Interannual variation of settling particles that reflect upper-ocean circulation in the southern Chukchi Borderland, 2010-2014

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Abstract

Changes in the lower-trophic marine ecosystem and biogeochemical cycles were considered with respect to the warming Arctic Ocean. The time series monitoring of the hydrography and marine settling particles supplies a large amount of information regarding the marine lower-trophic ecosystem in with respect to the changing Arctic Ocean. To investigate the interannual relationship between the settling particles and hydrographic conditions of the western Arctic Ocean, bottom-tethered sediment trap moorings were deployed at the Northwind Abyssal Plain (NAP) and at the Chukchi Abyssal Plain from October 2010 to September 2014 to the east and west of the Chukchi Borderland. The settling particles at both stations contained a significant amount of lithogenic matter, with biogenic particles being a lateral advection of shelf materials from shelf to basin. The many peaks of settling particle fluxes at Station NAP in 2013–2014 corresponded to the hydrographic events of passing oceanic eddies over the station, in addition to seasonal biological production. Additionally, abundant gelatinous matter was found in some summer samples. The settling flux data of particulate organic matter and the mole ratio and stable isotope ratios of particulate organic carbon and nitrogen in the settling particles reflected the changes in the composition of trapped plankton assemblages under various hydrographic conditions over the course of the four years of the study.

1. *Introduction*

Changes in physical oceanographic characteristics and atmospheric conditions related to recent retreats of sea ice in the Arctic Ocean influence characteristic marine ecosystems and biogeochemical cycles (e.g., Wassmann et al., 2011; Grebmeier, 2012; Ardyna et al., 2014; Berge et al., 2015; Hunt et al., 2015; Harada 2016). On the Pacific side of the Arctic Ocean, the annual and interannual variation of the lateral transportation of Pacific water to Arctic seas and the distribution of summer sea ice are important for changes in marine ecosystems and biogeochemical cycles. The Pacific water transports heat, freshwater, and shelf matter, such as nutrients and suspended particles, including plankton, to the basin. The Chukchi Borderland is one of the key areas where the spread of Pacific-origin waters to the basin can be monitored.

Interannual hydrographic variations, such as changes in surface ocean circulation, oceanic eddies, and sea ice condition should be reflected in the interannual variation of plankton assemblages and settling particle fluxes. Such information is important both for understanding changing Arctic marine ecosystems and for use as validation data for the development of numerical models for marine ecosystems in the Arctic Ocean. A collaborative study of the monitoring of settling particle fluxes using sediment traps and the physical oceanographic-marine ecosystem model that was conducted by Watanabe et al. (2014) has suggested that the westward advection of oceanic eddies containing shelf materials is key for explaining the temporal high flux of settling particles in the southern Northwind Abyssal Plain (NAP) Station of the Chukchi Borderland from fall 2010 to 2011. Using sediment trap samples from the NAP Station, the time series changes in the occurrence of some plankton groups and their relationships with hydrographic variations have been discussed (Watanabe et al., 2014; Ikenoue et al., 2015; Matsuno et al., 2014, 2015, 2016; Onodera et al., 2015, 2016; Tokuhiro et al., 2018). This discussion and the understanding of the settling flux and the composition of particulate biogenic and lithogenic matters, along with their relationship to the hydrographic background it produced are more significant in the context of data regarding previously studied plankton assemblages in sediment trap samples. This paper describes the interannual variation of settling particle flux and the composition of bulk particle components (particulate organic matter [POM], calcium carbonate, biogenic opal, and lithogenic materials) and examines the relationships between the obtained results and plankton assemblages in the studied samples as well as the hydrographic conditions around mooring sites in the Chukchi Borderland.

2. Material and methods

2.1. Mooring operations

The samples and hydrographic data were obtained using bottom-tethered moorings with a sediment trap in the southern Chukchi Borderland (Fig. 1). The deployment and recovery of sediment trap mooring was performed by R/V *Mirai* of the Japan Agency for Marine–Earth Science and Technology and Canadian ice breaker CCGS *Sir Wilfrid Laurier*, CCGS *Louis S. St-Laurent*, and CCGS *Amundsen*. The first annual deployment in the southern NAP occurred at the mooring ID of Station NAP10t from October 04, 2010, to September 28, 2011 (Table 1). At the turnaround of the mooring system, which occurs every September or October, the mooring deployment at the position NAP10t was continued until the end of September 18, 2013 (Table 1). Following this, the mooring NAP13t, positioned approximately 60-km south from NAP10t-12t, was adopted owing to unfavorable conditions of sea ice for deployment at NAP10t that began in September 2013. To compare the differences between the settling particle fluxes at NAP Station and the western area, where nitrate concentrations are higher than those at NAP Station (Nishino et al. 2011), the annual deployment of the sediment trap mooring CAP12t was conducted on the shelf slope on the southwestern side of the Chukchi Spur (Fig. 1). The following mooring deployment at the CAP12t position was cancelled owing to the conditions of the sea ice.

