

1 **Wind-driven interannual variability of sea ice algal production**

2 **in ~~over~~ the western Arctic Chukchi Borderland**

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Abstract

Seasonal and interannual variability in ~~the sinking flux of~~ biogenic particles ~~sinking flux~~ was ~~recorded using reported by the~~ multi-year bottom-tethered sediment trap ~~mooring systems~~ ~~measurements~~ in the Northwind Abyssal Plain (Station NAP: 75°N, 162°W, 1975-m water depth) of the western Arctic Chukchi Borderland. ~~Whereas the~~ Trapped particle flux ~~at a~~ ~~median depth of 184 m~~ had an obvious peak ~~and with the~~ dominance of sea ice-related diatom ~~assemblages~~ in August 2011. The observed particle flux was considerably suppressed throughout ~~the summer~~ ~~season in~~ 2012. In the present study, ~~the~~ response of ice algal production and biomass to wind-driven changes in ~~the physical environments~~ was addressed using a pan-Arctic sea ice-ocean modeling approach. A ~~S~~ sea ice ecosystem with ice algae was newly incorporated into the lower-trophic marine ecosystem model, which was previously coupled with a high-resolution (i.e., ~~5-km~~ horizontal grid size ~~of 5 km~~) ~~sea ice~~-ocean general circulation model. Seasonal ~~model~~ experiments covering two-year-long mooring periods indicated that primary productivity of ice algae around the Chukchi Borderland depended on basin-scale wind patterns ~~via through~~ various processes. Easterly winds ~~s~~ in the southern part of ~~a~~ distinct Beaufort High supplied ~~high abundance of~~ nutrient-rich water for euphotic zones of the NAP region via both surface Ekman transport of Chukchi shelf water and vertical turbulent mixing with underlying nutricline water ~~as~~ in 2011. In contrast, northwesterly winds ~~s~~ flowing in the northern part of ~~an~~ extended Siberian High transported oligotrophic water within the Beaufort Gyre circulation toward the NAP region ~~as~~ in 2012. The modeled ice algal biomass during ~~the summer~~ ~~season certainly~~ reflected the differences in nutrient distribution. The ~~modeled~~ sinking flux of ~~P~~ particulate ~~O~~ organic ~~N~~ nitrogen (PON) was comparable with the time series obtained from ~~the~~ sediment trap data in summer 2011. ~~In contrast~~ ~~On the other hand~~,

lateral advection of ~~shelf-origin~~ ice algal patches es of shelf origin during a great cyclone event
~~may might~~ have caused a modeled PON flux bias ~~on the PON flux~~ in 2012. Extending the ~~The~~
~~extension of~~ year-long measurements is expected to help illustrate the ~~illustration of~~ more
general features ~~on the of~~ ice-related biological processes in the Arctic Ocean ~~Arctic marine~~
~~biological pump~~.

Keywords: Arctic Ocean, Northwind Abyssal Plain, ice algae model, primary production, wind pattern

1. Introduction

The ~~R~~response of biogeochemical cycles to the decline in Arctic sea ice ~~decline~~ has become an important topic for a variety of communities. ~~The~~ ~~i~~Improved light conditions during ~~in~~ summer ~~have has~~ enhanced phytoplankton photosynthesis activity ~~of phytoplankton~~ in the Eurasian pelagic area of the Arctic Ocean (Wassmann, 2011). A widespread massive deposition of ice algal biomass was detected on the deep seafloor of the eastern Arctic basin (Boetius et al., 2013). On the other hand, the under-ice export of particulate organic carbon (POC) was limited by insufficient nutrient supply in the stratified central Arctic (Lalande et al., 2014). In the Beaufort Gyre region of the western Arctic, ~~the~~ freshwater accumulation suppressed ~~the~~ primary production ~~of phytoplankton~~ during the 2000s (McLaughlin et al., 2010; Nishino et al., 2011). It is ~~still~~ necessary to ~~further~~ fill in the observational ~~many~~ gaps to understand ~~the~~ spatial and temporal variability ~~of in the~~ biological processes of in the Arctic Ocean.

Sediment trap measurements are ~~is a~~ useful ~~tool~~ to capture year-long ~~signals of~~ biological activity signals. The locations of bottom-tethered traps have has been ~~however~~ confined to the north of the Laptev Sea (Fahl and Nöthig, 2007), Mackenzie shelf (Forest et al., 2007), and the deep Canada Basin (Honjo et al., 2010; Hwang et al., 2015). In our field campaign, ~~the~~ year-round bottom-tethered moorings, including with sediment trap instruments, have been deployed in the Northwind Abyssal Plain (NAP) of the Chukchi Borderland since October 2010 (Fig. 1). ~~At Station NAP (75°N, 162°W, 1,975 m water depth), e~~ Early-winter maxima of sinking particle flux with fresh organic material have been ~~were~~ captured every year annually at Station NAP (75°N, 162°W, 1,975 m water depth) (Watanabe et al., 2014; Onodera et al., 2015). The substantial quantities amount of lithogenic minerals in the trapped ~~partiele~~ particles suggest ~~reminded of~~ shelf-origin water transport toward the NAP region. Seasonal experiments using an

eddy-resolving (5 km grid size) pan-Arctic sea ice-ocean model indicated the effective role of Beaufort shelf-break eddies in the transport of ~~the~~ Chukchi shelf water with high biological productivity and in the consequent early-winter peaks of sinking biogenic flux at Station NAP (Watanabe et al., 2014). It should be noted that biological ~~production activity could~~ continued ~~inside these eddies moving in -during eddy migration inside~~ the southern Canada Basin.

Another finding obtained at Station NAP was remarkable interannual variability in ~~the summertime-summer~~ particle flux (Onodera et al., 2015; Ikenoue et al. 2015; Matsuno et al., 2015). ~~The~~ Trapped particle flux ~~peaked sharply had its sharp peak~~ in August 2011 ~~but and~~ was ~~considerably~~ suppressed ~~considerably during in~~ summer 2012. The diatom assemblage compositions suggest that year-to-year changes in the distribution of shelf-origin water and relatively oligotrophic water originating from the interior of the Canada Basin controls the particle flux around the Chukchi Borderland (Onodera et al., 2015). ~~The relative abundance of diatom valves suggested the dominance of oligotrophic water originating from the central Canada Basin in 2012.~~ This situation was supported by ocean current fields simulated ~~demonstrated~~ in a medium-resolution (25 km grid size) framework ~~by of~~ the pan-Arctic physical oceanographic model (Onodera et al., 2015). However, ~~the~~ reliable *in-situ* ~~data of~~ biological productivity and water mass transport data above the shallow trap depth (approximately 180–260 m) could not be available at Station NAP during the mooring periods (October 2010–September 2012). In particular, chlorophyll, nutrient concentration, and ocean velocity data from winter to early summer were insufficient. Further detailed investigation of the on more detailed background mechanisms associated with ~~for~~ summertime biogenic flux would be is highly valuable and possible using a coupled physical and marine ecosystem model. Whereas the main ~~major~~ content of observed diatom valves was the sea ice-related species (e.g.,

Fossula arctica (Onodera et al., 2015), sea ice ecosystem was not included in our previous model experiment (Watanabe et al., 2014). The lack of ice algae was a plausible factor for the summer~~time~~ delay of the simulated biogenic flux peak behind the trap data. These issues raised our motivation to incorporate ice-related biogeochemical processes in the model.

Ice algae models have a ~~There was~~ long history of ~~ice algae model~~ development. ~~A~~ Pioneering work was conducted on ~~for~~ the Antarctic fast ice ecosystem (Arrigo et al., 1993). For ~~In~~ the Arctic Ocean, one-dimensional ice algae models were ~~was~~ applied to landfast ice in ~~the~~ Resolute Passage of the Canadian Archipelago (Lavoie et al., 2005; Pogson et al., 2011) and offshore Barrow (Jin et al., 2006). ~~In the recent years, the~~ The modeled target region has been extended in recent years to include the entire whole Arctic Ocean (Dupont, 2012) and global domain (Deal et al., 2011; Jin et al., 2012). The analysis period covered from seasonal transition (Lavoie, 2005; Deal et al., 2011) to decadal variability (Jin et al., 2012; Dupont, 2012) and future projections (Lavoie et al., 2010). Most models assumed ~~d~~ that ice algal activity occurs ~~s~~ red primarily in the skeletal layer of the sea ice bottom (i.e., ice-water interface), where the layer thickness is ~~was~~ fixed at ~~to~~ 2 cm (Lavoie et al., 2005), 3 cm (Jin et al., 2012), and 5 cm (Dupont, 2012). The ice algal biomass sometimes reaches values ~~reached~~ three orders of magnitude larger at the ice-water interface than that in the upper part of the sea ice column (e.g., Jin et al., 2006; Dupont, 2012. Ocean surface water ~~Seawater in the ocean surface column~~ is a major nutrient supplier for ice algae in the skeletal layer. ~~The~~ Tidal mixing controls nutrient exchange rates s at the ice-water interface in the narrow shallow straits of the Canadian Archipelago (Lavoie et al., 2005). In a general viewpoint, More generally, it is reasonable that ~~the~~ nutrient flux is calculated as a function of the sea ice freezing/melting rate (Arrigo et al., 1993; Jin et al., 2006; Deal et al., 2014. However, On the other hand, in Dupont (2012) did not calculate, the

113 nutrient import due to sea ice freezing, ~~was neglected~~ following an observational view, where
114 nutrients trapped inside the sea ice column have minor contributions to ~~was not of great~~
115 ~~importance for an~~ ice algal bloom (Cota et al., 1991; Cota and Smith, 1991). ~~As The~~ grazing
116 pressure on ice algae ~~is was~~ considered ~~to be~~ weak in the sea ice column, ~~M~~most previous
117 models ~~hence~~ excluded zooplankton biology in the skeletal layer (Jin et al., 2006; Dupont,
118 2012) or prescribed a small grazing rate ~~to of~~ potential grazers (e.g., amphipods) (Lavoie, 2005).
119 The habitat of ice algae in the skeletal layer disappears gradually ~~Ice algae lose their habitat~~ due
120 to melting sea ice ~~melting~~. The assemblages released from the sea ice bottom partially act as
121 phytoplankton and become a food source for pelagic grazers ~~is converted to detritus and~~
122 ~~partially seed pelagic and benthic species~~ in the water column (Michel et al., 1993, 1996). Thus,
123 ~~the~~ complex ice algal processes ~~of ice algae~~ have been proposed and numerically formulated in
124 various ways ~~manners~~.

125 In the present study, ~~we addressed~~ seasonal and interannual variability of ice algal
126 production and biomass ~~in over~~ the Chukchi Borderland were addressed using a pan-Arctic sea
127 ice-ocean modeling approach (Fig. 1). We focused particularly on the relationships between ice-
128 related biogeochemical processes and wind-driven dynamics, such as shelf-basin exchanges,
129 local upwelling/downwelling, and vertical turbulent mixing. ~~In this effort, t~~To represent the
130 summer~~time~~ biogenic particle flux captured by sediment trap measurements, the simple sea ice
131 ecosystem was newly incorporated into a lower-trophic marine ecosystem model. Our model
132 coupled with a sophisticated high-resolution physical component is a powerful tool for the
133 above-mentioned subjects because of following issues. The Chukchi Borderland is composed of
134 complex topography such as long ridges, deep-sea plateaus, and steep shelf breaks. The sinking
135 biogenic flux available for comparison was obtained from the single-point mooring

136 measurements in this area. The source regions of surface water are distributed over the Chukchi
137 Sea, the East Siberian Sea, and the Canada Basin. The water mass transports are closely related
138 to shelf-basin boundary currents and baroclinic eddies. These complex topography and
139 mesoscale hydrographic features have been unresolved by previous basin-scale ice algae
140 models, which horizontal resolution was much coarser than the typical internal Rossby radius of
141 deformation in the polar region. The linkages between wind patterns, light and nutrient
142 preconditioning of ice algal bloom, and particle sinking are also unique viewpoints in the
143 present work. Modeling Configurations ~~of modeling~~ and sediment trap analyses are is
144 described in Section 2. Seasonal transitions of the modeled ice-ocean field, particularly those
145 ~~especially~~ around the NAP region, are traced in Section 3. Relationships between ~~of~~ the
146 interannual variability in biogeochemical properties and ~~with~~ wind patterns are examined in
147 Section 4. Uncertainties of the modeled processes are discussed in Section 5, based on
148 sensitivity experiments. The obtained findings ~~obtained in the present work~~ are summarized in
149 Section 65.

