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Phytoplankton production from melting ponds on Arctic sea ice

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[1] Recently, the areal extent of melt ponds within sea ice has rapidly increased during the Arctic Ocean summer. However, the biological impacts of melt ponds on the Arctic marine ecosystem have rarely been studied. Carbon and nitrogen uptake rates of phytoplankton were measured at 26 different melt ponds in 2005 and 2008, using a ^{13}C-^{15}N dual stable isotope tracer technique. Generally, the open ponds had relatively higher nutrients than closed ponds, but the nutrient concentrations in the open ponds were within a range similar to those in surrounding surface seawaters. Chlorophyll *a* (Chl *a*) concentrations in melt ponds ranged from 0.1 to 2.9 mg Chl *a* m^{-3} with a mean of 0.6 mg Chl *a* m^{-3} (SD = ±0.8 mg Chl *a* m^{-3}) in the Canada Basin in 2005, whereas the range of the Chl *a* concentrations was from 0.1 to 0.3 mg Chl *a* m^{-3} with a mean of 0.2 mg Chl *a* m^{-3} (SD = ±0.1 mg Chl *a* m^{-3}) in the central Arctic Ocean in 2008. The average annual carbon production in sea ice melt ponds was 0.67 g C m^{-3} (SD = ±1.03 g C m^{-3}) in the Arctic Ocean. Based on this study, recent annual carbon production of all melt ponds was roughly estimated to be approximately 2.6 Tg C, which is less than 1% of the total production in the Arctic Ocean.

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1. Introduction

[2] In the Arctic, meltwater can be partitioned into various reservoirs [*Eicken et al.*, 2002]. As described by *Eicken et al.* [2002], the downward percolation of meltwater into the porous ice matrix leads to a strong reduction in surface salinities of Arctic multiyear ice. This meltwater can be discharged through highly permeable ice or structural flaws and thus contribute to the freshwater flux at the ocean surface. Freshwater pooling in surface melt ponds is an important feature of summer Arctic sea ice. In general, the 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 surface albedo [*Perovich et al.*, 2002] and heat transmission [*Inoue et al.*, 2008]. Although recently areal coverage of melt ponds in summer has been estimated to reach up to 80% of the Arctic sea ice [*Lüthje et al.*, 2006], melt pond habitats associated with sea ice have been little studied in the Arctic Ocean [*Bursa*, 1963; *Gradinger*, 2002; *Gradinger et al.*, 2005; *Lee et al.*, 2011]. The biological impacts of melt ponds especially, have rarely been studied.

[3] Generally, two types of melt ponds in a sea ice field can be visually distinguished by their color. Deep blue melt ponds with salinities of about 29.0 are connected to seawater either by holes in the ice floes or via channels to the leads, whereas light sky blue ponds are freshwater habitats with a salinity of about 0.1 [*Gradinger*, 2002; *Lee et al.*, 2011]. In addition, the compositions of the plankton community in the melt ponds are different depending on pond types [*Gradinger*, 2002]. As described by *Gradinger* [2002], substantial concentrations of bacteria, phototrophic, and heterotrophic protists including *Chlamydomonas nivalis* and flagellated algae can be found in both types of the ponds. In salty ponds, higher concentrations of pennate diatoms such as *Nitzschia frigida* and *Nitzschia grunowii* occur compared to the freshwater ponds.

[4] In situ data were collected from two summer expeditions in the western Arctic Ocean in 2005 and 2008 (Figure 1). One is NOAA Arctic Exploration program in the Canada Basin on board the U.S. Coast Guard icebreaker *Healy* from 27 June to 26 July 2005 and another is the 3rd Chinese National Arctic Research Expedition (CHINARE) from late July to early September in 2008. These two expeditions provided a good opportunity to study various melt pond environments and compare them for differences between the lower and central Arctic Ocean. The objectives for this study were to define environmental characteristics of different melt ponds on sea ice floes, measure carbon and nitrogen uptake rates of

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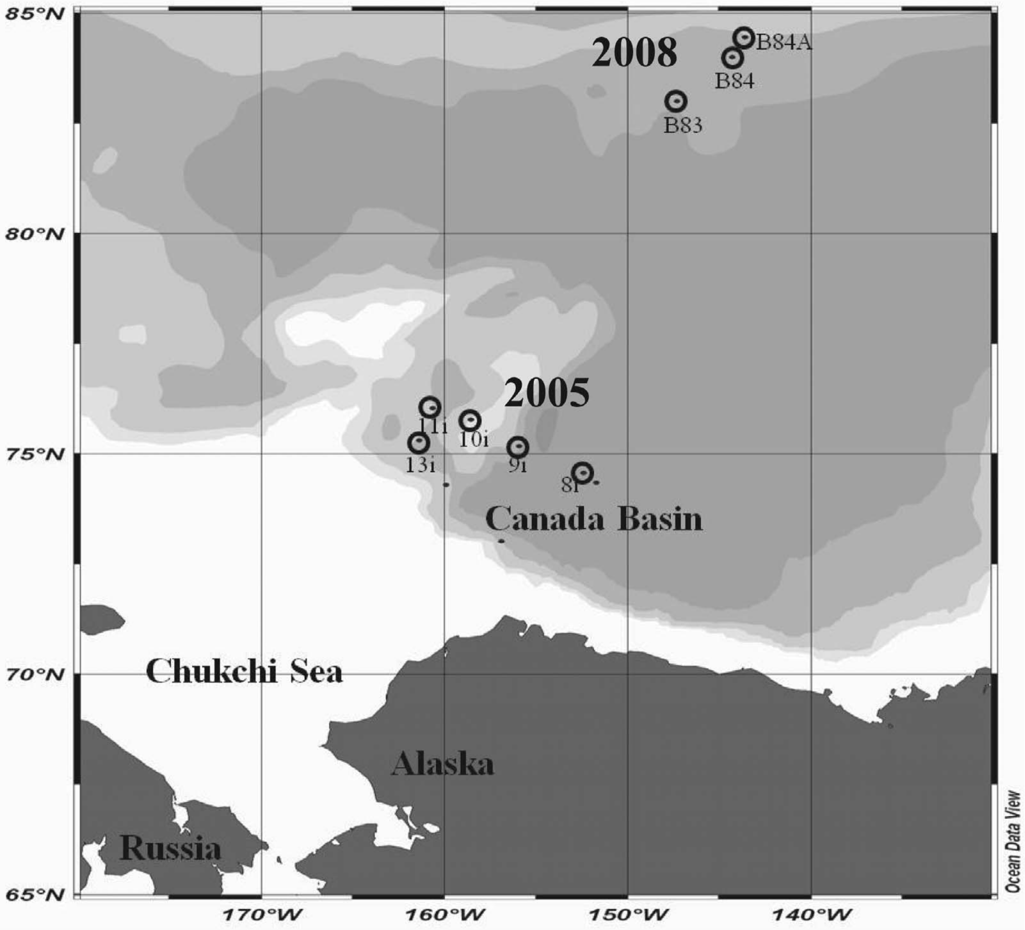

Figure 1. Locations of melting ponds on Arctic sea ice in 2005 and 2008.

phytoplankton in the ponds, and investigate effects of waters from the melt ponds on rates of phytoplankton production in surface seawater when pond waters mix with surface seawaters in the Arctic Ocean. This is the first paper to describe intensive and comprehensive measurements of phytoplankton primary productivity in many different melt ponds in sea ice floes in the Arctic Ocean.

