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Responses to Associate Editor and Referees

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Manuscript Number: bg-2015-179 (Biogeosciences)
Manuscript Title: Wind-driven interannual variability of sea ice algal production
in the western Arctic Chukchi Borderland

= Dear Dr. Toru Hirawake (Associate Editor) and Two Anonymous Referees =

Thank you very much for your courteous handling and reviews of our manuscript.
The revision was done following your constructive comments.

Before the detailed responses, we have three notes to be mentioned.
1) The manuscript title was changed a little bit (from “over” to “in”).

2) We found that the export of ice-derived PON into the water column was miscalculated in our previous experiments, so the corrected model program was rerun. As you can see the revised version, this correction had little influence on our simulation results and conclusions.

3) We performed a number of sensitivity experiments, following the comments of Referee #2. Their results were inserted in Section 5, and summary was moved to Section 6.

The responses with other major/minor changes are described below.
We hope that this revised version satisfies all of you.

= Dear Anonymous Referee #1 =

The paper "wind-driven interannual variability of sea ice algal production over the western Arctic Chukchi Borderland" by Watanabe et al. is a coupled ice ocean-ecosystem model study evaluating potential causes for the large difference in observed particle flux from sediment traps for two consecutive years. The model study is nicely done and thoroughly looks at several environmental factors responsible for interannual variability in the region. Results show reasonable links to wind patterns and related nutrient transport as well as irradiance, which highlights the use of models for analyses like this. I hence recommend the publication of the paper with minor revisions on the science and major revisions in language, (see below).

Thank you for your positive comments. We responded to various useful advices, and tried to improve unskilled languages with assistances of an English editing service in the revised version.

Additional general comments:

The ice algae component is new and some components might need further question, e.g. the lack of zooplankton grazing within the water column and the hybrid nutrient supply. However, with respect to the limited observations on sea ice algal processes and the early stage of sea ice algal modelling in regional scale models, the applied parameterizations seem no less applicable than other published parameterizations, and hence appropriate for the study. However I am missing at least a few number intercomparisons, giving an idea if the ice algae biomass is within the limited observations of the area (e.g. does the Icescape study show any ice algae obs?).

Actually, there are many uncertainties on sea ice ecosystems, and more various processes should be considered for the model improvements. To address this issue, sensitivity experiments were additionally conducted and described in Section 5 in the revised version.

For the lack of observations a ballpark comparison with other ice algae models would also be helpful (works by Dean, Jin and Dupont are cited, but no number comparison given). And finally a comment should be added expressing that a proper evaluation of the ice algae model with observed data is simply not possible at the time due to the lack of data. For the future I would suggest including the model it potential inter comparisons of ice algae models, when they come up as part of a group exercise. It seems that the only actual *observation used for comparison is the sediment flux/PON flux which doesn't correspond very well with the model results. However, this is discussed in the paper and essentially shows how such observations can trigger a modelling study.*

Thank you for this suggestion. In the revised version, the modeled ice algal biomass and primary production rate were compared with previous estimates based on field campaigns (e.g., Gradinger, 2009; Arrigo et al., 2010) and numerical modeling (e.g., Deal et al., 2011; Jin et al., 2012). Besides, in some sections, we noted that proper evaluations of the modeled properties, especially in winter, were difficult at this stage.

I think the paper would also profit from a discussion section, i.e. take out some of the discussion within the subsections of section 4 and combine in one discussion section. This might help to better link the various contributions to the discussed interannual variability.

In the revised version, Section 4.3 and 4.4 were replaced and rearranged.

Unfortunately there are some English language issues which make it hard to focus on the content. Particularly the authors seem to avoid the use of articles (the or a, about 100 in the whole article are missing), some are placed wrongly, sometimes they could be avoided if the noun would be used in plural rather than singular. I don't think this should cause the paper to be rejected, but the issue should be improved before publication. I will not go through the effort to list every single one of those missing articles, but I am adding a scanned copy, which I hope will give enough indication of where articles should be. Further to the English language, there are a few cases where I think a verb has been used inappropriately, so it changes the meaning of the sentence. I am indicating those for the authors to make sure the meaning is understood correctly.

We really appreciate for your kindness to correct grammars. We rechecked all the sentences with helps of an English editing service.

Detailed comments:

7740

l2 – was reported => was recorded???

