Deep-Sea Research II 120 (2015) 35–42

Contents lists available at ScienceDirect

Deep-Sea Research II

journal homepage: www.elsevier.com/locate/dsr2

Carbon contribution of sea ice floes in the Arctic Ocean

Sang H. Lee [a,*], Bo Kyung Kim [a], Hui-Tae Joo [a], Jung Woo Park [a], Jang Han Lee [a], Hyoung-Min Joo [b,1], Doo Byoul Lee [b], Chang-Keun Kang [c,2], Sung-Ho Kang [b]

[a] Department of Oceanography, Pusan National University, Geumjeong-gu, Busan 609-735, Republic of Korea
[b] Korea Polar Research Institute, KORDI, Incheon 406-840, Republic of Korea
[c] Ocean Science & Technology Institute, Pohang University of Science and Technology, Pohang 790-784, Republic of Korea

ARTICLE INFO

Available online 21 January 2014

Keywords:
Particulate organic carbon (POC)
Arctic sea ice floes
Melt ponds

ABSTRACT

To estimate detailed contributions of particulate organic carbon (POC) as a potential food source in various environments of the Arctic sea ice floes, intensive investigations were executed at two different types of sea ice stations (ST 1 and ST 2) in the northern Chukchi Sea during the summer period in 2011. The average uptake rates of carbon and nitrogen in melt ponds from this study were within the range measured previously. The surface ice of melt ponds at ST 1 had the highest POC concentration with a mean of 148.0 mg C m^{-3} (S.D.= ± 86.0 mg C m^{-3}), followed by sea ice cores at ST 2 (mean ± S.D.= 125.7 ± 128.2 mg C m^{-3}). The POC concentrations in melt ponds ranged between 90.0 mg C m^{-3} (S.D.= ± 12.7 mg C m^{-3}) and 103.9 mg C m^{-3} (S.D.= ± 47.7 mg C m^{-3}) at ST 1 and ST 2, respectively. Major POC contributors to melt ponds were diatoms with a mean biovolume contribution of 48.7% (S.D.= ± 39.1%) which was strongly related to *in situ* salinity. Although the total POC concentration of entire sea ice floes ranged from 2.8% to 5.3% of the POC concentration within the euphotic water column at the study locations, the carbon contribution of sea ice floes could be important to higher trophic levels because of the concentrated POC within sea ice floes.

1. Introduction

Sea ice floes containing sea ice algae provide an additional organic carbon source to the Arctic marine ecosystem (Michel et al., 2002; Lee et al., 2008). In the Arctic Ocean, the contribution of ice algae to the total primary production ranges from less than 1% to about 60% (Gosselin et al., 1997; Rysgaard et al., 2001). Although the ecological impact of the ice algal production appears to vary widely from region to region, it is potentially the most important food source for sympagic organisms (Lizotte, 2001; Michel et al., 2002). Especially, the recent thinning Arctic ice cover and subsequently enhanced light transmittance could increase carbon production within sea ice as well as phytoplankton production under sea ice (Mundy et al., 2009; Frey et al., 2011).

Melt ponds, a common feature of summer Arctic sea ice, of sea ice floes could be an important habitat for phytoplankton and/or ice algae and higher trophic levels such as sympagic meiofauna, under-ice amphipods, and juvenile arctic cod (Lee et al., 2011; Kramer and Kiko, 2011). These melt ponds are formed in the short Arctic summer by melting snow and then surface sea ice (Lüthje et al., 2006). Melt ponds after the summer sea ice melt onset have many impacts on the physical environment such as the surface albedo and heat transmission (Perovich et al., 2002; Inoue et al., 2008; Frey et al., 2011).

There are generally two types of melt ponds in a sea ice field that can be briefly distinguished by their color. Deep blue color of open melt ponds are directly connected to sea water by bottom holes in the ice floes, whereas light sky blue closed ponds are freshwater habitats with a salinity lower than 0.1 (Gradinger, 2002; Lee et al., 2011). As a result of the recent trend for smaller, younger, and thinner summer Arctic sea ice than previous decades ago (Maslanik et al., 2011; Kwok and Rothrock, 2009), the surface of the perennial arctic sea ice pack in summer is now being transformed from closed surface melt ponds into melt ponds with holes that connect the ponds with the underlying sea water. Moreover, recent areal coverage of melt ponds in summer has been estimated to reach up to 80% of the Arctic sea ice (Lüthje et al., 2006). Although sea ice and melt ponds are currently rapidly changing, melt pond habitats associated with sea ice have been little studied in the Arctic Ocean (Gradinger, 2002; Gradinger et al., 2005; Kramer and Kiko, 2011). Especially, the organic carbon contribution of various habitats on sea ice floes to the Arctic marine ecosystem has rarely been studied.

The objectives for this study were to define environmental characteristics of various melt ponds within sea ice floes, to measure *in situ* carbon and nitrogen uptake rates of phytoplankton in the ponds, and to estimate the carbon contribution of entire sea ice floes in the Arctic Ocean. It is believed that this is the first publication to determine the relative contribution of particulate

* Corresponding author. Tel.: +82 51 510 2256; fax: +82 51 581 2963.
E-mail addresses: sanglee@pusan.ac.kr (S.H. Lee), hmjoo77@gmail.com (H.-M. Joo), ckkang@postech.ac.kr (C.-K. Kang).
[1] Tel.: 82 32 260 6181.
[2] Tel.: 82 54 279 9503.

0967-0645/$ - see front matter © 2014 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.dsr2.2013.12.021

organic carbon (POC) as a potential food source to the Arctic marine ecosystem in melt pond waters, pond surface ice, and sea ice interior of Arctic sea ice floes.

2. Materials and methods

In situ data at two different sea ice stations (Fig. 1) were collected in the northern part of the Chukchi Sea in the western Arctic Ocean during the second summer of Korean Arctic expeditions on board the Korean icebreaker *Araon* from 30th July to 19th August, 2011.

2.1. Physical characteristics of melt ponds and sea ice

At two different types (multi-year ice and first-year ice) of sea ice stations, salinity and temperature were measured in various closed melt ponds with a YSI model 30 (YSI incorporated, Yellow Springs, Ohio). The analytical accuracy for salinity and temperature of the water samples was ±2% for salinity and ±0.1 °C for temperature. Surface layers of melt ponds at ST 1 (multi-year ice type) were slightly frozen (ice thickness < 1 cm) during the sampling time when the measurements of chlorophyll-a (Chl-a) and POC concentrations were collected. Several ice cores were extracted a few meters away from the melt pond sampling locations and measured for ice thickness, using a 8-cm diameter Kovacs ice corer. No visual indications of sediments or ice algae were found in the extracted ice cores. The ice cores were sectioned into 10 cm segments for later thawing in the laboratory to measure Chl-a and POC concentrations. The bottom 10 cm sections of the ice were further sectioned into 3 and 7 cm sections for more detailed analysis for Chl-a and POC concentrations.

