

Comparison of bottom sea-ice algal characteristics from coastal and offshore regions in the Arctic Ocean

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Abstract Ice-core observations were conducted at three arctic sites in early April 2003: one clean sediment-free site (Chukchi), one sediment-rich site (Beaufort) on landfast sea ice offshore Barrow, and one oceanic Ice Exercise (ICEX) site. Concentrations of inorganic nutrients at coastal sites were similar to but higher than those at the oceanic site. Chlorophyll-*a* (Chl-*a*) concentration was much higher in the Chukchi bottom ice than at the other two sites. However, large size Chl-*a* (>20 µm) dominated (>70%) the bottom-ice algal Chl-*a* at both the Chukchi and Beaufort sites, whereas the oceanic ICEX site was evenly occupied by large (>20 µm), medium (5–20 µm), and small Chl-*a* (0.7–5 µm). These in situ data were incorporated into an ocean-ecosystem model. The model results revealed that: (1) strong light attenuation by trapped sediments controlled ice-algal production at the Beaufort site; (2) the peak in ice algae occurred later at the oceanic site than at the Chukchi site because of thicker ice and the consequently reduced amount of light reaching the ice algae at the ice bottom; and (3) maximum production at the oceanic site reached only 10% the level at the Chukchi site because of nutrient limitation.

Keywords Ice algae · Inorganic nutrients · Arctic Ocean · Barrow · Landfast sea ice · Chl-*a*

Introduction

The contribution of ice algae, found at the ice–water interface, to total primary production ranges from less than 1% in coastal regions (Alexander and Chapman 1981) up to around 60% in the central ice-covered ocean of the Arctic (Gosselin et al. 1997). Although production appears to vary widely among regions, ice algae provide important food resources for sympagic organisms, amphipods, and pelagic copepods that live under the ice (Lizotte 2001; Michel et al. 2002) in the Arctic Ocean because in the spring, their growth begins a couple of months before phytoplankton development in the water column below (Apollonio 1965; Schnack-Schiel 2003; Lee et al. 2008a). Over the last several decades, higher temperatures have reduced the sea-ice extent and sea-ice thickness, as well as reduced the amount of thicker perennial sea ice in the Arctic Ocean, especially in the western part, (Vinnikov et al. 1999; Rothrock et al. 2003; Perovich and Richter-Menge 2009). These climate and ice changes may alter the relative contributions of sea-ice algae and phytoplankton with respect to the species and/or size composition of primary producers and new and total production (Lee et al. 2008a, b). In addition, the timing and length of spring blooms of ice algae could be altered by ongoing climate events (Lavoie et al. 2005; Lee et al. 2008a). However, their responses to current and projected climate changes are poorly understood because of the limited number of observations (Lee et al. 2008a; Gradinger et al. 2009), which do not adequately quantify the entire range of spatial variability in sea ice and sea-ice habitats in different oceanic regions.

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The significance of spatial variability was obvious when we compared ice-core data from several sites on the coastal fast ice and offshore pack ice in the Arctic Ocean in 2003. To assess this variability and its ecological significance, we used a combination of observations and an important tool, a vertical 1-D ocean ecosystem model, to interpret the observations and compare ecosystem changes under controlled conditions. The 1-D ice–ocean ecosystem model (Jin et al. 2006) was developed using time-series observations at one location on the landfast ice offshore Barrow in 2002 and 2003. However, simulating the large spatial variability in ice-algal biomass remains a tremendous challenge because ice and snow conditions differ from the coast to the Arctic basin, and especially because varying amounts of sediment are trapped within sea ice (Lee 2005; Gradinger et al. 2009). Gradinger et al. (2009) found that sediment within landfast sea ice had a profound impact on sea-ice biota as well as on the spring bloom development. The implications of these variations for ice-algal production and related ecosystems remain poorly understood because of a lack of observations. This study aims to improve our understanding of these implications by comparing different characteristics of ice, snow, nutrients, and sediment conditions and their impacts on ice-algal production patterns.

