—研究ノート—
Scientific note

Temporal changes in chlorophyll *a* and nitrate concentrations under fast ice near Syowa Station, Antarctica, in austral summer

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夏季の南極昭和基地周辺の定着氷下におけるクロロフィル *a* 及び硝酸塩濃度の時間変化

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要旨: 1996年12月30日，1997年1月12日及び21日に，南極昭和基地周辺のリュツォ・ホルム湾の4点において，水深5mから海底の間の数層から海水試料を得た．得られた試料を基にクロロフィル *a*（Chl *a*）及び硝酸塩（NO_3）濃度の鉛直分布を調べた．いずれの観測点においても表層の成層水中（<20 m）でChl *a* 及びNO_3濃度が時間とともに大きく変化した．両濃度には有意な負の関係があった（$n=40$, $P<0.01$）．この関係は，Chl *a* が$1\mu g\ l^{-1}$増加するときNO_3を$0.89\mu M$消費することを示唆する．しかしながら，本研究で見られたような厚い海氷（2.0–3.6 m）下における光強度は，植物プランクトンが増殖するのに厳しい条件にある．本研究で観測されたChl *a* の増加が，植物プランクトンが厚い定着氷下で増殖した結果とは考えにくい．好光条件の下でChl *a* を増加させ，NO_3を消費した海水が観測海域へ移流していたと考えられる．この移流が，厚い定着氷下で見かけ上Chl *a* が増加しNO_3が低下する要因と思われる．

Abstract: Seawater samples beneath fast ice were collected from several depths using a Niskin bottle at four sites near Syowa Station, Antarctica, on 30 December 1996, and 12 and 21 January 1997. Vertical distributions of chlorophyll *a* (Chl *a*) and nitrate (NO_3) concentrations were determined. Substantial temporal changes in Chl *a* and NO_3 concentrations occurred in the surface stratified layer (<20 m). There was a significant negative correlation between both the concentrations ($n=40$, $P<0.01$). This relationship suggests that an increase of $1\mu g\ l^{-1}$ of Chl *a* consumes 0.89 μM of NO_3 under fast ice. However, light limitation is severe for phytoplankton growing under thick sea ice (2.0–3.6 m), as observed in the present study. It is unlikely that the observed increases of Chl *a* result from phytoplankton growth under heavy fast ice. Seawater, in which Chl *a* has increased and NO_3 has been consumed under favorable light conditions, may be advected into the study area. This advection may be responsible for the apparent increase of Chl *a* and decrease of NO_3 concentrations under the heavy fast ice.

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1. Introduction

Phytoplankton production is well documented in the seasonal pack ice zone (Smith and Nelson, 1985), while the dynamics of phytoplankton in the fast ice area are less understood. The sea surface in Lützow-Holm Bay is covered by fast ice year-round (Takizawa *et al*., 1992). Under fast ice near Syowa Station, temporal variations of phytoplankton abundance in summer have been investigated by many authors (Hoshiai, 1969; Fukuchi *et al*., 1984; Satoh *et al*., 1986; Matsuda *et al*., 1987; Odate and Fukuchi, 1996; Ishikawa *et al*., 2001). These studies have shown that phytoplankton biomass increases under fast ice from mid to late summer.

An understanding of a relationship between nutrient supply and the formation of phytoplankton bloom is important in predicting ecosystem dynamics. However, such a relationship has not been shown in sea area near Syowa Station. The present study aims to show the temporal changes in the vertical distributions of chlorophyll *a* (Chl *a*) and nitrate (NO_3), which are utilized by phytoplankton for growth, in mid-summer, and to determine the relationship between these concentrations.

2. Materials and methods

Seawater samples beneath fast ice were collected using a Niskin bottle from several layers between the depths of 5 m and the bottom at Sites 38A, 38B, 38C, and 38D near Syowa Station, Antarctica, on 30 December 1996, and 12 and 21 January 1997 (Fig. 1). The depths at the sites were 111 m (38A), 86 m (38B), 42 m (38C), and 41 m (38D). Water temperature and salinity were profiled using a CTD (SBE 19plus, Sea-Bird Electronics Inc.) on 14 and 18 January 1997 at these sites.

For Chl *a* determination, seawater (100–200 m*l*) was filtered on Whatman GF/F filters. The filters were placed in glass vials, containing *N*,*N*-dimethylformamide (Suzuki and Ishimaru, 1990), and pigments were extracted in the dark at $-20^{\circ}C$ for 24 hours. Concentrations of Chl *a* were determined fluorometrically using a Turner Design Model 10R Fluorometer (Parsons *et al*., 1984), following calibratration with pure Chl *a* (Sigma Chemical Co.). Using part of the seawater samples, NO_3 concentrations were determined (Bergamin *et al*., 1978; Anderson, 1979; Gine *et al*., 1980). Underwater light intensity at the same sites as the present study has been published (Odate *et al*., 2004).

