

Author's response to editor Yutaka Watanuki

We are grateful to your comments and useful suggestions that improved our manuscript greatly. As described below, we have revised our manuscript. Please note that the expression in **red colored letters** are the ones provided by you whereas those in **purple** are our replies.

2014.2.17

Dear Dr Ikenoue

Thanks for extensive revision. You have done a lot of work. Revised version looks fine except for a part of discussion.

I think two referees are deeply interested in this paper and see the MS has high potential to be published but after extensive revision. I agree with them. The authors responded well to most of the comments, but failed to do so to some of comments or critics.

Reviewers suggest that authors did discussion with very weak evidence or logic at some points, 5.2 for an example (as in the comment by reviewer 2). Both reviewers indicated that discussion includes some unscientific "opinions". You do not need to give "opinions" in the scientific paper. I believe these points of discussion may not be essential for this paper. I suggest authors to reconsider the critics on these discussions. I do not say your opinions are wrong but I am not convinced with these.

Introduction looks nice. Authors clearly describe the aim of this MS as "We present radiolarian depth distributions and flux variations in the western Arctic Ocean, and discuss their seasonality and species associations in relation to the environmental conditions (temperature, salinity, depth, sea-ice concentration, and downward shortwave radiation)". Thus I again recommend that the authors focus on this exciting question that can be answered clearly using your original data while authors should try to shorten, remove or tone down the discussion of the origin, evolution (including adaptive change of morphological variation to stressful conditions), historical change of the distribution of the species. All these are also interesting questions, I agree. But these are not essential questions that can be answered by your original data given in this paper only. I believe the main critics of the reviewers are on the discussion of the these questions and these will go to the other papers.

The followings are the lists of replies by authors where I found flaws. For others the responses looks fine for me. My suggestions are in red. I strongly encourage authors to consider further revision, thanks. Revised version will be reviewed by subject editor and may or may not go to reviewers.

Yutaka Watanuki

Summary of revision

(1) Section 5.2.

According to your comments, we have deleted section 5.2. Characteristic and ongoing morphogenesis and speciation of radiolarians in the western Arctic Ocean.

We have deleted the following text.

“5.2. *Characteristic and ongoing morphogenesis and speciation of radiolarians in the western Arctic Ocean*

The radiolarian fauna observed in this study was characterized by high dominance of two families, the Cannobotryoidae and the Actinommidae (Fig. 3). *Amphimelissa setosa* is the dominant species, while the actinommids make a species association with a close affinity to the Norwegian Sea fauna. *Amphimelissa setosa* first appeared in the North Pacific and migrated into the North Atlantic through the Arctic Ocean during the Pleistocene interglacial optima (Matul and Abelmann, 2005). This species became extinct in the North Pacific close to the MIS 4/5 boundary (Kruglikova, 1999; Matul et al., 2002; Ikenoue et al., 2011), and has not been observed in recent materials in the North Pacific (Ikenoue et al., 2012a). Petrushevskaya (1979) pointed out that the arctic-boreal radiolarian species known from the Arctic Ocean basins had been originated from the early Postglacial Norwegian Sea polycystine radiolarian fauna. Bjørklund and Kruglikova (2003) also concluded that the modern radiolarian fauna in the Arctic Ocean had a close affinity to the Norwegian Sea radiolarian fauna. This is also supported by the species listed in Table 3, they all occur in the Norwegian Sea, except for the taxa that we at present classify as endemic to the Arctic Ocean. Inflow of radiolarians with waters from the northern part of the Bering Sea is probably negligible since the most abundant and typical radiolarian species in the recent Bering Sea such as *Stylochlamydidium venustum*, and *Ceratospyris borealis* are absent in the western Arctic Ocean. These two species are surface dwellers in the North Pacific (Tanaka and Takahashi, 2008) and are major species in the recent Bering Sea (Ikenoue et al., 2012a). Our results suggest that the radiolarian fauna in the western Arctic Ocean was characterized by a wide morphologic variability in the skeletons within the family Actinommidae and high standing stock of *Joergensenium* sp. A in the PWW (Table S6). *Actinomma* morphogroup A (58 specimens), *Actinomma* morphogroup B (57 specimens), *Joergensenium* sp. A (1,401 specimens), has so far only been observed in the western Arctic Ocean in our study. We have not seen this species outside the Arctic Ocean, neither in the North Pacific or in the North Atlantic. *Actinomma* morphogroup A and B and *Joergensenium* sp. A might be new species endemic for the western Arctic. Kruglikova et al. (2009) described two new species *Actinomma georgii* and *A. turidae*, and suggested the possibility of endemism for these two species. They also indicated a fifth group *Actinomma* indet. (their fig. 5, p. 32) which probably consists of still several undescribed species. Their argument was that the endemism arose as radiolarians had been rapidly evolving under the stressful conditions in the Arctic Ocean, and that speciation or morphogenesis within the family Actinommidae might be ongoing in the central Arctic Basin. Our results support this hypothesis, and suggest that local speciation or morphogenesis took place not only in the central Arctic basin, but also in the western Arctic Ocean. This is demonstrated by the occurrence of what we interpret as new and still undescribed *Actinomma* species. These new forms are very similar to *A. boreale*, but with a different structure of the medullary shells. Also within the radiolarian group Entactinaria, in the genus *Joergensenium*, one or two undescribed species are found. The reason for radiolarian species speciation in this area is still not understood but we can only speculate that this can be controlled by the harsh environmental stress (Allen and Gilooly, 2006; Kruglikova et al., 2009), particularly the extremely cold water masses under the sea-ice (−1.7°C) and the always-changing quality of the water masses, affected by the inflowing Pacific water.”

With this change,

We have changed section number as follows.

- 5.3. ----->5.2.
- 5.3.1. ----->5.2.1
- 5.3.2. ----->5.2.2.
- 5.3.3. ----->5.2.3.
- 5.3.4. ----->5.2.4.
- 5.4. ----->5.3.
- 5.4.1. ----->5.3.1.
- 5.4.2. ----->5.3.2
- 5.4.3. ----->5.3.3.

We have deleted “Table S6. Polycystine radiolarian species by family in the Arctic Ocean modified after Bjørklund and Kruglikova, 2003”

We have deleted the following references:

- Allen, A. P. and Gilooly, J. F.: Assessing latitudinal gradients in speciation rates and biodiversity at the global scale, *Ecol. Lett.*, 9, 947–954, 2006.
- Kruglikova, S. B.: Distribution of Polycystine radiolarians from recent and Pleistocene sediments of the Arctic-boreal zone, *Berichte zur Polarforschung (Reports on Polar Research)*, 306, 120–133, 1999.
- Matul, A., Abelmann, A., Tiedemann, R., Kaiser, A., and Nürnberg, D.: Late Quaternary polycystine radiolarian datum events in the Sea of Okhotsk, *Geo-mar. lett.*, 22, 25-32, 2002.
- Ikenoue, T., Takahashi, K., Sakamoto, T., Sakai, S., and Iijima, K.: Occurrences of radiolarian biostratigraphic markers *Lychnocanoma nipponica sakaii* and *Amphimelissa setosa* in Core YK07-12 PC3B from the Okhotsk Sea, *Memoirs of the Faculty of Science, Kyushu University. Series D, Earth and Planetary Sciences*, 32, 1-10, 2011.
- Petrushevskaya, M. G.: The history of the microplankton of the Norwegian Sea (on the Deep Sea Drilling materials). Academy of Sciences, USSR, Zoological Institute, Nauka, Leningrad, 77-183, 1979 (in Russian).
- Tanaka, S. and Takahashi, K.: Detailed vertical distribution of radiolarian assemblage (0-3000 m, fifteen layers) in the central subarctic Pacific, June 2006, *Mem. Fac. Sci., Kyushu Univ., Ser. D, Earth and Planet. Sci.*, 32, 49-72, 2008.

(2) DIET OF JUVENILE ACTINOMMIDS AND *A. l. leptodermum* Page 16661, line 18

According to your comment, we have revised the text in section 5.3.1.(changed to section 5.2.1.) as follows:

“It is most likely that the juvenile actinommids and *A. l. leptodermum* may be bound to the euphotic zone, and so can be herbivorous.”

have been changed to

“It is most likely that the juvenile actinommids and *A. l. leptodermum* may be bound to the euphotic zone.”

(3) Section 5.3.3. Upper AW association

According to your comment, we have revised section 5.3.3 (changed to 5.2.3.) Upper AW association as follows:

“*Ceratocyrtilis histricosus* occurred commonly in the upper AW (250-500 m) and rarely in the PWW. This species is a species interpreted as being introduced from the Norwegian Sea, most likely during the early Holocene, by the warm Atlantic water drifting through the Arctic Ocean (Kruglikova, 1999). Itaki et al. (2003) first noticed that *Ceratospyrilis histricosus* had not been observed in the Canada Basin during the 1950s and 1960s and he pointed out that the common occurrence of this species in the Chukchi and

Beaufort seas in 2000 might be an effect of the recent warming of the AIW. Itaki et al. (2003) also introduced that the temperature of the AIW in 1994 at the Chukchi-Mendeleyev boundary was higher by at least 0.2°C than in the 1950s and 1960s, from Swift et al (1997). Differing from Itaki et al. (2003), we first found this species in the PWW. According to McLaughlin et al. (2011), the mean temperature of the PWW within the Canada Basin increased slightly (~0.05°C) from 2003 to 2007 and then remained constant until 2010. According to Itaki et al. (2003), *C. histricosus* can survive in the temperature range of 0.5–4°C. Although our data on the temperature of the PWW is apparently lower than the lower limit for survival of this species (Fig. 2), the rare existence of this species in the PWW may be caused by unobserved warming in the PWW or by appearance of other optimistic conditions for *C. histricosus*. However, the warming in the AIW has already been recognized in 1994 (Swift et al., 1997) and a warming in the PWW is also reported by McLaughlin et al. (2011), suggesting that the recent warming of the PWW and AW might induce the expansion of the habitat of *C. histricosus* into the PWW. It is not so much the effect of the temperature itself that is causing the expanding distribution of *C. histricosus*, but the general temperature increase indicates that larger volumes of warmer AW is entering the Arctic Ocean. The increasing volumes of inflowing AW will therefore increase the chances for more exotic radiolarians to reach further and further into the Arctic Ocean.

Bjørklund et al. (2012) reported 98 tropical-subtropical radiolarian taxa in the area north of Svalbard in the eastern Arctic Ocean. They stated that there are always pulses of warm Atlantic water that do reach the Arctic Ocean, transporting warmer water fauna. We did not observe any tropical and subtropical radiolarian taxa in the western Arctic Ocean. However, future, continuous monitoring of the annual changes in the radiolarian fauna, including *C. histricosus*, in the western Arctic Ocean might be able to pick up this type of signal.”

have been changed to

“*Ceratocyrtis histricosus* occurred commonly in the upper AW (250-500 m) and rarely in the PWW. Itaki et al. (2003) first noticed that *Ceratospyris histricosus* had not been observed in the Canada Basin during the 1950s and 1960s and he pointed out that the common occurrence of this species in the Chukchi and Beaufort seas in 2000 might be an effect of the recent warming of the AW. Differing from Itaki et al. (2003), we first found this species in the PWW. According to Itaki et al. (2003), *C. histricosus* can survive in the temperature range of 0.5–4°C. However, our data on the temperature of the PWW (minimum value –1.6°C) is apparently 2°C lower (Fig. 2) than the lower limit for survival of this species, as reported by Itaki et al. (2003). Furthermore, Swanberg and Bjørklund (1987) reported on the temperature range of this species to be between 7-10°C in Sognefjorden, western Norway. This increases the temperature range from -1.6 to 10°C. Therefore it is not so much the effect of the temperature itself that is causing the expanding distribution of *C. histricosus*. The North Atlantic Oscillation (atmospheric High and Low pressure cells) control the flow of the surface water in the North Atlantic and a sustained increase of Atlantic inflow occurs, causing major changes in the water masses in the Arctic Ocean (Zhang et al., 1998). The temporary increasing volumes of inflowing AW might increase the chances for more exotic radiolarians to reach into the Arctic Ocean and the Chukchi Sea. Continuous monitoring of the annual changes in the radiolarian fauna in the western Arctic Ocean, including the occurrence of *C. histricosus*, might be able to pick up this type of signal.”

With this change, we have added the following references:

- Swanberg, N. R., and Bjørklund, K. R.: Radiolaria in the plankton of some fjords in western and northern Norway: the distribution of species, *Sarsia*, 72, 231-244, 1987.
- Zhang, J., Rothrock, D. A., and Steele, M.: Warming of the Arctic Ocean by a strengthened Atlantic inflow: Model results, *Geophys. Res. Lett.*, 25, 1745-1748, 1998.

We have deleted following references with this change.

Swift, J. H., Jones, E. P., Aagaard, K., Carmack, E. C., Hingston, M., Macdonald, R. W., McLaughlin, F. A., Perkin, R. G.: Waters of the Makarov and Canada basins, *Deep-Sea Res. Pt. II*, 44, 1503–1529, 1997.

Bjørklund, K. R., Kruglikova, S. B., and Anderson, O. R.: Modern incursions of tropical Radiolaria into the Arctic Ocean, *J. Micropalaeontol.*, 31, 139–158, doi:10.1144/0262-821X11-030, 2012.

(4) The problem of transporter of decomposition material as food of radiolarians in deep (page 16668, line 13-15)

According to your comment, we have deleted the following text in section 5.4.3.(changed to section 5.3.3.):

“This probably indicates that decomposing material from the primary production during the sea-ice free season was transported to great depths and might also act as a substrate for bacterial growth, providing the deep water radiolarians with sufficient food elements. We have no data to support this but in the Chukchi Sea, moderately high rates of bacterial production at the end of the growing season (July-August) have been found (Cota et al., 1996; Wheeler et al., 1996; Rich et al., 1997).”

With this change,

We have deleted the following references:

Cota, G. F., Pomeroy, L. R., Harrison, W. G., Jones, E. P., Peters, F., Sheldon Jr, W. M., and Weingartner, T. R.: Nutrients, primary production and microbial heterotrophy in the southeastern Chukchi Sea: Arctic summer nutrient depletion and heterotrophy, *Mar. Ecol. Prog. Ser.*, 135, 247-258, 1996.

Wheeler, P. A., Gosselin, M., Sherr, E., Thibault, D., Kirchman, D. L., Benner, R., Whitledge T. E.: Active cycling of organic carbon in the central Arctic Ocean, *Nature*, 380, 697-699, 1996.

Rich, J., Gosselin, M., Sherr, E., Sherr, B., & Kirchman, D. L.: High bacterial production, uptake and concentrations of dissolved organic matter in the Central Arctic Ocean, *Deep-Sea Res. Pt. II*, 44, 1645-1663, 1997.

COMMENTS FROM REVIEWER 1

LOCAL SPECIATION

Page 16660, line 8

Or: "... suggested the possibility of endemism for..."

We accepted your suggestion, and revised lines 7-13 as follows: "Kruglikova et al. (2009) described two new species *Actinomma georgii* and *A. turidae*, and suggested the possibility of endemism for these two species. They also indicated a fifth group *Actinomma* indet. (their fig. 5, p. 32) which probably consists of still several undescribed species. Their argument was that the endemism arose as radiolarians had been rapidly evolving under the stressful conditions in the Arctic Ocean, and that speciation or morphogenesis within the family Actinommididae might be ongoing in the central Arctic Basin.

