

Author's response

Dear Editor Yutaka Watanuki:

We are grateful to your comments and useful suggestions that improved our manuscript greatly. As described below, we have taken your comments and suggestions into account in the revised version of our manuscript. Please note that the expression in blue colored letters are the ones provided by you whereas those in black are our replies.

Associate Editor Initial Decision: Publish subject to minor revisions (Editor review) (02 Mar 2015) by Yutaka Watanuki

Comments to the Author:

Dear Dr Ikenoue,

Thanks for major revision. The MS is improved and will be acceptable. Contents of discussion seem to be appropriate. English, however, especially in the paragraphs that were revised extensively and those added to the MS, should be checked and edited very carefully again. Major revision sometimes makes new problems. Structure of the sentence also should be re-considered. For example, the first paragraph of the discussion section contains word "However" two times. This makes the paragraph weak. Also there are redundant wordings in some places.

Discussion on the factors expansion of *Ceratospyrus* should be described more clearly and shortly. How about the following ? "Ceratospyrus was not found in Canada Basin in 1950's and 1960's (Itaki et al. 2003) but we found it was common in upper AW in western Arctic in our sample collected in 2011. Since water temperature where this species occurred ranged from -1.6 (this study) to 10 C (Itaki et al. 2003, S & B 1987), slight increase of the temperature in the Arctic Sea (?? C, refs) during this period could not be a reason of the expansion of the range of this species . The change of North Atlantic Oscillation (atmospheric High and Low pressure cells) that controls the flow of the surface water in the North Atlantic has sustained the increase of Atlantic inflow in the Arctic Ocean (Zhang et al., 1998). This temporary increasing volumes of inflowing AW might increase the chances for more exotic radiolarians to expand their ranges into

the Arctic Ocean.” Does this mean that other Atlantic exotic radiolarians also expand the range into Arctic?

Authors are strongly suggested to re-consider the structure of the sentences in each paragraph and to polish English, and send the revised version. Subject editor will check the final MS.

With the best, Yutaka Watanuki

2015.3.2.

We accepted most of your suggestions you filled out our manuscript and used as it was.

According to your request and advice, English of our manuscript was checked and corrected by O. Roger Anderson, professor of Columbia University, widely known, one of the great specialists in Radiolaria.

We have consistently used the format of sea ice when it is a noun and sea-ice when it is an adjective or when it preceded and modified another word. Also all numbers less than 10 that were adjectives or modifiers have been changed to word format, not numerical format.

Section 5.2.3. Upper AW association

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

Ceratocyrtis histricosus was not found in the Canada Basin in 1950's and 1960's, and the common occurrence of this species in the AW in the Chukchi and Beaufort seas in 2000 might be an effect of the recent warming of the AW (Itaki et al., 2003). We also found this species was common in the upper AW and firstly found in the PWW in the western Arctic Ocean in our plankton tow samples collected in 2013. Since the water temperature where this species occurred ranged from -1.6 (this study) to 10°C (Swanberg and Bjørklund, 1987), slight increase of the temperature in the AW (0.2°C) and PWW (0.05°C) in the Arctic Ocean (Swift et al., 1997; McLaughlin et al., 2011) could not be a reason for the expansion of the range of this species. The change of North Atlantic Oscillation (atmospheric High and Low pressure cells) that controls the

flow of the surface water in the North Atlantic has sustained the increase of Atlantic inflow in the Arctic Ocean (Zhang et al., 1998). This temporary increasing volumes of inflowing AW might increase the chances for more exotic radiolarians to reach into the Arctic Ocean.

Page 14, lines 6-10

So what?

According to your comment, we deleted the following text:

“Bjørklund et al. (1998) reported its distribution in the western part of the GIN Seas, being dominant (up to 76%) at the Iceland Plateau and common (>20%) just north of the Iceland–Faeroe Ridge. In the eastern part of the Barents Sea, west of Novaja Zemlya, Bjørklund and Kruglikova (2003) reported *Amphimelissa setosa* as the dominant (77%) species.”

Page 14, lines 25-26

This is very confusing? Sg preferred warmer water but N&A said that this species adapted low temperature. Be careful in using LOW and WARM!

According to your comment, we have changed the text as follows:

“-----and is well adapted to low temperatures and low salinities-----“

has been changed to

“-----and is well adapted to temperatures of >0°C and low salinities-----”

Page 16, line 25

what? Ice edge ? ice fauna? very unclear

According to your comment, we have changed the text as follows:

“and its presence causes an alternation”

has been changed

“and the summer ice edge causes an alternation”

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. The radiolarian flux was comparable to that in the
31 North Pacific Ocean. *Amphimelissa setosa* was dominant during the season with open
32 water as well as at the beginning and at the end of the seasons with sea-ice cover.
33 During the **sea-ice** cover season, however, oligotrophic and cold-water tolerant

1 actinommids were dominant, productivity of radiolaria was lower, and species diversity
2 was greater. These suggest that the dynamics of **sea ice** are a major factor affecting the
3 productivity, distribution, and composition of the radiolarian fauna.

4
5 Keywords: Radiolarians, Western Arctic Ocean, Sea-ice, Beaufort Gyre, Sediment trap

6 7 **1. Introduction**

8 In recent years, summer **sea-ice** extent in the Arctic Ocean has decreased rapidly due
9 to global climate change (Stroeve et al., 2007, 2012). The **sea ice** in the Arctic Ocean
10 reached its minimum extent in September 2012; **the lowest** since the beginning of
11 satellite **observations** (NSIDC, 2012). The most remarkable **sea-ice** decrease was
12 observed in the western Arctic Ocean, on the Pacific side (Shimada et al., 2006; Comiso
13 et al., 2008; Markus et al., 2009). In the western Arctic Ocean, the advection of warm
14 North Pacific water through the Bering Strait contributes to both sea-ice melt in summer
15 and an inhibition of sea-ice formation during winter (Shimada et al., 2006; Itoh et al.,
16 2013).

17 Biological CO₂ absorption is an important carbon sink in the ice-free regions of the
18 Arctic Ocean (Bates et al., 2006; Bates and Mathis, 2009). Melting of sea-ice can both
19 enhance and reduce the efficiency of the biological pump in the Arctic Ocean,
20 depending on ocean circulation (Nishino et al., 2011). The Beaufort High, a
21 high-pressure system over the Canada Basin in the Arctic Ocean, drives the sea_ice and
22 the water masses anticyclonically, **forming** the Beaufort Gyre (**Fig. 1**). In the Canada
23 Basin, the Beaufort Gyre governs the upper ocean circulation (Proshutinsky et al., 2002),
24 and it has strengthened recently due to the decreasing **sea ice** (Shimada et al., 2006;
25 Yang, 2009). Melting of sea ice **reduces** the efficiency of the biological pump within the
26 Beaufort Gyre, **due to** deepening of the nutricline caused by freshwater accumulation
27 within the gyre (Nishino et al., 2011). Conversely, the efficiency of the biological pump
28 is enhanced outside the gyre because of nutrient supply from shelves and improved light
29 penetration (Nishino et al., 2011).