2. Model configuration and experimental design

2.1 Physical oceanographic model

The physical part of the coupled sea ice-ocean model ~~used in the present work~~ is the “Center for Climate System Research Ocean Component Model (COCO)” version 4.9 (Hasumi, 2006). The sea ice component includes a multi-thickness-category configuration based on that of Bitz et al. (2001) with a one-layer thermodynamic formulation (Bitz and Lipscomb, 1999), the linear-remapping method for category transfer (Lipscomb, 2001), and the elastic-viscous-plastic rheology (Hunke and Dukowicz, 1997). In addition to the open water category, the lower limit of sea ice thickness in each category is set to ~~be~~ 10, 30, 60, 100, 250, and 500 cm, respectively (i.e., 7 categories). The ocean component is a free-surface general circulation model formulated using ~~with~~ the advection scheme of Leonard et al. (1994) and the turbulence closure mixed-layer scheme of Noh and Kim (1999).

2.2 Marine ecosystem model

The COCO model was coupled with a lower-trophic marine ecosystem model, “North Pacific Ecosystem Model for Understanding Regional Oceanography (NEMURO)”. The detailed configuration of the original NEMURO model, which represented pelagic plankton species (i.e., diatom, flagellate, and copepod), was described in Kishi et al. (2007). ~~In the present work, t~~To address seasonality and interannual variability in ~~of~~ ice algal production and biomass, a sea ice ecosystem was ~~additionally~~ incorporated in the present work (Fig. 2 and Table 1). In the developed model (called ~~as~~ “Arctic NEMURO”, hereafter), the habitat of ice algae is confined to the 2-cm skeletal layer ~~with its thickness of 2 cm~~. The biogeochemical variables in the sea ice component comprise ice algae (IA), ice-related ~~fauna zooplankton (IFZI: neglected in the present experiment)~~, nitrate (NO₃), ammonium (NH₄), silicate (SIL), dissolved

organic nitrogen (DON), particulate organic nitrogen (PON), and opal (OPL). Each model grid has a single value per variable independent of the ice thickness category. ~~As the~~ ~~Since~~ sea ice bottom temperature is always kept at the freezing point of underlying ~~sea water~~ seawater, a relationship of $Q_{10} = 2$ adopted in the present model did not have substantial impacts on biogeochemical cycles in the sea ice column. ~~¶~~The growth rate of ice algae (GR) is calculated depending on light condition (L) and nutrient uptake (N_{up}) terms:

$$GR = GR_{max} \times L \times N_{up},$$

where the maximum growth rate GR_{max} is fixed ~~at~~ ~~to~~ a constant value of 0.8 d^{-1} .

The light condition term followed the original NEMURO formulation:

$$L = I / I_{opti} \times \exp(1 - I / I_{opti}),$$

$$I = PAR_{frac} \times SW^{\downarrow} \times (1 - \alpha_{sfc}) \times \exp(-k_{snow} H_{snow} - k_{ice} H_{ice}),$$

where I is photosynthetically active radiation (PAR) in the skeletal layer. The conversion coefficient from shortwave radiation to PAR (PAR_{frac}) is 0.43 following the previous models (Zhang et al., 2010; Dupont, 2012) so that 43% of shortwave flux is available for photosynthesis activity. Light transmission through the snow and sea ice columns is given by downward shortwave radiation from atmosphere (SW^{\downarrow}), snow/ice surface albedo (α_{sfc}), column thickness (H_{snow} , H_{ice}), and empirical extinction rates (k_{snow} , k_{ice}). The surface albedo (α_{sfc}) changes from 0.8 to 0.6 depending on snow/ice type and surface temperature during ~~the~~ summer ~~season~~. The light extinction rate (k_{snow} , k_{ice}) is set to 0.12 cm^{-1} for snow and 0.045 cm^{-1} for sea ice based on Aota and Ishikawa (1982). According to this constant rate, for example, ~~¶~~the light intensity in the skeletal layer corresponds to ~~is~~ approximately 10% (1%) of that absorbed into the surface of sea ice with its thickness of 50 cm (100 cm) (Fig. 3a). The light transmission is calculated in each thickness category (see the category arrangement in Section

2.1), and the under-ice average intensity is then obtained in each model grid. ~~A~~ ~~S~~ self-shading effect of ice algae is neglected. For weak-light adaptation of ice algae, the optimal light intensity (I_{opti}) is set to 10 W m^{-2} (cf., 104 W m^{-2} for pelagic phytoplankton (Kishi et al., 2007)). ~~The~~ ~~A~~ PAR of 5 and 20 W m^{-2} results in ~~a~~ ~~the~~ light condition term of 0.82 and 0.73, respectively (Fig. 3b).

The vertical exchange of biogeochemical variables between the skeletal layer and the ocean surface layer (suffixed as SKL and OCN, respectively, hereafter) is formulated in ~~a~~ ~~the~~ different manner for sea ice freezing and melting periods. During the freezing period, ocean-to-ice fluxes F_{OI} are proportional to sea ice freezing rate IFR:

$$F_{\text{OI}} = CF_{\text{OI}} \times (\text{NO}_3, \text{NH}_4, \text{SIL}, \text{DON})_{\text{OCN}} \times \text{IFR}.$$

The proportional coefficient CF_{OI} is set to 0.3, since first-year ice salinity is able to reach approximately 30-% of ocean salinity. In addition, all of the imported nutrients are accumulated concentrated-only in the skeletal layer ~~under an idealized assumption~~. The actual ice algae respond to nutrients concentrated in brine pockets and channels. However, the incorporation of such detailed structures in sea ice interiors is generally difficult for three-dimensional climate models. Here, we regard the skeletal layer as the reservoir of total imported nutrients under an idealized assumption. There is no import of particles such as pelagic planktons, PON, and OPL. During the melting period, ice-to-ocean fluxes F_{IO} are proportional to the sea ice melting rate IMR:

$$F_{\text{IO}} = (\text{IA}, \text{IF}, \text{NO}_3, \text{NH}_4, \text{SIL}, \text{DON}, \text{PON}, \text{OPL})_{\text{SKL}} \times \text{IMR}.$$

According to this formulation, the concentration of all biogeochemical variables in the sea ice component ~~decreases is reduced~~ to zero when sea ice entirely disappears due to the melting process in each model grid. ~~Although Whereas~~ sea ice melts from its surface, bottom, and flank,

respectively, it is difficult to separate these melting processes in terms of particle export. In general, ice surface meltwater sinks through internal brine channels and flushes out a part of materials in the skeletal layer ([Vancoppenolle et al., 2010](#)~~Pogson et al., 2011~~). Besides, ice algae have an ability to maintain their position under a slow melting rate, and the habitat is not immediately lost even after ice bottom melting. The methods adopted in the present work idealize ice-ocean exchange of biogeochemical variables within reasonable scopes.

~~There is uncertainty whether direct~~ The nutrient source of ice algal growth can be divided to is positioned in the sea ice column and or underlying ~~sea-water~~seawater. The present study assumes that ice algae utilize both ice/ocean nutrients depending on their biomass:

$$N_{up} = RN_{upSKL} \times N_{upSKL} + (1 - RN_{upSKL}) \times N_{upOCN},$$

$$RN_{upSKL} = 0.5 \times \{ \cos(\pi \times IA / KN_{upSKL}) + 1 \}, \text{ for } IA \leq KN_{upSKL},$$

where RN_{upSKL} is ~~the an~~ ice algal uptake ratio of nutrient in the skeletal layer, and KN_{upSKL} is a threshold value (Fig. 3c). When ice algal biomass IA exceeds KN_{upSKL} , only ~~sea-water~~seawater nutrients are is-utilized for their growth. The value of KN_{upSKL} is set to 1 mmol-N m^{-2} in the present experiments. As reported in Section 3.2, ~~sea the~~ ice nutrients are is preferentially consumed preferentially for the initial bloom of small-sized ice algae in early summer. According to the growth of ice algae, their nutrient source shifts to ~~sea-water~~seawater for the mature period. The “hybrid-type” formulation of nutrient uptake represents more realistic ice algal biology, where ice algae anchoring under ice floes gradually raise meter-long filaments in the water column (Boetius et al., 2013). In each model time step, the Michaelis-Menten relationship is applied to nutrient concentration in the skeletal layer and in the ocean surface layer (i.e., the uppermost ocean grid), respectively (Fig. 3d):

$$N_{upSKL} = \min\{ NO3_{SKL} / (NO3_{SKL} + K_{NO3}) \times \exp(-\Psi_{NH4} \times NH4_{SKL})$$

$$+ \text{NH4}_{\text{SKL}} / (\text{NH4}_{\text{SKL}} + \text{K}_{\text{NH4}}), \text{SIL}_{\text{SKL}} / (\text{SIL}_{\text{SKL}} + \text{K}_{\text{SIL}}) \},$$

$$N_{\text{upOCN}} = \min\{ \text{NO3}_{\text{OCN}} / (\text{NO3}_{\text{OCN}} + \text{K}_{\text{NO3}}) \times \exp(-\Psi_{\text{NH4}} \times \text{NH4}_{\text{OCN}})$$

$$+ \text{NH4}_{\text{OCN}} / (\text{NH4}_{\text{OCN}} + \text{K}_{\text{NH4}}), \text{SIL}_{\text{OCN}} / (\text{SIL}_{\text{OCN}} + \text{K}_{\text{SIL}}) \},$$

where the constant coefficients of half saturation for nitrate (K_{NO3}), ammonium (K_{NH4}), and silicate (K_{SIL}) and of ammonium inhibition (Ψ_{NH4}) have the same values (Table 1) as those of pelagic diatoms (i.e., large phytoplankton PL in the NEMURO model) (Kishi et al., 2007).

The ice algal biomass decreases due to ~~of ice algae is reduced by respiration,~~ mortality, ~~zooplankton~~ grazing, and sea ice melting. The respiration and mortality terms are ~~the~~ functions of ~~the only~~ ice algal biomass itself (under the freezing temperature assumption). In the present experiments, ~~there is no zooplankton~~ biomass of ~~ice-related fauna, sea ice component (ZI) is kept at zero,~~ and ~~zooplankton~~ the grazing pressure on ice algae is neglected ~~except for a sensitivity experiment in Section 5.4.~~ All ~~of~~ ice algae are ~~included in converted to ice-derived~~ PON ~~without any biological activities~~ after their export ~~into the~~ to water column by ~~melting~~ sea ice ~~melting. In this connection,~~ sSea ice assemblages sinks faster than other particles derived from pelagic plankton because ~~the aggregation of~~ ice algae ~~aggregate proceeds~~ before ~~the release from the sea ice bottom~~ the export to water column. ~~The German field campaign detected a~~ Boetius et al. (2013) indicated rapid sinking of ice-related species ~~(Boetius et al., 2013).~~ Hence, ~~the~~ The modeled PON is ~~hence~~ divided into two components with different sinking speeds. The sinking speeds of PON derived from ice algae ~~and from (pelagic plankton)~~ are ~~ranges~~ from ~~50 m d⁻¹ to 200 m d⁻¹~~ and from ~~(2 m d⁻¹ to 200 m d⁻¹)~~, respectively, following a cosine curve (Fig. 3e). ~~Below 1,000 m depth,~~ tThe sinking speed is maintained at 200 m d⁻¹ ~~below a depth of 1,000 m.~~ These profiles are reasonable, because ~~the~~ sinking of particulate organic materials generally accelerates with depths due to particle densification processes (e.g.,

aggregation in shallow depths and elimination of light/fragile organic materials ~~at in~~ middle depths) (Honda et al., 2013). The modeled OPL is treated in the same manner. We refer to the fast- and slow-sinking PON/OPL as fPON/fOPL and sPON/sOPL, respectively.

