**Revision Note on the revised manuscript, Sinking fate and carbon export of zooplankton fecal pellets: insights from time-series sediment-trap observations in the northern South China Sea (by Wang et al.), manuscript no. bg-2023-112, submitted for publication in Biogeosciences.**

We would like to thank two anonymous referees for their positive feedback and thoughtful comments concerning our manuscript. We have revised our manuscript in response to all the comments, and we sincerely hope the editor and referees will be satisfied with our revision. This Revision Note is written based on the annotated (using track changes) version of the manuscript (uploaded in the system). Below, the notes (in blue) explain how and where each point of comment has been addressed. The line numbers mentioned are new numbers in the annotated version of the manuscript.

**RC1: 'Comment on bg-2023-112', Anonymous Referee #1, 31 Jul 2023**

Review of a manuscript by H. Wang et al. entitled: "Sinking fate and carbon export of zooplankton fecal pellets: insights from time-series sediment trap observation in the northern South China Sea" submitted to Biogeosciences.

This is an interesting manuscript, which should become acceptable for publication after minor English editing. Suggestions for editing are listed below by line number.

**Reply:** Thank you for your effort reviewing our manuscript and your positive feedback, which have helped to improve the quality of the manuscript. We have read through all the comments carefully and have made related modifications. We highly appreciate your time and consideration.

**Comment #1:**
2: in the title, change "time-series sediment trap observation" to "time-series sediment-trap observations" and hyphenate all other double-word adjectives

**Reply:** We thank you for this correction. We have changed "time-series sediment trap observation" to "time-series sediment-trap observations" in Line 2 and hyphenated all other more-than-one-word adjectives in Lines 11, 69, 71, 130, 147, 160–161, 164–165, 190, 200, 211, 216, 231, 234, 246, 278, 286, 333, 383, 393, 404, 418, and 429 in the revised manuscript. For example, this is how I modified Line 2: *Sinking fate and carbon export of zooplankton fecal pellets: insights from time-series sediment-trap observations in the northern South China Sea*

**Comment #2:**
11: hyphenate "fecal-pellet-numerical (FPN) flux" and "fecal-pellet-carbon (FPC) flux" and hyphenate all other more-than-one-word adjectives

**Reply:** Thank you for this comment. As the reply to Comment #1, we have hyphenated "fecal-pellet-numerical (FPN) flux", "fecal-pellet-carbon (FPC) flux", and all other more-than-one-word adjectives in Lines 2, 11, 69, 71, 130, 147, 160–161, 164–165, 190, 200, 211, 216, 231, 234, 246, 278, 286, 333, 383, 393, 404, 418, and 429 in the revised manuscript. For example, this is how I modified Line 11: *The results show a seasonal variability in both fecal-pellet-numerical (FPN) flux and fecal-pellet-carbon (FPC) flux, with peaks in November to April and June to August.*

**Comment #3:**
80: change "Hydrological system" to "The hydrological system"

**Reply:** Thank you for pointing out this problem. We have changed "Hydrological system" to "The hydrological system" in Line 118-119 in the revised manuscript. Here's how I modified it: *The hydrological system of the northern SCS is complex due to the seasonal shift of the East Asian monsoon winds and the interplay of waters from the Kuroshio Current (Su, 2004; Caruso et al., 2006).*

**Comment #4:**
84: change "Combination" to "A combination"

**Reply:** Thank you for this comment. We have changed "Combination" to "A combination" in Line 123 in the revised manuscript. Here's how I modified it: *A combination of strong winter winds, water mixing, and surface cooling in the northern SCS drives winter convective overturning, leading to higher primary productivity during the winter monsoon than during other periods (Liu et al., 2002; Chen, 2005; Tseng et al., 2005).*

**Comment #5:**
165: delete "of"

**Reply:** Thank you for raising this question. We have deleted "of" in Line 205 in the revised manuscript. Here's how I modified it: *The major elements composing the fecal pellets were O, Si, C, and Ca, with minor proportions of Al and K, indicating that terrigenous minerals such as quartz and clay minerals may also be important components of fecal pellets (Figs. 4h, 5b).*

**Comment #6:**
Figures 4 and 5: the micrographs are too dark, with no contrast. If these had been taken using film and printed in a darkroom (as in the past) I would have used a different F-stop to take the micrographs, and different F-stops and contrast filters to print these photos. I do not know how to do this now, using digital photography, but these micrographs need to be re-taken.

**Reply:** We are grateful to you for pointing out this problem. We have adjusted the brightness and contrast of the photographs in Figures 4 and 5. We hope this correction meet your requirements.

**Comment #7:**
239: change "Besides," to "However,"

**Reply:** Thank you for this comment. We have changed "Besides," to "However," in Line 284 in the revised manuscript. Here's how I modified it: *However, the negative linear relationship was weaker at 1970 m compared to 500 m.*

**Comment #8:**
243: change "5 Discussions" to "5 Discussion"

**Reply:** Thank you for the advice. We have changed "5 Discussions" to "4 Discussion" in Line 307 in the revised manuscript. Here's how I modified it: *4 Discussion*

**Comment #9:**
246: change "The FPC flux" to "The FPC flux was"

**Reply:** We are so sorry for the incorrect writing here. We have changed "The FPC flux" to "The FPC flux was" in Line 311 in the revised manuscript. Here's how I modified it: *The FPC flux was also elevated, and the average flux during this period was 2 to 4 times higher than the average flux over the whole deployment period (Fig. 10b).*

**Comment #10:**
263: change "though in the oligotrophic seas" to "although in oligotrophic seas"

**Reply:** Thank you for this comment. We have changed "though in the oligotrophic seas" to "although in oligotrophic seas" in Line 328 in the revised manuscript. Here's how I modified it: *Therefore, although in oligotrophic seas, the monsoon system can increase the primary productivity, which allows for increased zooplankton biomass and promotes the export of carbon from their fecal pellets.*

**Comment #11:**
278: change "this additional nutrient" to "these additional nutrients"

**Reply:** Thank you for your suggestion. We have modified the sentence in Lines 344–346 in the revised manuscript. Here's how I modified it: *Summer precipitation can bring terrestrial organic matter from land into the ocean, resulting in the increased POC fluxes. These organic matters can also serve as a nutrient supply, contributing to the marine surface productivity, thus increasing zooplankton biomass and FPC fluxes (Fig. 10b; Meyers, 1997; Vizzini et al., 2005; Chen et al., 2017).*

**Comment #12:**
297: change "literatures," to "literature,"

**Reply:** Thank you for this advice. We have changed "literatures," to "literature," in Line 367 in the revised manuscript. Here's how I modified it: *According to the literature, ellipsoidal pellets could be attributed to copepods, pteropods, appendicularia, and larvae (González et al., 1994, 2004; Wilson et al., 2008; Wexels Riser et al., 2010; Gleiber et al., 2012).*

**Comment #13:**
309: change "number" to "amount"

**Reply:** Thank you for your constructive suggestion. We have changed "number" to "amount" in Line 380 in the revised manuscript. Here's how I modified it: *Therefore, it is likely that a large amount of fecal pellet production still occurs in the mesopelagic/bathypelagic zones to increase the export of fecal pellets to the deep sea, and these fecal pellets are characterized by strong cycling within the water column.*

**Comment #14:**
317: change "fecal pellet" to "fecal pellets"

**Reply:** Thank you for raising this question. We have changed "fecal pellet" to "fecal pellets" in Line 388 in the revised manuscript. Here's how I modified it: *Analysis of the internal composition of fecal pellets identified the presence of terrigenous minerals like quartz and clay minerals, with an elemental composition characterized primarily by O, Si, C, Ca, Al, and K (Figs. 4, 5).*

**Comment #15:**
322: hyphenate "laterally transported"

**Reply:** We are grateful to you for reviewing the manuscript so carefully. We have hyphenated "laterally transported" in Line 393 in the revised manuscript. Here's how I modified it: *Previous studies have demonstrated an increasing deep-sea POC flux in the northern SCS due to laterally-transported terrestrial organic carbon (Blattmann et al., 2018, 2019; Zhang et al., 2022).*

**Comment #16:**
323: hyphenate "highly-adaptable"

**Reply:** Thank you for this comment. We have hyphenated "highly adaptable" in Line 404 in the revised manuscript. Here's how I modified it: *This highly-adaptable species, which is widespread throughout the northern SCS and found in all water layers (Gong et al., 2017),* *and may play a critical role in fecal pellet fragmentation.*

**Comment #17:**
334: change “may play” to “and may play”

**Reply:** We feel sorry for our carelessness. We have changed “may play” to “and may play” in Line 405 in the revised manuscript. Here’s how I modified it: *This highly-adaptable species is widespread throughout the northern SCS in all water layers (Gong et al., 2017), and may play a critical role in fecal pellet fragmentation.*

**Comment #18:**
336: change “at K2 station” to “at Station K2”

**Reply:** Thank you for pointing out this problem. We have changed “at K2 station” to “at Station K2” in Line 407 in the revised manuscript. Here’s how I modified it: *Similarly, studies conducted at station K2 also provided evidence of fecal pellet fragmentation by repackaging of mesopelagic sinking debris (Wilson et al., 2008).*