30 Particle flux plays an important role in the carbon export (Francois et al., 2002).
31 Based on sediment trap samples from the Canada Basin and Chukchi Rise, Honjo et al.
32 (2010) found that the annual average of sinking particle flux was three orders of
33 magnitude smaller than that in epipelagic areas where the particle flux was the main

1 mechanism for carbon export to greater depths. However, Arrigo et al. (2012) observed
2 a massive algal biomass beneath fully consolidated pack ice far from the ice edge in the
3 Chukchi Sea during the summer, and suggested that a thinning ice cover increased light
4 transmission under the ice and allowed blooming of algae. Boetius et al. (2013) also
5 reported that the algal biomass released from the melting ice in the Arctic Ocean was
6 widely deposited at the sea floor in the summer of 2012. Therefore, it is inferred that **the**
7 biomass of zooplankton, **that were preying on the algae**, also changed seasonally under
8 the **sea ice** in the Arctic Ocean, as a result of the variable sea-ice conditions.
9 Microzooplankton are recognized as a key component of pelagic food webs (e.g.,
10 Kosobokova et al., 2002; Calbet and Landry, 2004), but the seasonal and interannual
11 changes in their communities within **sea-ice** regions are still poorly understood.

12 To understand the effect of **sea-ice** reduction on marine ecosystems in the Arctic
13 Ocean, we studied productivity, distribution, composition, and biological conditions of
14 living radiolarians in both plankton tow samples and sediment trap samples.

15 In our **study**, we have analyzed only the siliceous **taxa** of **the** class Rhizaria; and
16 herein we have used the definition of Radiolaria **to include them** as defined by Suzuki
17 and Aita (2011). In their taxonomic scheme, they include the following orders:
18 Collodaria, Nassellaria, Spumellaria, Acantharia and Taxopodia. In addition, we **also**
19 include **the** order Entactinaria, which Suzuki and Aita (2011) reported **became** extinct
20 during the Permian; but Bjørklund et al. (2008) demonstrated its presence also in recent
21 plankton and sediment samples. In this study, we have excluded **the** order Acantharia as
22 they have a skeleton of SrSO_4 ; and **also** Collodaria, a group that normally **does** not
23 possess a skeleton, or only with loose spines. Therefore, our study only includes forms
24 with a solid skeleton of SiO_2 . In this paper, we have chosen to include data also **for the**
25 order Phaeodaria, which **are no longer** assigned to Radiolaria, but to Cercozoa **based on**
26 recent molecular **phylogenetic studies** (Cavalier-Smith and Chao, 2003; Nikolaev et al.,
27 2004; Adl et al., 2005; Yuasa et al., 2005). To make the text read **more easily**, we
28 therefore use Radiolaria, or radiolarians when appropriate, to also include Phaeodaria.
29 **This is also intended** to make it possible for us to compare **previously** published data
30 from the north Pacific region, **where the Phaeodaria were included among the**
31 **Radiolaria** (Okazaki et al., 2003, 2005; Ikenoue et al., 2010, 2012a).

32 Radiolaria are one of the most common **marine** microzooplankton groups, they
33 secrete siliceous skeletons, and their **species-specific** abundance in a region is related to

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

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

28 This is the first extensive study of the seasonal and interannual flux changes of
29 radiolarians in the western Arctic Ocean. We present radiolarian depth distributions and
30 flux variations in the western Arctic Ocean, and discuss their seasonality and species
31 associations in relation to the environmental conditions (temperature, salinity, depth,
32 sea-ice concentration, and downward shortwave radiation).

33

2. Oceanographic setting

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

The deep water is divided into Atlantic Water (AW) and Canada Basin Deep Water (CBDW). The AW (250-900 m) is warmer (near or below 1°C), and saltier (near 35) than the surface waters, and originates from the North Atlantic Ocean, via the Norwegian Sea. The CBDW (below 900 m) is a cold (lower than 0°C) water mass located beneath the AW, and has the same salinity as the AW. The CBDW is formed by brine formation on the shelves, which makes the cold and dense saline water mass sink over the continental margin into the deep basins (Aagaard et al., 1985).

3. Materials and methods

3.1. Plankton tow samples

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

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

26 27 3.2. Hydrographic profiles

28 Profiles of temperature, salinity, dissolved oxygen, and chlorophyll *a* down to 1,000
29 m depth at stations 32 (Northwind Abyssal Plain) and 56 (southwestern Canada Basin)
30 in September 2013 (Nishino, 2013) were shown in Fig. 2a and b, respectively. At
31 Station 32, temperature showed a sharp decrease from the surface, down to about 25 m
32 depth with a sharp increase at the base of the SML. The PSW is generally cold (about
33 -1°C) with a maximum value (1.6°C) at about 50 m and shows a rapid decrease with

1 increasing depth. The PWW is the coldest water (minimum value -1.6°C) at about 200
2 m. The highest temperatures are found in the AW (near or below 1°C) at about 400 m
3 with a gradual decrease below 500 m. Salinity values (25-28) are **low** in the SML,
4 increasing rapidly with depth from 28-32 in the PSW. In the PWW there is a gradual
5 increase of salinity from 32 to 35, while there is a slight decrease below the PWW/AW
6 boundary. Dissolved oxygen **was maximum** ($405\ \mu\text{mol/kg}$) at the boundary between
7 SML and PWW, **rapidly decreased** with increasing depth in the PSW and PWW, and
8 **reached a minimum** value ($270\ \mu\text{mol/kg}$) around the boundary between PWW and AW,
9 and **increased slightly** below that. Chlorophyll *a* **concentrations**, higher than $0.1\ \text{mg m}^{-3}$,
10 **were** observed in **the** 0-80 m depth. Temperature, salinity, dissolved oxygen, and
11 chlorophyll *a* **were almost similar at** both Station 32 and Station 56, except for SML and
12 PSW. In the SML, salinity at Station 32 was slightly lower than at Station 56. In the
13 PSW, a temperature peak at Station 32 was about one degree higher, and a little deeper,
14 compared to Station 56. In **the** 0-80 m depth, chlorophyll *a* was a little higher at Station
15 56 than at Station 32.