3. Results and discussion

The following snow coverage depths were recorded on 30 December 1996 at the indicated sampling sites: 38A, 0.18 m; 38B, 0.37 m; 38C, 0.70 m; 38D, 0.48 m. The snow coverage decreased to 0.05 m, 0.06 m, 0.48 m and 0.36 m, respectively, on 21 January 1997. The sea ice thicknesses on 30 December 1996 were 2.29 m (38A), 2.06 m (38B), 3.59 m (38C) and 3.08 m (38D) and were 2.31 m (38A), 2.36 m (38B), 3.63 m (38C) and 3.05 m (38D) on 21 January 1997.

At all sites, the minimum temperature (*ca*. $-1.67^{\circ}C$) occurred between the depths of 20–30 m (Fig. 2), and salinity and sigma-*t* increased with depth with small differences

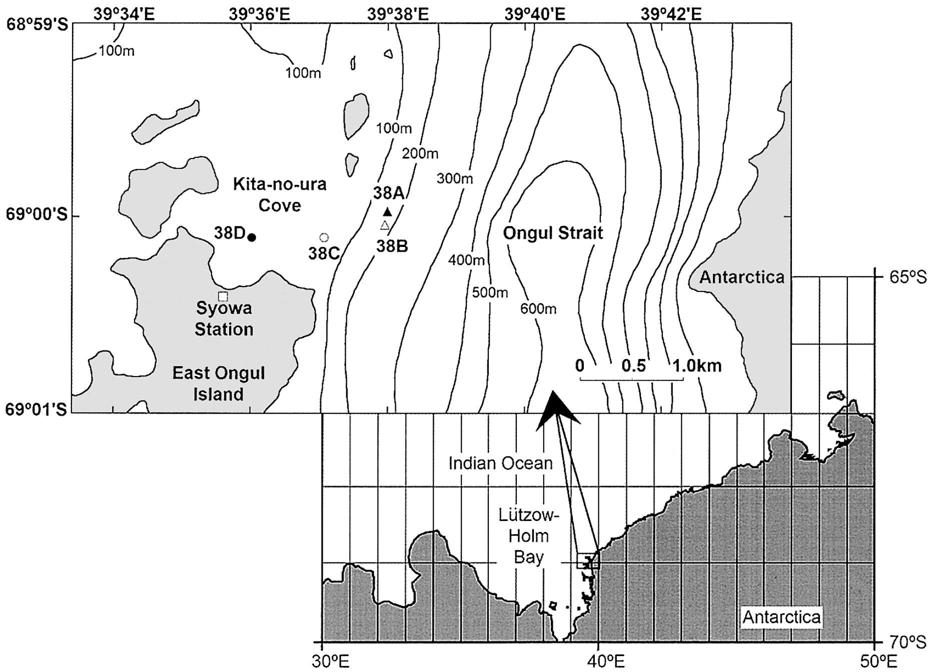

Fig. 1. Location of sampling sites on fast ice. Submarine topography (depth in meters) is redrawn after Fujiwara (1971).

between the sites. Similar physical properties were obtained on 14 and 18 January.

Chl *a* concentrations were consistently less than $1.0\,\mu g\ l^{-1}$ below the depth of 30 m throughout the observation period (Fig. 3). The average Chl *a* concentrations (mean $\pm$SD) on 30 December at depths of 5, 10 and 20 m among the four sites were 0.37 ± 0.07, 0.40 ± 0.05 and $0.29\pm0.08\,\mu g\ l^{-1}$, respectively. Considerable increases in Chl *a* concentration occurred above the temperature minimum layer from 30 December to 21 January. On 12 January the average Chl *a* concentrations for all sites were 6.15 ± 1.56 at 5 m, 3.69 ± 0.36 at 10 m and $1.40\pm0.28\,\mu g\ l^{-1}$ at 20 m. The concentrations further increased to 10.9 ± 1.76 at 5 m, 5.46 ± 0.43 at 10 m and $2.03\pm0.64\,\mu g\ l^{-1}$ at 20 m on 21 January. Differences of Chl *a* concentrations were significant between 12 and 21 January at the depths of 5 ($P<0.05$) and 10 m ($P<0.01$). During the observation period, the highest Chl *a* concentrations were found at the depth of 5 m at Site 38C, where snow coverage was heavy and sea ice was thick. As can be seen in Fig. 3, spatial variation was small compared to the temporal variation for Chl *a* concentrations.