Our results support this hypothesis, and suggest that local speciation or morphogenesis took place not only in the central Arctic basin, but also in the western Arctic Ocean."

<Endemism may be OK, but it does not necessarily indicate local speciation. I do not understand how does your results support Kruglikova et al. I believe your original results (8 species list at a single point in two years) may not increase the understanding of the species distribution and history so much.

According to your comments, we have deleted section 5.2. Please see Summary (1).

DIET OF JUVENILE ACTINOMMIDS AND *A. l. leptodermum*

Page 16661, line 18

That's a very thin logical link. In the absence of information specifically on these species (or at the very least the genus), I would delete this as too hypothetical.

According to your comment and comment 5-14 of reviewer 2, we added vertical profiles of chlorophyll a at station 32 and 56 to figure 2. "Small spumellarians might be herbivorous (Anderson 1983) so Actinommididae spp. Juvenile forms and *A. l. leptodermum* might therefore be bound to the euphotic zone where phytoplankton prevails." was changed to "Our results show that Actinommididae spp. juvenile forms and *A. l. leptodermum* are most abundant in the upper water layers where phytoplankton also prevails (Fig. 2). It is most likely that the juvenile actinommidids and *A. l. leptodermum* may be bound to the euphotic zone, and so can be herbivorous."

<I agree that this is very weak evidence. Many terrestrial carinivorous predators live in the place with high density of glasses but they do not eat glass. You need more strong evidence. High overlap of two species does not necessarily indicate prey-predator relationships.

According to your comment, we have revised the text in section 5.3.1. (changed to section 5.2.1.). Please see summary (2).

1) OCCURRENCE OF *Ceratospyrus histricosus* IN 2000

Page 16663, line 1-3

That's very slim evidence... that would translate to ca. 0.5 degree over last century or so. Do you really think that half a degree affects the distribution of a species that much? I would tend to rather believe that the studies from the 50s/60s simply did not pick it up, so there is more a sampling bias than a "warming trend" observation.

Thanks for your comment.

According to your comment and comments 5-16 and 5-19 of reviewer 2, we replaced Page 16662, line 21-22 as follows: “This species has not been observed in the Canada Basin during the 1950s and 1960s (Hülseman 1963, Tibbs 1967).” was changed to “Itaki et al. (2003) first noticed that *Ceratospyrus histricosus* had not been observed in the Canada Basin during the 1950s and 1960s and he pointed out that the common occurrence of this species in the Chukchi and Beaufort seas in 2000 might be an effect of the recent warming of the AIW “.

We added the following text to the end of the text on line 3 in page 16663:7

“It is not so much the effect of the temperature itself that is causing the expanding distribution of *C. histricosus*, but the general temperature increase indicates that larger volumes of warmer AW is entering the Arctic Ocean. The increasing volumes of inflowing AW will therefore increase the chances for more exotic radiolarians to reach further and further into the Arctic Ocean and the Chukchi Sea.”

<I understand that water flow play important roles in determining the species distribution rather than water temperature itself. Then how do you know the historical increase of flow rate of AIW? Does this slight increase of temperature indicate the increase of flow rate? Global warming just increases the temperature but may not influence the flow. You need references.

According to your comment, we have revised section 5.3.3 (changed to 5.2.3.) Upper AW association. Please see Summary (3).

2) TRANSPOTR OF DECOMPOSITION MATERAIL AS FOOD OF RADIORATIANS IN DEEP

Page 16668, line 13-15

I will mention this here, but similar examples occur at other spots in the text (essentially ALL your conclusions/hypotheses trying to link radiolarian abundances/flux and feeding habits): I do realise that you use mitigating words as "maybe", "probably", "suggest", etc, but these hypotheses are not based on anything factual, not a shred of data, and remain highly controversial. Just because a few deep-living radiolarian species increase in abundance, it does not necessarily mean that organic matter export to depth increases (and so on, and so on). It's just a conjecture, maybe not even an hypothesis.

If you had measurements of organic matter at various levels in the water column, and through time, and you would see some correlation to species abundance, you might have been able to formulate such an hypothesis. Even then, as you surely know, correlation is not causality, and such a coincidence between organic matter and species data would not prove the hypothesis.

Thanks for your comments. We revised the text as follows: 9 “This probably indicates that decomposing material from the primary production during the sea-ice free season was transported to great depths, giving nutrition to the deep water radiolarian fauna.” was changed to “This probably indicates that decomposing material from the primary production during the sea-ice free season was transported to great depths and might also act as a substrate for bacterial growth, providing the deep water radiolarians with sufficient food elements. We have no data to support this but in the Chukchi Sea, moderately high rates of bacterial production at the end of the growing season (July-August) have been found (Cota et al., 1996; Wheeler et al., 1996; Rich et al., 1997).”

<I totally agree with reviewer's comment; it does not necessarily mean that organic matter export to depth increases. Authors mentioned that "some lateral advection at a depth lower than 180m" play some role. Authors are suggested to remove this part from discussion. As you have no data to support (or reject) the hypothesis, you do not need to discuss.

According to your comment, we have revised section 5.4.3 (Changed to section 5.3.3). Please see Summary 4.

COMMENTS FROM REVIEWER 2

1) DIVERSITY INDEX, EVOLUTION AND ORIGIN

(iii)-a the fear of artificial high diversity and endemism in the Arctic Ocean As much is known to biologists and taxonomists, the diversity is significantly and artificially controlled by different taxonomic concepts.

<Reviewer give general question; not specific to specific taxon. Authors did the best. That is OK. But authors should be careful. I suggest that the it will be safer to tone down the discussion on species diversity and endemism of this groups of organisms where no good agreement of taxonomy has been made.

According to your comments, we have deleted section 5.2. Please see Summary (1).

(iii)-b the origin of the Arctic polycystine species. As your paper does not focus on the origin of the Arctic species, unconcluded opinions are better not to be used in your manuscript as much as possible"

<I agree with this general comment. I made a similar comment at the early stage of the review. Is [Arctic Ocean radiolarian fauna was introduced after the last Glaciation] your opinion or hypothesis generally accepted by the scientists working on this group of the organisms? If this "opinion" has been proposed already, your original data does not contribute much to the further understanding of the origin of this group as you give a data of species community at a single location not distribution, including historical, data. You do not need to discuss deeply where you do not have sufficient original data.

According to your comments, we have deleted section 5.2. Please see Summary (1).

Comment 5-19 A suggested discussion for your 5.3.3.

<Sorry. I still do not understand the logic of your response here. SEE 3) OCCURRENCE OF *Ceratospyrus histricosus* IN 2000 (REVIEWER 1)

According to your comment, we have revised section 5.3.3 (changed to 5.2.3.) Upper AW association. Please see Summary (3).

2) DISTRIBUTION AND ORIGIN

TO RENPOND TO THE COMMENT OF "The sentences about *Ceratocyrtis histricosus* will bring a misunderstanding to readers. The authors said "a warm Atlantic water species", but this mention is wrong. First of all, this species favors on the seawater of

0.5°C to 4°C (Itaki et al., 2003), **AUTHORS REPLY AS** “this species is originating from the Norwegian Sea and has been transported by the “warm Atlantic water”.

<Authors need good references. Your original data presented in this MS does not say anything about this. I do not understand why the authors can say that “Therefore its presence in the Chukchi Sea (0.5°C to 4°C) is not the temperature, which this species favors, but it has adapted to this temperature in the Chukchi Sea.” **Does it simply mean that the suitable temperature range of this species is broader than believed before?**

This species is a cosmopolitan species, including the southern oceans. Please see the distribution map of occurrence data shown below. Thus, this is NOT an Atlantic species. Yes the reviewer is correct, this is probably a cosmopolitan species. What we really mean when we say an “Atlantic water species” is that this species is being introduced to the Arctic Ocean through the Fram Strait, and that it is a member of the Norwegian Sea *C. histricosus* population that has been transported northwards by the Atlantic warm water (Gulf Current). We should try to restructure our statements on this. It is correct as the reviewer #2 state that *C. histricosus* is not only an Atlantic species, but it is still a question for the Arctic Ocean *C. cistricosus* population, from where did they come?

According to your comment, we have revised section 5.3.3 (changed to 5.2.3.) Upper AW association. Please see Summary (3).

5.2 Characteristic and ongoing speciation...

Comment 5-3 p. 16659 Lines 17 – 19 close affinity to the Atlantic fauna You need data. Comment 5-4 p. 16669, Lines 18 – 22. Petrushevskaya (1979).. Bjorklund and Kruglikova (2003)... This is NOT based on your data. You must add the discussion **BASED ON YOUR DATA.**

<The MS is not such a review paper discussing history of the distribution of the species. Your original data do not contribute much to such question. Such discussion can be made in the other paper where you review all studies on taxonomy and distribution of this group or organism.

What we are trying to say is that the fauna in the Chuchi Sea and the Pacific part (western part) of the Arctic Ocean is MAINLY recruited by fauna elements originating from the Norwegian Sea in the Early Holocene and now being brought around in the Arctic Ocean by the Gulf Stream, or with other words, Atlantic warm water.

We do not think there is any doubt that the Arctic Ocean polycystines mainly are being recruited from the Norwegian Sea during early Holocene time. The Norwegian Sea fauna is again is being recruited from the North Atlantic.

<This is possibly given by other researchers and will be correct. But authors should give strong evidence basing on your results supporting this “opinion”. Do not use much space just introducing the hypothesis provided by other people. How does your data given in this MS support or reject the hypothesis? I do not believe that the presence of species at single location (that is the data you give) contribute much for understanding the origin and distribution.

How to note the existence of this genus and this species in the previously published references?

Dear reviewer, we do NOT talk about analyzing previous papers! We talk about results from analyzing the material that we ourselves have available from the Arctic Ocean, Nordic Seas, Barents Sea, and the North Pacific, Sea of Okhotsk and the Bering Sea.

<Sorry, I'm very confused. You mentioned in the METHOD section that you did sampling at single location in the western Arctic Sea. Why can you talk about your results not presenting in this MS? Are these shown in the other papers? Give references.

According to your comments, we have deleted section 5.2. Please see Summary (1).

SECTION 5.2

Their argument was that the endemism arose as radiolarians had been rapidly evolving under the stressful conditions in the Arctic Ocean, and that speciation or morphogenesis within the family Actinommidae might be ongoing in the central Arctic Basin. Our results support this hypothesis, and suggest that local speciation or morphogenesis took place not only in the central Arctic basin, but also in the western Arctic Ocean.

< I do not understand what of your results support which hypothesis? (Endemism arose? Radiolarians had been rapidly evolving under the stressful conditions? Speciation or morphogenesis within the family Actinommidae might be ongoing in the central Arctic Basin?). Why does the occurrence of what we interpret as new and still undescribed Actinomma species support the some of these hypothesis? I suppose that a different structure of the medullary shells may support this but how?

The reason for radiolarian species speciation in this area is still not understood but we can only speculate that this can be controlled by the harsh environmental stress (Allen and Gilooly, 2006; Kruglikova et al., 2009), particularly the extremely cold water masses under the sea-ice (-1.7°C) and the always-changing quality of the water masses, affected by the inflowing Pacific water.

<Why do you believe that the low temperature and variable quality of the water induce speciation? Give rationale and evidence. How does your original data given here support this idea? As you say if this is only speculation, remove this. We do not need speculation without any evidence.

According to your comments, we have deleted section 5.2. Please see Summary (1).

OTHER COMMENTS

P2L3 Cold and well mixed water mass based on summer ice edge were [seemed to be: <EVIDENCE IS NOT SO SYTRONG] essential for high reproduction and growth of *A. setosa*.

According to your comment, we have revised the text in Abstract as follows:

“Cold and well mixed water mass based on summer ice edge were essential for high reproduction and growth of *A. setosa*.”

have been changed to

“Cold and well mixed water mass based on summer ice edge seemed to be essential for high reproduction and growth of *A. setosa*.”

<P9L26-28 Try to move references to METHODS and minimize the usage of references in RESULTS section. If you believe you can't, that will be OK.

We have left the text as it is.

1 Flux variations and vertical distributions of [siliceous Rhizaria \(Radiolaria and](#)
2 [Phaeodaria\)](#) in the western Arctic Ocean: [indices of environmental changes](#)

3
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22 23 **Abstract**

24 The vertical distribution of radiolarians was investigated using a vertical multiple
25 plankton sampler (100–0, 250–100, 500–250 and 1,000–500 m water depths, 62 µm
26 mesh size) at the Northwind Abyssal Plain and southwestern Canada Basin in
27 September 2013. To investigate seasonal variations in the flux of radiolarians in relation
28 to sea-ice and water masses, [a time series sediment trap system](#) was moored at Station
29 NAP (75°00'N, 162°00'W, bottom depth 1,975 m) in the western Arctic Ocean during
30 October 2010–September 2012. We [monitored species abundance changes in the](#)
31 [fourteen most abundant radiolarian taxa, and how they related](#) to the vertical
32 hydrographic structure in the western Arctic Ocean. The radiolarian flux was
33 comparable to that in the North Pacific Ocean. [Amphimelissa setosa was dominant](#)

1 [during the season with open water as well as at the beginning and at the end of the](#)
2 [seasons with sea ice cover. Cold and well mixed water mass based on summer ice edge](#)
3 [seemed to be essential for high reproduction and growth of *A. setosa*. Our data indicate](#)
4 [that *A. setosa* might have a three months life cycle.](#) During the sea-ice cover season,
5 however, oligotrophic and cold-water tolerant [actinommids](#) were dominant, productivity
6 of radiolaria was lower, and species diversity was greater. [This might be associated with](#)
7 [the seasonal increase of solar radiation stimulating the growth of algae on the ice and](#)
8 [other phytoplankton species under the sea-ice, upon which the actinommids can feed on.](#)
9 [This evidence suggests that the dynamics of sea-ice are a major factor affecting the](#)
10 [general biological productivity, distribution, and composition as demonstrated in the](#)
11 [radiolarian fauna.](#)

12
13 Keywords: Radiolarians, Western Arctic Ocean, Sea-ice, Beaufort Gyre, Sediment trap

14 15 **1. Introduction**

16 In recent years, summer sea-ice extent in the Arctic Ocean [has decreased](#) rapidly due
17 to global climate change (Stroeve et al., 2007, 2012). The sea-ice in the Arctic Ocean
18 reached [its](#) minimum extent in September 2012 since the beginning of satellite
19 observation (NSIDC, 2012). The most remarkable sea-ice decrease was observed in the
20 western Arctic Ocean, [on](#) the Pacific side (Shimada et al., 2006; Comiso et al., 2008;
21 Markus et al., 2009). In the western Arctic Ocean, the [advection of](#) warm [North Pacific](#)
22 water through the Bering Strait contributes to both sea-ice melt in summer and an
23 inhibition of sea-ice formation during winter (Shimada et al., 2006; Itoh et al., 2013).