2.2. Analysis of chlorophyll-a, nutrient, and POC concentrations

Water samples (0.5 L) for measuring total Chl-a and POC concentrations of phytoplankton were filtered using 0.7 μm pore-sized Whatman glass fiber filters (GF/F) (24 mm) during the cruise. Chl-a samples were extracted in 90% acetone placed in a freezer at −5 °C for 24 h and centrifuged following the procedure of Parsons et al. (1984). Concentrations of total and size-fractionated Chl-a were both measured onboard using a Trilogy fluorometer (Turner Designs, Inc., USA), which had been calibrated with commercially purified Chl-a preparations.

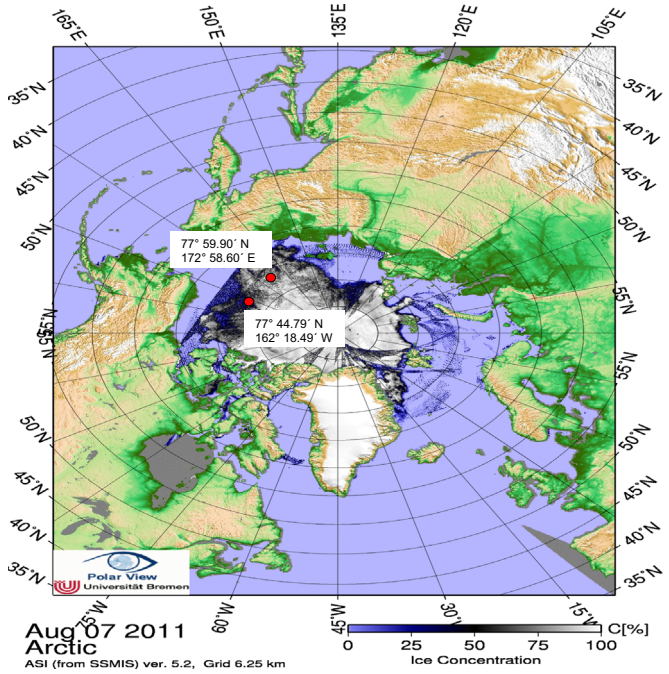

Fig. 1. Study sites for the two ice stations (ST 1: 77°44.79'N, 162°18.49'W; ST 2: 77°59.90'N, 172°58.60'W) and sea ice distribution in the Arctic Ocean during the study period. The sea ice image from http://www.iup.uni-bremen.de:8084/ssmis/.

The filters for POC measurements were immediately frozen and preserved for mass spectrometric analysis at the stable isotope laboratory of the University of Alaska Fairbanks (UAF), US. Particulate organic carbon and nitrogen and abundance of ^{13}C and ^{15}N were determined in the Finnigan Delta+XL mass spectrometer after HCl fuming overnight to remove carbonate.

Nutrient samples (100 mL) for measuring concentrations of phosphate (PO_4), nitrite plus nitrate (NO_2+NO_3), silicate ($Si(OH)_4$), and ammonium (NH_4) were analyzed onboard photometrically using an AutoAnalyser (Quattro; Bran+Luebbe, Germany), according to the manufacturer's manual. The concentrations of nitrate+nitrite and ammonium were used for calculating nitrogen uptake rates of phytoplankton at the productivity stations.

2.3. Analysis for species composition of phytoplankton in melt ponds

Water samples (125 mL) were preserved with glutaraldehyde (final concentration 1%) for algal species identification and community composition. Sample volumes of 50 to 100 mL were filtered through Gelman GN-6 Metricel filters (0.45 μm pore size, 25 mm diameter; Gelman Sciences, Inc., NY, USA). The filters were mounted on microscopic slides in a water-soluble embedding medium (HPMA, 2-hydroxypropyl methacrylate) on board. The slides were used for identification and estimation of cell concentrations (Crumpton, 1987) at the home laboratory in Korea. At least 300 cells were identified from each sample using a microscope (BX51, Olympus, Inc., Tokyo, Japan), with a combination of light and epifluorescence microscopy at 400× for microplankton, and at 1000× for autotrophic pico- and nanoplankton (Booth, 1993). A JEOL JSM-5600LV scanning electron microscope (JEOL, Inc., Tokyo, Japan) was used for species that could not be identified by light microscopy. Cell dimensions of dominant phytoplankton species were measured to the nearest 1 μm for subsequent estimations of biovolume using appropriate geometric shapes (Sun and Liu, 2003; Strathmann, 1967).

2.4. Carbon and nitrogen productivity

In situ carbon and nitrogen uptake experiments were conducted at 10 different melt ponds at the two ice floe stations in 2011, using a ^{13}C–^{15}N dual isotope tracer technique (Cota et al., 1996; Lee et al., 2012). For the uptake rates of carbon and nitrogen by phytoplankton in melt ponds, we followed the same procedure of Lee et al. (2012) for a comparison between the two studies. In short, two clear and one dark Nalgene polycarbonate bottles (0.5 L) were filled with water from each pond and then heavy isotope-enriched (98–99%) solutions of $H^{13}CO_3$ and $K^{15}NO_3$ or $^{15}NH_4Cl$ were added to the samples (Dugdale and Goering, 1967; Hama et al., 1983). After isotope inoculations were completed, the incubation bottles were kept at their *in situ* temperature and light in their original ponds. The bottles were retrieved after 3–5 h incubation and brought to the ship for filtration through pre-combusted GF/F filters. The filters were immediately frozen at −80 °C and preserved for mass spectrometric analysis at the stable isotope laboratory in the UAF.

3. Results

3.1. Environmental conditions of melt ponds and sea ice

The depths of most melt ponds in this study were 0.4–0.5 m and pond sizes varied largely at the two ice stations (Table 1). The

Table 1
Environmental parameters in melt ponds at the two ice stations in 2011.

Station	Number	Depth (m)	Width × length(m^2)	T (°C)	S (psu)	Chl-a (mg m^{-3})	pH	PO_4 (μM)	NO_2+NO_3 (μM)	NH_4 (μM)	SiO_2 (μM)
ST 1	mp1	0.4–0.5	10 × 12	0.3	0.5	0.12	6.25	0.16	0.50	0.57	1.13
	mp2	0.4–0.5	12 × 12	0.9	25.3	0.07	7.57	0.35	0.29	0.64	1.77
	mp3	0.4–0.5	8 × 10	0.9	23.8	0.16	7.61	0.39	0.29	0.50	2.03
	mp4	0.4–0.5	3 × 3	−1.1	13.5	0.14	7.35	0.19	0.57	0.57	1.07
	mp5	0.4–0.5	1.5 × 1.5	−0.9	17.4	0.06	6.18	0.03	0.43	0.50	0.23
	mp6	0.4–0.5	10 × 10	−1	2.7	0.15	6.43	0.06	0.29	0.57	1.28
ST 2	mp1	0.4–0.5	8 × 2	0.8	0	0.16	6.09	0.03	0.00	0.36	0.05
	mp2	0.4–0.5	10 × 8	−1.1	28.3	1.28	7.62	0.52	0.07	0.64	2.07
	mp3	0.4–0.5	5 × 4	0.6	0.6	0.48	6.28	0.06	0.00	0.43	0.12
	mp4	0.4–0.5	20 × 10	−1.3	22.4	0.16	7.98	0.10	0.00	0.43	0.55