**Comment #19:**
352: change “form the larger aggregate.” to “form larger aggregates.”

**Reply:** Thank you for this advice. We have changed “form the larger aggregate.” to “form larger aggregates.” in Line 423 in the revised manuscript. Here’s how I modified it: *Phytoplankton cells, zooplankton moults, and fecal pellets together form larger aggregates.*

**Comment #20:**
353: change “basin” to “basins”

**Reply:** Thank you for the comment. We have changed “basin” to “basins” in Line 425 in the revised manuscript. Here’s how I modified it: *Presence of deep-dwelling zooplankton communities and lateral inputs from the slope into the deep basins tend to increase the export of fecal pellet to the deep sea.*

**Comment #21:**
358: hyphenate “hydrodynamically-induced”

**Reply:** We are grateful to you for reviewing the manuscript so carefully. We have hyphenated “hydrodynamically induced” in Line 429 in the revised manuscript. Here’s how I modified it: *The evolving picture regarding the sinking fate of fecal pellets is therefore a coupling between the surface PP, repackaging and fragmentation by mesopelagic and bathypelagic zooplankton, lateral input by deep-sea currents and hydrodynamically-induced fragmentation.*

**Comment #22:**
394: change "twice higher" to "twice as high"

**Reply:** Thank you for this advice. We have changed "twice higher" to "twice as high" in Line 465 in the revised manuscript. Here's how I modified it: *Zooplankton fecal pellet fluxes were twice as high at 1970 m than at 500 m.*

**Comment #23:**
478: italicize "Oithona"

**Reply:** We feel sorry for our carelessness. We have italicized "Oithona" in Line 553 in the revised manuscript. Here's how I modified it: *González, H. E. and Smetacek, V.: The possible role of the cyclopoid copepod Oithona in retarding vertical flux of zooplankton fecal material, Mar. Ecol. Prog. Ser., 113, 233–246, https://doi.org/10.3354/meps113233, 1994.*

**Comment #24:**
478, 480, 484, 490: change "Gonzalez" to "González"

**Reply:** Thank you very much for pointing out the error here. We have changed "Gonzalez" to "González" in Lines 553, 555, 559, and 565 in the revised manuscript. For example, this is how I modified Line 555: *González, H. E., Daneri, G., Iriarte, J. L., Yannicelli, B., Menschel, E., Barria, C., Pantoja, S., and Lizarraga, L.: Carbon fluxes within the epipelagic zone of the Humboldt Current System off Chile: The significance of euphausiids and diatoms as key functional groups for the biological pump, Prog. Oceanogr., 83, 217–227, 1 https://doi.org/10.1016/j.pocean.2009.07.036, 2009.*

**Comment #25:**
503: change "Paffenhofer" to "Paffenhöfer"

**Reply:** We are very grateful to you for reviewing the manuscript so carefully. We have changed "Paffenhofer" to "Paffenhöfer" in Line 578 in the revised manuscript. Here's how I modified it: *Koster, M., Sietmann, R., Meuche, A., and Paffenhöfer, G. A.: The ultrastructure of a doliolid and a copepod fecal pellet, J. Plankton. Res., 33, 1538–1549, https://doi.org/10.1093/plankt/fbr053, 2011.*

**RC2: 'Comment on bg-2023-112', Anonymous Referee #2, 28 Sep 2023**

This is all in all a well written and interesting article, providing new insights into fecal pellet fluxes and their contribution in POC export in the northern SCS. Very nice figures, photographs of pellets, and generally thorough and very well explained text. I have minor comments and adjustments that should be addressed before publication.

**Reply:** We really appreciate your time and efforts to provide a detailed review. We would like to thank you for your valuable and constructive comments that have been so helpful to improve the manuscript.

**Comment #1:**
Title: This is the only place in the manuscript that "time-series" sediment traps are mentioned. Sediment trap details (Producer, etc.) missing from the Materials and Methods section.

**Reply:** Thank you very much for pointing out this problem. To better highlight the concept of "time-series" sediment trap samples, we have changed "sediment traps" to "time-series sediment traps" in Lines 9, 78–79, 129, 148, 190, 200, 211, 216, 231, 246, 278, 286, 304, 333, 383, 418, and 432 in the revised manuscript. For example, this is how I modified Line 9 in the abstract: *Here, we analysed zooplankton fecal pellets collected by two time-series sediment traps deployed on mooring TJ-A1B in the northern South China Sea (SCS) from May 2021 to May 2022.*

In addition, we have added detailed information of sediment traps in the "Material and Methods" section in Line 148 in the revised manuscript. Here's how I modified it: *Samples were collected by time-series sediment traps (McLane Parflux Mark78H-21 sediment trap) deployed on mooring TJ-A1B (20.06°N, 117.39°E, 2000 m water depth) in the northern SCS (Fig. 1).*

**Comment #2:**
Line 19: "by marine surface productivity" - this paper does not outline directly marine surface productivity, especially as shallowest trap is at 500 m. Recommend to focus on the papers findings in the abstract.

**Reply:** Thank you for raising this question. We have changed "by marine surface productivity" to "by primary productivity" in Line 19 in the revised manuscript. To investigate the environmental factors regulating the sinking and export of fecal pellets, we downloaded daily net primary production (PP) data of biomass expressed as carbon per unit volume in sea water from the Operational Mercator Ocean biogeochemical global ocean analysis and forecast system (https://data.marine.copernicus.eu/product/GLOBAL_ANALYSIS_FORECAST_BIO_001_028). Strong northeast monsoon and surface water cooling led to the mixing of the upper water column, importing nutrients from subsurface into the epipelagic layer, stimulating phytoplankton growth and increasing FPC flux in winter. As shown in Figure 10, significantly higher concentrations of productivity in winter corresponded to high POC fluxes and FPC fluxes. Therefore, we suggest that primary productivity is one of the important factors regulating the sinking fate of zooplankton fecal pellets in the northern South China Sea. The significance of primary productivity is mentioned in the abstract.

Here’s how I modified it: *This study highlights that the sinking fate of fecal pellets is regulated by primary productivity, deep-dwelling zooplankton community, and deep-sea currents in the tropical marginal sea, thus providing a new perspective for exploring the carbon cycle in the world ocean.* We hope this correction meet your requirement.

**Comment #3:**
Line 22: change “a process” with “a collection of processes” or similar. The BCP is not one process but a collection of many processes (correctly used in line 24).

**Reply:** Thank you for pointing out this problem. The BCP is indeed a collection of many processes. Therefore, we agree to the comment and replaced “a process” with “a collection of processes” in Line 23 in the revised manuscript. Here’s how I modified it: *The marine biological carbon pump (BCP) is a collection of processes whereby marine organisms mediate the transfer of carbon from the atmosphere to the deep ocean.*

**Comment #4:**
Line 27: Sentence starting with “As a key process” - consider rewording. Is it the zooplankton fecal pellets that reduced dissolution and degradation, or the zooplankton themselves that do by packaging the material into feral pellets that are harder to degrade? Also, fecal pellets themselves are not a process, so consider wording.

**Reply:** Thank you for this correction. We think it’s the zooplankton themselves that package the material into fecal pellets that are harder to degrade. We agree with you in pointing out that fecal pellets themselves are not a process. Therefore, we have modified this sentence by following your suggestion in Lines 28–29 in the revised manuscript. Here’s how I modified it: *As a key process of the BCP, zooplankton feed on phytoplankton and other materials and pack them into fecal pellets, thereby reducing the dissolution and degradation of organic matter during the sinking process and subsequently increase the particle sinking flux in the mesopelagic and bathypelagic zones (Wilson et al., 2008; Turner, 2015).*

**Comment #5:**
Line 32: first mention of amorphous pellets – define or mention that these are mostly fragmented pellets.

**Reply:** Thank you for the comment, we have defined amorphous fecal pellets in Line 34 in the revised manuscript. Here’s how I modified it: *Several studies have revealed that the concentration of fecal pellets in the deep sea is significantly lower compared to the production rate of fecal pellets in the surface waters, and the presence of amorphous fecal pellets (mostly fragmented pellets) has been observed, indicating significant consumption during the sinking process (Juul-Pedersen et al., 2006; Wilson et al., 2008; Goldthwait and Steinberg, 2008; Kobari et al., 2010, 2016; Stukel et al., 2013; Miquel et al., 2015).*

**Comment #6:**

Line 36: define or explain coprorhexy, coprophagy and coprochaly if mentioned.

**Reply:** Thank you for the comment, we have defined coprorhexy, coprophagy and coprochaly in Lines 37–39 in the revised manuscript. Here's how I modified it: *Noji et al. (1991) categorized copepod behaviour in fecal pellet consumption into three different types: coprorhexy (fragmentation of fecal pellets), coprophagy (ingestion of fecal pellets), and coprochaly (loosening of fecal pellets).*

**Comment #7:**
Line 40: "may affect the POC export" - remove "the"; define/explain efficiency of the BCP otherwise it is difficult for reader to understand.

**Reply:** Thank you for your constructive suggestion. In order to be able to give the reader a better understanding, we have removed "the" and explained the "efficiency of the BCP" in Lines 44–46 in the revised manuscript. Here's how I modified it: *The efficiency of the BCP depends on the carbon export flux and the retention of remineralized carbon in the deep ocean. As a key component of the carbon cycle, fragmentation, decomposition, and repackaging of fecal pellets may affect POC export and regulate the efficiency of the BCP.*

**Comment #8:**
Line 41: you introduce studies focusing on biogeochemical mechanisms but the rest of the paragraph describes FP fluxes with depth, which is not a biogeochemical mechanism. Consider rewording.