24 [Biological CO₂ absorption](#) is an important carbon sink in the [ice-free regions of](#) the
25 Arctic Ocean (Bates et al., 2006; Bates and Mathis, 2009). Melting of sea-ice can both
26 enhance and reduce the [efficiency of the](#) biological pump in the Arctic Ocean,
27 depending on ocean circulation (Nishino et al., 2011). The Beaufort High, a
28 [high-pressure system](#) over the Canada Basin in the Arctic Ocean, drives the sea-ice and
29 the water masses anticyclonically, as the Beaufort Gyre ([Fig. 1](#)). In the Canada Basin,
30 the Beaufort Gyre governs the upper ocean circulation (Proshutinsky et al., 2002), [and it](#)
31 [has strengthened](#) recently due to the decreasing sea-ice (Shimada et al. 2006; Yang
32 2009). [Melting of sea ice reduce the efficiency of the biological pump within the](#)
33 [Beaufort Gyre because of deepening of the nutricline caused by freshwater](#)

1 [accumulation within the gyre \(Nishino et al., 2011\). Conversely, the efficiency of the](#)
2 [biological pump is enhanced outside the gyre because of nutrient supply from shelves](#)
3 [and improved light penetration \(Nishino et al., 2011\).](#)

4 Particle flux plays [an](#) important role in the carbon export (Francois et al., 2002).
5 [Based on sediment trap samples from](#) the Canada Basin and Chukchi Rise, Honjo et al.
6 (2010) found that [the](#) annual average of sinking particle flux was three orders of
7 magnitude smaller than that in epipelagic areas where the particle flux [was the main](#)
8 [mechanism](#) for carbon export to greater depths. However, Arrigo et al. (2012) observed
9 a massive algal biomass beneath fully consolidated pack ice far from the ice edge in the
10 Chukchi Sea during the summer, and suggested that a thinning ice cover increased light
11 transmission under the ice and allowed blooming of algae. Boetius et al. (2013) also
12 reported that the algal biomass released from the melting ice in the Arctic Ocean was
13 widely deposited at the sea floor in the summer of 2012. Therefore, it is inferred that
14 biomass of zooplankton also changed seasonally under the sea-ice in the Arctic Ocean,
15 as a result of the variable sea-ice conditions. Microzooplankton are recognized as a key
16 component of pelagic food webs (e.g., [Kosobokova et al., 2002](#); Calbet and Landry,
17 2004), [but](#) the seasonal and interannual changes [in their](#) communities within sea ice
18 regions [are](#) still poorly understood.

19 To understand the effect of sea ice reduction on marine ecosystems in the Arctic
20 Ocean, we studied productivity, distribution, composition, and biological [conditions](#) of
21 living radiolarians [in both](#) plankton tow samples and sediment trap samples.

22 [In our study we have analyzed only the siliceous forms of class Rhizaria and herein](#)
23 [we have used the definition of Radiolaria as defined by Suzuki and Aita \(2011\). In their](#)
24 [taxonomic scheme they include the following orders: Collodaria, Nassellaria,](#)
25 [Spumellaria, Acantharia and Taxopodia. In addition we do include order Entactinaria](#)
26 [which Suzuki and Aita \(2011\) reported getting extinct during the Permian, but](#)
27 [Bjørklund et al. \(2008\) demonstrated its presence also in recent plankton and sediment](#)
28 [samples. In this study we have excluded order Acantharia as they have a skeleton of](#)
29 [SrSO₄ and Collodaria, a group that normally do not possess a skeleton or only with](#)
30 [loose spines. Therefore, our study only includes forms with a solid skeleton of SiO₂. In](#)
31 [this paper we have chosen to include data also on order Phaeodaria which have not been](#)
32 [assigned to Radiolaria but to Cercozoa in recent studies using molecular biology](#)
33 [\(Cavalier-Smith and Chao, 2003; Nikolaev et al., 2004; Adl et al., 2005; Yuasa et al.,](#)

1 2005). To make the text read well we therefore use Radiolaria, or radiolarians when
2 appropriate, to also include Phaeodaria, this to make it possible for us to compare
3 already published data from the north Pacific region (Okazaki et al., 2003, 2005;
4 Ikenoue et al., 2010, 2012a).

5 Radiolaria are one of the most common microzooplankton groups, they secrete
6 siliceous skeletons, and their abundance in a region is related to temperature, salinity,
7 productivity and nutrient availability (Anderson, 1983; Bjørklund et al., 1998; Cortese
8 and Bjørklund, 1997; Cortese et al., 2003). Their genus and family levels taxa also
9 respond to various oceanographic conditions by altering their distribution patterns and
10 compositions (Kruglikova et al., 2010, 2011). In recent studies, Ikenoue et al. (2012a, b)
11 found a close relationship between water mass exchanges and radiolarian abundances
12 based on a fifteen-year long time-series observation on radiolarian fluxes in the central
13 subarctic Pacific. Radiolarian assemblages are also related to the vertical hydrographic
14 structure (e.g., Kling, 1979; Ishitani and Takahashi, 2007; Boltovskoy et al., 2010),
15 therefore variations in their abundance and proportion might be useful environmental
16 proxies for water mass exchanges at each depth interval, especially as some of them
17 occur in response to recent climate change (e.g., ocean circulation, expansion and
18 decline of sea-ice, influx of water mass from other regions).

19 The radiolarian assemblages in the western Arctic Ocean has been studied mainly
20 based on the samples collected by plankton tow at ice-floe stations (Hülsemann, 1963,
21 Tibbs, 1967), and in the Beaufort Sea in summer of 2000 (Itaki et al., 2003) or in
22 surface sediment samples, mainly over the Atlantic side of the Arctic Ocean (Bjørklund
23 and Kruglikova (2003). Bernstein (1931, 1932, 1934) reported on six Polycystina, two
24 Acantharia and two Taxopodia species, but did not give any information on abundance
25 in the Barents Sea and Kara Sea for the Polycystina, but for the Acantharia and
26 Taxopodia she reported them to be abundant, with a maximum occurrence in the deeper
27 and warmer Atlantic water. Meunier (1910) also reported on Acantharia, Taxopodia and
28 Nassellaria in the Kara Sea and the Arctic Ocean, but he stated (page 196) that his
29 material was not rich in radiolarians. However, the knowledge of the geographical and
30 the depth distribution of living radiolarians is still limited, and their seasonal and annual
31 changes have not been studied in the western Arctic Ocean because of seasonal sea-ice
32 coverage.

33 This is the first extensive study of the seasonal and interannual flux changes of

1 radiolarians in the western Arctic Ocean. We present radiolarian depth distributions and
2 flux variations in the western Arctic Ocean, and discuss their seasonality and species
3 associations in relation to the environmental conditions (temperature, salinity, depth,
4 sea-ice concentration, and downward shortwave radiation).

5 6 **2. Oceanographic setting**

7 The hydrography in the western Arctic Ocean has been discussed in several studies
8 (e.g., Aagaard et al., 1985; McLaughlin et al., 2011) and the upper 1,000 m of the water
9 column can be divided into five distinct water masses. The surface water is
10 characterized by low temperature and low salinity water (Aagaard et al., 1981) and can
11 be subdivided into three layers, i.e. Surface Mixed Layer (SML), Pacific Summer Water
12 (PSW), Pacific Winter Water (PWW). The SML (0-25 m) is formed in summer by
13 sea-ice melt and river runoff and is characterized by very low salinities (less than 28).
14 The PSW (25-100 m) and PWW (100-250 m) are cold halocline layers originating from
15 the Pacific Ocean via the Bering Sea. The PSW flows along the Alaskan coast and
16 enters the Canada Basin through the Bering Strait and Barrow Canyon (Coachman and
17 Barnes, 1961) (**Fig. 1**). The PSW is relatively warmer and less saline (30-32 in the
18 1990s, 28-32 in the 2000s, according to Jackson et al., 2011) than the PWW. The PSW
19 is further classified into warmer and less saline Alaskan coastal water and cooler and
20 more saline Bering Sea water (Coachman et al., 1975), which originate from Pacific
21 water that is modified in the Chukchi and Bering Seas during summer. The Alaskan
22 coastal water is carried by a current along the Alaskan coast, and spread northwards
23 along the Northwind Ridge by the Beaufort gyre depending on the rates of ice cover and
24 decay (Shimada et al., 2001). The PWW is characterized by a temperature minimum (of
25 about -1.7°C) and originates from Pacific water that is modified in the Chukchi and
26 Bering Seas during winter (Coachman and Barnes, 1961). The PWW is also
27 characterized by a nutrient maximum and its source is regenerated nutrients from the
28 shelf sediments (Jones and Anderson, 1986).

29 The deep water is divided into Atlantic Water (AW) and Canada Basin Deep Water
30 (CBDW). AW (250-900 m) is warmer (near or below 1°C) and saltier (near 35)
31 intermediate water than the surface waters, and is originating from the North Atlantic
32 Ocean, via the Norwegian Sea. The CBDW (below 900 m) is a cold (lower than 0°C)
33 water mass located beneath the AW and has the same salinity as the AW. The CBDW is

1 formed by the brine formation on the shelves, which makes cold and saline water mass
2 sink over the continental margin into the deep basins (Aagaard et al., 1985).

3 4 **3. Materials and methods**

5 *3.1. Plankton tow samples*

6 Plankton tow samples were collected by vertical multiple plankton sampler (VMPS).
7 [The instrument](#) (mesh size: 62 μm , open mouth area: 0.25 m^2) was towed from 4 layers
8 (100-0, 250-100, 500-250, and 1,000-500 m) at 2 stations (Station 32 in Northwind
9 Abyssal Plain, 74°32'N, 161°54'W; Station 56 in southwestern Canada Basin, 73°48'N,
10 159°59'W) ([Fig. 1 and Table 1](#)) in September 2013. Hydrographical data (temperature,
11 salinity, [dissolved oxygen, and chlorophyll *a*](#)) down to 1,000 m water depth were
12 simultaneously obtained from a CTD ([Conductivity Temperature Depth profiler](#)) cast.
13 The volume of seawater filtered through the net was estimated using a flow meter
14 mounted in the mouth ring of the plankton net.

15 The samples collected by VMPS were split with a Motoda box splitter and a rotary
16 splitter (McLaneTMWSD-10). The split samples were fixed with 99.5% ethanol for
17 radiolarian studies. Plankton samples were stained with Rose-Bengal to discriminate
18 between living and dead specimens. The split samples were sieved through a stainless
19 screen with 45 μm mesh size. Remains on the screen were filtered through Gelman®
20 membrane filters with a nominal pore size of 0.45 μm . The filtered samples were
21 desalted with distilled water. [The edges of each filtered sample were cut according to](#)
22 [slide size in wet condition and mounted on glass slides on a slide warmer. Xylene was](#)
23 [added to the dried filters and samples, which were then permanently mounted with](#)
24 [Canada balsam](#). Radiolarian taxa were identified and counted with a compound light
25 microscope at 200 x or 400 x magnification. [Plankton tow samples were stained with](#)
26 [Rose-Bengal to discriminate between living and dead specimens. Specimens that clearly](#)
27 [stained bright red were interpreted as living cells, while cells that did not stain red, or](#)
28 [just barely indicated a red shine, were interpreted as dead because of the lacking](#)
29 [protoplasm. This is also in accordance to Okazaki et al. \(2004\)](#). All specimens on a slide
30 were identified and counted, and their individual numbers were converted to standing
31 stocks (No. specimens m^{-3}).

32 33 *3.2. Hydrographic profiles*

1 Profiles of temperature, salinity, dissolved oxygen, [and chlorophyll *a*](#) down to 1,000
2 m depth at stations 32 (Northwind Abyssal Plain) and 56 (southwestern Canada Basin)
3 in September 2013 are from Nishino (2013) and shown in [Fig. 2a and b](#), respectively. At
4 Station 32, temperature showed sharp decrease from the surface and down to about 25
5 m depth with a sharp increase at the base of SML. The PSW is generally cold (about
6 -1°C) with a maximum value (1.6°C) at about 50 m and shows a rapid decrease with
7 increasing depth. The PWW is the coldest water (minimum value -1.6°C) at about 200
8 m. Highest temperatures are found in the AW (near or below 1°C) at about 400 m with a
9 gradual decrease below 500 m. Salinity showed low values (25-28) in the SML,
10 increasing rapidly with depth from 28-32 in the PSW. In the PWW there is a gradual
11 increase of salinity from 32 to 35, while there is a slight decrease below the PWW/AW
12 boundary. Dissolved oxygen showed maximum value ($405\ \mu\text{mol/kg}$) at the boundary
13 [between](#) SML and PWW, rapid decrease with increasing depth in the PSW and PWW,
14 minimum value ($270\ \mu\text{mol/kg}$) around the boundary [between](#) PWW and AW, and slight
15 increase below [that](#). [Chlorophyll *a* higher than \$0.1\ \text{mg m}^{-3}\$ was observed in 0-80 m](#)
16 [depth](#). Temperature, salinity, dissolved oxygen, [and chlorophyll *a*](#) show almost similar
17 values at both Station 32 and Station 56 except for SML and PSW. In the SML, salinity
18 at Station 32 was slightly lower than at Station 56. In the PSW, a temperature peak at
19 Station 32 was about one degree higher, and a little deeper, compared to Station 56. [In](#)
20 [0-80 m depth, chlorophyll *a* was a little higher at Station 56 than at Station 32](#).

21 22 3.3. Sediment trap samples

23 Particle flux samples were collected by a sediment trap (SMD26 S-6000, open
24 mouth area $0.5\ \text{m}^2$, Nichiyu Giken Kogyo, Co. Ltd.) rotated at 10–15-day intervals
25 moored at 184 m (4th October 2010–28th September 2011)-260 m (4th October
26 2011–18th September 2012) and 1,300 m (4th October 2010–28th September
27 2011)-1,360 m (4th October 2011–18th September 2012) at Station NAP (Northwind
28 Abyssal Plain, $75^{\circ}00'\text{N}$, $162^{\circ}00'\text{W}$, bottom depth 1,975 m)_([Fig. 1; Table 2](#)). The
29 mooring system was designed to set the collecting instrument at approximately 600 m
30 above the sea floor. This depth of the moored sediment traps was chosen in order to
31 avoid possible inclusion of particles from the nepheloid layer, reaching about 400 m
32 above the seafloor (Ewing and Connary, 1970). Recoveries and redeployments of the
33 traps were carried out on the Canadian Coast Guard Ship I/B (ice breaker) “Sir Wilfrid

1 Laurier” and R/V “Mirai” of Japan Agency for Marine-Earth Science and Technology.
2 The sample cups were filled with 5% buffered formalin seawater before the sediment
3 trap was deployed. This seawater was collected from 1,000 m water depth in the
4 southern Canada Basin, and was membrane filtered (0.45 µm pore size). The seawater
5 in the sample cups was mixed with sodium borate as a buffer (pH 7.6–7.8) and 5%
6 formalin was added as a preservative.

