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Observations of marine snow and fecal pellets in a sediment trap mooring in the northern South China Sea

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Abstract
Sediment traps are an important tool for studying the source, composition and sedimentation processes of sinking particulate matter in the ocean. An *in situ* observational mooring (TJ-A-1) is located in the northern South China Sea (20.05°N, 117.42°E) at a water depth of 2 100 m and equipped with two sediment traps deployed at 500 m and 1 950 m. Samples were collected at 18-day intervals, and 20 samples were obtained at both depths from May 2014 to May 2015. Large amounts of fecal matter and marine snow were collected in the lower trap. The fluxes of marine snow and fecal pellets exhibited a fluctuating decrease between May 2014 and early August 2014 and then stabilized at a relatively low level. Scanning electron microscopy observations revealed that the main components of the marine snow and fecal pellets were diatoms, coccolithophores, radiolarians, and other debris, all of which are planktons mostly produced in photic zone. Used in conjunction with the particle collection range estimates from the lower trap and data on ocean surface chlorophyll, these marine snow and fecal pellets were related to the lateral transport of deep water and not vertical migrations from overlying water column. Moreover, the source area might be southwest of Taiwan.

Key words: northern South China Sea, sediment trap, marine snow, fecal pellets

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1 Introduction

Sediment traps consist of a broad funnel with a collecting jar at the bottom and are used to capture sinking particles in a water column, and they are intended to be used not only to quantify the flux of organic and inorganic particles in oceans and lakes but also to serve as collectors for sinking particle samples for chemical and physical analyses (Chen and Jin, 2013). Sediment traps are mainly free floating, neutral floating and moored (Honjo and Doherty, 1988; Valdes and Price, 2000). Among them, deep sea moored time-series sediment traps are the most widely used. This kind of trap can automatically change the sample cup at a preset sampling time and interval while underwater and continuously record changes in sedimentation from a few weeks to several years, thereby realizing high temporal and spatial resolution of sedimentation particle sampling (Chen et al., 2015).

Marine particulate matter can record information on physical, chemical and biological processes within the ocean during formation, change, and settling. The collection and measurement of sedimentary particles at different depths from different water environments and studying the source, composition, temporal and spatial changes in particulate matter and controlling factors, as well as sea surface physical and chemical conditions, play important roles in the study of modern marine sediments and biogeochemical processes (Chen and Jin, 2013). Marine snow and zooplankton feces are packaged and sink rapidly, and they are considered important components of rapid particulate flux in the sea (Longhurst and Harrison, 1988; Sun et al., 2016). Marine snow is a very common and widespread phenomenon in the ocean and refers to organic aggregates >500 μm in size (Alldredge and Silver, 1988; Simon et al., 2002). Marine snow contains many types of particles that originate from a variety of sources, including diatoms, dinoflagellate flocs, fecal aggregates, and a variety of miscellaneous debris (Alldredge, 1998). As one of the food sources for pelagic organisms, marine snow has received extensive attention (Silver and Gowing, 1991; Turner, 2002). After feeding on phytoplankton or other organisms, zooplankton produce particulate excreta known as fecal pellets, which are common particulate organic matter in seawater (Sun et al., 2016). Different components of zooplankton communities produce different types and sizes of fecal pellets (Turner, 2015). Due to their large size and high density, zooplankton excrete fecal matter with a sinking rate that can reach tens to hundreds of meters per day (Turner, 2002). However, the estimated sinking particulate carbon fluxes contributed by recognizable zooplankton fecal pellets are highly variable (Ducklow et al., 2001; Dubischar and Bathmann, 2002). Sediment traps can be used to collect sedimentation particles at different depths and observe the sinking processes of marine snow and fecal pellets from the sea surface to the deep sea (Matsueda et al., 1986; Sampei et al., 2009).

In recent decades, the study of sediment traps in the South China Sea (SCS) has mainly focused on the variation in opal fluxes, particle fluxes, and total organic carbon fluxes (Chen et al., 1998, 2000, 2015); plankton species diversity, including foraminifera, coccolithophore and diatoms, and productivity variations (Lin et al., 2005; Wan et al., 2010; Xiang et al., 2015); terrigenous fluxes and their sources (Zhang et al., 2014, 2018); and

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^{210}Pb and ^{234}Th isotope geochemistry measurements (Chung et al., 2004, Hung and Gong, 2010). Particulate matter research in the SCS has mainly focused on fluxes and constituents, and relatively few studies have focused on the mechanisms of rapid sinking in the ocean. Reports have shown that fine-grained sediments derived from Taiwan's rivers are transported to the mooring site evaluated in this study through potential deep water currents (Liu et al., 2010, 2016). These deep water currents are believed to potentially trap and transport sediments from source areas southwestward and finally release them in the deep basin of the SCS (Zhao et al., 2015). In this study, samples of marine snow and fecal pellets were collected from sediment traps in the northern SCS, and they provided important information for elucidating the rapid sinking process of particulate matter and determining the movement of deep water masses. Our research also provides further evidence for lateral transportation in the northern SCS.