Modified

l20 rm certainly – superfluous

Removed

l21 The simulated sinking flux

Modified

l23 suggest: the ice algal patch with shelf origin (if that is what is meant)

Modified

l26 on=> of

Corrected

7741

l11 => fill many gaps ??? observational gaps ?

Modified

L14 rm however

Removed

l21/22 This sentence does not make sense – rephrase

Rephrased

l26/27 What does the last sentence mean?

Rephrased

7742

l6 demonstrated => simulated ?

Modified

L16 was – is a

Corrected

L16 A pioneer work => Pioneering Work

Corrected

L20 target region ? Modelled region?

Corrected

L27 reached three => reached values three

Corrected

L28/29 suggest:

Seawater in the ocean surface column is => The ocean surface water is

Modified

7743

L10 lose – loose

Rephrased

L10 Modeling configurations

Modified

7744

L20 rm additionally

Removed

L21 called as => called

Modified

7745

L17-19 not clear if this is preset or out of the parameterization => clarify

The light extinction rate is given by a constant value. So, the ratio of light intensity in the skeletal layer to that absorbed into the sea ice surface depends on just sea ice thickness.

7746

L21-22 Unclear, please rephrase

Rephrased

7747

L20 How does respiration reduce biomass?

In our model as well as the original NEMURO model, budget of ice algal biomass is calculated by "[growth (GR)] – [respiration] – [mortality] and so on". But, "biomass reduction by respiration" was surely an inappropriate phrase. So, "respiration" was removed in the revised version.

L23/24 This is stated multiple times in the text, I think it can be stated once and them be ignored (Why introduce the variable in the first place?)"

"ZI" was renamed to ice-related fauna "IF" (living in sea ice) following a comment of Referee #2. The phrase "zooplankton grazing on ice algae" meant "grazing by zooplankton living in the water column. This sentence was modified.

L27 The German...tested ..(ref) => Boetius et al. 2013 indicated rapid . . ..

Modified

7748

L19 vertical grid width => vertical resolution

Modified

L20 rm level 2x

Removed

L23 rm - in the 2011(2012)case

This part was moved to a previous sentence, because we needed to name these experiments for following discussions. "The 2011 (2012) case" corresponds to the model experiments throughout the manuscript.

7749

L1 Is there a reference or info to the prescribed Bering Strait inflow?

Two references and short explanations were added.

L19 divided into

Modified

7750

L9 and 14 was => were

Corrected

Last paragraph, please clarify if you are still talking about the model

(e.g. compared with simulated sea ice conditions ?)

Modified

L22/23 The negative anomaly.... attributed to two melting events I think this should be "can be attributed" otherwise it would mean the lower sea ice causes the melting events rather than the melting events cause the lower sea ice???

Modified

7751

L27 rm area

Removed

7752

L12-17 Is this still ice algae or pelagic? Are there any numbers from observations?

We referred to ice algae in this paragraph. Besides, ice algal biomass and primary production rate were compared more with previous studies.

L22 rapidly improved => rapidly increased????

Modified

L28/29 same as before could be attributed not could attributed

Corrected

7753

L6 in landfast ice, rm one

Removed

L12/13 upwelling or downwelling???

In this sentence, "early winter" intended a period from October to early November when Ekman downwelling was dominant. Modified

L18 by up to

Rephrased

L21/22 nitrite content had to reflect =>nitrate content reflected

Modified

7754

L1 rm certainly

Removed

L17/18 which ranged lower => which had lower

Modified

L27 rm "timing" after beginning

Removed

7755

L1 recorded => simulated (?)

Modified

L8 in sea ice => of sea ice

Corrected

L16/17 The use of would implied that it would have done that but it actually didn't, it is not clear if this is what the authors want to say. If so please add why it didn't

Rephrased

7756

L3 which warm pool

"warm water pool" meant "warm water area along marginal ice zones", which was not shown in any figures. This sentence was revised.

L7 induced Ekman . . . => unclear, please clarify

This part was separated to two sentences.

L15 preconditioning, rm certainly

Modified

L22 abundance => concentrations of nitrate were

Modified

7757

L2 was fixed or was initialized?

The tracer value in the defined shelf-break region was continuously fixed. Modified

L9-11 Besides ...coast – I do not understand this sentence, please rephrase

This part described a model performance of the tracer experiment, but was not directly related to the NAP region. Removed

L18 January of 2011 and 2012 (rm seasons)

In this sentence, the years of “November” were 2010 and 2011, respectively. The word “seasons” was rephrased to “winter periods”.