Materials and methods

Three distinct sampling sites (Fig. 1) were chosen; the first site represented clean (sediment-free) coastal conditions (Chukchi site), the second was a sediment-rich site (Beaufort site) on landfast ice off Barrow, and the third was

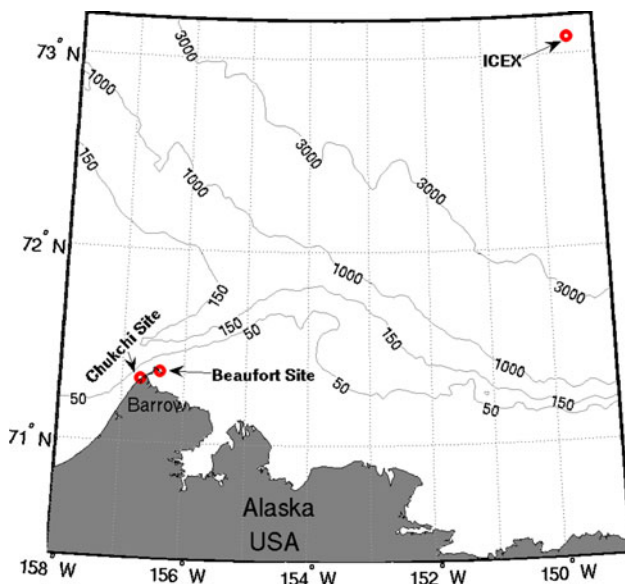


Fig. 1 Sampling locations for three sites in the Arctic Ocean. Contours denote water depths in meters

an oceanic site on first-year sea ice at the 2003 ICEX (Ice Exercise) ice camp (ICEX site). Field observations were conducted six and three times, respectively, at the Chukchi site and Beaufort site in 2003. For comparison of bottom sea-ice algal characteristics from different locations during a similar observation period, the field data in early April 2003 (Table 1) were used, and other data were used only for a reference in this study. The Chukchi Sea site, west of Barrow, was located on landfast ice close to the Barrow Arctic Science Consortium (BASC), Barrow, Alaska; the site was sampled on 3 and 4 April 2003. No visible sediments were contained in the sea-ice cores sampled near the BASC, whereas the upper ice cores from the Beaufort site to the north of Barrow had a strongly sedimented band (mean \pm standard deviation: 24.5 ± 4.7 cm, $n = 10$). Ice thicknesses were 1.30 ± 0.07 , 1.50 ± 0.09 , and 1.80 ± 0.08 m at the Chukchi, Beaufort, and ICEX sites, respectively, and snow depths were 2–4 cm at all locations (Table 1). At the two nearshore sampling sites, the water depth below the ice was approximately 4–5 m. In contrast, the ICEX site was located on drifting pack ice, and the water depth below the ice was about 1,000 m.

Water samples (4.5 L) were obtained using a Kemmerer water sampler lowered through sea-ice core holes. After return back to field laboratories, sub-samples (0.2 L) were frozen without filtration for later analysis of major nutrient concentrations in the home laboratory at the University of Alaska Fairbanks. Another set of sub-samples (1.5 L) was filtered for total and size-fractionated chlorophyll-*a* (Chl-*a*). Samples for the determination of total Chl-*a* were filtered onto Whatman GF/F glass fiber filters (24 mm). Size-fractionated Chl-*a* was determined using samples passed sequentially through 20 and 5- μ m nucleopore filters (47 mm), and Whatman GF/F filters (47 mm). The filtrates were kept frozen at -20°C and returned to the home laboratory for analysis. For nutrients within ice, three ice cores per site were obtained using 8-cm diameter SIPRE corers; cores were cut into 10-cm portions in the field. The bottom 10-cm section of each core was further sectioned into 3- and 7-cm length portions for more detailed analysis of the vertical distribution, since most of the ice-algal biomass was concentrated in the bottom 3 cm of the ice cores at Barrow (Lee et al. 2008b). Ice sections of three replicate cores were melted together in the dark at room temperature. Right after melting was completed, sub-samples (0.2 L) from each section were frozen without filtering for later analysis of nutrients, and another set of sub-samples (1.0 L) was filtered for Chl-*a* concentration analyses.

Light levels below the ice bottom were measured around solar noon with a LI-COR underwater 4π light sensor at 1-m intervals through a separate core hole, which was covered with three layers of ice cubes and snow to reduce excess light transmission through the hole. A radiation

Table 1 Description of three arctic sites in 2003

Station	Location		Sampling date	Ice thickness (cm)	Snow depth (cm)	Bottom light intensity ($\mu\text{E m}^{-2} \text{s}^{-1}$)
	Latitude (N)	Longitude (W)				
Chukchi	71° 20'	156° 42'	3–4 April	130 (± 0.07)	2–4	11.5
Beaufort	71° 21'	156° 24'	5–6 April	150 (± 0.09)	2–4	<0.1
ICEX	73° 0.9'	148° 47'	8–10 April	180 (± 0.08)	2–4	–

The data for bottom light intensity were obtained from Dr. R. Gradinger (IMS, UAF)

reference (2π LI-190 quantum sensor) remained at the ice surface, providing a reference for changes caused by cloud cover. Light intensities at the Chukchi and Beaufort sites were 11.5 and $0.01 \mu\text{E m}^{-2} \text{s}^{-1}$, respectively (Table 1). Light intensity was not determined at the ICEX site because the light meter malfunctioned under the severe cold conditions experienced at the time of observation.