2.2. Sediment trap samples

The time series sediment trap SMD26S-6000 (Nichiyu Giken Kogyo, Co. Ltd.) was used for all deployed moorings. The sediment trap was deployed at a depth of approximately 180–260-m depth for all moorings, including CAP12t, and at a deeper layer, approximately 1300-m deep, for NAP10t-13t (Table 1). The water depths of NAP10t-12t, NAP13t, and CAP12t are ~1975 m, 1973 m, and 447 m, respectively (Table 1). The sampled period of each cup is 10-15 days (Supplementary Table 1). The sample bottle attached to the sediment trap was filled with filtered sea water obtained at 1000 m depth of NAP station and in the southwestern Canada Basin. The antiseptic agent for trapped organic matter in the trap bottle was pH-neutralized formalin (4-5 v/v %) with sodium tetraborate. The recovered sediment trap samples were sieved using a 1-mm mesh to remove swimmers. The filtrated sample was evenly split into 10 subsamples using the wet sample divider WSD-10 (McLane Research Laboratories, Inc.). Then, 1–3 of the 10 subsamples were filtered using a weighted polycarbonate filter (pore size 0.45μm) and were desalted with Milli-Q water. This filter was dried in the desiccator with diphosphorus pentoxide for a few days. The dried filter was weighed to calculate total mass flux (TMF), and then the particles of the weighed sample detached from the filter were lightly milled to homogenize. The powder samples were sued to analyze the bulk components (carbon, nitrogen, biogenic opal, and others) and stable isotope analyses of the particulate organic carbon (POC) and particulate nitrogen (PN). The contents of particulate carbon and nitrogen were measured using the elemental analyzer FlashEA from Thermo Fisher Scientific. The POC was analyzed after hydrochloric acid gas treatment in the desiccator to remove carbonate. The particulate inorganic carbon was estimated by the difference of total particulate carbon and POC content. The POM contents were estimated using Redfield ratio and the POC contents. The stable isotope analyses of POC and PN were done using the mass spectrometer Delta Plux XP IRMS by Thermo Fisher Scientific. This paper simply describes the stable isotope ratios of POC and PN as $d^{13}C$ and $d^{15}N$, respectively. The mole ratio POC/PN is given as C/N in this paper. Biogenic opal analyses were conducted through alkali leaching (Mortlock and Froelich, 1989) and molybdate yellow methodology. In bulk component analyses, the remainder of the POM, $CaCO_3$, and biogenic opal in the total mass was treated as other, which largely includes lithogenic matters with possible errors in the bulk component analysis. In addition, elementary analysis using ICP-AES was conducted for the first deployment samples of NAP10t.

2.3. Hydrographic data and deployed sensors

The daily concentrations of sea ice and downward short-wave radiation around the NAP and CAP Stations were obtained from re-analyzed data from the National Centers for Environmental Prediction/Climate Forecast System Reanalysis (Saha et al., 2010).

Hydrographic sensors were attached to the moorings CAP12t and NAP13t (Table 2). The applied sensors are CT for CAP12t and NAP13t, current (ADCP and electromagnetic sensors), turbidity, chlorophyll-a, and ice profiling sonar for NAP13t (Table 2). Two different units of turbidity sensors (FTU: Formazin Turbidity Unit, or FNU: Formazin Nephelometric Unit) for NAP13t were not unified at one unit. Those sensors were mainly moored in upper 300 m where there are pacific-origin and melt waters. The backscattered data obtained by ADCP from NAP13t was used to estimate the qualitative change in particle concentrations in water using the method of Deines (1999). In the estimation process of particle concentration by ADCP, the method of removing the influence of the attenuation of acoustic signals for a depth of 140 m is described in Itoh et al. (submitted).

3. Hydrographic backgrounds

The Chukchi Borderland is located in a frontal area between the oceanic Beaufort Gyre, with its oligotrophic surface water, in the east and a relatively eutrophic water mass in west (Nishino et al., 2011). The east–west gradient of the nitrate concentrations in the Chukchi Borderland suggests a higher settling flux of biogenic particles in the west, where CAP12t was deployed, than in the east, where the NAP Station series was deployed (Watanabe et al., 2014).

Previous research has suggested that the development of oceanic eddies off the Barrow Canyon and their westward advection to the NAP region along the outside of the Beaufort Gyre are an important temporal transport mechanism of shelf material inputs to the sediment trap samples obtained at NAP10t (Watanabe et al., 2014; Harada, 2016). The size and center of the Beaufort Gyre changes year to year (Mizobata et al., 2016). Following the physical oceanographic model for the Arctic Ocean, Onodera et al. (2015) and Watanabe et al. (2015) suggested that the NAP12t was covered by the oceanic Beaufort Gyre.

Condition of downward shortwave radiation was similar between NAP and CAP stations (Fig. 2a). The data shows that there is polar night period in November-January. Sea ice covered the NAP region from October to August (Fig. 2b). The ice-cover period at CAP12t began about 1 week earlier than it did at NAP12t. The sonar profiling record for the sea ice that was taken from the top of NAP13t mooring (~23 m depth) showed that the daily mean thickness of the sea ice grew from October 2013 to May 2014 and shrank beginning in July 2014 (Fig. 2b). The maximum daily mean thickness at the end of April 2014 was 19.6 m. Thicker sea ice (mean thickness of 5.4 m) temporarily passed over NAP13t in mid-August 2014.