7758

L2 What is basin side plankton biomass?

“basin-side plankton” meant “plankton in the western Arctic basin”. Rephrased

L11-12 Besides . . .

This sentence missies at least one word to understand it, please rephrase

Corrected

L17 intend mortality => lead to loss

Modified

L23-25 unclear, please rephrase

This sentence was removed because of less importance.

7759

L6 The flux amount was underestimated

Corrected

L8 rm was before originated

Corrected

L10 took ??? => was

Modified

L11-12 The 67 – Don't understand this sentence, please clarify

We would like to show a ratio of PON flux at the shallow trap to the ocean surface flux from the sea ice bottom. Revised

L14 The simulated PON flux (?)

Here and below make clear when talking about model and when talking about obs!

This paragraph was revised following your comments.

L23 the cold core eddy which was generated by a narrow jet

or the cold core eddy that generated a narrow jet ???

The former is right. Corrected

I would consider putting the following section or at least part of it into a discussion, since it links the PON flux with the previous investigation of physical structures (wind etc)

The original Section 4.4 was replaced with Section 4.3 and rearranged in the revised version. A part of discussion on PON flux was moved to Section 5.3.

7760

L2 The surface flux which was remarkably

Modified

L7 sea floe => ice flow

Modified to "sea ice floe" (meaning a piece of sea ice pack)

L8 It was => it is

Corrected

L11 attributed to=> from

Modified

L14 wind speed or vector wind????

"wind speed" (an absolute value of wind vectors) was correct.

L15 paid attention => considered

Modified

L19 did => does

Corrected

L26 deepening of the trap from 260 to 320m suggests an inclination

Modified

L29 could => can

Modified

7761

L1 rm from ours , would => should

Modified

L15-17 This sentence needs to be rephrased

In this sentence, “pelagic diatom” was rephrased to “phytoplankton”, and “higher-trophic plankton” was rephrased to “zooplankton”.

L21 remains => contains or suggestion:

A lot of uncertainties still remain with respect to the PON sinking process.

Modified

L23 Suggest

Biogeochemical structures in the western Arctic

Modified

7762

L5 assumed => suggested

Modified

L11/12 sentence confusing, I think it should read:. . . northwesterly wind associated with an extension of the Siberian High distributed oligotrophic water from within the Canada Basin toward the northern Chukchi shelf.(??)

Modified

Figures/captions

Figure 2 caption

decomposition (December) – looks like an autocorrect error...

Thank you for your notice. Although we described “(Dec)” in the submitted manuscript, this error in the printed version was overlooked.

Figure 3 caption non-dimension => non-dimensional

Corrected

Figure 4/(6)/7,(8)

It is really hard to see what is the dashed line, maybe use a light grey or colored line instead???

Black lines were changed to colored lines.

Figure 6 caption

I do not understand the last sentence

“The column content” meant “the content integrated vertically in the sea ice column”. This sentence showed just the unit conversion from “m^{-2}” to “m^{-3}”.

Figure 9

captions suggest giving the color coding after the indicator variable

e.g, skeletal layer (blue lines) . . . water column (pink lines)

suggest change: Total PON fluxes of (red lines) model outputs and (gray bars) trap values . . .. to Total simulated (red lines) and observed (gray bars) PON fluxes at 180m.

Modified

Fig 11

The thin white lines indicating the isobaths cannot be seen, hence get confused with the thick white contours. Any other color options????

Color of isobaths was changed to orange.

Please also note the supplement to this comment: http://www. biogeosciences-discuss.net/12/C3000/2015/bgd-12-C3000-2015-supplement.pdf

We sincerely appreciate your kindness.

The manuscript was totally revised following your notes.

= Dear Anonymous Referee #2 =

The study by Watanabe et al. focuses on the output of a lower trophic ecosystem model for the Arctic Ocean, including sea ice algal components. It demonstrates the relevance of wind, and the resulting ocean physical and biological responses including the vertical export of biological material from the euphotic zone with a focus on the relevance of the sea ice component. This is an interesting research idea and question, and the model output demonstrates interannual variability in the biological response due to the physical environment. As such the research questions and many parts of manuscript deserve to be published. However, it requires substantial revision to clarify its contents and make it most useful for the reader.