16

17 *3.3. Sediment trap samples*

18 Sinking particles were collected by a sediment trap (SMD26 S-6000, open mouth
19 area $0.5\ \text{m}^2$, Nichiyu Giken Kogyo, Co. Ltd.) rotated at 10–15-day intervals moored at
20 184 m (4th October 2010–28th September 2011), 260 m (4th October 2011–18th
21 September 2012), and 1,300 m (4th October 2010–28th September 2011), **and** 1,360 m
22 (4th October 2011–18th September 2012) at Station NAP (Northwind Abyssal Plain,
23 $75^{\circ}00'\text{N}$, $162^{\circ}00'\text{W}$, bottom depth 1,975 m) (**Fig. 1; Table 2**). The mooring system was
24 designed to set the collecting instrument at approximately 600 m above the sea floor.
25 This depth of the moored sediment traps was chosen in order to avoid possible inclusion
26 of particles from the nepheloid layer, reaching about 400 m above the seafloor (Ewing
27 and Connary, 1970). Recoveries and redeployments of the traps were carried out on the
28 Canadian Coast Guard Ship I/B (ice breaker) “Sir Wilfrid Laurier” and R/V “Mirai” of
29 **the** Japan Agency for Marine-Earth Science and Technology. The sample cups were
30 filled with 5% buffered formalin seawater before the sediment trap was deployed. This
31 seawater was collected from 1,000 m water depth in the southern Canada Basin, and
32 was membrane filtered ($0.45\ \mu\text{m}$ pore size). The seawater in the sample cups was mixed
33 with sodium borate as a buffer (pH 7.6–7.8) **with** 5% formalin **added** as a preservative.

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

16 We made slides of both the coarse ($>45 \mu\text{m}$) and the fine ($<45 \mu\text{m}$) fraction of each
17 sample. For the enumeration of radiolarian taxa in this study, we counted all specimens
18 of radiolarian skeletons larger than $45 \mu\text{m}$ encountered on a slide. Each sample was
19 examined under an Olympus compound light microscope at **200x** or **400x** magnification
20 for species identification and counting. The radiolarian flux (No. specimens $\text{m}^{-2} \text{day}^{-1}$)
21 was calculated from our count data using the following formula:

$$22 \quad \text{Flux} = N * V / S / D \quad (1)$$

23 where N is the counted number of radiolarians, V the aliquot size, S the aperture area of
24 the sediment trap (0.5 m^2), and D the sampling interval (day). Diversity indices using
25 the Shannon-Weaver log-base 2 formula (Shannon and Weaver, 1949) were calculated
26 for total radiolarians

$$27 \quad H = -\sum P_i \log_2 P_i \quad (2)$$

28 where H is the diversity index, P is the contribution of species (relative abundance in
29 total radiolaria) and i is the order of species.

30 As supplemental environmental data, the moored sediment trap depth and the water
31 temperature (accuracy of $\pm 0.28^\circ\text{C}$) were monitored every hour (sensor type: ST-26S-T).
32 Moored trap depth for the upper trap was **inadvertently** lowered by about 80 m during
33 the second year (**approximately** 260 m depth) than during the first year (**approximately**

1 180 m depth), caused by entanglement of the mooring ropes. During July-August in
2 2012, the moored trap depth was lowered to about 300 m, because of intensified water
3 currents (Fig. S1). Time-series data of sea-ice concentration around Station NAP during
4 the mooring period were calculated from the sea-ice concentration data set
5 (http://iridl.ldeo.columbia.edu/SOURCES/.IGOSS/.nmc/.Reyn_Smith_OIv2/, cf.
6 Reynolds et al., 2002).

7

8 3.4. Taxonomic note

9 The species described by Hülsemann (1963) under the name of *Tholospyris*
10 *gephyristes* is not a member of the Spyridae. This species has been accepted as a
11 Spyridae by most workers, but this species lacks the sagittal ring that is typical for the
12 Spyridae. We have, therefore, assigned this species to the family Plagiacanthidae. We
13 suggest this species be renamed to *Tripodiscium gephyristes* until a proper taxonomic
14 analysis has been undertaken, and have used this designation hereafter.

15

16 4. Results

17

18 4.1. Radiolarians collected by plankton tows

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

27

28 4.1.1. Standing stocks and diversities of radiolarians

29 The abundance of living radiolarians at Station 32 was about two times higher than
30 at Station 56 at each depth interval in the upper 500 m, the depth level at which the
31 abundance of living radiolarians decreased with increasing water depth at both stations
32 (Fig. 2a and b). The abundance of dead radiolarians also decreased with water depth at
33 both stations, except for 100–250 m depth at Station 32 (Fig. 2a and b). The abundance

1 of dead radiolarians was generally higher than living radiolarians at both stations,
2 except for in the 0–100 m depth at Station 32. The living radiolarian diversity index was
3 low in the 0-100 m depth interval, increased with depth, reached a maximum at about
4 400 m, and then slightly decreased below 500 m depth at both stations.

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

18

19 | 4.1.2. Vertical distribution of radiolarian species

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

25 Adult and juvenile forms of *Amphimelissa setosa* were mainly distributed in the
26 0–250 m depth at both stations. In the 0-100 m depth, adult and juvenile stages were
27 dominant (70% and 28%, respectively) at Station 32, and were abundant at Station 56
28 (23% and 7%, respectively), following the juvenile *Actinomma* spp. (56%). In the
29 100–250 m depth, *A. setosa* was the dominant species at both stations. At Station 32,
30 the abundance of *A. setosa* in the 100–250 m depth interval was lower than in the 0–100
31 m depth, whereas at Station 56, the abundance in the 100-250 m depth was almost the
32 same as in the 0–100 m depth.

33 Actinommidae spp. juvenile forms and *Actinomma l. leptodermum* were absent in

1 the 0–100 m depth at Station 32; but both, especially Actinommidae spp. juvenile forms
2 (56%), were abundant at Station 56. Both were common in the 100–250 m depth at both
3 stations (8% and 4%, respectively at Station 32; 14% and 7%, respectively at Station
4 56), and decreased in abundance in the 250–500 m depth. *Spongotrochus glacialis* was
5 rare in the 0–100 m depth at Station 32 (0.4%) but with a slight increase at Station 56
6 (1.4%). In deeper layers *S. glacialis* was rare.

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

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

20

21 4.2. Radiolaria collected by sediment trap

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

32

33 4.2.1. Radiolarian flux and diversity in the upper trap

1 The highest total radiolarian fluxes in the upper trap were observed during the
2 beginning of the sea-ice cover season (November in 2010 and 2011, >10,000 specimens
3 $\text{m}^{-2} \text{day}^{-1}$) (Fig. 5). The fluxes were higher during the open-water season
4 (August–October in 2011; average, 5,710 specimens $\text{m}^{-2} \text{day}^{-1}$), and around the end of
5 the sea-ice cover season (July–August in 2011, >4,000 specimens $\text{m}^{-2} \text{day}^{-1}$) than
6 during the sea-ice cover season (December–June, average in 2011, 944 specimens m^{-2}
7 day^{-1} ; average in 2012, 723 specimens $\text{m}^{-2} \text{day}^{-1}$). The fluxes varied from 114 to
8 14,677 specimens $\text{m}^{-2} \text{day}^{-1}$ with an annual mean of 2,823 specimens $\text{m}^{-2} \text{day}^{-1}$. The
9 diversity of radiolarians, however, was higher during the sea-ice cover season (>3) than
10 during the open water season (<2) (Fig. 5). The diversity indices were negatively
11 correlated with the total radiolarian fluxes ($r = -0.91$) (Fig. 6).