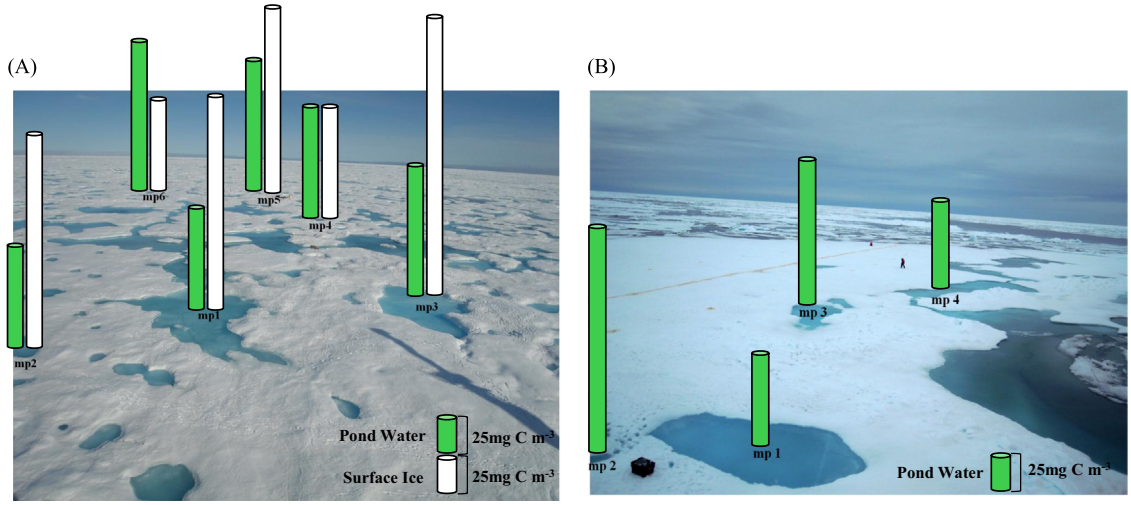

Fig. 2. Spatial distribution of POC in melt pond water and surface ice at the two ice stations. (A) ST 1 and (B) ST 2.

mean sea ice thicknesses were 1.9 and 1.4 m, respectively, at ST 1 (multi-year sea ice type) and ST 2 (first-year sea ice type). The temperature range in melt ponds did not greatly vary at the two ice stations (Table 1). The temperature of water in melt ponds at ST 1 ranged from −1.1 to 0.9 °C (mean ± S.D. = −0.2 ± 0.1 °C), whereas the temperature at ST 2 ranged from −1.3 to 0.8 °C (mean ± S.D. = −0.3 ± 1.1 °C). In comparison, the ranges of salinity were substantially larger among melt ponds (Table 1). The salinity in the ponds ranged from 0.5 to 25.3 (mean ± S.D. = 13.9 ± 10.4) and 0 to 28.3 (mean ± S.D. = 12.8 ± 14.7), respectively at ST 1 and ST 2.

The average nutrient concentrations in melt ponds were 0.20 (S.D. = ± 0.15 μM), 0.40 (S.D. = ± 0.12 μM), 0.56 (S.D. = ± 0.05 μM), and 1.25 μM (S.D. = ± 0.63 μM) at ST 1, whereas 0.18 (S.D. = ± 0.23), 0.02 (S.D. = ± 0.04 μM), 0.47 (S.D. = ± 0.12 μM), and 0.70 μM (S.D. = ± 0.94 μM) at ST 2, respectively, for phosphate, nitrate, ammonium and silicate (Table 1).

3.2. Chl-a concentrations in melt ponds

Chl-a concentrations in melt ponds ranged from 0.06 to 0.16 mg Chl-a m^{-3} with a mean of 0.12 mg Chl-a m^{-3} (S.D. = ± 0.04 mg Chl-a m^{-3}) at ST 1 (Table 1). In comparison, the Chl-a concentrations of the surface thin ice of melt ponds at ST 1 ranged from 0.08 to 0.51 mg Chl-a m^{-3} (mean ± S.D. = 0.19 ± 0.16 mg Chl-a m^{-3}) which was relatively higher than those in melt ponds but not statistically different. The Chl-a concentrations at ST 2 ranged from 0.16 to 1.28 mg Chl-a m^{-3} with a mean of 0.52 mg Chl-a m^{-3} (S.D. = ± 0.53 mg Chl-a m^{-3}).

3.3. POC concentrations in melt ponds and sea ice

POC concentrations in melt ponds ranged from 76.6 to 108.7 mg C m^{-3} (mean ± S.D. = 90.0 ± 12.7 mg C m^{-3}) and from 66.5 to 168.0 mg C m^{-3} (mean ± S.D. = 103.9 ± 47.7 mg C m^{-3}) at ST 1 and ST 2, respectively (Fig. 2). In the surface ice of melt ponds at ST 1, the POC concentrations ranged from 58.4 to 305.6 mg C m^{-3} with a mean of 148.0 mg C m^{-3} (S.D. = ± 86.0 mg C m^{-3}) (Fig. 2). The ranges of POC concentrations within sea ice cores were from 19.5 to 135.3 mg C m^{-3} (mean ± S.D. = 59.7 ± 34.1 mg C m^{-3}) at ST 1 and from 19.3 to 435.7 mg C m^{-3} (mean ± S.D. = 125.7 ± 128.2 mg C m^{-3}) at ST 2 (Fig. 3). The POC concentrations within sea ice were not highest at the bottom sections of the sea ice. Generally, the POC concentrations increased from the bottom to 20–30 cm sections and then decreased up to the upper ice sections (Fig. 3). The top ice sections at ST 1 had the highest POC concentration within the sea ice cores. For comparison, the vertical profiles of POC concentrations in the water column near the two stations are provided in Fig. 4. The POC concentrations from the surface to 1% light water depth ranged from 56.7 to 72.8 mg C m^{-3} (mean ± S.D. = 63.5 ± 6.3 mg C m^{-3}) and from 47.4 to 62.9 mg C m^{-3} (mean ± S.D. = 54.5 ± 4.6 mg C m^{-3}) at ST 1 and ST 2, respectively (Fig. 4). The maximum POC concentrations in the water column were found at 40–60 m water depths.