The current direction for the upper water column at NAP13t was largely northwest to westward (Fig. 3). The mean current speed for the particle sampling period was 6 ± 5 cm/s at depths of ~170 m, which was 20 m above the shallower sediment trap of NAP13t (Fig. 4). The increase in the speed of the current and the change in its direction, along with the change in the water mass, were observed at the deployed sensor depths (Fig. 3). Some of these current change events probably reflected the passing of the oceanic eddy at NAP13t. The eddy event for NAP13t was recognized at least four times, according to ADCP data (Table 3). The first eddy event was observed during the latter half of September 2013. In this event, Bering summer water and cold, newly-ventilated Pacific winter water was observed at depths of 25–45 and 170–215 m, respectively (Fig. 4a, b, c). The direction of the current quickly changed from northeast to southwest. As the eddy moved westward, this eddy appeared to be of an anticyclonic type, with a cold core at depths of 100–150 m. The second eddy event was observed in November 2013. The rapid increase of salinity at depths of ~170 and ~200 m and suggests upwelling of deeper waters for the second eddy event (Fig. 4a, b, c). If the temporal upwelling for the second eddy event reflected a passing cyclonic eddy, the cyclonic eddy probably moved around NAP13t from the west to the east, judging by the direction change of the current, from northward to southeast. The third event, occurring in January 2014, and the fourth event, extending from the end of May to early June 2014 are judged to be westward motions of anticyclonic oceanic eddies. The fifth eddy event for July 2014 was minor compared to previous eddy events. However, there was clock-wise current change in the period (Fig. 3). In addition, Kawaguchi et al. (2016) reported the occurrences of anticyclonic oceanic eddies around the position of NAP10t-12t in September 2014. The temporal upwelling of Atlantic water observed at 196 m in late August-early September 2014 might be related to the eddy event around NAP10t-12t.

4. Results

4.1. Station NAP

The TMF and the bulk component of the settling particles obtained by the shallower traps of NAP10t and NAP11t has been published by Watanabe et al (2014) and Onodera et al. (2015). Using previously published data, we compiled our results with other flux data from the deeper trap of NAP10t-11t and the entire data sets of NAP12t and NAP13t (Fig. 5).

4.1.1 TMF

For the entire sampled duration at NAP10t-12t, from October 4, 2010, to September 17, 2012, the TMF ranged from 5.0 to 263.3 mg m^{-2} d^{-1} (median: 31.8 mg m^{-2} day^{-1}) for shallow trap and from <0.1 to 259.3 mg m^{-2} day^{-1} (median: 19.4 mg m^{-2} day^{-1}) for deep traps (Fig. 5c, d). The shallow and deep sediment traps of NAP13t showed the similar and relatively high TMF ranged from 3.1 to 342.3 mg m^{-2} day^{-1} (median: 31.0 mg m^{-2} day^{-1}), and from 2.4 to 180.2 mg m^{-2} day^{-1} (median: 47.0 mg m^{-2} day^{-1}), respectively. The maximum TMF was clearly observed in early winter and summer, with the exception of a low flux period of 2012 (Fig. 5).

4.1.2 Bulk components of trapped settling particles

The most abundant composition of the bulk components of trapped particles was “others” (total mass – biogenic materials) , which is almost entirely composed of lithogenic matter in many studied samples (median: ~ 69% for NAP Shallow and Deep trap sample. see supplementary Table 1). The elemental composition analyzed for NAP10t shows high aluminum content, ranging from 5.8 to 7.6 wt% and from 6.1 to 8.0 wt% for shallow and deep trap samples, respectively. The ranges of POC content in the settling particles were 1.6–21.7 wt% and 1.1–15.5 wt% for shallow and deep trap samples, respectively. The estimated %POM content based on %POC and the Redfield ratio was 4.6–62.0 wt% and 3.2–44.4 wt% for shallow and deep trap samples. Biogenic component (POM+CaCO3+Biogenic Opal) ranged from 14.0 to 68.0, and from 12.0 to 74.4 wt% for shallow and deep trap samples, respectively.

With the exception of 2012, the POC and PN fluxes had remarkable increase in January–February, July–September, and November–December (Fig. 6a, b). The mole ratio for C/N ranged from 6.2 to 12.7 for all samples of the NAP Station (Fig. 6c). The average mole ratio for C/N at the deep trap for the entire studied period is 1.2 higher than that for the shallower trap. The large discrepancy of the C/N relationship between shallower and deeper traps was usually observed in low POC flux periods at deep trap (Fig. 6c). Stable isotopes of d^{13}C and d^{15}N ranged from −29.3 to −20.9, and from 3.7 to 12.0 in all NAP Station samples (Fig. 6d, e). Although the C/N ratio, d^{13}C, and d^{15}N showed no clear seasonality, the changes in those data suggested temporal changes of trapped particle contents. In April 2011, the mole ratio for C/N decreased and that for d^{15}N increased (Fig. 6c, e). The shallower trap sample for this event contained many specimens of tiny juvenile amphipods. The deeper trap sample for this event contained fragments of biogenic matter, which might have originated from higher nutrient level organisms. The lowest values for the C/N ratio, d^{13}C, and d^{15}N were observed in shallower sediment trap samples in late July–August 2012 (Fig. 6c, e). Low d^{15}N values of less than 5 were observed only for this event. Beginning in October 2012, d^{15}N and d^{15}C quickly increased to standard or higher levels relative to the earlier period of the study. In contrast with the result for summer 2012, the d^{13}C and mole ratios of C/N increased in August 2013. At NAP13t, beginning with fall 2013, the time series pattern of mole ratio of C/N and d^{15}N for shallower trap had an opposite correlation (Fig. 6c, e).

The PIC flux was lower than the biogenic opal and POC (Fig. 6f, g). The %PIC was lower than 5.3 wt% and 5.7 wt% for shallow and deep trap samples. Clear seasonality was not observed in the

PIC flux (Fig. 6f), and the temporal increase of PIC was due to trapped microzooplankton bearing calcareous shells (Watanabe et al., 2014). The relative contents of biogenic opal over the entire sampled duration were 0.9–71.7 wt% (median: 14.2 wt%) and 7.4–20.2 wt% (median: 12.0 wt%) for shallow and deep trap samples (Fig. 6g). With seasonal decreases of sea ice concentration and sea ice thickness, settling fluxes of biogenic opal, POC and PN increased in early summer except for 2012 (Figs. 2b, 6g).

