―研究ノート―
Scientific note

Empirical relationship between sea ice thickness and underwater light intensity based on observations near Syowa Station, Antarctica, in austral summer

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夏季の南極昭和基地周辺における観測から得られた海氷厚と水中光量の経験的関係

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要旨: 1996年12月30日，1997年1月3日，11日，17日，29日に，南極昭和基地周辺海域の4点において水中の光合成有効放射（PAR）を測定した．4測点の氷厚及び積雪は，それぞれ2.06–3.64 m及び0.04–0.70 mであった．海氷直下のPARは，0.1–6.6μmol m^{-2} s^{-1}と見積もられた．氷厚と海氷直下のPARの間には，有意な負の相関があった．過去の値からも同様の関係式が得られた．これら極域で得られた全ての値を用いて，氷厚と水中PARの間の経験的関係式を求めた．得られた式は，氷上の雪により空中PARが約20%に減少した後，海氷1 mでPARが一桁低くなることを示す．

Abstract: Underwater light intensity was measured as photosynthetically active radiation (PAR) at four sites near Syowa Station, Antarctica, on 30 December 1996, and 3, 11, 17, and 29 January 1997. The sites were covered with several different thicknesses of sea ice (2.06–3.64 m) and snow (0.04–0.70 m). The estimated PAR intensities just under the sea ice were 0.1–6.6μmol m^{-2} s^{-1}. There was a significant negative correlation between sea ice thickness and PAR just under the sea ice. A similar relationship was obtained when the previously reported values in the literature were analyzed. Using data from the present and previous studies, an empirical equation is proposed. The equation implies that snow layer reduces the incidence to about 20% of surface irradiance, and that PAR decreases by one order of magnitude with each 1 m increase of the sea ice thickness.

1. Introduction

The sea surface near Syowa Station (69°00′S, 39°35′E) on East Ongul Island in Lützow-Holm Bay, Antarctica, is covered with sea ice year-round, and the sea ice only breaks out of the bay every few years due to wind and/or current action (Takizawa *et al*., 1992). In this bay, new sea ice can grow to one to two meters thick in a year, while

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the thickness of multi-year sea ice reaches several meters (Takizawa *et al*., 1992). Phytoplankton under the sea ice is light-limited as sea ice and snow reduce penetration of the incident solar radiation (Smith and Sakshaug, 1990). In spite of the severe light conditions, phytoplankton biomass increases under the sea ice near Syowa Station in mid to late summer (*e.g*., Hoshiai, 1969).

Odate and Fukuchi (1996) suggested that the thickness of sea ice affects underwater light intensity, resulting in a horizontally heterogeneous distribution of phytoplankton abundance. However, they could not discuss the growth of phytoplankton under sea ice in detail since they did not measure the underwater light. The purpose of this study is to determine the relationship between the underwater light intensity and sea ice thickness, based on measurements under various thicknesses of sea ice near Syowa Station.

2. Materials and methods

Underwater light was measured as photosynthetically active radiation (PAR: 400–700 nm) at four sites near Syowa Station (Sites 38A, 38B, 38C, and 38D in Fig. 1), Antarctica, on 30 December 1996, and 3, 11, 17, and 29 January 1997. A spherical quantum meter, QSI200 (Biospherical Instruments, San Diego, CA, USA), was deployed from a hole (about 0.3 m in diameter). The hole was not covered when light measurements were being conducted. The depth was recorded at 1–3 s intervals using a time and depth-recording data-logger, the UWE200DT (Little Leonardo, Tokyo, Japan), which was attached to the quantum meter. On 30 December and 3 January, deployment of the quantum meter was conducted in open water (the diameter was about 30 m) behind the icebreaker *Shirase*, which was anchored off Syowa Station (Fig. 1). The PAR measurements were conducted within a two-hour period (12 : 00–14 : 00 local time) on each sampling day.