In the home laboratory, inorganic nutrient concentrations (nitrate, ammonium, silicate, and phosphate) were measured using an automated nutrient analyzer (ALPKEM RFA model 300) following the methods of Whitledge et al. (1981). The accuracies of the nutrient concentration measurements were $\pm 0.02 \mu\text{M}$ for phosphate and nitrite and $0.1 \mu\text{M}$ for nitrate, ammonium, and silicate. For Chl-*a* concentrations, the filters were extracted in a 3:2 mixture of 90% acetone and DMSO (Webb et al. 1992) in a freezer (-5°C) for 24 h and centrifuged following the procedure of Parsons et al. (1984). Concentrations of Chl-*a* were measured using a Turner Designs model 10-AU fluorometer, which had been calibrated with commercially purified Chl-*a* preparations. After measuring Chl-*a* concentrations, $100 \mu\text{l}$ of 10% HCl solution was added to the extracted solution, and the tube was stored in a test-tube rack for approximately 1990s to allow Chl-*a* to degrade into phaeopigments. A final fluorescence reading was taken after acidification. The methods and calculations for Chl-*a* and phaeopigments were based on Parsons et al. (1984).

A 1-D ocean ecosystem model (Jin et al. 2006) was applied to the three sites to compare the pattern, timing, and magnitude of ice-algal carbon production rates. The model was conducted with the following forcing: (1) calculated shortwave radiation under meteorological conditions (cloud cover, specific humidity, wind, air temperature, and pressure) from 6-hourly readings of the National Center for Environmental Protection (NCEP) reanalysis data (Jin et al. 2006); (2) temporally varying snow and ice thickness time series observed at the Chukchi site. Initial conditions included observed nutrients (NO_3 , NH_4 and Si) in water and ice, and ice algae in February. The light attenuation coefficient for snow was 20 cm^{-1} . The light attenuation coefficients for pure ice (Chukchi site and ICEX sites) were 5 m^{-1} for the top 10 cm of ice and 1 m^{-1} for the ice below 10 cm based on Perovich (1996). The light attenuation coefficients

for sediment-laden ice (Beaufort site) were set as 10.90 m^{-1} for the top 10 cm of ice and 2.18 m^{-1} for the ice below 10 cm. At this premisses, the effects of temperospatial varying light (daily, seasonal changes, and under ice conditions with/without sediments), nutrients, and ice/snow conditions on the development of ice algae were studied. The ice algal biomass was simulated in a nitrogen unit and converted to a carbon and Chl-*a* unit with fixed ratios according to Jin et al. (2006):

$$1 \text{ g cm}^{-2} = 9.4 \text{ mmol N m}^{-2}$$

$$1 \text{ mg Chl-}a \text{ m}^{-3} = 0.46 \text{ mmol N m}^{-3}.$$

Results and discussion

Nutrient concentrations in sea ice and water

In general, concentrations of nitrate (NO_3), phosphate (PO_4), and ammonium (NH_4) were low ($<1.0 \mu\text{M}$), whereas the silicate ($\text{Si}(\text{OH})_4$) concentration was relatively high ($>3 \mu\text{M}$) in the surface water layer above 30 m water depth under the sea ice at the ICEX site (Fig. 2a). In comparison, nutrient concentrations at the Chukchi and Beaufort sites were almost identical to each other. At both sites, the concentrations were ~ 8.5 , 1.5, 0.5, and $20.0 \mu\text{M}$ for nitrate, phosphate, ammonium, and silicate, respectively. Although the concentration of ammonium was lower at the Chukchi and Beaufort sites than at the ICEX site, other inorganic nutrients were much higher at both sites because nutrients can easily be introduced from shore or bottom seepage in coastal areas.