2 Materials and methods

2.1 *Sediment trap moorings*

A subsurface mooring system was deployed at Station TJ-A-1 in the northern South China Sea (20.05°N, 117.42°E, 2 100 m water depth; Zhang et al., 2014; Zhao et al., 2015) (Fig. 1), on which two traps with sampling areas of 0.5 m^2 were arranged at water depths of 500 m and 1 950 m. The samples used in this study were all taken from the lower trap (1 950 m) and collected from May 2014 to May 2015. Samples were collected at 18-day intervals, and there were 20 samples collected in total. Each collection cup was filled with filtered seawater containing a 3.33 g/L $HgCl_2$ and 33.3 g/L NaCl solution for poisoning and sample preservation during deployment and after recovery.

2.2 *Fecal pellets and marine snow analyses*

In the laboratory, samples were wet-sieved through a 1 mm-mesh screen to remove swimmers which entered the collection cups actively. The smaller size fractions (<1 mm) was evenly divided into four parts with a rotary splitter for different research. One aliquot was used for this research. The samples were sieved with 63 μm sieve and then dried at temperatures below 40°C.

Flocculent marine snow and particulate matter were separated under a stereomicroscope in dried samples. Additionally, particles recognizable as fecal pellets were counted per sample under a stereomicroscope. Pellet shapes and sizes were used to determine general zooplankton group. Cylindrical pellets are generally produced by large copepods, decapods and euphausiids (Yoon et al., 2001). Elliptical fecal pellets are attributed to appendicularians and are characterized by slightly pointed on both ends (Sampei et al., 2009; Wilson et al., 2013; Miquel et al., 2015).

The mass of marine snow was weighed using an electronic balance with a precision of one milligram. Additionally, the marine snow weight was divided by the weight of the fraction of sample to show the mass percentage of marine snow, and this process was also performed for the fecal pellets.

Randomly selected intact pellets and dissected pellets for the identification of contents were prepared for electron microscopy by fixing them on a glass slide with an optically photosensitive gum. The marine snow was prepared for electron microscopy by directly fixed onto conductive tape, coated with gold. Marine snow and fecal pellets were photographed under the scanning electron microscope (Quanta 650 FEG).

3 Results

The presence of fecal pellets was observed in each of the lower trap samples. Most of them were elliptical and a few had irregular shapes. The surfaces of the complete fecal pellet were regular and smooth. The fecal pellets were dark gray and uneven in size and had a diameter of approximately 0.1–0.2 mm and an aspect ratio of approximately 2–5.

Scanning electron microscope pictures showed fecal pellets in detail (Fig. 2a). Large amounts of fragments of coccolithophorids (Figs 2b, c) and various types of broken diatoms (Fig. 2d) were visible within the fecal pellets. Peritrophic membranes formed by

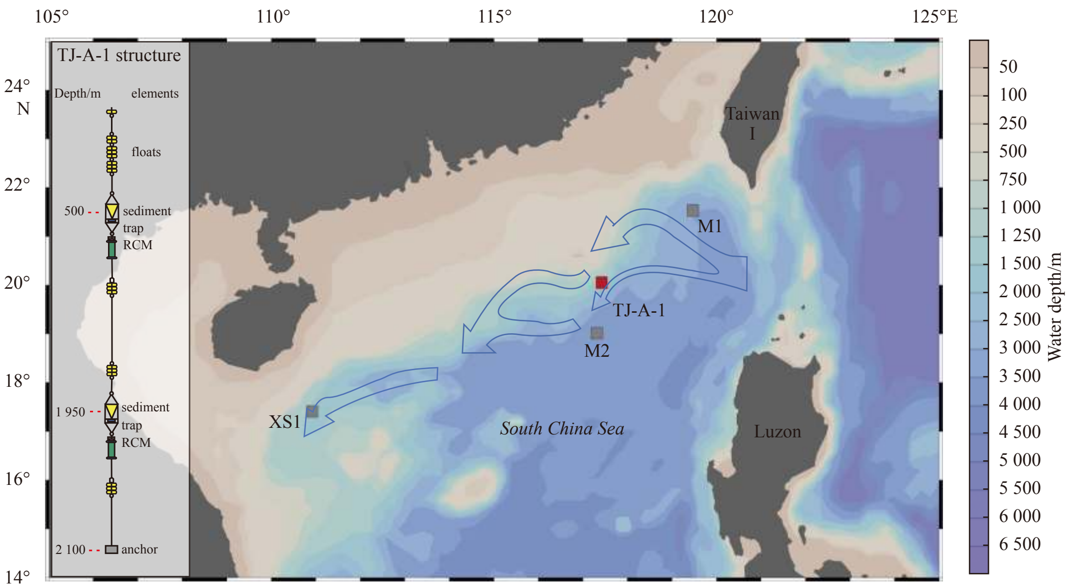

Fig. 1. Location of sediment traps TJ-A-1 (red square, this study), XS1, M1 and M2 (gray squares) in the northern SCS (Chung et al., 2004; Liu et al., 2014) and the vertical structure of the mooring sediment trap (Zhao et al., 2015). The blue arrows indicate the SCS contour current (Qu et al., 2006; Zheng and Yan, 2012).