3. Results and discussion

Snow coverage was 0.18 m (38A), 0.37 m (38B), 0.70 m (38C), and 0.47 m (38D) on 30 December 1996. The snow coverage decreased throughout the observation period, and was 0.05 m (38A), 0.04 m (38B), 0.35 m (38C), and 0.33 m (38D) on 29 January 1997. The sea ice thickness was 2.29 m (38A), 2.06 m (38B), 3.58 m (38C), and 3.08 m (38D) at the beginning of the present study. The sea ice thickness tended to increase slightly and reached 2.54 m (38A), 2.32 m (38B), 3.64 m (38C), and 3.16 m (38D) at the end of the study. Deeper snow coverage and thicker sea ice were observed at Sites 38C and 38D than at Sites 38A and 38B.

Underwater PAR exponentially decreased with depth in the open water behind the icebreaker *Shirase* (Fig. 2). The same observations under sea ice revealed that underwater PAR sharply decreased by the depth of about 10 m and gradually decreased below about 10 m. In particular, underwater PAR continued to decrease more in deeper layers at Sites 38C and 38D than at Sites 38A and 38B where snow depth and sea ice thickness were less. The sharp decrease of PAR from the surface to *ca.* 10 m was considered to have resulted from light penetrating through the hole, which was

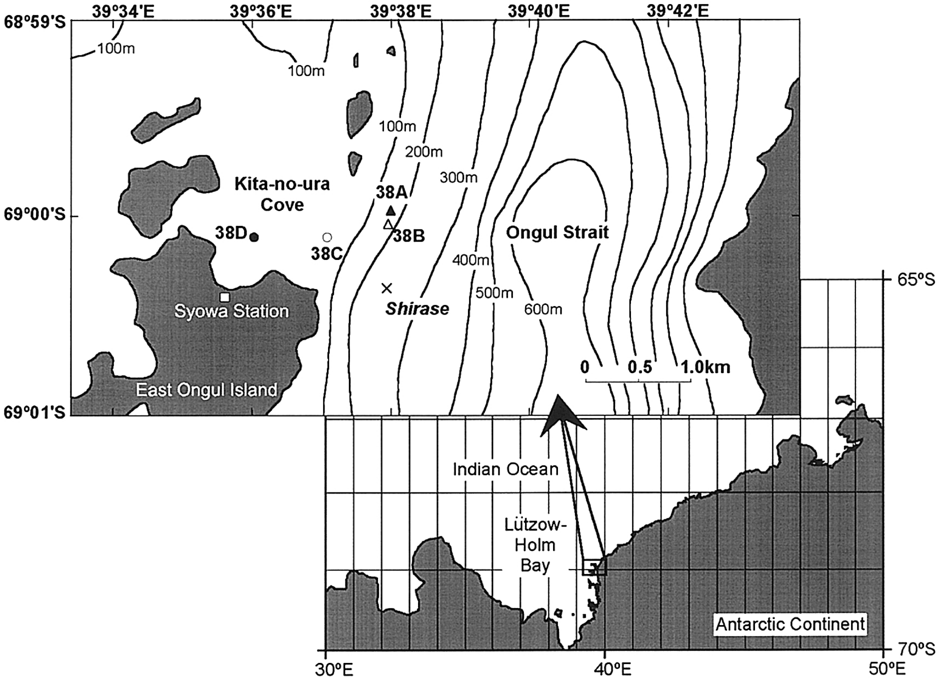

Fig. 1. Location of sampling sites on sea ice near Syowa Station. The cross indicates the position at which the icebreaker Shirase was anchored. Submarine topography (depth in meters) was redrawn after Fujiwara (1971).