3.4. Species compositions of phytoplankton in melt ponds

In terms of cell number (abundance) of phytoplankton in melt ponds, the phytoplankton was mainly dominated (~70%) by

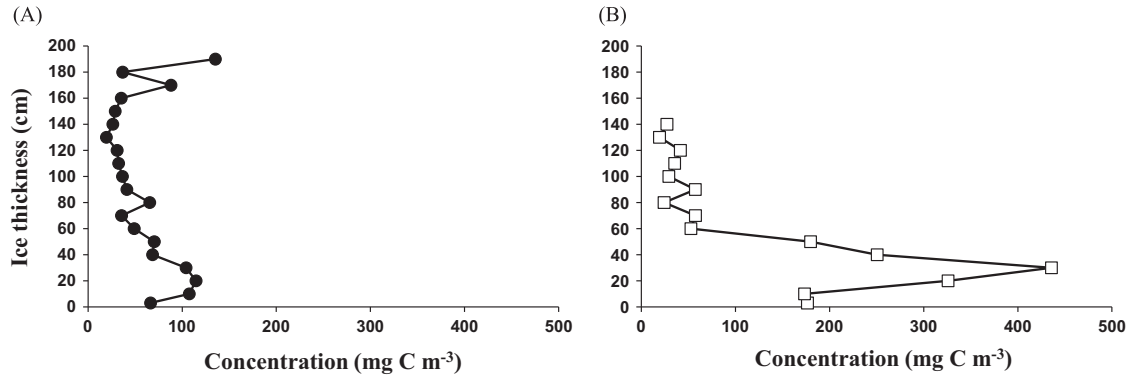

Fig. 3. Vertical profiles of POC concentration within sea ice cores at the two ice stations.

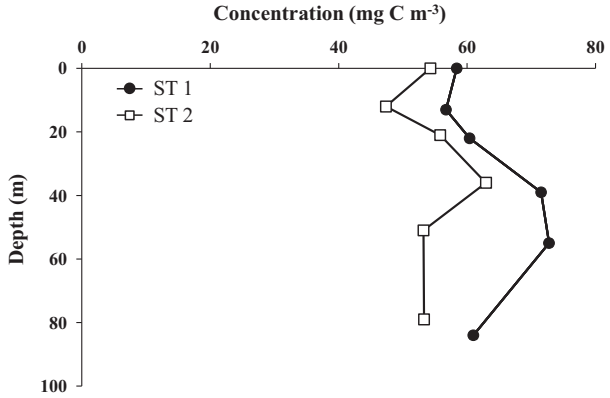

Fig. 4. Vertical profiles of POC concentration within euphotic water column at the two ice stations.

unidentified pico+nano-sized cells followed by unidentified micro-sized cells (13.3%) (Table 2). The contributions of *Pyramimonas* sp. and diatoms were 8.9% and 8.8%, respectively. However, the average biovolume contribution of all diatoms was about 48.7% (S.D.= ± 39.1%) for the phytoplankton community in the melt ponds although the range was very wide from 0% to 97.2% (Table 3). Pearson's correlation matrix was used to test for relationships between the biovolume of phytoplankton and environmental factors (temperature, salinity, Chl-a concentrations, PH, and nutrient concentrations). No significant correlation for any single species and physicochemical factors was found in this study. However, we found a strong positive relationship ($y=2.9695x+8.7808$, $R^2=0.7629$, $n=10$) between the biovolume contribution of all diatoms and water salinity and a strong negative relationship ($y=-2.8588x+8.5811$, $R^2=0.7687$, $n=10$) between the biovolume contribution of other species (excluding all diatoms) and water salinity in melt ponds (Fig. 5).

3.5. Carbon and nitrogen uptake rates of phytoplankton in melt ponds

The carbon uptake rates of phytoplankton in melt ponds ranged from 0.01 to 0.08 mg C m^{-3} h^{-1} (mean ± S.D.= 0.03 ± 0.03 mg C m^{-3} h^{-1}) and 0.04 to 1.03 mg C m^{-3} h^{-1} (mean ± S.D.= 0.40 ± 0.43 mg C m^{-3} h^{-1}) at ST 1 and ST 2, respectively (Fig. 6). The average rate in melt ponds at ST 2 was almost one order of magnitude higher than that at ST 1, but not statistically different because of the high spatial variation in the carbon uptake rate among ponds.

The nitrogen uptake rates in melt ponds at ST 1 ranged from < 0.001 to 0.002 mg N m^{-3} h^{-1} (mean ± S.D.= 0.001 ± 0.001 mg N m^{-3} h^{-1}) and from 0.001 to 0.007 mg N m^{-3} h^{-1} (mean ± S.D.= 0.003 ± 0.002 mg N m^{-3} h^{-1}), respectively, for nitrate and ammonium (Fig. 7). In comparison, the nitrogen uptake rates in melt ponds at ST 2 ranged from 0.018 to 0.058 mg N m^{-3} h^{-1} with a mean of 0.028 mg N m^{-3} h^{-1} (S.D.= ± 0.020 mg N m^{-3} h^{-1}) and from 0.015 to 0.097 mg N m^{-3} h^{-1} (mean ± S.D.= 0.050 ± 0.036 mg N m^{-3} h^{-1}) (Fig. 7). Generally, the ammonium uptake rates were higher than nitrate uptake rates of phytoplankton in melt ponds (*t*-test, $p<0.05$ for ST 1 and $p=0.35$ for ST 2).

With the hourly carbon and nitrogen uptake rates (Figs. 6 and 7) and the assumption of 24 h daylight (Lee et al., 2012), the daily carbon and total nitrogen production rates of phytoplankton in the melt ponds at the two stations in this study were estimated to range from 0.3 to 49.2 mg C m^{-3} d^{-1} (mean ± S.D.= 8.6 ± 15.1 mg C m^{-3} d^{-1}) and from 0.1 to 7.4 mg N m^{-3} d^{-1} (mean ± S.D.= 1.6 ± 2.4 mg N m^{-3} d^{-1}), respectively.

4. Discussion

4.1. Environmental conditions in melt ponds

Salinity in closed ponds largely varied from 0 to 28.3 (Table 1), depending on the stage and physical structure of melt ponds within sea ice floes, such as cracks or connections to the underlying sea water. There were no discernible trends of nutrient concentrations of phosphate, nitrite and nitrate, silicate, and ammonium in different melt ponds (Table 1). The nutrient concentrations were generally low but not totally depleted except nitrite plus nitrate concentrations at most melt ponds of ST 2. Although there was a large variation of nutrient concentrations in melt ponds between the two sea ice stations, the mean nutrient concentrations in the melt ponds were slightly higher at ST 1 than ST 2. In comparison to the results from Lee et al. (2012), the nutrient concentration ranges were similar between the present and their studies except the ammonium concentrations were significantly higher in this study (*t*-test, $p<0.01$).

The average Chl-a concentration (0.19 mg Chl a m^{-3}) in the surface ice of melt ponds at ST 1 was relatively higher than those (0.12 mg Chl a m^{-3}) in melt ponds. Although the difference was not at a statistically significant level because of a large spatial variation, this might provide evidence for the accumulation theory of Garrison et al. (1983). They proposed that 50 times greater Chl-a concentration in young sea ice samples than those from surface waters are physically concentrated through a mechanism in which frazil ice crystals rising to the surface to form new sea ice harvest the algal cells. In general, the range (0.1–0.5 mg Chl a m^{-3}) of average Chl-a concentrations in the melt ponds at the two stations from this study was within 0.2–0.6 mg Chl a m^{-3} of Lee et al. (2012).

Table 2
Species composition of phytoplankton (cell abundance, cells L^{-1}) in melt ponds at the two ice stations.