**Reply:** We apologize for the inappropriate expression here. Thank you for the advice. The point of this paragraph is to illustrate that numerous studies on fecal pellets have focused on their production, sinking, degradation, and recycling processes. Previous studies have found that changes in fecal pellet characteristics and fluxes at different depths can serve as an indicator of zooplankton behaviour. As a ubiquitous component of sinking particles, the numerical and carbon flux of fecal pellet in the water column is influenced by multiple factors, including zooplankton community structures, marine dynamic processes, and even bacterial activities. Therefore, we have revised the sentence in Lines 47–48 and added a more detailed interpretation in Lines 49–50 to discuss the variation trend of FP fluxes with depth, which requires specific analysis in different ocean regions. Here's how I modified it: *Numerous studies have been conducted in the global ocean to explore the production, sinking, degradation, and recycling processes of zooplankton fecal pellets (González et al., 2000; Gleiber et al., 2012; Belcher et al., 2017; Le Moigne, 2019). Changes in the characteristics and fluxes of fecal pellets at varying depths can be utilized as an indicator of zooplankton behaviour (Wilson et al., 2008).* We hope this correction meet your requirements.

**Comment #9:**
Line 42: avoid use of the word "obvious". Reword to "clear" or other words that are less

definite. Please consider changing or removing this word throughout the manuscript (e.g. lines 281 and 285).

**Reply:** Thank you for your comment, we have checked out the manuscript and changed all the "obvious" to "clear" in Lines 50, 349, and 353 in the revised manuscript. For example, this is how I modified Line 50: *Previous studies have observed clear differences in fecal pellet flux with increasing water depth, mostly showing a decreasing trend (Viitasalo et al., 1999; Wexels Riser et al., 2007).*

**Comment #10:**
General introduction: Perhaps mention active flux / zooplankton mediated injection pump (Boyd et al. 2019 *Nature*).

**Reply:** Thank you for this helpful suggestion. The carbon export of organic particles in the ocean is not only dependent on gravitational settling, but "particle injection pumps" also contribute to the increase in deep-sea carbon export flux. Diurnal vertical migration behaviour of zooplankton can directly transport carbon from epipelagic zones to mesopelagic and bathypelagic zones, by passing rapid remineralization zone. zooplankton mediated injection pump is indeed an important mechanism for BCP to drive carbon storage in the deep ocean. Therefore, we have added zooplankton mediated injection pump and added relevant reference (Boyd et al. 2019 *Nature*) in Lines 42–44 in the revised manuscript. Here's how I modified it: *In addition, diurnal vertical migration results in active subsurface transport, and thus, zooplankton mediated injection pump is considered an important mechanism for BCP to increase deep-sea carbon export flux (Boyd et al., 2019).*

**Comment #11:**
Line76/ "2. Study Area": Nice summary, but this should be part of the Methods (2.1) instead of its own section?

**Reply:** Thank you for your advice. We have moved "2. Study Area" to "2.1 Study area" in Material and Methods section in Lines 115–145 in the revised manuscript.

**Comment #12:**
Section 2.1 Sediment trap deployment: Information lacking about the sediment traps. No make/producer. Also, why was a different concentration of fixative added to the different trap depths? If this is common practice, please provide reference.

**Reply:** Thank you for raising this question. We have added detailed information of sediment traps in the "Material and Methods" section in Line 148 in the revised manuscript. Here's how I modified it: *Samples were collected by time-series sediment traps (McLane Parflux Mark78H-21 sediment trap) deployed on mooring TJ-A1B (20.06°N, 117.39°E, 2000 m water depth) in the northern SCS (Fig. 1).*

Prior to deployment of the sediment traps, we added mercury chloride to the sample bottles in order to retard microbial activity in the trapped material. There are significantly more particles such as phytoplankton, zooplankton and microorganisms in the UP trap at 500 m, so more mercury chloride should be used, resulting in different concentration of fixative added to the different trap depths. Our group has been deploying sediment traps in the South China Sea for 12 years, and this method has been used well. The addition of different concentrations of mercury chloride has proved to be very necessary in favor of better preservation of the samples, as used in articles such as Li et al., 2022; Blattmann et al., 2018, 2019. We hope this reply meet your requirement.

**Comment #13:**
Section 4. Results: Hydrological results missing from the results section. Since it is outlined in methods and included in figures in the discussion, a brief results section is missing. Lines 248–253 could be considered as results instead of discussion.

**Reply:** Thank you for pointing out this problem. Because the hydrological parameters are outlined in methods and included in figures in the discussion, their data results are necessary to be presented. We agree to the comment and added "3.4 Hydrological conditions" section in Lines 289–306 in the revised manuscript. Here's how I modified it: *Southwest winds prevailed in the study area from June to September and northeast winds from late October to May (Fig. 9a). During the observation period, wind speed ranged from 0.2 to 19.8 m $s^{-1}$. Wind speed was low during the inter-monsoon period (6.4 ± 3.2 m $s^{-1}$) and increased in late October, reaching up to 8–10 m $s^{-1}$ in winter (Fig. 9a). Sea surface temperature (SST) varied between 24 to 31°C, with an average of 27 ± 2°C, and showed distinct seasonal variation (Fig. 9b). SST was generally high during summer and autumn (>28°C), declined continuously after November, reaching a minimum (24°C) in January and March. Mixed layer depth (MLD) ranged from 11 to 95 m, with an average value of 35 ± 22 m (Fig. 9c). MLD was typically shallow (<40 m) during spring and summer, increased in autumn and reached its maximum (95 m) in late December (Fig. 9c). Primary productivity (PP) varied between 4 to 34 mg $m^{-3}$ $d^{-1}$ with an average value of 12 ± 6 mg $m^{-3}$ $d^{-1}$ (Fig. 9d). PP showed a weak peak in December (25 mg $m^{-3}$ $d^{-1}$) and a strong peak in February. Precipitation ranged from 0 to 32 mm $d^{-1}$ with an average value of 3 mm $d^{-1}$ (Fig. 9e). Precipitation throughout the year was concentrated in June-October (7 ± 8 mm $d^{-1}$), with a maximum value occurred in August and low precipitation during winter (1 ± 2 mm $d^{-1}$). Sea water velocity fluctuated throughout the year (0.01–0.38 m $s^{-1}$), averaging 0.17 ± 0.07 m $s^{-1}$ (Fig. 9f). The maximum value occurred during the winter monsoon period.*

**Comment #14:**
Line 154: "significantly different between two depths" - how so? Which depth was darker? Or Refer to Fig. 3

**Reply:** We are so sorry for the incorrect writing here. There was no significant difference in the color of fecal pellets between two depths. We have deleted this part of the sentence in

Lines 193–194 in the revised manuscript. Here's how I modified it: *Fecal pellets were often brown in appearance.*

**Comment #15:**
Lines 176–184: Where there any size/biovolume changes across seasons (i.e. were they smaller or bigger on average during certain times of the year?)

**Reply:** Thank you for raising this question. We checked at the data and found that the seasonal variation in fecal pellet biovolume at 1970 m was not significant. Changes in the biovolume of fecal pellets across seasons were observed at 500 m. The biovolume of ellipsoidal, cylindrical and spherical pellets was higher on average in June-August and December-February, and the biovolume of amorphous pellets was elevated in December-April. We have added the corresponding contents in Lines 226–228 in the revised manuscript. Here's how I modified it: *At 500 m, the average biovolume of ellipsoidal, cylindrical, and spherical pellets was higher in June-August and December-February and those of amorphous pellets was elevated from December to April. Whereas, at 1970 m, the seasonal variation in biovolume for all shape was not significant.*

**Comment #16:**
Lines 191–192: Which months had minimum and maximum? "… from a minimum of 216 pellets m-2 d-1 in __(month)__, to a max..__(month). Was it the same for both depths?

**Reply:** Thank you for the question. The minimum value of FPN flux at 500 m was in May and the maximum value was in December. Whereas, the minimum value of FPN flux at 1970 m was in October and the maximum value was in May. The months corresponding to the two depths are not the same. We have added the months corresponding to the minimum and maximum values of fluxes in Lines 235–237 in the revised manuscript. Here's how I modified it: *FPN flux varied considerably throughout the year, from a minimum of 216 pellets* $m^{-2}$ $d^{-1}$ *in May to a maximum of 2518 pellets* $m^{-2}$ $d^{-1}$ *in December at 500 m, while at 1970 m, this value spanned a range of 597–4573 pellets* $m^{-2}$ $d^{-1}$*, with the minimum value occurring in October and the maximum in May.*

**Comment #17:**
Line 246: "of the total POC flux", consider changing to "of the total annual POC flux"

**Reply:** We agree to the comment and changed "of the total POC flux" to "of the total annual POC flux" in Line 310 in the revised manuscript. Here's how I modified it: *The POC flux during this period constituted over 75% of the total annual POC flux (Fig. 10a).*

**Comment #18:**
Line 278: "this additional nutrient" - terrestrial OM is not just bring in one additional nutrient so this sentence is slightly confusing to read. Consider rewording.

