Author's Response

Dear editor and two anonymous referees,

All comments by two anonymous referees were constructive and helpful to revise the manuscript. We greatly appreciate two referees and editor. A point-by-point response to the reviewer's comments are the same as the contents in the reply to the specific comments by referees #1 and #2.

Two figures (Figs. 5 and 6) are newly prepared in the revised manuscript. Table A1 is removed and moved to the supplementary material.

In the last part of this document, a marked-up manuscript version is prepared. Almost text corrections text are shown in the editorial record.

Best Regards,

Jonaotaro Onodera

Review comments by Referees #1 and #2, and the author's reply

Abstract

-We studied time-series fluxes of diatom particles and their relationship to hydrographic variations from 4 October 2010 through 18 September 2012 using bottom-tethered sediment trap moorings deployed at Station NAP (75 N, 162 W; 1975m water depth) in the western Arctic Ocean.

I think it is misleading to mention that you studied diatom fluxes in relation to hydrographic variations as no in-situ measurements of hydrographic conditions were collected or presented. Also, please specify that there are 2 traps deployed and mention their deployment depths in the Abstract.

The sentences were revised as "We studied time-series fluxes of diatom particles and their relationship to simulated hydrographic variations from 4 October 2010 through 18 September 2012 using bottom-tethered sediment trap moorings with two sediment traps deployed at 180 m and 1300 m depths at Station NAP (75°N, 162°W; 1975-m water depth) in the western Arctic Ocean."

L2 p15216: replace “through” by “to”

The word “through” was replaced by “to”.

L7 p15216: 98 taxa are plural and should be “98 taxas”.

The word “taxa” is plural form of “taxon” as far as I know. We did not change this word.

Introduction

-The sea-ice decrease and related oceanographic changes, such as increases in water temperature...

The relationship between a decrease in sea ice and an increase in water temperature is not as straightforward as the authors describe here. Please clarify if the following statement regarding enhanced primary production is related to a decrease in sea ice or an increase in temperature and support with appropriate references.

This sentence was removed during the re-organization of sentences in the introduction.

-...recent environmental changes have influenced the diatom flora and diatom productivity (e.g. Arrigo et al., 2008, 2012; Lowry et al., 2014)

It is not appropriate to cite these papers to discuss diatom flora and productivity as these studies present satellite-derived results and do not mention diatoms. It is not possible to distinguish the type of phytoplankton associated with chl a measurements obtained from remote sensing.

The sentence and references were revised as follows. “Diatoms are one of the dominant phytoplankton in the Chukchi Sea (Sukhanova et al., 2009; Coupel et al., 2012; Joo et al., 2012; Laney and Sosik, 2014), and the recent environmental changes have influenced the diatom flora and phytoplankton phenology (Arrigo et al., 2012; Ardyna et al., 2014).”

-In the cryopelagic Canada Basin, where the major primary producer is picoplankton, the biogenic particle flux into the deep sea has been quite low (Honjo et al., 2010).

Please provide values and contrast them with other regions of the Arctic Ocean.

In the re-organization of Introduction section, the sentence was rewritten as follows. “In the cryopelagic Canada Basin, where the major primary producer is picoplankton, the biogenic particles are remineralized in the upper water column and particulate organic carbon (POC) supplied into the deep sea are essentially composed of allochthonous old carbon (Honjo et al., 2010).” The POC values in the cryopelagic Canada Basin (Honjo et al., 2010) and at Station NAP (Watanabe et al., 2014) were added in the introduction.

-The decrease in sea-ice cover results in the intensification of the Beaufort Gyre (McPhee, 2013). . .
This sentence suggests that the decrease in sea ice cover leads to the intensification of the Beaufort Gyre when in fact the geostrophic current intensification appears to have played a significant role in the recent disappearance of old ice in the Canada Basin (McPhee, 2013). McPhee states that the intensification of the Beaufort Gyre seems to be the result of atmospheric forcing and not of a decrease in sea ice cover. This statement must be clarified.

As the referee #1 pointed out, the description regarding McPhee (2013) was incorrect. The sentence was partially removed and was rewritten as "The decrease in sea-ice cover results in deepening of the nutricline in the central part of the Beaufort Gyre (McLaughlin and Carmack, 2010; Nishino et al., 2011a), …"

-. . .and deepening of the nutricline (Nishino et al., 2011a). . .
Actually, Nishino et al. state that a decrease in sea ice may either enhance or reduce the biological pump (deeper or shallower nutricline) depending on ocean circulation.
So again, this statement is not accurate and the literature is not cited appropriately.

The deepening of the nutricline is estimated in the central part of the Beaufort Gyre. According to Nishino et al. (2011), shallower nutricline will be observed in the edge part of the gyre. The description "deepening of the nutricline" is revised as "deepening of the nutricline in the central part of the Beaufort Gyre".

-. . .whereas there has been no year-round monitoring study of settling particles except for that by Watanabe et al. (2014).
This should be reformulated as results presented in this study are in large part the same as presented in the Watanabe et al. paper.

This part was rewritten as follows: "Based on the first year-round monitoring of settling particle flux in the southern Northwind Abyssal Plain by Watanabe et al. (2014), it was suggested that the large amount of settling biogenic and lithogenic particles in November-December 2010 was transported from the Chukchi Sea shelf by the westward advection of cold eddy which developed around the off Barrow Canyon in early summer 2010."

-The only previous report on a time-series of diatom fluxes in the basin of the Arctic

Ocean is that by Zernova et al. (2000). . .
Although the deep Fram Strait is not a central basin, it would be worth mentioning that long-term diatom fluxes were also reported by Bauerfeind et al. (2009) at the HAUSGARTEN observatory.

Based on the suggestion, Bauerfeind et al. (2009) was newly included in the Introduction.

The information and references presented in the introduction are relevant but not well organized. Some sentence cut the flow of the text as L12 p15217, which link with the text before and after is not clear.

The sentences and some references in the introduction was re-organized.

I would expect to have the proportions of diatoms in the total carbon fluxes over the shelves and basin. Such information would help to understand the importance to monitor the diatoms flux offshore where picoplankton actually dominates the production.

With the reference by Ardyna et al (2011), difference of dominant phytotplankton in eutrophic and oligotraphic waters were shortly mentioned in the introduction.

You cite a previous work of Watanabe et al., (2014). The main result of its studies should be presented in the introduction. Same for the Zernova et al. (2000), what is their main finding? There is few information about sedimentation rates offshore so you need to present them.

The main results of Watanabe et al. (2014) and Zernova et al. (2000) were presented. The difference of this study from Watanabe et al. (2014) was also written in the revised introduction.

L9 L13 p15218: Be cautious, the results observed at a unique station cannot be extrapolated to the whole western Arctic Ocean. For example, the Canada basin exhibits different hydrography and communities than the Chukchi borderland and sedimentation dynamics are certainly different there.

As you mentioned, there are differences in hydrography and communities. In the sentence describing objectives of this paper, target area was corrected as “the Northwind Abyssal Plain” from “the Western Arctic Ocean”.

L 21 p15216: I don’t think temperature is the main factor of increasing primary production over the shelf. What about light? Nutrients?

As far as I refer the paper by Wang et al. (2013), temperature was the main factor for increasing primary production in future. However, the biological reaction to environmental change is various in the Arctic Ocean. The description "such as temperature" was removed from the sentence.

L23 p15216: I suggest "dominant phytoplankton"
The words "major phytoplankton" was changed to "dominant phytoplankton".

L1 p15217: "has been quite low". Why use the past, it is not low anymore?
We used the words as a present participle. The words "has been quite low" were simply rewritten as "is quite low".

L3 to L5 p15217: I suggest to merge these two sentences and reformulates by using "zooplankton fecal pellets" and "shell-bearing microplankton" as the subjects of the sentence.
The sentences were merged and rewritten as follows. "The low productivity of shell-bearing microplankton and zooplankton fecal pellets, which have a role as ballast for settling organic matter, limits the function of biological pump in the oligotrophic cryopelagic Canada Basin (Honjo et al., 2010)."

L8 p15217: deepening of the nutricline. The reference to McLaughlin and Carmack 2010 should be added.
The reference "McLaughlin and Carmack 2010" was added.