Thank you for your positive and many constructive comments. We addressed each suggestion with more information.

First I would like to state, that the entire manuscript requires substantial language editing by a native speaker, as frequent language issues are distracting from the contents. This is going to be a substantial task.

We apologize for distractions owing to unskilled English writing. The manuscript was totally revised with assistances of an English editing service.

Secondly I encourage the authors to make a stronger link between the model output and the observations from the field. This has not been strongly developed so far and is missing in many sections.

Whereas we focused on seasonal transitions from winter to early summer, unfortunately, *in-situ* data of nutrients, chlorophyll, even temperature and salinity could not be obtained in the NAP region during the target periods. We also recognized lacks of model validation data and in turn insufficient information triggered model experiments. In this situation, what we could do was comparisons with previous studies, although main target region and period were different from ours in most cases. In the revised version, various estimates based on observational and modeling works were cited to validate the simulation results.

I recommend to restructure the manuscript according to a more conventional style so that the authors truly provide a thorough discussion of the various aspects of the model output. This is by far the weakest part of the manuscript, which reads in large parts more like a report than a peer reviewed publication. The authors should also be asked to reflect the current state of the literature. It appears to be very important to more clearly explain the *building blocks of the model and justify the chosen variables and parameters, followed by a sensitivity analysis. All model output should be compared to field observations.*

Discussions about the model outputs were added throughout the revised manuscript. We performed various sensitivity experiments and described their results in “new” Section 5.

Specific comments:

Abstract

The abstracts provide a general overview about the study purpose and the outcome. It will be much clearer after a language editing.

We revised the manuscript following comments from a language editing service.

I suggest to add the depth of the sediment traps (line 6).

Added

I have a major issue with the use of sediment trap to understand sea ice algal primary productivity. Statements like in line 13 are wrong, as traps only capture export production and not true in situ primary production. The abstract highlights the differences in the model output and field observations and the interannual differences.

“Seasonal experiments” in line 13 intended “model experiments (the 2011 and 2012 cases). Rephrased

Introduction

The introduction provides a short overview about the research question of vertical flux measurements, sea ice algal modeling and fate of sea ice algae after ice melt. It appeared to me rather unstructured, and the readers were left alone to link the various sections.

We appealed that the present study focused on various relationships of wind-driven dynamics with ice-related biogeochemical processes using a high-resolution three-dimensional model in the revised version.

The references appear outdated in many parts, and some of the information is misleading or wrong. Several key papers about primary production, vertical flux and shelf basin exchange for the Chukchi/Beaufort Seas are not used to make the case. For example: newer models dealing with ice algal activity include Duarte et al. 2015 (J. Mar. Systems), work by Tedesco, or Moreau et al. 2015 (J. Geophys Res.). For Chukchi Sea: Moran et al.

2005 - flux (Deep Sea Res.), Gradinger 2009 – sea ice algae (Deep Sea Res.) Again thorough language editing is needed to clarify the scientific message.

The references were updated throughout the revised version. Three chapters in the “Sea Ice” book were also checked and cited [Leventer et al., 2003; Arrigo et al., 2010; Bluhm et al., 2010].

Pg 7742, line 4:

how can relative abundances suggested nutrient conditions, not clear from the text.

Nutrient conditions in the euphotic layer could be deciphered in diatom flora compositions. The lower sinking flux of total diatom valves and the larger ratio of oligotrophic species observed at Station NAP in 2012 indicated substitution of upper water masses from shelf-origin waters to surface waters of the Canada Basin. This part was revised.

Pg. 7743, line 5:

not clear to me: during freezing brine convection is a major supplier of nutrients into the ice, as well as boundary layer processes.

Dupont [2012] assumed that nutrients imported via sea ice freezing had minor contribution to “ice algal bloom”, compared with them provided by boundary layer processes. On the other hand, our model considered both processes. This part was revised a little bit.

Same page line 11: the statement that melt causes sea ice algae to be detritus is wrong – by definition, they are then phytoplankton. Detritus is defined as dead organic material.

Modified

Material and methods

Section 2 explains the model components. It uses an established model for ocean properties. The sea ice component is explained in general, however it lacks detail to fully understand the applied approach. It is hard to assess the value of the output if there is great uncertainty in the validity of the input. For sea ice, they suggest a maximum growth rate of 0.8 per day for sea ice algae. This appears to be high compared to the maximum rate suggested by Eppley (1972) of 0.85 – how were temperature effects compensated?