Less variation was noted in NO_3 concentrations (29–31 μM) below the depth of 30 m (Fig. 3). Substantial temporal changes of NO_3 concentration occurred in the surface stratified layer (<20 m) during the observation period. The average NO_3 concentrations on 12 January were 24.7 ± 0.46, 25.5 ± 0.14 and $27.8\pm0.82\,\mu M$ at the depths of 5, 10 and 20 m, respectively. The average NO_3 concentrations decreased to 19.1 ± 0.53 at 5 m, 23.8 ± 0.29 at 10 m and $27.3\pm0.79\,\mu M$ at 20 m on 21 January. NO_3 concentrations were significantly lower on 21 January than 12 January at 5 m ($P<0.01$)

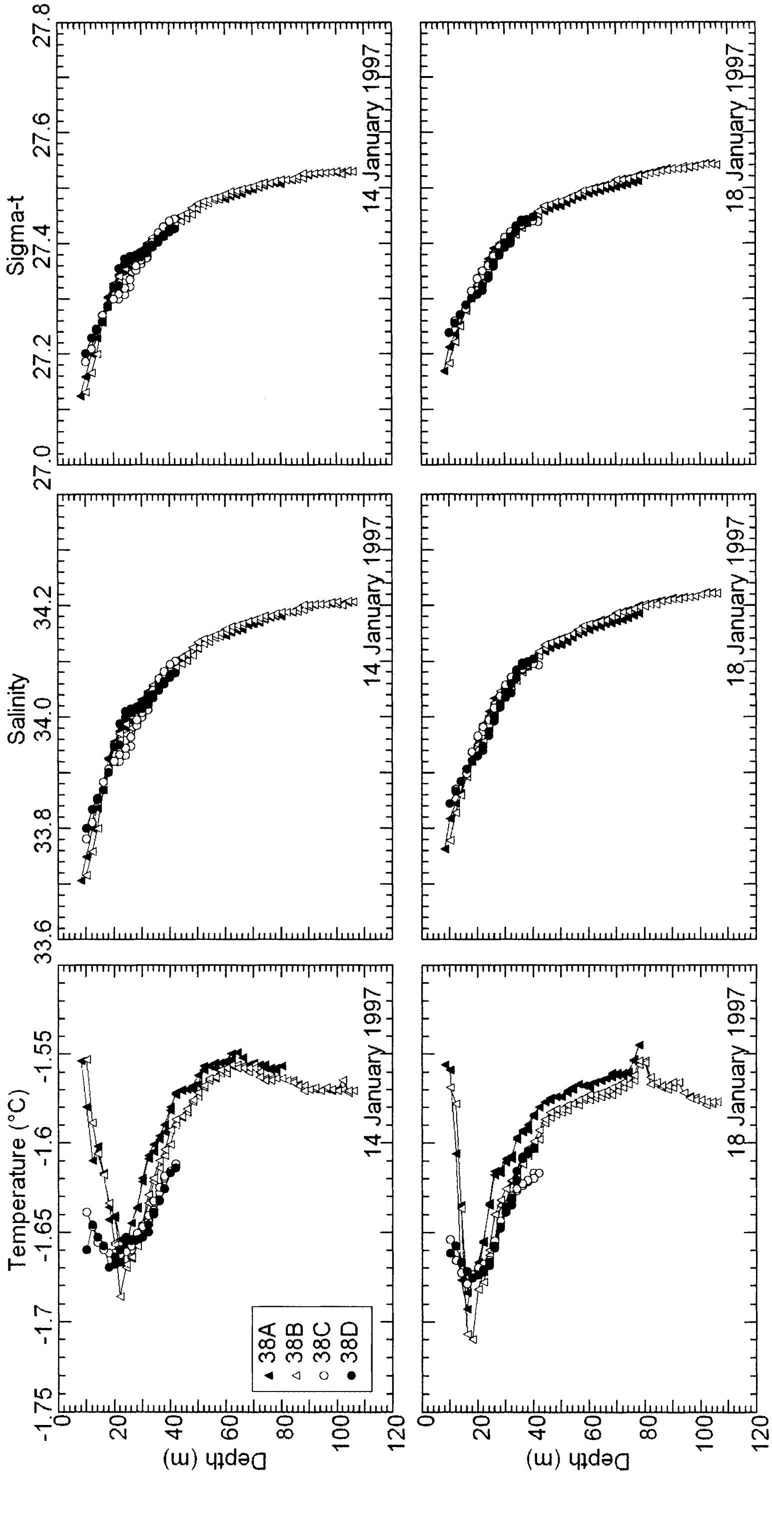

*Fig. 2. Vertical distributions of water temperature, salinity, and sigma-*t *at Sites 38A (closed triangle), 38B (open triangle), 38C (open circle), and 38D (closed circle) on 14 (upper) and 18 (lower) January 1997.*