Gelatinous matter such as Appendicularian houses and small jellyfish were abundant in July–early September 2011 and 2014 (Fig. 6a, 7). Because much of this gelatinous material, including some biogenic matter, such as fecal pellets, remained in the 1 mm mesh sieve intended to separate swimmers from settling particles (<1 mm), the TMF and %POC figures for the jelly event are probably underestimates.

4.1.3 Turbidity and ADCP backscattered data of NAP13t

The daily mean for turbidity at the top buoy of NAP13t (nominal depth: 25m) was usually lower than 0.3 FTU. The maximum daily mean for turbidity at the top buoy temporarily reached 13 FTU in December 2013 (Fig. 8a). The daily mean turbidity at depths of ~170 m, which is 20 m above the shallower sediment trap, ranged from 0.9 to 1.1 FNU throughout the sampled duration. The acoustic strength of the ADCP data for the depth interval of 12–116 m shows relatively greater particle concentrations in the upper water, at depths shallower than 50 m, in late September 2013, late January 2014, and after May 2014 (Fig. 8b). The acoustic strength at a depth of 170 m was relatively high in September 2013, late December 2013–early March 2014, and late May–September 2014 (Fig. 8c). These high signal periods at ~170 m basically correspond to a mid–high signal for depths of 12–50 m (Fig. 8b).

4.2. CAP12t

4.2.1 TMF

The range of the TMF at CAP12t was from 2.8 to 255.1 mg m^{-2} day^{-1} (Fig. 9a), which was similar to the TMF range at NAP12t. The high TMF for CAP12t was observed from March to early May 2013 (Fig. 9a), by contrast with the high TMF periods for NAP12t (Fig. 5). The particle flux in summer 2013 was lower than in high flux event of March–May 2013. However, note that the gelatinous matter that remained on the 1-mm mesh during sample treatment, was observed in the trap sample bottles from July 20 to August 08, 2013.

4.2.2 Bulk components of trapped settling particles

The content rate of lithogenic matters at CAP12t was 3-63% (median: 46%), which was lower than that at NAP stations. The contribution of biogenic opal to TMF at this station (11-53 wt%) was relatively higher than that at NAP stations. At the period of maximum TMF observation, in March, biogenic particle fluxes such as POC, PN and biogenic opal also increased (Fig. 9). In the periods of lower TMF, in winter and summer (from May 16 to July 29, 2014), the lithogenic particle flux based on "others" composition decreased whereas POC and PN fluxes did not decrease or increased. The POC% in the low TMF periods from December 10, 2013, to January 16, 2014, and from May 16 to July 29, 2014, became higher because of relative decrease of lithogenic material. The increase of POC flux (Fig. 9b) in summer reflected biological production, including gelatinous materials. The increase of PN flux in summer was not so high compared to the POC flux (Fig. 9c). The mole ratio of C/N ranged from 6.9 to 18.3 (Fig. 9d). The highest C/N ratio was observed in the presence of abundant gelatinous matter in the trap bottles. The stable isotope for $d^{13}C$ and $d^{15}N$ ranged from −29.1 to −21.9, and from 7.5 to 14.0, respectively (Figs. 8e, 8f). PIC contents were usually low, and the flux was less than 0.3 mg m^{-2} day^{-1} (Fig. 9g), lower than that found at NAP Station (Fig. 6f). Biogenic opal flux showed the maximum in March 2013 (Fig. 9h), which is comparable to the summer flux maximum of shallower sediment trap at NAP13t (Fig. 6g). However, as mentioned below, the microscopic observation suggested that fragment of diatom frustules is the major component of trapped biogenic opal in March 2013.

5. Discussion

5.1. Time series fluctuation of settling particle flux reflecting hydrography

5.1.1 Change in TMF dominated by hydrographic condition at NAP13t

In the intensified current condition reaching to ~0.2 m s^{-1} just below the shallower trap for the first oceanic eddy event in the early period (late half of September 2013, Table 3)) of NAP13t observations (Fig. 4d, e), the settling particle flux at shallower trap depths may not have reflected the true amount of settling particle flux (Fig. 8d). The turbidity and back-scatter strength of the single point ADCP deployed at depths that are ~20 m above the shallower trap shows that particle concentrations in water were commonly abundant but lower than those of later periods (Fig. 8c). The increases in TMF at deeper trap depths during the same period can be interpreted as a reflection of higher particle concentrations in the upper water column. According to the vertical distribution of particle concentrations and TMF data, many particles in the water during the first eddy event were in the Bering summer water at a depth of around 25 m, and the cold winter water in the deeper layer appeared during the eddy event (Fig. 4). When the second eddy, which was considered cyclonic, passed NAP13t in late November 2013, TMF and the backscattered strength of the ADCP did not increase, likely due to the upwelling of deeper waters with relatively low particle concentration. It appears that the high TMF period, beginning in late December 2013, did not correspond to an eddy event. However, the particle concentration in the upper water with a depth of around 20 m began to increase in December 2013, and a mass of water with abundant particles temporally expanded in depth when the third eddy core passed NAP13t in early January 2014 (Figs. 4 and 7). The core depth of the third oceanic eddy was ~50 m, and mean current speeds around the shallower trap was 7.8±1.8 m s^{-1} and 4.5±1.9 cm s^{-1} at 170 m and 209 m for the event #3. Therefore, the condition of the current that influences trapping efficiency for the shallower trap was stable for the eddy event #3 (Fig. 4). These observations suggest that the appearance of water with large amounts of particles and an increase in TMF from December 2013 can be related to the third oceanic eddy event. When the fourth eddy event occurred in the end of May 2014, the acoustic signal for particle concentration increased, although TMF did not increase, likely because of the high current speed during the eddy event. When the settling particle fluxes increased in July 2014, no rapid increase of speed or change in the direction of the current suggesting passing oceanic eddy were clearly observed. The increases of particle concentration for upper 50m (Fig. 8b) and settling particle flux in July 2014 may reflect an influence of seasonal sea ice retreat (Fig. 2b). However, a circular change in the direction of the current was observed at depths of around 50–170 m in July (Fig. 4). Kawaguchi et al. (2016) detected westward anticyclonic cold eddies with core depths of 100–150 m around the position of NAP10-12t in early September 2014. If this change in the direction of the current reflected passing oceanic eddies, the high TMF in August–September 2014 can be (at least partially) explained by advection of shelf materials with a passing oceanic eddy in addition to an increase of vertical particle transport by seasonal retreat of sea ice and increases of biological production in summer.