Species	ST 1						ST 2			
	mp1	mp2	mp3	mp4	mp5	mp6	mp1	mp2	mp3	mp4
Cylindrotheca sp. 80–100 μm				10,974						
Cylindrotheca sp. 130–150 μm								439		
Fragilariopsis sp. 10–20 μm				43,896						
Fragilariopsis sp. 50–60 μm										585
Fragilariopsis sp. 70–80 μm										878
Navicula sp. 10–20 μm						585				
Navicula sp. 30–40 μm					585			878		
Navicula sp. 40–50 μm					878					
Navicula sp. 50–60 μm		1317	878							
Navicula sp. 70–80 μm				878						
Nitzschia sp. 70–80 μm				10,974						
Thalassionema sp. 30–40 μm		7901								
Thalassionema sp. 50–60 μm								18,290		
Thalassionema oceania 50–70 μm		6584								
Thalassiosira sp. < 10 μm				5487		293				
Thalassiosira sp. 10–20 μm										5487
Thalassiosira sp. 20–30 μm	229	3073		293	878			3512		
Thalassiosira sp. 30–50 μm			142,661					30		
Unidentified pennate diatom 5–10 μm							9145			
Unidentified pennate diatom 10–20 μm							210,334			
Unidentified pennate diatom 40–60 μm		60,357	19,314	1756						
Unidentified pennate diatom 50–70 μm			98,765							
Unidentified pennate diatom 80–100 μm					293			1317		
Unidentified centric diatom 20–30 μm			11,413							
Dinobryon belgica 10–20 μm						43,896				
Dictyocha speculum 20–30 μm										293
Meringosphaera mediterranea 10–20 μm			38,409			585		878		
Pyramimonas sp. 5–10 μm		21,948	131,687	93,278		71,331		27,435		181,070
Unidentified sp. < 2 μm	340,192	192,044	170,096	137,174	757,202	98,765	1,252,858	621,856	137,174	230,453
Unidentified sp. 2–10 μm	175,583	95,034			131,687	224,966	82,305	466,392		
Unidentified sp.10–20 μm	38,409	10,974	175,583	164,609		38,409		100,594	32,922	186,557

Table 3
Biovloume contribution (%) of major phytoplankton in melt ponds at the two ice stations.

Species	ST 1						ST 2			
	mp1	mp2	mp3	mp4	mp5	mp6	mp1	mp2	mp3	mp4
Diatoms	**8.10**	**96.95**	**97.21**	**72.64**	**74.34**	**1.69**	**14.12**	**52.57**	**0.00**	**69.59**
Cylindrotheca sp.	0.00	0.00	0.00	14.61	0.00	0.00	0.00	2.17	0.00	20.97
Fragilariopsis sp.	0.00	0.00	0.00	4.04	0.00	0.00	0.00	0.00	0.00	12.02
Navicula sp.	0.00	2.66	0.13	3.63	22.33	1.26	0.00	1.65	0.00	0.00
Nitzschia sp.	0.00	0.00	0.00	45.42	0.00	0.00	0.00	0.00	0.00	0.00
Thalassionema sp.	0.00	2.90	0.00	0.00	0.00	0.00	0.00	10.12	0.00	0.00
Thalassiosira sp	8.10	8.25	77.60	1.96	33.24	0.42	0.00	23.84	0.00	36.61
Unidentified pennate diatoms	0.00	83.14	17.31	2.97	18.77	0.00	14.12	14.78	0.00	0.00
Unidentified centric diatoms	0.00	0.00	2.18	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Others	**0.00**	**0.48**	**1.25**	**2.50**	**0.00**	**24.23**	**0.00**	**2.31**	**0.00**	**8.42**
Dinobryon belgica 10–20	0.00	0.00	0.00	0.00	0.00	6.71	0.00	0.00	0.00	0.00
Dictyocha speculum 20–30	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.05
Meringosphaera mediterranea 10–20	0.00	0.00	1.04	0.00	0.00	2.20	0.00	0.83	0.00	0.00
Pyramimonas sp.	0.00	0.48	0.20	2.50	0.00	15.32	0.00	1.48	0.00	8.37
Unidentified sp.	**91.90**	**2.57**	**1.54**	**24.86**	**25.66**	**74.08**	**85.88**	**45.13**	**100.00**	**21.98**

4.2. Species compositions of phytoplankton in melt ponds

The diversity of phytoplankton composition in melt ponds varied (Table 2) in relation to different salinity conditions in pond waters (Table 1). A high diversity of phytoplankton existed in high salinity ponds. In nearly freshwater ponds (salinity < 2.7), mostly unidentified pico + nano cells were largely dominant (mean ± S.D. = 81.3 ± 10.9%) with the low abundance of diatom species (mean ± S.D. = 3.6 ± 7.0%). Similarly, Gradinger (2002) observed higher concentrations of pennate diatoms such as *Nitzschia frigida* and *Nitzschia grunowii* in saltier ponds than in brackish water ponds. In this study, the diatom contribution to the total biovolume of phytoplankton was positively related to *in situ* salinity in melt ponds (Fig. 5). That is, the diatom contribution in this study was low in melt ponds with low salinity (< 2.7) and high in high salinity (> 13.5) melt ponds.

The species composition of phytoplankton in the melt ponds from this study was largely different from those in Lee et al. (2011). Phytoplankton diversity based on the Shannon–Wiener diversity index was also significantly higher in the present study (*t*-test, $p < 0.05$). Lee et al. (2011) found that mostly small (nano + pico-sized) flagellates dominating the phytoplankton communities in open and closed ponds in the Arctic Ocean. The flagellate *Dinobryon belgica* was the second dominant in open ponds where salinities

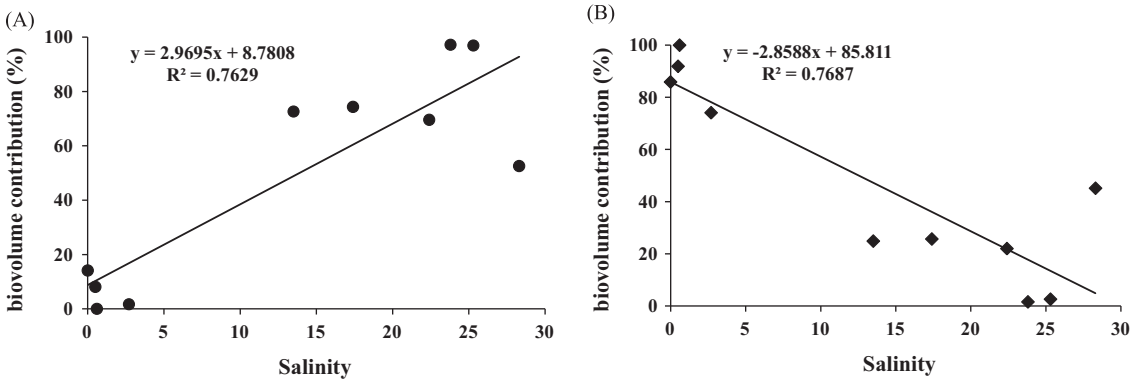

Fig. 5. Relationship between contributions of diatom (A) and other species (B) to total phytoplankton biovolume and water salinity in melt ponds.

