (KATTNER *et al.*, 1983; MAYZAUD *et al.*, 1989; HAYAKAWA *et al.*, 1996).

In the present study, vertical fluxes of fatty acids were measured in the sinking particles collected by a sediment trap during the austral summer in Breid Bay, Antarctica. The aims of this study are to: 1) deduce the sources of the sinking organic compounds in this oceanic area; and 2) determine the changes of the growth stage of phytoplankton during the overlying bloom based on the compositional changes in fatty acids in the sinking particles.

2. Materials and Methods

2.1. Sampling and chemical analyses

A mooring system consisting of a continuous chlorophyll-measuring buoy, a time-series sediment trap and an acoustic release was deployed from 28 December 1985 to 13 February 1986 at a station located at 70°11.536′S and 24°18.679′E (water depth, 300 m) in Breid Bay, Antarctica (Fig. 1). The chlorophyll measuring buoy was set at a depth of 51 m as described in detail by FUKUCHI *et al.* (1988). The sediment trap consisting of a PVC cone, a control unit and a rotating collector with 12 sampling

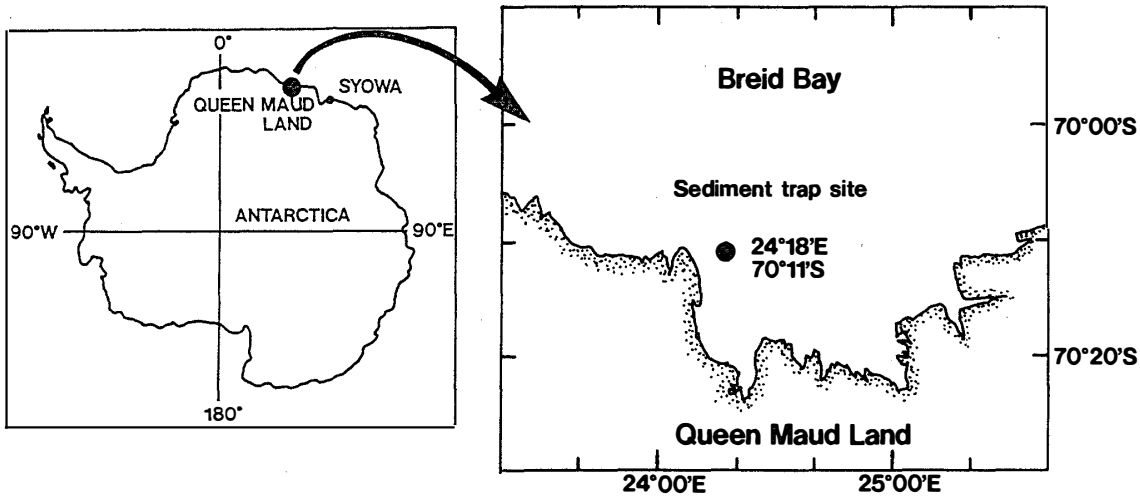

Fig. 1. Location of the time-series sediment trap in Breid Bay, Antarctica.

bottles was moored at a depth of 111 m. The mouth of the PVC cone of the sediment trap had a diameter of 0.5 m. It was covered with a honeycomb baffle (3×3 cm mesh). Sinking particles were collected at intervals of 3.5 days. As a preservative, sodium chloride was added to the sea water in the sampling bottles to give excess salinity. Though the preservation of organic compounds this way is incomplete, the decomposition of the organic matter in the sampling bottles were not serious, because the distribution pattern of chlorophyll *a* (Chl *a*) and other organic materials did not decrease simply with time during the experiment.

After retrieving the trap, Chl *a* concentration was measured with a fluorometric method on board immediately (STRICKLAND and PARSONS, 1968) using aliquots of the sinking particles. Active swimmers in the sampling bottles were removed. All samples were kept frozen in a deep freezer at −20°C until analysis. Organic carbon in the sinking particles was analyzed using a CHN analyzer (HANDA *et al.*, 1992).