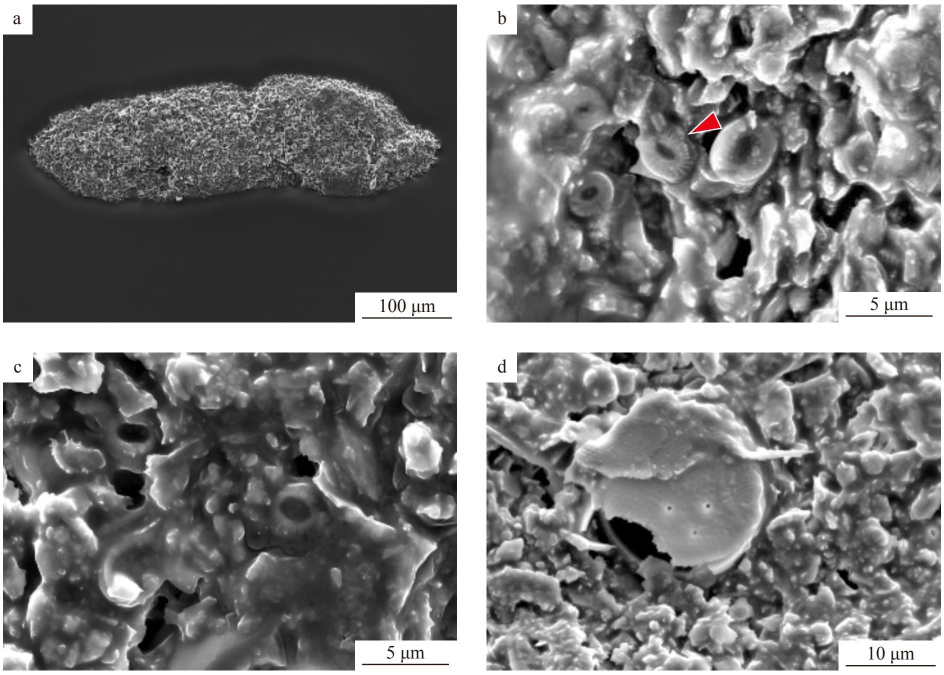

Fig. 2. Images of fecal pellets. a. Intact fecal pellet; b. dissected fecal pellet, with the red arrow indicating a coccolithophorid; c. peritrophic membranes on the surface of a fecal pellet; d. broken diatoms in the fecal pellet.

organic matter could also be observed on the surface of fecal pellets (Fig. 2c). Based on the shape and size of the fecal pellets, elliptical fecal pellets were found to be produced by appendicularians (Sampei et al., 2009; Wilson et al., 2013; Miquel et al., 2015).

The marine snow in the trap was light grayish brown, flocculent and amorphous. It contained various types of plankton debris, diatoms (Figs 3a, b), foraminifera (Fig. 3c), radiolarian (Fig. 3d). Diatoms accounted for a dominant position, mainly included *Coscinodiscus*, *Nitzschia*, *Bacteriastrum*, *Chaetoceros*, *Thalassionema* and so on. Most of the diatoms in marine snow was broken and less well-preserved based on the scanning electron microscopy results.

Both vertical flux of fecal pellets in pellets number and marine snow flux were high variable and showed that there was a certain correlation between them during the collection time. The most apparent temporal trend in marine snow flux was distinct

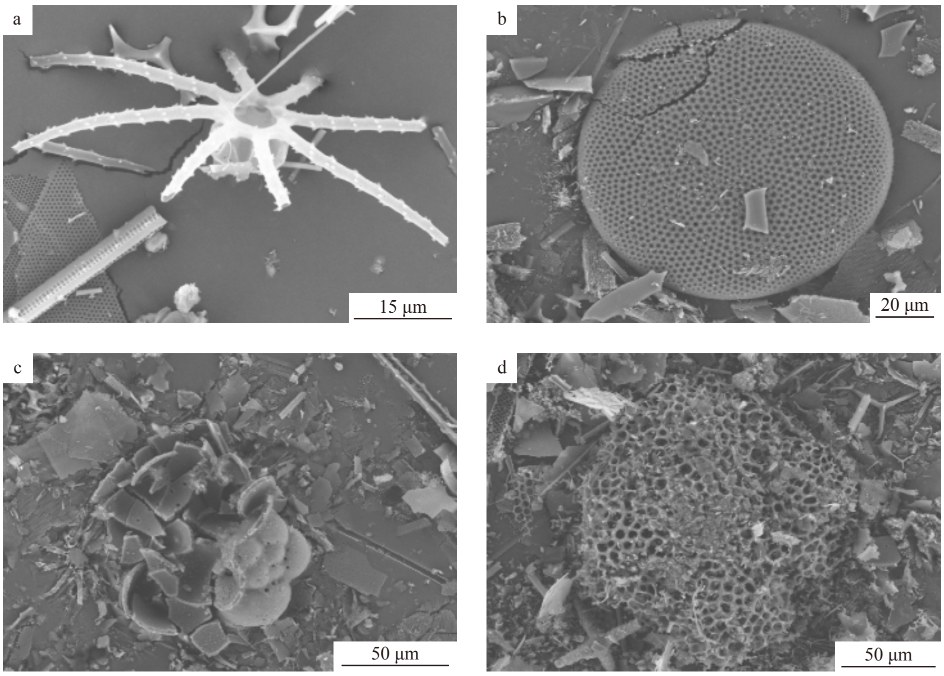

Fig. 3. Scanning electron microscopy images of marine snow. a. *Bacteriastrum* (Diatom); b. *Coscinodiscus* (Diatom); c. foraminifera; d. radiolarian.

variation (Fig. 4a). Marine snow flux was high at the end of May 2014 reaching its highest value of approximately 13.00 mg m^{-2}d^{-1}. From the end of May 2014 to August 2014, the marine snow flux rapidly decreased to 0.78 mg/(m^2·d), and it then gradually increased from the end of September to mid-October 2014; however, the flux fluctuated by approximately 0.45–3.89 mg/(m^2·d).