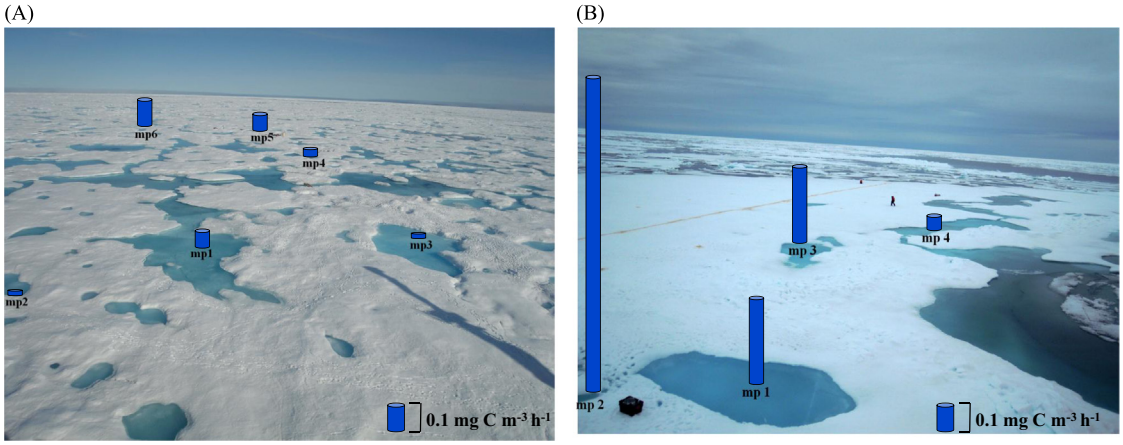

Fig. 6. Spatial distribution of carbon uptake rates of phytoplankton in melt pond waters at the two ice stations. (A) ST 1 and (B) ST 2.

ranged from 28.1 to 28.6, whereas *Pyramimonas* sp. was the second dominant species in the two closed ponds (Lee et al., 2011). No diatom species were found in melt ponds in their study, whereas many different species and a high number cell abundance of diatoms were observed, especially at relatively higher salinity (>13.5) ponds in this study (Table 2). The discrepancy in species composition between this and the previous study might have resulted from different salinity conditions. Diatoms were abundant in saltier melt pond waters and other species (excluding all diatoms) were generally abundant in fresher melt ponds (Fig. 5). In fact, the salinity range of closed melt ponds in Lee et al. (2011) was much lower (<5.1) than in the present study with a wide range of 0 to 28.3 (Table 1). In addition to different salinity conditions, different sampling locations and times between the two studies might provide possible explanations. Their melt ponds were located in the high central Arctic Ocean (83–85°N) from late August to early September in 2008, whereas in this study the two ice stations were at lower latitudes (77–78°N) in the northern part of the Chukchi Sea for 6–11 August, 2011.

4.3. Carbon and nitrogen uptake rates of phytoplankton in melt ponds

The mean carbon uptake rate (mean $\pm$ S.D. $= 0.36 \pm 0.62$ mg C m^{-3} h^{-1}) in melt ponds at the two ice stations from this study was within the range of 0.01 to 2.12 mg C m^{-3} h^{-1} of Lee et al. (2012). Actually, they found that the carbon uptake rates in melt ponds were significantly higher (mean $\pm$ S.D. $= 0.47 \pm 0.58$ mg C m^{-3} h^{-1}) at lower latitude locations (74–76°N) of the Canada Basin than those (mean $\pm$ S.D. $= 0.09 \pm 0.11$ mg C m^{-3} h^{-1}) at higher latitude stations (82–84°N) in the central Arctic Ocean studied by Lee et al. (2012). The authors suggested that light intensity change with latitudes and seasons is an important factor to control the carbon uptake rates in the melt ponds. In fact, the mean carbon uptake rate (0.36 mg C m^{-3} h^{-1}) in melt ponds at the two ice stations (77–78°N) in this study was within the middle of the range between those at lower latitude (74–76°N) and higher latitude locations (82–84°N) in Lee et al. (2012). In addition, another important factor may be the observation dates were different among the studies. This study on sea ice stations were executed mainly between 6th and 11th August, 2011, whereas the previous observations were 27 June-26 July, 2005 at lower latitude (74–76°N) and 29 August–3 September, 2008 at higher latitude locations (82–84°N) (Lee et al., 2012).

On average, the daily carbon production in all the melt ponds (8.6 mg C m^{-3} d^{-1}) in this study was almost identical as the production (7.4 mg C m^{-3} d^{-1}) in Lee et al. (2012). In terms of production per square meter, the average daily carbon production in melt ponds is 4.3 mg C m^{-2} d^{-1} in this study, given the average depth of 0.5 m in melt ponds (Table 1). Based on a 90 day summer melt season (Tschudi et al., 2008), the estimated mean annual carbon production in melt ponds was 0.39 g C m^{-2} in this study which is identical with that (0.40 g C m^{-2}) in Lee et al. (2012).

The range (mean $\pm$ S.D. $= 1.6 \pm 2.4$ mg N m^{-3} d^{-1}) of the total nitrogen uptake rate in the melt ponds in this study was within the rates (0.2–3.9 mg N m^{-3} d^{-1}) measured by Lee et al. (2012). In fact, like the carbon uptake rate discussed above, the average total nitrogen uptake rate in this study was more similar to that

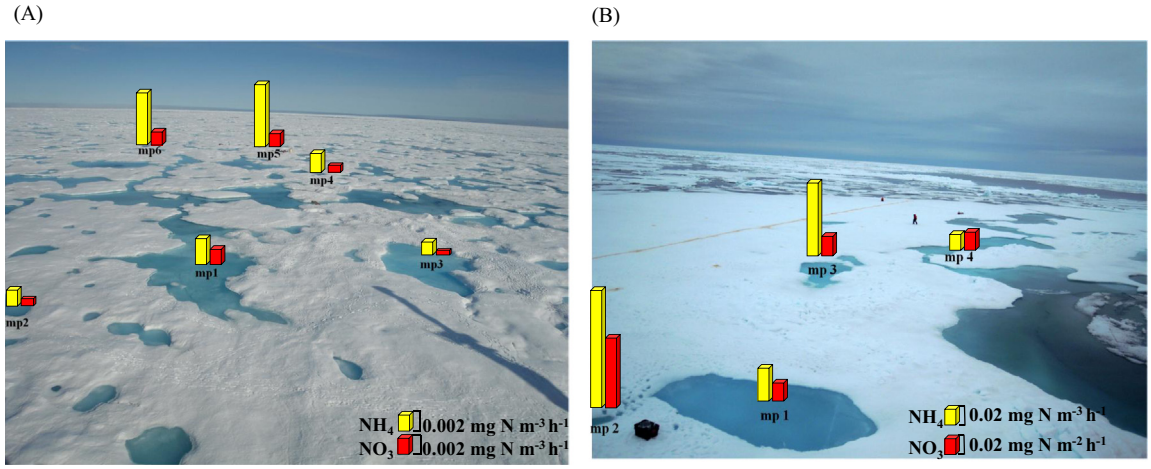

Fig. 7. Spatial distribution of nitrogen uptake rates of phytoplankton in melt pond waters at the two ice stations. (A) ST 1 and (B) ST 2.