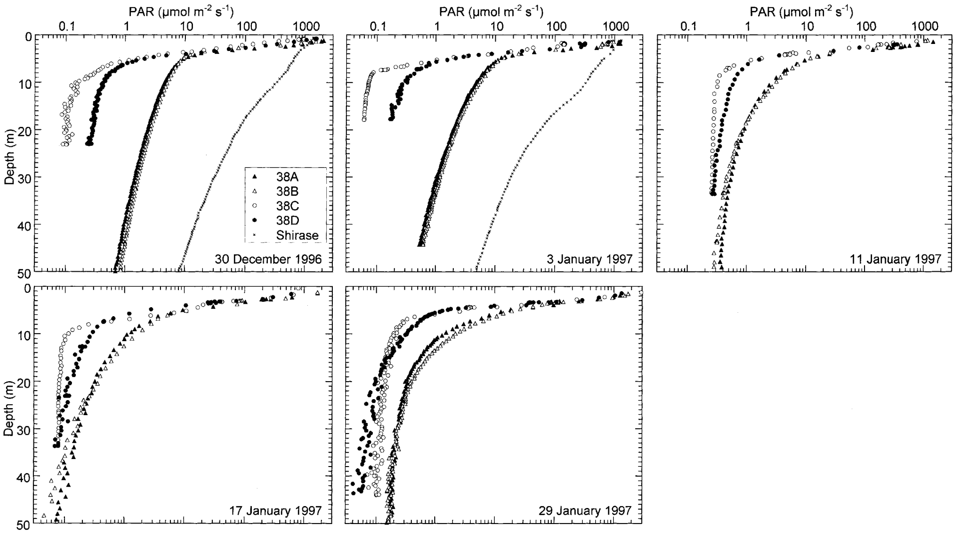

Fig. 2. Vertical profiles of underwater PAR beneath sea ice at Sites 38A (▲), 38B (△), 38C (○), and 38D (●). The same observations were done in open water behind the icebreaker Shirase (×).

artificially opened for deployment of the instrument. It is recommended to cover the hole with opaque material during the measurement.

The PAR data collected between the surface and 10 m contained an artificial disturbance. To reduce the artificial disturbance as much as possible, regression analyses were applied for PAR vs depth below 10 m. Significant relationships were obtained in all cases ($P < 0.01$). Hence, PAR just under the sea ice was extrapolated from the regression lines. The estimated PAR intensities were 0.9–6.4 μmol m^{-2} s^{-1} at Site 38A, 1.3–6.6 μmol m^{-2} s^{-1} at Site 38B, 0.1–0.2 μmol m^{-2} s^{-1} at Site 38C, and 0.3–0.6 μmol m^{-2} s^{-1} at Site 38D. On average, PAR just under the sea ice was one order of magnitude lower at Sites 38C and 38D than at Sites 38A and 38B.

The relationship between sea ice thickness and PAR just under the sea ice (intensity relative to PAR at the surface) is shown in Fig. 3, with results from similar observations in the literature. There was a significant negative correlation between sea ice thickness and PAR just under the sea ice based on the present results observed near Syowa Station (solid line in Fig. 3, $r^2 = 0.69$, $n = 20$, $P < 0.01$).