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

21

22 4.2.2. Radiolarian flux and diversity in the lower trap

23 Total radiolarian flux in the lower trap varied from 0 to 22,733 specimens $\text{m}^{-2} \text{day}^{-1}$
24 with an annual mean of 4,828 specimens $\text{m}^{-2} \text{day}^{-1}$ (Fig. 5). The fluxes were high
25 during November–December, both in 2010 and 2011 and during March in 2011
26 (>10,000 specimens $\text{m}^{-2} \text{day}^{-1}$), while extremely low (average, 21 specimens $\text{m}^{-2} \text{day}^{-1}$)
27 during May–September in 2012. Diversity did not change greatly, and increased slightly,
28 during May–July 2011, and in April 2012 when the radiolarian fluxes were low. The
29 diversity indices were weakly negatively correlated with the radiolarian fluxes ($r =$
30 -0.52) (Fig. 6).

31 Adult and juvenile stages of *Amphimelissa setosa* were dominant throughout the
32 sampling periods (range, 66–92%; average, 82%). The relative abundance of *A. setosa*
33 juveniles was slightly increased in 2012 in comparison to 2010 and 2011.

1

2 **5. Discussion**

3 *5.1. Comparison between Arctic and North Pacific Oceans*

4 Biogenic particle flux into the deep sea in the Canada Basin was generally assumed
5 to be low due to the low productivity of siliceous and calcareous microplankton (Honjo
6 et al., 2010). However, we observed high radiolarian fluxes (14,677: upper trap, 22,733:
7 lower trap) at Station NAP during the **open-water** season, and around the beginning and
8 the end of **the** sea-ice cover season in 2011-2012. The annual means (2,823: upper trap,
9 4,823: lower trap) were comparable to those observed in several areas of the North
10 Pacific Ocean (Fig. 8, Table S5). The radiolarian flux in the upper trap was high during
11 July-November and low during December-June. Moreover, radiolarian flux in the lower
12 trap was extremely low during May-September 2012. The mean of radiolarian fluxes
13 during the period when radiolarian fluxes were higher than 1σ (3,489: upper trap; 5,675:
14 lower trap) showed a higher value (7,344: upper trap; 11,871: lower trap) than at any
15 other stations in the North Pacific Ocean (Table S5). The biogenic opal collected in this
16 study mainly consisted of radiolarians and diatoms based on our microscopic
17 observations. Other siliceous skeletons (silicoflagellate skeletons, siliceous
18 endoskeleton of dinoflagellate genus *Actiniscus*, chrysophyte cysts, ebridian flagellates,
19 and palmales) were minor components in the same trap samples (Onodera et al., 2014).
20 Although more than half of the contribution to total particulate organic carbon is largely
21 unknown at station NAP (Onodera et al. 2014), our study showed that the siliceous
22 skeletons of radiolarians and diatoms might play an important role in the export of
23 biogenic silica to the deep Arctic Ocean.

24

25 *5.2. Vertical distribution of species and hydrographic structure*

26 *5.2.1. PSW and PWW association*

27 *Amphimelissa setosa* and its juvenile stages were found in shallow cold-water in
28 both stations 32 and 56. Specifically, they were more abundant in the SML and PSW
29 (0-100 m) at Station 32 than Station 56. At Station 32, these two water masses exhibited
30 warmer temperature (about one degree higher at the temperature peak) than Station 56;
31 indicating that cold to moderately warm (-1.2 to 1.6°C), and well mixed water masses
32 were more favorable for this species than perennial cold water masses such as PWW
33 (100-250 m). Dolan et al. (2014) showed that density of *A. setosa* in the Chukchi Sea

1 | was lower in 2012, when sea ice coverage was less and chlorophyll *a* concentrations
2 | were higher, than in 2011. Thus, the density of phytoplankton protoplasm containing
3 | chlorophyll *a* might not be related to the abundance of *A. setosa*. This is **consistent** with
4 | our finding that the abundance of *A. setosa* **was** fairly lower at Station 56 where density
5 | of chlorophyll *a* was a little higher than that at Station 32. **Thus**, the favorable condition
6 | for *A. setosa* **is** related to a cold and well mixed water mass in the summer sea-ice edge.

7 | *A. setosa* dominated (60-86%) the radiolarian assemblage through the upper 500 m
8 | of the water column in the Chukchi Sea and the Beaufort Sea, and **thus** can be an
9 | indicator of cold Arctic surface water (Itaki et al., 2003). Bernstein (1931) noted that
10 | this species **lives** in the cold (-1.68 to -1.29°C) and saline (34.11 to 34.78) waters in the
11 | Arctic Ocean. Matul and Abelmann (2005) also suggested that *A. setosa* prefers
12 | well-mixed, cold and saline surface/subsurface waters.

13 | Actinommidae spp. juvenile forms, *Actinomma l. leptodermum* **and** *Spongotrochus*
14 | *glacialis* were mainly distributed in the PSW and PWW. *Actinomma l. leptodermum*
15 | and *Actinomma boreale* had been reported **previously as forming a taxonomic** group
16 | (e.g., Samtleben et al., 1995) due to identification problems, particularly of the juvenile
17 | stages. **However**, the adult stages can be separated into two species following Cortese
18 | and Bjørklund (1998). *Actinomma l. leptodermum* were absent in the water masses of
19 | SML and PSW at Station 32, but they were abundant in these water masses at Station
20 | 56. At Station 56, SML and PSW water masses were colder (-1.2 to 0.6°C) and more
21 | homogeneous than at Station 32; indicating that Actinommidae spp. juvenile forms and
22 | *A. l. leptodermum* preferred slightly warmer water than PWW (-1.6°C). **We found** that
23 | Actinommidae spp. juvenile forms and *A. l. leptodermum* are most abundant in the
24 | upper water layers where phytoplankton also prevails (**Fig. 2**). It is most likely that the
25 | juvenile actinommidas and *A. l. leptodermum* may be bound to the euphotic zone.
26 | *Spongotrochus glacialis* also preferred warmer water than PWW. This species inhabited
27 | surface water in the Okhotsk Sea, and is well adapted to temperatures of >0°C and low
28 | salinities (Nimmergut and Abelmann 2002). Okazaki et al. (2004) reported *S. glacialis*
29 | as a subsurface dweller with abundance maximum in the 50–100 m interval in the
30 | Okhotsk Sea, associated with **peaks in** the phytoplankton production.