L17 p15217: Bad tense used. I suggest begin the sentence by "While the shelf has been substantially monitored, the year round studies. . .over the basins. . ."
The sentence was revised. "While the shelf and shelf slope areas of the Arctic Ocean where there have been substantially monitored (i.e., Hargrave et al., 1989; Fukuchi et al., 1993; Wassmann et al., 2004; Forest et al., 2007, 2011; Gaye et al., 2007; Sampei et al., 2011), the year-round study of sinking biogenic particles over the basins is still limited, except for a few studies (Fahl and Nöthig, 2007; Lallande et al., 2009; Honjo et al., 2010; O'Brien et al., 2013).

L23 p15217: "whereas" wrong term.
The sentence "…(Honjo et al., 2010) whereas there has been…" was revised as "…(Honjo et al., 2010). However, there has been…".

L29 p15217: replace “among” by “between”.

The word “among” was replaced to “between”.

Material and Methods

-Because the moored sediment trap array at Station NAP did not include equipment to measure current velocity, temperature, or salinity (i.e., acoustic Doppler current profiler [ADCP] or conductivity–temperature–depth [CTD] sensors). . .

If there were no equipment to measure temperature, how come water temperatures recorded at the shallow trap are presented in the Results and figure 2? The pressure and temperature sensor mentioned in the Results section must be described in the Material and Methods section.

Temperature and pressure sensors have been mounted on the sediment trap. Water temperature at moored trap depth presented in text and Fig 2 is based on the monitoring data by these sensors. The sentences were revised as follows. “The deployed sediment trap mounts pressure and temperature sensors. Because the moored sediment trap array at Station NAP did not include equipment to measure current velocity, and salinity, …”

There is some useless information presented in this section, which make the reading difficult. I underline some of them in the specific comments. I’m not familiar with models and I would like to have a more clear explanation of the models used and its parameterization. I don’t really understand how the initial conditions are chosen and how these conditions affect the model. Why changing to COCO 3.4 and NCEP1?

The methods for model study were rewritten. All the specific comments were applied to correct the text. We hope the revised method section is easier to understand.

The end of the section is imprecise. I don’t understand which “seasonal experiments” and which “major variability” you talking about. Please precise the parameters and experiments you describe.

The sentences in the end of this section were rewritten.

L12 p.15218: removed “twice” and add “Two” at the beginning of the sentence.

The sentence was collected as suggested.

L15-16 p.15218: unclear, it look like you sample each 10-15 days? Specify if it’s an automatized system? If it’s automatized why not choose the same time lag between each sampling? Please provide more information about the sampling method here.

The sampling schedule was manually decided. High resolution sampling (10days interval) was set for late spring - summer, instead sampling resolution became low (15days) for fall-winter.

L16 p.15218: Remove “The record . . .show that”

Deleted.

L17-18 p.15218: By reading this sentence I first understand the trap depths vary from 60m to 80m along the experiment. Then I understand two traps were deployed by depth. Please clearly indicate there are two traps at shallow depths (180m and 260m) and two traps at deep depth (1300m and 1360m).

In order to avoid the misleading, the sentence was revised.

L19 p.15218: Indicate quickly what is the purpose of the neutralized formalin.

The words “as an antiseptic (pH~8.2)” were added.

L20 p.15218: change “all of the . . . traps” by “the samples from both traps except the one. . .”

The sentence was changed based on the suggestion.

L21 p.15218: Why some traps have very low volume? Have you a technical reason to support the fact you discard them from the analysis? If not you will bias the quantitative measurements by removing them from the study.

Some samples with very low particle volume are essentially reflecting low flux of settling particles rather than technical problem of trapping settling particles. The temporal deepening of moored sediment trap in July 2012 might affect the trapping efficiency as mentioned in text. The sample volume of those samples were too low to analyze the bulk component and diatom analysis. In this study, quantitative measurements for annual flux was not conducted.

L24 p.15218: What is the difference between the pore size and the grid size?

The pore size determines the particle size remained on the filter. The grid size means the interval of printed grid lines on the filter. The microscopic observation was conducted along the grid lines.

Results

There is still a large amount of sea ice algae collected in the upper trap when there is no more ice at the end of August and in September 2011. As the ice recedes towards the north, could it be that these ice algae fluxes actually reflect lateral advection from the north?

The sea ice-related diatom *Fossula arctica*, which was dominant in summer 2011, is observed as not only an attached form to sea ice but also as a plankton (Cramer, 1999). In addition to our diatom data, occurrence of the Pacific water copepods in the summer 2011 also suggests the temporal input of shelf waters into the studied region. Although we do not have the *in situ* observation data on primary productivity and plankton biocoenosis at Station NAP in summer 2011, high diatom productivity supported by the advected nutrient-rich shelf waters and high flux of settling diatoms are estimated with the simulated hydrographic situation of summer 2011.

-*Melosira arctica*, which was commonly observed at Station LOMO2 (Zernova et al., 2000) and under summer sea ice in the Amundsen and Nansen basins (Boetius et al., 2013), was rarely observed in the studied samples...

Melosira arctica was not commonly observed under sea ice by Boetius et al. in the Amundsen and Nansen Basins, it was rather commonly observed on the deep seafloor of the Arctic basins. Also, even if *Melosira arctica* was rarely observed, information should be provided regarding how much and when.

It would also be interesting to present the proportion of intact cells vs resting spores, which could potentially inform on the origin of the ice algae (and ice).

The description was corrected based on the comment and additional paper (Lallande et al. 2009). Because the abundance of *Melorira arctica* was very low in this study, the occurrence notice of *M. arctica* was plotted in Figure 3c and 3d. The flux data of *M. arcitica* is included in supplementary data table. Unfortunately, I did not distinguish the intact cells from all encountered diatoms during the cell counting work for all samples.

I found the result clearly presented. However, the description of the Figure 3c and 3d are difficult to follow. The results referring to the shallow traps should be more clearly differentiate from the results associated to the deep traps. To increase the clarity of section 3.3, I suggest to present first the upper trap and then depict the difference and similarity observed in the deep trap like the author has done in the first paragraph of the 3.3 sections. I like the idea to present a temporal succession of species but the authors should clearly keep the timeline when describing the figure.

The description of Figure 3c and 3d were revised. The time-series succession of major diatom species were described. In addition maximum value of relative abundances for dominant species, and difference in settling diatom flora between shallow and deep traps were written.

The tables A1a, A1b are far too long. I suggest a table with average values of the parameters for relevant time period/seasons and move the full table as a supplementary material.

We ask the editor to move these tables to supplementary material.

End of 3.1: How currents could deepens the trap. I expect the opposite effect; currents should incline the mooring and thus decrease the depth.

As you expected, the temporal deepening of sediment trap moored-depth is due to the incline of the bottom-tethered mooring by intensified currents. We slightly modified the sentence.

L10-11 p.15221: Please mentioned the exceptionally low fluxes and bulk content in the entire years 2012 and provide some values to compare with 2010 and 2011. What kind of particle is represented by the white color in 2012 (figure 2e)?

The white area of bulk component in Fig 2e represents that no bulk component analysis was fully/partially conducted because of limited sample volume. This is shortly mentioned in the last sentence of figure caption for Fig 2e.

L10-11 p.15222: I don't agree. There is interesting difference between shallow and deep traps. The summer peak is significantly higher than the winter peak at deep traps, the summer material seems more preserved than the winter material. You should present and discuss these facts in the discussion section.

The description was revised based on the comment as follows. "The high diatom flux season at the deep trap depth was similar to that at the shallow trap depths (Fig. 3a, b). However, there was different from shallow trap data that total diatom flux at deep trap in summer 2011 was higher than that in winter maxima." Although I do not have the certain evidence, the possible reason of minor winter flux maximum at deep trap is not only decomposition of biogenic particles but also the horizontal diffusion effect of settling particles in deep sea under the eddy as simulated by Siegel et al (1990). This was shortly included in the last paragraph of Discussion section 4.2.

L4-6 p.15224: Explain why the fact you just find the needle-like valve rather than the intact cells indicate a high diatom POC flux from Rhizosolenia and Proboscia.

Because I did not distinguish the intact cells from all encountered diatoms during the counting work, diatom POC flux derived by diatom cell size and count data (including empty cells) sometime become overestimate and exceed total POC flux. The genera *Rhizosolenia* and *Proboscia* have a large carbon content per cell while there occurrences in November 2011 were as usually needle-like end part of empty *Rhizosolenia* and *Probosocia* cells.

L7-9 p.15222: Remove "in contrast" because you start a new idea here. To highlight the fact it's the highest values I suggest to write "The maximum fluxes reached . . . and . . . in winter 2010 and 2011, respectively.