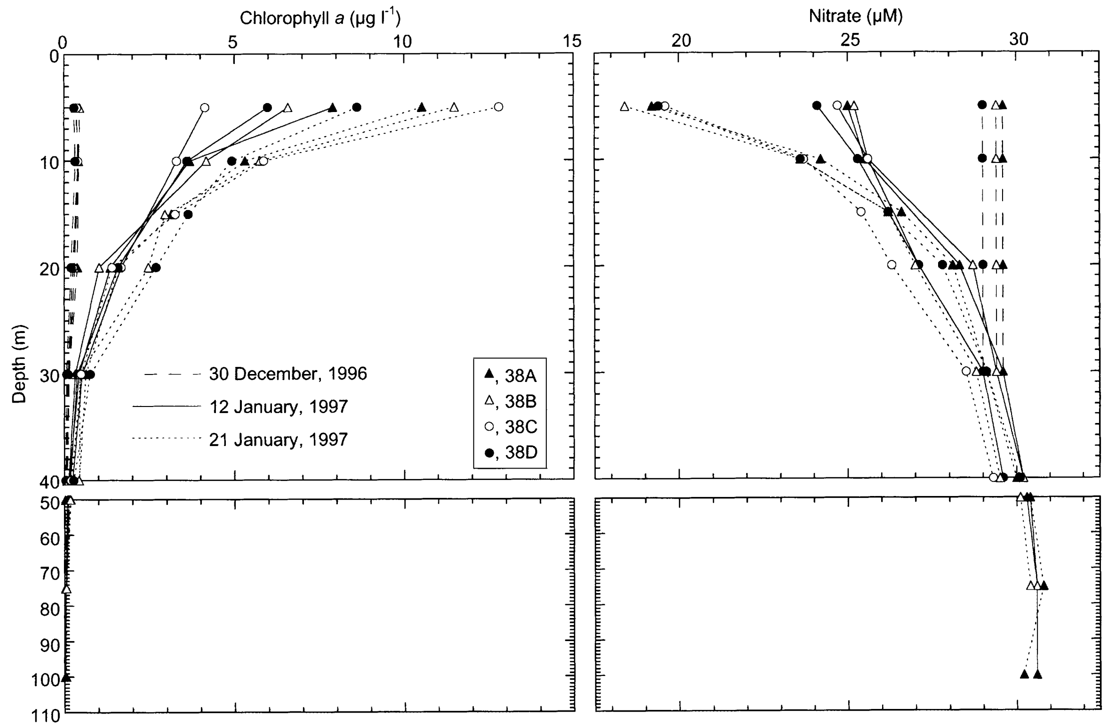

Fig. 3. *Vertical distributions of concentrations of Chl* a *(left) and NO_3 (right) at Sites 38A (closed triangle), 38B (open triangle), 38C (open circle), and 38D (closed circle) on 30 December 1996 (broken lines), 12 (solid lines) and 21 (dotted lines) January 1997. NO_3 concentrations at 30 m on 12 January were assumed to be uniformly distributed in the top 30 m on 30 December 1996 (see text).*

and 10 m ($P<0.01$).

Although NO_3 concentrations were not determined at the end of December, the concentrations below the temperature minimum layer can be assumed to be the same as in the top 30 m since vertical mixing of the surface water extended only to the temperature minimum layer during the winter season (Ishii *et al.*, 1998). Using all the data sets in Fig. 3, the relationship between Chl *a* and NO_3 concentrations was analyzed (Fig. 4). NO_3 significantly decreased with the increase in Chl *a* ($n=40$, $P<0.01$); an increase of 1 $\mu g\ l^{-1}$ of Chl *a* corresponds to a decrease of 0.89 μM of NO_3. A similar relationship was found by Schloss *et al.* (2002) in Potter Cove, King George Island. They observed that Chl *a* increased from almost zero to 36 $\mu g\ l^{-1}$, consuming *ca.* 27 μM of NO_3 (Schloss *et al.*, 2002), meaning that an increase of 1 $\mu g\ l^{-1}$ of Chl *a* consumes 0.75 μM of NO_3. Edwards *et al.* (2003) found the relationship between nitrogen supply (the sum of nitrate, nitrite and ammonium) and the formation of Chl *a* biomass to be 0.43–1.05 μM N (μg Chl *a*)$^{-1}$. Our result, 0.89 μM N (μg Chl *a*)$^{-1}$, is within the range of Edwards *et al.* (2003) although we considered only nitrite as a nitrogen source.