Parameter values in the sea ice ecosystem model were summarized in Table 1. Model uncertainties were addressed through sensitivity experiments in Section 5 in the revised version. As skeletal layer temperature is kept almost at the freezing point of sea water, a relationship of Q_{10} = 2 adopted in the present model did not have substantial impacts on ice algal production.

The nutrient exchange calculation is difficult to follow. The sea ice algae are exposed to the brine nutrient concentrations and not bulk concentrations of melted ice– did they include brine pumping during freezing? How were conditions in the brine calculated? Are any of the suggested variables and parameters for determining the algal growth response related to any published measurements or are they just guesses – this needs to be much better explained for all algal growth variables. I suggest to include a table similar to Diane Lavoie (2005) modeling paper table 1, including references for the used variables and parameters chosen.

We know some 1-D models that explicitly calculated brine processes (e.g., gravity drainage). However, the incorporation of detailed structures in sea ice interiors such as brine pockets and channels is generally difficult for 3-D climate models. Reasons are put on a wide range of subjects from technical problems of advection scheme and to necessity of enormous computational resources. Therefore, we regard the skeletal layer as the reservoir of total imported nutrients under an idealized assumption. The additional explanations were inserted in Section 2.2 and 5.2 in the revised version. In addition, parameter values in the sea ice ecosystem model were summarized in Table 1, and the references were introduced in Table 1 caption.

As a side note – there is no zooplankton in sea ice – check the definition of plankton. You should use the term sea ice fauna or sympagic fauna for those animals living inside the ice. However there is true feeding of zooplankton on sea ice (e.g. Durbin 2013 paper from Bering Sea).

Thank you for these comments and information. The term was modified to “ice-related fauna”, and a grazing process in sea ice was tested in a sensitivity experiment (Case 4) in the revised version.

Regarding the export – it is not clear from the paper, whether any part of the released sea ice algae are consumed in the surface waters by zooplankton or stay there as part of the phytoplankton community to start the pelagic spring bloom – how are these two processes included? Also dissolution of diatom frustules can be substantial –accounted in any way?

In the original case, ice algae released from the sea ice bottom became just sinking materials without biological activities (i.e., no photosynthesis and zooplankton grazing pressure in the water column). These processes were addressed through sensitivity experiments and discussed in Section 5 in the revised version.

Section 2.3

I would like to know whether the pacific inflow matches the observations from e.g. Woodgate and others.

The prescribed velocity, temperature, and salinity were based on Woodgate et al. [2005]. References and short explanations were added.

I do not understand pg 7749, line 5: does "dissolution" refer to bacterial remineralization including e.g. annamox processes or what is meant by this?

Here, we referred to decomposition and remineralization processes shown in Figure 2. Anammox processes were not included in our model yet.

Same page, line 8: what is the lower limit of ice algal concentration?

As the import of ice algal seeds from the water column was not represented in our model, the setting of a lowest value of biomass is necessary for initial ice algal growth. Otherwise, the modeled ice algae cannot start the blooming even when light and nutrient are available. Such treatment is generally used in marine ecosystem models (e.g., Zhang et al., 2010). This sentence was rephrased.

Section 2.4

The traps were deployed in two very different depths in the two years – any impacts on the results? Also why were PON filters acidified? Did you remove swimmers prior to analyses from the filters?

The additional explanations were inserted Section 2.4 and 4.3 in the revised version.

Section 3

The biological representation of the model output is rather limit. N to Chl ratios can vary widely, and comparisons are made to outdated review papers (e.g. Cota et al. 1991) – here a thorough discussion of model output in comparison with real data is needed. E.g read studies by Sang Lee. Also I would encourage the authors to conduct a detailed sensitivity analysis – see e.g. studies by Jin.

References for model validation were updated. And, we performed various sensitivity experiments and discussed their results in Section 5 in the revised version.

The section of imported nutrients does not offer anything new – this has been published several times how important the pelagic nutrient pool is for sea ice algae – again, here it needs a more in-depth discussion and comparison to observational data.

The performance of hybrid nutrient uptake formulation was discussed through sensitivity experiments (Case 2) in Section 5.2 in the revised version.