~~Since the Arctic NEMURO is implemented in three-dimensional frameworks,~~ The horizontal advection of biogeochemical variables in the sea ice component is also calculated, as the Arctic NEMURO is implemented in a three-dimensional framework. The divergence (convergence) of sea ice velocity causes loss (accumulation) of each material as well as snow and ice volumes. ~~Whereas The~~ actual ridging process is accompanied by complex deformation, whereas the modeled sea ice ecosystem is ~~consistently~~ kept consistently in the skeletal layer with ~~a its~~ constant 2-cm thickness ~~of 2-cm~~ for simplicity.

2.3 Experimental design

The model domain contains the entire Arctic Ocean, the Greenland-Iceland-Norwegian (~~GIN~~) sSeas, and the northern part of the North Atlantic (Fig. 1). The horizontal resolution is 5 km, and there are $1,400 \times 1,000$ grids. There are 42 hybrid σ -z vertical levels. ~~The v~~ Vertical resolution grid width varies from 2 m at the top ~~level~~ to 500 m at the bottom ~~level~~. The σ -coordinate composed of three levels is applied ~~to in~~ the uppermost 10 m. We performed two one-year experiments (called the 2011 and 2012 cases), in which, ~~where~~ the 5-km grid model was integrated from October 2010 (2011) to September 2011 (2012) ~~in the 2011 (2012) case~~ to examine ~~the~~ seasonal and interannual variability in ~~of~~ ice algae. The initial sea ice and ocean physical fields for these experiments were obtained from ~~the a~~ 1979–2011 decadal experiment ~~from 1979 to 2011~~ using the 25-km grid version (Onodera et al., 2015). The atmospheric forcing components were constructed from the National Centers for Environmental

Prediction/Climate Forecast System Reanalysis (NCEP/CFSR) 6-hourly dataset (Saha et al., 2010). ~~At the Bering Strait, Pacific water inflow with a seasonal cycle was prescribed is provided at the Bering Strait, based on Woodgate et al. (2005). Following our previous modeling study (e.g., Watanabe, 2011), the idealized seasonal cycles of northward velocity, temperature, and salinity are prescribed such that the annual mean inflow is 0.8 Sv ($1 \text{ Sv} \equiv 10^6 \text{ m}^3 \text{ s}^{-1}$) and temperature (salinity) reaches a maximum in September (March). Monthly climatological data of~~ nitrate and silicate concentrations derived from the World Ocean Atlas 2013 ~~(WOA13)~~ (Garcia et al., 2013) ~~are were~~ used for ~~a~~ restoring along the lateral boundary region of the model domain, and ~~the summer time~~ climatology ~~is were~~ assigned to the initial fields of ocean nutrients. ~~As PON and opal Since geochemical dissolution from in~~ sea bottom sediments ~~are is a~~ crucial nutrient sources ~~for over~~ the Arctic shelves ~~via decomposition and remineralization processes~~, the fluxes ~~in of~~ ammonium, DON, and silicate ~~are were~~ added to the deepest layers just above the shelf bottom as in Watanabe et al. (2014). ~~Sea ice nutrients are initially non-existent in In~~ the skeletal layer, ~~sea ice nutrient is initially zero~~, and ~~the lowest the lower limit of~~ ice algal concentration ~~of ($0.02 \text{ mmol-N m}^{-3}$)~~ is ~~given for initial growth (i.e., seeding). given for seeding.~~ The relationship of $1 \text{ mmol-N} = 80 \text{ mgC} = 1.6 \text{ mgChl}$ is assumed using a C/Chl mass ratio of 50 and a C/N Redfield ratio of 6.625 to compare the model outputs with observational estimates, as in Watanabe et al. (2012).

2.4 Sediment trap analysis

The bottom-tethered sediment traps (SMD26S-6000, NiGK Cooperation) have been moored at Station NAP (75°N , 162°W , 1,975-m water depth) since October 2010. ~~The~~ Deployment and turnaround were conducted by the Japanese R/V Mirai and the Canadian Coast Guard Ship Sir Wilfrid Laurier. ~~In the first year from October 4, 2010 to September 27,~~

314 ~~2011, s~~Sinking particles ~~were sampled~~ ~~sampling was conducted~~ at the depths of 181–218 m
315 (median, ÷ 184 m) ~~during the first year from October 4, 2010 to September 27, 2011. In the~~
316 ~~second year from October 4, 2011 to September 17, 2012, t~~The trap depth was 247–319 m
317 (median, ÷ 256 m) ~~during the second year from October 4, 2011 to September 17, 2012.~~ These
318 sediment traps collected 26 samples approximately every two weeks during their one-year
319 deployment. ~~The recovered trap samples were sieved through 1-mm mesh to remove swimmers,~~
320 ~~and The trapped~~ particles < 1 mm were ~~evenly~~ divided evenly into ~~to~~ 10 sub-samples. ~~The~~
321 ~~One of 10 aliquot samples was filtered, and was desalted using Milli-W water. and t~~The dried
322 ~~sample was weighed, and it one~~ was then ground ~~well-grinded~~ and mixed using an ~~by~~ agate mill.
323 PON and POC contents were analyzed in one sequence. ~~Before the PON analysis, t~~The
324 powdered samples were decalcified in ~~vapour of~~ hydrochloric acid vapor in a desiccator for
325 eight hours to remove particulate inorganic carbon. Sodium hydroxide pellets were placed then
326 ~~put in the~~ desiccator to neutralize the samples. ~~The~~ PON content in the treated samples was
327 sequentially analyzed by a the CHN analyzer (NCS2500, Thermo Quest). ~~The s~~Sinking PON
328 flux was calculated based on PON content, sampling period, ~~opening~~ area of the sediment trap
329 (0.5 m^2), and aliquot size of the treated sample (1/10). The detailed analysis method and diatom
330 valve fluxes were described in Onodera et al. (2015). The structures of radiolarians and
331 copepods captured in by the same traps were reported in Ikenoue et al. (2015) and Matsuno et al.
332 (2015), respectively.

3. Seasonal transition ~~in over~~ the Chukchi Borderland

3.1 Physical environments

We defined the NAP region ~~as that~~ enclosed by 74°–76°N and 159°–165°W for ~~the~~ following analyses (Fig. 1). Monthly mean values of the NCEP/CFSR cloud fraction, downward shortwave radiation, wind speed at ~~a the~~ height of 10 m, snow depth, sea ice thickness, and sea ice concentration averaged in the NAP region ~~are were~~ summarized in Table ~~24~~. The modeled physical variables ~~were was then~~ checked (Fig. 4). ~~In both the 2011 and 2012 cases, t~~The NAP region was entirely covered by sea ice during the winter and spring seasons from December to April, and sea ice concentration ~~gradually~~ decreased gradually from May to September in both the 2011 and 2012 cases (Fig. 4a). The area-mean sea ice thickness reached approximately 200 cm in April (Fig. 4b), which was a typical value north of the Chukchi Sea (Haas et al., 2010). The declines ~~in of~~ sea ice concentration and thickness ~~were was~~ consistent with the sea ice melting period from May to September (Fig. 4c). The mechanical divergence of sea ice flow fluctuated within the range of $\pm 0.2 \text{ d}^{-1}$ in early winter and late summer (Fig. ~~42~~d).

Compared with ~~the~~ sea ice conditions simulated in the 2011 case, the early-winter covering of sea ice was somewhat delayed in the 2012 case. Although sea ice ~~melting~~ continued to melt until mid-November, ~~the~~ winter sea ice thickness was greater ~~became larger~~ in the 2012 case. The anomalous wind pattern could account for thicker ice transport toward the NAP region, as suggested in Section 4.1. The negative anomaly of sea ice thickness in the 2011 case was additionally caused by ~~attributed to~~ two melting events in November and December (Fig. 4c) and ~~the~~ blanket effect of more snow accumulation on ~~the~~ top of ~~the~~ sea ice (not shown). The faster rate of sea ice decline caused earlier sea ice opening in the 2012 case (Figs. 4a-b), partly ~~due owing~~ to lower surface albedo from ~~with~~ less snow cover. These snow and sea ice

differences were compatible with the NCEP/CFSR data (Table 24). In addition, the enhanced mechanical divergence of sea ice flow from mid-July to August ~~has~~ accelerated the sea ice reduction in 2012 (Fig. 4d). ~~The ice~~ algal biomass in ~~a the~~ specific region can change based on ~~could be changed by~~ sea ice divergence events. The detailed processes associated with cyclone activities are ~~will be~~ discussed in Section 4.43.

As ice algal ~~Since the~~ primary production ~~of ice algae highly~~ depends highly on nutrient conditions in the underlying ocean surface layer, ~~the~~ replenishment of nitrate and silicate from ~~nutricline~~ depths in the nutricline water column is substantially important. ~~For the analysis,~~ ~~The~~ Ekman upwelling and downwelling velocities were ~~velocity was~~ calculated from the modeled ocean surface stress fields (i.e., the combination of wind stress in open water area and ice-ocean stress under sea ice ~~cover~~). ~~During the winter period,~~ ~~The~~ week-long Ekman downwelling occurred in both ~~the~~ cases during the winter, as usually seen inside the Beaufort Sea (Yang, 2009), and ~~a the~~ strong upwelling event appeared in the 2011 case (Fig. 4e). In July–August, the ~~sign of~~ Ekman velocity sign was opposite between the two cases. ~~It would be considered that~~ ~~The~~ mid-summer Ekman downwelling (upwelling) played a role in the nutricline deepening (shoaling) in the 2011 (2012) case. The vertical turbulent mixing was characterized by vertical diffusivity diagnosed using the closure scheme of Noh and Kim (1999) in the present model. ~~It was shown that the~~ ~~T~~urbulent mixing was activated during ~~the~~ winter ~~season~~ in the 2011 case (Fig. 4f). During ~~In~~ the other periods, the smaller values of modeled vertical diffusivity by one or two orders indicated that the mixing process had a relatively minor impact on nutrient entrainment in the NAP region. ~~The summertime stratification with sea ice meltwater has been suggested to delay ice algal growth (Michel et al., 1996; Pogson et al., 2011).~~

3.2 Ice algal production

The modeled ~~ice algal primary~~ production of ~~ice algae~~ demonstrated remarkable spatial and interannual variability in the western Arctic Ocean (Fig. 5). ~~Whereas the a~~Annual production exceeded $0.6 \text{ mmol-N m}^{-2}$ over ~~the most area of~~ the Chukchi Sea shelf, ~~whereas the~~ low productivity ~~\leq below~~ $0.1 \text{ mmol-N m}^{-2}$ was located in the central Canada Basin. The shelf-basin contrast ~~in of~~ ice algal production was previously detected by the trans-Arctic Ocean expedition ~~operated~~ in the 1990s (Gosselin et al., 1997) and represented by decadal model simulations (Jin et al., 2012; Dupont, 2012). In the 2011 case, the local maximum appeared north of the Chukchi and Beaufort shelf breaks (Fig. 5a). ~~On the other hand, the~~ ~~whereas~~ ice algal productivity was ~~considerably~~ suppressed considerably around the Beaufort Gyre region in the 2012 case (Fig. 5b). The negative anomaly widely covered the western Arctic except the coastal shelves and the northern part of Chukchi Borderland (Fig. 5c). Station NAP was located near the shelf-basin boundary and also showed the negative anomaly.