2.2. *Fatty acid analysis*

Lipid materials were extracted from the sinking particles with chloroform: methanol (2:1, v:v). The lipid containing chloroform fraction was separated from the methanol fraction by addition of distilled water, dried using a rotary evaporator and disolved in *n*-hexane.

Heneicosanoic acid (21:0) as an internal standard was added to an aliquot of the extracts for analysis of fatty acids. Samples were saponified with 0.5N KOH/ methanol. Subsequently, saponified fatty acids were esterified to their methyl esters using 14% BF_3/methanol, and then the fatty acid methyl esters were extracted with *n*-hexane. Fatty acid methyl esters were cleaned up by thin layer chromatography (TLC) using TLC plates coated with Silica gel G (Analtech Inc.). A mixture of benzene : hexane (1:1, v:v) was used as the solvent. Fatty acid methyl esters were detected by a Shimadzu GC-9A gas chromatograph equipped with an FID and a fused silica capillary column (FFS ULBON HR-Thermo-3000B, 25 m length, 0.25 mm i.d., Shinwa Industry Co. Ltd.), and were quantified by the internal standard method. N_2 was used as the carrier gas at 0.9 m*l*/min. The column temperature was programmed from 130–180°C at 2°C/min and held at 180°C for 15 min, subsequently raised to 210°C at 2°C/min and held isothermally at 210°C.

Each of the GC peaks was identified by comparing their retention times with those of authentic standards as well as by mass spectrometry on a gas chromatograph-mass spectrometer (GC-MS). The GC-MS (JEOL JMS-DX302) was equipped with a fused silica capillary column (FFS ULBON HR-SS-10, 25 m length, 0.25 mm i.d., Shinwa Industry Co. Ltd.) and the compounds were identified using the electron ionization method and the chemical ionization method using isobutane gas.

3. Results

3.1. *Downward fluxes of chlorophyll* a *and organic carbon*

Chl *a* fluxes of sinking particles varied in the range of 0.09 to 2.14 mg m^{-2} day^{-1} (Fig. 2A). Chl *a* fluxes increased from the beginning of the observation period and reached their maximum between samples 5 and 7, and thereafter decreased rapidly in