31 | 32 | 5.2.2. PWW association

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

16 17 5.2.3. Upper AW association

18 *Ceratocyrtis histicosus* was not found in the Canada Basin in 1950's and 1960's,
19 and the common occurrence of this species in the AW in the Chukchi and Beaufort seas
20 in 2000 might be an effect of the recent warming of the AW (Itaki et al., 2003). We also
21 found this species was common in the upper AW and firstly found in the PWW in the
22 western Arctic Ocean in our plankton tow samples collected in 2013. Since the water
23 temperature where this species occurred ranged from -1.6 (this study) to 10°C
24 (Swanberg and Bjørklund, 1987), slight increase of the temperature in the AW (0.2°C)
25 and PWW (0.05°C) in the Arctic Ocean (Swift et al., 1997; McLaughlin et al., 2011)
26 could not be a reason for the expansion of the range of this species. The change of
27 North Atlantic Oscillation (atmospheric High and Low pressure cells) that controls the
28 flow of the surface water in the North Atlantic has sustained the increase of Atlantic
29 inflow in the Arctic Ocean (Zhang et al., 1998). This temporary increasing volumes of
30 inflowing AW might increase the chances for more exotic radiolarians to reach into the
31 Arctic Ocean.

32 33 5.2.4. Lower AW association

1 *Pseudodictyophimus plathycephalus*, Plagiacanthidae gen. et sp. indet. (Pl. 8, Figs.
2 11-18), and *Cycladophora davisiana* were abundant in the cold and oxygenated lower
3 AW at both Stations 32 and 56. Although, the distribution patterns of these two species
4 in PWW and upper AW water masses were slightly different between Station 32 and
5 Station 56, the temperature, salinity, and dissolved oxygen were similar at both stations.
6 Their abundance might, therefore, reflect the influence of other variables than
7 hydrographic conditions alone. *Pseudodictyophimus g. gracilipes* is widely distributed
8 in the World Ocean, and inhabits the surface layer at high latitudes, but dwells at greater
9 depths at low latitudes (Ishitani and Takahashi, 2007; Ishitani et al., 2008). Itaki et al.
10 (2003) reported that the maximum depth *P. g. gracilipes* occurred at 0-50 m in the
11 Chukchi Sea, and 25-50 m in the Beaufort Sea. However, in our results, *P. g. gracilipes*
12 did not show any specific vertical distribution, and its abundance was low.

13

14 5.3. Seasonal and annual radiolarian flux

15 5.3.1. Radiolarian fauna and seasonal sea-ice concentration

16 Seasonal radiolarian fluxes at Station NAP were characterized by the high
17 dominance of a few species and by the changes of their ratios in the upper trap with the
18 seasonal changes in sea-ice concentration. *Amphimelissa setosa* adult and its juvenile
19 forms were dominant during the open-water season and around the beginning and the
20 end of ice-cover seasons, while the actinommids (Actinommidae spp. juvenile forms,
21 *Actinomma l. leptodermum*, and *Actinomma boreale*) were dominant during the
22 ice-cover season (Fig. 5). These observations might explain the regional difference in
23 the radiolarian species distribution in the Arctic Ocean. *Amphimelissa setosa* were
24 dominant in Arctic marginal sea sediments (Iceland, Barents, and Chukchi Seas) where
25 sea ice disappeared in the summer, but Actinommidae were dominant in the central
26 Arctic Ocean (Nansen, Amundsen, and Makarov Basins) where the sea surface was
27 covered by sea ice throughout the year (Bjørklund and Kruglikova, 2003). Zasko et al.
28 (2014) also reported that *A. setosa* was essentially absent in the plankton samples in the
29 central polar basins.

30 The summer ice edge hosts well-grown ice algae and ice fauna (Horner et al., 1992;
31 Michel et al., 2002; Assmy et al., 2013), and the summer ice edge causes an alternation
32 between stable water masses and deep vertical mixing where the nutrients are brought to
33 the surface (Harrison and Cota, 1991), with both conditions being favorable for primary

1 productivity. Swanberg and Eide (1992) found that abundance of *A. setosa* and its
2 juveniles was correlated well with chlorophyll *a* and phaeopigments along the ice edge
3 in summer in the Greenland Sea. Dolan et al. (2014), however, reported that the
4 abundance of *A. setosa* was not always related to high chlorophyll *a* in locales with low
5 sea-ice concentration, as we also have found. Therefore, we interpreted that a cold and
6 well mixed water mass along summer ice edge were essential for high reproduction and
7 growth of *A. setosa*.

8 From the upper trap, a flux peak of *A. setosa* juveniles occurred at the end of the
9 sea-ice season, and that the flux peak of adult *A. setosa* occurred at the beginning of the
10 sea-ice season (Fig. 7). The time interval between these peaks might indicate that *A.*
11 *setosa* has a three months life cycle. *Pseudodictyophimus clevei* also shows flux peaks
12 during the beginning of the sea-ice season (November-December) (Fig. 7). These two
13 species seem to prefer to live in a cold water mass with sea-ice formation. On the
14 contrary, juvenile stages of actinommids were dominant during the ice-cover season
15 (Fig. 5). Therefore, we interpreted the actinommids to be tolerant of oligotrophic
16 conditions and are able to live in stratified cold water masses. Itaki and Bjørklund
17 (2007) reported that reproduction could occur even during the juvenile stage in at least
18 some actinommids, because they frequently found conjoined juvenile Actinommidae
19 skeletons in the Japan Sea sediments. Furthermore, the flux of Actinommidae spp.
20 juvenile forms increased towards the end of the sea-ice cover season, accompanied by
21 an increase in downward shortwave radiation (Fig. 5 and 7). This might indicate that the
22 Actinommidae spp. juvenile form can feed on algae growing on the ice, or prey on other
23 phytoplankton under the sea ice.

24 This study showed that the productivity of radiolarians was high, but diversity was
25 low, during summer season with low sea-ice concentration in the western Arctic Ocean
26 (Fig. 5 and 6). In contrast, radiolarian fauna in the sediment trap that was moored in the
27 Okhotsk Sea showed high diversity during the summer season (Okazaki et al., 2003).
28 The maximum total radiolarian flux during the summer season around the sea-ice edge
29 and the open water is characterized by high dominance of *A. setosa* (>90%) in our
30 sampling area. Such high dominance of a single species does not occur in the Okhotsk
31 Sea, where the main nine taxa contributed to more than 60% of the radiolarian
32 assemblage (Okazaki et al., 2003). *Amphimelissa setosa*, which has a small and delicate
33 siliceous skeleton, might respond directly and rapidly to the changes of water mass

1 conditions near **the** summer ice edge. The contrast of seasonal diversity between these
2 two areas seems to be due to the differences in the species composition and in their
3 responses to water mass changes that may differ between these two areas.