In the NAP region, the modeled ice algal bloom started in June and produced ~~a the~~ peak biomass of $0.7 \text{ mmol-N m}^{-2}$ at the beginning of August in the 2011 case (Fig. 6a). The peak timing was a few months later than the pan-Arctic averages simulated in previous models (Jin et al., 2012; Deal et al., 2011), partly because the NAP region is located north of highly productive shelves. An additional reason for the lagged peak phase may be attributed to a lower photosynthetic response to incoming solar irradiance in the present model setting. Sensitivity to optimum light intensity is shown in Section 5.1. The Hovmöller diagram visualized the vivid shelf-basin contrast along the 75°N line (Fig. 6b). The bloom signal was quite weak inside the Canada Basin. ~~A The~~ massive ice algal bloom up to 10 mmol-N m^{-2} ~~was simulated occurred~~ in July over the Chukchi northern shelf to the west of the NAP region. ~~When the relationship of 1~~

mmol N = 1.6 mg Chl was applied as in Watanabe et al. (2012). The modeled ice algal shelf biomass north of the Chukchi Sea was consistent with the lower range of 1–340 mgChl m⁻² in the Arctic sea ice (Arrigo et al., 2010) coastal waters estimated in Cota et al. (1991) (10–300 mg Chl m⁻²) and an order of magnitude smaller than that measured in Resolute Passage (160 mgChl m⁻²; Michel et al., 1996). The Chukchi Borderland has shifted from a perennial ice-covered area to a seasonal ice zone in recent years. Multi-year ice would have dimmed the ice algal bloom until the past decades in this area. It is also reasonable that substantially less amounts of nutrients restricted ice algal growth to the level below the pan-Arctic averages. In the 2012 case, the initial bloom timing was further delayed by one month and the ice algal biomass was clearly smaller than that of compared with the 2011 case (Figs. 6a, c).

As introduced in Section 2.2, ice algal the primary production rate of ice algae was calculated using the empirical functions of light condition and nutrient uptake terms. The light condition in the skeletal layer of the sea ice column was slowly recovered slowly after the end of polar night (February in the NAP region) and then increased rapidly due to thinning of was then rapidly improved by the snow/ice thinning in May (Fig. 7a). The peak values of PAR (3.5 W m⁻² in the 2011 case, and 2.2 W m⁻² in the 2012 case) were recorded in mid-July after the summer solstice. Although Even though sea ice melting continued until September, the light intensity turned to decrease in accordance with the annual cycle of solar radiation. As Since the optimal light intensity for ice algal growth (I_{opti}) was set to 10 W m⁻² in the present experiments, the light condition term varied in phase with the PAR transition (Fig. 7b). The weaker summer light intensity in the 2012 case could be attributed to the depressed shortwave radiation due to with more cloud cover (Table 21), despite in spite of thinner sea ice in August (Fig. 4b). The cyclone impact on light conditions is will be described in Section 4.43.

The nutrient conditions in the sea ice and water columns showed remarkable interannual variability. ~~The s~~Sea ice nitrate content ~~peaked at reached the peak value of~~ 0.6 mmol-N m⁻² (0.2 mmol-N m⁻²) in the 2011 (2012) case (Fig. 8a), ~~which. This amount~~ was an order of magnitude smaller than ~~in~~ landfast ice ~~one in the~~ Resolute Passage of ~~the~~ Canadian Archipelago (Cota and Smith, 1991). Potential factors ~~contributing to for~~ the difference included ~~the~~ nutrient environment in the underlying water column and ~~the~~ sea ice freezing rate, because ~~the~~ nutrient accumulation in the skeletal layer was induced by ocean-to-ice flux during ~~the~~ sea ice freezing period (see ~~the~~ formulation in Section 2.2). ~~At In~~ the beginning period of ~~the~~ one-year model integration, the nutricline ~~depth~~ was located at ~~the depth of~~ 20 m in the NAP region (Figs. 8b-c). ~~The early winter~~ Ekman downwelling ~~helped deepen the contributed to~~ nutricline ~~deepening from October to early November~~ in both ~~the~~ cases (Fig. 4e). In the 2011 case, ~~the~~ Ekman upwelling was also evident in November. However, the duration was just one week, so ~~that~~ the Ekman contribution with ~~a its~~ peak of 0.8 m d⁻¹ played a minor role in ~~the~~ nutrient entrainment. ~~The M~~more important ~~contributory key~~ process was ~~the occurrence of~~ strong mixing during ~~the~~ winter ~~season~~ in the 2011 case, as shown ~~by in~~ the enhanced vertical diffusivity (Fig. 4f). ~~According to these processes, the The resultant~~ surface nitrate concentration ~~reached increased up to~~ 2 mmol-N m⁻³ (Fig. 8b), and ~~a the~~ significant part was imported ~~into to~~ the skeletal layer ~~of sea ice bottom~~ (Fig. 8a). In contrast, the oligotrophic water stayed over the nutricline, ~~which was at a whose depth was~~ nearly constant ~~depth~~ or somewhat deepened ~~during for the~~ winter ~~time~~ in the 2012 case (Fig. 8c). ~~The s~~Sea ice nitrate content ~~had to reflected~~ the ocean surface value ~~of < below~~ 1 mmol-N m⁻³. ~~The s~~Sea ice silicate, which had ~~a~~ similar difference to nitrate, was not a limiting factor for ice algal growth in the NAP region (not shown). The ~~rate of~~ sea ice freezing ~~rate~~ also differed between ~~the~~ two cases. The total amount of thermal sea ice growth

from October to April was 160 (136) cm in the 2011 (2012) cases. Whereas we focused on the seasonal transitions from winter to early summer, *in-situ* data of nutrient concentration and sea ice freezing rate were unavailable for the target region and period. Accordingly, proper evaluations of the modeled properties, particularly during winter, were difficult at this stage. At least, the model results suggested that ~~the~~ preconditioning of nutrient accumulation in the sea ice column during the freezing period controlled the interannual variability in the ice algal bloom~~the initial bloom of ice algae~~. The influences of the basin-scale wind pattern and water mass transport on the nutrient environment ~~are will be~~ analyzed in Section 4.

~~The *n*~~ Nutrient availability for ice algal primary production ~~of ice algae certainly~~ reflected the difference in this the above-mentioned preconditioning. Based on the ~~The~~ present model formulation, formulated that sea ice nutrients were consumed primarily during an ~~was primarily consumed for the~~ initial stage of the ice algal bloom, ~~and that the matured ice algae could utilize~~ nutrients in the ocean surface layer were utilized for further blooms. According to ~~the~~ ice algal growth (Fig. 6a), the uptake ratio of sea ice nutrients (RN_{upSKL}) shifted from 1 to 0.7 within a few weeks of July in the 2011 case (Fig. 7c). When the half-saturation constant for nitrate uptake (K_{NO_3}) was set to 6 mmol-N m^{-3} for ice algae as well as pelagic diatoms (PL in the present model), the nitrate uptake term before the ice algal bloom was approximately 0.9 (0.7) in the 2011 (2012) case (Fig. 7d). ~~By multiplying the light condition term (Fig. 7b), t~~ The growth ratio between the two cases became 1.8 at the beginning of June after multiplying the light condition term (Fig. 7b). The larger growth rate accounted for the earlier initial ice algal bloom ~~of ice algae~~ in the 2011 case (Fig. 6a). ~~The *s*~~ Sea ice nitrate was ~~rapidly~~ depleted rapidly by this initial bloom and partially by ~~the~~ export to the water column with melting sea ice ~~melting~~ (Fig. 8a). The subsequent following decrease in the RN_{upSKL} value represented ~~the~~

utilization of ~~the~~ underlying ~~sea-water~~seawater nutrients (Fig. 7c). The ~~additional~~ further bloom ~~then~~ occurred in late July (Fig. 6a). In the 2012 case, the ~~decrease in the decline of~~ nutrient uptake term lagged behind the 2011 case in accordance with the delay of ~~the~~ initial bloom (Fig. 7d). The ocean nutrient uptake term, which ~~had ranged~~ lower values during the ice freezing period, gradually became comparable with the 2011 case. ~~However, the~~ The higher RN_{upSKL} value, except in early August, ~~however~~ restricted ~~the~~ ocean nutrient uptake in the 2012 case (Fig. 7c).

As expected, the seasonal transition of ~~the~~ ice algal biomass was similar to ~~the~~ daily primary productivity (Figs. 9a-b). In the present model experiments, ~~the~~ primary production derived from nutrients in the skeletal layer and in the water column was calculated separately. In the 2011 case, the nutrient source ~~for the of~~ ice algal bloom ~~changed~~ ~~transited~~ from ~~the~~ sea ice column for the first ~~primary production~~ peak of ~~primary production~~ ($23 \mu\text{mol-N m}^{-2} \text{d}^{-1}$) to ~~sea-water~~seawater for the second larger peak of $82 \mu\text{mol-N m}^{-2} \text{d}^{-1}$. ~~The second peak value of ~~~ $6.6 \text{ mgC m}^{-2} \text{d}^{-1}$ was close to the field-based estimates of $4\text{--}9 \text{ mgC m}^{-2} \text{d}^{-1}$ on the Beaufort shelf and slopes (Gradinger, 2009) and $< 10 \text{ mgC m}^{-2} \text{d}^{-1}$ in the Arctic basins (Deal et al., 2011). ~~Thus, the~~ The model results indicated that ~~the~~ nutrients imported in ~~the~~ sea ice column determined the beginning ~~timing~~ of ~~the~~ ice algal bloom, and that ocean nutrients ~~have had~~ a greater contribution to annual ~~ice algal primary production of ice algae, as reported previously~~ (Gradinger, 2009). ~~The comparison with the PON export to the underlying water column suggested that more than half of the organic nitrogen was remineralized in the sea ice column~~ (Fig. 9a). In the 2012 case, the peak of primary production simulated in early August was $35 \mu\text{mol-N m}^{-2} \text{d}^{-1}$ (Fig. 9b). ~~In this regard, the~~ The relative contribution of ocean nutrients to primary productivity ~~in the 2012 case~~ was less than ~~that in~~ the 2011 case. ~~The peak value of primary~~

496 ~~production recorded in early August was $35 \mu\text{mol N m}^{-2} \text{d}^{-1}$.~~ The August peak in PON export
497 flux exceeding ice algal productivity was attributed to lateral advection of shelf-origin sea ice
498 floes. The detailed discussions are presented in Section 4.3 and 4.4.
499
500

4. Wind-driven dynamics associated with ice algal productivity~~impacts on ice algal variability~~

To examine background mechanisms for year-to-year changes in ice algal productivity, wind-driven sea ice and ocean dynamics in the western Arctic Ocean were addressed.~~To address background mechanisms for the western Arctic ice algal variability on the seasonal to interannual timescales, sea ice and ocean responses to wind forcing were investigated.~~