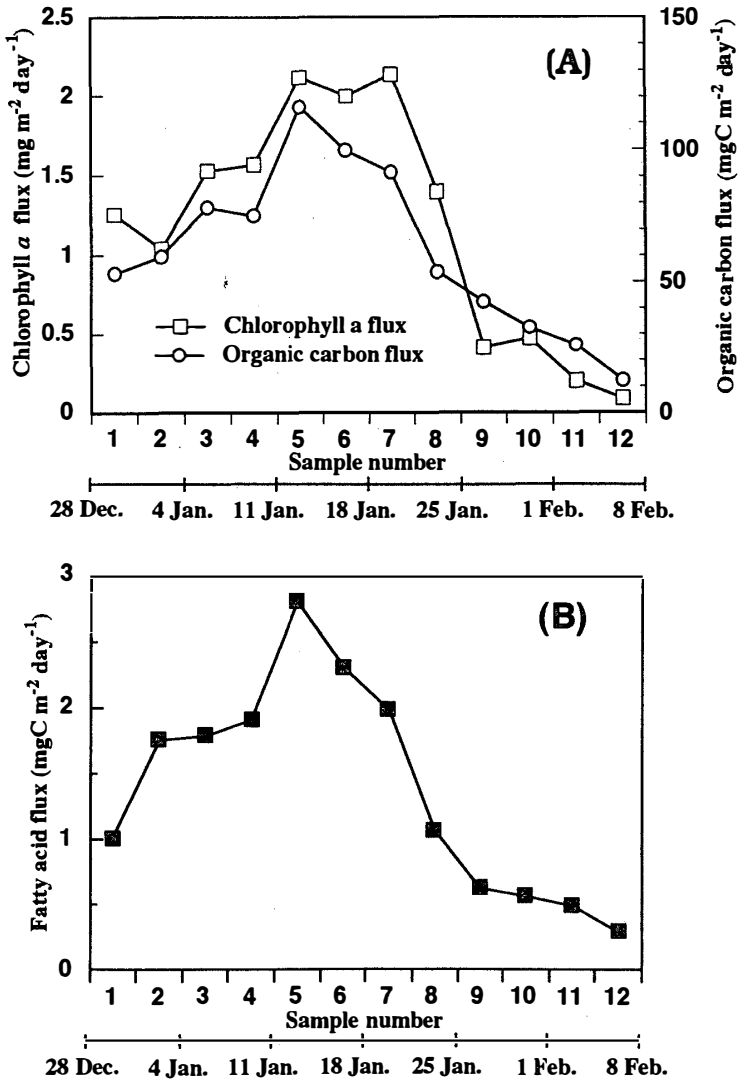

Fig. 2. Vertical fluxes of (A) chl a and organic carbon (after FUKUCHI et al., 1988) and (B) fatty acids in the sinking particles in Breid Bay.

samples 8 toward 12 in late January 1986. Vertical fluxes of organic carbon varied in the range of 12.3 to 116 mg m^{-2} day^{-1} with the maximum centered in sample 5 (Fig. 2A).

3.2. *Vertical fluxes and compositions of fatty acids in the sinking particles*

Vertical fluxes of total fatty acids in the sinking particles were the highest in sample 5 (Fig. 2B). The change in the fatty acid flux during the experiment was very similar to that of Chl *a* and organic carbon fluxes. Fatty acids represented 1.5–2.9% (mean 2.2%) of the sinking organic matter as a carbon base.

Fatty acids in the sinking particles had carbon numbers from 13 to 26. The major fatty acids were tetradecanoic acid (14:0), hexadecanoic acid (16:0), octadecanoic acid (18:0) and 9-hexadecenoic acid (16:1) (Table 1). The content of 16:1 was relatively high between sample 1 and 7, whereas 14:0 and 18:0 acid were high between samples 8 and 12. The contents of 16:0 and 9-octadecenoic acid (18:1 n–9) in the

Table 1. Fatty acid compositions of the sinking particles collected in Breid Bay, Antarctica.