2. Materials and Methods

2.1. Physical Characteristics in Melt Ponds

[5] At productivity stations, salinity and temperature in various melt ponds were measured with a YSI model 85 in 2005 and a YSI model 30 in 2008. The analytical accuracy for salinity and temperature of the water samples was ±2% for salinity and ±0.1°C for temperature. Ice thicknesses were measured a few meters away from the melt pond sampling locations after ice cores were extracted. No visual colors for sediments or ice algae were found on the extracted ice cores.

2.2. Chlorophyll *a* Analysis

[6] Samples for the determination of total chlorophyll *a* (Chl *a*) were filtered onto Whatman GF/F glass fiber filters (24 mm) and the filters were kept frozen until their analysis on board. They were extracted in a 3:2 mixture of 90% acetone and DMSO [*Webb et al.*, 1992], placed in a freezer

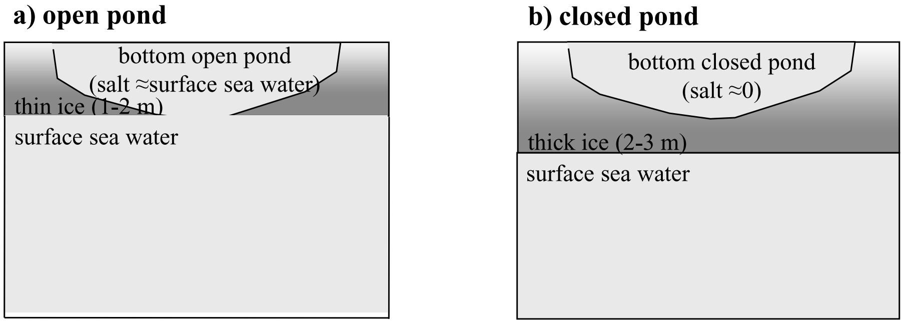
a) open pond
b) closed pond

Figure 2. Two types of melt ponds in the Arctic Ocean: (a) open pond and (b) closed pond.

Table 1. Environmental Parameters of the Melt Ponds in 2005

Station (Latitude, Longitude)	Date	Pond Name	Pond Type	Pond Depth (m)	Diameter (m)	Salinity	Temperature (°C)	Ice Thickness (m)
Station 8i (74°34.50′N, 152°04.90′W)	11 Jul	mp-1	closed	-	-	0.4	0.5	1.8
Station 9i (75°11.13′N, 155°56.80′W)	14 Jul	mp	closed	-	-	2.5	0.5	1.5
	14 Jul	mp-1	closed	-	-	2.0	0.6	1.5
	14 Jul	mp-2	closed	-	-	2.0	0.5	1.5
	14 Jul	mp-3	closed	-	-	1.6	0.4	1.5
	14 Jul	mp-4	closed	-	-	1.2	0.7	1.5
	14 Jul	mp-5	closed	-	-	0.6	0.7	1.5
	14 Jul	mp-6	closed	-	-	1.0	0.5	1.5
Station 10i (75° 42.60′N, 158°30.80′W)	15 Jul	mp-1	closed	-	-	3.4	1.2	1.7
	15 Jul	mp-2	closed	-	-	-	-	1.7
	15 Jul	mp-3	closed	-	-	-	-	1.7
Station 11i (76°01.95′N, 160°37.35 W)	16 Jul	mp-1	closed	-	-	2.2	0.5	1.4
	16 Jul	mp-2	closed	-	-	2.3	0.5	1.4
Station 13i (75°17.87′N, 161°20.37′W)	20 Jul	mp-1	closed	-	-	25.3	0.5	1.4
	20 Jul	mp-2	closed	-	-	5.1	0.5	1.5
Average				-	-	3.8	0.6	1.5

Table 2. Environmental Parameters of the Melt Ponds in 2008

	Date	Name	Pond Type	Pond Depth (m)	Diameter (m)	Salinity	Temperature (°C)	Ice Thickness (m)
Station B83 (82°59.80′N, 147°18.50′W)	18 Aug	mp-1	open	1.1	6.1	28.6	1.5	1.1
	18 Aug	mp-2	open	1.0	4.4	28.2	1.5	1.2
	18 Aug	mp-3	open	0.8	-	28.1	1.5	1.1
Station B84 (83°59.82′N, 144°16.50′W)	18 Aug	mp-1	closed	0.5	8.7	2.6	0	3.2
	18 Aug	mp-2	closed	0.5	7.2	2.4	0	4.5
Station B84A (84°26.54′N, 143°26.54′W)	22 Aug	mp-1	closed	0.6	12.5	3.2	0.2	2.5
	22 Aug	mp-2	closed	0.5	1.5	0.2	0.1	-
	22 Aug	mp-3	closed	0.4	-	5.6	−0.1	2.8
	24 Aug	mp-4	closed	0.9	6.5	22.1	−1.0	-
	24 Aug	mp-5	closed	0.7	5.8	3.3	0.1	-
	24 Aug	mp-6	closed	0.6	4.2	1.1	0.1	2.2
Average				0.6	6.6	5.1	−0.1	2.8

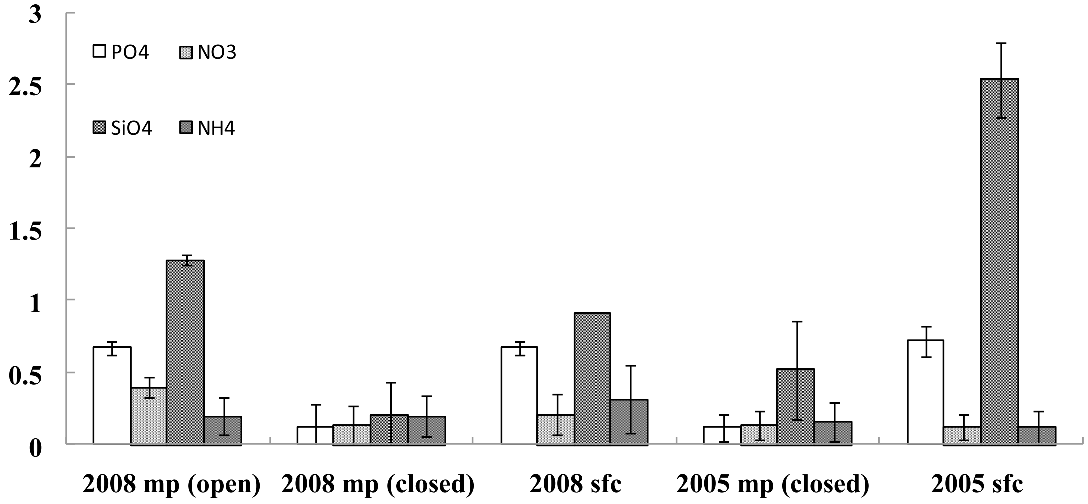

Figure 3. Major inorganic nutrient concentrations in melt ponds and surrounding surface seawaters in the Arctic Ocean in 2005 and 2008. On the *x* axis: mp, melt pond; sfc, surface seawater.