5.1.2 Interannual variation of trapped biogenic particles reflecting hydrography at NAP Station

The relationships among the time series fluctuation of particle concentration in upper 50m waters, settling particle fluxes and changes in hydrographic conditions observed at NAP13t suggest that oceanic eddies play a partially significant role as a transporter of shelf materials advected to the mooring position. This relationship was estimated through the collaborative study of settling particle flux at NAP10t and the application of a physical oceanographic model developed exclusively for the Arctic Ocean (Watanabe et al., 2014). Because settling particles are dominated by lithogenic materials, the interannual variation of TMF reflects the status change of ocean currents for the upper water column, such as the oceanic eddy passing, as mentioned above.

The interannual variation of $d^{13}C$, $d^{15}N$, the ratio of C/N, and the flux of trapped plankton groups for every spring and summer from 2011 to 2014 suggest a difference in biogeochemical conditions for lower trophic production, in addition to the physical hydrographic conditions. When the biogenic opal and POC fluxes at NAP10t increased slightly in April–May 2011 (Fig. 6a, g), large diatom species such as *Coscinodiscus* spp. contributed to the flux of POC (Onodera et al., 2015). Although the settling flux of other siliceous microplankton radiolarians slightly increased during this period (Ikenoue et al., 2015), the contribution of the shell to the biogenic opal flux was low (Ikenoue et al., in prep.). The abundance of the herbivore copepoda *Calanus hyperboreus* increased in March–May

2011 (Matsuno et al., 2013, 2015). In addition to seasonal primary production under sea ice and the lateral advection of re-suspended matter, the contribution of fecal pellets resulting from the grazing pressure effect suggests settling POM and biogenic opal fluxes. The sudden increase of d^{15}N and corresponding decrease of C/N in April 2011 can be primarily explained by the abundant trapped small zooplankton that are less than 1 mm, which is largely a number of juvenile amphipods detached from the abdominal part of one parent specimen during sample treatment. This is supported by the stable isotope values for amphipods, which show a d^{15}N of ~11‰ and a d^{13}C of ~ −25.4‰ around the Beaufort Gyre (Pomerleau et al., 2014). The quite low values of d^{13}C, reaching to −28.6‰ at the shallow trap in July 2011, were lower than the ~27‰ found for POC in the Chukchi Sea (Zhang et al., 2012). The phytoplankton growing under high pCO_2 in cold water are able to tolerate such low d^{13}C values (Tesi et al., 2018). The decreases of d^{13}C in late June–July 2011 also reflect zooplankton ecology. For this timing, rapid increases in numbers of silicoflagellate skeletons were observed with many fecal pellets in the trapped particles in shallow traps but not in the deep traps (Onodera et al., 2016). From late June to July 2011, the composition of three fecal-pellet types suggested intensified grazing pressure by copepoda and raptorial amphipod (Matsuno et al., 2016). The hydrographic conditions of active primary production may have a primary influence on the stable isotope condition of carbon and nitrogen in zooplankton for herbivorous feeding, as reported for the Beaufort Sea (Forest et al., 2011).

It is unclear why decreases in d^{13}C in June–July 2011 began at the deep trap 2 weeks earlier than at the shallow trap. Takeuchi et al. (unpublished) showed a difference in time series trend for the composition of lithogenic matter that originates in deep and shallow trap samples, using rare earth element analysis. In general, the origin area of trapped particles for the deeper sediment trap may be different, and broader, than that at the shallower trap, although it can also depend on the particle sinking rate (Siegel et al., 2008). Horizontal diffusion of settling particles with low sinking rate is estimated under mesoscale oceanic eddy (Siegel et al., 1990). If we follow the numerical model (Siegel et al., 1990), the particles transported by eddy approaching to mooring position can be reached earlier at the deeper trap than at the shallower trap, for some values of distance between the oceanic eddy and the mooring position.