4 Relatively higher fluxes of *Actinomma boreale*, *Spongotrochus glacialis*, and
5 *Joergensenium* sp. A during the sea-ice free season in the upper trap in summer of 2012
6 compared to summer of 2011 might be due to the deeper mooring depth of the upper
7 trap after October 2011 (Fig. 7 and S1); because, in general, these three species are
8 more abundant at depths deeper than the first upper trap depth at about 180 m (Fig. 3a).
9 Although, *Ceratocyrtis histricosus* and *Tripodiscium gephyristes* were mainly
10 distributed in deeper depths (>250 m) than the upper trap depth (Fig. 4), flux of these
11 two species in the upper trap apparently increased in the summer of 2012. The water
12 temperature at the upper trap increased during this period (Fig. 7 and S1). We, therefore,
13 interpreted this increase of *Ceratocyrtis histricosus* and *Tripodiscium gephyristes* to be
14 related to the mixing of **the nutrient-rich** and warm upper AW **with the** lower PWW.

16 5.3.2. Radiolarian fauna and interannual difference in ocean circulation

17 Intensification of geostrophic currents on the periphery of **the** Beaufort Gyre (Fig. 1)
18 has been reported in recent years (Nishino et al., 2011; McPhee, 2013). This
19 intensification is caused by **an** increasing volume of water from **melting** sea ice in
20 association with the reduction of arctic summer **sea ice** and the river runoff to the basins
21 (Proshutinsky et al., 2009; Yamamoto-Kawai et al., 2008). The total radiolarian flux
22 during summer (July-September) was lower in 2012 than in 2011 in both the upper and
23 lower traps (Fig. 5). Flux of most radiolarian taxa was also lower during summer of
24 2012 (Fig. 7). On the other hand, fluxes of the actinomids (*Actinommidae* spp.
25 juvenile forms, *Actinomma l. leptodermum*, and *Actinomma boreale*), possibly adapted
26 to cold and oligotrophic water, was greater during December 2011-September 2012
27 than during December 2010-September 2011. *Actinommidae* spp. juvenile forms and *A.*
28 *l. leptodermum* were most abundant in the depth interval of 0-100 m at Station 56 in the
29 southwestern Canada Basin. Therefore, we suspected that the cold and oligotrophic
30 water in the Canada Basin began to spread to Station NAP in the Northwind Abyssal
31 Plain from December 2011, and continued to affect the radiolarian fluxes at least until
32 September 2012. McLaughlin et al. (2011) reported that the position of the center of the
33 Beaufort Gyre shifted westwards, and that the area **influenced by** the gyre **has** spread

1 northwards and westwards in recent years. Moreover, **the** high-resolution pan-Arctic
2 Ocean model results also showed that the Beaufort Gyre expanded by shifting its center
3 from the Canada Basin interior to the Chukchi Borderland in 2012 compared with 2011;
4 and the ocean current direction in the surface 100 m layer switched northwestward to
5 southwestward in December 2011 (E. Watanabe, personal communication, 2014). Thus,
6 recent intensification of Beaufort Gyre currents associated with sea-ice reduction, would
7 have affected the surface water mass conditions and as well as the ecological conditions
8 in the western Arctic Ocean.

10 5.3.3. Vertical and lateral transport

11 Flux peaks of total radiolarians in the lower trap are delayed by about two weeks in
12 comparison to the upper trap (**Fig. 5**). Therefore, the sinking speed of the aggregated
13 radiolarian particle flux between these depths were averaged to 74 m day^{-1} during
14 November-December 2010, 86 m day^{-1} during July-August 2011, and 73 m day^{-1} during
15 November 2011. Watanabe et al. (2014) simulated movement of cold and warm eddies
16 using a high-resolution pan-Arctic Ocean model, and suggested that the high total mass
17 flux during October-December 2010 at Station NAP, as we **found**, was mainly due to
18 the enhancement of the marine biological pump by an anti-cyclonic cold eddy.
19 Shelf-break eddies induce the lateral transport of re-suspended bottom sediments
20 composed of old carbon, and enhance the biological pump (O'Brien et al., 2013;
21 Watanabe et al., 2014). Actually, the passage of a cold eddy was observed as a cooling
22 and a deepening of the moored trap depth in the corresponding period (**Fig. S1**).
23 *Amphimelissa setosa* was the most dominant species (>90%) and showed the highest
24 flux ($13,840 \text{ specimens m}^{-2} \text{ day}^{-1}$) during November 2010 in the upper trap. The flux of
25 this species **during November 2010 in the upper trap** was about $3,500 \text{ specimens m}^{-2}$
26 **day**⁻¹ higher **than that in 2011** and kept a highest value half a month longer than that in
27 2011. The cold eddy passage would transport a cold and well mixed water mass,
28 conditions favorable for *A. setosa*. **Therefore**, the cold eddy passage, in addition to
29 seasonal water mass variations with sea ice formation, would enhance the high
30 radiolarian flux.

31 Radiolarian fluxes in the lower trap were generally higher than in the upper trap,
32 except for May-September 2012 (**Fig. 5**). The extremely low fluxes in the lower trap
33 during this interval might be due to a decrease of aggregate formation. The latter

1 process, which helps rapid sinking of biogenic particles, would be suppressed by influx
2 of oligotrophic surface water originating from the Beaufort Gyre in the Canada Basin.
3 In the southwestern Canada Basin (Station 56), high standing stock of dead radiolarian
4 specimens (Fig. 2) might indicate an inefficient biological pump in this area. In addition,
5 fluxes of Actinommidae spp. juvenile forms were lower in the lower trap, in spite of
6 their high abundance in the upper trap since December 2011. We suggest that the
7 disappearance of fluxes of Actinommidae spp. juvenile forms in the lower trap might be
8 due to lack of aggregate formation.

9 Higher abundance in the lower trap of species having a wider vertical distribution
10 (*Pseudodictyophimus g. gracilipes*, *P. plathycephalus*) or intermediate to deep water
11 distribution (*Ceratocyrtis histicosus*, *Tripodiscium gephyristes*, Plagiacanthidae gen. et
12 sp. indet., and *Cycladophora davisiana*) might be attributed to the reproduction of these
13 species at a depth level situated between the upper and lower traps. The flux of
14 *Pseudodictyophimus g. gracilipes*, *P. plathycephalus*, Plagiacanthidae gen. et sp. in det.
15 and *Cycladophora davisiana* in the lower trap was high during July-August 2011. [The](#)
16 [flux of most](#) of the radiolarian species in the lower trap also peaked during March 2011,
17 a period of heavy ice cover and low downward shortwave radiation. In addition, in the
18 lower trap the flux peak during March in 2011 was made up of more than 80% of *A.*
19 *setosa*, a definite surface water species. However, during this period a similar peak was
20 not found in the upper trap. Therefore, the flux peaks during March 2011 could be
21 derived from some lateral advection at a depth lower than 180 m or a re-suspension of
22 shelf sediments.