Section 4

Section 4.1

Data on ice velocity seems reasonable, this section is lacking any comparison to observational data.

SLP and wind fields have been obtained from popular reanalysis products partly reflecting field data. Ekman transport in the southern Beaufort Sea was estimated with a previous study (Yang, 2009). Direction of sea ice motion was additionally compared between satellite-based and modeled daily time series.

Section 4.2

Again more or less a description of the model output and no discussion of the output. The flow regime in the area is complicated as outlined in many peer reviewed papers, that could form the basis for a discussion. The 2014 book chapter by Kinney et al. provides a useful analysis for the Bering sea region. Weingartner et al. 2013 for Chukchi Sea etc.

The flow regimes in the Chukchi Sea and shelf-break regions have already been analyzed in our previous papers [e.g., Watanabe and Hasumi, 2009; Watanabe, 2011; Watanabe et al., 2012; Watanabe et al., 2014]. So, the detailed descriptions on shelf circulation were omitted in the present manuscript. Instead, vertical nitrate profiles in the NAP region were added in Figure 11, and we further referred to the contribution of lateral transport in the revised version. Finally, the findings obtained by this 3-D modeling were linked to the observed diatom compositions.

Section 4.3

The analysis of the impact of various environmental factors on ice algal productivity would benefit from a sensitivity analysis (see above).

Original Section 4.3 was replaced with Section 4.4 in the revised version. We performed a sensitivity experiment, where no biogeochemical processes in the sea ice column were calculated in August 2012. The result supported that lateral advection was essentially important for the biased PON flux.

Section 4.4

Good that the authors conduct a comparison of field observations and model output in this section. I recommend to explore further the role of advective processes leading to *sedimentation event (for 2011 May peak). I did not find a clear explanation what happens to the ice algae during periods of strong ice melt (e.g. loss of 4 cm d-1) – are all the algae lost into the water – and how is growth reseeded in the new bottom layer?*

Section 4.4 was replaced with Section 4.3 in the revised version. As no ice-related taxa were trapped at Station NAP in May 2011 [Onodera et al., 2015], we plan to explore this early peak in future papers. In the present study, ice algal production was focused on. In the original case, all of ice algae exported to the water column by melting release was included immediately in the ice-related PON without being suspended and seeding. One sentence was added, and a sensitivity experiment (Case 4) addressed this process in the revised version.

Wind-driven interannual variability of sea ice algal production in ~~over~~ the western Arctic Chukchi Borderland

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Abstract

Seasonal and interannual variability in the ~~sinking flux of~~ biogenic particle~~s~~ 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 t~~Trapped particle flux at a median depth of 184 m had an obvious peak and ~~with the~~ dominance of sea ice-related diatom assemblages~~valve~~ in August 2011. ~~, t~~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 environment~~s~~ 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 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 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 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 ~~particle~~ 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 t~~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~~ summer~~time~~ 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~~ ~~p~~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 assume~~d~~ that ice algal activity occurs~~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 t~~Tidal mixing controls nutrient exchange rates 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., 2011~~). However, ~~On the other hand, in~~ Dupont (2012) did not calculate~~, the~~

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

In the present study, ~~we addressed~~ seasonal and interannual variability of ice algal production and biomass in ~~over~~ the Chukchi Borderland were addressed using a pan-Arctic sea ice-ocean modeling approach (Fig. 1). We focused particularly on the relationships between ice-related biogeochemical processes and wind-driven dynamics, such as shelf-basin exchanges, local upwelling/downwelling, and vertical turbulent mixing. ~~In this effort, t~~To represent the summer~~time~~ biogenic particle flux captured by sediment trap measurements, the simple sea ice ecosystem was newly incorporated into a lower-trophic marine ecosystem model. Our model coupled with a sophisticated high-resolution physical component is a powerful tool for the above-mentioned subjects because of following issues. The Chukchi Borderland is composed of complex topography such as long ridges, deep-sea plateaus, and steep shelf breaks. The sinking biogenic flux available for comparison was obtained from the single-point mooring measurements in this area. The source regions of surface water are distributed over the Chukchi Sea, the East Siberian Sea, and the Canada Basin. The water mass transports are closely related to shelf-basin boundary currents and baroclinic eddies. These complex topography and mesoscale hydrographic features have been unresolved by previous basin-scale ice algae models, which horizontal resolution was much coarser than the typical internal Rossby radius of deformation in the polar region. The linkages between wind patterns, light and nutrient preconditioning of ice algal bloom, and particle sinking are also unique viewpoints in the present work. Modeling ~~C~~configurations ~~of modeling~~ and sediment trap analyses are ~~is~~ described in Section 2. Seasonal transitions of the modeled ice-ocean field, particularly those ~~especially~~ around the NAP region, are traced in Section 3. Relationships between ~~of~~ the interannual variability in biogeochemical properties and ~~with~~ wind patterns are examined in Section 4. Uncertainties of the modeled processes are discussed in Section 5, based on sensitivity experiments. The obtained findings ~~obtained in the present work~~ are summarized in Section 6~~5~~.