Vertical distributions of inorganic nutrients in the ice cores from the different locations are compared in Fig. 2b. Nitrate, phosphate, and silicate concentrations were low ($<0.8 \mu\text{M}$) within the sea ice at the ICEX site, whereas the ammonium concentration was lowest ($\sim 0.9 \mu\text{M}$) at the bottom of the ice core, and higher concentrations were exhibited in the middle. The average ratios of total dissolved inorganic nitrogen to phosphate from the three sites were 6.0 ± 0.38 in the water and 7.7 ± 2.16 in the bottom 3 cm of the ice, much lower than the ratio found by Redfield et al. (1963). In contrast, the dissolved inorganic nitrogen to silicate ratio was 0.4 ± 0.05 in surface water,

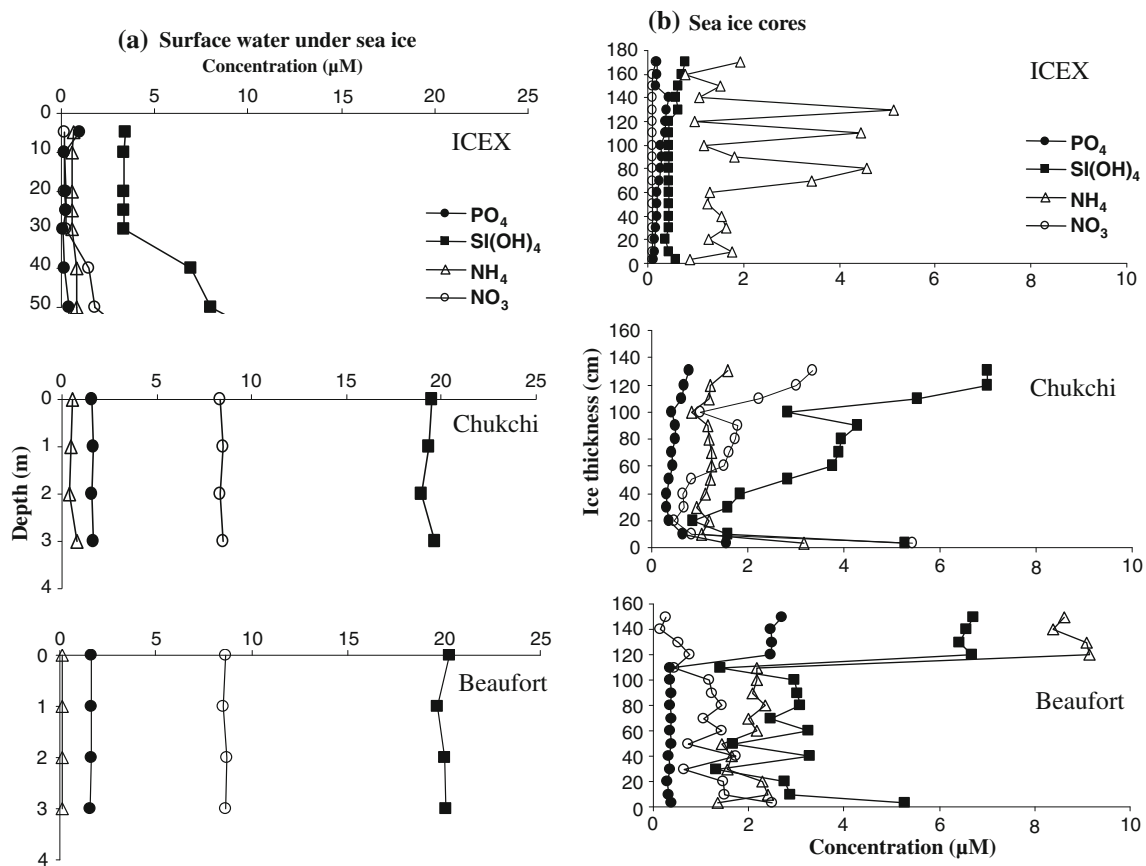


Fig. 2 Inorganic nutrient concentrations in surface waters under sea ice (a) and within sea ice (0 cm is the bottom of the sea ice) (b) at three sites

which was substantially lower than the Redfield ratio of 1.1, but it was 1.4 ± 0.56 for bottom ice, which was somewhat larger than the Redfield ratio. This suggests a potential deficiency in nitrogen relative to phosphate in the upper water layer and the bottom layer of ice in the Barrow and ITEX regions. The concentration of nitrogen was low relative to silicate in the surface water, whereas silicate was low relative to nitrogen in the bottom ice.