The sentence was changed based on the suggestion.

L24 p.15222: How dominance can be low?

The sentence was corrected as follows. "The observed relative abundance of sea ice-related diatoms in total diatoms was less than 23% in summer 2012."

L29 p.15222 to L3 p.15223: These sentences are repetitive to express just one idea. It can be reduce to " The biogenic materials collected in this study were primarily of marine origin. Â˙z. By the way, such general observation should be at the beginning of the paragraph about species composition.

Based on the suggestion, the sentence "The diatoms encountered … species." was deleted. The following sentence "Because diatom species usually observed … were primarily of marine origin." was moved to the upper part of paragraph on diatom species composition.

L19-22 p.15223: The sentence is unclear. Please reformulate maybe split in two sentences.

The sentence was split in two sentences.

L26 p.15223: *Chaetoceros* appear very low on the Fig. 4. So I would not consider this group as a dominant one for POC flux. Conversely, *Thalassiosira* appear an important group to consider for POC flux.

There was mistake in the legend of Fig. 4. The legends of *Chaetoceros* and *Thalassiosira* must be swapped. In addition, the graph data for *Chaetoceros* contains the data both vegetative cells and resting spores. *Chaetoceros* vegetative cells rather than spores were important for POC flux. The text "(resting spores)" was deleted.

L2 p.15224: The name "*Fossula arctica*" doesn't appear on the graph 4 so I suggest to write "The ice-related algae *F. arctica*. . ..".
We changed the sentence as referee #2 suggested.

Discussion

-In contrast to the situation in 2011, the limited influence of shelf-origin sea-ice and shelf waters around Station NAP in 2012. . .
Here it is implied that the ice does not have the same origin in 2011 and 2012, while sea ice concentration was similar for both years. Again, the origin of the ice could be further discussed using backtracking with satellite data. The authors should make a distinction between water and ice origin.

The additional figures (Figs. 5 and 6) representing sea ice flow by satellite and our model was prepared. Regarding to the addition of new figures, text in the method section was revised. We think that the additional data and our interpretation on settling diatom fluxes are not contradict. Previous Figures 5 and 6 were re-numbered as Figures 7 and 8, respectively.

A statement made in the Introduction: . . .the intensification of sea-surface circulation resulting from the sea-ice decline promotes lateral shelf–basin interactions (Nishino et al., 2011b; Watanabe and Hasumi, 2009)...
If a decline in sea ice results in an intensification of circulation promoting lateral shelf basin interactions, then a larger lateral advection of matter due to more frequent eddies should have been recorded in 2012 due to the record low ice extent. The authors should discuss the fact that their results in 2012 contradict their introductory statement.

The increasing eddy formation by sea-ice decrease is clary observed in decadal time scale. In the intra- and interannual time scale as discussed in this paper, eddy formation also reflects a condition of wind systems. As far as we see the simulated hydrographic condition, the eddy-induced lateral transport of shelf materials to Station NAP is the event of early winter. It is considered that the advected shelf materials transported by eddies do not directly influence to the summer diatom flux. In schematic view point, the eddy track is observed along the edge of the Beaufort Gyre. However, Station NAP in summer 2012 was within the Beaufort Gyre rather than the edge of gyre, and we may not clearly detect the eddy's influence in the settling particles at Station NAP in October-December 2012. The studied period of this paper ends in early September 2012, and the following samples are under the analysis from last month. The results from October 2012 will be shown in another paper in future. In addition, our co-author Dr. Eiji Watanabe is working on the physical oceanographic study in detail now. The confirmation of eddy formation along the shelf break of western Arctic Ocean in summer 2012 and the relationship with decreased sea-ice condition are the out of objectives in this paper, but will be presented in other papers.

Also, as the eddy-induced biological pump would be enhanced by sea ice retreat, how can you explain that the model showed the presence of a drifting anti-cyclonic cold eddy in October-December 2010 only but not in 2011 or 2012?

Although the model experiment for eddy advection at Station NAP was conducted for the hydrographic situation only in November-December 2010 because of limited super computer resource, eddy occurrence and westward advection along the edge of Beaufort Gyre is commonly figured. As the cause of particle flux maxima in November-December of 2010 and 2011, westward advection of eddies originated from off the Barrow Canyon are the strongest candidate to explain the results. Another mooring at Station NAP from October 2013 to September 2014 has deployed current meter and other equipment such as CTD and chlorophyll sensors. Further discussion on the material advection will be proceeded in near future.

Finally, there is a distinct important physical event occurring in July 2012 (recorded from the pressure-temperature sensor) that is not discussed in the manuscript. The authors should explain what caused the trap to go deeper and into warmer waters. A similar event also appears to have occurred in May 2012.

This physical event had been mentioned in the last part of section 3.1 "Oceanographic features and mooring conditions". The temporal deepening of bottom-tethered trap usually reflect a tilted mooring by strong lateral current. Because deployment of current meter with sediment trap started from the next deployment after October 2012 we do not have the certain evidence on this event. Just as one possibility, cyclones in the Arctic Ocean for July 2012 might be influenced to the temporal hydrographic change around the study area. Although the deepening of shallow trap in May 2012 was minor compared to that in July 2012, the increase of water temperature at shallow trap depth suggests the shallowing boundary of the Pacific and the Atlantic water layers. The event in May

2012 was shortly mentioned in the revised manuscript. The cyclone in May 2012 shortly passed over Station NAP, which might cause the temporal upwelling of the Atlantic water.

In section 4.1, the beginning of the paragraph should be better presented. I suggest to first present your hypothesis of the advection of shelf waters. After, you could detail the different findings and observations that drive you to such conclusion.

The one sentence was added as follows. “Because the phytoplankton productivity and phytoplankton assemblage is clearly different between the Chukchi Sea shelf and the Canada Basin, the settling diatom flux at Station NAP should reflect the times-series hydrographic variations.”

I not convinced with the last sentence of the section. All along you explain diatoms are probably advected from the shelf in 2011 while oligotrophic waters are advected in 2012. Then you conclude a highest primary production in 2011 but you don’t have any measures of primary production or nutrient. Moreover, if the diatoms are advected, they don’t support local primary production. Please provide more clues to support such conclusions.

The term of primary productivity in the section 4.1 had to be replaced to diatom flux because we have no time-series observation data regarding primary productivity. We just suggested the influence of shelf waters rather than variation of primary productivity at Station NAP.

I enjoy reading the section 4.2 and 4.3 that are well written and very interesting. I pointed out the term "unique" in L18 p.15227. Maximum winter diatom fluxes were observed both in 2010 and 2011 and not at a unique occasion. Are the cold-eddies mechanisms responsible for these two maxima? Is there evidence than cold-eddies propagates mainly in autumn-early winter?

We removed the word “unique” from the sentence. Although the model experiment for eddy advection at Station NAP in November-December 2011 was not conducted, eddy occurrence and westward advection is usually figured in the southwestern Canada Basin. As the cause of particle flux maxima in November-December of 2010 and 2011, westward advection of eddies originated from off the Barrow Canyon are the strongest candidate to explain the results.

L13-17 p.15228: I’m not sure about the relevance of this comparison, the Honjo et al.,

(2010) trap was deployed largely deeper (3067) which could easily explain the lower fluxes.

According to schematic diagram in Honjo et al. (2010), lower POC flux in subsurface of Canada Basin is estimated. The POC flux at ~120 m depth at 75°N and ~200 m depth at 80°N in the Canada Basin is about 10 and 7 mmol m^{-2} yr^{-1}, respectively. The annual POC flux at Station NAP for the first deployment period is about 27 and 20 mmol m^{-2} yr^{-1} at shallow and deep traps, respectively.

L17-18 p.15224: It's more precise to say the presence of *F.Arctica* suggest the presence of sea-ice transported from the Chukchi shelf.

The sentence was changed based on the suggestion. "The high dominance of *Fossula arctica* at Station NAP in summer 2011 suggests the presence of sea-ice transported from the Chukchi Sea shelf."

L23-26 p.15224: Please write the full name *Proboscia eumorpha* to facilitate the understanding.

The words "*P. eumorpha*" in the sentence was replaced by "*Proboscia eumorpha*".

L6 p.15225: "suppress" must be change by "absence of" in the whole section.

Instead of the word "suppress", "lower", "reduce" or "absence of" were used in the section.

L20 p.15225: Unclear, what did you compare with 2011: the position or the height of the gyre.