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~~y~~). 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~~ (IF~~ZI: 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. ~~t~~The growth rate of ice algae (GR) is calculated depending on light condition (L) and nutrient uptake (N_{up}) terms:

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

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, ~~T~~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:

$$F_{OI} = CF_{OI} \times (NO3, NH4, SIL, DON)_{OCN} \times IFR.$$

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:

$$F_{IO} = (IA, IF, NO3, NH4, SIL, DON, PON, OPL)_{SKL} \times IMR.$$

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:

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

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

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 the~~ir~~ 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):

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

$$+ NH4_{SKL} / (NH4_{SKL} + K_{NH4}),\ SIL_{SKL} / (SIL_{SKL} + K_{SIL}) \},$$

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

$$+ NH4_{OCN} / (NH4_{OCN} + K_{NH4}),\ SIL_{OCN} / (SIL_{OCN} + K_{SIL}) \},$$

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, s~~Sea ice assemblages sink~~s~~ 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, t~~The 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 depth~~s~~ 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, t~~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) s~~Seas, and the northern part of the North Atlantic (Fig. 1). The horizontal resolution is 5 km, and there are 1,400 × 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 Sv ≡ 10^6 m^3 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 mmol-N m^{-3}~~)~~ is given for initial growth (i.e., seeding).~~given for seeding.~~ The relationship of 1 mmol-N = 80 mgC = 1.6 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~~ ~~d~~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,~~

~~2011, s~~Sinking particles were sampled ~~sampling was conducted~~ at ~~the~~ depths of 181–218 m (median,~~:~~ 184 m) during the first year from October 4, 2010 to September 27, 2011. ~~In the second year from October 4, 2011 to September 17, 2012, t~~The trap depth was 247–319 m (median,~~:~~ 256 m) during the second year from October 4, 2011 to September 17, 2012. These sediment traps collected 26 samples approximately every two weeks during their one-year deployment. The recovered trap samples were sieved through 1-mm mesh to remove swimmers, and ~~The trapped~~ particles < 1 mm were ~~evenly~~ divided evenly into ~~to~~ 10 sub-samples. ~~The o~~One of 10 aliquot samples was filtered, and was desalted using Milli-W water. ~~and t~~The dried sample was weighed, and it ~~one~~ was then ground ~~well grinded~~ and mixed using an ~~by~~ agate mill. PON and POC contents were analyzed in one sequence. ~~Before the PON analysis, t~~The powdered samples were decalcified in ~~vapour of~~ hydrochloric acid vapor in a desiccator for eight hours to remove particulate inorganic carbon. Sodium hydroxide pellets were placed ~~then put~~ in the desiccator to neutralize the samples. ~~The~~ PON content in the treated samples was sequentially analyzed by a ~~the~~ CHN analyzer (NCS2500, Thermo Quest). ~~The s~~Sinking PON flux was calculated based on PON content, sampling period, open~~ing~~ area of the sediment trap (0.5 m^2), and aliquot size of the treated sample (1/10). The detailed analysis method and diatom valve fluxes were described in Onodera et al. (2015). The structures of radiolarians and copepods captured in ~~by~~ the same traps were reported in Ikenoue et al. (2015) and Matsuno et al. (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 2~~1~~. 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 ±0.2 d^{-1} in early winter and late summer (Fig. 4~~2~~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 2~~1~~). 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 i~~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 4.4~~3~~.