7 The samples were first sieved through 1 mm mesh to remove larger particles, which
8 are not relevant for the present study. The samples were split with a rotary splitter
9 (McLaneTMWSD-10). At first, we used 1/100 aliquot size of the samples to make
10 microslides for microscope work (species identification). We made additional slides in
11 case of low radiolarian specimen numbers. In order to remove organic matter and
12 protoplasm, 20 ml of 10% hydrogen peroxide solution are added to the samples in a 100
13 ml pyrex beaker, and heated (not boiling) on a hot plate for one hour. After this reaction
14 was completed, Calgon® (hexametaphosphate, surfactant) solution was added to
15 disaggregate the sample. The treated samples were then sieved through a screen (45 µm
16 mesh size). Both the coarse (>45 µm) and fine (<45µm) fractions were filtered through
17 Gelman membrane filters with a nominal pore size of 0.45µm and desalted with
18 distilled water. The edges of each filtered sample were cut according to slide size in wet
19 condition and mounted on glass slides on a slide warmer. Xylene was added to the dried
20 filters and samples, which were then permanently mounted with Canada balsam.

21 We made slides of both the coarse (>45 µm) and the fine (<45 µm) fraction of each
22 sample. For the enumeration of radiolarian taxa in this study, we counted all specimens
23 of radiolarian skeletons larger than 45 µm encountered on a slide. Each sample was
24 examined under an Olympus compound light microscope at 200 x or 400 x
25 magnification for species identification and counting. The radiolarian flux (No.
26 specimens m⁻² day⁻¹) was calculated from our count data using the following formula:

$$27 \text{ Flux} = N * V / S / D \quad (1)$$

28 where N is the counted number of radiolarians, V the aliquot size, S the aperture area of
29 the sediment trap (0.5 m²), and D the sampling interval (day). Diversity indices using
30 the Shannon-Weaver log-base 2 formula (Shannon and Weaver, 1949) were calculated
31 for total radiolarians

$$32 H = -\sum P_i \log_2 P_i \quad (2)$$

33 where H is the diversity index, P is the contribution of species (relative abundance in

1 [total radiolaria](#)) and i is the order of species.

2 As supplemental environmental data, the moored sediment trap depth and the water
3 temperature (accuracy of + 0.28°C) were monitored every hour (sensor type: ST-26S-T).
4 Moored trap depth for the upper trap was lowered by about 80 m during the second year
5 (about 260 m depth) than during the first year (about 180 m depth), [caused by](#)
6 [entanglement of the mooring ropes](#). [During July-August in 2012, the moored trap depth](#)
7 [was lowered to about 300 m, because of intensified water currents](#) (Fig. S1).
8 Time-series data of sea-ice concentration around Station NAP during the mooring
9 period were calculated from the sea-ice concentration data set (http://iridl.ldeo.columbia.edu/SOURCES/.IGOSS/.nmc/.Reyn_Smith_OIv2/, cf. Reynolds et al., 2002).

12 3.4. Taxonomic note

13 The species described by Hülsemann (1963) under the name of *Tholospyris*
14 *gephyristes* is not a Spyridae. This species has been accepted as a Spyridae by most
15 workers, but this species [lacks the](#) sagittal ring that is typical for the Spyridae. We have
16 therefore [assigned this species to](#) the family Plagiacanthidae. [We suggest this species be](#)
17 [renamed to *Tripodiscium* *gephyristes* until a proper taxonomic analysis has been](#)
18 [undertaken](#).

20 4. Results

22 4.1. Radiolarians collected by plankton tows

23 A total of 43 radiolarian taxa (12 Spumellaria, 3 Entactinaria, 26 Nassellaria, and 2
24 Phaeodaria) were identified in the plankton tow samples (Table 3). [We have observed](#)
25 [taxopodians, but they have not been identified according to the two species as defined](#)
26 [by Meunier \(1910\), nor have they been quantified. Furthermore, we have not been able](#)
27 [to observe any collodarian individuals although we cannot exclude their presence in the](#)
28 [Arctic Ocean \(Lovejoy et al., 2006; Lovejoy & Potvin, 2011\).](#) The numbers of
29 individuals for each radiolarian taxon are in Tables S1 (Station 32) and S2 (Station 56).

31 4.1.1. Standing stocks and diversities of radiolarians

32 The abundance of living radiolarians at Station 32 was about two times [higher than](#)
33 at Station 56 at each depth interval in the upper 500 m, [the depth level at which](#) the

1 abundance of living radiolarians decreased with increasing water depth at both stations
2 (Fig. 2a and b). The abundance of dead radiolarians also decreased with water depth at
3 both stations except for 100–250 m depth at Station 32 (Fig. 2a and b). The abundance
4 of dead radiolarians was generally higher than living radiolarians at both stations except
5 for in the 0–100 m depth at Station 32. The living radiolarian diversity index was low in
6 the 0–100 m depth interval, increased with depth, reached a maximum at about 400 m,
7 and then slightly decreased below 500 m depth at both stations.

8 At Station 32, *Amphimelissa setosa* (58%) and *Amphimelissa setosa* juvenile (22%)
9 were dominant, and *Joergensenium* sp. A (6%), *Pseudodictyophimus clevei* (4%),
10 Actinommidae spp. juvenile forms (3%), and *Actinomma leptodermum leptodermum*
11 (1%) were common (Fig 3a). At Station 56 the Actinommidae spp. juvenile forms
12 (38%) and *Amphimelissa setosa* (29%) were dominant, and *Actinomma leptodermum*
13 *leptodermum* (6%), *Amphimelissa setosa* juvenile (6%), *Pseudodictyophimus clevei*
14 (5%), and *Joergensenium* sp. A (4%) were common (Fig 3b). We defined the 2-shelled
15 forms of Actinommidae as juvenile. Then the 3 and 4 shelled forms will be adult. For
16 the *Amphimelissa setosa* we defined those with cephalis only as juveniles. Those with a
17 well developed cephalis and with a barely or well developed thorax are defined as adult.
18 Actinommidae spp. juvenile forms are mostly two-shelled juvenile forms of *Actinomma*
19 *leptodermum leptodermum* and *Actinomma boreale*, making it impossible to separate
20 between the two.

21 22 4.1.2. Environmental significance of the vertical distribution of radiolarian species

23 We selected fourteen abundant radiolarian taxa to show their relation to the vertical
24 hydrographic structure in the western Arctic Ocean (Fig. 4). The selected taxa were
25 radiolarian taxa with 1% or higher relative abundance through the upper 1,000 m of the
26 water column at either of the two stations and with high relative abundance in each
27 water depth.

28 Adult and juvenile forms of *Amphimelissa setosa* were mainly distributed in the
29 0–250 m depth at both stations. In the 0–100 m depth, adult and juvenile stages were
30 dominant (70% and 28%, respectively) at Station 32, and at Station 56 (23% and 7%,
31 respectively) following the juvenile *Actinomma* spp. (56%). In the 100–250 m depth, *A.*
32 *setosa* was the dominant species at both stations. At Station 32, the abundance of *A.*
33 *setosa* in the 100–250 m depth interval was lower than in the 0–100 m depth, whereas at

1 Station 56, the abundance in the 100-250 m depth was almost the same as in the 0–100
2 m depth.

3 Actinommidae spp. juvenile forms and *Actinomma l. leptodermum* were absent in
4 0–100 m depth at Station 32, but both, especially Actinommidae spp. juvenile forms
5 (56%), were abundant at Station 56. Both were common in the 100-250 m depth at both
6 stations (8% and 4%, respectively at Station 32; 14% and 7%, respectively at Station
7 56), and decreased in abundance in the 250–500 m depth. *Spongotrochus glacialis* was
8 rare in the 0-100 m depth at Station 32 (0.4%) but with a slight increase at Station 56
9 (1.4%). In deeper layers *S. glacialis* was rare.

10 *Joergensenium* sp. A, *Pseudodictyophimus clevei*, and *Actinomma boreale* were
11 abundant in the 100–250 m depth at both stations. *Joergensenium* sp. A was absent in
12 the 0–100 m depth but abundant in the 100–250 m depth and rare in deeper depths.
13 *Pseudodictyophimus clevei* was found throughout from the surface to 1,000 m depth,
14 but was rare at Station 32 except for in 100-250 m. *Actinomma boreale* was rare and
15 mainly found in the 100–250 m depth at both stations.

16 *Ceratocyrtis histricosus* was mainly found in the 250–500 m depth, and occurred
17 also in the 100–250 m depth at both stations. *Tripodiscium gephyristes* was widely
18 distributed below 100 m depth at Station 56, while at Station 32 this species was scarce
19 at all depth layers. *Pseudodictyophimus g. gracilipes* occurred in very low numbers at
20 both stations through the upper 1,000 m. *Pseudodictyophimus plathycephalus*,
21 Plagiacanthidae gen. et sp. indet., and *Cycladophora davisiana* were most abundant
22 below 500 m depth at both stations.

23

24 4.2. Radiolaria collected by sediment trap

25 A total of 51 radiolarian taxa (15 Spumellaria, 3 Entactinaria, 31 Nassellaria, and 2
26 Phaeodaria) were identified in the upper and lower sediment trap samples at Station
27 NAP during 4th October 2010–18th September 2012 (Table 3). We have observed
28 taxopodians, but they have not been identified nor quantified. Furthermore, we have not
29 been able to observe any collodarian individuals. The number of radiolarians counted in
30 each sample ranged from 8 to 1,100 specimens in the upper trap, and from 0 to 2,672
31 specimens in the lower trap (Tables S3 and S4). There were 15 samples with fewer than
32 100 specimens (2 samples in upper trap, 13 samples in lower trap). Most of the species
33 recognized in our sample materials are shown in Plates 1-9.

4.2.1. Radiolarian flux and diversity in the upper trap

The highest total radiolarian fluxes in the upper trap were observed during the beginning of sea-ice cover season (November in 2010 and 2011, >10,000 specimens $\text{m}^{-2} \text{day}^{-1}$) (Fig. 5). The fluxes were higher during the open water season (August–October in 2011, average, 5,710 specimens $\text{m}^{-2} \text{day}^{-1}$) and around the end of sea-ice cover season (July–August in 2011, >4,000 specimens $\text{m}^{-2} \text{day}^{-1}$) than during the sea-ice cover season (December–June, average in 2011, 944 specimens $\text{m}^{-2} \text{day}^{-1}$; average in 2012, 723 specimens $\text{m}^{-2} \text{day}^{-1}$). The fluxes varied from 114 to 14,677 specimens $\text{m}^{-2} \text{day}^{-1}$ with an annual mean of 2,823 specimens $\text{m}^{-2} \text{day}^{-1}$. The diversity of radiolarians, however, was higher during the sea-ice cover season (>3) than during the open water season (<2) (Fig. 5). The diversity indices were negatively correlated with the total radiolarian fluxes ($r = -0.91$) (Fig. 6).

Species composition varied seasonally. Adult and juvenile *Amphimelissa setosa* were most dominant (90%) during the sea-ice free season, and the beginning and the end of sea-ice cover season. The juvenile and adult forms were abundant in earlier and later seasons, respectively (Fig. 7). During the sea-ice cover season, however, Actinommidae spp. juvenile forms (range, 0–51%; average, 18%), *Actinomma leptodermum leptodermum* (range, 0–14.6%; average, 4%), *Actinomma boreale* (range, 0–33%; average, 4%) were dominant. Relatively high percentages of *Pseudodictyophimus clevei*, *Pseudodictyophimus gracilipes*, *Tripodiscium gephyristes* were also observed during the sea-ice cover season.

4.2.2. Radiolarian flux and diversity in the lower trap

Total radiolarian flux in the lower trap varied from 0 to 22,733 specimens $\text{m}^{-2} \text{day}^{-1}$ with an annual mean of 4,828 specimens $\text{m}^{-2} \text{day}^{-1}$ (Fig. 5). The fluxes were high during November–December both in 2010 and 2011 and during March in 2011 (>10,000 specimens $\text{m}^{-2} \text{day}^{-1}$), while extremely low (average, 21 specimens $\text{m}^{-2} \text{day}^{-1}$) during May–September in 2012. Diversity did not change greatly, and increased slightly during May–July 2011, and in April 2012 when the radiolarian fluxes were low. The diversity indices were weakly negatively correlated with the radiolarian fluxes ($r = -0.52$) (Fig. 6).

Adult and juvenile stages of *Amphimelissa setosa* were dominant throughout the

1 sampling periods (range, 66–92%; average, 82%). The relative abundance of *A. setosa*
2 juvenile was slightly increased in 2012 in comparison to 2010 and 2011.

3 4 **5. Discussion**

5 *5.1. Comparison between Arctic and North Pacific Oceans*

6 Biogenic particle flux into the deep sea in the Canada Basin was generally assumed
7 to be low due to the low productivity of siliceous and calcareous microplankton, which
8 plays an important role in the biological pump process (Honjo et al., 2010). However,
9 we observed high radiolarian fluxes (14,677: upper trap, 22,733: lower trap) at Station
10 NAP during the open water season and around the beginning and the end of sea-ice
11 cover season in 2011-2012. The annual means (2,823: upper trap, 4,823: lower trap)
12 were comparable to those observed in several areas of the North Pacific Ocean (Fig. 8,
13 Table S5). However the radiolarian fluxes in the upper trap showed an apparent
14 abundant season (July-November) and a sparse season (December-June) in a year, and
15 that the lower trap also showed an extremely low flux during May-September 2012.
16 Therefore we regarded the period when radiolarian fluxes were higher than 1σ (3,489:
17 upper trap; 5,675: lower trap) as a contributing period. As a result, the mean of
18 radiolarian fluxes during the contributing period in the western Arctic Ocean showed a
19 higher value (7,344: upper trap; 11,871: lower trap) than at any other stations in the
20 North Pacific Ocean (Table S5). The biogenic opal collected in this study mainly
21 consisted of radiolarians and diatoms based on our microscopic observations. Other
22 siliceous skeletons (silicoflagellate skeletons, siliceous endoskeleton of dinoflagellate
23 genus *Actiniscus*, chrysophyte cysts, ebridian flagellate, and palmales) are minor
24 components in the same trap samples (Onodera et al., 2014), therefore siliceous
25 skeletons of radiolarians and diatoms might play an important role to export biogenic
26 silica to the deep Arctic. Onodera et al. (2014) also estimated the diatom contribution to
27 POC flux at station NAP, but more than half of the contribution to total POC has not
28 been explained yet. Relatively high flux of radiolarians in arctic microplankton might
29 contribute to a substantial part of the POC flux.

30 31 *5.2. Vertical distribution of species and hydrographic structure*

32 *5.2.1. PSW and PWW association*

33 *Amphimelissa setosa* and its juvenile stages were found in shallow cold-water in

1 both stations 32 and 56. Specifically, they were more abundant in the SML and PSW
2 (0-100 m) at Station 32 than Station 56. At Station 32, these two water masses exhibited
3 warmer temperature (about one degree higher at the temperature peak) than Station 56;
4 indicating that cold to moderately warm (-1.2 to 1.6 °C), and well mixed water mass
5 were more favorable for this species than perennial cold water masses such as PWW
6 (100-250 m). According to Dolan et al. (2014), *A. setosa* showed significantly lower
7 abundances with higher chlorophyll *a* concentrations of 2012, the low sea ice year,
8 compared to the year of 2011 with higher sea ice and lower chlorophyll *a* concentrations.
9 Thus, the abundance of phytoplankton protoplasm with the remains of chlorophyll *a* is
10 not related with the abundance of *A. setosa*. This is harmonious with our result that
11 chlorophyll *a* was a little higher at Station 56 but the abundance of *A. setosa* at Station
12 56 was fairly lower than that at Station 32 in contrast to Actinommidae spp. juvenile
13 forms, *Actinomma l. leptodermum*. Therefore the favorable condition for *A. setosa* is
14 related to cold and well mixed water mass and any other organisms except for those
15 from phytoplankton near the summer sea-ice edge. The vertical and geographic
16 distribution of *A. setosa* has been described in several previous studies. This species
17 dominated (60-86%) the radiolarian assemblage through the upper 500 m of the water
18 column in the Chukchi Sea and the Beaufort Sea and so can be an indicator of cold
19 Arctic surface water (Itaki et al., 2003). Bernstein (1931) noted that this species live in
20 the cold (-1.68°C to -1.29°C) and saline (34.11 to 34.78) waters in the Arctic Ocean.