4.1 Wind and sea ice patterns

~~The i~~Interannual variability~~es~~y in sea ice motion and ocean surface currents~~s~~ in the Beaufort Sea ~~are is~~ closely related to the atmospheric circulation pattern (Yang, 2009; Proshutinsky et al., 2009). We compared the winter mean sea level pressure (SLP) and wind stress fields constructed from the NCEP/CFSR reanalysis data between the two years. ~~The w~~Wind stress was calculated from the daily mean SLP using a protocol of the Arctic Ocean Model Intercomparison Project (AOMIP) protocol (<http://www.whoi.edu/page.do?pid=30576>). ~~In the winter season of 2010–2011,~~ An anti-cyclonic wind pattern was accompanied by a ~~the~~ weak Beaufort High around the Canada Basin during winter 2010–2011 (Fig. 10a). The easterly wind in the southern Beaufort Sea was favorable for transporting ~~would have favored the transport of nutrient-rich~~ Chukchi shelf water toward the southern Canada Basin and ~~with~~ the NAP region via the Ekman process. Ekman transport was analytically estimated with a seawater density of $1.025 \times 10^3 \text{ kg m}^{-3}$ and a Coriolis coefficient of $1.4 \times 10^{-4} \text{ s}^{-1}$. A sea ice-ocean stress value of 0.1 Pa , which was frequently recorded along the Chukchi shelf break during early winter in the 2011 case, yielded an Ekman transport value of $0.7 \text{ m}^2 \text{ s}^{-1}$ ($1.8 \text{ km}^2 \text{ mon}^{-1}$). This value is close to the November climatology in the southern Beaufort Sea (Yang, 2009) and indicates a shelf-

basin water exchange of $900 \text{ km}^3 \text{ mon}^{-1}$ for a shelf break axis length of 500 km. In contrast, ~~On the other hand, in winter 2011–2012,~~ high SLP ~~was~~ extended from ~~the~~ Siberian Arctic to the western Arctic Ocean ~~in winter 2011–2012~~ (Fig. 10b). Accordingly, ~~a~~ northwesterly wind prevailed in the Beaufort Sea. ~~In this situation, no definite shelf water transport toward the NAP region was expected by the winter wind fields. It is reasonable that the anomalous wind pattern forced southward transport of oligotrophic water mass within the Beaufort Gyre and eventually lessened nutrient availability over the Chukchi Borderland.~~

The changes in wind patterns were consistent with the modeled physical environments in the NAP region, where several differences between the 2011 and 2012 cases were described in Section 3.1. For October–~~to early~~ November ~~2011 (i.e., the beginning period of~~ in the 2012 case), localized anti-cyclonic wind forcing ~~was closely related to~~ ~~had close relationships with~~ the modeled negative rate of sea ice growth, convergence of sea ice velocity, and Ekman downwelling in the NAP region (Figs. 4c–e). ~~The wind-driven warm water intrusion toward the marginal ice zone~~ ~~The autumn advection of sea ice floes toward warm water pool~~ induced the lateral/bottom melting ~~of sea ice floes~~ ~~along the marginal ice zone, in spite of the enhanced upward heat flux with cold air intrusion~~ (not shown). The convergence ~~in of~~ sea ice velocity increased sea ice thickness via mechanical ridging processes, in contrast to sea ice melting occurring during the same period. ~~, and induced~~ ~~†~~ The continuous Ekman downwelling ~~was also accompanied by the sea ice convergence. For the period afterwards~~ ~~When we looked at December–January,~~ the positive anomaly of sea ice thickness was produced by ~~the~~ southward transport of thicker sea ice from the central Arctic in the 2012 case (Fig. 4b). The direction of ~~winter~~ sea ice flow around the NAP region ~~clearly obviously~~ differed between ~~the~~ two years (Figs. 10c–~~d~~), as ~~previously~~ detected ~~previously~~ by ~~the~~ satellite-based ~~and modeled spatial~~

~~patterns sea ice motion vectors~~ (Onodera et al., 2015). ~~Both the daily time series in the Polar~~
~~Pathfinder sea ice motion vectors (Fowler et al., 2013) and in the simulation results showed the~~
~~successive southward advection of sea ice from late October 2011 to January 2012 (Figs. 10d, f).~~
The distance of sea ice movement ~~reached several hundred km during this period~~~~exceeded 500~~
~~km for two months~~ when sea ice velocity was ~~5~~ 40-cm s⁻¹ (ca. 130 km mon⁻¹). ~~These results~~
~~suggest that the anomalous wind pattern forced southward transport of oligotrophic sea ice and~~
~~water masses within the Beaufort Gyre and eventually lessened nutrient availability in the~~
~~Chukchi Borderland.~~

4.2 Nutrient and shelf-break tracer distributions

The nutrient preconditioning ~~that occurred~~ before the ~~ice algal~~ blooming period ~~of ice algae~~
~~certainly~~ reflected the wind-driven ~~sea ice and~~ water mass transport, ~~as~~ suggested in Section 4.1.
The spatial distribution of ~~the~~ ocean nitrate concentration was characterized by ~~a the~~ sharp
meridional gradient across the Chukchi and Beaufort shelf breaks (Figs. 11a-b), as captured by
a number of ship-based observations (~~e.g.~~, Nishino et al., 2011). The modeled vertical average
in the top 30 m reached 10 mmol-N m⁻³ in the central Chukchi Sea and was ~~≤ below~~ 1 mmol-N
m⁻³ in the Canada Basin. As shown in Fig. 8, ~~there was a different tendency of the~~ nitrate
content around the NAP region ~~tended to differ~~. In the 2011 case, relatively high ~~nitrate~~
~~concentrations were~~ ~~abundance of nitrate was~~ distributed from the northern shelf of ~~the~~ Chukchi
Sea to ~~the~~ east of Northwind Ridge along 75°N (Fig. 11a). On the other hand, the shelf-basin
contrast ~~in of~~ nitrate content was still apparent even in the southern area of Chukchi Borderland
in the 2012 case (Fig. 11b).

To explore ~~the paths of the pathways of~~ shelf-break water ~~mass~~, a virtual passive tracer was provided along the shelf-basin boundary. We chose the tracer source region sandwiched by the 100–200-m isobaths ~~of 100 and 200 m. Through each one-year experiment,~~ The tracer value was fixed ~~continuously~~ to one (i.e., 100% concentration) at depths of 0–200 m ~~from the ocean surface to 200 m depth~~ in the defined region ~~through each one-year experiment. The~~ advection and diffusion of ~~the~~ tracer in the other regions ~~were was~~ calculated as well as ~~sea water~~ seawater temperature and salinity. The modeled distribution in March 2011 indicated that the tracer provided along the shelf-basin boundary region was transported from the Chukchi northern shelf toward the ~~interior of the~~ Canada Basin ~~interior~~. The ~~tracer~~ northern edge ~~of the tracer~~ matched the nitrate-rich area in the 2011 case (Fig. 11a). ~~The vertical profile of nitrate concentration in the NAP region reflected the deepening nutricline driven by the Ekman downwelling in October (Figs. 4e and 11c). Subsequently, nitrate content in the upper 50 m showed a net increase during December–January, which could be explained by lateral input rather than local vertical mixing. Hence, The model results hence indicated that the~~ Ekman transport of Chukchi shelf water ~~along with, in addition to the~~ energetic turbulent mixing, enhanced nutrient availability for ice algae in the NAP region. ~~Besides the southward spread of shelf-break tracer appeared especially south of the Barrow Canyon along the Alaskan northwestern coast. It has been reported that anti-cyclonic wind around the Beaufort High sometimes drove the up-canyon flow (Itoh et al., 2013). Thus the tracer pathway was closely related to basin-scale wind pattern. To the contrary In contrast,~~ in March 2012, the tracer signal was quite weak over the Chukchi Borderland (Fig. 11b). ~~No significant change appeared in the vertical nitrate profile during winter after the wind-driven downward shift (Fig. 11d). The~~ spread of fresher basin water blocked ~~the intrusion of~~ shelf water ~~intrusion~~ and weakened ~~the~~

turbulent mixing. The density stratification plausibly controlled ocean subsurface mixing, as
since wind speed averaged ~~was comparable on the averages~~ from November to January of the
2011 and 2012 winter periods ~~seasons~~ was comparable (Table 24). This mechanism was
consistent with previous findings, in which ~~where~~ the mixed layer depth ~~was~~ correlated with
hydrographic structures rather than wind forcing in the western Arctic (Peralta-Ferriz et al.,
2015).

Onodera et al. (2015) categorized the sinking diatom assemblages in the sediment trap
samples at Station NAP into 98 taxa. The dominant species during summer 2011 were *Fossula*
arctica and the *Fragilariopsis* group (*F. cylindrus* and *F. oceanica*), which are common in ice
algae in the shelf region (Cremer, 1999). Their relative abundances were minor in the sinking
diatom flora during summer 2012. Instead, the major diatom in August 2012 was planktic
species such as *Thalassionema nitzschioides*, which was commonly observed in the Canada
Basin. In addition, the sinking flux of total diatom valves in August 2012 was considerably
lower than that in August 2011. The observed diatom compositions and valve fluxes were
consistent with the above-mentioned physical backgrounds. The modeled nitrate distribution
and tracer pathway supported the suggestion that ~~the winter~~ transport of oligotrophic water
from the interior of the Canada Basin ~~interior~~ toward the NAP region ~~was~~ would be an
important factor suppressing ice algal ~~for the suppressed primary~~ productivity during of ice
~~algae in~~ summer 2012.

4.3 PON flux

The time series of sinking PON flux in the NAP region was compared with the sediment
trap data. ~~Following the ice algal bloom, in the 2011 case, t~~The modeled PON flux in the 2011
case at 180 m gradually increased gradually from June and peaked at 18 ~~had a peak of 15~~ $\mu\text{mol-}$

$\text{N m}^{-2} \text{ d}^{-1}$ ~~at the depth of 180 m~~ in mid-August following the ice algal bloom (Fig. 9c). Flux >
~~The flux above~~ $8 \mu\text{mol-N m}^{-2} \text{ d}^{-1}$ continued until the end of the model integration (i.e.,
 September). The flux amount was underestimated in August ~~early summer~~ and became
 comparable afterward with the trap values. PON flux at 180 m corresponded to 79% of the
ocean surface value exported from the sea ice bottom during July–September 2011 (Figs. 9a, c).
It should be noted that ice algae released from the skeletal layer were included immediately in
the ice-derived PON without being suspended and seeding in the present model setting. The
 major component of PON flux ~~was~~ originated from ice algae, as observed in the analysis of
 diatom valve compositions (Onodera et al., 2015). ~~The PON export from skeletal layer to~~
~~underlying water column caused by sea ice melting took approximately~~ $17 \mu\text{mol-N m}^{-2} \text{ d}^{-1}$
~~during mid-summer. The 67 % of surface flux remained before its dissolution to DON and~~
~~ammonium at the shallow trap depth of 180 m in August. The comparison with primary~~
~~production rate suggested that more than half of the organic nitrogen was remineralized in the~~
~~sea ice column (Fig. 9a, c).~~ The PON flux derived from pelagic phytoplankton and zooplankton
~~gradually~~ increased gradually in August and peaked at ~~reached the peak value of~~ $6 \mu\text{mol-N m}^{-2}$
 d^{-1} in early September (Fig. 9c). ~~Although the total biomass of pelagic plankton groups was an~~
~~order of magnitude larger than the ice algal biomass (not shown),~~ In the 2011 case, the
 dominance of ice-derived PON for the sinking flux was associated with its faster sinking speed
 (Section 2.2 and Fig. 3e), although the total biomass of pelagic plankton groups was an order of
magnitude larger than that of the ice algal biomass (not shown). The sediment trap data
 captured another peak ~~in of~~ PON flux during ~~in~~ May 2011, when the model experiment could
not reproduce the peak. Neither spring bloom of ice algae nor pelagic phytoplankton was
 expected due to ~~for the sake of the~~ thick ice cover in the NAP region (Fig. 4b and Table 2). This

event ~~may have been~~ ~~might be~~ caused by transport of shelf water ~~transport~~ with lithogenic materials of sea bottom sediments. A candidate driver was ~~a the~~ cold-core eddy generated from a narrow jet along the Chukchi shelf break (Spall et al., 2008; Llinás et al., Llinas, 2009). The background mechanisms for the spring peak are beyond the scope ~~out of scopes~~ in the present study and will be analyzed in the future. ~~as a future work.~~

~~The~~ PON flux in the 2012 case produced a distinct mid-summer peak at the ocean surface and ~~at the depth of~~ 180 m, although the trapped sample volume was too low to estimate nitrogen content in summer 2012 (Fig. 9b, d). The trap depth of 247–319 m in 2012, which was deeper than that of 181–218 m in 2011, may have caused biases in the comparison between the two years. Importantly, PON flux in 2012 was markedly lower than the 1,300-m flux in 2011 (Onodera et al., 2015). Again, Mmost of the modeled PON flux was ~~the~~ ice-derived ~~one again~~. The contribution of pelagic-derived PON in the 2012 case was rather less than in the 2011 case. ~~The e~~Enhanced sea ice melting of up to 4 cm d⁻¹ assisted the peak flux ~~peak~~ in early August (Fig. 4c). ~~However, t~~The ice-ocean surface flux was remarkably greater ~~larger~~ than the ice algal ~~primary~~ production rate, indicating ~~of ice algae indicated~~ that one-dimensional sea ice processes ~~cannot~~ ~~could not~~ account for ~~the~~ PON flux in the NAP region (Figs. 9b, d). We ~~then~~ traced lateral advection of the ice algal biomass around the Chukchi Borderland in the next section.