Fecal pellet flux displayed a similar pattern to marine snow flux. From May 2014 to May 2015, fecal pellet flux varied considerably through the year, from a maximum of 17.0 pellets m^{-2}·d^{-1} to a minimum of 0 pellets m^{-2}·d^{-1} (Fig. 4b). The highest fecal pellet flux was recorded at the end of May 2014, and the lowest value occurred in September 2014. From the end of May 2014 to the end of September 2014, it essentially exhibited a rapid decline from 17.0 pellets m^{-2}·d^{-1} to 0 pellets m^{-2}·d^{-1}, and until May 2015, fecal pellet flux fluctuated between 0 and 4 pellets m^{-2}·d^{-1}. The overall trend of the fecal pellet flux, especially during the rapid decline from May to September 2014, was highly consistent with the changes in the flux of marine snow.

The ratio of marine snow to sample weight was relatively high from May to early August 2014 and accounted for more than 60%. Meanwhile, the mass percentage was relatively low during the rest of the year (Fig. 4c). The sample collected at the end of September had a higher ratio because the sample weight was below the precise measurement sensitivity. For the fecal pellets, the value obtained by dividing the amount by the weight of the samples was also high from May to August 2014 and lower for the rest of the time period (Fig. 4d).

4 Discussion

4.1 *Lateral transport of marine snow and fecal pellets*

Marine snow and fecal pellets are formed in the upper seawater, and as an important part of the biological pump (Longhurst and Harrison, 1988), their formation and changes are closely related to the life cycles of phytoplankton and zooplankton in the ocean. On the west coast of Sweden, during a diatom bloom, the number of diatoms increased significantly and the contact between them increased. The rapid aggregation and sedimentation of the bloom made it possible to observe that the in situ concentration of marine snow had reached a peak (Tiselius and Kuylenstierna, 1996). Moreover, during the diatom bloom, the fecal pellet carbon fluxes in the sediment also increased. Graf (1989) concluded that a pulse of fecal pellets from the copepods accounted for 92% of the total carbon settling to the deep North Atlantic at the end of a spring bloom in May. According to the results of Station TJ-A-1, we can roughly divide the obtained data into two periods: the higher flux from May to early August 2014 and the lower flux in the rest of the year. However, between May 2014 and May 2015 in the traps at Station TJ-A-1 in the northern SCS, marine snow and fecal pellets were found in only the bottom sediment trap (1 950 m), even other planktons including planktonic foraminifera and pteropods were commonly found in the upper sediment trap (500 m) (Huang, unpublished data). If the marine snow and fecal pellets in the bottom sediment trap are from the in situ vertical settlement as indicated by previous results (Alldredge and Silver, 1988; Simon et al., 2002; Turner, 2002), then marine snow and fecal pellets should also be found in the upper sediment trap. However, this hypothesis is not consistent with the actual observations from Station TJ-A-1. In addition, the area where the sediment trap was placed, the concentration of chlorophyll a (*Chl* a) in the surface seawater was not at a high level while marine snow and fecal pellets were not observed in the upper sediment trap at Station TJ-A-1. Therefore, the sources of the bottom marine sediments are mainly due to horizontal transport rather than in situ vertical sinking.

Higher total particle flux (TPF) at greater depths in the northern SCS imply that lateral inputs are strong. At site XS1 (17°24.5′N, 110°55.0′E, Fig.1), TPF averaged 111 mg/(m^2·d) at 500 m water depth, while at 1 500 m water depth, TPF averaged 418 mg/(m^2·d), which was about four times that in the upper layer trap (Liu et al., 2014). At site M1 (21°32′N, 119°28′E), mean TPF increased from 284 mg/(m^2·d) at 248 m depth to 486 mg/(m^2·d) at 948 m water