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6

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10

11 **Table captions**

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

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

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

19

20 **Supplement table captions**

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

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

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

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

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

29

30 **Figure captions**

31 Fig. 1. Map of the Chukchi and Beaufort Seas showing the locations of sediment traps
32 (solid triangle) and plankton tows (solid circles). Gray arrows indicate the cyclonic
33 circulation of the Beaufort Gyre and the inflow of Pacific water through the Bering

1 Strait, respectively.

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

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

11 Fig. 4. Depth distributions of fourteen living radiolarians in plankton samples at stations
12 32 (a) and 56 (b).

13 Fig. 5. (a) Total radiolarian fluxes, diversity index and sea-ice concentration in upper
14 trap at Station NAP. **Two** samples with fewer than 100 specimens are marked with **an**
15 asterisk. Sea-ice concentration data are from Reynolds et al. (2002)
16 (http://iridl.ldeo.columbia.edu/SOURCES/IGOSS/.nmc/.Reyn_SmithOIv2/). (b)
17 Radiolarian faunal compositions in upper trap at Station NAP. (c) Downward short
18 wave radiation at the surface of **sea ice** and ocean (after sea-ice opening) around Station
19 NAP from National Centers for Environmental Prediction-Climate Forecast System
20 Reanalysis (NCEP-CFSR) (Saha et al., 2010). (d) Total radiolarian fluxes and
21 Shannon-Weaver diversity index in the lower trap at Station NAP. **Thirteen** samples
22 with fewer than 100 specimens are marked with **an** asterisk. (e) Radiolarian faunal
23 compositions in lower trap at Station NAP. Barren area: no samples due to trap failure.

24 Fig. 6. Scatter plots of diversity indices and total radiolarian fluxes at upper (a) and
25 lower trap (b). In these plots, samples with fewer than 100 specimens were excluded.

26 Fig. 7. Two-year fluxes of major radiolarian taxa at Station NAP during the sampling
27 period.

28 Fig. 8. Box plot of total radiolarian fluxes at Station NAP and previous studied areas in
29 the North Pacific Ocean (Okazaki et al., 2003, 2005; Ikenoue et al., 2010, 2012a).
30 Summary information of previous sediment trap studies in the North Pacific Ocean is
31 shown in table S5.

32

33 **Supplement figure caption**

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

2

3 **Plate lists**

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

20 Scale bar = 100 µm for all figures.

21

22 **Plate 2.** 1–4. *Actinomma* morphogroup B. 1, 2. *Actinomma* morphogroup B, same
23 specimen. NAP10t Deep #4. 3, 4. *Actinomma* morphogroup B juvenile, same specimen.
24 NAP10t Deep #15. 5, 6. *Drymyomma elegans* (Jørgensen, 1900), same specimen.
25 NAP10t Deep #14. 7–9. *Actinomma friedrichdreyeri* (Burrige, Bjørklund and
26 Kruglikova, 2013), same specimen. NAP11t Deep #4. 10–11. *Cleveiplegma boreale*
27 (Cleve, 1899), same specimen. NAP11t Deep #12.

28 Scale bar = 100 µm for all figures.

29

30 **Plate 3.** 1–4. *Arachnosphaera dichotoma* (Jørgensen, 1900). 1, 2. *Arachnosphaera*
31 *dichotoma*, same specimen. NAP11t Deep #5. 3, 4. *Arachnosphaera dichotoma*, same
32 specimen. NAP11t Deep #4. 5–8. *Streblacantha circumtexta*? (Jørgensen, 1905). 5, 6.
33 *Streblacantha circumtexta*? juvenile form, same specimen NAP10t Deep #12. 7, 8.

1 *Streblacantha circumtexta*? Juvenile form, same specimen. NAP10t Shallow #23. 9–11.
2 *Spongotrochus glacialis* (Popofsky, 1908). 9. *Spongotrochus* aff. *glacialis*. NAP10t
3 Shallow #24. 10, 11. *Spongotrochus glacialis*, same specimen. NAP10t Shallow #22. 12.
4 *Stylodictya* sp. NAP10t Shallow #16.
5 Scale bar = 100 µm for all figures.

6
7 **Plate 4.** 1–7. *Joergensenium* spp. 1, 2, 3. *Joergensenium* sp. A, same specimen. NAP10t
8 Deep #12. 4, 5. *Joergensenium* sp. A, juvenile forms of 1–3, same specimen. NAP11t
9 Deep #4. 6, 7. *Joergensenium* sp. B, same specimen. NAP11t Deep #9. 8–9.
10 *Enneaphormis rotula* (Haeckel, 1881), same specimen. NAP11t Deep #4. 10–11.
11 *Enneaphormis enneastrum* (Haeckel, 1887), same specimen. NAP10t Deep #12. 12–16.
12 *Protoscenium simplex* (Cleve, 1899). 12, 13, 14. *Protoscenium simplex*, same specimen.
13 NAP10t Deep #12. 15, 16. *Protoscenium simplex*, same specimen. NAP10t Deep #12.
14 Scale bar = 100 µm for all figures.

15
16 **Plate 5.** 1–6. *Ceratocyrtis histricosus* (Jørgensen, 1905). 1, 2, 3. *Ceratocyrtis*
17 *histricosus*, same specimen. NAP10t Deep #12. 4, 5, 6. *Ceratocyrtis histricosus*, same
18 specimen. NAP10t Deep #12. 7–10. *Ceratocyrtis galeus* (Cleve, 1899). 7, 8.
19 *Ceratocyrtis galeus*, same specimen. NAP10t Deep #6. 9, 10. *Ceratocyrtis galeus*, same
20 specimen. NAP10t Deep #4. 11–12. *Arachnocorys umbellifera* (Haeckel, 1862), same
21 specimen apical view. NAP10t Deep #4. 13–16. *Cladoscenium tricolpium* (Haeckel,
22 1887). 13, 14. *Cladoscenium tricolpium*, same specimen. NAP10t Deep #6. 15, 16.
23 *Cladoscenium tricolpium*?, same specimen. NAP10t Deep #14. 17–18. *Lophophaena*
24 *clevei* (Petrushevskaya, 1971), same specimen. NAP10t Shallow #14. 19–27.
25 *Phormacantha hystrix* (Jørgensen, 1900). 19, 20. *Phormacantha hystrix*, same specimen.
26 NAP10t Deep #12. 21, 22. *Phormacantha hystrix*, same specimen. NAP10t Deep #12.
27 23, 24, 25. *Phormacantha hystrix*, same specimen. NAP10t Deep #12. 26, 27.
28 *Phormacantha hystrix*, same specimen. NAP10t Deep #12.
29 Scale bar = 100 µm for all figures.

30
31 **Plate 6.** 1–4. *Peridium longispinum*? (Jørgensen, 1900). 1, 2. *Peridium longispinum*?
32 same specimen. NAP11t Deep #4. 3, 4. *Peridium longispinum*?, same specimen.
33 NAP11t Deep #4. 5–6. *Plectacantha oikiskos* (Jørgensen, 1905), same specimen.