21 Matul and Abelmann (2005) also suggested that *A. setosa* prefers well-mixed, cold and
22 saline surface/subsurface waters. Bjørklund et al. (1998) reported its distribution in the
23 western part of the GIN Seas, being dominant (up to 76%) at the Iceland Plateau and
24 common (>20%) just north of the Iceland–Faeroe Ridge. In the eastern part of the Barents
25 Sea, west of Novaja Zemlya, Bjørklund and Kruglikova (2003) reported *Amphimelissa*
26 *setosa* as the dominant (77%) species.

27 Actinommidae spp. juvenile forms, *Actinomma l. leptodermum*, *Spongotrochus*
28 *glacialis* were mainly distributed in the PSW and PWW and preferred different water
29 masses from *Amphimelissa setosa*. *Actinomma l. leptodermum* and *Actinomma boreale*
30 had been reported as a group (e.g., Samtleben et al., 1995), due to identification
31 problems, particularly of the juvenile stages, but the adult stages can be separated into
32 two species following Cortese and Bjørklund (1998). *Actinomma l. leptodermum* were
33 absent in the water masses of SML and PSW at Station 32, but they were abundant in

1 these water masses at Station 56. At Station 56, SML and PSW water masses were
2 colder (-1.2 to 0.6 °C) and more homogeneous than at Station 32; indicating that
3 Actinommidae spp. juvenile forms and *A. l. leptodermum* preferred slightly warmer
4 water than PWW (-1.6 °C). Our results show that Actinommidae spp. juvenile forms
5 and *A. l. leptodermum* are most abundant in the upper water layers where phytoplankton
6 also prevails (Fig. 2). It is most likely that the juvenile actinommid and *A. l.*
7 *leptodermum* may be bound to the euphotic zone. *Spongotrochus glacialis*, showing a
8 similar vertical distribution as Actinommidae spp. juvenile forms and *Actinomma l.*
9 *leptodermum*, also preferred warmer water than PWW. This species inhabited surface
10 water in the Okhotsk Sea, and is well adapted to low temperatures and low salinities
11 (Nimmergut and Abelmann 2002). Okazaki et al. (2004) reported *S. glacialis* as a
12 subsurface dweller with abundance maximum in the 50–100 m interval in the Okhotsk
13 Sea, associated with the phytoplankton production.

14 15 5.2.2. PWW association

16 *Joergensenium* sp. A, *Pseudodictyophimus clevei*, and *Actinomma boreale*, were
17 mainly distributed in the PWW. *Joergensenium* sp. A and *P. clevei* might prefer cold
18 water (-1.7°C) with low turbulence. The depth distribution of *Joergensenium* sp. A was
19 restricted to the PWW (100-250 m) and the upper AW (250-500 m), but *P. clevei* was
20 more widely distributed. *Joergensenium* sp. A has not yet been described from recent
21 radiolarian assemblages, so it can be suggested that this species might occur only on the
22 Pacific side of the Arctic Ocean and might serve as an indicator for the PWW layer.
23 Standing stocks of *A. boreale* were lower than Actinommidae spp. juvenile forms and *A.*
24 *l. leptodermum* at both stations, and mainly occurred in the PWW. In the surface
25 sediments of the Greenland, Iceland and Norwegian Seas, *A. boreale* is associated with
26 warm (Atlantic) water, whereas *A. l. leptodermum* seems to have broader environmental
27 tolerance, as it is associated with both the cold East Greenland Current and the warm
28 Norwegian Current water (Bjørklund et al., 1998). Other environmental factors such as
29 salinity, food availability, or seasonal differences of their growth stages due to the
30 sampling period might influence the standing stocks of *A. boreale*.

31 32 5.2.3. Upper AW association

33 *Ceratocyrtis histicosus* occurred commonly in the upper AW (250-500 m) and

1 rarely in the PWW. Itaki et al. (2003) first noticed that *Ceratospyris histricosus* had not
2 been observed in the Canada Basin during the 1950s and 1960s and he pointed out that
3 the common occurrence of this species in the Chukchi and Beaufort seas in 2000 might
4 be an effect of the recent warming of the AW. Differing from Itaki et al. (2003), we first
5 found this species in the PWW. According to Itaki et al. (2003), *C. histricosus* can
6 survive in the temperature range of 0.5–4°C. However, our data on the temperature of
7 the PWW (minimum value –1.6°C) is apparently 2°C lower (Fig. 2) than the lower limit
8 for survival of this species, as reported by Itaki et al. (2003). Furthermore, Swanberg
9 and Bjørklund (1987) reported on the temperature range of this species to be between
10 7-10°C in Sognefjorden, western Norway. This increases the temperature range from
11 -1.6 to 10°C. Therefore it is not so much the effect of the temperature itself that is
12 causing the expanding distribution of *C. histricosus*. The North Atlantic Oscillation
13 (atmospheric High and Low pressure cells) control the flow of the surface water in the
14 North Atlantic and a sustained increase of Atlantic inflow occurs, causing major
15 changes in the water masses in the Arctic Ocean (Zhang et al., 1998). The temporary
16 increasing volumes of inflowing AW might increase the chances for more exotic
17 radiolarians to reach into the Arctic Ocean. Continuous monitoring of the annual
18 changes in the radiolarian fauna in the western Arctic Ocean, including the occurrence
19 of *C. histricosus*, might be able to pick up this type of signal.

21 5.2.4. Lower AW association

22 *Pseudodictyophimus plathycephalus*, Plagiacanthidae gen. et sp. indet. (Pl. 8, Figs.
23 11-18), and *Cycladophora davisiana* were abundant in the cold and oxygenated lower
24 AW at both stations. However, their distribution patterns in PWW and upper AW water
25 masses were slightly different between Station 32 and Station 56 whereas temperature,
26 salinity, and dissolved oxygen have similar values at both stations. Their standing stocks
27 might therefore reflect [the influence of other variables than](#) hydrographic conditions
28 [alone](#). *Pseudodictyophimus g. gracilipes* is widely distributed in the [World Ocean](#), and
29 known to inhabit the surface layer at high latitudes, [while living](#) at greater depth at low
30 latitudes (Ishitani and Takahashi, 2007; Ishitani et al., 2008). Itaki et al. (2003) reported
31 that the maximum depth *P. g. gracilipes* occurred at 0-50 m in the Chukchi Sea and
32 25-50 m in the Beaufort Sea. However, in our results, *P. g. gracilipes* did not show any
33 specific vertical distribution, and its standing stocks were low.

5.3. Seasonal and annual radiolarian flux

5.3.1. Radiolarian fauna and seasonal sea-ice concentration

Seasonal radiolarian fluxes at Station NAP were characterized by the high dominance of a few species and the changes of their ratios in the upper trap with the seasonal changes in sea-ice concentration. *Amphimelissa setosa* adult and its juvenile forms were dominant during the open-water season and around the beginning and the end of ice-cover seasons, while the actinommids (Actinommidae spp. juvenile forms, *Actinomma l. leptodermum*, *Actinomma boreale*) were dominant during the ice-cover season (Fig. 5). These observations might explain the regional difference in the radiolarian species distribution in the Arctic Ocean. *Amphimelissa setosa* were dominant in Arctic marginal sea sediments (Iceland, Barents, and Chukchi Seas) where sea-ice disappeared in the summer but Actinommidae were dominant in the central Arctic Ocean (Nansen, Amundsen, and Makarov Basins) where the sea surface was covered by sea-ice throughout the year (Bjørklund and Kruglikova, 2003). Zasko et al. (2014) also reported that *A. setosa* was essentially absent in the plankton samples in the central polar basins. The summer ice edge hosts well-grown ice algae and ice fauna (Horner et al., 1992; Michel et al., 2002; Assmy et al., 2013) and its presence causes an alternation between stable water masses and deep vertical mixing where the nutrients are brought to the surface (Harrison and Cota, 1991), with both conditions being favorable for primary productivity. Swanberg and Eide (1992) found that abundance of *A. setosa* and its juveniles was correlated well with Chlorophyll *a* and phaeopigments along the ice edge in summer in the Greenland Sea. Dolan et al. (2014), however, reported that the abundance of *A. setosa* was not entirely related to high Chlorophyll *a* with low sea-ice concentration as we have said in section 5.3.1. Therefore we interpreted that cold and well mixed water mass based on summer ice edge and maybe also other ice fauna elements were essential for high reproduction and growth of *A. setosa*.

From the upper trap, a flux peak of *A. setosa* juvenile occurred at the end of the sea-ice season, and that the flux peak of adult *A. setosa* occurred at the beginning of the sea-ice season (Fig. 7). The time interval between these peaks might indicate that *A. setosa* has a three months life cycle. *Pseudodictyophimus clevei* also shows flux peaks during the beginning of the sea-ice season (November-December) (Fig. 7). These two species seem to prefer to live under a cold water mass with sea-ice formation. On the

1 contrary, juvenile stages of actinommids were dominant during the ice-cover season
2 (Fig. 5). Therefore, we interpreted the actinommids to be tolerant of oligotrophic and
3 stratified cold water masses. Itaki and Bjørklund (2007) reported that reproduction
4 could occur even at the juvenile stage in at least some actinommids since they
5 frequently found conjoined juvenile Actinommidae skeletons in the Japan Sea
6 sediments. Furthermore, the flux of Actinommidae spp. juvenile forms increased
7 towards the end of the sea-ice cover season, accompanied by an increase in downward
8 shortwave radiation (Fig. 5 and 7). This might indicate that Actinommidae spp. juvenile
9 form can feed on algae growing on the ice or other phytoplankton under the sea-ice.
10 Therefore, A. setosa and the juvenile actinommids might have different nutritional
11 niches.

12 This study showed that the productivity of radiolarians was high, but diversity was
13 low, during summer season with low sea-ice concentration in the western Arctic Ocean
14 (Fig. 5 and 6). In contrast, radiolarian fauna in the sediment trap set in the Okhotsk Sea
15 showed high diversity during summer season (Okazaki et al., 2003). The maximum total
16 radiolarian flux during the summer season around the sea-ice edge and the open water is
17 characterized by high dominance of *A. setosa* (>90%) in our area. Such high dominance
18 of a single species does not occur in the Okhotsk Sea, where the main nine taxa
19 contributed with more than 60 % of the radiolarian assemblage (Okazaki et al., 2003).
20 Amphimelissa setosa, which has a small and delicate siliceous skeleton, might respond
21 to water mass conditions near summer ice edge both more directly and more rapidly.
22 The contrast of seasonal diversity between these two areas was due to the difference of
23 species composition and their response to water mass changes with low sea-ice.

24 *Actinomma boreale*, *Spongotrochus glacialis*, *Joergensenium* sp. A were probably
25 related to food supply to the PWW during the sea-ice free season. Relatively higher
26 fluxes of these three species in the upper trap in summer 2012 compared to summer
27 2011 might be due to an effect of the deeper mooring depth of the trap after October
28 2011 (Fig. 7 and S1). This might be caused by their vertical distribution patterns, as they
29 are more abundant at depths lower than the first upper trap depth (about 180 m) (Fig.
30 3a). On the other hand, *Ceratocyrtis histricosus* and *Tripodiscium gephyristes* in the
31 upper trap showed increase in their fluxes from May to September in summer 2012. The
32 water temperature at the upper trap depth also increased during the same period (Fig. 7
33 and S1), we therefore interpreted their increase to be related to the mixing of nutrient

1 and warm upper AW and [lower](#) PWW, rather than a decrease in sea ice concentrations
2 due to their preference [for](#) the warm, upper AW.

3 4 [5.3.2. Radiolarian fauna and *interannual* difference in ocean circulation](#)

5 Intensification of geostrophic currents on the periphery of Beaufort Gyre (Fig. 1) has
6 been reported in recent years (Nishino et al., 2011; McPhee, 2013). This intensification
7 is caused by increasing volume of water from sea-ice melt associated with the reduction
8 of arctic summer sea-ice and the river runoff to the basins (Proshutinsky et al., 2009;
9 Yamamoto-Kawai et al., 2008). The total radiolarian flux showed lower production
10 during summer (July-September) in 2012 than in 2011 in both [the](#) upper and, [especially](#),
11 lower traps ([Fig. 5](#)). Most radiolarian taxa also showed lower flux during summer of
12 2012 ([Fig. 7](#)). On the other hand, fluxes of [the actinommids](#) (Actinommidae spp.
13 juvenile forms, *Actinomma l. leptodermum*, *Actinomma boreale*), [possibly](#) adapted to
14 cold and oligotrophic water, showed higher values during December 2011-September
15 2012 than during December 2010-September 2011. Actinommidae spp. juvenile forms
16 and *A. l. leptodermum* were most abundant in the depth interval of 0-100 m at Station
17 56 in the southwestern Canada Basin. Therefore, we interpreted [these data to mean](#) that
18 cold and oligotrophic water in the Canada Basin began to spread to Station NAP in the
19 Northwind Abyssal Plain from December 2011 and continued to affect the radiolarian
20 fluxes at least until September 2012. McLaughlin et al. (2011) reported that the position
21 of the center of the Beaufort Gyre shifted westwards and that the area under the
22 influence of the gyre spread northwards and westwards in recent years. Moreover,
23 high-resolution pan-Arctic Ocean model results also showed that the Beaufort Gyre
24 expanded [by shifting](#) its center from the Canada Basin interior to the Chukchi
25 Borderland in 2012 compared with 2011, and the ocean current direction in the surface
26 100 m layer switched northwestward to southwestward in December 2011 (E. Watanabe,
27 personal communication, 2014). Thus, recent intensification of Beaufort Gyre [currents](#)
28 associated with sea-ice reduction, would have affected the surface water mass
29 conditions and [as well as](#) the [ecological conditions](#) in the western Arctic Ocean.