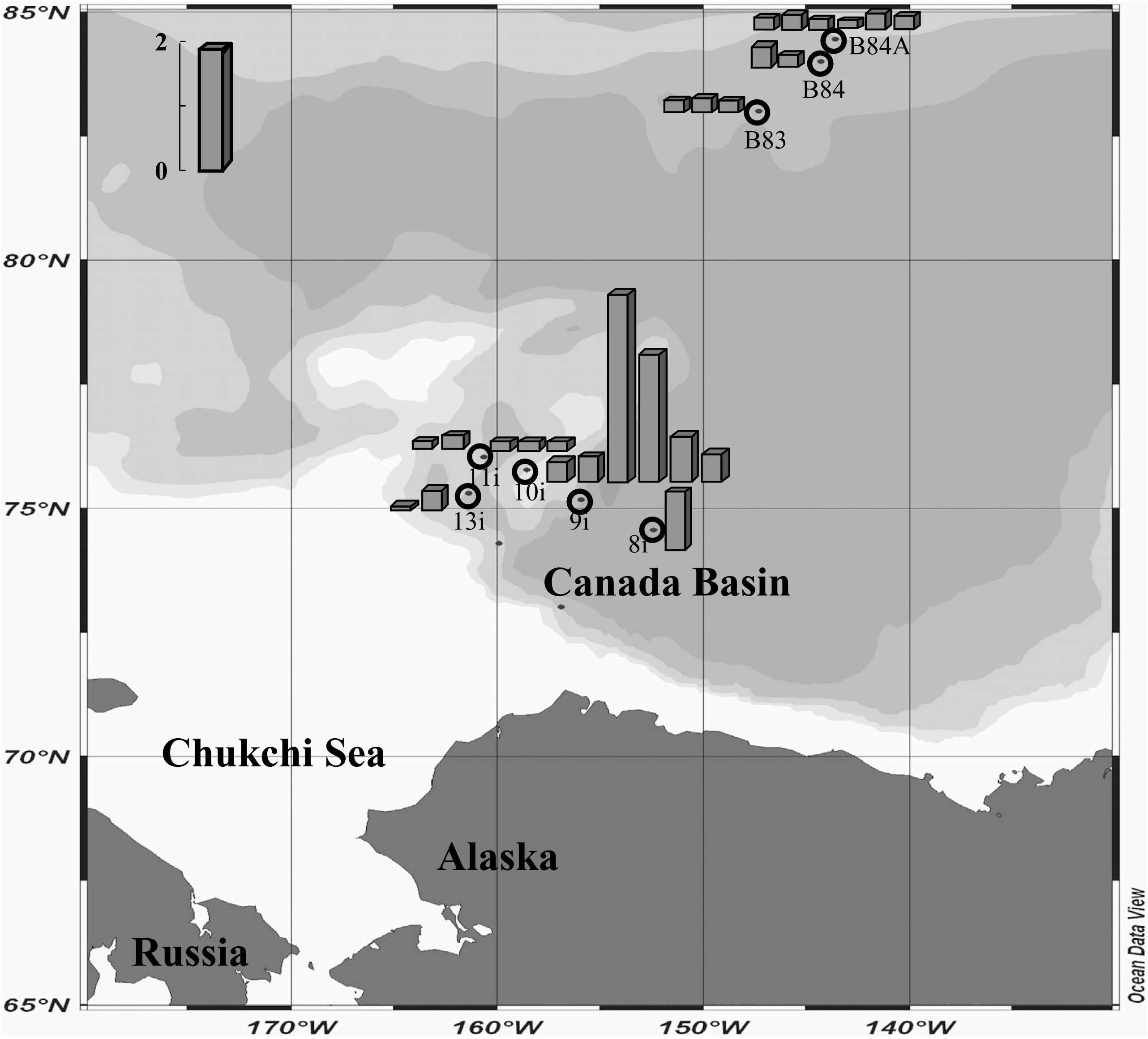

Figure 4. Chlorophyll *a* (Chl *a*) concentration (mg Chl *a* m^{-3}) in the melt ponds in 2005 and 2008. The Chl *a* concentrations at B83, B84, and B84A were estimated by their particulate organic carbon (POC) contents in the melt ponds using a linear relationship (Figure 5, $y = 0.0034X - 0.0842$, $R^2 = 0.8283$) between POC and Chl *a* concentration in 2005.

at −5°C for 24 h and centrifuged following the procedure of *Parsons et al.* [1984]. Chl *a* concentrations were measured shipboard using a Turner Designs model 10 AU fluorometer calibrated with commercially purified Chl *a* preparations. Chl *a* concentrations for melt ponds were analyzed only in 2005. The Chl *a* concentrations in 2008 were estimated by a linear regression from particulate organic carbon (POC) contents and Chl *a* concentrations based on the 2005 data set (see section 3.2).

2.3. Carbon and Nitrogen Productivity

[7] In situ carbon and nitrogen uptake rates were measured at 15 different melt ponds on 5 ice floe stations in 2005 and 11 melt ponds on 3 stations in 2008, using a ^{13}C-^{15}N dual isotope tracer technique [*Cota et al.*, 1996; *Lee and Whitledge*, 2005; *Lee et al.*, 2010]. To measure the uptake rates of carbon and nitrogen by phytoplankton in the melt ponds, two clear and one dark Nalgene polycarbonate bottles (1.2 L) were filled with the 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 to obtain concentrations of ~0.2 mM ($^{13}CO_2$), ~0.8 μM ($^{15}NO_3$), and ~0.2 μM ($^{15}NH_4$) [*Dugdale and Goering*, 1967; *Hama et al.*, 1983]. After isotope inoculations were completed, the incubation bottles were incubated in the ponds from which waters were originally collected and kept at their in situ temperature and light for 3–5 h. After incubation, the bottles were retrieved and brought to the ship in a dark, insulated box for filtration through precombusted Whatman GF/F filters. The filters were immediately frozen at −20°C and preserved for mass spectrometric analysis at the stable isotope laboratory of the University of Alaska Fairbanks. Carbon and nitrogen