**Reply:** Thank you for pointing out this issue, and we apologize for any confusion caused by this unclear expression. Terrestrial OM can directly supplement POC fluxes, resulting in an increase in POC fluxes. Meanwhile, these organic matters can also act as a nutrient supply to promote marine primary productivity, resulting in increased zooplankton biomass and elevated FPC fluxes. We have modified the sentence in Lines 344–346 in the revised manuscript. Here's how I modified it: *Summer precipitation can bring terrestrial organic matter from land into the ocean, resulting in the increased POC fluxes. These organic matters can also serve as a nutrient supply, contributing to the marine surface productivity, thus increasing zooplankton biomass and FPC fluxes (Fig. 10b; Meyers, 1997; Vizzini et al., 2005; Chen et al., 2017).*

**Comment #19:**
Line 283: "southwestern Taiwan have been transported" - how sure are you of their origin? Perhaps change to "are likely transported" or similar.

**Reply:** Thank you for the valuable comment. It is true that there is no direct evidence of their origin, but it is still a possibility. We agree to the comment and changed "have been transported" to "are likely transported" in Line 351 in the revised manuscript. Here's how I modified it: *These fecal pellets from southwestern Taiwan are likely transported to the northern SCS by deep-sea currents, which coincided with the previously reported high FPC flux recorded in May 2014 (Gao et al., 2020).*

**Comment #20:**
Line 287: "Role of zooplankton repackage in fecal pellet export" - Repackage? Reworking? The grammar here doesn't make sense and hard to know what you mean. Consider rewording.

**Reply:** Thank you for pointing out this problem. We further investigated the literatures and learned how to express it clearly. We believe the word "repackaging" is more accurate (Wilson et al., 2008; Gleiber et al., 2012; Belcher et al., 2017). Thus, we have changed "repackage" to "repackaging" in Line 355 in the revised manuscript. Here's how I modified it: *4.2 Role of zooplankton repackaging in fecal pellet export*

**Comment #21:**
General section 5.2: Consider adding one sentence about uncertainty in using the same carbon conversion factor for the whole year and for all fecal pellet shapes and zooplankton producers. This could change the FPC export quite a bit, so worth a mention.

**Reply:** We think this is an excellent suggestion. Measurement of the carbon-volume conversion factor requires sufficient sample amount; however, there were insufficient numbers of fecal pellets in the samples. Therefore, we used the conversion factor of 0.036 mg C $mm^{-3}$ measured in the southern SCS (Li et al., 2022). Many fecal pellet studies used the same carbon: volume conversion factor for different types of fecal pellets (e.g., González and Smetacek, 1994; González et al., 2000; Wilson et al., 2008). Although using the same conversion factor, regardless of sampling season, site, water depth, and fecal pellet type, it can still provide adequate information of the fecal pellet carbon flux and its contribution to the overall POC flux. In fact, most of the fecal pellet studies didn't measure the carbon: volume conversion factor by themselves, but directly used the conversion factor from previous studies (e.g., Carroll et al., 1998; Shatova et al., 2012; Wilson et al., 2013). The reality is that this method is widely used in the phytoplankton and zooplankton fecal pellet research. We have added the sentences in Lines 358–361 in the revised manuscript. Here's how I modified it: *Admittedly, using the same carbon conversion factor for the whole year and for all fecal pellet shapes and zooplankton producers could lead to uncertainty. Despite this uncertainty, our data still provide adequate information on FPC flux and its contribution to total POC flux in the northern SCS.*

**Comment #22:**
Line 288: should read "repackaging by deep-sea dwelling zooplankton"

**Reply:** Thank you for the comment. We have changed "repackaging of deep-dwelling zooplankton" to "repackaging by deep-sea dwelling zooplankton" in Lines 356–357 in the revised manuscript. Here's how I modified it: *Assemblage of different types and sizes of fecal pellets varied with depth, providing an indication of the repackaging by deep-sea dwelling zooplankton in the water column (Wilson et al., 2008).*

**Comment #23:**
Line 344: "zooplankton grazing" - do you mean grazing here or reworking/fragmentation?

**Reply:** Thank you for pointing out this problem. We mean that zooplankton reworking (ingestion and other behaviours) and hydrodynamic changes combine to cause fragmentation of fecal pellets in the northern South China Sea. Therefore, we have changed "grazing" to "reworking" in Line 415 in the revised manuscript. Here's how I modified it: *Therefore, the fragmentation of fecal pellets in the northern SCS shows the joint effect of zooplankton reworking and hydrodynamic changes.*

**Comment #24:**
Line 350: change "variable" to "various"

**Reply:** Thank you for your comment, we have changed "variable" to "various" in Line 421 in the revised manuscript. Here's how I modified it: *In the northern SCS, various mechanisms affect the carbon export of zooplankton fecal pellets (Fig. 13).*

**Comment #25:**
Line 350: Here you use "euphotic zone" but in Figure 12 you use "Epipelagic". Be consistent.

**Reply:** Thank you for your advice. We have modified this throughout the manuscript. With these two words, we are trying to convey the same concept. Thus, for consistency with Figure 12, we have changed "euphotic" to "epipelagic" in Lines 25, 341, 378, 422, and 463 in the revised manuscript. For example, this is how I modified Line 25: *Marine organisms inhabiting the upper water column can fix atmospheric* $CO_2$ *through photosynthesis, producing particulate organic carbon (POC) in the epipelagic zone.*

**Comment #26:**
Line 355-356: "consumed and reworked by zooplankton grazing and strong hydrodynamic activities" seems to imply hydrological activities consume and rework the pellets. Consider changing to "consumed and reworked by zooplankton grazing and fragmented by strong hydrodynamic activities"

**Reply:** Thank you very much for raising this point. We agree to the comment and have modified this sentence following your suggestion in Line 427 in the revised manuscript. Here's how I modified it: *However, amorphous pellets are fragmented during the sinking process, indicating that surface-produced pellets are likely to be consumed and reworked by zooplankton grazing and fragmented by strong hydrodynamic activities.*

**Comment #27:**
Line 357: "repackaging", change to "repackaging and fragmentation"

**Reply:** Thank you for this constructive advice. We have changed "repackaging" to "repackaging and fragmentation" in Line 428 in the revised manuscript. Here's how I modified it: *The evolving picture regarding the sinking fate of fecal pellets is therefore a coupling between the surface primary production, repackaging and fragmentation by mesopelagic and bathypelagic zooplankton, lateral input by deep-sea currents and hydrodynamically-induced fragmentation.*

**Comment #28:**
Line 366: Remove "However," and switch sentence around to read "The contribution of fecal pellets to the total annual carbon flux was lower in the northern SCS compared to the southern SCS, possibly due to…"

**Reply:** Thank you for this comment. We removed "However," and switched sentence around to read "The contribution of fecal pellets to the total annual carbon flux was lower in the northern SCS compared to the southern SCS, possibly due to…" in Lines 437–439 in the revised manuscript. Here's how I modified it: *The contribution of fecal pellets to the total annual carbon flux was lower in the northern SCS compared to the southern SCS, possibly due to their higher degree of fragmentation and degradation (Li et al., 2022).*

**Comment #29:**
Line 369: Replace "biospheric" with "biogenic"

**Reply:** Thank you for this comment. We have replaced "biospheric" with "biogenic" in Line 440 in the revised manuscript. Here's how I modified it: *Even though 87% of the sinking POC in the northern SCS was from marine biogenic origin, the majority may have come from phytoplankton cells such as Prochlorococcus and Synechococcus, zooplankton moults, zooplankton carcasses, and large aggregates (Zhang et al., 2019, 2022).*

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# Sinking fate and carbon export of zooplankton fecal pellets: insights from time-series sediment-~~–~~trap observations in the northern South China Sea

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**Abstract.** The sinking of zooplankton fecal pellets is a key process in the marine biological carbon pump, facilitating the export of particulate organic carbon (POC). Here, we analysed~~analyzed~~ zooplankton fecal pellets collected by two time-series sediment traps deployed on mooring TJ-A1B in the northern South China Sea (SCS) from May 2021 to May 2022. The results show a seasonal variability in both fecal-~~–~~pellet-~~–~~numerical (FPN) flux and fecal-~~–~~pellet-~~–~~carbon (FPC) flux, with peaks in November to April and June to August. It implies that the fecal pellet flux is largely regulated by the East Asian monsoon system. Vertical analysis further shows that FPN and FPC fluxes are higher at 1970 m than at 500 m water depth, with larger pellets occurring in the deeper water, indicating a significant influence of mesopelagic/bathypelagic zooplankton community and lateral transport on deep-sea~~ fecal pellet carbon~~ FPC export. However, the biovolume of amorphous pellets decreases significantly from 500 m to 1970 m water depth, implying that these fecal pellets are broken and fragmented during the sinking process, possibly due to zooplankton grazing and disturbance by deep-sea currents. The contribution of fecal pellets to total POC export in the northern SCS is in average 3.4% and 1.9% at 500 m and 1970 m water depths, respectively. This study highlights that the sinking fate of fecal pellets is regulated by primary productivity~~marine surface productivity~~, deep-dwelling zooplankton community, and deep-sea currents in the tropical marginal sea, thus providing a new perspective for exploring the carbon cycle in the world ocean.