Sample number	No. 1	No. 2	No. 3	No. 4	No. 5	No. 6	No. 7	No. 8	No. 9	No. 10	No. 11	No. 12
Sample date	28 Dec–1 Jan	1–4 Jan	4–8 Jan	8–11 Jan	11–15 Jan	15–18 Jan	18–22 Jan	22–25 Jan	25–29 Jan	29 Jan–1 Feb	1–5 Feb	5–8 Feb
Fatty acid												
13:0	0.5	0.3	0.5	0.1	0.1	0.1	0.1	0.9	0.9	0.1	0.4	3.6
14:0	8.0	7.5	7.9	7.9	8.9	9.1	10.3	14.1	13.0	16.6	12.3	5.8
15:0	3.0	3.0	2.9	2.5	2.0	2.1	2.3	2.0	2.2	1.5	1.7	7.5
16:0	28.0	24.6	25.3	26.4	22.7	21.3	23.8	26.6	25.8	26.9	30.3	25.9
17:0	2.0	3.4	2.4	2.0	2.3	1.4	1.2	0.7	0.8	0.6	0.7	1.2
18:0	7.0	3.2	2.4	9.6	3.2	3.0	10.8	13.5	14.5	15.7	23.3	14.6
19.0	0.2	0.2	0.2	0.1	0.3	0.1	0.3	0.5	0.7	0.6	0.1	0.3
20:0	1.1	0.3	0.3	0.4	0.3	0.2	0.2	0.7	1.5	0.3	0.4	3.1
22:0	0.6	0.3	0.2	0.4	0.3	0.4	0.4	0.5	0.7	0.6	0.8	2.7
24:0	0.4	0.2	0.2	0.4	0.2	0.3	0.3	0.3	0.4	0.5	0.3	1.0
26:0	0.1	t*	t	t	t	0.1	t	t	0	0	0	0
∑Saturated	50.9	43.1	42.3	49.9	40.3	38.0	49.8	59.9	60.4	63.3	70.3	65.5
14:1	3.7	1.1	1.2	0.6	0.3	0.3	0.3	0.1	0.8	0.4	0.2	6.9
16:1	25.8	37.3	39.0	31.9	28.0	28.5	28.8	18.6	16.8	13.7	11.5	9.3
18:1n-9	7.3	7.7	8.4	7.5	7.5	7.3	2.9	4.1	5.1	5.4	4.6	6.6
18:1n-7	1.6	0.8	1.1	1.4	2.0	2.9	0.2	0.5	0.7	0.7	0.9	1.2
20:1	0.1	0.3	0.2	0.5	0.2	0.4	0.1	0.8	0.6	0.7	0.9	1.6
22:1	0	t	t	t	t	t	t	t	0.1	0	0	0
24:1	0.12	t	t	0.2	0.2	0.1	0.1	0.3	0.2	0.2	0.2	0
∑Monounsaturated	38.6	47.4	49.9	42.2	38.2	39.7	32.5	24.5	24.4	21.1	18.2	25.4
16:2	1.3	1.2	0.7	0.6	1.5	1.7	1.0	0.8	0.9	0.5	0.5	0.9
16:3	0	0	0	0	0.7	0	0.3	0	0.1	0	0	0.3
18:2	1.6	2.3	2.2	2.0	1.7	1.7	1.8	1.4	1.3	2.3	1.5	2.45
18:3	1.1	1.1	1.0	0.6	2.0	3.5	2.6	2.3	4.2	3.4	2.3	1.64
18:4	0.2	0.3	0.1	0.1	1.3	1.5	1.4	0.8	0.3	0.7	0.2	0.29
20:5	0.9	2.8	0.8	0.7	9.1	7.3	5.1	2.4	0.8	1.5	0.6	0.3
22:6	0.2	0.3	0.1	0.2	0.5	0.5	0.5	0.2	0.2	0.7	0.3	0
∑Polyunsaturated	5.2	8.0	4.9	4.1	16.7	16.2	12.6	7.8	7.8	9.1	5.4	5.8
iso 15:0	0.9	0.3	0.4	0.5	0.4	0.5	0.6	0.8	1.4	0.6	0.9	1.5
anteiso 15:0	0.4	0.1	0.2	0.4	0.5	0.7	1.0	1.4	1.8	1.4	1.0	0.5
iso 17:0	2.5	0.7	1.1	1.1	1.3	2.8	1.0	2.6	2.2	2.8	2.0	0.3
anteiso 17:0	1.4	0.4	1.2	1.8	2.7	2.2	2.5	3.0	2.1	1.7	2.3	0.8
∑Branched	5.3	1.5	2.9	3.7	4.8	6.2	5.1	7.8	7.5	6.6	6.1	3.1
Total	100	100	100	100	100	100	100	100	100	100	100	100

(expressed as % total fatty acids)
*t: trace (<0.1%)

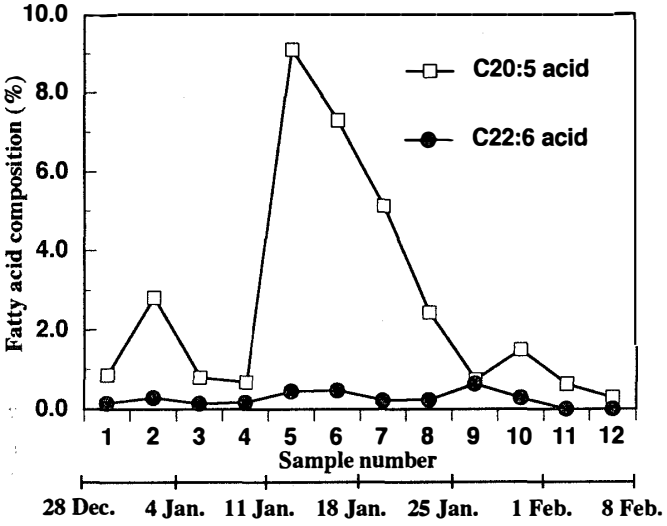

Fig. 3. Changes in the composition of 20:5 and 22:6 of the sinking particles in Breid Bay.