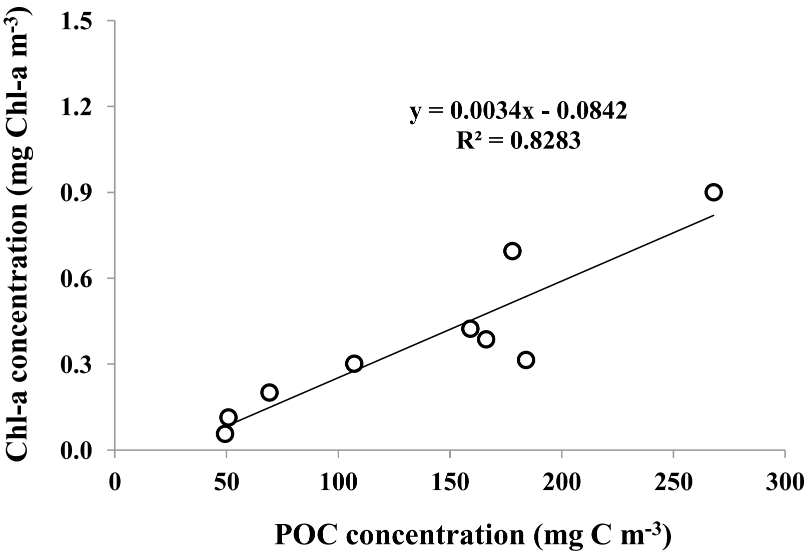

Figure 5. The relationship between Chl *a* (mg Chl *a* m^{-3}) and POC (mg C m^{-3}) concentrations in the melt pond waters in 2005.

production rates were calculated following the same procedures of *Lee et al.* [2010]. Dark carbon uptake values were subtracted from light carbon uptake values assuming that the measured dark uptake rates were from bacterial processes [*Gosselin et al.*, 1997]. Dark nitrogen uptake rates, however, were not subtracted because of the relatively abundant light environment during the incubations [*Smith and Harrison*, 1991].

2.4. Nutrient Concentrations

[8] Water samples for macronutrient and chlorophyll *a* (Chl *a*) concentration analyses were collected from various melt ponds at productivity stations. Immediately after water sampling, inorganic phosphate (PO_4), nitrate (NO_3), silicate ($Si(OH)_4$), and ammonium (NH_4) concentrations were analyzed on board the ship using an automated nutrient analyzer (ALPKEM RFA model 300) in 2005. In 2008, phosphate, silicate, and nitrate + nitrite were analyzed using a SKALAR San^{++}Flow analyzer, and ammonium and nitrite were analyzed using a Shimadzu UV-1206 spectrophotometer. The analytical system's accuracy for nutrient concentrations in the water samples was ±0.02 μM for phosphate and nitrite and 0.1 μM for nitrate, ammonium, and silicate in 2005 and 2008.

3. Results

3.1. Environmental Conditions in Melt Ponds

[9] Generally, two types of sea ice melt ponds –bottom closed and open bottom were found in the Arctic Ocean in 2005 and 2008 (Figure 2). The mean depth and diameter of closed ponds in 2008 were 0.6 m (SD = ±0.2 m) and 6.6 m (SD = ±03.5 m), respectively (Table 1). No data are available for the information in 2005. The mean sea ice thicknesses were 1.5 and 2.8 m in 2005 and 2008, respectively (Tables 1 and 2). The temperatures of water in closed melt ponds ranged from 0.5 to 1.2°C (mean ± SD = 0.6 ± 0.2°C) in 2005, whereas the temperatures in 2008 were from −1.0 to 0.2°C (mean ± SD = −0.1 ± 0.4°C), a difference that may be partly due to the slightly late summer sampling data in 2008. The salinities in the ponds ranged from 0.4 to 25.3 (mean ± SD = 3.8 ± 6.3) and 0.2 to 22.1 (mean ± SD = 5.1 ± 7.1) in 2005 and 2008, respectively. The mp-1 at station 13i in 2005 and mp-4 at station B84A in 2008 had highest salinities among the closed ponds.

[10] The average nutrient concentrations were 0.12 (SD = ±0.09 μM), 0.13 (SD = ±0.10 μM), 0.52 (SD = ±0.35 μM), and 0.16 μM (SD = ±0.14 μM) in 2005, whereas 0.11 (SD = ±0.17), 0.14 (SD = ±0.14 μM), 0.21 (SD = ±0.22 μM), and 0.20 (SD = ±0.14 μM) μM in 2008 for phosphate, nitrate, silicate, and ammonium, respectively (Figure 3).

3.2. Chlorophyll *a* Concentrations in Melt Ponds in 2005

[11] Chl *a* concentrations in melt ponds ranged from 0.1 to 2.9 mg Chl *a* m^{-3} with a mean of 0.6 mg Chl *a* m^{-3} (SD = ±0.8 mg Chl *a* m^{-3}) in the Canada Basin in 2005 (Figure 4). For comparison, the Chl *a* concentrations at B83, B84, and B84A in 2008 were estimated by their particulate organic carbon (POC) concentrations in the melt pond water using a linear relationship between POC and Chl *a* concentration in 2005 (Figure 5). The range of the estimated Chl *a* concentrations in 2008 was from 0.1 to 0.3 mg Chl *a* m^{-3} with a mean of 0.2 mg Chl *a* m^{-3} (SD = ±0.1 mg Chl *a* m^{-3}) in the central Arctic Ocean which was much lower than that in the Canada Basin in 2005 (Figure 4).

3.3. Carbon and Nitrogen Uptake Rates of Phytoplankton in Melt Ponds

[12] The carbon uptake rates of phytoplankton in melt ponds in 2005 and 2008 ranged from 0.03 to 2.12 mg C m^{-3} h^{-1} (mean ± SD = 0.47 ± 0.58 mg C m^{-3} h^{-1}) and 0.01 to 0.34 mg C m^{-3} h^{-1} (mean ± SD = 0.09 ± 0.11 mg C m^{-3} h^{-1}), respectively (Figure 6). Uptake rates were significantly (*t* test, $p < 0.05$) higher in melt ponds during 2005 than for 2008.