## 1 Introduction

The marine biological carbon pump (BCP) is a collection of processes whereby marine organisms mediate the transfer of carbon from the atmosphere to the deep ocean. Marine organisms inhabiting the upper water column can fix atmospheric $CO_2$ through photosynthesis, producing particulate organic carbon (POC) in the epipelagic~~euphotic~~ zone. Subsequently, a series of processes transport the POC, including phytoplankton cells, zooplankton fecal pellets, moults~~molts~~, carcasses, and aggregates, from surface to deeper layers of the ocean, representing a significant component of the global carbon cycle (Fowler and Knauer, 1986; Steinberg and Landry, 2017). As a key process of~~in~~ the BCP, zooplankton feed on phytoplankton and other materials and pack them into fecal pellets, thereby reducing ~~fecal pellets can reduce ~~the dissolution and degradation of organic matter during the sinking process and subsequently increase the particle sinking flux in the mesopelagic and bathypelagic zones (Wilson et al., 2008; Turner, 2015). During the sinking process, most zooplankton fecal pellets are susceptible to being ingested by other zooplankton or degraded by bacteria. Several studies have revealed that the concentration of fecal pellets in the deep sea is significantly lower compared to the production rate of fecal pellets in the surface waters, and the presence of amorphous fecal pellets (mostly fragmented pellets) has been observed, indicating significant consumption during the sinking process (Juul-Pedersen et al., 2006; Wilson et al., 2008; Goldthwait and Steinberg, 2008; Kobari et al., 2010, 2016; Stukel et al., 2013; Miquel et al., 2015). Copepods are the primary consumers of fecal pellets, with retention rates ranging from 30% to 98% (Svensen et al., 2012; Turner, 2015). Noji et al. (1991) categorized copepod behaviour~~behavior~~ in fecal pellet consumption into three different types: coprorhexy (fragmentation of fecal pellets), coprophagy (ingestion of fecal pellets), and coprochaly (loosening of fecal pellets). These processes are thought to reduce the carbon export of fecal pellets in the deep sea (Noji et al., 1991). However, the repackaging of larger zooplankton inhabiting the mesopelagic zones, accompanied by their in-situ production of large fecal pellets, may contribute to an increasing flux of deep-sea fecal pellets (Urrère and Knauer, 1981; Shatova et al., 2012; Manno et al., 2015; Belcher et al., 2017). In addition, diurnal vertical migration results in active subsurface transport, and thus, zooplankton mediated injection pump is considered an important mechanism for BCP to increase deep-sea carbon export flux (Boyd et al., 2019). The efficiency of the BCP depends on the carbon export flux and the retention of remineralized carbon in the deep ocean. As a key component of the carbon cycle, fragmentation, decomposition, and repackaging of fecal pellets may affect ~~the~~ POC export and regulate the efficiency of the BCP.

Numerous studies have been conducted in the global ocean to explore the ~~biogeochemical mechanisms of zooplankton fecal pellets during~~ production, sinking, degradation, and recycling processes of zooplankton fecal pellets (González et al., 2000; Gleiber et al., 2012; Belcher et al., 2017; Le Moigne, 2019). Changes in the characteristics and fluxes of fecal pellets at varying depths can be utilized as an indicator of zooplankton behaviour (Wilson et al., 2008). Previous studies have observed ~~obvious~~ clear differences in fecal pellet flux with increasing water depth, mostly showing a decreasing trend (Viitasalo et al., 1999; Wexels Riser et al., 2007). However, in certain regions, such as the Northeast Pacific, Mediterranean Sea, Sargasso Sea, and Southern Ocean, fecal pellet fluxes tend to increase in the deep layer (Urrère and Knauer, 1981; Fowler et al., 1991; Wassmann et al., 2000; Shatova et al., 2012; Manno et al., 2015; Belcher et al., 2017). This variation in the trend of fecal pellet flux with water depth is influenced by the composition of local zooplankton community and efficiency of the BCP. Different shapes and sizes of fecal pellets have different sinking rates, which contribute differently to the POC export (Wilson et al., 2008; Manno et al., 2015; Turner, 2015; Steinberg and Landry, 2017; Qiu et al., 2018). In the high-latitude eutrophic seas, fecal pellets tend to exhibit a high contribution to the total POC flux (Juul-Pedersen et al., 2006; Wilson et al., 2008; Manno et al., 2015). However, the contribution in the subpolar mesotrophic seas and low-latitude oligotrophic seas is significantly lower. Pilskaln and Honjo (1987) reported that fecal pellets account for less than 5–10% of sinking flux in tropical and subtropical regions. Taylor (1989) also reported that fecal pellets contribute a minimal fraction (6%) of the POC flux in the central North Pacific. Roman and Gauzens (1997) suggested that the contribution of fecal pellets to the total carbon flux was quite small in the tropical Pacific, and that most fecal pellets produced in the surface waters were ingested during sinking.

The South China Sea (SCS) is considered as an oligotrophic tropical sea and a source of $CO_2$ (Su, 2004; Cao et al., 2020). Owing to its unique geographical and physicochemical characteristics, the organic carbon flux and its regulatory processes in the SCS are subject to significant spatiotemporal variability. Previous studies have investigated the composition and flux of sinking POC in the northern and central SCS, which vary with the East Asian monsoon system. Notably, the peak occurrence of sinking POC has been observed during the northeast monsoon period (Chen et al., 1998; Liu et al., 2007; Li, H. et al., 2017; Zhang et al., 2019, 2022; Blattmann et al., 2018, 2019). Based on the C/N ratio and stable/radiocarbon-isotope analyses, the vertical vector of modern POC turns out to be 87% ± 4% of the sinking POC in the northern SCS, with the lateral vector accounting for the remaining 13% (Zhang et al., 2022). The contribution of laterally-supplied POC becomes more significant with increasing depth, which is largely derived from lithogenic organic carbon transported by the deep-sea currents and resuspension of slope sediments (Blattmann et al., 2018; Zhang et al., 2022). In the southern SCS, Li et al. (2022) conducted the first study of zooplankton fecal pellet characteristics, numerical fluxes, and carbon fluxes in the tropical marginal sea, showing that fecal pellets contribute 0.4–30.0% to the total POC flux. Despite the dominance of marine-origin organic carbon in sinking POC in the northern SCS, detailed studies of the rapidly sinking particles are sparse, and the contribution of fecal pellets to the total carbon flux remains uncertain. To better understand the efficiency and biogeochemical cycling of the BCP in the northern SCS, we collected sinking zooplankton fecal pellets from mesopelagic and bathypelagic waters using two time-series sediment traps to quantify the role of fecal pellets in POC export. By analysing analyzing the shape, quantity, internal composition, and carbon content of zooplankton fecal pellets, we gained more specific insights into the sinking fate of these pellets in tropical marginal seas and highlighted the importance of fragmentation during the sinking process in determining the carbon flux transferred to the deep sea.

## 2 Study area

The SCS is a large marginal sea with an area of about $3.5\times10^6$ km$^2$ and an average depth of about 1350 m (Wang and Li, 2009). The study area is located in the northern SCS, where a warm and humid southwest monsoon prevails in summer (June to August), while a dry and cold northeast monsoon prevails in winter (November to April) (Chu and Wang, 2003) (Fig. 1). The hHydrological system of the northern SCS is complex due to the seasonal shift of the East Asian monsoon winds and the interplay of waters from the Kuroshio Current (Su, 2004; Caruso et al., 2006). Surface circulation of the northern SCS also shows a seasonal shift from a large cyclonic gyre in winter to a weak cyclonic gyre in summer (Su, 2004). Contour currents have been found to dominate sediment transport processes on the deep-sea slope at 1600–2400 m water depth, transporting Taiwan-sourced sediments westward (Zhao et al., 2015; Liu et al., 2010, 2016). A cCombination of strong winter winds, water mixing, and surface cooling in the northern SCS drives winter convective overturning, leading to higher primary productivity during the winter monsoon than during other periods (Liu et al., 2002; Chen, 2005; Tseng et al., 2005). Rainfall in the northern SCS is seasonally variable, with increased rainfall during the summer (Zhang et al., 2019). Typhoons, mesoscale eddies, and other dynamical processes are also well developed in the northern SCS (Su, 2004; Wang and Li, 2009).