sinking particles were constant in the range of 21.3–30.3% and 2.9–8.4% of total fatty acids respectively in all samples. 11-octadecenoic acid (18:1 n–7) and branched C_{15} and C_{17} acids (br–15:0 and br–17:0) were detected in the ranges of 0.2–2.9% and 1.5–7.8% of total fatty acids respectively. Branched C_{15} and C_{17} acids increased toward the end of the experiment. Among the polyunsaturated fatty acids with carbon numbers over 20, eicosapentaenoic acid (20:5) and docosahexaenoic acid (22:6) were detected in all samples. The contents of 20:5 were extensively high from samples 5 to 7 (5.1–9.1%), while the contents of 22:6 were low (<0.7%) in all the samples (Fig. 3).

4. Discussion

4.1. Source of fatty acid in sinking particles

Close similarities in the temporal variation patterns of fatty acid and Chl *a* fluxes suggested that fatty acids were mostly of phytoplankton origin (Fig. 2B). Microscopic observations revealed that the sinking particles in all samples were dominated by the diatom *Thalassiosira antarctica*, whereas fecal pellets accounted for only a small part of the total particles (FUKUCHI *et al.*, 1988). Since some early studies of the fatty acid composition of the diatom *Thalassiosira* showed that 14:0, 16:0, 16:1, 16:3 and 20:5 were the dominant fatty acids (ACKMAN *et al.*, 1968; ORCUTT and PATTERSON, 1975; VOLKMAN *et al.*, 1989; DUNSTAN *et al.*, 1994), the high content of these fatty acids of the sinking particles suggested that most of the sinking organic particles were derived from this kind of diatom.

However, some components of fatty acids indicated other possible sources of the sinking organic matter. Br–15:0, br–17:0 and 18:1 n–7 of the sinking particles indicated bacterial influence on the organic matter, because these acids are generally considered as biomarkers of bacteria (PERRY *et al.*, 1979, VOLKMAN *et al.*, 1980) and normally represented less than 10% of total fatty acids in sinking particles (DEBAAR *et al.*, 1983; REEMTSMA *et al.*, 1990; NAJEDEK, 1993).

The content of 18:1 was low in the range of 2.9–8.4% in the sinking particles (Table 1). WAKEHAM *et al.* (1984) suggested that the dominance of 18:1 in particulate matter is an indicator of zooplankton materials, because crustacean zooplankton have 18:1 which exceeds 50% of the total fatty acids. On the other hand, prymnesiophytes *Phaeocystis*, which is one of the major phytoplankton in the Antarctic Ocean, has 18:1 of 5–13% to total fatty acids (NICHOLS *et al.*, 1991). We could not distinguish the source of 18:1 in the sinking particles, but the small content of 18:1 of total fatty acids suggests that zooplankton- and prymnesiophyte-derived materials were minor in the sinking organic matter. In addition, the small content of 22:6 of the fatty acids also showed a small contribution of zooplankton in the sinking particles, because this acid is abundant in crustacean zooplankton, (7.5–25.9% for several euphausiids, JOSEPH, 1989; 27.0–30.4% for shallow copepods, MORRIS, 1971).

Though 18:0 fluxes of the sinking particles was almost constant, Octadecanoic acid (18:0) was one major component of fatty acids in the sinking particles during the latter half of the mooring period (Table 1). The content of 18:0 is small in fatty acid of Antarctic diatoms (NICHOLS *et al.*, 1993), prymnesiophytes (NICHOLS *et al.*, 1991) and crustaceans (JOSEPH, 1989). In contrast, TANOUE *et al.* (1982) reported that the 18:0 content of suspended particles in the Southern Ocean were over 10% of total fatty acids at surface water. The existence of some components of the 18:0 therefore can suggests that non-living suspended particles were included in the sinking particles.