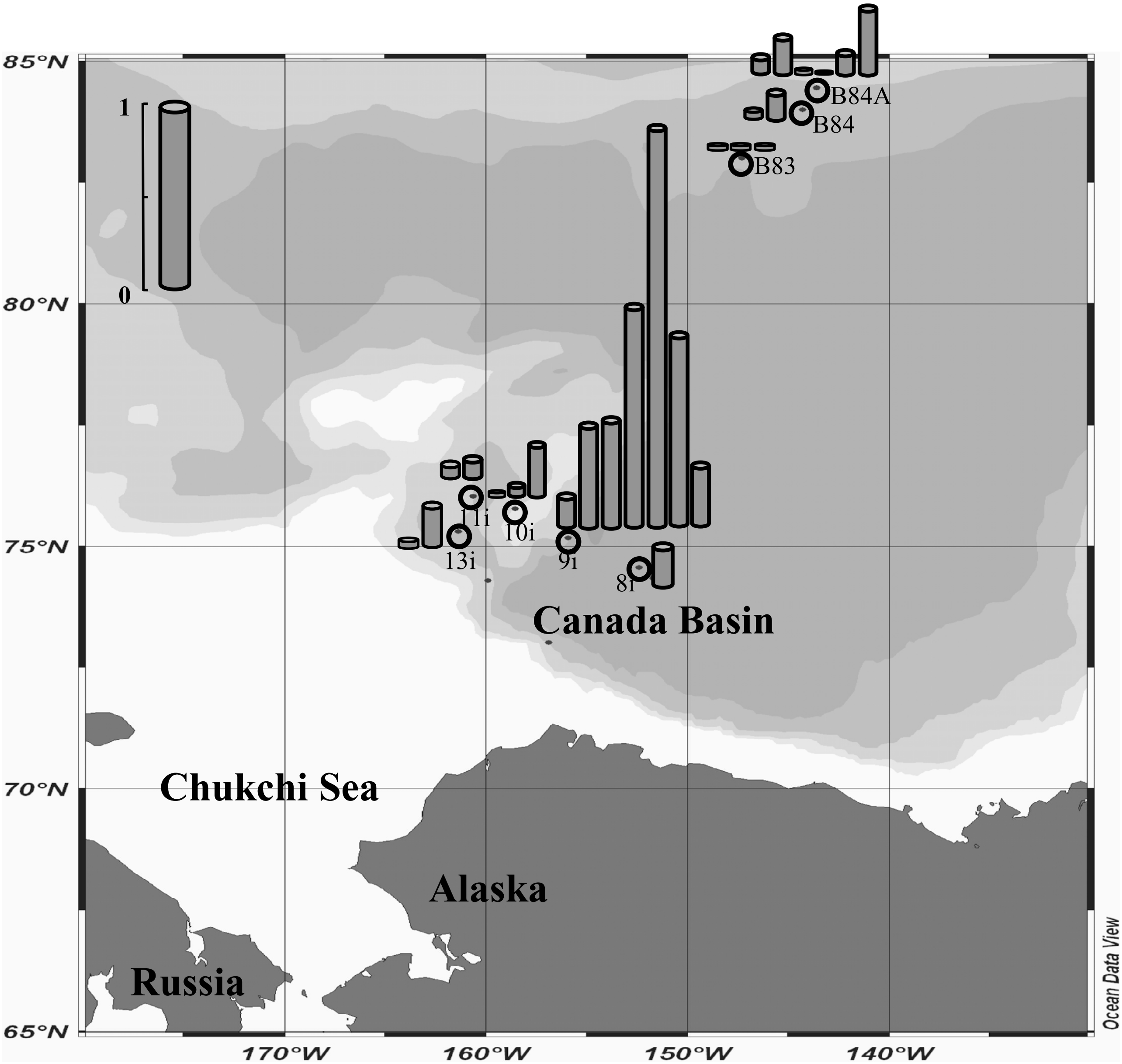

Figure 6. Hourly carbon uptake rate (mg C m^{-3} h^{-1}) in the melt ponds in 2005 and 2008.

[13] In order to check possible effects of meltwaters on phytoplankton in surrounding surface waters after release from the melt ponds, mixing experiments were undertaken with different pond waters at station B84A in 2008 (Figure 7). Two different waters were just mixed and carbon uptake rates were measured after 3–4 h incubation. The carbon uptake rate in a mixed water sample (Figure 7, bar B: 50% of surface ocean water and 50% of the melt pond water) was not different from 100% surface water (Figure 7, bar A). However, the surface ocean water mixed with the pond water filtered through GF/F filters (Figure 7, bar C) assuming all phytoplankton removed out from the melt pond water had significantly (*t* test, $p < 0.01$) lower uptake rates than only surface ocean water (Figure 7, bar A). In comparison, the uptake rate of surface ocean water mixed with brine water containing algae (Figure 7, bar D) from an ice core hole at station B84A was significantly (*t* test, $p < 0.01$) higher than that of 100% ocean surface water (Figure 7, bar A). In contrast, the uptake rate of carbon in ocean water mixed with filtered brine water (Figure 7, bar E) was similar to that of only surface ocean water (Figure 7, bar A).

[14] The uptake rates of total nitrogen (nitrate + ammonium) in melt ponds ranged from 0.020 to 0.962 mg N m^{-3} h^{-1} (mean ± SD = 0.269 ± 0.338 mg N m^{-3} h^{-1}) and from 0.002 to 0.060 mg N m^{-3} h^{-1} (mean ± SD = 0.015 ± 0.018 mg N m^{-3} h^{-1}) in 2005 and 2008, respectively (Figure 8). The uptake rates of total nitrogen in melt ponds were also significantly (*t* test, $p < 0.05$) higher in the Canada Basin in 2005 than the central Arctic Ocean in 2008. With the hourly uptake rate (Figure 8) and the assumption of 24 h daylight [*Subba Rao and Platt*, 1984], the daily total nitrogen production rate of phytoplankton in the melt ponds in the Canada Basin in 2005 was estimated to range from 0.48 to 23.10 mg N m^{-3} d^{-1}, with a mean of 6.45 mg N m^{-3} d^{-1}

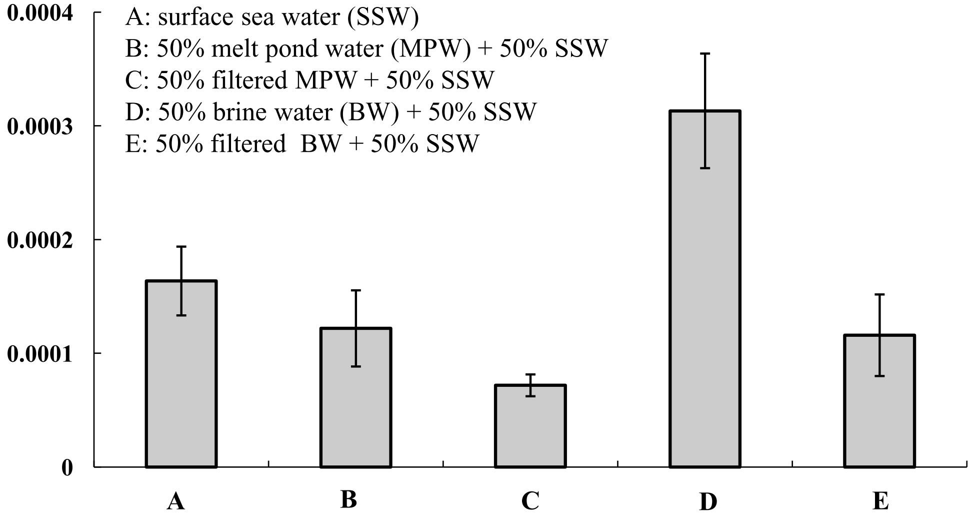

Figure 7. Carbon uptake rates (h^{-1}) of phytoplankton from mixing water experiments.