The concentrations of nutrients (except ammonium) at the Chukchi and Beaufort sites were relatively higher throughout the sea-ice cores than at the ITEX site (Fig. 2b); this pattern was accentuated in the bottom and top sections of the ice. This indicates that the nutrients in the ice, especially in the bottom section, originated from the underlying seawater (Meguro et al. 1967); thus, higher nutrient concentrations within sea ice correspond to higher concentrations in the underlying seawater at Barrow sites, whereas lower concentrations in sea ice correspond to lower concentrations in the water at the ITEX site. The high concentrations of nutrients in the top layer of the sea ice at Barrow sites could also be a source of nutrients for algae located at the bottom of the ice at a

later time as the top layer of sea ice is desalinated (Meguro et al. 1967).

Chl-*a* concentrations and simulated biomass patterns of ice algae

A relatively low Chl-*a* concentration ($<0.2 \text{ mg m}^{-3}$) for phytoplankton was measured in the water column beneath the sea ice at all sites, whereas Chl-*a* concentrations in the ice cores (Fig. 3) showed considerable variation among sites during a similar period. Approximately 94 and 85% of the ice algae Chl-*a* at the Chukchi and ITEX sites, respectively, was concentrated in the bottom layer of the ice. In contrast, ice-algal Chl-*a* was not concentrated at the ice bottom at the Beaufort site, and the bottom layer accounted for only 20% of the vertical Chl-*a* distribution because the sediments trapped in the sea ice reduced light availability in the bottom layer. Thus, ice algal Chl-*a* at the bottom of the Beaufort ice was not much higher than the Chl-*a* above it. Examination of the distribution of ice-algal Chl-*a* sizes at the three sites (Table 2) showed that the coastal sites (Chukchi and Beaufort) were dominated

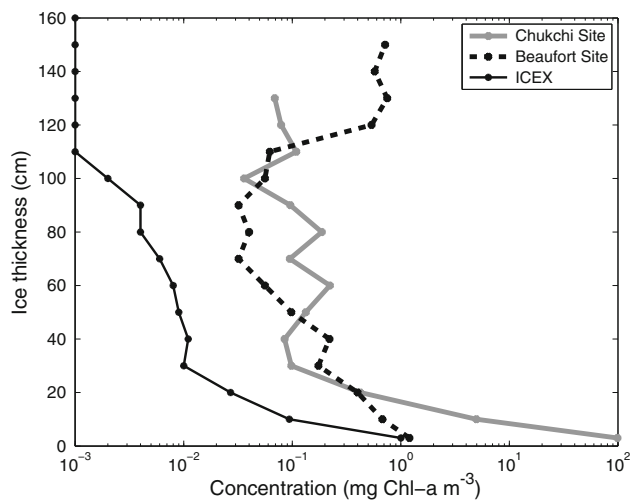


Fig. 3 Chl-*a* distribution patterns within sea ice from three sites (0 cm is the *bottom* of the sea ice)

Table 2 Compositions of size-fractionated chlorophyll-*a* of bottom-ice algae and phytoplankton from different sites in 2003

Site	Ice algae			Phytoplankton		
	A	B	C	A	B	C
Chukchi	75	21	4	55	24	21
Beaufort	71	27	2	27	57	16
ICEX	36	33	31	4	10	86

A: >20 μm , B: 5–20 μm , and C: 0.7–5 μm

Unit: %

(>70%) by large size Chl-*a* (>20 μm), and less than 5% of the total Chl-*a* concentration was small size Chl-*a* (0.7–5 μm), whereas the oceanic ICEX site was evenly occupied by large (>20 μm), medium (5–20 μm), and small size Chl-*a* (0.7–5 μm).