4.2. Ratios of unsaturated fatty acids to saturated fatty acids as an indicator of diatom growth activity in the sinking particles

Ratios of unsaturated fatty acids (UFA) to saturated fatty acids (SAFA) are shown in Fig. 4A. In the sinking particles in Breid Bay, these ratios were high between sample 1 and 7 compared to those in the latter period (samples 8–12). The variation pattern of these ratios was similar to that of $\delta^{13}C$ values of organic carbon reported earlier by HANDA *et al.* (1992) (Fig. 4B), who showed the high $\delta^{13}C$ values of organic carbon between sample 1 and 7, suggesting the high growth rate of phytoplankton in the euphotic layer during the diatom bloom. The present result on the high UFA/SAFA ratios of the sinking particles can indicate growth activity of the overlying diatoms during the bloom as well as the previous results (POHL and ZURHEIDE, 1979; HAYAKAWA *et al.*, 1996).

4.3. High content of 20:5 in the sinking particles

Contents of 20:5 increased rapidly between samples 5 and 7 (Fig. 3). The 20:5 is normally present in sizeable quantities in diatoms, cryptomonads and haptophytes (POHL and ZURHEIDE, 1979; KAYAMA *et al.*, 1989; VOLKMAN *et al.*, 1989). The rapid increase in 20:5 was not due to a change in phytoplankton species composition, because the microscopic observations revealed (FUKUCHI *et al.*, 1988) that there was no substantial change in the species composition of phytoplankton within the sinking particles during the experiment. Polyunsaturated fatty acids can also be found in other marine organisms such as zooplankton (SCHULTZ and QUINN, 1977; WAKEHAM *et al.*, 1984). High abundance of 20:5 between samples 5 and 7 could be presumed as a sign of zooplankton influence in the sinking particles. However, 22:6, also an