(SD = ±8.10 mg N m^{-3} d^{-1}). In contrast, the rate of phytoplankton in the melt ponds in the central Arctic Ocean in 2008 ranged from 0.04 to 1.44 mg N m^{-3} d^{-1}, with a mean of 0.35 mg N m^{-3} d^{-1} (SD = ±0.42 mg N m^{-3} d^{-1}). Based on the ratio of nitrate uptake rate/total nitrate + ammonium uptake rate, *f* ratios ranged from 0.50 to 0.92 (mean ± SD = 0.81 ± 0.16) in 2005, whereas they ranged from 0.12 to 0.51 (mean ± SD = 0.27 ± 0.11) in 2008 (Figure 9) which were significantly lower (*t* test, $p < 0.01$) than those in 2005.

4. Discussion

4.1. Environmental Conditions in Different Types of Melt Ponds

[15] Two types of melt ponds associated with sea ice were found in the Arctic Ocean in 2005 and 2008. Closed melt ponds were light, sky blue with depths of ~0.6 m in 2008 and bottom layers generally closed to the surrounding sea. In the closed ponds, salinities ranged from ~0 to 25 (Tables 1 and 2), depending on the stage and physical structure, such as cracks or connections to seawater [*Gradinger*, 2002]. Open ponds were deep blue with depths of 1–2 m, depending on sea ice thickness, whose bottom layers were open to the seawater below. Because the waters in the open ponds were connected with surface seawaters, the salinities in the open pond were quite similar to those in surrounding surface waters. In comparison, *Gradinger et al.* [2005] found salinities ranged from 0.2 to 11.1 with a median value of 0.3 in their melt ponds.

[16] The concentrations of phosphate (PO_4), nitrate (NO_3), silicate ($Si(OH)_4$), and ammonium (NH_4) were low (<1.0 μM) in closed melt ponds yet not totally nutrient deplete in either year (Figure 3). The nutrient concentrations in open ponds were a little higher than those in closed ponds, but concentrations in the open ponds were within a range similar to those in surrounding surface seawaters near the ponds in 2008.

4.2. Chlorophyll *a* Concentrations in Melt Ponds

[17] Surprisingly, the average Chl *a* concentrations in melt ponds were higher than those of surface water column in the same study locations in 2005 and 2008. In general, Chl *a* concentrations in the Canada Basin were low (<0.5 mg Chl *a* m^{-3}) throughout the water column in the 60 m upper layer in 2005 [*Lee et al.*, 2010]. They found that Chl *a* concentrations at the surface ranged from <0.1 to 0.3 mg Chl *a* m^{-3}, with a mean of 0.1 mg Chl *a* m^{-3}, whereas the Chl *a* at the deep Chl *a* maximum layer depth located at ~40 m depth at most stations ranged from 0.2 to 1.0 mg Chl *a* m^{-3}, with a mean of 0.5 mg Chl *a* m^{-3}. In comparison, *Gradinger et al.* [2005] reported the Chl *a* concentrations in melt ponds ranging from 0.1 to 7.5 mg Chl *a* m^{-3} with a mean of 2.3 mg Chl *a* m^{-3} (SD = ±3.0 mg Chl *a* m^{-3}) which were higher than those at subice water in 2002 and 2003. Although their average Chl *a* concentrations were much higher than the concentrations found in this study, they were not statistically significant different because of the large variation of Chl *a* concentrations within the melt ponds (Figure 4). The spatial variations between the two studies sites could account for such differences. Our study locations were mainly in the western Canada Basin, whereas their locations were mostly in the eastern Canada Basin in 2002. In fact, their lowest value (0.1 mg Chl *a* m^{-3}) at the C1 station among the ponds was obtained in the western part of the Basin which was within the range of the Chl *a* concentration in this study. Another potential explanation for the discrepancy might be different grazing impacts on phytoplankton, although no data are available for our study. Sympagic meiofauna and under-ice amphipods can be found in melt ponds, depending on bottom ice conditions of ponds [*Kramer and Kiko*, 2011]. These animals can reduce substantially phytoplankton biomass in melt ponds (H.-U. Dahms, personal communication, 2011).

4.3. Carbon and Nitrogen Uptake Rates of Phytoplankton in Melt Ponds

[18] The carbon uptake rate averaged from the melt ponds was one order of magnitude higher than that in surface water layer below the sea ice during the same period in 2005 reported by *Lee et al.* [2010]. They found that the carbon uptake rates of phytoplankton below the ice ranged from