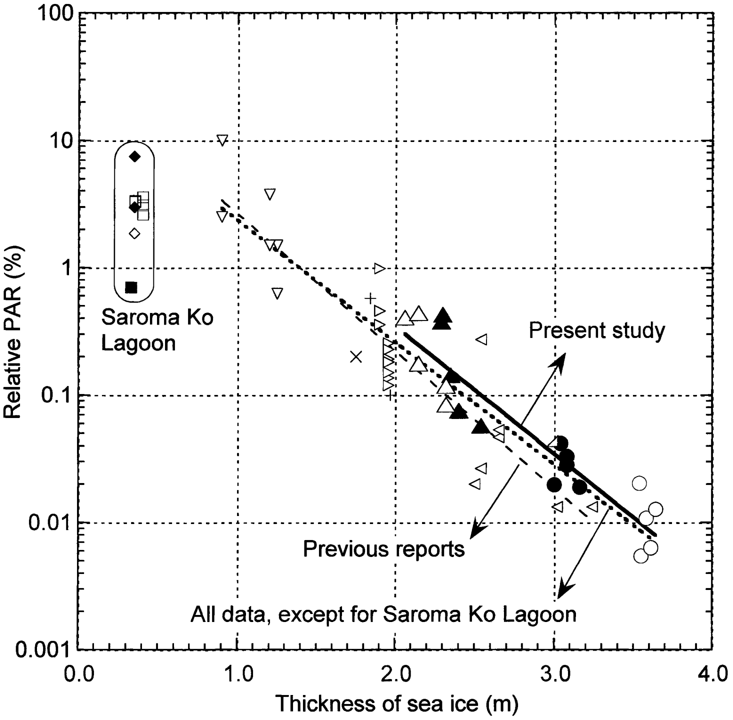

Fig. 3. Relationship between thickness of sea ice and PAR just under sea ice (intensity relative to PAR at the surface) at Sites 38A (▲), 38B (△), 38C (○), 38D (●). Similar data from the literature are shown. Arctic: Demers et al. (1995) (▷), Suzuki et al. (1997) (+), Hegseth (1992) (▽). Antarctic: Palmisano et al. (1987) (◁), SooHoo et al. (1987) (⊿), McMinn et al. (1999) (×). Saroma Ko Lagoon: Kudoh (1995) (◇), Suzuki et al. (1995) (◆), Demers et al. (1995) (□), Kishino (1993) (■).

$$y = 35e^{-2.3x}, \tag{1}$$

where x and y represent sea ice thickness (m) and relative PAR (%), respectively. The PAR values in the present study were obtained under sea ice with a thickness of 2.06–3.64 m. The previously reported PAR values were obtained under sea ice with a thickness of less than 3.24 m. Few observations were conducted under sea ice as thick as in the present study, particularly at Site 38C where sea ice thickness was 3.54–3.64 m.

A significant relationship similar to that in the present study was found based on values reported from other sea areas in the Antarctic as well as Arctic areas (Palmisano *et al.*, 1987: SooHoo *et al.*, 1987: Hegseth, 1992: Demers *et al.*, 1995: Suzuki *et al.*, 1997: McMinn *et al.*, 1999) (broken line in Fig. 3, $r^2 = 0.66$, $n = 27$, $P < 0.01$).

$$y = 31e^{-2.5x}. \tag{2}$$

This means that our estimates of PAR under the ice are consistent with previous observations in polar regions.

Using all polar data from present and previous studies, except data from Saroma Ko Lagoon (northeastern Hokkaido, Japan), an empirical relationship was defined between sea ice thickness and underwater PAR (dotted line in Fig. 3, $r^2 = 0.66$, $n = 47$, $P < 0.01$).

$$y = 21e^{-2.2x}. \tag{3}$$

The y-intercept implies that the snow layer will reduce the incidence to about 20% of surface irradiance as suggested by Smith and Sakshaug (1990). The slope of the equation shows that PAR decreases by one order of magnitude with each 1 m increase of sea ice, although there is large variation for similar thicknesses of sea ice. Similarly, Sullivan *et al.* (1984) also showed that 1 m of sea ice attenuates about 80% of the incident radiation in McMurdo Sound. The large variation seems to have resulted from the degree of snow cover because snow is extremely opaque to light (Smith and Sakshaug, 1990). On the other hand, the quality of sea ice (*i.e.,* presence of ice algae, brine pockets, and air bubbles) also affects attenuation of light (Smith and Sakshaug, 1990). PAR levels deviate below the regression line for data from the Saroma Ko Lagoon (Kishino, 1993: Demers *et al.*, 1995: Kudoh, 1995: Suzuki *et al.*, 1995), where sea ice develops in thicknesses of up to several tens of centimeters (Shirasawa and Ingram, 1995). This deviation is due to the quality of sea ice since water in Saroma Ko Lagoon contains much more suspended matter than oceanic waters (Kishino, 1994).

The empirical relationship implies that the snow layer reduces the incidence to about 20% of surface irradiance and PAR decreases by one order of magnitude with each 1 m increase in sea ice thickness. Hence, the relative light intensity under sea ice 2 m thick is equivalent to 0.1 to 1% of the surface light level, and is usually considered the bottom of the euphotic zone. Light conditions become severe for phytoplankton growth when the thickness of sea ice is greater than 2 m. For example, PAR just under the sea ice was extrapolated as 0.1–0.6 μmol m^{-2} s^{-1} at Sites 38C and 38D. From the Canadian Arctic and Alaska, the 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). It is considered that no algal growth occurs beneath sea ice if the thickness becomes greater than 3 m.

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