~~We further considered other possible factors for the discrepancy of PON flux between the modeled and trap data. Whereas the present model prescribed the fixed vertical profile of sinking speed (Fig. 3e), actual sedimentation depends on ballast distribution in addition to aggregation and elimination of light/fragile organic materials. When the source region of sea ice and surface water in the NAP region was the central Canada Basin, insufficient amount of~~

ballast particles would have allowed slower sinking of PON (Honjo et al., 2010). The variable sinking speed including ballast particles might improve the model performance on PON flux. It has also been reported that ice algae exported to water column could continue their production activity as well as pelagic diatom behavior, and that a part of ice algae is considered to become a food source of higher trophic plankton (Michel et al., 1996; Gradinger et al., 2009). The grazed algae should be treated as the slower sinking PON derived from pelagic species so that this conversion would lessen the PON flux. Besides, the PON derived from phytoplankton and zooplankton possibly has difference sinking speed. Thus it should be kept in mind that PON sinking process still remains a lot of uncertainties.

4.4 Impact of great cyclone activity

~~It was suggested that In summer 2012,~~ an extreme cyclone event was suggested to be a supplementary factor for ~~the~~ drastic sea ice reduction, ~~particularly especially~~ in the western Arctic, and the ~~subsequent consequent~~ record minimum extent of Arctic sea ice ~~in summer 2012~~ (Simmonds and Rudeva, 2012; Zhang et al., 2013). A ~~previous~~ modeling analysis ~~previously~~ indicated that plankton productivity over the Chukchi, East Siberian, and Laptev shelves was enhanced by vertical mixing with nutrient replenishment and lateral ~~plankton~~ transport of ~~basin-side plankton from the western Arctic basin biomass~~ during the cyclone storm (Zhang et al., 2014). It is assumed that synoptic cyclone activities have both positive and negative contributions to ice algal production. In the 2012 case, the event-like shoaling of ~~the~~ upper part of ~~the~~ nutricline was caused by mixing and upwelling processes in the NAP region, where the southern part of ~~the~~ great cyclone passed and marginal ice floes were located in early August (Fig. 12a). The modeled vertical diffusivity ~~was~~ maintained ~~at~~ background values partly because strong density stratification suppressed turbulent mixing until July 2012 (Figs. 4f).

During the cyclone event with ~~high enlarged~~ wind speeds (Table ~~24~~), ~~the~~ vertical mixing of nearly $10 \text{ cm}^2 \text{ s}^{-1}$ ~~then~~ reached ~~a the~~ depth of 20 m (Figs. 4f). Besides, the Ekman upwelling ~~that~~ continued from July 15 to August 29 could have worked on nutricline shoaling of 3.3 m (Fig. 4e). However, this timing of nutrient replenishment overlapped with ~~the~~ release of ice algae from the skeletal layer due to active sea ice melting (Fig. 8c), and ~~the mixing and upwelling processes hardly enhanced~~ ice algal productivity ~~on was hardly recovered by these processes~~. Mechanical ~~sea ice~~ divergence ~~of sea ice~~ associated with cyclonic wind fields rather contributed to the reduction ~~in of~~ ice algal biomass in the specific region (Fig. 4d). Whereas the outward movement of sea ice floes itself did not ~~lead to loss intend mortality~~ of ice algae, solar heat absorption into the exposed open water fractions enhanced lateral/bottom melting of sea ice and corresponding ~~release of ice algae. algal release~~. The light conditions for ice algal growth ~~was~~ also changed ~~during the cyclone event by cyclone activities~~ with extensive cloud cover. The NCEP/CFSR reanalysis data showed ~~a the~~ depression ~~in of~~ solar irradiance in the southern part of ~~the~~ cyclone passage, where ~~an the~~ early August shortwave flux in 2012 was lower ~~than~~ ~~relative to the 2011 one~~ by approximately 20 W m^{-2} (not shown). ~~When no snow cover, sea ice thickness of 50 cm, surface albedo of 0.6 were assumed, the downward shortwave radiation of 100 W m^{-2} leaded the PAR of 4.3 W m^{-2} in the skeletal layer of sea ice column.~~ The negative anomaly of light intensity corresponded to ~~a the~~ decrease in the light condition term for ice algal growth by less than 0.1.

Here, we performed a sensitivity experiment in which all biogeochemical processes in the sea ice ecosystem were halted in August 2012. In this idealized experiment (called the “no ice algal activity case”), only lateral advection and sea ice-ocean fluxes were allowed in the sea ice column. All physical and pelagic marine ecosystem processes were calculated as in the original

2012 case. Although there was no ice algal production in August, both the modeled ice algal biomass and PON flux increased in the NAP region (Figs. 12c-d). These enhanced signals could only be explained by horizontal transport of larger biomass from neighboring regions. The differences from the original case corresponded to additional production of ice algae flowing into the NAP region. Thus, lateral advection was essentially important during the 2012 cyclone period.

In the 2012 case, westerly winds ~~were~~ intensified in the southern part of ~~a~~ cyclone passage and transported shelf-origin ice algal patches toward the Northwind Ridge. Each sea ice floe ~~could be~~ moved approximately 150 km eastward during ~~for~~ August 3–10 (Fig. 12b). Although the direction of sea ice motion (87.4°T) was similar to the satellite-based vectors (82.8°T), the modeled drift speed (20.3 cm s^{-1}) was markedly faster than the latter (5.1 cm s^{-1}) during the cyclone period. It ~~is was~~ plausible that the peculiar advection caused a sudden increase in elevation of ice algal biomass and ~~an the~~ overestimation of ~~the~~ modeled PON flux in the NAP region (Figs. 6a and 12b). ~~Local The local~~ biases on sea ice velocity may have arisen from ~~possibly arose attributing to~~ atmospheric momentum input and sea ice dynamics. In the present experiments, the conversion from SLP to ~~the~~ wind stress field (i.e., the AOMIP protocol referred ~~to~~ in Section 4.1) was formulated with specific turning angles, which varied depending on geostrophic wind speed (Proshutinsky and Johnson, 1997). ~~The u~~Uncertainties in ~~the~~ reanalysis SLP data should also be ~~considered, paid attention,~~ because the maximum strength of ~~the~~ great cyclone in August 2012 calculated from the data assimilation system depended on ~~the~~ number of radiosonde profiles (Yamazaki et al., 2015). ~~In addition, T~~the traditional rheology of sea ice internal stress has been developed for climate models with grid spacing much coarser than 10 km and ~~does did~~ not guarantee ~~the its~~ accuracy of ice floe dynamics, especially in the

marginal ice zone. Thus, ~~the~~ speed and direction of the modeled ice algal advection around the Chukchi Borderland ~~may might~~ have deviated in August 2012, ~~whereas t~~ These biases had less impact on the basin-scale sea ice and ocean circulation.

Another concern is the event-like deepening of the shallow sediment trap at Station NAP in July 2012 (Onodera et al., 2015). ~~An The~~ intensified ocean current occasionally sometimes inclines the upper part of the bottom-tethered mooring system during storms. ~~under storm activities.~~ The anchored sea bottom depth of 1,975 m and ~~the~~ deepening of the trap ~~depth~~ from 260 ~~m~~ to 320 m suggests an ~~leaded the~~ inclination angle of approximately 15°. It was reported that ~~the~~ trapping efficiency and particle components ~~s~~ were remarkably influenced ~~by for the~~ tilting > ~~range larger than~~ 30° (Gardner, 1985). If this previous examination ~~can could~~ be applied despite the in spite of its different trap shape, ~~from ours, the tilting of a~~ 15° tilt should ~~would not have a~~ significantly impact ~~on the~~ trapping efficiency. In addition, strong ocean currents > ~~greater than~~ 10 cm s⁻¹ sometimes reduces ~~the~~ trapping efficiency (Baker et al., 1988). However, the modeled horizontal velocity at the trap depths was below 2 cm s⁻¹, ~~even during~~ the cyclone period event (not shown). It should also be noted that the trapped PON flux was continuously negligible throughout ~~the summer season in~~ 2012, not only for the temporal cyclone event.

5. Sensitivity experiments

Although the present model experiments show the interannual variability in ice algal primary production and sinking biogenic particle flux in the NAP region, various sea ice-related processes still need to be considered. Here, we refer to the 2011 case analyzed in previous sections as the original case and performed sensitivity experiments using different model settings (Fig. 13). The first three cases (Cases 1–3) address uncertainties in the model parameters. In the next three cases (Cases 4–6), the grazing pressure on ice algae and the treatments of ice algae released into the water column are discussed. All the sensitivity experiments were initiated from the modeled fields at the beginning of March in the original case for the saving of computational resources and conducted until September (i.e., seven months integration).

5.1 Optimum light intensity for ice algal production (Case 1)

It is difficult to estimate accurately the photosynthesis-irradiance relationships of ice-related flora. Ice algae adapt well to weaker light intensity compared with that of pelagic phytoplankton (Arrigo et al., 2010). In the original case, the optimum light intensity for ice algal production I_{opti} was set to 10 W m^{-2} . Grading (2009) reported that the minimum requirement for ice algal growth was typically $< 1 \mu\text{E m}^{-2} \text{ s}^{-1}$ based on laboratory incubation experiments. When the relationship of $1 \text{ W m}^{-2} \sim 4.56 \mu\text{E m}^{-2} \text{ s}^{-1}$ is applied following Lavoie et al. (2005), I_{opti} may be a smaller value. Here, we performed two sensitivity experiments with different I_{opti} values (Case 1). When I_{opti} was set to 5 W m^{-2} (20 W m^{-2}), the summer peak in the light condition term was 0.9 (0.3) in the NAP region (Figs. 3b and 7a). Relaxing the light limitation resulted in an earlier and stronger ice algal bloom (Fig. 14a). The initial bloom

occurred in early June and the second peak of ice algal biomass increased to $1.2 \text{ mmol-N m}^{-2}$ (cf. $0.7 \text{ mmol-N m}^{-2}$ in the original case). The phase and magnitude of the modeled PON flux shifted similarly and were still comparable with the trap data (Fig. 14b). In contrast, restricted light conditions dampened the ice algal productivity to a peak biomass of $0.1 \text{ mmol-N m}^{-2}$ (Fig. 14a). The resultant decreased release of ice algae into the water column delayed the seasonal increase in the PON flux (Fig. 14b). The difference in ice algal biomass did not alter the flux during late summer, which was derived mainly from pelagic plankton. Based on these sensitivity experiments, an optimum light intensity of 10 W m^{-2} or below was recommended for the formulation adopted. Other choices can be made for the light condition term. Ice algae may not suffer from photo-inhibition even when the skeletal layer receives strong irradiance diffused from neighboring open leads during ice melting periods. A saturated light condition in accordance with increasing PAR can be represented, for example, by the hyperbolic tangent function used in Lavoie et al. (2005). Besides, the shelf-shading effect of ice algae reduces ice algal productivity in massive blooming regions (Pogson et al., 2011).