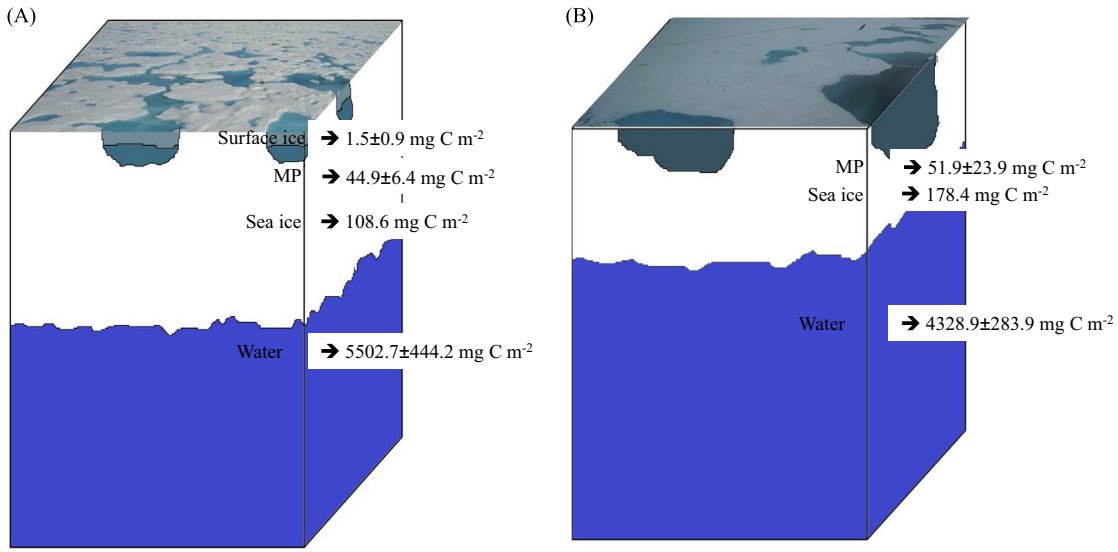

Fig. 8. Total carbon budgets of sea ice floes at the two ice stations. (A) ST 1 and (B) ST 2.

(mean ± S.D. = 3.9 ± 4.9 mg N m^{-3} d^{-1}) at lower latitude locations in 2005 than the rate (mean ± S.D. = 0.2 ± 0.3 mg N m^{-3} d^{-1} at higher latitude locations in 2008.

4.4. POC contribution of sea ice floes

In terms of POC per square meter, the concentration was the highest in sea ice (108.6 mg C m^{-2} and 178.4 mg C m^{-2}, respectively at ST 1 and ST 2) followed by the POC concentration in melt ponds (44.9 ± 6.4 mg C m^{-2} and 51.9 ± 23.9 mg C m^{-2}, respectively, at ST 1 and ST 2) (Fig. 8). In comparison, the POC concentration in the euphotic water column under the sea ice floes was several ten times higher (5502.7 ± 444.2 mg C m^{-2} and 4328.9 ± 283.9 mg C m^{-2}, respectively, at ST 1 and ST 2) than those in sea ice and melt ponds. The total POC concentrations (including surface sea ice, melt ponds, and sea ice) of sea ice floes were about 2.8–5.3% of the POC concentration of the euphotic water column from surface to 1% light depth. This contribution of sea ice floes to total carbon budget in Arctic marine ecosystem might be insignificant. However, considering the concentrating effect, the carbon contribution of sea ice floes could be very important to consumer level grazers which feed on primary producers. In terms of POC concentration per liter, surface sea ice in melt ponds had the highest POC concentration (mean ± S.D. = 148.0 ± 86.0 mg C m^{-3}) (Fig. 2) followed by concentrations of melt ponds and sea ice. Therefore, the concentrated food source in melt ponds of sea ice floes could be more efficient to grazers than that in the water column which is widely dispersed throughout the euphotic water column from surface to 80 m water depth. Lee et al. (2011) previously described a formation of large algal masses (mostly *Melosira arctica*) attached to refreezing surface ice in melt ponds in the high Arctic Ocean during the late summer season. They observed many copepod nauplia and ciliates within the microalgal accumulations and small specimens of Arctic cod around their study sites. Recently, Kramer and Kiko (2011) found that a large variety of sympagic meiofauna and under-ice amphipods inhabited the bottom of melt ponds, which differed distinctly from those reported previously. They suggested that the melt ponds in sea ice floes will become increasingly good habitat for metazoans in the Arctic Ocean, because the melt ponds can supply sufficient food sources to the animals immigrating to the ponds (Kramer and Kiko, 2011).

In addition to the quantity of food source, the quality of phytoplankton to grazers might be different between melt ponds and the water column. Macromolecular composition (polycarbonates, proteins, and lipids) of phytoplankton in melt ponds were different than

those in water column. Especially, the amount of protein compositions was significantly higher (t-test, $p < 0.01$) in melt ponds than in the water column (Lee and Yun, unpublished data). The phytoplankton with high protein content could provide nitrogen-sufficient food for higher trophic levels, since protein carbon is assimilated with a much higher efficiency by grazers than those of other macromolecules (Scott, 1980; Lindqvist and Lignell, 1997).

5. Conclusions

In this study, we described the POC concentrations measured in various sea ice habitats of sea ice floes in the Arctic Ocean. Considering the ongoing decline of sea ice in the Arctic Ocean, it is important to know the overall contribution of sea ice floes to the total POC budget in the Arctic marine ecosystem. Based on the limited data from this study, the total POC contribution of entire sea ice floes (including surface sea ice, melt ponds, and sea ice) was 3–5% of the POC concentration in the euphotic water column. This POC contribution is far higher than the contribution (1%) of the carbon production only from melt ponds in Lee et al. (2012). Similarly, the POC concentration only from melt ponds was about 1% of the POC concentration in the euphotic water column in the present study. However, the actual contribution of carbon production of sea ice floes could be higher when the production within the sea-ice in the Arctic Ocean is included. In this study, carbon measurements were executed only at two sea ice floes (multi-year ice and first-year ice) due to logistic problems such as a limited ship time and difficulties in accessibility, which resulted in a possible underestimation of the total carbon contribution of sea ice floes in the Arctic Ocean. Therefore, a more through set of intensive field measurements on sea ice stations is important to better estimate the total organic carbon budget of marine ecosystems in the Arctic Ocean.

Acknowledgments

We thank the crew members of the Korean Icebreaker *Araon*. Especially, we are grateful to Dr. Hans-Uwe Dahms for critical amendments on an earlier manuscript. We very much appreciate the constructive comments by three anonymous reviewers, which greatly improved the earlier version of the manuscript. This work was supported by Grants for Korea-Polar Ocean in Rapid Transition (K-PORT; PM13020) Program funded by the Ministry of Oceans and Fisheries, Korea.