30 31 [5.3.3. Vertical and lateral transport](#)

32 Flux peaks of total radiolarians in the lower trap are delayed by about two weeks in
33 comparison to the upper trap (Fig. 5). Therefore, the sinking speed of the aggregated

1 radiolarian particle flux between these depths were averaged to 74 m day⁻¹ during
2 November-December 2010, 86 m day⁻¹ during July-August 2011, and 73 m day⁻¹ during
3 November 2011. Watanabe et al. (2014) simulated movement of cold and warm eddies
4 using a high-resolution pan-Arctic Ocean model, and suggested that the high total mass
5 flux during October-December 2010 at Station NAP, as we determined using sediment
6 samples, was mainly due to the enhancement of the marine biological pump by an
7 anti-cyclonic cold eddy. Shelf-break eddies induce the lateral transport of resuspended
8 bottom sediments composed of old carbon, and enhance the biological pump (O'Brien
9 et al., 2013; Watanabe et al., 2014). Actually, the passage of a cold eddy was observed
10 as a cooling and a deepening of the moored trap depth in the corresponding period (Fig.
11 S1). Amphimelissa setosa was the most dominant species (>90%) and showed the
12 highest flux (13,840 specimens m⁻² day⁻¹) during November 2010 in the upper trap.
13 The flux of this species was about 3,500 specimens m⁻² day⁻¹ higher and kept the
14 highest value half a month longer than that in 2011. The cold eddy passage would
15 transport a cold and well mixed water mass, conditions favorable for *A. setosa*.
16 Therefore the cold eddy passage in addition to seasonal water mass variations with sea
17 ice formation would enhance the high radiolarian flux.

18 Radiolarian fluxes in the lower trap were generally higher than in the upper trap
19 except for May-September 2012 (Fig. 5). The extremely low fluxes in the lower trap
20 during this interval might be due to a decrease of aggregate formation. The latter
21 process, which helps rapid sinking of biogenic particles, would be suppressed by influx
22 of oligotrophic surface water originating from the Beaufort Gyre in the Canada Basin.
23 In the southwestern Canada Basin (Station 56), high standing stock of dead radiolarian
24 specimens (Fig. 2) might indicate an inefficient biological pump in this area. In addition,
25 fluxes of Actinommidae spp. juvenile forms were lower in the lower trap, in spite of
26 their high abundance in the upper trap since December 2011. We suggest that the
27 disappearance of fluxes of Actinommidae spp. juvenile forms in the lower trap might be
28 due to lack of aggregate formation.

29 Higher abundance in the lower trap of species having a wider vertical distribution
30 (*Pseudodictyophimus g. gracilipes*, *P. plathycephalus*) or intermediate to deep water
31 distribution (*Ceratocyrtis histicosus*, *Tripodiscium gephyristes*, Plagiacanthidae gen. et
32 sp. indet., and *Cycladophora davisiana*) might be attributed to the reproduction of these
33 species at a depth level situated between the upper and lower traps. The seasonal

1 changes in the fluxes of intermediate and deep dwellers to the lower trap would reflect
2 the availability of food supply. The flux of *Pseudodictyophimus g. gracilipes*, *P.*
3 *plathycephalus*, *Plagiacanthidae* gen. et sp. in det. and *Cycladophora davisiana* in the
4 lower trap was high during July-August 2011. Most of the radiolarian species in the
5 lower trap also peak during March 2011, a period of heavy ice cover and low downward
6 shortwave radiation. In addition, in the lower trap the flux peak during March in 2011
7 was made up of more than 80% of *A. setosa*, a definite surface water species. However,
8 during this period a similar peak was not found in the upper trap. Therefore, the flux
9 peaks during March 2011 could be derived from some lateral advection at a depth lower
10 than 180m or a re-suspension of shelf sediments.

11 12 **Acknowledgements**

13 We are grateful to the captain, officers and crews of the CCGS Sir Wilfrid Laurier,
14 R.V. Mirai (JAMSTEC), operated by GODI, R/V, Dr. Humfrey Melling (IOS, Canada),
15 Dr. Shigeto Nishino for their help in the mooring operation and sampling collection. We
16 are thankful to Dr. A. Matul (P.P. Shirshov Institute of Oceanology, Russian Academy of
17 Sciences, Moscow) for critically reading and commenting on our manuscript. We
18 similarly thankful to G. Cortese for his detailed comments and correcting our English,
19 this greatly improved our manuscript. We are thankful to one anonymous reviewer who
20 had some good and helpful comments and suggestions. This work was supported by
21 JSPS KAKENHI Grant Number 22221003 to NH and JSPS KAKENHI Grant Number
22 24•4155 and 26740006 to TI. TI received partial fund from Tatsuro Matsumoto
23 Scholarship Fund of the Kyushu University. This work was partly carried out when TI
24 was visiting the Natural History Museum, University of Oslo in 2013.

25 26 **References**

- 27 Aagaard, K., Coachman, L. K., and Carmack, E.: On the halocline of the Arctic Ocean,
28 Deep-Sea Res. Pt. I, 28, 529–545, 1981.
- 29 Aagaard, K., Swift, J. H., and Carmack, E. C.: Thermohaline circulation in the Arctic
30 Mediterranean seas, J. Geophys. Res., 90, 4833–4846, 1985.
- 31 Adl, S. M., Simpson, G. B., Farmer, M. A., Andersen, R. A., Anderson, O. R., Barta, J.
32 R., Bowser, S. S., Brugerolle, G., Fensome, R. A., Fredericq, S., James, T. Y.,
33 Karpov, S., Kugrens, P., Krug, J., Lane, C. E., Lewis, L. A., Lodge, J., Lynn, D. H.,

- 1 Mann, D. G., Mccourt, R. M., Mendoza, L., Moestrup, Ø., Mozley-Standridge, S. E.,
2 Nerad, T. A., Shearer, C. A., Smirnov, A. V., Spiegel, F. W., and Taylor, M. F. J. R.:
3 The new higher level classification of Eukaryotes with emphasis on the taxonomy of
4 protists, *J. Eukaryot. Microbiol.* 52, 399–451, 2005.
- 5 Anderson, O. R.: *Radiolaria*, Springer, New York, 365 pp., 1983.
- 6 Arrigo, K. R., Perovich, D. K., Pickart, R. S., Brown, Z. W., van Dijken, G. L., Lowry,
7 K. E., Mills, M. M., Palmer, M. A., Balch, W. M., Bahr, F., Bates, N. R.,
8 Benitez-Nelson, C., Bowler, B., Brownlee, E., Ehn, J. K., Frey, K. E., Garley, R.,
9 Laney, S. R., Lubelczyk, L., Mathis, J., Matsuoka, A., Mitchell, B. G., Moore, G. W.
10 K., Ortega-Retuerta, E., Pal, S., Polashenski, C. M., Reynolds, R. A., Scheiber, B.,
11 Sosik, H. M., Stephens, M., and Swift, J. H.: Massive phytoplankton blooms under
12 Arctic sea ice, *Science*, 336, 1408, doi:10.1126/science.1215065, 2012.
- 13 Assmy, P., Ehn, J. K., Fernández-Méndez, M., Hop, H., Katlein, C., Sundfjord, A.,
14 Bluhm, K., Daase, M., Engel, A., Fransson, A., Granskog, M. A., Hudson, S. R.,
15 Kristiansen, S., Nicolaus, 5 M., Peeken, I., Renner, A. H. H., Spreen, G., Tatarek, A.,
16 and Wiktor, J.: Floating ice–algal aggregates below melting Arctic Sea ice, *PLoS*
17 *ONE*, 8, e76599, doi:10.1371/journal.pone.0076599, 2013.
- 18 Bailey, J. W.: Notice of microscopic forms found in the soundings of the Sea of
19 Kamtschatka, *Am. J. Sci. Arts*, 22, 1–6, 1856.
- 20 Bates, N. R. and Mathis, J. T.: The Arctic Ocean marine carbon cycle: evaluation of
21 air-sea CO₂ exchanges, ocean acidification impacts and potential feedbacks,
22 *Biogeosciences*, 6, 2433–2459, doi:10.5194/bg-6-2433-2009, 2009.
- 23 Bates, N. R., Moran, S. B., Hansell, D. A., and Mathis, J. T.: An increasing CO₂ sink in
24 the Arctic Ocean due to sea-ice loss, *Geophys. Res. Lett.*, 33, L23609,
25 doi:10.1029/2006GL027028, 2006.
- 26 Bernstein, T.: Protist plankton of the North-west part of the Kara Sea, Transactions of
27 the Arctic Institute, 3, 1–23, 1931 (in Russian with English summary).
- 28 Bernstein, T.: Über einige arktische Radiolarien, Arch. Protistenkunde, 76, 217–227,
29 1932.
- 30 Bernstein, T.: Zooplankton des Nordlichen teiles des Karischen Meeres, Transactions
31 of the Arctic Institute, 9, 3–58, 1934 (in Russian with German summary).
- 32 Bjørklund, K. R. and Kruglikova, S. B.: Polycystine radiolarians in surface sediments in
33 the Arctic Ocean basins and marginal seas, *Mar. Micropaleontol.*, 49, 231–273,

1 2003.

2 Bjørklund, K. R., Cortese, G., Swanberg, N., and Schrader, H. J.: Radiolarian faunal
3 provinces in surface sediments of the Greenland, Iceland and Norwegian (GIN) seas,
4 Mar. Micropaleontol., 35, 105–140, 1998.

5 [Bjørklund, K. R., Dumitrica, P., Dolven, J. K., and Swanberg, N. R.: Joergensenium](#)
6 [rotatile n. gen., n. sp. \(Entactinaria, Radiolaria\): its distribution in west Norwegian](#)
7 [fjords, Micropaleontology, 53, 457–468, 2008.](#)

8 Bjørklund, K. R., Itaki, T., and Dolven, J. K.: Per Theodor Cleve: a short résumé and his
9 radiolarian results from the Swedish Expedition to Spitsbergen in 1898, J.
10 Micropalaeontol., 33, 59–93, 2014.

11 Boetius, A., Albrecht, S., Bakker, K. B., Bienhold, C., Felden, J., Fernández-Méndez,
12 M., Hendricks, S., Katlein, C., Lalande, C., Krumpfen, T., Nicolaus, M., Peeken, I.,
13 Rabe, B., Rogacheva, A., Rybakova, E., Somavilla, R., and Wenzhöfer, F.: Export of
14 algal biomass from the melting arctic sea ice, Science, 339, 1430–1432,
15 doi:10.1126/science.1231346, 2013.

16 Boltovskoy, D., Kling, S. A., Takahashi, K., and Bjørklund, K. R.: World atlas of
17 distribution of recent polycystina (Radiolaria), Palaeontol. Electron., 13, 1–230,
18 available at: http://palaeo-electronica.org/2010_3/215/index.html (last access: 29
19 November 2014), 2010.

20 Burrige, A. K., Bjørklund, K. R., Kruglikova, S. B., and Hammer, Ø.: Inter- and
21 intraspecific morphological variation of four-shelled *Actinomma* taxa (Radiolaria) in
22 polar and subpolar regions, Mar. Micropaleontol., 110, 50–71, 2013.

23 Calbet, A. and Landry, M. R.: Phytoplankton growth, microzooplankton grazing, and
24 carbon cycling in marine systems, Limnol. Oceanogr., 49, 51–57, 2004.

25 [Cavalier-Smith, T.: A revised six-kingdom system of life, Biol. Rev., 73, 203-266, 1998.](#)
26 [Cavalier-Smith, T.: The phagotrophic origin of eukaryotes and phylogenetic](#)
27 [classification of Protozoa, Int. J. Syst. Evol. Micr., 52, 297-354, 2002.](#)

28 Cavalier-Smith, T. and Chao, E. E. Y.: Phylogeny and classification of phylum Cercozoa
29 (Protozoa), Protist, 154, 341–358, 2003.

30 Cleve, P. T.: Plankton collected by the Swedish Expedition to Spitzbergen in 1898, Kgl.
31 Svenska Vetensk. Akad. Hand., 32, 1–51, 1899.

32 Coachman, L. and Barnes, C. A.: The contribution of Bering Sea water to the Arctic
33 Ocean, Arctic, 14, 147–161, 1961.

- 1 Coachman, L. K., Aagaard, K., and Tripp, R. B.: Bering Strait: the regional physical
2 oceanography, University of Washington Press, Seattle, 172 pp., 1975.
- 3 Comiso, J. C., Parkinson, C. L., Gersten, R., and Stock, L.: Accelerated decline in the
4 Arctic sea ice cover, *Geophys. Res. Lett.*, 35, L01703, doi:10.1029/2007GL031972,
5 2008.
- 6 Cortese, G. and Bjørklund, K. R.: The morphometric variation of *Actinomma boreale*
7 (Radiolaria) in Atlantic boreal waters, *Mar. Micropaleontol.*, 29, 271–282, 1997.
- 8 Cortese, G. and Bjørklund, K. R.: The taxonomy of boreal Atlantic Ocean.
9 Actinommida (Radiolaria), *Micropaleontology*, 44, 149–160, 1998.
- 10 Cortese, G., Bjørklund, K. R., and Dolven, J. K.: Polycystine radiolarians in the
11 Greenland–Iceland–Norwegian seas: species and assemblage distribution, *Sarsia:*
12 *North Atlantic Marine Science*, 88, 65–88, 2003.
- 13 [Dolan, J. R., Yang, E. J., Kim, T. W. and Kang, S.-H.: Microzooplankton in a warming](#)
14 [Arctic: A comparison of tintinnids and radiolarians from summer 2011 and 2012 in](#)
15 [the Chukchi Sea, *Acta Protozool.*, 53, 101–113, 2014.](#)
- 16 Dolven, J. K., Bjørklund, K. R., and Itaki, T.: Jørgensen’s polycystine radiolarian slide
17 collection and new species, *J. Micropalaeontol.*, 33, 21–58, 2014.
- 18 Dumitrica, P.: *Cleveplegma* n. gen., a new generic name for the radiolarian species
19 *Rhizoplegma boreale* (Cleve, 1899), *Revue de Micropaléontologie*, 56, 21–25, 2013.
- 20 Ehrenberg, C. G.: Über die Bildung der Kreidefelsen und des Kreidemergels durch
21 unsichtbare Organismen, *Abhandlungen, Jahre 1838*, K. Preuss. Akad. Wiss., Berlin,
22 59–147, 1838.
- 23 Ehrenberg, C. G.: Über das organischen Leben des Meeresgrundes in bis 10 800 und 12
24 000 Fuss Tiefe, *Bericht, Jahre 1854*, K. Preuss. Akad. Wiss., Berlin, 54–75, 1854.
- 25 Ehrenberg, C. G.: Über die Tiefgrund-Verhältnisse des Oceans am Eingange der
26 Davisstrasse und bei Island, *Monatsberichte. Jahre 1861*, K. Preuss. Akad. Wiss.,
27 Berlin, 275–315, 1862.
- 28 Ehrenberg, C. G.: Mikrogeologischen Studien über das kleinste Leben der
29 Meeres-Tiefgrunde aller Zonen und dessen geologischen Einfluss, *Abhandlungen*,
30 *Jahre 1873*, K. Preuss. Akad. Wiss., Berlin, 131–399, 1873.
- 31 Ehrenberg, C. G.: Fortsetzung der mikrogeologischen Studien als Gesamt-Uebersicht
32 der mikroskopischen Palaontologie gleichartig analysirter Gebirgsarten der Erde,
33 mit specieller Rucksicht auf den Polycystinen-Mergel von Barbados, *Abhandlungen*,