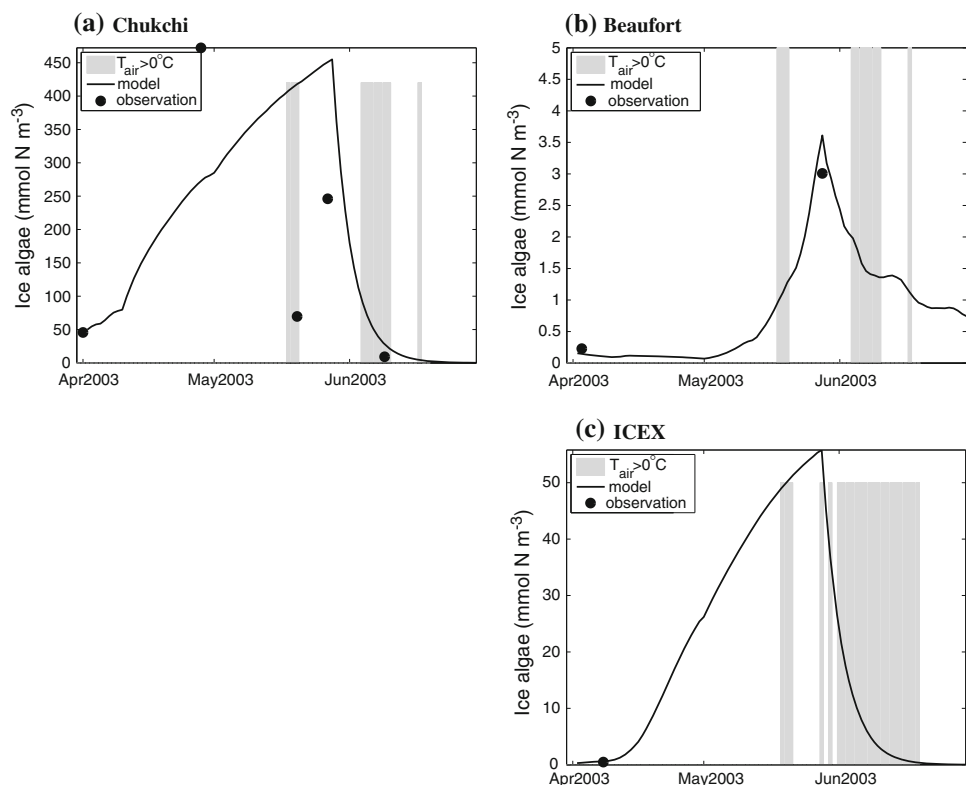
Are the different stages of development observed in bottom-ice algae at the three stations a result of differences in light, nutrients, and ice and snow conditions? To answer this question, a 1-D ocean ecosystem model (Jin et al. 2006) was applied to the algal biomasses at the three sites (Fig. 4). Parameters (temperature, salinity, nutrients, and Chl-*a*) measured at each site in early April 2003 were used as initial conditions to simulate algal growth patterns from early April to June 2003. The model results compensate for the lack of further field observations at the ICEX site after early April 2003 and fill temporal gaps between observations at the other sites. The patterns, magnitude, and duration of ice-algal peaks were quite different among locations (Fig. 4). In particular, the magnitude of the peak at the Beaufort site was only 1%

as large as that of the Chukchi site; because other conditions (water depth, nutrients, and initial Chl-*a*) were similar between those two sites (Lee 2005). This result demonstrates how dramatically sediments in the sea ice can affect ice-algal biomass by regulating light intensity through the sea ice. The model also indicated that the ice-algal peak at the ICEX site started later, and the peak magnitude was approximately 10% of the value reached at the Chukchi site. This later peak development at ICEX was due to the lower light intensity at the ice bottom; the ice cover at the ICEX site was 40% thicker, which would allow approximately 50% less light to reach the bottom ice layer (Andersen 1989). However, the lower magnitude of the ICEX peak (Fig. 4) was mainly due to lower nutrient concentrations. This agrees with the sensitivity analysis performed for the Chukchi site by Jin et al. (2006), which showed that doubling the light intensity shifted peak production to an earlier time but did not increase annual ice-algal production, whereas doubling the initial nutrient concentrations significantly increased peak magnitude.

Summary and conclusions

Since arctic seas exhibit considerable geographic variation in ice-algal productivity depending on environmental conditions, it is important to assess this variability to enhance our understanding of how arctic marine ecosystems may respond to climate change. This study showed that nutrient concentrations in oceanic first-year sea ice differed from those in coastal landfast ice, creating differences in bottom-ice algal biomass in model simulations. The model simulations also showed large effects from sediments trapped within sea ice, which further regulated ice-algal biomass. The size composition of Chl-*a* differed between oceanic and coastal sites, which could lead to different fates for ice algae after they are released from the ice. Larger cells and cell aggregations may sink rapidly and contribute to the benthos, whereas smaller cells may remain suspended in the water column to seed algal blooms or to be eaten by zooplankton, thereby contributing to pelagic systems. However, other factors may also influence sinking velocity, such as silicate frustules or adhering sediments (Tremblay et al. 1989). Therefore, we suggest that additional biophysical observations in various sea-ice habitats in the Arctic Ocean are needed to enhance coupled ice–ocean–ecosystem models for different regions of the Arctic Ocean. Improved understanding of ice-algae production in sea ice, and of the fate of that production, is essential to better understand the impacts of current and projected climate changes on Arctic marine ecosystems.

Fig. 4 Measured values and simulated patterns of ice-algal biomass at three sites in 2003



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