The sentence was rewritten as follows. "The COCO model demonstrated that the sea-surface height was higher over the entire western Arctic basin and the maximum height was located more to the western side of the basin in summer 2012 than those in summer 2011."

The marked-up manuscript

Diatom flux reflects water-mass conditions on the southern Northwind Abyssal Plain, Arctic Ocean

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ABSTRACT:

We studied time-series fluxes of diatom particles ~~and their relationship to simulated hydrographic variations~~ from 4 October 2010 ~~through~~ to 18 September 2012 using bottom-tethered ~~sediment trap~~ moorings with two sediment traps deployed at 180 m and 1300 m depths at Station NAP (75°N, 162°W; 1975-m water depth) in the western Arctic Ocean. This paper discusses on the relationship of time-series diatom fluxes with satellite-based sea ice motion and simulated hydrographic variations. We observed clear maxima of the diatom valve flux in November–December of both 2010 and 2011, and in August 2011. Diatoms in samples were categorized into 98 taxa. The diatom flux maxima were characterized by many resting spores in November–December and by the sea ice-associated diatom *Fossula arctica* in August 2011. These assemblages along with abundant clay minerals in the samples suggest a significant influence of shelf-origin materials transported by mesoscale eddies, which developed along the Chukchi Sea shelf break. In contrast, the fluxes of total mass and diatoms were reduced in summer 2012. We hypothesize that this suppression reflects the influx of oligotrophic water originating from the central Canada Basin. A physical oceanographic model demonstrated that oligotrophic surface water from the Beaufort Gyre was supplied to Station NAP from December 2011 to early half of 2012.

KEY WORDS: diatom, phytoplankton, sinking particle flux, sediment trap, Northwind Abyssal Plain, Arctic Ocean

1. Introduction

There are numerous studies reporting the significant influence of the recent declining trend in Arctic sea-ice extent (Stroeve et al., 2012) on marine ecosystems (i.e., Grebmeier et al., 2010; Wassmann and Reigstad, 2011; Wassmann et al., 2011). ~~The sea-ice decrease and related oceanographic changes, such as increases in water temperature, allow enhanced primary production in the Chukchi Sea (Wang et al., 2013). Diatoms are one of the major phytoplankton in the Chukchi Sea (Coupel et al., 2012), and the recent environmental changes have influenced the diatom flora and diatom productivity (e.g. Arrigo et al., 2008, 2012; Lowry et al., 2014). In the cryopelagic Canada Basin, where the major primary producer is picoplankton, the biogenic particle flux into the deep sea has been quite low (Honjo et al., 2010). The limited functioning of the biological pump essentially results from the low productivity of shell-bearing microplankton and zooplankton in oligotrophic waters (Honjo et al., 2010). The shell-bearing microplankton have a role as ballast for settling organic matter, and zooplankton produce fecal pellets. Both of these types of particles are important in biological pump processes.~~

In the Canada Basin of ~~in~~ the western Arctic Ocean, t~~T~~he decrease in sea-ice cover results in ~~the intensification of the Beaufort Gyre (McPhee, 2013) and~~ deepening of the nutricline in the central part of the Beaufort Gyre (McLaughlin and Carmack, 2010; Nishino et al., 2011a)~~, whereas improved light penetration may support primary production in the deep chlorophyll maximum layer (Yun et al., 2012)~~. ~~In addition, t~~The intensification of sea-surface circulation ~~resulting from the sea-ice decline~~ promotes lateral shelf–basin interactions (Nishino et al., 2011b; Watanabe and Hasumi, 2009), which influence to ecosystems and biogeochemical cycles. ~~The upper water column in the Chukchi Borderland can be affected by three characteristic water masses: Pacific water, East Siberian Shelf water, and Beaufort Gyre water (Nishino et al., 2011a). As one of the major contributors to the biological pump, diatoms in the offshore regions along the Chukchi Sea shelf are likely affected by these recent dramatic environmental changes.~~

~~Compared to~~While the shelf and shelf slope areas of the Arctic Ocean ~~where there have been many~~have been substantially monitored~~ing studies~~ (i.e., Hargrave et al., 1989; Fukuchi et al., 1993; Wassmann et al., 2004; Forest et al., 2007, 2011; Gaye et al., 2007; Sampei et al., 2011), the year-round study of sinking biogenic particles ~~in~~ over the ~~Arctic Ocean~~ basins is still limited, except for a few studies (Fahl and Nöthig, 2007; Lallande et al., 2009; Honjo et al., 2010; O'Brien et al., 2013). In the cryopelagic Canada Basin, where the major primary producer is picoplankton, the biogenic particles are remineralized in the upper water column and particulate organic carbon (POC) supplied into the deep sea are essentially composed of allochthonous old carbon (Honjo et al., 2010). The low productivity of shell-bearing microplankton and zooplankton fecal pellets, which have a role as ballast for settling organic matter, limits the function of biological pump in the oligotrophic cryopelagic Canada Basin (Honjo et al., 2010).~~In the Chukchi Borderland, the ice-tethered drifting sediment trap "S97-120m" was deployed in 1998 (Honjo et al., 2010), whereas there has been no year-round monitoring study of settling particles except for that by Watanabe et al. (2014).~~ A long-term sediment trap experiment containing observation of diatom fluxes have been conducted in the Fram Strait (Bauerfeind et al., 2009). The only previous report on an annual time-series of diatom fluxes in the basin of the Arctic Ocean is that by Zernova et al. (2000), whose target region was at Station LOMO2 off the Laptev Sea. Zernova et al. (2000) showed high diatom production and high settling fluxes of diatom particles under sea-ice at Station LOMO2 during the seasonal maximum of solar radiation. Lallande et al. (2014) compared short-term monitoring data on diatom flux in the Laptev Sea during 1995, Fram Strait in 1997, and central Arctic Ocean in 2012. They suggested that nutrient supply is the key factor for summer diatom production and POC flux in the central Arctic Basin. In the Chukchi Borderland, the ice-tethered drifting sediment trap "S97-120m" was deployed in 1998, and relatively high POC flux compared to that in the Canada Basin was observed (Honjo et al., 2010). Based on the first year-round monitoring of settling particle flux in the southern Northwind Abyssal Plain by Watanabe et al. (2014), it was suggested that the large amount of settling biogenic and lithogenic particles in November-December 2010 was transported from the Chukchi Sea shelf by the westward advection of cold eddy which developed around the off Barrow Canyon in early summer 2010.

Diatom dominances in phytoplankton assemblages are usually observed in eutrophic waters whereas dominance of flagellates and picoplankton rather than diatoms are observed in oligotrophic waters such as central basin (Ardyna et al., 2011; Coupel et al., 2012; Lallande et al., 2014). Diatoms are one of the dominant phytoplankton in the Chukchi Sea (Sukhanova et al., 2009; Coupel et al., 2012; Joo et al., 2012; Laney and Sosik, 2014), and the recent environmental changes have influenced the diatom flora and phytoplankton phenology (Arrigo et al., 2012; Ardyna et al., 2014). As one of the major contributors to the biological pump, settling diatom fluxes in the offshore regions along the Chukchi Sea shelf are likely affected by the recent dramatic environmental changes.

In this paper, we present new findings on the settling flux of diatom valves and the relationships ~~among~~ between diatom valve flux, sinking diatom flora, and upper water-mass properties in the southern Northwind Abyssal Plain from October 2010 to September 2012. The Chukchi Sea is one of the obvious areas of retreating summer sea-ice (Stroeve et al., 2012). The upper water column in the Chukchi Borderland can be affected by three characteristic water-masses: Pacific water, East Siberian Shelf water, and Beaufort Gyre water (Nishino et al., 2011a). Watanabe et al. (2014) documented the eddy-induced winter maximum of settling particle flux at Station NAP. This early-winter event should be observed in settling diatom flux. This paper newly mentions on the summer flux of settling diatom particles in addition to winter flux maximum event of diatom flux. ~~The Chukchi Sea is one of the obvious areas of retreating summer sea-ice (Stroeve et al., 2012).~~ The present paper is the first report on year-round diatom floral flux after the clear trend of declining sea-ice in the western Arctic Ocean. We expect that the recent hydrographic changes in the western Arctic Ocean will be reflected in the settling diatom flux and associated assemblages. The objectives of this paper are (1) to report the variation in diatom flux and assemblage, and (2) to consider how hydrographic changes in the upper water column are reflected in the diatom assemblage and diatom flux in the Northwind Abyssal Plain~~western Arctic Ocean~~.