- 1 Jahre 1875, K. Preuss. Akad. Wiss., Berlin, 1–225, 1875.
- 2 Ewing, M. and Connary, S.: Nepheloid layer in the North Pacific, in: Geological
3 Investigations of the North Pacific, edited by: Hays, J. D., Geol. Soc. Am. Mem.,
4 126, 41–82, 1970.
- 5 Francois, R., Honjo, S., Krishfield, R., and Manganini, S.: Factors controlling the flux
6 of organic carbon to the bathypelagic zone of the ocean, Global Biogeochem. Cy.,
7 16, 1087, doi:10.1029/2001GB001722, 2002.
- 8 Haeckel, E.: Die Radiolarien (Rhizopoda Radiaria) – Eine Monographie, Reimer, Berlin,
9 572 pp., 1862.
- 10 Haeckel, E.: Über die Phaeodarien, eine neue Gruppe kieselschaliger mariner
11 Rhizopoden, Jenaische Zeitschrift für Naturwissenschaft, 14, 151–157, 1879.
- 12 Haeckel, E.: Prodromus Systematis Radiolarium, Entwurf eines Radiolarien-Systems
13 auf Grund von Studien der Challenger-Radiolarien, Jenaische Zeitschrift für
14 Naturwissenschaft, 15, 418–472, 1881.
- 15 Haeckel, E.: Report on the Radiolaria collected by the H.M.S. *Challenger* during the
16 Years 1873–1876, Report on the Scientific Results of the Voyage of the H.M.S.
17 *Challenger*, Zoology, 18, 1–1803, 1887.
- 18 Harrison, W. G. and Cota, G. F.: Primary production in polar waters: relation to nutrient
19 availability, Polar Res., 10, 87–104, 1991.
- 20 Hertwig, R.: Der Organismus der Radiolarien, Jenaische Denkshr., 2, 129–277, 1879.
- 21 Honjo, S., Krishfield, R. A., Eglinton, T. I., Manganini, S. J., Kemp, J. N., Doherty, K.,
22 Hwang, J., Mckee, T. K., and Takizawa, T.: Biological pump processes in the
23 cryopelagic and hemipelagic Arctic Ocean: Canada Basin and Chukchi Rise, Prog.
24 Oceanogr., 85, 137–170, 2010.
- 25 Horner, R. A., Ackley, S. F., Dieckmann, G. S., Gulliksen, B., Hoshiai, T., Legendre, L.,
26 Melnikov, I. A., Reeburgh, W. S., Spindler, M., and Sullivan, C. W.: Ecology of sea
27 ice biota. 1. Habitat, terminology, and methodology, Polar Biol., 12, 417–427, 1992.
- 28 Hülseman, K.: Radiolaria in plankton from the Arctic drifting station T-3, including the
29 description of three new species, Arc. Inst. North Am. Tech. Pap., 13, 1–52, 1963.
- 30 Ikenoue, T., Ishitani, Y., Takahashi, K., and Tanaka, S.: Seasonal flux changes of
31 radiolarians at Station K2 in the Western Subarctic Gyre, Umi no Kenkyu
32 (Oceanography in Japan), 19, 165–185, 2010 (in Japanese, with English abstract).
- 33 Ikenoue, T., Takahashi, K., and Tanaka, S.: Fifteen year time-series of radiolarian fluxes

1 and environmental conditions in the Bering Sea and the central subarctic Pacific,
2 1990–2005, *Deep-Sea Res. Pt. II*, 61–64, 17–49, 2012a.

3 Ikenoue, T., Ueno, H., and Takahashi, K.: *Rhizoplegma boreale* (Radiolaria): a tracer for
4 mesoscale eddies from coastal areas, *J. Geophys. Res.*, 117, C04001,
5 doi:10.1029/2011JC007728, 2012b.

6 Ishitani, Y. and Takahashi, K.: The vertical distribution of Radiolaria in the waters
7 surrounding Japan, *Mar. Micropaleontol.*, 65, 113–136, 2007.

8 Ishitani, Y., Takahashi, K., Okazaki, Y., and Tanaka, S.: Vertical and geographic
9 distribution of selected radiolarian species in the North Pacific, *Micropaleontology*,
10 54, 27–39, 2008.

11 Itaki, T. and Bjørklund, K. R.: Conjoined radiolarian skeletons (Actinommidae) from
12 the Japan Sea sediments, *Micropaleontology*, 53, 371–389, 2007.

13 Itaki, T., Ito, M., Narita, H., Ahagon, M., and Sakai, I.: Depth distribution of
14 radiolarians from the Chukchi and Beaufort Seas, western Arctic, *Deep-Sea Res. Pt.*
15 *I*, 50, 1507–1522, 2003.

16 Itoh, M., Nishino, S., Kawaguchi, Y., and Kikuchi, T.: Barrow Canyon fluxes of volume,
17 heat and freshwater revealed by mooring observations, *J. Geophys. Res.*, 118,
18 4363–4379, 2013.

19 Jackson, J. M., Allen, S. E., McLaughlin, F. A., Woodgate, R. A., and Carmack, E. C.:
20 Changes to the near surface waters in the Canada Basin, Arctic Ocean from
21 1993–2009: a basin in transition, *J. Geophys. Res.*, 116, C10008,
22 doi:10.1029/2011JC007069, 2011.

23 Jones, E. P. and Anderson, L. G.: On the origin of the chemical properties of the Arctic
24 Ocean halocline, *J. Geophys. Res.*, 91, 10759–10767, 1986.

25 Jørgensen, E.: Protophyten und Protozoen im Plankton aus der norwegischen Westküste,
26 *Bergens Museumus Aarbog* 1899, 6, 51–112, 1900.

27 Jørgensen, E.: The Protist plankton and the diatoms in bottom samples, Plates
28 VIII–XVIII, *Bergens Museuns Skrifter*, 1, 49–151, 1905.

29 Kling, S. A.: Vertical distribution of polycystine radiolarians in the central North Pacific,
30 *Mar. Micropaleontol.*, 4, 295–318, 1979.

31 [Kosobokova, K. N., Hirche, H. -J. and Scherzinger, T.: Feeding ecology of](#)
32 [Spinocalanus antarcticus, a mesopelagic copepod with a looped gut, *Mar. Biol.*, 141,](#)
33 [503–511, 2002.](#)

- 1 Kozur, H. and Möstler, H.: *Entactinaria subordo* Nov., a new radiolarian suborder,
2 Geologisch Paläontologische Mitteilungen, Innsbruck, 11, 399–414, 1982.
- 3 Kruglikova, S. B., Bjørklund, K. R., Hammer, Ø., and Anderson, O. R.: Endemism and
4 speciation in the polycystine radiolarian genus *Actinomma* in the Arctic Ocean:
5 description of two new species *Actinomma georgii* n. sp., and *A. turidae* n. sp., Mar.
6 Micropaleontol., 72, 26–48, 2009.
- 7 Kruglikova, S. B., Bjørklund, K. R., Dolven, J. K., Hammer, Ø., and Cortese, G.:
8 High-rank polycystine radiolarian taxa as temperature proxies in the Nordic Seas,
9 Stratigraphy, 7, 265–281, 2010.
- 10 Kruglikova, S. B., Bjørklund, K. R., and Hammer, O.: High rank taxa of Polycystina
11 (Radiolaria) as environmental bioindicators, Micropaleontology, 57, 483–489, 2011.
- 12 [Lovejoy, C. and Potvin, M.: Microbial eukaryotic distribution in a dynamic Beaufort](#)
13 [Sea and the Arctic Ocean, J. Plankton Res., 33, 431–444, 2011.](#)
- 14 [Lovejoy, C., Massana, R., and Pedrós-Alió, C.: Diversity and distribution of marine](#)
15 [microbial eukaryotes in the Arctic Ocean and adjacent seas, Appl. Environ. Microb.,](#)
16 [72, 3085–3095, doi:10.1128/AEM.72.5.3085-3095.2006, 2006.](#)
- 17 Markus, T., Stroeve, J. C., and Miller, J.: Recent changes in Arctic sea ice melt onset,
18 freezeup, and melt season length, J. Geophys. Res., 114, C12024,
19 doi:10.1029/2009JC005436, 2009.
- 20 Matul, A. and Abelmann, A.: Pleistocene and Holocene distribution of the radiolarian
21 *Amphimelissa setosa* Cleve in the North Pacific and North Atlantic: evidence for
22 water mass movement, Deep-Sea Res. Pt. II, 52, 2351–2364, 2005.
- 23 McLaughlin, F. A., Carmack, E., Proshutinsky, A., Krishfield, R. A., Guay, C. K.,
24 Yamamoto-Kawai, M., Jackson, J. M., and Williams, W. J.: The rapid response of
25 the Canada Basin to climate forcing: From bellwether to alarm bells, Oceanography,
26 24, 146–159, doi:10.5670/oceanog.2011.66, 2011.
- 27 McPhee, M.: Intensification of geostrophic currents in the Canada Basin, Arctic Ocean,
28 J. Climate, 26, 3130, doi:10.1175/JCLI-D-12-00289.1, 2013.
- 29 [Meunier, A.: Microplankton des Mers de Barents et de Kara, Duc d'Orléans, Campagne](#)
30 [arctique de 1907, 255 pp., 1907.](#)
- 31 Michel, C., Nielsen, T. C., Nozais, C., and Gosselin, M.: Significance of sedimentation
32 and grazing by ice micro- and meiofauna for carbon cycling in annual sea ice
33 (northern Baffin Bay), Aquat. Microb. Ecol., 30, 57–68, 2002.

- 1 Murray, J.: The Radiolaria. Narrative of the cruise of the H.M.S. “*Challenger*” with a
2 general account of the scientific results of the expedition, in: Report from the
3 Voyage of the H.M.S. *Challenger*, edited by: Tizard, T. H., Moseley, H. N.,
4 Buchanan, J. Y., and Murray, J., Narrative, 1, 219–227, 1885.
- 5 Müller, J.: Über die Thalassicollen, Polycystinen und Acanthometren des Mittelmeeres,
6 Abhandlungen, Jahre 1858, K. Preuss. Akad. Wiss., Berlin, 1–62, 1858.
- 7 Nikolaev, S. I., Berney, C., Fahrni, J., Bolivar, I., Polet, S., Mylnikov, A. P., Aleshin, V.
8 V., Petrov, N. B., and Pawlowski, J.: The twilight of Heliozoa and rise of Rhizaria,
9 an emerging supergroup of amoeboid eukaryotes, P. Natl. Acad. Sci. USA, 101,
10 8066–8071, 2004.
- 11 Nimmergut, A. and Abelmann, A.: Spatial and seasonal changes of radiolarian standing
12 stocks in the Sea of Okhotsk, Deep-Sea Res. Pt. I, 49, 463–493, 2002.
- 13 Nishino, S., Kikuchi, T., Yamamoto-Kawai, M., Kawaguchi, Y., Hirawake, T., and Itoh,
14 M.: Enhancement/reduction of biological pump depends on ocean circulation in the
15 sea-ice reduction regions of the Arctic Ocean, J. Oceanogr., 67, 305–314,
16 doi:10.1007/s10872-011-0030-7, 2011.
- 17 Nishino, S.: R/V *Mirai* cruise report MR13-06, 226 pp., available at:
18 www.godac.jamstec.go.jp/darwin/datatree/e (last access: 29 November 2014),
19 JAMSTEC, Yokosuka, Japan, 2013.
- 20 NSIDC (National Snow and Ice Data Center): Arctic sea ice extent settles at record
21 seasonal minimum, available at: <http://nsidc.org/arcticseaicenews/2012/09/> (last
22 access: 29 November 2014), 2012.
- 23 O’Brien, M. C., Melling, H., Pedersen, T. F., and Macdonald, R.W.: The role of eddies
24 on particle flux in the Canada Basin of the Arctic Ocean, Deep-Sea Res. Pt. I, 71,
25 1–20, 2013.
- 26 Okazaki, Y., Takahashi, K., Yoshitani, H., Nakatsuka, T., Ikehara, M., and Wakatsuchi,
27 M.: Radiolarians under the seasonally sea-ice covered conditions in the Okhotsk
28 Sea: flux and their implications for paleoceanography, Mar. Micropaleontol., 49,
29 195–230, 2003.
- 30 Okazaki, Y., Takahashi, K., Itaki, T., and Kawasaki, Y.: Comparison of radiolarian
31 vertical distributions in the Okhotsk Sea near the Kuril Islands and in the
32 northwestern North Pacific off Hokkaido Island, Mar. Micropaleontol., 51, 257–284,
33 2004.

- 1 Okazaki, Y., Takahashi, K., Onodera, J., and Honda, M. C.: Temporal and spatial flux
2 changes of radiolarians in the northwestern Pacific Ocean during 1997–2000,
3 *Deep-Sea Res. Pt. II*, 52, 2240–2274, 2005.
- 4 [Onodera, J., Watanabe, E., Harada, N., and Honda, M. C.: Diatom flux reflects
5 water-mass conditions on the southern Northwind Abyssal Plain, Arctic Ocean,
6 *Biogeosciences Discuss.*, 11, 15215–15250, doi:10.5194/bgd-11-15215-2014, 2014.](#)
- 7 Petrushevskaya, M. G.: Radiolarians of orders Spumellaria and Nassellaria of the
8 Antarctic region (from material of the Soviet Antarctic Expedition), in: *Studies of*
9 *Marine Fauna IV(XII): Biological Reports of the Soviet Antarctic Expedition*
10 (1955–1958), edited by: Andriyashev, A. P. and Ushakov, P. V., Academy of
11 Sciences of the USSR, Zoological Institute, Leningrad, 3, 2–186, 1967 (translated
12 from Russian and published by Israel Program for Scientific Translations, 1968).
- 13 Petrushevskaya, M. G.: Radiolyarii Nassellaria v planktone Mirovogo Okeana,
14 *Issledovaniya Fauny Morei*, 9, 1–294, 1971 (+ App., 374–397), Nauka, Leningrad,
15 in Russian.
- 16 Popofsky, A.: Die Radiolarien der Antarktis (mit Ausnahme der Tripyleen), in: *Deutsche*
17 *Südpolar-Expedition 1901–1903. X, Zoologie*, 2, part 3, edited by: Drygalski, E.,
18 Georg Reimer, Berlin, 184–305, 1908.
- 19 Proshutinsky, A., Bourke, R. H., and McLaughlin, F. A.: The role of the Beaufort Gyre
20 in Arctic climate variability: seasonal to decadal climate scales, *Geophys. Res. Lett.*,
21 29, 2100, doi:10.1029/2002GL015847, 2002.
- 22 Proshutinsky, A., Krishfield, R., Timmermans, M. L., Toole, J., Carmack, E.,
23 McLaughlin, F., Williams, W. J., Zimmermann, S., Itoh, M., and Shimada, K.:
24 Beaufort Gyre freshwater reservoir: state and variability from observations, *J.*
25 *Geophys. Res.*, 114, C00A10, doi:10.1029/2008JC005104, 2009.
- 26 Reynolds, R. W., Rayner, N. A., Smith, T. M., Stokes, D. C., and Wang, W.: An
27 improved in situ and satellite SST analysis for climate, *J. Climate*, 15, 1609–1625,
28 2002.
- 29 Riedel, W. R.: Subclass radiolaria, in: *The Fossil Record*, edited by: Harland, W. B. et
30 al., Geol. Soc. London, London, UK, 291–298, 1967.
- 31 Saha, S., Moorthi, S., Pan, H. L., Wu, X. R., Wang, J. D., Nadiga, S., Tripp, P., Kistler,
32 R., Woollen, J., Behringer, D., Liu, H. X., Stokes, D., Grumbine, R., Gayno, G.,
33 Wang, J., Hou, Y. T., Chuang, H. Y., Juang, H. M. H., Sela, J., Iredell, M., Treadon,

1 R., Kleist, D., Van Delst, P., Keyser, D., Derber, J., Ek, M., Meng, J., Wei, H. L.,
2 Yang, R. Q., Lord, S., Van den Dool, H., Kumar, A., Wang, W. Q., Long, C.,
3 Chelliah, M., Xue, Y., Huang, B. Y., Schemm, J. K., Ebisuzaki, W., Lin, R., Xie, P. P.,
4 Chen, M. Y., Zhou, S. T., Higgins, W., Zou, C. Z., Liu, Q. H., Chen, Y., Han, Y.,
5 Cucurull, L., Reynolds, R. W., Rutledge, G., and Goldberg, M.: The NCEP climate
6 forecast system reanalysis, *B. Am. Meteorol. Soc.*, 91, 1015–1057, 2010.