Among the four annual deployment records of the settling particle fluxes at NAP Station in this study, particle flux data from early 2012 to middle 2013 (Fig. 5) showed an unusual annual pattern. As far as suspected from mooring depth change for NAP11t-NAP12t (Fig. 5a, b), subsurface current condition around the shallower trap was stable except for July 2013 (Onodera et al. 2015). The low particle fluxes at both shallow and deep traps might mainly reflect low settling particle condition in addition to particle trapping efficiency mainly estimated for July 2013. Onodera et al. (2015) suggested that the continuation of low particle fluxes at NAP12t and diatom assemblage in trap samples similar to those in the Canada Basin reflected a westward shift of oligotrophic water masses in the Beaufort Gyre. Matsuno et al. (2016) suggested a similar change in hydrographic condition, based on the absence of barnacle and bivalve larvae in sediment trap samples for summer 2012. Nitrogen in the southwestern Canada Basin during the summer is usually depleted in surface waters, by contrast with its phosphate concentrations (Shiozaki et al., 2018). Blais et al. (2012) and Shiozaki et al. (2018) reported findings of nitrogen fixation and its role in the nitrogen cycle in the Arctic Ocean. In relation to those hydrographic conditions for summer 2012, the low d^{15}N values for POM may suggest that there was partial contribution of nitrogen fixation for POM formation. In the central Canada Basin in September 2012, with its low sea ice concentrations, the pCO_2 in surface water was ~30 μatm greater than that in the northern Canada Basin, which had a great deal of sea ice (Islam et al., 2017). The fact that the lowest level of d^{13}C appeared in summer 2012 seems to suggest that the POM settled and trapped in the deployed sediment trap was formed owing to the condition of the lower growth rate of phytoplankton and the condition of high pCO_2 in surface water with reduced sea ice. The temporarily intensified current, as suspected by changes in the mooring depth of the sediment trap for July 2012 (Fig. 5a, b), might take trapped particles far from the vicinity of the mooring station. However, the possibility for the specific influence of the intensified current such as change of trapping efficiency (Matsuno et al. 2014) to lower levels of d^{13}C and d^{15}N remains unclear, as the d^{13}C and d^{15}N values remained low until September 2012. The increase of stable isotope values in October 2012 (Fig. 6d, e) suggests that the clear influence of the oligotrophic water ceased around the end of September. The diatom assemblages in the trap samples also changed from oligotrophic planktic flora to ice-related flora (Onodera, unpublished) even in the ice-free condition at Station NAP for early October 2012 (Fig. 2b). The change in biogeochemical data that occurred from September to October 2012 suggests a change in the major direction of the current, probably associated with a shift of the distribution of the Beaufort Gyre.

Higher sea ice concentrations in summer 2013 led to the interannual hydrographic characteristics observed at NAP Station for the four summer seasons from 2011 to 2014 (Fig. 2b). Continuous ice-free condition at Station NAP was observed for September (or late August – September) in 2011, 2012, and 2014 whereas the ice-free ocean condition was limited in summer 2013 (Fig. 2b). The highest d^{13}C, which appeared in late July–early August 2013 (Fig. 6d), suggests that ice algae particles contributed to the trapped settling particles. According to microscopic observations of the samples, the diatom flora in the trap samples for this period was dominated by ice-related species (Onodera, unpublished). For the Chukchi and Beaufort Seas in spring–summer 2002, the d^{13}C of the POC in sea ice ranged from −25.1 to −14.2‰, and it was linearly correlated with POC concentrations (Gradinger, 2009). Tesi et al. (2018) showed that the POC produced by ice algae in the East Siberian Sea has a heavier of d^{13}C, reaching about −21‰. In general, the ice algae under sea ice on the Pacific side of the Arctic Ocean are more abundant on the shelf side than in the oligotrophic Canada Basin (Nelson et al., 2014). In addition to the input of particles from ice algae to the deployed sediment trap, the flux of lithogenic material increased in summer 2013.

The temporary decrease in C/N and increase in d^{15}N preceding the high biogenic particle fluxes of June–early September 2014 are essentially caused by trapped small zooplankton in the studied samples from the shallow trap, as indicated for the case of summer 2011. The highest POC and PN fluxes for the shallower trap in summer 2014 were observed in lithogenic matter (Figs. 5 and 6), which may reflect the cold anticyclonic eddies with higher suspended particle concentrations in the eddy core located ~27 km north of NAP13t in early September 2014 (Kawaguchi et al., 2016).

It is unclear that oligotrophic condition and low flux of settling particles at Station NAP in 2012 can be treated as one of future condition at Station NAP in progressed global warming. Throughout four-year monitoring on settling particles, the low particle-flux trend in 2012 with minimum summer ice extent was different from time-series settling particle flux in other years. The position and area of oceanic Beaufort Gyre, which influenced to low flux of settling particles in 2012, reflects dynamics of atmospheric circulation over the Arctic Ocean (Proshutinsky et al. 2009, Regan et al. 2019). Decadal time-scale researches on Arctic climatology and physical oceanography suggests that recent physical condition over the Arctic tends to bring westward expansion of oceanic Beaufort Gyre. However, there is no clear research results to explain that those recent climatological physical dynamics can be explained as the reflection of global warming.

5.1.3 CAP Station

The ranges of d^{13}C found at CAP Station (-29.1 ~ -21.9) are higher than those at shallower trap of NAP12t (-28.2 ~-21.2), which suggests that much of the influence of POM originated from the shallower Chukchi Sea shelf, based on the d^{13}C distribution over the Chukchi Sea (Zhang et al., 2012). In contrast to what was expected before the mooring deployment was begun, based on recent nitrate distribution patterns in the Chukchi Borderland (Nishino et al., 2011), the settling particle flux at CAP12t was not higher than that found at NAP12t. This is probably due to the interannual variations of water mass distribution in 2012–2013. Because the data obtained at CAP Station only covered 1 year, additional study with more data and samples is required to for the relationship between settling particles and hydrographic condition around CAP Station to be properly characterized.