1 NAP10t Deep #12. 7–11. *Pseudodictyophimus clevei* (Jørgensen, 1900). 7, 8, 9.
2 *Pseudodictyophimus clevei*, same specimen. NAP10t Deep #12. 10, 11.
3 *Pseudodictyophimus clevei*, same specimen. NAP10t Deep #12. 12–13.
4 *Pseudodictyophimus gracilipes gracilipes* (Bailey, 1856), same specimen. NAP10t
5 Deep #12. 14–19. *Pseudodictyophimus* spp. juvenile forms. 14, 15. *Pseudodictyophimus*
6 indet., juvenile forms same specimen. NAP10t Deep #12. 16, 17. *Pseudodictyophimus*
7 indet., juvenile forms, same specimen. NAP10t Deep #12. 18, 19. *Pseudodictyophimus*
8 indet., juvenile forms same specimen. NAP10t Deep #12. 20–23. *Pseudodictyophimus*
9 *gracilipes* (Bailey, 1856) *bicornis* (Ehrenberg, 1862). 20, 21. *Pseudodictyophimus*
10 *gracilipes bicornis*, same specimen. NAP11t Deep #4. 22, 23. *Pseudodictyophimus*
11 *gracilipes bicornis*, same specimen. NAP11t Deep #4.

12 Scale bar = 100 µm for all figures.

13

14 **Plate 7.** 1–3. *Pseudodictyophimus gracilipes* (Bailey, 1856) *multispinus* (Bernstein,
15 1934) 1, 2. *Pseudodictyophimus gracilipes multispinus*, same specimen. NAP10t
16 Shallow #2. 3. *Pseudodictyophimus gracilipes multispinus*. NAP11t Shallow #2. 4–12.
17 *Pseudodictyophimus plathycephalus* (Haeckel, 1887). 4, 5, 6. *Pseudodictyophimus*
18 *plathycephalus*, same specimen. NAP10t Deep #12. 7, 8. *Pseudodictyophimus*
19 *plathycephalus*, same specimen. NAP10t Deep #12. 9, 10. *Pseudodictyophimus*
20 *plathycephalus*, same specimen. NAP10t Deep #12. 11, 12. *Pseudodictyophimus*
21 *plathycephalus*, same specimen. NAP11t Deep #4. 13–14. *Tetraplecta pinigera*
22 (Haeckel, 1887), same specimen. NAP10t Deep #12.

23 Scale bar = 100 µm for all figures.

24

25 **Plate 8.** 1–10. *Tripodiscium gephyristes* (Hülsemann, 1963). 1, 2. *Tripodiscium*
26 *gephyristes*, same specimen. NAP10t Deep #12. 3, 4, 5 *Tripodiscium gephyristes*, same
27 specimen. NAP10t Deep #12. 6, 7, 8. *Tripodiscium gephyristes*, same specimen.
28 NAP10t Deep #12. 9, 10. *Tripodiscium gephyristes*, same specimen. NAP10t Deep #12.
29 11–18. Plagiacanthidae gen. et sp. indet. 11, 12. Plagiacanthidae gen. et sp. indet.
30 juvenile, same specimen. NAP10t Deep #12. 13, 14. Plagiacanthidae gen. et sp. indet.,
31 same specimen. NAP10t Deep #12. 15, 16. Plagiacanthidae gen. et sp. indet., same
32 specimen. NAP10t Deep #12. 17, 18. Plagiacanthidae gen. et sp. indet. juvenile, same
33 specimen. NAP10t Deep #12. 19–22. *Artostrobus annulatus* (Bailey, 1856). 19, 20.

1 *Artostrobos annulatus*, same specimen. NAP10t Deep #12. 21, 22. *Artostrobos*
2 *annulatus*, same specimen. NAP10t Deep #12. 23–30. *Artostrobos joergenseni*
3 (Petrushevskaya, 1967). 23, 24. *Artostrobos joergenseni*, same specimen. NAP10t Deep
4 #12. 25, 26. *Artostrobos joergenseni*, same specimen. NAP10t Deep #12. 27, 28.
5 *Artostrobos joergenseni*, same specimen. NAP10t Deep #12. 29, 30. *Artostrobos*
6 *joergenseni*, same specimen. NAP10t Deep #12.

7 Scale bar = 100 μ m for all figures.

8

9 **Plate 9.** 1, 2. *Cornutella stylophaena* (Ehrenberg, 1854), same specimen. NAP10t Deep
10 #12. 3, 4. *Cornutella longiseta* (Ehrenberg, 1854), same specimen. NAP10t Deep #12.
11 5–9. *Cycladophora davisiana* (Ehrenberg, 1862). 5. *Cycladophora davisiana*, NAP11t
12 Deep #4. 6, 7. *Cycladophora davisiana*, same specimen. NAP10t Deep #12. 8, 9.
13 *Cycladophora davisiana*, same specimen. NAP10t Deep #12. 10–11. *Lithocampe a*_.
14 *furcaspiculata* (Popofsky, 1908). same specimen. NAP10t Deep #12. 12–13.
15 *Lithocampe platycephala* (Ehrenberg, 1873). 12. *Lithocampe platycephala*. NAP10t
16 Deep #13. 13. *Lithocampe platycephala*. NAP11t Deep #14. 14–21. *Sethoconus*
17 *tabulatus* (Ehrenberg, 1873). 14, 15. *Sethoconus tabulatus*, same specimen. NAP10t
18 Deep #12. 16, 17. *Sethoconus tabulatus*, same specimen. NAP10t Deep #12. 18, 19.
19 *Sethoconus tabulatus*, same specimen. NAP10t Deep #12. 20, 21. *Sethoconus tabulatus*,
20 same specimen. NAP10t Deep #12. 22–33. *Amphimelissa setosa* (Cleve, 1899). 22, 23.
21 *Amphimelissa setosa*, same specimen. NAP10t Deep #12. 24, 25. *Amphimelissa setosa*,
22 same specimen. NAP10t Deep #12. 26, 27. *Amphimelissa setosa*, same specimen.
23 NAP10t Deep #12. 28, 29. *Amphimelissa setosa*, same specimen. NAP11t Deep #4. 30,
24 31. *Amphimelissa setosa*, same specimen. NAP10t Deep #12. 32, 33. *Amphimelissa*
25 *setosa*, same specimen, apical view. NAP11t Deep #4. 34–39. *Amphimelissa setosa*
26 juvenile. 34, 35. *Amphimelissa setosa* juvenile, same specimen. NAP11t Deep #14. 36,
27 37. *Amphimelissa setosa* juvenile, same specimen. NAP10t Deep #12. 38, 39.
28 *Amphimelissa setosa* juvenile, same specimen. NAP11t Deep #14. 40–41. *Lirella melo*
29 (Cleve, 1899), same specimen. NAP10t Deep #14. 42–43. *Protocystis harstoni* (Murray,
30 1885), same specimen. NAP10t Deep #18.

31 Scale bar = 100 μ m for all figures.