7 Samtleben, C., Schäfer, P., Andrulleit, H., Baumann, A., Baumann, K. H., Kohly, A.,
8 Matthiessen, J., and Schröder-Ritzrau, A.: Plankton in the Norwegian–Greenland
9 Sea: from living communities to sediment assemblages – an actualistic approach,
10 *Geol. Rundsch.*, 84, 108–136, 1995.

11 Shannon, C. E. and Weaver, W.: *The Mathematical Theory of Communication*,
12 University of Illinois Press, Urbana, 125 pp., 1949.

13 Shimada, K., Carmack, E. C., Hatakeyama, K., and Takizawa, T.: Varieties of shallow
14 temperature maximum waters in the western Canadian Basin of the Arctic Ocean,
15 *Geophys. Res. Lett.*, 28, 3441–3444, 2001.

16 Shimada, K., Kamoshida, T., Itoh, M., Nishino, S., Carmack, E., McLaughlin, F.,
17 Zimmermann, S., and Proshutinsky, A.: Pacific Ocean inflow: influence on
18 catastrophic reduction of sea ice cover in the Arctic Ocean, *Geophys. Res. Lett.*, 33,
19 L08605, doi:10.1029/2005GL025624, 2006.

20 Stroeve, J., Holland, M. M., Meier, W., Scambos, T., and Serreze, M.: Arctic sea ice
21 decline: faster than forecast, *Geophys. Res. Lett.*, 34, L09501,
22 doi:10.1029/2007GL029703, 2007.

23 Stroeve, J. C., Serreze, M. C., Holland, M. M., Kay, J. E., Malanik, J., and Barrett, A. P.:
24 The Arctic’s rapidly shrinking sea ice cover: a research synthesis, *Climatic Change*,
25 110, 1005–1027, doi:10.1007/s10584-011-0101-1, 2012.

26 Suzuki N. and Aita Y.: Achievement and unsolved issues on radiolarian studies:
27 Taxonomy and cytology, *Plank. Benth. Res.*, 6, 69–91, 2011.

28 Swanberg, N. R., and Bjørklund, K. R.: Radiolaria in the plankton of some fjords in
29 western and northern Norway: the distribution of species, *Sarsia*, 72, 231-244, 1987.

30 Swanberg, N. R. and Eide, L. K.: The radiolarian fauna at the ice edge in the Greenland
31 Sea during summer, 1988, *J. Mar. Res.*, 50, 297–320, 1992.

32 Takahashi, K.: Radiolaria: flux, ecology, and taxonomy in the Pacific and Atlantic, in:.,
33 *Ocean Biocoenosis*, Ser. 3, edited by: Honjo, S., Woods Hole Oceanographic

- 1 Institution Press, Woods Hole, MA, 303 pp., 1991.
- 2 Takahashi, K. and Honjo, S.: Vertical flux of Radiolaria: a taxon-quantitative sediment
3 trap study from the western tropical Atlantic, *Micropaleontology*, 27, 140–190,
4 1981.
- 5 Tibbs, J. F.: On some planktonic Protozoa taken from the track of Drift Station Arlis I,
6 1960–1961, *J. Arct. Inst. N. Am.*, 20, 247–254, 1967.
- 7 Watanabe, E., Onodera, J., Harada, N., Honda, M. C., Kimoto, K., Kikuchi, T., Nishino,
8 S., Matsuno, K., Yamaguchi, A., Ishida, A., and Kishi, M. J.: Enhanced role of
9 eddies in the Arctic marine biological pump, *Nat. Commun.*, 5, 3950,
10 doi:10.1038/ncomms4950, 2014.
- 11 Welling, L. A.: Environmental control of radiolarian abundance in the central equatorial
12 Pacific and implications for paleoceanographic reconstructions, Ph.D. thesis,
13 Oregon State Univ., Corvallis, 314 pp., 1996.
- 14 Yamamoto-Kawai, M., McLaughlin, F. A., Carmack, E. C., Nishino, S., and Shimada,
15 K.: Freshwater budget of the Canada Basin, Arctic Ocean, from salinity, $\delta^{18}O$, and
16 nutrients, *J. Geophys. Res.*, 113, C01007, doi:10.1029/2006JC003858, 2008.
- 17 Yang, J.: Seasonal and interannual variability of downwelling in the Beaufort Sea, *J.*
18 *Geophys. Res.*, 114, C00A14, doi:10.1029/2008JC005084, 2009.
- 19 Yuasa, T., Takahashi, O., Honda, D., and Mayama, S.: Phylogenetic analyses of the
20 polycystine Radiolaria based on the 18s rDNA sequences of the Spumellarida and
21 the Nassellarida, *Eur. J. Protistol.*, 41, 287–298, 2005.
- 22 Zhang, J., Rothrock, D. A., and Steele, M.: Warming of the Arctic Ocean by a
23 strengthened Atlantic inflow: Model results, *Geophys. Res. Lett.*, 25, 1745-1748,
24 1998.

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26 **Table captions**

27 Table 1. Logistic and sample information for the vertical plankton tows for radiolarian
28 standing stock (S. S.) at two stations during R/V *Mirai* Cruise MR13-06

29 Table 2. Locations, mooring depths, standard sampling interval, and sampled duration
30 of sediment trap station in the western Arctic Ocean. *Details of the exact durations for
31 each sample are shown in tables S3 and S4.

32 Table 3. List of 51 radiolarian taxa encountered in the plankton tow and sediment trap
33 samples. All taxa are found in the trap, and * refer to taxa found in trap only.

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Supplement table captions

Table S1. Radiolarian counts of living and dead specimens (45µm-1 mm) in plankton tows at Station 32

Table S2. Radiolarian counts of living and dead specimens (45µm-1 mm) in plankton tows at Station 56

Table S3. Radiolarian counts (45µm-1 mm) in upper trap at Station NAP

Table S4. Radiolarian counts (45µm-1 mm) in lower trap at Station NAP

Table S5. Summary information of previous sediment trap studies in the North Pacific Ocean

Figure captions

Fig. 1. Map of the Chukchi and Beaufort Seas showing the locations of sediment trap (solid triangle) and plankton tows (solid circles). Gray arrows indicate the cyclonic circulation of the Beaufort Gyre and the inflow of Pacific water through the Bering Strait, respectively.

Fig. 2. Depth distributions of total dead and living radiolarians at stations 32 (a), and 56 (b) in comparison to vertical profiles of temperature, salinity, dissolved oxygen, and chlorophyll *a* (Nishino, 2013), and living radiolarian diversity index (Shannon and Weaver, 1949). The different water masses are identified as: Surface Mixed Layer (SML), Pacific Summer Water (PSW), Pacific Winter Water (PWW), Atlantic Water (AW), and Canada Basin Deep Water (CBDW).

Fig. 3. Compositions of living radiolarian assemblages in plankton samples through the upper 1000 m of the water columns at stations 32 (Northwind Abyssal Plain) (a) and 56 (southwestern Canada basin) (b).

Fig. 4. Depth distributions of fourteen living radiolarians in plankton samples at stations 32 (a) and 56 (b).

Fig. 5. (a) Total radiolarian fluxes, diversity index and sea-ice concentration in upper trap at Station NAP. 2 samples with fewer than 100 specimens are marked with asterisk. Sea-ice concentration data are from Reynolds et al. (2002) (http://iridl.ldeo.columbia.edu/SOURCES/.IGOSS/.nmc/.Reyn_SmithOIv2/). (b) Radiolarian faunal compositions in upper trap at Station NAP. (c) Downward short wave radiation at the surface of sea-ice and ocean (after sea-ice opening) around Station

1 NAP from National Centers for Environmental Prediction-Climate Forecast System
2 Reanalysis (NCEP-CFSR) (Saha et al., 2010). (d) Total radiolarian fluxes [and](#)
3 Shannon-Weaver diversity index in the lower trap at Station NAP. 13 samples with
4 fewer than 100 specimens are marked with asterisk. (e) Radiolarian faunal compositions
5 in lower trap at Station NAP. Barren area; no samples due to trap failure.
6 Fig. 6. Scatter plots of diversity indices and total radiolarian fluxes at upper (a) and
7 lower trap (b). In these plots, samples with fewer than 100 specimens were excluded.
8 Fig. 7. Two-year fluxes of major radiolarian taxa at Station NAP during the sampling
9 period.
10 Fig. 8. Box plot of total radiolarian fluxes at Station NAP and previous studied areas in
11 the North Pacific Ocean ([Okazaki et al., 2003, 2005](#); [Ikenoue et al., 2010, 2012a](#)).
12 [Summary information of previous sediment trap studies in the North Pacific Ocean is](#)
13 [shown in table S5.](#)

14 15 **Supplement figure caption**

16 Fig. S1. Moored trap depth and the water temperature in the upper trap.

17 18 **Plate lists**

19 **Plate 1.** 1–4. *Actinomma boreale* (Cleve, 1899). 1, 2. *Actinomma boreale*, same
20 specimen. NAP10t Shallow #23. 3, 4. *Actinomma boreale*, same specimen. NAP10t
21 Shallow #24. 5–10. *Actinomma leptodermum leptodermum* (Jørgensen, 1900). 5, 6.
22 *Actinomma leptodermum leptodermum*, same specimen. NAP10t Deep #12. 7, 8.
23 *Actinomma leptodermum leptodermum*, same specimen. NAP10t Deep #12. 9, 10.
24 *Actinomma leptodermum leptodermum*, same specimen. NAP10t Deep #12. 11–14.
25 *Actinomma* morphogroup A. 11, 12. *Actinomma* morphogroup A, same specimen.
26 NAP10t Deep #4. 13, 14. *Actinomma* morphogroup A, same specimen. NAP10t Deep
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28 Bjørklund, 1998). 15, 16. *Actinomma leptodermum longispinum*, same specimen.
29 NAP10t Deep #12. 17, 18. *Actinomma leptodermum longispinum* juvenile, same
30 specimen. NAP10t Deep #12. 19–24. Actinommidae spp. juvenile forms. 19, 20.
31 *Actinomma* sp. indet., same specimen. NAP10t Deep #12. 21, 22. *Actinomma* sp. indet.,
32 same specimen. NAP10t Deep #12. 23, 24. *Actinomma* sp. indet., same specimen.
33 NAP10t Deep #12. 25–26. *Actinomma turidae* (Kruglikova and Bjørklund, 2009), same

1 specimen. NAP10t Deep #22.

2 Scale bar= 100 µm for all figures.

3

4 **Plate 2.** 1–4. *Actinomma* morphogroup B. 1, 2. *Actinomma* morphogroup B, same
5 specimen. NAP10t Deep #4. 3, 4. *Actinomma* morphogroup B juvenile, same specimen.
6 NAP10t Deep #15. 5, 6. *Drymyomma elegans* (Jørgensen, 1900), same specimen.
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8 Kruglikova, 2013), same specimen. NAP11t Deep #4. 10–11. *Cleveiplegma boreale*
9 (Cleve, 1899), same specimen. NAP11t Deep #12.

10 Scale bar= 100 µm for all figures.

11

12 **Plate 3.** 1–4. *Arachnosphaera dichotoma* (Jørgensen, 1900). 1, 2. *Arachnosphaera*
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14 specimen. NAP11t Deep #4. 5–8. *Streblacantha circumtexta?* (Jørgensen, 1905). 5, 6.
15 *Streblacantha circumtexta?* juvenile form, same specimen NAP10t Deep #12. 7, 8.
16 *Streblacantha circumtexta?* Juvenile form, same specimen. NAP10t Shallow #23. 9–11.
17 *Spongotrochus glacialis* (Popofsky, 1908). 9. *Spongotrochus aff. glacialis*. NAP10t
18 Shallow #24. 10, 11. *Spongotrochus glacialis*, same specimen. NAP10t Shallow #22. 12.
19 *Stylodictya* sp. NAP10t Shallow #16.

20 Scale bar= 100 µm for all figures.

21

22 **Plate 4.** 1–7. *Joergensenium* spp. 1, 2, 3. *Joergensenium* sp. A, same specimen. NAP10t
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29 Scale bar= 100 µm for all figures.

30

31 **Plate 5.** 1–6. *Ceratocyrtis histricosus* (Jørgensen, 1905). 1, 2, 3. *Ceratocyrtis*
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33 specimen. NAP10t Deep #12. 7–10. *Ceratocyrtis galeus* (Cleve, 1899). 7, 8.

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2 specimen. NAP10t Deep #4. 11–12. *Arachnocorys umbellifera* (Haeckel, 1862), same
3 specimen apical view. NAP10t Deep #4. 13–16. *Cladoscenum tricolpium* (Haeckel,
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6 *clevei* (Petrushevskaya, 1971), same specimen. NAP10t Shallow #14. 19–27.
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9 23, 24, 25. *Phormacantha hystrix*, same specimen. NAP10t Deep #12. 26, 27.
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11 Scale bar= 100 µm for all figures.
12

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27 Scale bar= 100 µm for all figures.
28

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32 *Pseudodictyophimus plathycephalus* (Haeckel, 1887). 4, 5, 6. *Pseudodictyophimus*
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3 *plathycephalus*, same specimen. NAP11t Deep #4. 13–14. *Tetraplecta pinigera*
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5 Scale bar= 100 µm for all figures.

6
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8 *gephyristes*, same specimen. NAP10t Deep #12. 3, 4, 5 *Tripodiscium gephyristes*, same
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12 juvenile, same specimen. NAP10t Deep #12. 13, 14. Plagiacanthidae gen. et sp. indet.,
13 same specimen. NAP10t Deep #12. 15, 16. Plagiacanthidae gen. et sp. indet., same
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17 *annulatus*, same specimen. NAP10t Deep #12. 23–30. *Artostrobos joergenseni*
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22 Scale bar= 100 µm for all figures.

23
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29 *furcaspiculata* (Popofsky, 1908). same specimen. NAP10t Deep #12. 12–13.
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32 *tabulatus* (Ehrenberg, 1873). 14, 15. *Sethoconus tabulatus*, same specimen. NAP10t
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13 Scale bar= 100 µm for all figures.