2. Materials and methods

Two y~~Y~~ear-round deployments of a bottom-tethered mooring with two conical time-series sediment traps (model SMD26S-6000; Nichiyu Giken Kogyo Co. Ltd., Tokyo, Japan) were conducted ~~twice~~ at Station NAP on the southern Northwind Abyssal Plain (75°N, 162°W; 1975-m water depth) from 4 October 2010 through 27 September 2011 and from 4 October 2011 through 17 September 2012. Sediment trap with pressure and temperature sensors was deployed at shallow depth (about 180-260m) and deep depth (1300-1360m). The settling particles were collected for 10–15 days per sample. ~~The record of the pressure sensor mounted on the sediment trap shows that the sediment traps were deployed at depths of about 180–260 m and 1300–1360 m.~~ Before sediment-trap deployment, the 26 sampling cups of each trap were filled with seawater containing ~~4~~5% neutralized formalin as an antiseptic (pH~8.2). In this study we analyzed ~~all of~~ the samples from ~~shallower and deeper~~ both traps~~,~~ except ~~for some samples~~the one that contained a very low volume of trapped particles.

The recovered sediment-trap samples were sieved through a 1-mm mesh to remove swimmers (Matsuno et al., 2014), and then the fine size-fraction (less than 1 mm) was split into appropriate aliquots (1/1000) for diatom analysis by using a wet sample divider (WSD-10; McLane Research Laboratories, East Falmouth, Massachusetts, USA). One of the aliquots was filtered onto a membrane filter (0.45-µm pore size) with a 3-mm grid. The sample was desalted by rinsing with Milli-Q water, and then the sample filter was dried overnight in an oven at 50 °C. Two sample filters were prepared for each sample, and then one of the filters was mounted on a microscope glass slide with Canada balsam.

~~Diatom~~Sample filters mounted~~s~~ on the glass slides were counted for diatoms under a light microscope at 600× magnification. ~~The other~~A duplicate sample ~~filter~~ was observed~~used~~ using~~for~~ scanning electron microscope observation after osmium coating. A minimum of 400 diatom valves (including resting-spore valves) per sample were identified, usually to species or genus level. Diatom fluxes were estimated on the basis of valve counts, aliquot size, filtered area (535 mm^2), area of sample filter observed, aperture area of sediment trap ~~opening~~ (0.5 m^2), and the sampling period (Onodera et al., 2005) ~~(Appendix Table A1)~~. As described in a previous microplankton flux study in the southeastern Beaufort Sea (Forest et al., 2007), the flux of diatom-derived ~~particulate organic carbon~~POC (~~POC;~~ hereafter, diatom POC flux) was estimated on the basis of diatom cell size and an equation for converting cell volume to carbon content per diatom cell (Menden-Deuer and Lessard, 2000). The method for bulk component analysis is described by Watanabe et al. (2014).

~~Data for s~~Sea-ice concentration and light intensity ~~at the sea surface (or at the top of sea ice if present) around~~ close to Station NAP during the sampling period were obtained from the National Centers for Environmental Prediction (NCEP)/Climate Forecast System Reanalysis (CFSR) (Saha et al., 2010). Sea surface temperature (SST) at Station NAP was ~~derived~~ taken from the National Oceanographic and Atmospheric Administration (NOAA) OI.v2 SST (Reynolds et al., 2002). Because the moored sediment trap array at Station NAP did not include equipment to measure current velocity, ~~temperature, or~~and salinity~~ (i.e., acoustic Doppler current profiler [ADCP] or conductivity-temperature-depth [CTD] sensors)~~, satellite-based sea ice motion data and numerical simulation results from a physical oceanographic model known as the Center for Climate System Research Ocean Component Model (COCO) (Hasumi, 2006) were applied to estimate the sea ice and ocean current conditions in the western Arctic Ocean during the sampling period. The National Snow and Ice Data Center (NSIDC) provided the Polar Pathfinder 25 km EASE-Grid sea ice motion vectors, version 2 (Fowler et al., 2013). This dataset was constructed from multiple satellite sensors, such as Special Sensor Microwave / Imager (SSM/I), Advanced Microwave Scanning Radiometer-Earth Observing System (AMSR-E), and Advanced Very High Resolution Radiometer (AVHRR), and in-situ measurements of the International Arctic Buoy Programme (IABP). In our study, the monthly mean vector data were downloaded from the NSIDC website (http://nsidc.org/data/docs/daac/nsidc0116_icemotion.gd.html). The pan-Arctic ice-ocean model has the horizontal grid size of about 25 km and 28 vertical levels, where the layer thickness varies from 2 m in the uppermost level to 500 m below 1000 m depth. The sea ice part includes a one-layer thermodynamic formulation (Bitz and Lipscomb, 1999) and elastic-viscous-plastic rheology (Hunke and Dukowicz, 1997). The ocean component is a free-surface ocean general circulation model formulated with the uniformly third-order polynomial interpolation algorithm (Leonard et al., 1994) for horizontal advection scheme. The model domain contains the entire Arctic Ocean, the Greenland-Iceland-Norwegian seas, and the northern part of the North Atlantic. The spin-up experiment was initiated from the temperature and salinity fields of Polar Science Center Hydrographic Climatology version 3.0 (Steele et al., 2001), no ocean circulation, and no sea ice. The interannual experiment from 1979 to 2012 was then performed. ~~The model simulation was executed from 1979 to 2012.~~ Whereas most parts of experimental designs were the same as in Watanabe (2013) and Watanabe and Ogi (2013), the model version was upgraded from COCO 3.4 to 4.9 and the atmospheric forcing dataset was changed from NCEP1 (Kalnay et al., 1996) to the NCEP/CFSR in the present study. ~~, a physical oceanographic model known as the Center for Climate System Research Ocean Component Model (COCO) version 4.9 (Hasumi, 2006) was applied to estimate the condition of the upper water column in the western Arctic~~

~~Ocean during the sampling period. The horizontal grid size of this pan-Arctic ice–ocean model was about 25 km, and there were 28 vertical levels. The model simulation was executed from 1979 to 2012 using the NCEP/CFSR atmospheric forcing data. Whereas most parts of experimental designs were the same as in Watanabe (2013) and Watanabe and Ogi (2013), the model version and atmospheric forcing dataset were changed from COCO 3.4 and NCEP1 (Kalnay et al., 1996), respectively. These simulated sea-ice and ocean fields were used as initial conditions for the seasonal experiments reported in Watanabe et al. (2014). These previous analyses suggest that the model captured the major variability in the western Arctic Ocean.~~

3. Results

3.1 Oceanographic features and mooring conditions

Station NAP is located at the southwestern edge of the Beaufort Gyre (Fig. 1), and is occasionally influenced by relatively oligotrophic waters of the Beaufort Gyre (Nishino et al., 2011a). The study area is in polar night from early November through early February (Fig. 2a). The CFSR shortwave radiation at the sea surface (or surface of sea ice) ranged from 0 to 378 W m^{-2} (Fig. 2a). Station NAP is located in a seasonal sea-ice zone, and is covered by sea-ice from late October through July (Fig. 2b). Sea surface temperature temporarily increased to about 2 °C in early August in 2011 and 2012 (Fig. 2d~~e~~).

The upper water column around the study area is categorized by four water masses (McLaughlin et al., 2011). Under the surface mixed layer (about the upper 25 m), Pacific summer water is observed at 25–100 m water depth (salinity approximately 31–32; Steele et al., 2004). Cold Pacific winter water (temperature minimum at 150 m, salinity around 33; Coachman and Barnes, 1961) is found under the Pacific summer water (100–250 m water depth). Higher salinity water originating from the Atlantic Ocean is observed under the Pacific winter water.

According to the logged data from pressure and temperature sensors attached to the sediment traps, the shallower sediment trap was moored at a water depth of 181–218 m (median, 184 m) for the first deployment period, and at 247–319 m (median, 256 m) for the second (Fig. 2c). Therefore, the shallow trap was in Pacific winter water during the sampling period, except for in May and July 2012 (Fig. 2c, d). In July 2012, the depth of the shallower trap ~~increased~~

deepened to 320 m in the warm Atlantic water layer, probably because of intensified water currents and incline of mooring, which might have temporarily decreased the trapping efficiency for sinking particles (Matsuno et al., 2014). Although the deepening of shallow trap in May 2012 was minor compared to that in July 2012, the increase of water temperature at shallow trap depth suggests the shallowing upper boundary of the Atlantic water layer. The deeper sediment trap was moored at 1318–1378 m for the entire sampling period.