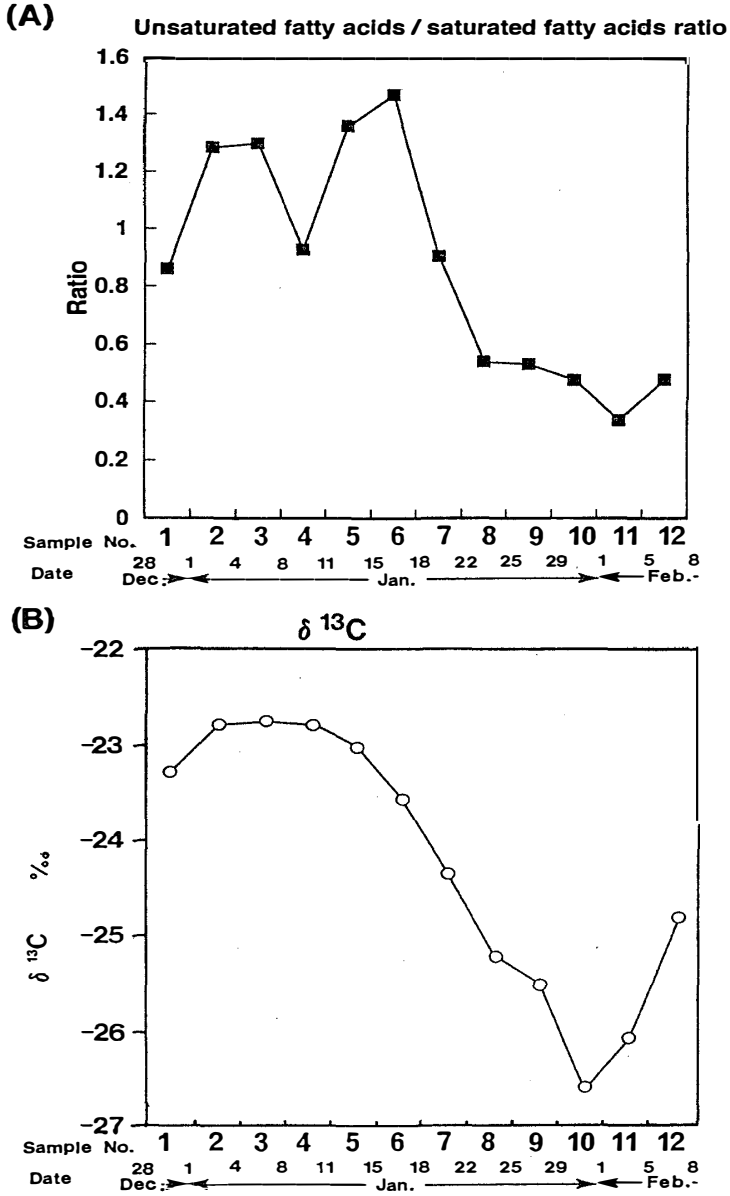

Fig. 4. (A) Temporal variations of the ratios of unsaturated fatty acids (UFA) to saturated fatty acids (SAFA) and (B) $\delta^{13}C$ values of organic carbon (after HANADA et al., 1992) in the sinking particles in Breid Bay.

indicator of zooplankton (WAKEHAM *et al.*, 1984) was low in the sinking particles, suggesting that the source of 20:5 was not zooplankton but diatoms.

According to these facts, we can conclude that the high abundance of 20:5 in the sinking particles at the middle of the bloom was due to a change in the biochemical composition of the diatom bloom as it progressed. Early studies on fatty acid in phytoplankton showed that diatoms contained a large amount of 20:5 when environmental conditions were optimal for cell growth (MORRIS *et al.*, 1985; COHEN *et al.*, 1988) or when phytoplankton were in their exponential or stationary phases of growth (KATTNER *et al.*, 1983; ARAO *et al.*, 1987; HAYAKAWA *et al.*, 1996). In the present study, the period with high abundance of 20:5 in the sinking particles

(samples 5 and 7) corresponded with the late exponential phase and early stationary phase of the diatom bloom as inferred from changes in the organic carbon and Chl *a* content of sinking particles which reached their peak and started decreasing thereafter.

The low values of 20:5 fluxes during the beginning of the bloom are not explained clearly. MORRIS *et al.* (1985) suggested that the production of long-chain unsaturated fatty acids such as 20:5 is relatively low when cells are dividing rapidly as would have been the condition during the early exponential phase of the diatom bloom in Breid Bay. This is supported by the high contents of 16:1 in the sinking particles during the same periods. The biosynthesis of 16:1 in diatoms takes place over a short pathway and so occurs easily, while the biosynthesis of 20:5 takes place over a long pathway involving additional elongation and desaturation steps (MORENO *et al.*, 1979).

NICHOLS *et al.* (1993) reported a high content of 20:5 n–3 of total fatty acids in sea ice diatom communities in McMurdo Sound during the bloom. The 20:5 produced by diatom communities during the bloom can be transported to the deep water directly by means of sinking particles. The 20:5 is an essential dietary component of many marine organisms which lack the ability to biosynthesize them (KANAZAWA *et al.*, 1979).

5. Conclusions

Fatty acids of sinking particles collected in Breid Bay during the austral summer were mainly derived from diatoms. The temporal variation in fatty acid fluxes indicated changes in the growth activity of the overlying diatom community. Our results suggests that the increase in sinking fluxes during the observation was due to the accumulation of diatom population, of which growth was induced by favorable environmental conditions in the surface water.

High amounts of 20:5, which is a labile compound in diatoms in surface waters could be transported to the deep water by sinking particles during the bloom. The fresh organic matter can be transported to the sea floor as a result of aggregation and flocculation of cells during a diatom bloom. That is important for maintaining communities of benthic organisms under the ice.

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