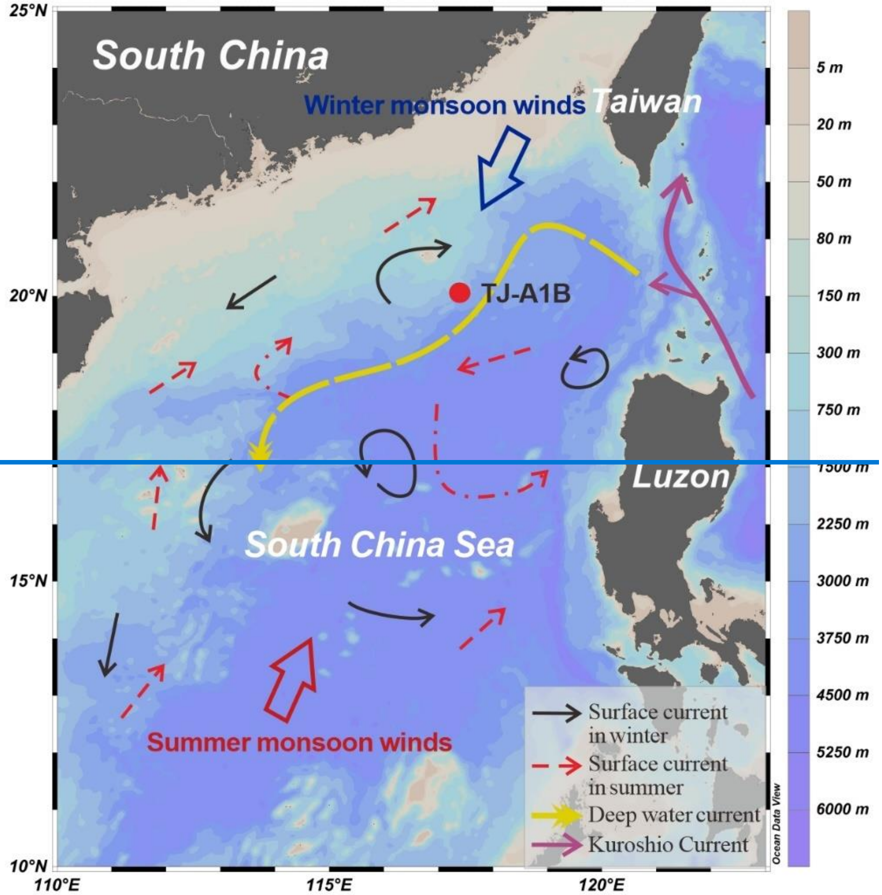



**Figure 1.** Monsoon and current systems in the South China Sea (SCS) (after Liu et al., 2016). Location of the sediment_ trap mooring TJ-A1B is indicated. Ocean Data View software was used to generate the map (Schlitzer, 2023).

Zooplankton species in the northern SCS mainly include Hydromedusae, Siphonophorae, Pteropoda, Ostracoda, Copepoda, Amphipoda, Euphausiacea, Chaetognatha, Appendiculariae, Thaliacea, and larvae (Fig. 2a; Li et al., 2021; Gong et al., 2017). Among these, copepods have the largest number of species, contributing 30% of the total identified species (Ren et al., 2021; Ge et al., 2021). Copepods are also the most abundant group, contributing about 80% of the total abundance, followed by ostracods and chaetognaths (Fig. 2a). Zooplankton abundance is the highest between 0–100 m water depth and consistently decreases with increasing depth (Fig. 2b; Gong et al., 2017; Li et al., 2021). The average zooplankton biomass is 35 mg $m^{-3}$, with a slight increase at 350–600 m water depth (Gong et al., 2017). Below 300 m, there is a noticeable increase in the proportion of copepods to the total abundance, with some copepod species (including *Calanoides carinatus*, *Bradyiditus armatus*, *Chiridius gracilis*, and *Euchirella curticauda*) only found at 450–1000 m water depth (Du et al., 2014; Li et al., 2021).

Furthermore, on a seasonal scale, zooplankton abundance in the northern SCS increases significantly during the winter monsoon period, while it declines during the inter-monsoon period (Li et al., 2004; Li et al., 2021).

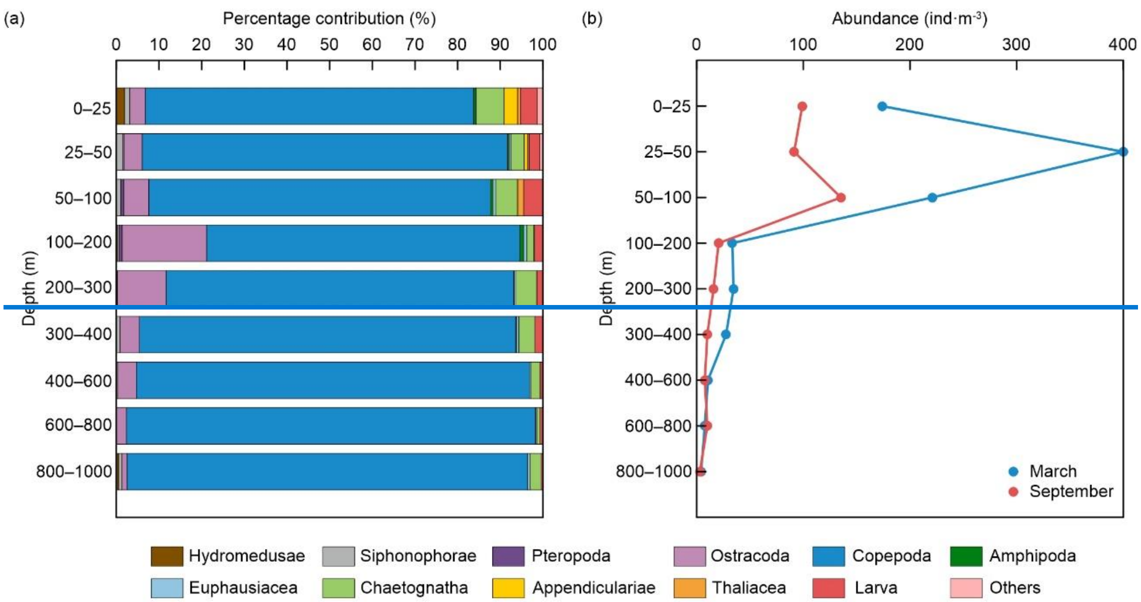



**Figure 2.** Vertical distribution of (a) species richness percentage and (b) total abundance of zooplankton from 0 to 1000 m depths in the northern SCS. Data from Li et al. (2021).

## 23 Material and Methods

### 2.1 Study area

The SCS is a large marginal sea with an area of about $3.5\times10^6$ $km^2$ and an average depth of about 1350 m (Wang and Li, 2009). The study area is located in the northern SCS, where a warm and humid southwest monsoon prevails in summer (June to August), while a dry and cold northeast monsoon prevails in winter (November to April) (Chu and Wang, 2003) (Fig. 1). The hydrological system of the northern SCS is complex due to the seasonal shift of the East Asian monsoon winds and the interplay of waters from the Kuroshio Current (Su, 2004; Caruso et al., 2006). Surface circulation of the northern SCS also shows a seasonal shift from a large cyclonic gyre in winter to a weak cyclonic gyre in summer (Su, 2004). Contour currents have been found to dominate sediment transport processes on the deep-sea slope at 1600–2400 m water depth, transporting Taiwan-sourced sediments westward (Zhao et al., 2015; Liu et al., 2010, 2016). A combination of strong winter winds, water mixing, and surface cooling in the northern SCS drives winter convective overturning, leading to higher primary productivity during the winter monsoon than during other periods (Liu et al., 2002; Chen, 2005; Tseng et al., 2005). Rainfall in the northern SCS is seasonally variable, with increased rainfall during the summer (Zhang et al., 2019). Typhoons, mesoscale eddies, and other dynamical processes are also well developed in the northern SCS (Su, 2004; Wang and Li, 2009).

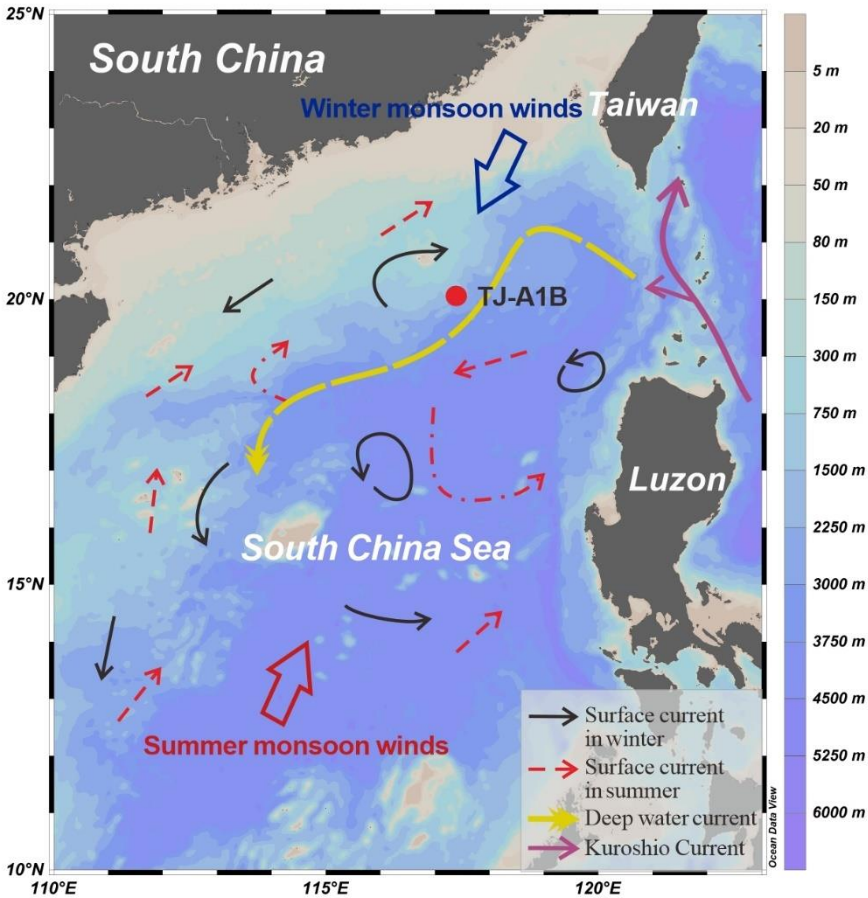



**Figure 1.** Monsoon and current systems in the South China Sea (SCS) (after Liu et al., 2016). Location of the time-series sediment-trap mooring TJ-A1B is indicated. Ocean Data View software was used to generate the map (Schlitzer, 2023).