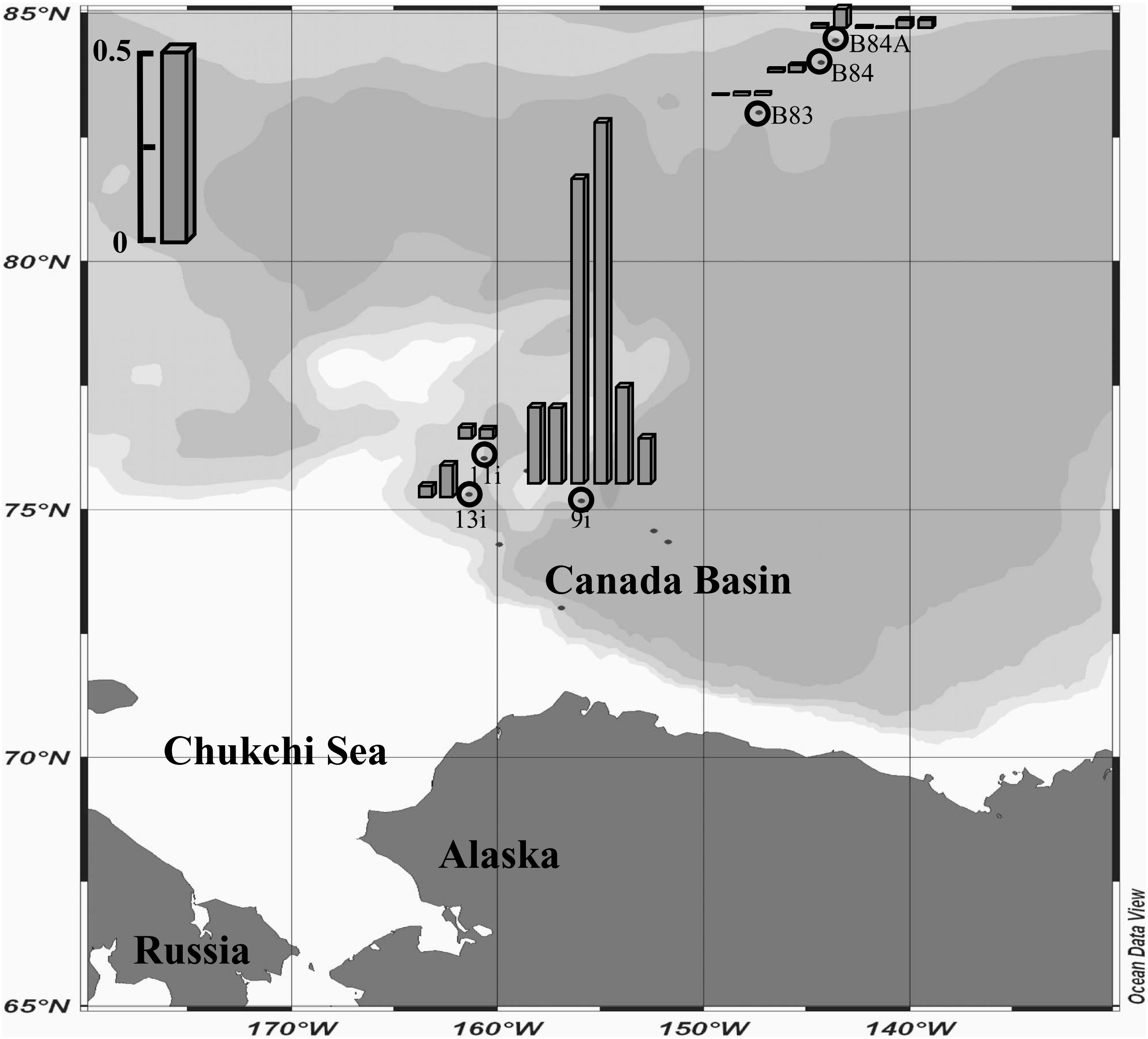

Figure 8. Hourly total (nitrate + ammonium) nitrogen uptake rate (mg N m^{-3} h^{-1}) in the melt ponds in 2005 and 2008.

0.002 to 0.396 mg C m^{-3} h^{-1} with a mean of 0.053 mg C m^{-3} h^{-1} (SD = ±0.073 mg C m^{-3} h^{-1}) in the Canada Basin in 2005. The average carbon uptake rate in melt ponds in 2008 was also higher compared to the surrounding surface layer (S. H. Lee, unpublished data, 2008), although not on statistically significant level. A comparison of melt ponds showed that the carbon uptake rates in melt ponds were significantly higher in the Canada Basin in 2005 than the central Arctic Ocean in 2008 (Figure 6). Different light intensities depending on latitudes might cause the different carbon uptake rates since there was approximately 7 degree latitude difference between the two studies in 2005 and 2008 (Figure 1). In addition, this difference between the two periods might be different sampling times. The observation period in 2005 was from 27 June to 26 July which is about one month earlier than that in 2008. In fact, a strong seasonal variation in the phytoplankton biomass and photosynthetic rate was suggested to cause the large difference in daily carbon productivity of water column in the Arctic Ocean [*English*, 1961; *Yun et al.*, 2011]. In this study, the specific uptake rates (no biomass considered) were not significantly different between 2005 and 2008, indicating the higher productivity was driven mainly by higher biomass considered as POC concentration rather than faster growth rates in the melt ponds in 2005 than 2008. Different nutrient (mainly nitrogen) limitation levels of phytoplankton in the melt ponds might be another explanation based on C/N and *f* ratios (more discussion later) in 2005 and 2008. Given the carbon and nitrogen uptake ratios in this study, the average assimilated C/N uptake ratios (mole/mole) of phytoplankton were 3.5 (SD = ±2.7) and 7.3 (SD = ±3.6) in 2005 and 2008, respectively. The lower C/N ratio suggests less nitrogen limitation condition of phytoplankton in 2005 than 2008. In addition, the significant higher *f* ratio in 2005 indicates that potential growth of phytoplankton community by nitrate was higher in 2005 than 2008 because new nitrogen (e.g., nitrate)

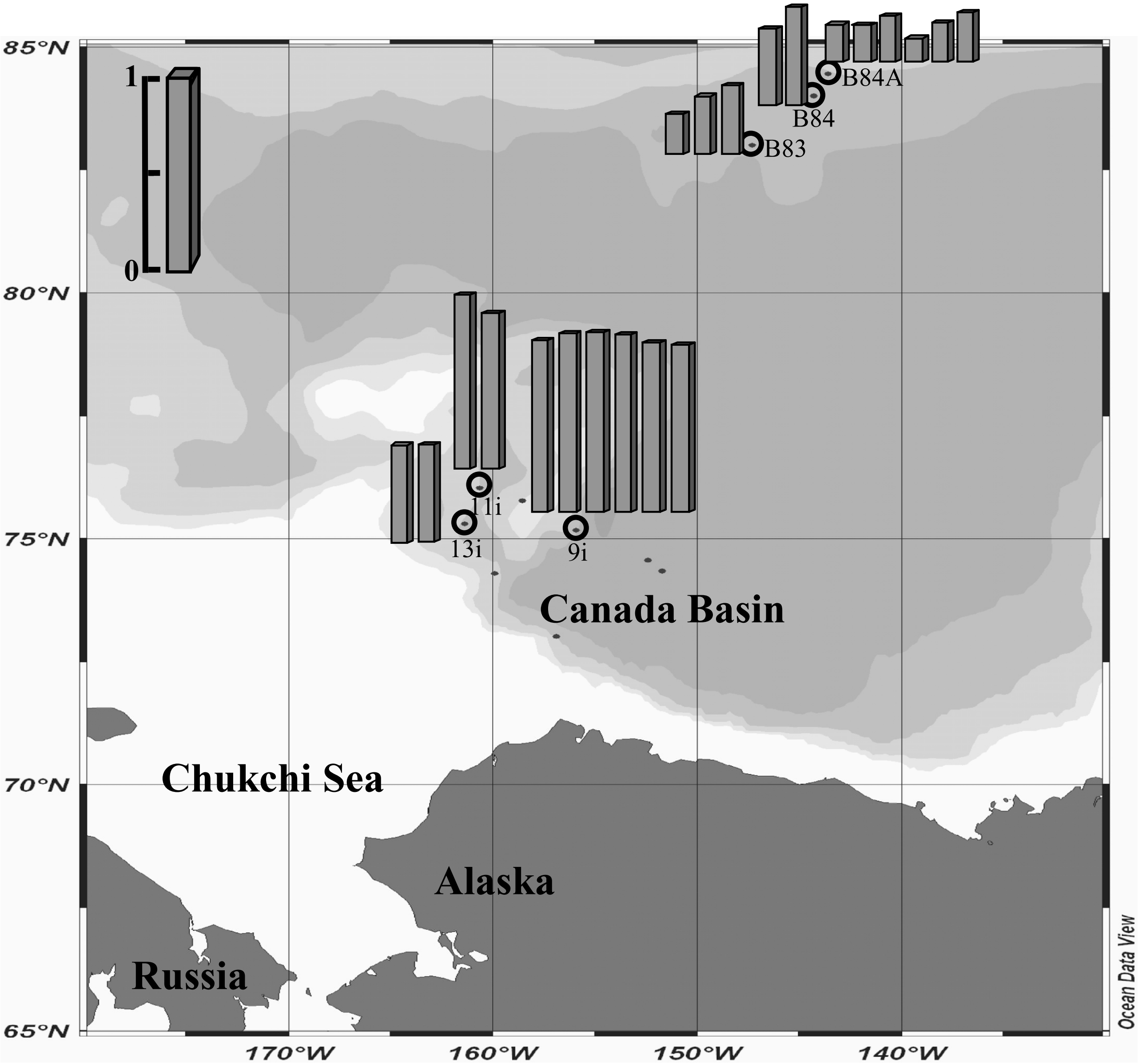

Figure 9. The *f* ratio in the melt ponds in 2005 and 2008.

increases the phytoplankton size whereas regenerated nitrogen such as ammonium keeps phytoplankton in a healthy state [*Dugdale and Goering*, 1967].