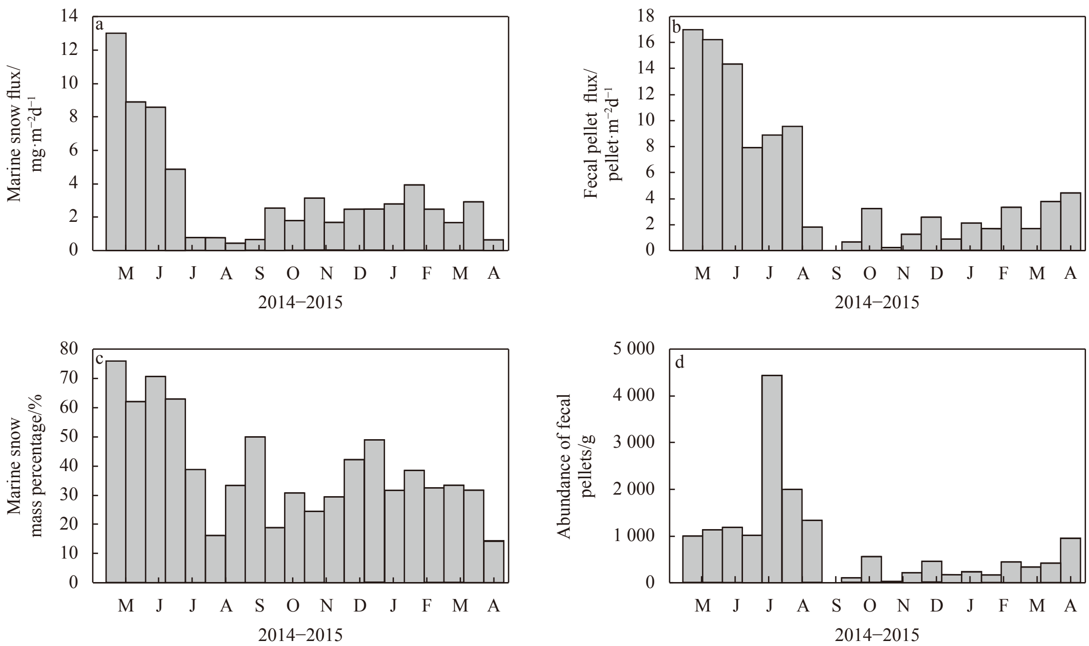

Fig. 4. a. Marine snow flux; and b. fecal pellet flux during 2014 and 2015 in the deep layer at Station TJ-A-1; c. mass percentage of marine snow; d. abundance of fecal pellets.

depth, and continuously increased to 554 mg/(m²·d) at 2 848 m water depth (Chung et al., 2004). Similarly at site M2 (19°01′N, 117°32′E) average TPF increased from about 200 mg/(m²·d) to 260 mg/(m²·d), corresponding to depths from 1 240 m to 3 230 m (Chung et al., 2004). Higher TPF at greater water depths could be explained by lateral sediment transport by contour current which is defined as the along-slope component of the deep water current (Fig 1, Zheng and Yan, 2012). Station TJ-A-1 was also located on/around a major current route, whose sediment may be a mixture from vertical and horizontal transportation. In addition, the clay mineral compositions obtained from station TJ-A-1 confirmed that tremendous amounts of sediment derived from Taiwan are transported southwestward to the northwestern SCS (Liu et al., 2016).

Reports have shown that contour currents are important transport and sedimentary phenomena that control a majority of deep-sea sedimentation (Rebesco et al., 2014). Equipped with an Acoustic Doppler Current Profiler (ADCP), the sediment trap at the mooring system TJ-A-1 yielded a continuous time-series of current velocity (zonal velocity and meridional velocity). Then, the sub-inertial along-slope and cross-slope velocities (u and v) were obtained. According to the contour direction and velocity from September, 2011 to May 2013, the velocity of the contour current generally varied in the range of –5 to 3 cm/s, and the dominant direction of the deep current was ~250° to true north (Zhao et al., 2015). The suspended sediment concentrations were generally low during intervals of northeastward flows because the Taiwanese rivers were the major sources of fine sediment to the region (Liu et al., 2010, 2016; Zhang et al., 2014; Zhao et al., 2015). Reflection seismic profiles indicate that there were some active NE–SW direction bottom current channels on the northern continental slope of the SCS, which led to the accumulation of discontinuous drifts. Moreover, these drifts propagated southwestward following the direction of the bottom currents (Shao et al., 2007). The marine snow and fecal pellets in the samples of the bottom sediment trap at Station TJ-A-1 may have been brought by the northeast contour current.

4.2 *Estimate of source regions*

Waniek et al. (2000) provided a calculation method for evaluating the effects of horizontal advection and particle sinking speed on particle fluxes as measured by moored sediment traps. The results showed that the distance and direction between a given sediment trap and the region where the particles were produced depends on the mean sinking velocity of the particles, the horizontal velocity field above the trap and the deployment depth of the trap (Waniek et al., 2000). In this study, since in situ data were not available at Station TJ-A-1, the velocities of horizontal advection at depths of 100, 400, 1 700, and 2 000 m (Zhao et al., 2015; Yang et al., 2008) were selected from the northern SCS (Table 1). The velocity of each water layer used was obtained by averaging the velocity of the upper and lower depths. We selected only the current velocity data in the dominant direction of the deep water current for calculation. Using the above method, the trajectories of particulate matter collected by the 1 950 m layer sediment trap at Station TJ-A-1 were calculated.

Table 1. Monthly average velocities used in our calculations

Water depth/m	Monthly average velocity/cm·s^{-1}	Source
100	31.01	Yang et al., 2008
400	17.37	Yang et al., 2008
1 700	1.57	Zhao et al., 2015
2 000	2.13	Zhao et al., 2015

Sinking rates of marine snow and fecal pellets were related to their composition (Alldredge and Silver, 1988; Turner, 2002). And diatoms dominated in our marine snow and fecal pellet samples. As the peaks in fecal pellet carbon fluxes were accompanied by similar peaks in diatoms were found in sediment traps located in the eastern Fram Strait showing that diatoms sank at a similar speed to appendicularian fecal pellets (Lalande et al., 2016). In addition, the sinking velocity of the diatom-related particles at the site SCS-N (18.5°N, 116°E) from the sea surface to the deep SCS was estimated to be ~30–50 m/d by comparing the surface chlorophyll abundance and species of diatoms in sediment traps at depths of 1 003 m and 3 226 m (Ran et al., 2015). The position of the SCS-N site was close to that of Station TJ-A-1. Therefore, if the variation in sedimentation velocity due to the increase in depth during sedimentation was not considered, then the time required to reach the 1 950 m depth from the seawater surface was estimated to be approximately 40–66 days. Given that typical sinking speed of large particles is considered to be a constant 50 m/d, we calculated the sediment source distance in the northeast direction that could be collected by the 1 950 m trap. As the depth of the deployed trap increases, the range of source distance of particulate matter that the trap can collect increases. At the position of the sediment trap TJ-A-1, the maximum lateral displacement between the origin at the sea surface and the trap deployed at 2 000 m was greater than 400 km (Fig. 5).