Zooplankton species in the northern SCS mainly include Hydromedusae, Siphonophorae, Pteropoda, Ostracoda, Copepoda, Amphipoda, Euphausiacea, Chaetognatha, Appendiculariae, Thaliacea, and larvae (Fig. 2a; Li et al., 2021; Gong et al., 2017). Among these, copepods have the largest number of species, contributing 30% of the total identified species (Li, K. et al., 2017; Ren et al., 2021; Ge et al., 2021). Copepods are also the most abundant group, contributing about 80% of the total abundance, followed by ostracods and chaetognaths (Fig. 2a). Zooplankton abundance is the highest between 0–100 m water depth and consistently decreases with increasing depth (Fig. 2b; Gong et al., 2017; Li et al., 2021). The average zooplankton biomass is 35 mg $m^{-3}$, with a slight increase at 350–600 m water depth (Gong et al., 2017). Below 300 m, there is a noticeable increase in the proportion of copepods to the total abundance, with some copepod species (including *Calanoides carinatus*, *Bradyiditus armatus*, *Chiridius gracilis*, and *Euchirella curticauda*) only found at 450–1000 m water depth (Du et al., 2014; Li et al., 2021).

Furthermore, on a seasonal scale, zooplankton abundance in the northern SCS increases significantly during the winter monsoon period, while it declines during the inter-monsoon period (Li et al., 2004; Li et al., 2021).

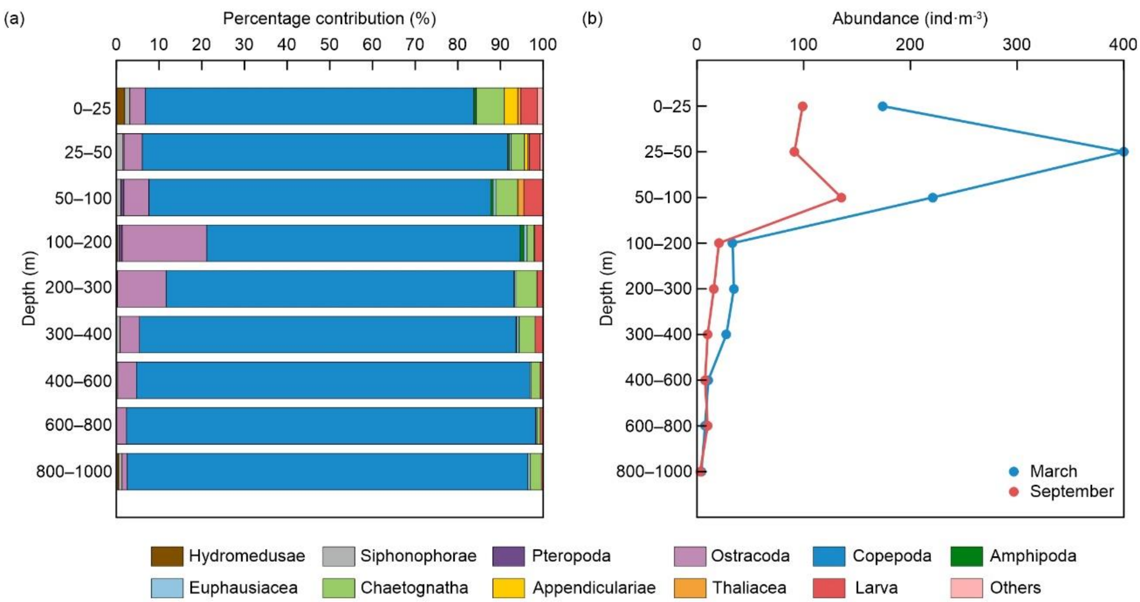



**Figure 2.** Vertical distribution of (a) species richness percentage and (b) total abundance of zooplankton from 0 to 1000 m depths in the northern SCS. Data from Li et al. (2021).

## 23.21 Sediment–-trap deployment

Samples were collected by time-series sediment traps (McLane Parflux Mark78H-21 sediment trap) deployed on mooring TJ-A1B (20.06°N, 117.39°E, 2000 m water depth) in the northern SCS (Fig. 1). Two traps (UP and DW) were deployed at 500 m and 1970 m water depths, respectively, each with a sampling area of 0.5 $m^2$. Samples were collected at 18-day intervals from May 2021 to May 2022 (except for the first sample, which covered only three days), resulting in a total of 42 samples (21 samples for each trap). Prior to deployment of the traps, each sample bottle was pre-filled with 0.6 g (for the trap at 500 m) or 0.3 g (for the trap at 1970 m) $HgCl_2$, along with 33.3 g NaCl per 1000 ml of deionized water to prevent microbial activity and ensure the reliability of organic geochemical analysis.

## 23.32 Sample analysis

The samples were wet sievedseived using a 1 mm mesh to remove swimmers. The small fractions (<1 mm) were then equally aliquoted using a splitter, and one wet portion was used for the analysis of zooplankton fecal pellets. POC content and flux were determined using the methods outlined in detail by Li et al. (2022). The wet samples were filtered through a 20 µm Nitex © mesh, followed by rinsing on a gridded petri dish. These samples were examined under a Zeiss Stemi 508 stereomicroscope coupled to a Zeiss Axiocam 305 digital camera. Fecal pellets were photographed and counted by shape to obtain the fecal-pellet--numerical (FPN) flux (Li et al., 2022). Pellets were classified into four shapes: ellipsoidal, cylindrical, spherical, and amorphous. Biovolumes of the first three fecal pellet shapes were calculated from the formulas for an ellipsoid, cylinder, and sphere (Sun and Liu, 2003), while the biovolume of amorphous fecal pellets was estimated through best-fit ellipsoid calculations (Kumar et al., 2010). The fecal pellet biovolume was then converted to carbon content to determine the fecal-pellet--carbon (FPC) flux and its contribution to the POC flux, by using the conversion factor of 0.036 mg C $mm^{-3}$ measured in the southern SCS (Li et al., 2022), which is similar to the conversion factor commonly used in tropical and subtropical marginal seas (Urban-Rich et al., 1998; Kobari et al., 2010).

Fecal pellets selected from eight samples at two different depths were prepared for scanning electron microscopy (SEM) and energy-dispersive spectrometry (EDS) to identify their internal structure and to determine elemental composition. 6–7 fecal pellets of different shapes (ellipsoidal, cylindrical, spherical, and amorphous) and aggregates were randomly selected from each sample.

### 2~~3~~.4~~3~~ Hydrological parameters

To investigate the environmental factors regulating the sinking and export of fecal pellets, we analysed ~~analyzed~~ several relevant physical and biogeochemical parameters. For daily wind speed (10 m zonal and meridional components of surface wind), data were derived from the Atmospheric Composition Reanalysis 4 product (https://ads.atmosphere.copernicus.eu/cdsapp#!/dataset/cams-global-reanalysis-eac4), with a spatial resolution of 0.25°×0.25°. Daily sea surface temperature (SST) data were retrieved from the Copernicus Climate Change Service (https://cds.climate.copernicus.eu/cdsapp#!/dataset/satellite-sea-surface-temperature), which provides SST data with a horizontal resolution of 0.05°×0.05°. For daily ocean mixed layer depth (MLD) defined by potential density anomaly and surface water velocity, data were retrieved from the Operational Mercator global ocean analysis and forecast system (https://data.marine.copernicus.eu/product/GLOBAL_ANALYSISFORECAST_PHY_001_024/description), with spatial resolutions of 0.25°×0.25° and 0.083°×0.083°, respectively. Daily net primary production (PP) data of biomass expressed as carbon per unit volume in sea water with a spatial resolution of 0.25°×0.25° were obtained from the Operational Mercator Ocean biogeochemical global ocean analysis and forecast system (https://data.marine.copernicus.eu/product/GLOBAL_ANALYSIS_FORECAST_BIO_001_028). Daily precipitation data with a horizontal resolution of 1.0°×1.0° were provided by the Global Precipitation Climatology Project (https://cds.climate.copernicus.eu/cdsapp#!/dataset/satellite-precipitation).

## 34 Results

### 34.1 Fecal pellet characteristics

Microscopic analysis of the time-series sediment~~-~~trap samples revealed fecal pellets of various shapes (ellipsoidal, cylindrical, spherical, and amorphous). All shapes were found both at 500 m (Fig. 3a) and 1970 m (Fig. 3b). Among them, ellipsoidal, cylindrical, and spherical pellets were intact with smooth edges, while amorphous pellets were degraded with broken edges. Notably, their peritrophic membranes were partially absent. Fecal pellets were often brown in appearance.~~, which were significantly different between the two depths.~~ Ellipsoidal, cylindrical, and spherical pellets sizes were larger at 1970 m, whereas amorphous fecal pellets sizes were larger at 500 m (Fig. 3, detailed photographs can be found in Supplementary Figs. S1–S21). In addition to zooplankton fecal pellets, a number of transparent and flocculent aggregates were also present in the samples, which were more common in the winter samples (Fig. 3, Figs. S1–S21).