The high particle flux found in March 2013 can be explained as the lateral advection of re-suspended sediment on the shelf. The high particle flux in March 2013 may have reflected the input of warmer Pacific water, which moved in a current westward along the shelf edge of the Chukchi Sea. The increase in water temperatures in March 2013, from about −1.2 to −0.8°C at a depth of ~90 m (Fig. 4f), suggests an influence of advected warmer Pacific water to the sub sea-surface of the mooring position of CAP12t during the event (Watanabe et al., 2017). Microscopic observation suggests that the high biogenic opal in this period can be explained by the presence of many fragments of diatom frustules, which are treated as re-suspended particles. As has been already noted regarding on this hydrographic event, in Watanabe et al. (2017), the westward advection of Pacific water along the northern shelf of Chukchi Sea was the main contributor to lateral material transportation. Throughout the entire observation period, the contributions of oceanic eddy advection at CAP12t was unclear or negligible because of their location.

5.2. Gelatinous matter

At the outset of this study, the settling particles obtained were defined as being smaller than 1 mm, following precedent in sediment trap studies (e.g. Honjo et al., 2008). The discarded Appedicularian houses gravitationally sink to ocean interior, and it has a characteristic of settling particles.although their sizes are larger than 1 mm (Fig. 7). Because POC flux in this study is the results for particles smaller than 1mm, the contribution of gelatinous matters such as large Appendicularia house to the trapped settling samples in this study is not reflected in the obtained analysis data because of the methodology used. Some larger planktons such as Phaeodaria larger than 1mm may partially contribute to settling POC flux (e.g., Ikenoue et al. 2019). However, the particles remained on 1mm sieve in this study is almost swimmers such as copepoda and amphipoda. The occurrence pattern of abundant Appendicularian houses in this study may suggest that the contribution of Appendicularian houses to POC flux is patchy but locally and temporally important. Regarding the temporary occurrence of abundant gelatinous matter in this study, mainly composed of discarded Appendicularian houses, their likely importance for Arctic marine ecosystems should be noted. Appendicularia around the study area are mainly distributed along the shelf break of the Canada Basin and on the Chukchi Sea shelf (Lane et al., 2008; Hopcroft et al., 2010), and their abundance is markedly increased compared to the levels noted in the 1950s (Lane et al., 2008), as an effect of grazing on micro and meso plankton, including Copepoda (Lalande et al., 2011), the vertical transport of POC and other suspended particles, including microplastics, to the deep ocean (Deibel et al., 2005; Lalande et al., 2011; Katija et al., 2017), and the food source for fish in the Chukchi Sea (Nakano et al., 2016). The Appendicularia *Oikopleura vanhoeffeni* were commonly observed in the midst of phytoplankton blooms at a depth of around 50 m near the ice edge of the shelf slope in the southwestern Canada Basin in late July 2005 (Raskoff et al., 2010). The gelatinous event at NAP Station in summer 2011 was complete when the settling diatom flora changed from planktic to ice-related taxa just before the retreat of the sea ice retreat (Onodera et al., 2015). *Oikopleura vanhoeffeni* in Newfoundland has a habitat range of −1.3 to 4.6°C for water temperature and 32.3 to 32.7 for water salinity (Choe and Deibel, 2008). Because Appendicularia are filter feeders, the phytoplankton bloom under sea ice around the study region in early summer (Arrigo et al., 2012; Lowry et al., 2014) could be more favorable than feeding the largely ice algae attached to sea ice from below in low saline water. Because detailed analysis on gelatinous matters were not performed for the trap samples, additional study on this topic is necessary, using new sediment trap samples around the study region.

5.3. Contribution of resuspended biogenic matters

As estimated from the high abundance of lithogenic matter in the samples, trapped biogenic particle matter is expected to contain re-suspended particles originating in the sediment of the shelf region. The increase of biogenic matter flux in the non-productive season can be basically explained as laterally transported matter. The distinction between biogenic particle flux in the resuspended component and upper water origin is important for the understanding of the potential of primary productivity and the biological carbon pump around the mooring station. Magen et al. (2010) estimated different origins for POM in the southern Beaufort Sea using end members for the ratio of POC and total particulate nitrogen, $d^{13}C$ for POC and $d^{15}N$ for total particulate nitrogen. However, the end member for $d^{13}C$ of POC, showing the coastal origin of POC, is similar to the $d^{13}C$ value for phytoplankton in $d^{13}C$-depleted water (Tesi et al., 2017). Thus, the estimation of the quantitative contribution of resuspended biogenic matter to total biogenic matter using analyzed items was not successfully performed in this study. According to Takeuchi et al. (unpublished), who analyzed rare earth elements in settling particles obtained from NAP10t, trapped lithogenic particles had a mixture of three different sources: the Mackenzie Delta, the Yukon River, and East Siberian regions. They suggested that sources of lithogenic matter for shallow and deep traps changed with time. Resuspended biogenic matter could be an additional source of food for benthos and nekton assemblages in the study region. Relative to the relationship between changing physical oceanographic conditions and marine ecosystems, it is likely that monitoring the behavior of advected particles will be important for assessing future Arctic marine ecosystems.