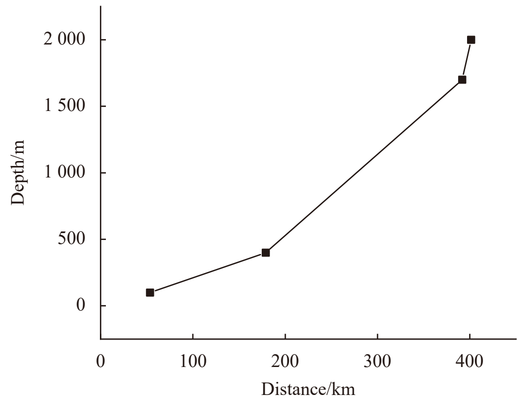

Fig. 5. Range of source distance of particulate matter that the trap can collect in the northeast direction.

The sea surface Chl *a* concentration data monthly were derived from the MODIS (Moderate Resolution Imaging Spectroradiometer) database in the areas between 15°N to 25°N and 107°E to 122°E, with a spatial resolution of 4 km×4 km. The Chl *a* concentration was used as an indicator of sea surface productivity. We compared the monthly Chl *a* concentration data from March 2014 to May 2015, and found that in April and May 2014, there was a significant area of high Chl *a* concentration off the southwestern shore of Taiwan, which was approximately 3 mg/m³ (Fig. 6). In addition, Chen et al. (2016) calculated the ten-year (2003-2012) median timing of the annual Chl *a* concentration climax in East Asian marginal seas. The results suggested that the peak time of diatom blooms in the southwestern part of Taiwan is during April of each year. This region is also located within the distance range where the particle matters was produced. Therefore, we speculated that marine snow and fecal pellets formed in large quantities during the diatom blooms around April and May, and after a period of time, they were packed and sank from the light

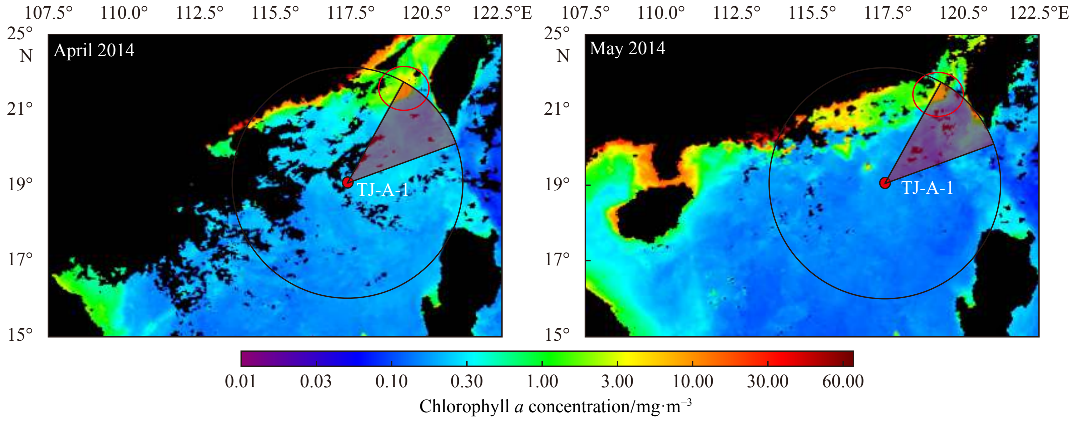

Fig. 6. Chlorophyll *a* concentrations in the northern South China Sea during April and May 2014. The sector area represents the most likely source area.

transmission layer of the ocean to the deep ocean. These particles were then transported from the southwest of Taiwan by the northeast contour current to the northern SCS, and they were collected by the deep-layer sediment trap at Station TJ-A-1. The whole process of marine snow settlement, transportation and collection occurred over 2 months.

5 Conclusions

The fecal pellets were mostly elliptical and a few had irregular shapes, which are presumably the result of them being produced by appendicularians. The fecal pellets contained many fragments of coccolithophorids and diatoms. Electron microscopy observations showed that the marine snow was a gray-brown amorphous flocculent dominated by diatoms and containing pieces of radiolarians, coccolithophorids, diatoms, and foraminifera. During the study period from May 2014 to May 2015, the fluxes of marine snow and fecal pellets in the bottom sediment trap at Station TJ-A-1 in the northern SCS reached an annual peak from May to early August 2014, and it declined rapidly during that period of time. After early August 2014, the changes in the fluxes of marine snow and fecal pellets tended to be stable. The ratios of marine snow weight or fecal pellet number to the sample weights were relatively high from May to early August 2014, and the percentage was relatively low for the rest of the year.

Marine snow and fecal pellets were produced in the photic zone of the ocean and sank rapidly and were transported to the bottom of the ocean with a large amount of organic matter. A comparison of this information with observations from the upper-layer trap from the same station showed that the marine snow and fecal pellets in the bottom trap were not from in situ vertical settlement but rather were transported by deep contour currents. We calculated the distance range that could be produced by the bottom sediment trap collection. A comparison of the time and area of the diatom bloom in the northern SCS during the spring of 2014 indicated that the increase in marine snow and fecal pellets from May to July 2014 in the TJ-A-1 bottom trap may coincide with the spring diatom bloom off the southwestern coast of Taiwan during April and May of the same year.