It is known that phytoplankton biomass increases under fast ice in mid to late summer near Syowa Station (*e.g.*, Hoshiai, 1969). The present study has further shown that the increase in Chl *a* concentrations accompanies a decrease of NO_3. This

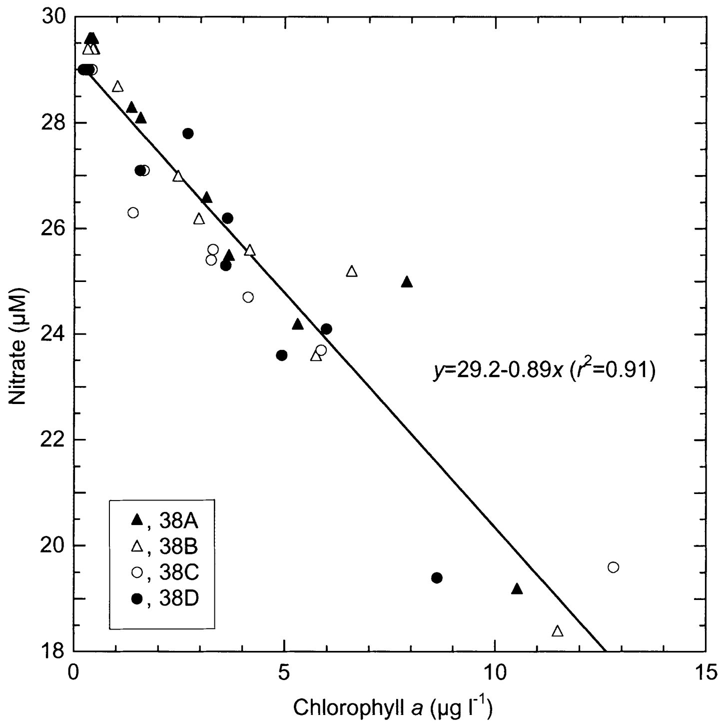

Fig. 4. Relationship between concentrations of Chl a *and NO_3 in the top 20 m of water columns. Site 38A, closed triangle; Site 38B, open triangle; Site 38C, open circle; Site 38D, closed circle.*

relationship suggests an increase in Chl *a* under fast ice resulting from phytoplankton growth, which consumes NO_3. However, the relationship between Chl *a* and NO_3 concentrations does not always mean that a phytoplankton bloom occurs under fast ice near Syowa Station. Our previous study (Odate *et al.*, 2004) showed that the mean photosynthetically active radiation (PAR) just under the sea ice was 0.9–6.6 μmol m^{-2} s^{-1} at Sites 38A and 38B, and 0.1–0.6 μmol m^{-2} s^{-1} at Sites 38C and 38D. Odate *et al.* (2004) concluded that light intensities particularly limit phytoplankton growth under sea ice thicker than 2 m; no algal growth occurred beneath sea ice of thickness greater than 3 m since threshold values of PAR for algal photosynthesis and growth have been found to be 0.6–7.6 μmol m^{-2} s^{-1} (Gosselin *et al.*, 1985; Smith *et al.*, 1989).

The present results showed that Chl *a* concentrations increased even at depths between 5 and 20 m at Sites 38C and 38D (Fig. 3), where sea ice thickness was greater than 3 m. The PAR present to depths of 5 m at Sites 38C and 38D would be similar to that at depths below about 30 m at Sites 38A and 38B (Odate *et al.*, 2004). If phytoplankton could grow under the PAR levels observed at 5 m depth at Sites 38C and 38D, Chl *a* concentrations would be expected to increase below the depth of 30 m at Sites 38A and 38B. However, no increase in Chl *a* and decrease in NO_3 below the depth of 30 m at Sites 38A and 38B (Fig. 3) was observed, implying that no photosynthetic growth of phytoplankton occurred under the low PAR conditions at Sites 38C and 38D. Therefore, the increases of Chl *a* observed at Sites 38C and 38D did not result from phytoplankton blooms there. Taking account of the threshold level of PAR for algal photosynthesis (Gosselin *et al.*, 1985; Smith *et al.*, 1989), it can hardly be considered that the observed increases of Chl *a* result from phytoplankton growth under fast ice even at Sites 38A and 38B. Seawater containing a high biomass of phytoplankton, which grew and consumed NO_3 under favorable light conditions, may be advected into the study area. Hence, this advection may be responsible for the apparent increase of Chl *a* and decrease of NO_3 concentrations under the heavy fast ice.

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