5.2 Nutrient sources for ice algal production (Case 2)

The present model adopted the hybrid nutrient uptake formulation. Ice algal productivity depends on the uptake ratio between sea ice and water nutrients. Here, we performed three experiments (Case 2). When the threshold value KN_{upSKL} is increased to $1.5 \text{ mmol-N m}^{-2}$, (cf. $1.0 \text{ mmol-N m}^{-2}$ in the original case), the ice algal growth rate reflects nutrient availability in the sea ice column more strongly (Fig. 3c). Conversely, the decrease in KN_{upSKL} to $0.5 \text{ mmol-N m}^{-2}$ accelerates the uptake of seawater nutrients. However, the modeled ice algal biomass and PON flux were not sensitive to this range of KN_{upSKL} (Figs. 14c-d). As in the original case (Figs.

7c and 9a), the major source of ice algal production was seawater nutrients, even when only 20% of the biomass could utilize (i.e., $RN_{upSKL} = 0.8$). On the other hand, both the ice algal biomass and PON flux dropped remarkably in another experiment, in which uptake of sea ice nutrients was halted throughout the integration period (Figs. 14c-d). The slower growth rate with lower concentrations of seawater nutrients prevented ice algal seeds from blooming to the same level as in the original case before sea ice melting loss (Fig. 7d). The nutrient reservoir (and high concentration) in the sea ice column is important for the initial acceleration in an ice algal bloom, and nutrient availability in the ocean surface layer controls peak biomass.

The exchange rate of dissolved materials at the ice-water interface generally depends on molecular and turbulent diffusion processes. Lavoie et al. (2005) assumed that nutrient replenishment from the underlying mixed layer was proportional to friction velocity varying with the tidal cycle. The tidal effect is important in some regions such as the narrow straits of the Canadian Archipelago. However, the essential improvement would be necessary for its application to the entire Arctic Ocean. In this connection, the ocean-to-ice nutrient flux is proportional to the CF_{OI} coefficient during the ice freezing period. A CF_{OI} value of 0 or 1 is clearly unrealistic, because a significant portion of *in-situ* seawater nutrients remains inside the sea ice column, and the residual is ejected to the underlying water column after sea ice freezing as well as salinity. The original case adopted a CF_{OI} value of 0.3, following a first-year ice salinity of ~ 10 psu. Smaller CF_{OI} values suppress nutrient accumulation in the skeletal layer during the freezing period and delay the initial ice algal bloom. Another assumption in the present model is that all of the sea ice nutrients are concentrated only in the skeletal layer with its constant thickness (cf. 2 cm in the original case), instead of brine pockets and channels that were not represented in the present model. An increase in the layer thickness reduces nutrient

“concentration” (not total amount integrated in the entire sea ice column) and consequently delays an ice algal bloom. For example, a nitrate content of $0.6 \text{ mmol-N m}^{-2}$, which was recorded in April of the original 2011 case (Fig. 8a), yields a concentration of 30 mmol-N m^{-3} (12 mmol-N m^{-3}) and a nitrate condition term of 0.91 (0.80) in the skeletal layer with 2-cm (5-cm) thickness. A time-varying biologically active layer with brine volumes (Tedesco et al., 2010) and multiple separate sea ice layers (Pogson et al., 2011) have been proposed to represent ice algal habitats more precisely. These uncertainties in sea ice nutrients seem to have an impact on ice algal production.

5.3 Sinking speed of ice-derived PON (Case 3)

The present model prescribed the fixed vertical profile of particle sinking speed (Fig. 3e). In the original case, the sinking speed of ice-derived PON varied from 50 m d^{-1} in the uppermost model layer to 200 m d^{-1} at a depth of 1,000 m. This speed range was comparable with the previous estimate of $> 85 \text{ m d}^{-1}$ between the shallow (180 m) and deep (1,300 m) traps at Station NAP in August 2011 (Onodera et al., 2015). The PON exported from the sea ice bottom reached a depth of 180 m within four days under the model profile. As the decomposition rate from PON to ammonium and DON was set to 0.2 d^{-1} at 0°C , approximately half (47%) of the ice-derived PON was dissolved above a depth of 180 m. Here, we performed two experiments (Case 3), in which the minimum sinking speed was set to 200 (20) m d^{-1} in the faster (slower) sinking case (cf. 50 m d^{-1} in the original case). The remaining ratio of ice-derived PON after dissolution in these cases is theoretically 82% and 20% at a 180-m depth, respectively. Sinking speed hardly affected ice algal biomass (Fig. 14e), although the vertical nutrient profile in the water column had quite minor changes. On the other hand, PON flux

differed significantly between the two cases (Fig. 14f). The earlier and larger peak in the PON flux appeared in the faster sinking case. The flux range obtained in Case 3 was smaller than the sensitivity to the optimum light intensity evaluated in Case 1.

Actual sedimentation of biogenic particles depends on the ballast distribution in addition to aggregation and elimination of light/fragile organic materials. When the source region of sea ice and surface water in the NAP region was the central Canada Basin, an insufficient quantity of ballast particles would have allowed slower PON sinking (Honjo et al., 2010). A variable sinking speed depending ballast particles may improve a model performance on the PON flux. Besides, the PON derived from phytoplankton and zooplankton possibly has a different sinking speed. The faster sinking speed of fecal pellets may account for a substantial portion of the particle flux as observed in Resolute Passage (Michel et al., 1996). Thus, many uncertainties remain with respect to the PON sinking process.

5.4 Grazing on ice algae (Case 4)

Previous observations detected a significant quantity of ice-related fauna including amphipods in the sea ice column (Bluhm et al., 2010). It was also reported that ice algal assemblages suspended under the ice bottom layer were an important food source for pelagic grazers (e.g., copepods) during the early stages of sea ice melting (Michel et al., 1996). Here, the impact of the grazing process on ice algal biomass was examined (Fig. 13). In Case 4, the concentration of ice-related fauna (IF) changed from zero in the original case (i.e., no grazing pressure on ice algae throughout the integration period) to $0.02 \text{ mmol-N m}^{-3}$ on March 1. The rate of IF grazing on ice algae was calculated following the Ivlev relationship:

$$\text{Grz} = \max \{0, \text{Grz}_{\max} \times (1 - \exp\{\lambda (IA^* - IA)\})\},$$

where the maximum grazing rate Grz_{max} of 0.4 d^{-1} at $0\text{ }^{\circ}\text{C}$, the Ivlev constant λ of $1.4\text{ (mmol-N m}^{-3}\text{)}^{-1}$, and the feeding threshold value IA^* of $0.04\text{ mmol-N m}^{-3}$ were given, as well as the grazing of mesozooplankton (ZL) on pelagic diatom (PL) in the original NEMURO model (Kishi et al., 2007). The Ivlev formulation assumes that no grazing occurs at an ice algal concentration IA lower than IA^* . The modeled ice algal biomass showed the rapid decline after a similar peak compared with the original case (Fig. 4g). The ice-related fauna gradually increased following the ice algal bloom. A resultant peak of the IF biomass was $0.07\text{ mmol-N m}^{-2}$. This grazing process slightly contributed to the reduced PON flux (Fig. 14h). After sea ice melting, the released IF was included in ZL in the water column. For the sake of the enhanced grazing pressure in the water column, the phytoplankton biomass was also smaller than in the original case (not shown). We used same parameter values of the grazing process as pelagic planktons. When the skeletal layer is regarded as a refuge for ice algae from potential grazers, the maximum rate and consequent impact of grazing in the sea ice column should be smaller.

5.5 Transfer from ice algae to phytoplankton (Case 5)

It has been reported that a part of ice algae exported to the water column could continue their production activities as phytoplankton and become a zooplankton food source (Michel et al., 1993; Leventer, 2003; Gradinger et al., 2009). In Case 5, a constant ratio of ice algae released from the sea ice bottom was included in pelagic diatom (PL). The seeding partition was set to 0.5, assuming that a half of the released algae behaved in the form of living intact cells and the residual was included in the ice-related PON. Although the increased PL became a competitor of ice algae for the uptake of seawater nutrients in the uppermost ocean layer, the comparison with the original case showed little difference in the ice algal biomass (Figs. 14i).

On the other hand, the ice-derived algae staying alive in the water column were eventually included in the slower-sinking PON produced from pelagic species. These processes contributed to the decrease in PON flux at the trap depth (Fig. 14j). There is a wide uncertainty of seeding ratios of the released ice algae. For example, the ratio was set to 0.1 by Jin et al. (2012). To assess an impact of ice algal seeding to phytoplankton bloom and sinking biogenic fluxes more accurately, simultaneous measurements of diatom compositions both in the sea ice and water columns would be necessary.

5.6 Grazing on ice-derived PON (Case 6)

Zooplankton grazing on sinking biogenic particles could influence the quantity and composition of export fluxes in the water column. In Case 6, ZL grazing on ice-derived PON (fPON in the present model) was considered using the Ivlev equation:

$$\text{Grz} = \max\{0, \text{Grz}_{\max} \times (1 - \exp\{\lambda (\text{fPON}^* - \text{fPON})\})\},$$

where Grz_{\max} of 0.4 d^{-1} and λ of $1.4 (\text{mmol-N m}^{-3})^{-1}$ were given as well as Case 4. The feeding threshold value fPON^* was set to zero, and the contributions of other potential grazers (ZS and ZP in the present model) were neglected, for simplicity. This type of grazing hardly affected the ice algal biomass as in Case 3 (Fig. 14k), and the PON flux also showed little difference from the original case (Fig. 14l). A fPON concentration of $0.5 \mu\text{mol-N m}^{-3}$ arising in mid-August yielded a grazing rate Grz of $2.8 \times 10^{-4} \text{ d}^{-1}$. As the ZL concentration was still nearly $50 \mu\text{mol-N m}^{-3}$ in the upper 50 m, the grazed amount of fPON was $0.014 \mu\text{mol-N m}^{-3} \text{ d}^{-1}$ at the flux peak. The grazed ratio of 0.028 d^{-1} based on the above estimate was an order of magnitude smaller than the decomposition rate (see Section 5.3). This result indicated that the impact of zooplankton grazing on ice-derived PON was negligible, at least in the NAP region. In addition,

912 | zooplankton would not efficiently capture fast-sinking aggregates as shown in Lake Saroma
913 | (Nishi and Tabeta, 2005). Suspended algae are rather preferable for zooplankton growth
914 | (Michel et al., 1996).
915

65. Summary

~~The western Arctic b~~Biogeochemical structures in the western Arctic were addressed using a sea ice-ocean modeling approaches. In the present work, the sea ice ecosystem with ice algal activity was newly incorporated into a the pelagic-type marine ecosystem model. We assumed that ice algae could utilize nutrients (nitrate, ammonium, and silicate) both in the skeletal layer of sea ice ~~column~~ and in the ocean surface layer (i.e., ~~sea water~~seawater nutrients). The ratio of the nutrient source varied depending on ice algal biomass. This “hybrid-type” nutrient uptake formulation is an option expected to represent more realistic characteristics of ice algal biology.