3.2 Total mass flux and bulk components

As previously reported by Watanabe et al. (2014), the total mass flux showed clear annual maxima in November–December in both 2010 and 2011 (Fig. 2e, f). The major component of trapped particles was lithogenic silt-clay minerals (Fig. 2e). There was another peak in total mass flux in summer 2011, but this summer peak did not appear in 2012. The time-series of biogenic opal flux showed variations similar to those of total mass flux ($r = 0.93$ for shallow trap data, $n = 34$)~~, and biogenic opal flux increased in November–December~~ (Fig. 2e). Microscopic observation suggests that the biogenic opal in the studied material consisted mainly of diatom valves and radiolarian shells (Ikenoue et al., 2014). The trap samples also contained low numbers of silicoflagellate skeletons, siliceous endoskeleton of dinoflagellate genus *Actiniscus*, chrysophyte cysts, ebridian flagellate~~,~~ and palmales. The contribution of these siliceous flagellates to POC and biogenic opal fluxes~~ in this study~~ appears minor compared to the contribution from diatoms and radiolarians. This result is different from a previous ~~study~~ observation on the Mackenzie Shelf in the southwestern Beaufort Sea that showed a significant contribution by small flagellates to the POC flux~~ on the Mackenzie Shelf in the southeastern Beaufort Sea~~ (Forest et al., 2007).

3.3 Diatom valve flux and species composition

The total diatom flux captured in the shallow trap showed clear seasonality (Fig. 3a). A relatively high flux of diatom valves was observed in November–December 2010, August–September 2011, and November–December 2011 (Fig. 3a). The sinking diatom flux rapidly increased in August 2011, when the sea-ice retreated at Station NAP (Figs. 2b, 3a). The maximum of the total diatom flux at the shallow trap depth in summer 2011 reached 11.3 × 10^6 valves m^{-2} d^{-1} in the period from 18 to 31 August. This maximum was approximately 28% of the diatom flux maximum at Station LOMO2 (150-m trap depth) in summer 1996 (Zernova et al., 2000). In 2012, a seasonal increase in total diatom flux started after June. However, in contrast to summer 2011, there was no clear maximum of diatom flux as the same as low total mass flux in June–September 2012. ~~In contrast, t~~The ~~flux~~ maximum fluxes reached 17.5 × 10^6 valves m^{-2} d^{-1} and 10.8 × 10^6 valves m^{-2} d^{-1} in early winter 2010 and 2011~~ reached 17.5 × 10^6 valves m^{-2} d^{-1} and 10.8 × 10^6 valves m^{-2} d^{-1}~~, respectively. The ~~seasonality~~ high diatom flux season~~in total diatom flux~~ at the deep trap ~~depth~~ was similar to that at the shallow trap~~ depths~~ (Fig. 3a, b). However, there was different between two traps that total diatom flux at deep trap in summer 2011 was higher than those in early winter maxima of 2010 and 2011.

The diatoms found in all samples examined were categorized into 98 taxa (Table 1). Because diatom species usually observed in fresh or low-salinity water were very rare, the biogenic materials collected in this study were primarily of marine origin. In the shallow trap samples, t~~T~~he genera *Thalassionema* and *Chaetoceros* (subgenus *Hyalochaete*) were the major components~~ in shallow trap samples~~ from late October 2010 to early July 2011 ~~and from late November 2011 to early July 2012~~ (Fig. 3c~~, Table A1~~). *Chaetoceros* relatively increased in late November-December 2010. *Thalassionema* relatively increased in the low flux period and reached to 70% in March 2011. Then, t~~The relative abundances of~~ *Fragilariopsis* (*oceanica* and ~~*F.*~~ *cylindrus*), which are sea ice-related diatom species (Ren et al., 2014), gradually increased from April to August 2011. The sinking diatom assemblage in summer 2011 was mainly composed of *Fossula arctica*, one of the common sea-ice diatoms in the Arctic Ocean (Cremer, ~~1998~~1999; von Quillfeldt, 2003). The maximum relative abundance of *F. arctica* was 80% in 14-28 September 2011. After the period of *F. arctica* dominance, the relative abundance of *Proboscia eumorpha* increased in shallow trap samples in October~~ through early~~ November 2011 (Fig. 3c).

The sinking diatom flora during the high flux period of November–December 2011 was essentially the same as that in 2010, although the relative abundance of *Chaetoceros* resting spores was relatively minor compared to other diatoms (Fig. 3a, b). The relative increases of *Fragilariopsis* and *Fossula* were not observed in 2012. The ~~observed dominance~~ relative abundance of sea ice-related diatoms was less than 23%~~low~~ in summer 2012. Instead, relative abundance of planktic diatoms such as *Thalassiosira* spp. and *Nitzschia* spp. increased in settling diatom assemblage in summer 2012.

In comparison of shallow and deep trap diatom floras, the dominant species in settling diatom flora of two traps were the same in the periods of diatom flux maxima (Fig. 3d). However, time-series succession of major diatom species in deep trap samples were unclear compared to that of shallow trap. The clear increase in the relative abundance of *Proboscia* observed at shallow trap in October-November 2011 was not observed at deep trap

Melosira arctica, which was commonly observed at Station LOMO2 (Zernova et al., 2000) and under summer sea ice in the northern Laptev Sea (Lallande et al., 2014) ~~in the Amundsen and Nansen basins (Boetius et al., 2013)~~, was rarely observed in ~~the studied~~our samples (<2% numerical valve abundance). ~~The diatoms encountered are mainly marine planktic and sea ice-related species. Because diatom species usually observed in fresh or low-salinity water were very rare, the biogenic materials collected in this study were primarily of marine origin.~~ It has been reported that *Neodenticula seminae* is an endemic species in the subarctic North Pacific (Hasle, 1976; Yanagisawa and Akiba, 1990). This species ~~and~~ has been expanding its distribution to the North Atlantic Ocean via the Arctic Ocean since 1999 (Reid et al., 2007). At Station NAP, *N. seminae* frustules and their fragments were sporadically observed in both shallow and deep trap samples (Fig. 3c, d). Some diatom valves were observed within aggregated clay minerals, which are considered an allochthonous component originating from the Chukchi Sea shelf.

3.4 Sinking speed

Using the time-lag between the observed flux maxima at the shallow and deep trap depths, we estimated the average sinking speed of aggregated diatom particles between these depths at 37–75 m d^{-1} in November 2010 and >85 m d^{-1} in August 2011. The faster sinking speed in August 2011 was primarily due to the abundant gelatinous material of zooplanktonic origin and the larger particle sizes resulting from chains of the diatoms *Fossula arctica* and *Fragilariopsis* spp.

3.5 Diatom POC flux

In order to estimate the diatom contribution to POC flux, the diatom POC flux is required instead of the flux data for diatom valve abundance. Time-series fluctuations in the diatom POC flux and in the dominant taxa in diatom POC estimation differ from those of the diatom valve flux because of the temporary increases in the flux of larger centric diatoms (Figs. 3 and 4). The estimated diatom POC flux is based on observed valve numbers. It is therefore difficult to estimate the influence of selective decomposition of diatom valves and diatom carbon on the POC flux during the sinking process. In November–December ~~during the years of this study, the major taxa comprising diatom POC~~most of the POC was ~~ere~~ attributed to *Coscinodiscus*, *Rhizosolenia*, and *Chaetoceros* ~~(resting spores)~~ (Fig. 4). A temporary increase in diatom POC flux was caused by the appearance of large *Coscinodiscus* in late March and from mid-April to early May 2011. The ice-related algae *Fossula arctica* was the primary species in diatom POC flux during August–September 2011. The high diatom POC flux from *Rhizosolenia* and *Proboscia* in November 2011 was evidenced by the abundant occurrence of the end parts of their needle-like valves rather than the abundant occurrence of intact cells. Thus, the diatom POC flux in November 2011 became overestimate and exceeded total POC flux. *Proboscia* was dominant in the eastern Chukchi Sea shelf waters in September–October 2010 (J. Onodera, unpublished data). The diatom POC flux in summer 2012 was composed mainly of *Thalassiosira* spp. Although vegetative *Chaetoceros* (subgenus *Hyalochaete*) and *Thalassionema* were numerically abundant, their contribution to diatom POC was relatively minor because their cell volume is one to five orders smaller than ~~that of species of~~ *Coscinodiscus*, *Rhizosolenia*, *Proboscia*, and *Thalassiosira*.