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References

Alldredge A. 1998. The carbon, nitrogen and mass content of marine snow as a function of aggregate size. Deep Sea Research Part I: Oceanographic Research Papers, 45(4–5): 529–541, doi: 10.1016/S0967-0637(97)00048-4

Alldredge A L, Silver M W. 1988. Characteristics, dynamics and significance of marine snow. Progress in Oceanography, 20(1): 41–82, doi: 10.1016/0079-6611(88)90053-5

Chen Jianfang, Chen Ronghua, Wiesner M G, et al. 2000. Amino acids amino sugars and carbohydrates in settling planktonic tests and their implications for the South China Sea. Oceanologia et Limnologia Sinica (in Chinese), 31(6): 596–603

Chen Liumei, Jin Zhangdong. 2013. A review of sediment trap techniques and their applications for understanding of settling particle in lakes and oceans. Journal of Earth Environment (in Chinese), 4(3): 1346–1354

Chen Cheng, Mao Zhihua, Han Guoqi, et al. 2016. Latitudinal and interannual variations of the spring phytoplankton bloom peak in the East Asian marginal seas. Acta Oceanologica Sinica, 35(12): 81–88, doi: 10.1007/s13131-016-0867-0

Chen Jianfang, Wiesner M G, Li Hongliang, et al. 2015. Biogeochemical fluxes and biological pump composition in the South China Sea. Bulletin of Mineralogy, Petrology and Geochemistry (in Chinese), 34(5): 911–919

Chen Jianfang, Zheng Lianfu, Wiesner M G, et al. 1998. Estimations of primary production and export production in the South China Sea based on sediment trap experiments. Chinese Science Bulletin, 43(7): 583–586, doi: 10.1007/BF02883645

Chung Y, Chang H C, Hung G W. 2004. Particulate flux and ^{210}Pb determined on the sediment trap and core samples from the northern South China Sea. Continental Shelf Research, 24(6): 673–691, doi: 10.1016/j.csr.2004.01.003

Dubischar C D, Bathmann U V. 2002. The occurrence of faecal material in relation to different pelagic systems in the Southern Ocean and its importance for vertical flux. Deep Sea Research Part II Topical Studies in Oceanography, 49(16): 3229–3242, doi: 10.1016/S0967-0645(02)00080-2

Ducklow H W, Steinberg D K, Buesseler K O. 2001. Upper ocean carbon export and the biological pump. Oceanography, 14(4): 50–58, doi: 10.5670/oceanog.2001.06

Graf G. 1989. Benthic-pelagic coupling in a deep-sea benthic community. Nature, 341(6241): 437–439, doi: 10.1038/341437a0

Honjo S, Doherty K W. 1988. Large aperture time-series sediment traps; design objectives, construction and application. Deep Sea Research Part A. Oceanographic Research Papers, 35(1): 133–149, doi: 10.1016/0198-0149(88)90062-3