The modeled ice algal primary production ~~of ice algae~~ demonstrated noticeable interannual variability as suggested ~~assumed~~ by ~~the~~ previous sediment trap analyses ~~analysis~~ in the NAP region. It was found that year-to-year changes in ice algal production ~~the ice algal variability~~ was closely related to ~~the change in~~ pan-Arctic-scale wind patterns. In winter 2010–2011, strong easterly winds around the Beaufort High induced ~~the~~ basin-ward Ekman transport of shelf-origin surface water and vertical turbulent mixing with underlying nutricline ~~waters~~shoaling. The higher nitrate concentrations were ~~abundance of nitrate was~~ then distributed in the southern Beaufort Sea and the Chukchi Borderland. On the other hand, in winter 2011–2012, northwesterly winds associated with an extension of the Siberian High distributed ~~supplied~~ oligotrophic water from ~~within~~ the central Canada Basin toward the northern Chukchi shelf. Hence, The ice algal productivity in the NAP region was ~~hence~~ suppressed by a deeper nutricline, in addition to cloud shading of solar irradiance, until early summer.

The modeled summer biogenic particle flux in the NAP region was comparable with the sediment trap data in 2011 and but was remarkably overestimated in 2012. In summer 2012,

lateral advection processes ~~es should have~~ resulted in the enhanced PON flux, because the ice-ocean flux ~~value at the ocean surface~~ exceeded ice algal production in the same location. ~~During the passage of great cyclone in~~In August, westerly winds intensified in the southern part of ~~the~~ cyclone transported ~~the~~ shelf-origin ice algal patches toward the NAP region. This cyclone event ~~may might~~ have caused the model biases on sea ice motion and ~~resultant~~ biogenic particle flux. We further considered several model uncertainties through the sensitivity experiments. The modeled ice algal biomass was highly sensitive to optimum light intensity. PON flux in the water column varied depending on particle sinking speed in addition to ice algal productivity. The impacts of various grazing processes on PON flux were relatively minor within the present cases. However, more possibilities should also be addressed in future studies. ~~The s~~Successive observations and model improvements are indispensable to ~~gather obtain more~~ ubiquitous general findings on ice-related biological processes~~the Arctic biological pump processes~~.

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Table captions

Table 1. Parameters in the sea ice ecosystem model. The values of ice algae are same as those of large phytoplankton in the original NEMURO model (Kishi et al., 2007). The PAR fraction followed Zhang et al. (2010), and the light extinction rates were derived from Aota and Ishikawa (1982). The parameter values of nitrogen and silicon flows in the skeletal layer were same as those in the water column, which were also provided by Kishi et al. (2007).

Table 2. Monthly mean values of NCEP/CFSR cloud fraction (n. d.), downward shortwave radiation (W m^{-2}), 10 m wind speed (m s^{-1}), snow depth (cm), sea ice thickness (cm), and sea ice concentration (n. d.) averaged in the NAP region. 2011 (2012) corresponds to the period from October 2010 (2011) to September 2011 (2012) to compare the model results.

Figure captions

Figure 1. Bathymetry of the pan-Arctic sea ice-ocean model COCO. Location of Station NAP is indicated by a red dot in the left enlarged view. The NAP region defined in the present study is enclosed by 74° – 76° N and 159° – 165° W. ~~The M~~model integration period covers 33 years from 1979 to 2011 only for the physical oceanographic part using the 25 km resolution version, and the obtained fields are given as initial condition for one year experiment from October 2010 (2011) to September 2011 (2012) in the 2011 (2012) case using the 5 km resolution version with marine ecosystem components.

Figure 2. Schematic image and configuration of the Arctic NEMURO model. Nitrogen and silicon flows are composed of photosynthesis (Photo), shell formation (Shell), respiration (Res), excretion (Exc), mortality (Mor), grazing (Grz), predation (Prd), egestion (Ege), decomposition (~~Dec~~), remineralization (Rem), nitrification (Nit), ~~and~~ sinking (Sink). Ice algal habitat is confined to the skeletal layer of sea ice bottom. Ice-related ~~fauna (IF) zooplankton (ZI)~~ is ~~calculated only in a sensitivity experiment (Case 4)~~~~neglected for simplicity in the present experiments~~. Exchange of biogeochemical variables with ~~the~~ pelagic ecosystem is allowed at ~~the~~ ice-ocean interface.

Figure 3. Relationships of (a) light extinction rate (non-dimensional (n. d.)) v. s. thickness of (dashed line) snow and (solid line) sea ice (cm), (b) light condition term (n. d.) v. s. light intensity (PAR) (W m^{-2}), (c) ice nutrient uptake ratio RN_{upSKL} (n. d.) v. s. ice algal biomass (mmol-N m^{-2}), (d) nitrate condition term (n. d.) v. s. nitrate concentration (mmol-N m^{-3}), and (e) sinking speed of PON derived from (solid line) ice algae and (dashed line) pelagic plankton

groups (m d^{-1}) v. s. depth in the water column (m), respectively, in the Arctic NEMURO model.
See more information in Section 2.2.

Figure 4. Seasonal transition of daily mean modeled variables in the NAP region. (a) Sea ice concentration (n. d.), (b) sea ice thickness (cm), (c) thermal growth rate of sea ice (cm d^{-1}), (d) divergence of sea ice velocity (d^{-1}), (e) Ekman upwelling velocity diagnosed using ocean surface stress fields (m d^{-1}), and (f) vertical diffusivity at the depth of 20 m ($\text{cm}^2 \text{ s}^{-1}$) in the ~~(solid line)~~ 2011 (red line) and ~~(dashed line)~~ 2012 (blue line) cases. Note that negative values in (c), (d), and (e) correspond to sea ice melting, convergence of sea ice velocity, and Ekman downwelling, respectively. Vertical diffusivity in (f) is shown in a logarithm scale.

Figure 5. Modeled annual primary production of ice algae in the (a) 2011 and (b) 2012 cases (mmol-N m^{-2}). The difference between the two cases is shown in (c). Yellow dots denote the location of Station NAP. White dots represent the eastern and western limits of 75°N section in Figs. 6b-c.

Figure 6. Modeled seasonal transition of ice algal biomass (a) in the NAP region and (b-c) along the 75°N line (mmol-N m^{-2}). Sea floor depths along the east-west section are also plotted (m). Red Solid-line in (a) and Hovmöller diagram in (b) correspond to the 2011 case. Blue Dashed-line in (a) and the diagram in (c) correspond to the 2012 case. The ~~column~~-content of 1 mmol-N m^{-2} in the sea ice column corresponds to the concentration of 50 mmol-N m^{-3} when the skeletal layer thickness is set to 2 cm.

Figure 7. Modeled seasonal transition of (a) light intensity (PAR) in the skeletal layer (W m^{-2}), (b) light condition term (n. d.), (c) ice nutrient uptake ratio RN_{upSKL} (n. d.), and (d) nitrate condition term (n. d.) in the NAP region in the ~~(solid line)~~ 2011 (red line) and ~~(dashed line)~~ 2012 (blue line) cases. Each term in (b-d) corresponds to ice algal value. In (d), the condition terms in the (thick lines) skeletal layer and (thin lines) ocean surface layer are shown.

Figure 8. Modeled seasonal transition of nitrate concentration (a) in the skeletal layer (mmol-N m^{-2}) and (b-c) in the top 100 m of water columns (mmol-N m^{-3}). ~~Red Solid~~ line in (a) and vertical profile in (b) correspond to the 2011 case. ~~Blue Dashed~~ line in (a) and the profile in (c) correspond to the 2012 case.

Figure 9. Modeled (a-b) primary production rate of ice algae and (c-d) PON flux in the NAP region in the (a, c) 2011 and (b, d) 2012 cases ($\mu\text{mol-N m}^{-2} \text{d}^{-1}$). In (a-b), the daily rate of total primary production (black lines) and those derived from nutrients in the ~~(blue lines)~~ skeletal layer (light blue lines) and ~~(pink lines)~~ water column (purple lines) are ~~also~~ shown. The export flux of PON from the sea ice bottom to the underlying water column is overlaid by olive lines. In (c-d), the total simulated (black lines) and observed (gray bars) PON fluxes at 180 m of (red lines) model outputs and (gray bars) trap values are compared ~~at the depth of 180 m~~. The fluxes originating from ~~(green lines)~~ ice algae (green lines) and ~~(orange lines)~~ pelagic plankton groups (orange lines) are also shown. ~~The export flux from sea ice bottom to underlying water column is shown by black lines.~~

Figure 10. (a-b) (contours) Sea level pressure (SLP) (hPa) and (vectors) wind stress averaged (a) from November 2010 to January 2011 and (b) from November 2011 to January 2012. SLP is obtained from the NCEP/CFSR dataset, and wind stress vectors are calculated from the SLP field using the AOMIP formulation. Unit vector of wind stress is 0.1 Pa. ~~(e-d)~~ Direction of ~~(c-d)~~ satellite-based and (e-f) modeled sea ice velocity in the NAP region (degree). Only daily five ~~day~~-averages whose velocity exceededs 5 10-cm s⁻¹ in the (c, e) 2011 and (d, f) 2012 periodseases-are plotted. Positive (negative) values of the direction correspond to northward (southward), and solid (dashed) bars indicate westward (eastward) motions, respectively. For example, a solid bar of -45° means southwestward direction of 225 °T.

Figure 11. Modeled nitrate concentration ~~averaged in the top 30 m of water column~~-(mmol-N m⁻³). The daily mean fields averaged in the top 30 m of water columns on March 1 in the (a) 2011 and (b) 2012 cases are shown in the upper panels. In these experiments, a passive tracer is provided from the ocean surface to sea floor of 100–200 m depth along shelf-basin boundary sandwiched by ~~thick~~-white contours. Black contours correspond to a tracer value of 0.2 (0–30 m average). Orange Thin white-lines denote the isobaths of 1,000 and 3,000 m. The vertical profile in the NAP region on (black) October 1, (blue) December 1, and (magenta) February 1 in the (c) 2011 and (d) 2012 cases are shown in the lower panels.

Figure 12. (a) NCEP/CFSR (contours) sea level pressure (hPa) and (shade) sea ice concentration (n. d.) on August 6, 2012. (b) Modeled (contours) PON flux at the depth of 180 m and (vectors) sea ice motion averaged for August 3–10 in the 2012 case. The flux contours of 5, 10, and 20 μmol-N m² d⁻¹ are shown around the Chukchi Borderland. The sea ice motion is

overlaid every ten grid (i.e., approximately 50 km), and its unit vector is 20 cm s^{-1} . Red dots denote the location of Station NAP. August time series of the modeled (c) ice algal biomass (mmol-N m^{-2}) and (d) PON flux ($\mu\text{mol-N m}^{-2} \text{ d}^{-1}$) in the 2012 case (black lines) and the no ice algal activity case (blue lines).

Figure 13. Schematic image of sensitivity experiments. In Case 4, the grazing pressure of ice-related fauna (IF) on ice algae (IA) and the transition from IF to mesozooplankton (ZL) after sea ice melting were calculated for the seeding. In Case 5, a part of IA was treated as large phytoplankton (PL) after sea ice melting. In Case 6, the ZL grazing on fast-sinking Particulate Organic Nitrogen (fPON) was calculated in the water column, and the formulation of slow-sinking one (sPON) was not changed.

Figure 14. Modeled seasonal transition of (a, c, e, g, i, k) ice algal biomass (mmol-N m^{-2}) and (b, d, f, h, j, l) PON flux ($\mu\text{mol-N m}^{-2} \text{ d}^{-1}$) in the NAP region in (a-b) Case 1, (c-d) Case 2, (e-f) Case 3, (g-h) Case 4, (i-j) Case 5, and (k-l) Case 6. Black thin lines correspond to the original 2011 case. The results with I_{opti} of 5 (20) W m^{-2} in Case 1, KN_{upSKL} of 0.5 (1.5) mmol-N m^{-2} in Case 2, PON sinking speed of 200 (20) m d^{-1} in Case 3 are shown by magenta (blue) lines, respectively. The biomass of ice-related fauna is shown by an olive line in Case 4.