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, t~~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, t~~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 t~~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~~Turbulent 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 mmol-N m^{-2} over ~~the~~ most ~~area~~ of the Chukchi Sea shelf, whereas ~~the~~ low productivity $<$ ~~below~~ 0.1 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 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), t~~The modeled ice algal ~~shelf~~ biomass north of the Chukchi Sea was ~~consistent~~ within 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 p~~Peak values of PAR (3.5 W m^{-2} in the 2011 case, and 2.2 W m^{-2} in the 2012 case) were ~~was~~ 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 2~~1~~), despite ~~in spite of~~ thinner sea ice in August (Fig. 4b). The cyclone impact on light conditions is ~~will be~~ described in Section 4.4~~3~~.

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 include~~d~~ 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 suggest~~ed~~ 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_{NO3}) 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 μmol-N m^{-2} d^{-1}~~)~~ to ~~sea water~~seawater for the second larger peak of 82 μmol-N m^{-2} d^{-1}. The second peak value of ~ 6.6 mgC m^{-2} d^{-1} was close to the field-based estimates of 4–9 mgC m^{-2} d^{-1} on the Beaufort shelf and slopes (Gradinger, 2009) and < 10 mgC m^{-2} d^{-1} in the Arctic basins (Deal et al., 2011). ~~Thus t~~The model results indicate~~d~~ that ~~the~~ nutrients imported in the sea ice column determine~~d~~ 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 μmol-N m^{-2} d^{-1} (Fig. 9b). ~~In this regard, t~~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~~

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

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 variabilities~~y~~ in sea ice motion and ocean surface currents 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 × 10^3 kg m^{-3} and a Coriolis coefficient of 1.4 × 10^{-4} 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 m^2 s^{-1} (1.8 km^2 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 km^3 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 t~~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-f~~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 ~~10~~ 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, t~~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 a~~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, ~~T~~the model results ~~hence~~ indicate~~d~~ 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 2~~1~~). 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~~ µmol-

N m^{-2} d^{-1} ~~at the depth of 180 m~~ in mid-August following the ice algal bloom (Fig. 9c). Flux > ~~The flux above~~ 8 μmol-N m^{-2} 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~~ originating~~ed~~ 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 μmol-N m^{-2} 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 μmol-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 sediment~~s~~. 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., ~~Lilinas,~~ 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, ~~M~~most 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~~ trace~~d~~ 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 (Fig~~s~~. 4f).

During the cyclone event with high ~~enlarged~~ wind speeds (Table 2~~1~~), ~~the~~ vertical mixing of nearly 10 cm^2 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 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 reduce~~s~~ ~~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}. Gradinger (2009) reported that the minimum requirement for ice algal growth was typically < 1 μE m^{-2} s^{-1} based on laboratory incubation experiments. When the relationship of 1 W m^{-2} ~ 4.56 μE m^{-2} 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 mmol-N m^{-2} (cf. 0.7 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 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 mmol-N m^{-2}, (cf. 1.0 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 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 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 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 mmol-N m^{-3} on March 1. The rate of IF grazing on ice algae was calculated following the Ivlev relationship:

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

where the maximum grazing rate Grz_{max} of 0.4 d^{-1} at 0 °C, the Ivlev constant λ of 1.4 (mmol-N $m^{-3})^{-1}$, and the feeding threshold value IA* of 0.04 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 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:

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

where $\mathrm{Grz}_{\max}$ of 0.4 d^{-1} and λ of 1.4 (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 μmol-N m^{-3} arising in mid-August yielded a grazing rate Grz of 2.8×10^{-4} d^{-1}. As the ZL concentration was still nearly 50 μmol-N m^{-3} in the upper 50 m, the grazed amount of fPON was 0.014 μmol-N m^{-3} 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, zooplankton would not efficiently capture fast-sinking aggregates as shown in Lake Saroma (Nishi and Tabeta, 2005). Suspended algae are rather preferable for zooplankton growth (Michel et al., 1996).

6~~5~~. Summary

~~The western Arctic b~~Biogeochemical structures in the western Arctic were addressed using a sea ice-ocean modeling approach~~es~~. 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 ~~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~~1~~. 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 (cm^2 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 (μmol-N m^{-2} 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. ~~(c-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 exceeded~~s~~ 5 ~~10~~ cm s^{-1} in the (c, e) 2011 and (d, f) 2012 periods~~cases~~ ~~-~~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 m^2 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 (μmol-N m^{-2} 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 (μmol-N m^{-2} 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.