[19] In general, many researchers speculate that nutrient input from brine channels or melt ponds of sea ice might stimulate phytoplankton growth near sea ice. However, our experiments showed no difference in the carbon uptake rates of phytoplankton in the ocean surface waters and in melt pond water containing ambient growing algae, when they were tested separately or mixed (Figure 7). This result indicates no serious effect of the melt pond waters on the growth of phytoplankton at surface ocean water, although the water in the closed ponds had lower salinities and nutrient concentrations than the ocean surface water. In contrast, the uptake rate of surface ocean water mixed with brine water containing algae was significantly higher than that of only ocean surface water because there was higher algal biomass in the brine water than the surface ocean water. Based on these mixing experiments, the water itself without phytoplankton from closed melt ponds or brine water might not increase or decrease the total carbon uptake rate of surface ocean water after they were mixed. However, the microalgal communities in the closed ponds or brine waters could enhance the total carbon uptake rates of phytoplankton in surface ocean waters, depending on their biomass in the waters of the melt ponds or brine channels. However, these results in this study were obtained from a single experiment at only one station in 2008 to give a rough idea about some potential effects of waters from melt ponds on phytoplankton at surface ocean layer in the Arctic Ocean. More specific investigations (e.g., physiological conditions of cells) will be needed to determine whether melt pond waters increase or decrease the Arctic carbon production.

[20] In terms of the nitrogen production per square meter, the rates ranged from 0.29 to 13.86 mg N m^{-2} d^{-1}, with a mean of 3.87 mg N m^{-2} d^{-1} (SD = ±4.86 mg N m^{-2} d^{-1}) in

2005, whereas the rates ranged in 2008 from 0.02 to 0.86 mg N m^{-2} d^{-1}, with a mean of 0.21 mg N m^{-2} d^{-1} (SD = ±0.25 mg N m^{-2} d^{-1}). In comparison, the total nitrogen production rate of under-ice phytoplankton integrated from the ice bottom to about 60 m water depth in the Canada Basin in 2005 ranged from 5.5 to 50.9 mg N m^{-2} d^{-1}, with a mean of 20.2 mg N m^{-2} d^{-1} [*Lee et al.*, 2010]. Although the estimated mean uptake rates from this study were lower than those in the work of *Lee et al.* [2010], they were within the ranges of the mean rate recorded by *Pautzke* [1979] for the northern Canada Basin (5.0 mg N m^{-2} d^{-1}) and by *Lee and Whitledge* [2005] for the eastern Canada Basin (0.8 mg N m^{-2} d^{-1}). Although the *f* ratio in 2008 (mean ± SD = 0.27 ± 0.11) was reasonable for phytoplankton in the Arctic Ocean, the *f* ratio (mean ± SD = 0.81 ± 0.16) of the melt ponds in 2005 from this study is surprisingly high compared to the range reported in other regions in the western Arctic Ocean [*Horner et al.*, 1974; *Cota et al.*, 1996; *Lee and Whitledge*, 2005; *Lee et al.*, 2010]. This high ratio is identical as the maximum *f* ratio measured previously in the Northeast Water Polynya [*Smith et al.*, 1997]. In comparison, *Horner et al.* [1974] found that the *f* ratio obtained in Prudhoe Bay during summer was 0.40 and *Cota et al.* [1996] reported the range from 0.05 to 0.38 obtained in the southeastern Chukchi Sea during August. In addition, *Lee et al.* [2010] measured 0.36 under sea ice in the Canada Basin in 2005, which is a value similar to others in the western Arctic Ocean. Based on higher *f* ratios in 2005 than 2008 (Figure 9), nitrate was a predominant nitrogen source for the growth of phytoplankton in melt ponds in 2005, whereas ammonium was a main nitrogen source in 2008 although the ambient nutrient concentrations except silicate in melt ponds were not significantly different between 2005 and 2008 (Figure 3). In fact, we found mostly nano- and pico-sized flagellates dominated the phytoplankton communities in the closed and open ponds in 2008. These small phytoplankton depend on ammonium rather than nitrate for their growth [*Lee and Whitledge*, 2005].

5. Conclusions

[21] We described first carbon and nitrogen production rates measured from various melt ponds in sea ice floes in the Arctic Ocean. To check how much melt ponds contributes for the total primary production in the Arctic Ocean, we estimated roughly the annual carbon production from phytoplankton in Arctic melt ponds although estimating annual primary production from snapshot observations might be uncertain because there are seasonal and annual changes in carbon production rates of phytoplankton in the Arctic Ocean. Based on 24 h daylight [*Subba Rao and Platt*, 1984] and 90 day summer melt season [*Tschudi et al.*, 2008], the estimated mean annual carbon production in melt ponds was 0.67 g C m^{-3} (SD = ±1.03 g C m^{-3}) on sea ice in the Arctic Ocean. In terms of production per square meter, the annual carbon production was about 0.40 g C m^{-2} since the average depth of the closed melt ponds was about 0.6 m in 2008 (Table 2). According to the National Snow and Ice Data Center (NSIDC), the average sea ice extent from June to September during recent years was about 8 million km^2 in the Arctic Ocean. *Lüthje et al.* [2006] recently found that areal coverage of melt ponds in summer reaches up to 80% of the Arctic sea ice. Considering these observations, the total carbon production in the all melt ponds was estimated about 2.6 Tg C yr^{-1} in the whole Arctic Ocean. This production is a small contribution (less than 1%) to the recent total production (400 $\sim$ 500 Tg C yr^{-1}) in the Arctic Ocean [*Pabi et al.*, 2008; *Arrigo et al.*, 2008]. However, the contribution of the melt ponds could be higher if compared with the production in the sea ice-covered Arctic Ocean, since the productivity domain in the work of *Pabi et al.* [2008] is the open water part of the Arctic Ocean within the Arctic Circle. Therefore, it could be important in the carbon budget in the Arctic Ocean which has not been considered previously. Currently we do not know how ongoing climate changes, such as increasing temperature and decreasing concentration and thickness of sea ice, influence on the melt pond ecosystems and consequently higher trophic animals in the Arctic Ocean. More intensive field measurements are needed for better understanding these unique habitats in the Arctic Ocean.

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