6. Summary

To understand the relationships between hydrographic conditions and settling particle fluxes, time series sediment traps were deployed annually and interannually at NAP Station and at CAP12t on the shelf slope of the western Chukchi Sea, from October 2010 to September 2014. Although the resulting data were limited to 4 years, the influence of hydrographic conditions on settling particle flux in the Chukchi Borderland was obvious. The trapped settling particles contained a great deal of shelf-origin materials. At NAP Station, many maxima of settling particle fluxes corresponded to passing events of oceanic eddy advections along the oceanic Beaufort Gyre. When the oligotrophic surface water of the Canada Basin covered the Chukchi Borderland in 2012, the settling particle flux did not increase at NAP Station, although it did increase at CAP12t in March 2013, as a reflection of the westward transportation of warm Pacific water on the shelf, rather than its vertical transport of in situ biological production. These lateral advections of reworked organic matter are able to support benthos and nekton in downstream areas, and meaning that further monitoring and model prediction will be important to come to an understanding of alterations in Arctic marine ecosystems.

Author's contribution

JO: analysis of total mass, C, N, opal, field work for mooring deployment and recovery

EW: input as physical oceanographer

MI: supply of CT and WH sensors and their data, and Fig. 8b

NH: PI, comments to this ms

MCH: ICP element analysis of NAP10t samples

AT: supply of Aanderaa & Xylem sensors and their data for NAP13t, and Fig. 8c

YT: supply of Nichiyu equipment, comment on particle transport

TK: supply of CT data (CAP12t), and cruise logistics, field work for mooring deployment and recovery

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Table titles and figure captions

Table 1. Deployment summary for sediment trap moorings. Time of sampled duration is 00:00 AM (UTC). Trap depths are means of moored depths during deployment.

Table 2. Moored equipment at Stations NAP10t-13t and CAP12t.

Table 3. Major events in passing oceanic eddies estimated for current data of NAP13t (Kawaguchi, 2017, Pers. Comm. for events #1–4).

Figure 1. Map of research area with schematic of major surface ocean currents based on Corlett and Pickart (2017). Abbreviations for geographic features follow. CAP: Chukchi Abyssal Plain, CS: Chukchi Spur, NAP: Northwind Abyssal Plain, and NWR: Northwind Ridge. Bathymetry data are from the International Bathymetric Chart of the Arctic Ocean (Jakobsson et al., 2012).

Figure 2. Climate Forecast System Reanalysis (CFSR) reanalysis data (Saha et al., 2010) for downward shortwave radiation at sea surface (or on snow/sea ice) and sea ice concentration at NAP and CAP Stations for the entire deployment period, with measured ice thickness for the deployment period for NAP13t. (a) Shortwave radiation, (b) sea ice concentration (line), and sea ice thickness (shade) for NAP13t.

Figure 3. Progressive daily current vector at depths of 50 m, 100 m, ~170 m, and ~210 m at NAP13t from September 10, 2013 (starting point), to September 16, 2014 (respective ending points). The dots on each line represent the first day of each month, from October 2013 to September 2014.

Figure 4. Daily means for hydrographic data from NAP13t and CAP12t. (a)–(c) Temperature and salinity with moored depth of CT sensors of NAP13t. Color of depth curve shows water mass group in the Chukchi Sea (Corlett and Pickart, 2017). (d) East–west current speed and (e) north–south current speed. Arrows represent the period of major event on oceanic eddy detection. (f) Temperature and salinity at top buoy (~90 m depth) of CAP12t. Color bar shows water mass group (Corlett and Pickart, 2017).

Figure 5. Time series fluctuation of moored sediment trap depths and settling particle fluxes at NAP10t-13t. (a) and (b) daily means of moored sediment trap depths and (c) TMF for shallower and deeper sediment traps.

Figure 6. Time series fluctuation of particulate organic carbon (POC) and particulate nitrogen (PN) at NAP10t-13t. (a) Daily settling flux for POC, (b) daily settling flux for PN, (c) mole ratio for C/N, (d) stable carbon isotope ratio for POC, and (e) stable nitrogen isotope ratio for PN. The shallow trap data are shown in gray, and those of deep trap are in black. The short bars under (a) show periods of temporal mass occurrence of gelatinous matters (Fig. 7).

Figure 7. The photograph of recovered sediment trap samples containing abundant gelatinous matters (mainly Appendicularian house) from NAP13t in July 30 – August 12, 2014. (a) the sample of shallow trap, and (b) the sample of deeper trap. The scale bar = 1cm.

Figure 8. Daily means of turbidity, signal strengths of ADCP, and TMF at NAP13t. (a) Turbidity at depths of 25 m and 170 m: note unit differences. (b) Acoustic signal strength of ADCP WH300, (c) acoustic signal strength of ADCP deployed at depths of ~170 m, and (d) TMF in logarithm. Black bar at top of panel indicates that current speed exceeded 20 cm/s at 170 m depth. The larger dB of acoustic backscattered intensity shows relatively abundant particle concentration.

Figure 9. Time series fluctuations of settling particle flux at ~265 m depth for CAP12t. (a) TMF, (b)

POC flux, (c) PN flux, (d) C/N ratio, (e) stable carbon isotope ratio for POC, (f) stable nitrogen isotope ratio for PN, (g) PIC flux, and (h) biogenic opal flux. The short bar under (b) shows period of temporal mass occurrence of gelatinous matters (Fig. 7).

Supplementary Table 1. The dataset used in this study. There are six spread sheets including used data. It will be archived in the Arctic Data archive System (ADS, https://ads.nipr.ac.jp/).