4. Discussion

4.1 Summer diatom flux and changes in upper water masses

Because the phytoplankton productivity and phytoplankton assemblage is clearly different between the Chukchi Sea shelf and the Canada Basin, the settling diatom flux at Station NAP should reflect the times-series hydrographic variations. The diatom flux and species composition observed in summer 2011 and 2012 probably reflected the dominance of different water masses—shelf water or oligotrophic Beaufort Gyre water—in the upper water column. The high dominance of *Fossula arctica* at Station NAP in summer 2011 suggests the presence of sea-ice transported from the highly productive~~influence of~~ Chukchi Sea shelf~~ waters with high productivity~~. According to data for the biogeographic diatom distribution in the Laptev Sea, *F. arctica* is mainly observed~~ mainly~~ in the sea-ice assemblage around shelf zones rather than on the basin side (Cremer, ~~1998~~1999). The relatively high flux of lithogenic material in 2011 also suggests that many of the particles trapped in this study originated primarily from the Chukchi Sea shelf. During October 2010, there was a high cell density of *Proboscia~~.~~ eumorpha* over the eastern Chukchi Sea shelf, whereas there was a low cell density of *Proboscia* species in water samples from the southwestern Canada Basin and the Northwind Abyssal Plain (J. Onodera, unpublished data). The relative increase in *P. eumorpha* after the period of *F. arctica* dominance in 2011 probably suggests the influence of Chukchi shelf waters on Station NAP. The transport of coastal water toward Station NAP in summer 2011 was also inferred from the trapped Pacific copepod *Neocalanus cristatus* (Matsuno et al., 2014). Abundant gelatinous zooplankton material, such as ~~appendicularian~~ “houses” of appendicularian Oikopleuridae (S. Chiba, pers. comm.), was also observed in August-September 2011. In contrast to the situation in 2011, the limited influence of shelf-origin sea-ice and shelf waters around Station NAP in 2012 are evidenced by the ~~suppressed~~ absences of biogenic and lithogenic particle fluxes and the rare occurrences of *F. arctica* and other coastal biogenic particles ~~such as appendicularian houses~~ in January–September 2012.

To examine the background mechanisms for the suppressed biogenic fluxes in summer 2012, we addressed the relationship between horizontal advection and settling particle fluxes using the satellite-based sea ice motion data and the pan-Arctic ice–ocean model. The sea ice and water mass properties at Station NAP should be considered to be occasionally influenced by inter-annual variability in the Beaufort Gyre circulation. First, we checked the Polar Pathfinder sea ice motion vectors. The seasonal averages in the western Arctic Ocean were plotted in Fig. 5. During the winter season from November 2010 to January 2011, an anti-cyclonic sea ice circulation (normally called as Beaufort Gyre) appeared over the Canada Basin and Chukchi Borderland. This pattern subsided once in early spring and was then recovered for the summer season from May to July 2011. Thus the source region of sea ice around Station NAP would have been the southern Beaufort Sea in 2011. On the other hand, southward sea ice motion prevailed from winter to spring 2012. The anti-cyclonic circulation was shown in following early summer, but its strength was clearly weaker than 2011. The difference between two years also indicated that shelf-origin sea ice less affected settling particle fluxes around Station NAP in 2012.

Next, we analyzed the results from our inter-annual experiment using the 25-km grid COCO model. The spatial pattern of simulated sea ice motion was nearly consistent with ~~highly similar to~~ the satellite-based one ~~and leaded to the consistent conclusion~~ (Fig. 6). We then compared the simulated sea-surface height in the western Arctic Ocean using the summertime averages in 2011 and 2012 (Fig. 7). In general, the spatial pattern of sea surface height reflects the intensity and location of the oceanic Beaufort Gyre. The COCO model demonstrated that the sea-surface height was higher over the entire western Arctic basin and the maximum height was located more to the western side of the basin in summer 2012 than those in summer 2011. This difference between the two years indicates that the Beaufort Gyre expanded toward the Chukchi Borderland in 2012.

The five-year time-series of simulated ocean current direction in the surface 100-m layer shows that a northwestward current frequently prevailed east of Station NAP (Fig. 8). ~~To examine the background mechanisms for the suppressed biogenic fluxes in summer 2012, we investigated the relationship between horizontal advection and primary productivity using the pan-Arctic ice-ocean modeling approach. The water mass properties at Station NAP should be considered to be occasionally influenced by inter-annual variability in the Beaufort Gyre circulation. Here we analyzed the results from our inter-annual experiment using the 25-km grid COCO model. We first compared the simulated sea-surface height in the western Arctic Ocean using the summertime averages in 2011 and 2012 (Fig. 5). In general, the spatial pattern of sea surface height reflects the intensity and location of the oceanic Beaufort Gyre. The COCO model demonstrated that the sea-surface height was higher over the entire western Arctic basin, and the maximum height was in summer 2012, more to the western side of the basin compared to summer 2011. The difference between the two years indicates that the Beaufort Gyre expanded with shifting of its center from the Canada Basin interior to the Chukchi Borderland in 2012. The five-year time-series of ocean current direction in the surface 100-m layer shows that a northwestward current frequently prevailed east of Station NAP (Fig. 6).~~ This situation favors the spread of shelf-origin water with high abundance of coastal diatom taxa and lithogenic materials toward the Chukchi Borderland. The model results also show that the current direction switched southwestward in December 2011. Because the central Canada Basin is known as an oligotrophic region (Nishino et al., 2011a), the transport of nutrient-poor basin water toward Station NAP would be a possible factor for explaining the ~~suppressed~~ lower ~~primary productivity~~diatom flux in summer 2012. These model results suggest that variations in the Beaufort Gyre significantly influenced nutrient availability and the consequent biogenic fluxes at Station NAP.

4.2 Lateral advection of coastal diatoms in early winter

Based on biogeographic characteristics, much of the *Chaetoceros* resting spores and other coastal diatoms in the studied samples can be regarded as allochthonous materials transported from shelf to basin. Compared to previous studies of particulate carbon fluxes in the Arctic Ocean (summarized in Wassmann et al., 2004), the early winter maximum of POC flux in our study is unusual under conditions of sea-ice cover and polar night. No diatom flux maximum was observed in any early winter during the previous diatom flux study at Station LOMO2 (Zernova et al., 2000). Because polar diatoms show tolerance to low light intensity (Lee et al., 2008), the autumn diatom ~~productivity~~ production probably continued under sea-ice cover and decreasing solar radiation at Station NAP after late October (Fig. 2a, b). However, the high diatom ~~productivity~~ production and subsequent flux of settling diatoms and other biogenic particles, comparable to the summer situation, cannot be explained on the basis of the general seasonality of primary production and sinking particle flux in the seasonal sea-ice zone of the Arctic Ocean (Wassmann et al., 2004; Wassmann and Reigstad, 2011). In this study, we also observed the annual maximum of lithogenic particle flux during the period of the high flux of sinking diatoms in November–December (Figs. 2 and 3; Watanabe et al., 2014). In the early winter of ~~every~~ each year, the origin of diatom particles comprising the diatom flux maximum around Station NAP should be treated as a complex of transported shelf-origin materials and autochthonous diatoms. The dominance of *Chaetoceros* (subgenus *Hyalochaete*) spp. and their resting spores, and abundant silt-clay minerals in the studied samples, suggests the substantial influence of Chukchi Sea shelf waters.

The increased supply of coastal diatoms and lithogenic materials in early winter can be explained by several possible mechanisms for their transport from shelf to basin. Re-suspension of shelf bottom materials into the upper water column would cause the continuous dominance of lithogenic materials with coastal diatom valves in the studied particles at Station NAP. In addition, suspended neritic diatoms are incorporated into sea ice and driven offshore (Różańska et al., 2008). However, sea-ice drift and the usual re-suspension of shelf materials cannot fully explain the early winter flux maxima of diatoms and lithogenic particles at Station NAP. The high-resolution pan-Arctic Ocean model COCO demonstrated that a drifting anti-cyclonic cold eddy generated north of Point Barrow in June 2010 passed Station NAP at the 100- to 200-m water depth during late October–early December 2010 (Watanabe et al., 2014). The simulated cold eddy passage was consistent with the observed event-like cooling and deepening of the moored trap depth that we recorded in late October–December 2010 (Fig. 2c, d). In addition, this eddy continued to pull cold water from the outer shelf during the early part of its passage from off Point Barrow toward Station NAP. Therefore, the movement of the cold eddy could account for the appearance of the high proportion of shelf bottom-water at Station NAP in late October–early December (Fig. S2.2 in Watanabe et al., 2014).