Hung C C, Gong G C. 2010. POC/^{234}Th ratios in particles collected in

sediment traps in the northern South China Sea. Estuarine, Coastal and Shelf Science, 88(3): 303–310, doi: 10.1016/j.ecss.2010.04.008
Lalande C, Nöthig E M, Bauerfeind E, et al. 2016. Lateral supply and downward export of particulate matter from upper waters to the seafloor in the deep eastern Fram Strait. Deep Sea Research Part I: Oceanographic Research Papers, 114: 78–89, doi: 10.1016/j.dsr.2016.04.014
Lin Huiling, Liu J T, Hung Gwowei. 2005. Foraminiferal shells in sediment traps: Implications of biogenic particle transport in the Kao-ping submarine canyon, Taiwan. Continental Shelf Research, 25(18): 2261–2272, doi: 10.1016/j.csr.2005.09.001
Liu Jianguo, Clift P D, Yan Wen, et al. 2014. Modern transport and deposition of settling particles in the northern South China Sea: Sediment trap evidence adjacent to Xisha Trough. Deep Sea Research Part I: Oceanographic Research Papers, 93: 145–155, doi: 10.1016/j.dsr.2014.08.005
Liu Zhifei, Colin C, Li Xiajing, et al. 2010. Clay mineral distribution in surface sediments of the northeastern South China Sea and surrounding fluvial drainage basins: Source and transport. Marine Geology, 277(1–4): 48–60, doi: 10.1016/j.margeo.2010.08.010
Liu Zhifei, Zhao Yulong, Colin C, et al. 2016. Source-to-sink transport processes of fluvial sediments in the South China Sea. Earth-Science Reviews, 153: 238–273, doi: 10.1016/j.earscirev.2015.08.005
Longhurst A R, Harrison W G. 1988. Vertical nitrogen flux from the oceanic photic zone by diel migrant zooplankton and nekton. Deep Sea Research Part A. Oceanographic Research Papers, 35(6): 881–889, doi: 10.1016/0198-0149(88)90065-9
Matsueda H, Handa N, Inoue I, et al. 1986. Ecological significance of salp fecal pellets collected by sediment traps in the eastern North Pacific. Marine Biology, 91(3): 421–431, doi: 10.1007/BF00428636
Miquel J C, Gasser B, Martín J, et al. 2015. Downward particle flux and carbon export in the Beaufort Sea, Arctic Ocean; the role of zooplankton. Biogeosciences, 12(16): 5103–5117, doi: 10.5194/bg-12-5103-2015
Qu Tangdong, Girton J B, Whitehead J A. 2006. Deepwater overflow through Luzon Strait. Journal of Geophysical Research: Oceans, 111: C01002
Ran Lihua, Chen Jianfang, Wiesner M G, et al. 2015. Variability in the abundance and species composition of diatoms in sinking particles in the northern South China Sea: Results from time-series moored sediment traps. Deep Sea Research Part II: Topical Studies in Oceanography, 122: 15–24, doi: 10.1016/j.dsr2.2015.07.004
Rebesco M, Hernández-Molina F J, Van Rooij D, et al. 2014. Contourites and associated sediments controlled by deep-water circulation processes: State-of-the-art and future considerations. Marine Geology, 352: 111–154, doi: 10.1016/j.margeo.2014.03.011
Sampei M, Forest A, Sasaki H, et al. 2009. Attenuation of the vertical flux of copepod fecal pellets under Arctic sea ice: evidence for an active detrital food web in winter. Polar Biology, 32(2): 225–232, doi: 10.1007/s00300-008-0523-z
Shao Lei, Li Xuejie, Geng Jianhua, et al. 2007. Deep water bottom current deposition in the northern South China Sea. Science in China Series D: Earth Sciences, 50(7): 1060–1066, doi: 10.1007/s11430-007-0015-y
Silver M W, Gowing M M. 1991. The "particle" flux: Origins and biological components. Progress in Oceanography, 26(1): 75–113, doi: 10.1016/0079-6611(91)90007-9
Simon M, Grossart H P, Schweitzer B, et al. 2002. Microbial ecology of organic aggregates in aquatic ecosystems. Aquatic Microbial Ecology, 28(2): 175–211
Sun Jun, Li Xiaoqian, Chen Jianfang, et al. 2016. Progress in oceanic biological pump. Haiyang Xuebao (in Chinese), 38(4): 1–21
Tiselius P, Kuylenstierna M. 1996. Growth and decline of a diatom spring bloom phytoplankton species composition, formation of marine snow and the role of heterotrophic dinoflagellates. Journal of Plankton Research, 18(2): 133–155, doi: 10.1093/plankt/18.2.133
Turner J T. 2002. Zooplankton fecal pellets, marine snow and sinking phytoplankton blooms. Aquatic Microbial Ecology, 27: 57–102, doi: 10.3354/ame027057
Turner J T. 2015. Zooplankton fecal pellets, marine snow, phytodetritus and the ocean's biological pump. Progress in Oceanography, 130: 205–248, doi: 10.1016/j.pocean.2014.08.005
Valdes J R, Price J F. 2000. A neutrally buoyant, upper ocean sediment trap. Journal of Atmospheric and Oceanic Technology, 17(1): 62–68, doi: 10.1175/1520-0426(2000)017<0062:ANBUOS>2.0.CO;2
Wan Sui, Jian Zhimin, Cheng Xinrong, et al. 2010. Seasonal variations in planktonic foraminiferal flux and the chemical properties of their shells in the southern South China Sea. Science China Earth Sciences, 53(8): 1176–1187, doi: 10.1007/s11430-010-4039-3
Waniek J, Koeve W, Prien R D. 2000. Trajectories of sinking particles and the catchment areas above sediment traps in the northeast Atlantic. Journal of Marine Research, 58(6): 983–1006, doi: 10.1357/002224000763485773
Wilson S E, Ruhl H A, Smith K L Jr. 2013. Zooplankton fecal pellet flux in the abyssal northeast Pacific: A 15 year time-series study. Limnology and Oceanography, 58(3): 881–892, doi: 10.4319/lo.2013.58.3.0881
Xiang Rong, Liu Jianguo, Wang Dongxiao, et al. 2015. Seasonal flux variability of planktonic foraminifera during 2009-2011 in a sediment trap from Xisha Trough, South China Sea. Aquatic Ecosystem Health & Management, 18(4): 403–413
Yang Qingxuan, Liang Xinfeng, Tian Jiwei, et al. 2008. Observation on the current in the northern South China Sea and spectrum analysis. Oceanologia et Limnologia Sinica (in Chinese), 39(6): 561–566
Yoon W D, Kim S K, Han K N. 2001. Morphology and sinking velocities of fecal pellets of copepod, molluscan, euphausiid, and salp taxa in the northeastern tropical Atlantic. Marine Biology, 139(5): 923–928, doi: 10.1007/s002270100630
Zhang Yanwei, Liu Zhifei, Zhao Yulong, et al. 2014. Mesoscale eddies transport deep-sea sediments. Scientific Reports, 4(1): 5937
Zhang Yanwei, Liu Zhifei, Zhao Yulong, et al. 2018. Long-term in situ observations on typhoon-triggered turbidity currents in the deep sea. Geology, 46(8): 675–678, doi: 10.1130/G45178.1
Zhao Yulong, Liu Zhifei, Zhang Yanwei, et al. 2015. *In situ* observation of contour currents in the northern South China Sea: Applications for deepwater sediment transport. Earth and Planetary Science Letters, 430: 477–485, doi: 10.1016/j.epsl.2015.09.008
Zheng Hongbo, Yan Pin. 2012. Deep-water bottom current research in the Northern South China Sea. Marine Georesources & Geotechnology, 30(2): 122–129