References

Booth, B.C., 1993. Estimating cell concentration and biomass of autotrophic plankton using microscopy. In: Kemp, P.F., Sherr, B.F., Sherr, E.B., Cole, J.J. (Eds.), Handbook of Methods in Aquatic Microbial Ecology. Lewis Publishers, Boca Raton, pp. 199–205

Cota, G.F., Pomeroy, L.R., Harrison, W.G., Jones, E.P., Peters, F., Sheldon, W.M., Weingartner, T.R., 1996. Nutrients, primary production and microbial heterotrophy in the southeastern Chukchi Sea: Arctic summer nutrient depletion and heterotrophy. Mar. Ecol. Progress Ser. 135, 247–258.

Crumpton, W.G., 1987. A simple and reliable method for making permanent mounts of phytoplankton for light and fluorescence microscopy. Limnol. Oceanogr. 32, 1154–1159.

Dugdale, R.C., Goering, J.J., 1967. Uptake of new and regenerated forms of nitrogen in primary productivity. Limnol. Oceanography 12, 196–206.

Frey, K.E., Perovich, D.K., Light, B., 2011. The spatial distribution of solar radiation under a melting Arctic sea ice cover. Geophys. Res. Lett. 38, L22501, http://dx.doi.org/10.1029/2011GL049421.

Garrison, D.L., Ackley, S.F., Buck, K.R., 1983. A physical mechanism for establishing algal populations in frazil ice. Nature 306, 363–365.

Gosselin, M., Levasseur, M., Wheeler, P.A., Booth, B.C., 1997. New measurements of phytoplankton and ice algal production in the Arctic Ocean. Deep-Sea Res. II 44, 1623–1644.

Gradinger, R., 2002. In: Bitton, G. (Ed.), Encyclopedia of Environmental Microbiology. Wiley, New York, pp. 2833–2844

Gradinger, R., Meiners, K., Plumley, G., Zhang, Q., Bluhm, B., 2005. Abundance and composition of the sea-ice meiofauna in off-shore pack ice of the Beaufort Gyre in summer 2002 and 2003. Polar Biol. 28, 171–181.

Hama, T., Miyazaki, T., Ogawa, Y., Iwakuma, T., Takahashi, M., Otsuki, A., Ichimura, S., 1983. Measurement of photosynthetic production of a marine phytoplankton population using a stable ^{13}C Isotope. Mar. Biol. 73, 31–36.

Inoue, J., Kikuchi, T., Perovich, D.K., 2008. Effect of heat transmission through melt ponds and ice on melting during summer in the Arctic Ocean. J. Geophys. Res. 113, C05020, http://dx.doi.org/10.1029/2007JC004182.

Kwok, R., Rothrock, D.A., 2009. Decline in Arctic sea ice thickness from submarine and ICESat records: 1958–2008. Geophys. Res. Lett. 36, L15501, http://dx.doi.org/10.1029/2009GL039035.

Kramer, M., Kiko, R., 2011. Brackish meltponds on Arctic sea ice-a new habitat for marine metazoans. Polar Biol. 34, 603–608.

Lee, S.H., Whitledge, T.E., Kang, S.H., 2008. Spring time production of bottom ice algae in the landfast sea ice zone at Barrow, Alaska. J. Exp. Mar. Biol. Ecol. 367, 204–212.

Lee, S.H., McRoy, C.P., Joo, H.M., Gradinger, R., Cui, X., Yun, M.S., Chung, K.H., Kang, S.H., Kang, C.K., Choy, E.J., Son, S.H., Carmack, E., Whitledge, T.E., 2011. Holes in progressively thinning arctic sea ice lead to new ice algae habitat. Oceanography 24, 302–308.

Lee, S.H., Stockwell, D.A., Joo, H.M., Son, Y.B., Kang, C.K., Whitledge, T.E., 2012. Phytoplankton production from melting ponds on Arctic sea ice. J. Geophys. Res. 117, C04030, http://dx.doi.org/10.1029/2011JC007717.

Lindqvist, K., Lignell, R., 1997. Intracellular partitioning of $^{14}CO_2$ in phytoplankton during a growth season in the northern Baltic. Mar. Ecol. Prog. Ser. 152, 41–50.

Lizotte, M.P., 2001. The contributions of sea ice algae to Antarctic marine primary production. Am. Zool. 41, 57–73.

Lüthje, M., Feltham, D.L., Taylor, P.D., Worster, M.G., 2006. Modeling the summertime evolution of sea-ice melt ponds. J. Geophys. Res. 111, C02001, http://dx.doi.org/10.1029/2004JC002818.

Maslanik, J., Stroeve, J., Fowler, C., Emery, W., 2011. Distribution and trends in Arctic sea ice aglae through spring 2011. Geophys. Res. Lett. 38, L13502, http://dx.doi.org/10.1029/2011GL047735.

Michel, C., Nielsen, T.G., Nozais, C., Gosselin, M., 2002. Significance of sedimentation and grazing by ice micro- and meiofauna for carbon cycling in annual sea ice (northern Baffin Bay). Aquat. Microb. Ecol. 30, 57–68.

Mundy, C.J., Gosselin, M., Ehn, J., Gratton, Y., Rossnagel, A., Barber, D.G., Martin, J., Tremblay, J.-E., Palmer, M., Arrigo, K.R., Darnis, G., Fortier, L., Else, B., Papakyriakou, T., 2009. Contribution of under-ice primary production to an ice-edge upwelling phytoplankton bloom in the Canadian Beaufort Sea. Geophys. Res. Lett. 36, L17601, http://dx.doi.org/10.1029/2009GL038837.

Parsons, T.R., Maita, Y., Lalli, C.M., 1984. A Manual of Chemical and Biological Methods for Seawater Analysis. Pergamon Press, New York.

Perovich, D.K., Grenfell, T.C., Light, B., Hobbs, P.V., 2002. Seasonal evolution of the albedo of multiyear Arctic sea ice. J. Geophys. Res. 107 (C10), 8044, http://dx.doi.org/10.1029/2000JC000438.

Rysgaard, S., Kühl, M., Glud, R.N., Hansen, J.W., 2001. Biomass, production and horizontal patchiness of sea ice algae in a high-Arctic fjord (Young Sound, NE Greenland). Mar. Ecol. Prog. Ser. 223, 15–26.

Scott, J.M., 1980. Effect growth rate of the food alga on the growth/ingestion efficiency of a marine herbivore. J. Mar. Biol. Assoc. UK 60, 681–702.

Strathmann, R.R., 1967. Estimating the organic carbon content of phytoplankton from cell volume, cell area or plasma volume. Limnol. Oceanogr. 12, 411–418.

Sun, J., Liu, D., 2003. Geometric models for calculating cell biovolume and surface area for phytoplankton. J. Plankton Res. 25, 1331–1346.

Tschudi, M.A., Maslanik, J.A., Perovich, D.K., 2008. Derivation of melt pond coverage on Arctic sea ice using MODIS observations. Remote Sens. Environ. 112, 2605–2614.