Based on the observed characteristics of diatom floral fluxes and the physical oceanographic simulation, we suggest that the ~~unique~~ early-winter maximum of diatom flux observed in this study is primarily caused by a drifting cold eddy that developed along the shelf break off Point Barrow (Watanabe et al., 2014). The smaller maximum of diatom flux at deep trap in early winter is probably reflecting the eddy diffusion of settling particles under eddy (Siegel et al., 1990) in addition to biogenic particle decomposition. Whereas eddy-induced lateral transport of coastal materials has been reported in the Canada Basin (O’brien et al., 2011, 2013; Nishino et al., 2011b), the eddy in this study, composed of Pacific-origin waters with lower density, did not flow down the shelf slope. Because the shallow sediment trap was moored at about 260 m during the second deployment, the direct influence of the cold eddy was not detected by the temperature and pressure sensors attached to the sediment trap. However, a similar eddy-induced transport event of shelf materials to the basin in early winter 2011 is evident in the high diatom flux, the characteristic diatom assemblage, and the high abundance of lithogenic clay particles.

4.3 Role of diatoms in the biological pump

Because biogenic opal has a ballast effect on the export of particulate organic matter to deep basins (Honjo et al., 2008; Honda and Watanabe 2010), the biological pump is usually effective in diatom-rich oceans such as the Aleutian Basin in the Bering Sea (Takahashi et al., 2002), the subarctic North Pacific (Honda et al., 2002; Takahashi et al., 2002; Honda and Watanabe, 2010), and the Southern Ocean (Honjo et al., 2008). However, most settling autochthonous POC in the central Canada Basin is remineralized within subsurface layers (Honjo et al., 2010). Fresh POC is not supplied to deeper layers, even though there is primary production of 2–4 mol C m^{-2} y^{-1} (Honjo et al., 2010). The primary producers in the cryopelagic Canada Basin are mainly green algae and other picoplankton (e.g., Coupel et al., 2012). The limited amounts of diatoms supplying biogenic ballast and fecal pellets are the causes of an ineffective biological pump in the Canada Basin (Honjo et al., 2010). The relatively abundant POC fluxes at Station NAP, in comparison to those at the subsurface and~~at~~ sediment-trap Station CD04-3067m (trap depth: 3067 m)~~–~~ in the central Canada Basin (Honjo et al., 2010), ~~a~~re due to the higher lateral carbon transport from the Chukchi Sea shelf, autochthonous production of phyto- and zooplankton around Station NAP (Watanabe et al., 2014).

The diatoms collected in our samples sometimes retained the chain form of frustules. In particular, frustules with residual protoplasm were also observed in the summer samples. Their occurrence suggests that the carbon supplied to the deep sea in the Northwind Abyssal Plain includes not only old carbon transported from the shelf or sea-floor ridge but also fresh carbon produced around the study area. When the influence of shelf-origin water is obvious at Station NAP, as in 2011, the biological pump at Station NAP will be relatively active owing to abundant supplies of biogenic and lithogenic particles. In contrast, when oligotrophic water from the central Canada Basin was supplied to Station NAP, as observed in early 2012, the sinking particle flux at Station NAP was limited. In this situation, the efficiency of the biological pump might be reduced~~the biological pump might be suppressed~~ to a level comparable to that in the central Canada Basin. Therefore, on the Chukchi shelf side of the outer Beaufort Gyre, primary productivity and the biological pump are influenced by the spatial distribution of upper water masses (Nishino et al., 2011a). When oligotrophic sea-surface waters ~~suppress~~ reduce the summer particle flux, as evident in summer 2012, the eddy effect on lateral advection of shelf materials to the basin (Nishino et al., 2011b; O'Brien et al., 2011, 2013; Watanabe et al. 2014) becomes important to the seasonality of organic matter flux and the composition of the sinking microplankton flora in the study area (Watanabe et al., 2014).

Author contributions

N.H. planned the research project. J.O. carried out the diatom analysis and offshore work of sediment-trap mooring experiments. E.W. implemented the physical oceanographic model. M.C.H. analyzed the biogenic opal in sediment trap samples. J.O. and E.W. prepared the manuscript with contributions from all co-authors.

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Table and figure captions

Table 1. Diatom taxa found in sediment trap samples from Station NAP collected from 4 October 2010 to 18 September 2012. The symbols "*" and "?" indicate sea ice-related taxa, and uncertain identification in this study, respectively.

~~Table A1. Sampling schedules for sediment trap deployments NAP10t and NAP11t, the bulk components, and diatom assemblage data of sediment trap samples from 4 October 2010 to 18 September 2012. The data periods are expanded from Watanabe et al. (2014). The event time on the dates of initial sampling and sample-cup closing is 0:00 (midnight). The symbol "- - " indicates that the analysis was not conducted because of a limited sample volume. Methods for bulk component analyses are from Watanabe et al. (2014).~~

Figure 1. Bathymetric map around Station NAP (solid black circle at 75°N, 162°W) in the western Arctic Ocean, and schematic of sea-surface circulation over the Chukchi Sea shelf and in the southern Canada Basin (Danielson et al., 2011). NR, Northwind Ridge; NAP, Northwind Abyssal Plain; CP, Chukchi Plateau; CS, Chukchi Spur; CAP, Chukchi Abyssal Plain; AMR, Alpha-Mendeleev Ridge complex.

~~–~~Figure 2. Time-series data at Station NAP from 1 October 2010 through 18 September 2012. (a) Climate Forecast System Reanalysis (CFSR) reanalysis data of shortwave radiation, (b) CFSR reanalysis data of sea-ice concentration, (c) depth log of moored shallow trap, (d) water temperature recorded at moored shallow trap (black line), and NOAA OI.v2 weekly sea-surface temperature at Station NAP (gray line), (e) total mass flux and bulk components of sinking particles at shallow trap depth (data period was expanded from Watanabe et al., 2014), and (f) total mass flux and bulk components at deep trap depth. Blank areas in bulk component data indicate no analysis because of limited sample volume.

Figure 3. Total diatom flux and settling diatom assemblage at Station NAP from 4 October 2010 through 17 September 2012. (a) Sinking diatom flux at shallow trap, (b) sinking diatom flux at deep trap, (c) relative diatom valve abundance excluding *Chaetoceros* spores at

shallow trap, and (d) relative diatom valve abundance excluding *Chaetoceros* spores at deep trap. Blanks in time-series data indicate periods with no data because of limited sample volume or periods without sampling because of mooring turnaround. The plot data is listed in Table A1.

Figure 4. Time-series fluxes of total POC and diatom-derived carbon at Station NAP. (a) Shallow trap, and (b) deep trap.

Figure 5. Sea ice motion vectors in the western Arctic Ocean derived from the Polar Pathfinder dataset in (a-c) 2011 and (e-f) 2012. (g-i) Their difference (2012 minus ~~–~~2011). Seasonal averages for (a,d,g) November to January, (b,e,h) February to April, and (c,f,i) May to July were calculated from monthly mean data. Each vector in the EASE grid was interpolated to the COCO model grid for comparison, and the obtained vectors are shown every eight grid (approximately 200 km). Unit vector corresponds to 5 cm s^{-1}. The location of Station NAP is presented by the red circular symbol. Thin contours indicate isobaths of 100 m, 1000 m, and 3000 m.

Figure 6. Same as Figure 5, but the COCO model result.

Figure ~~5~~7. Sea surface height (cm) in the western Arctic Ocean obtained from the COCO model. The summertime averages over June, July, and August are shown for (a) 2011 and (b) 2012. Black contours trace isobaths of 100 m, 1000 m, and 3000 m. The white contours indicate a sea surface height of zero. The purple line corresponds to 75°N, used for modeled current direction in Figure ~~6~~8. Red dots show the location of Station NAP. Purple dots represent the east and west limits of the horizontal section in Figure ~~6~~8.

Figure ~~6.~~8 Modeled ocean current direction averaged from the surface to 100-m depth across an east–west section along 75°N (see purple line in Figure ~~5~~6). The vertical axis represents an inter-annual time-series from 2008 to 2012. Blue (red) color indicates a northwestward (southwestward) ocean current.