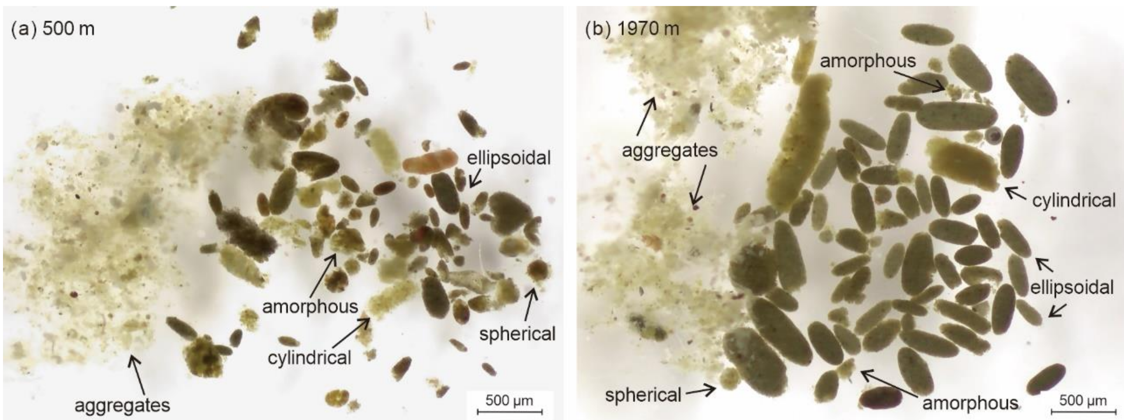
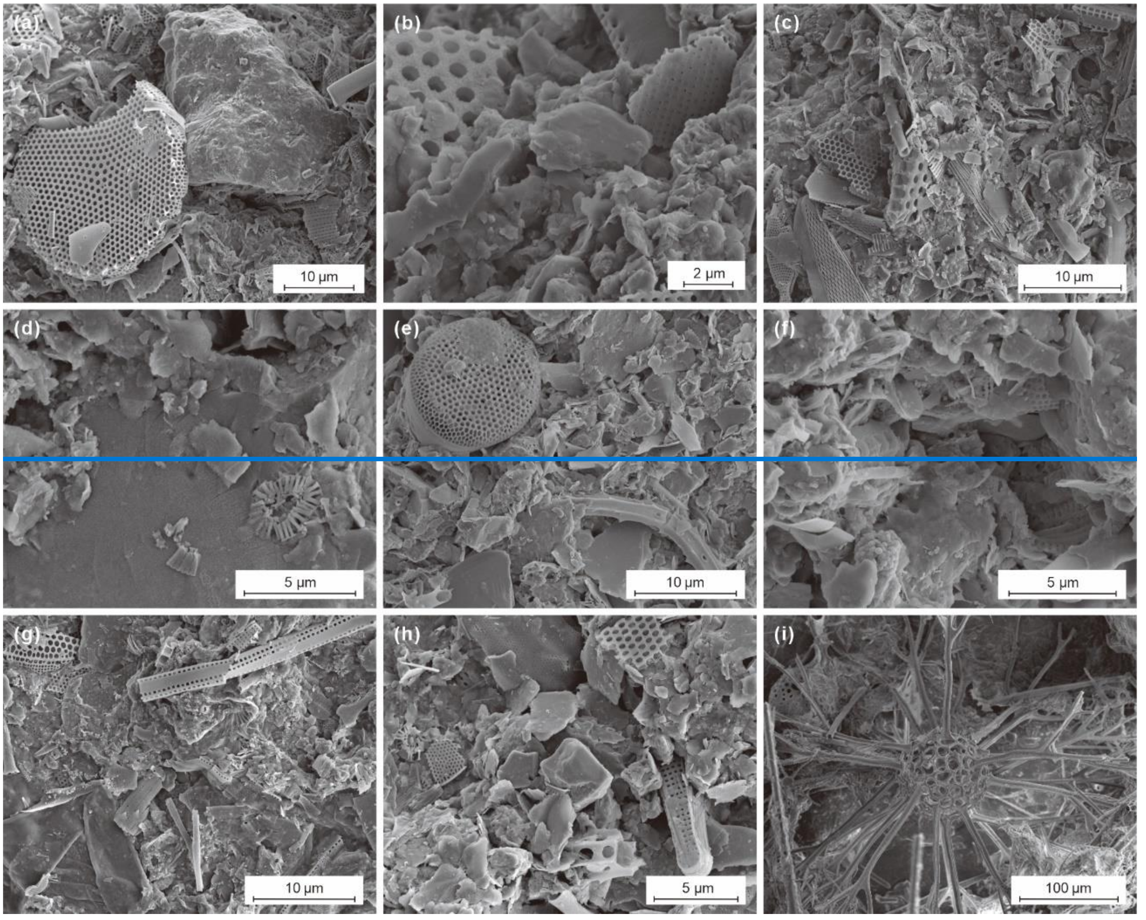



**Figure 3.** Light microscopy photographs of four morphological types of zooplankton fecal pellets and aggregates collected from (a) 500 m and (b) 1970 m water depths of time-series sediment~~-~~trap mooring TJ-A1B in the northern SCS.

The internal components of the fecal pellets were mainly composed of diatoms, e.g., *Coscinodiscus* (Fig. 4a, ~~and 4~~e), *Thalassionema* (Fig. 4h), *Hemiaulus* (Fig. 4g), and *Nitzschia* (Fig. 4g), as well as coccoliths (Fig. 4d) and lithogenic particles (Figs. 4h, ~~and~~ 5b). In contrast, the aggregates had a looser structure, and consisted mainly of radiolarians, diatoms, sponge spicules, and foraminifers (Fig. 4i). The major elements composing ~~of~~ the fecal pellets were O, Si, C, and Ca, with minor proportions of Al and K, indicating that terrigenous minerals such as quartz and clay minerals may also be important components of fecal pellets (Figs. 4h, ~~and~~ 5b).


(a)
10 μm
(b)
2 μm
(c)
10 μm
(d)
5 μm
(e)
10 μm
(f)
5 μm
(g)
10 μm
(h)
5 μm
(i)
100 μm

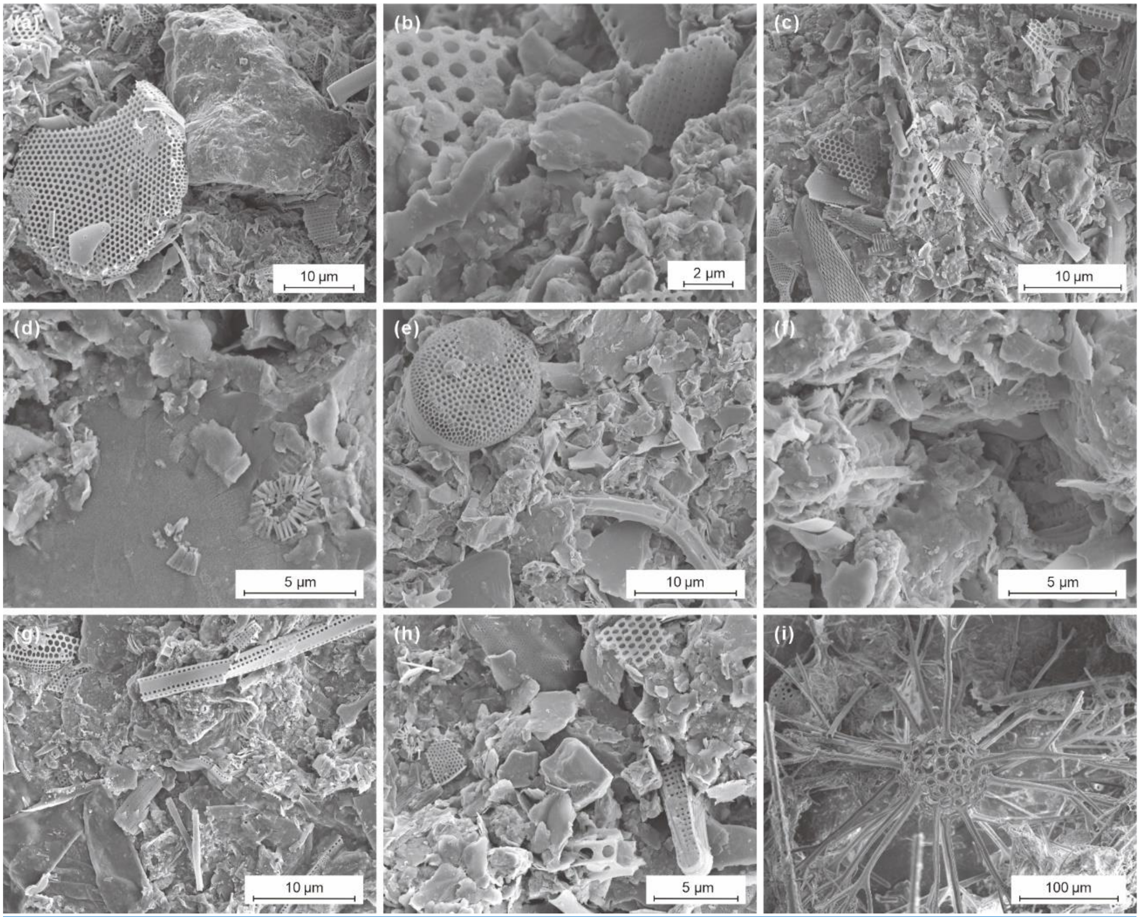
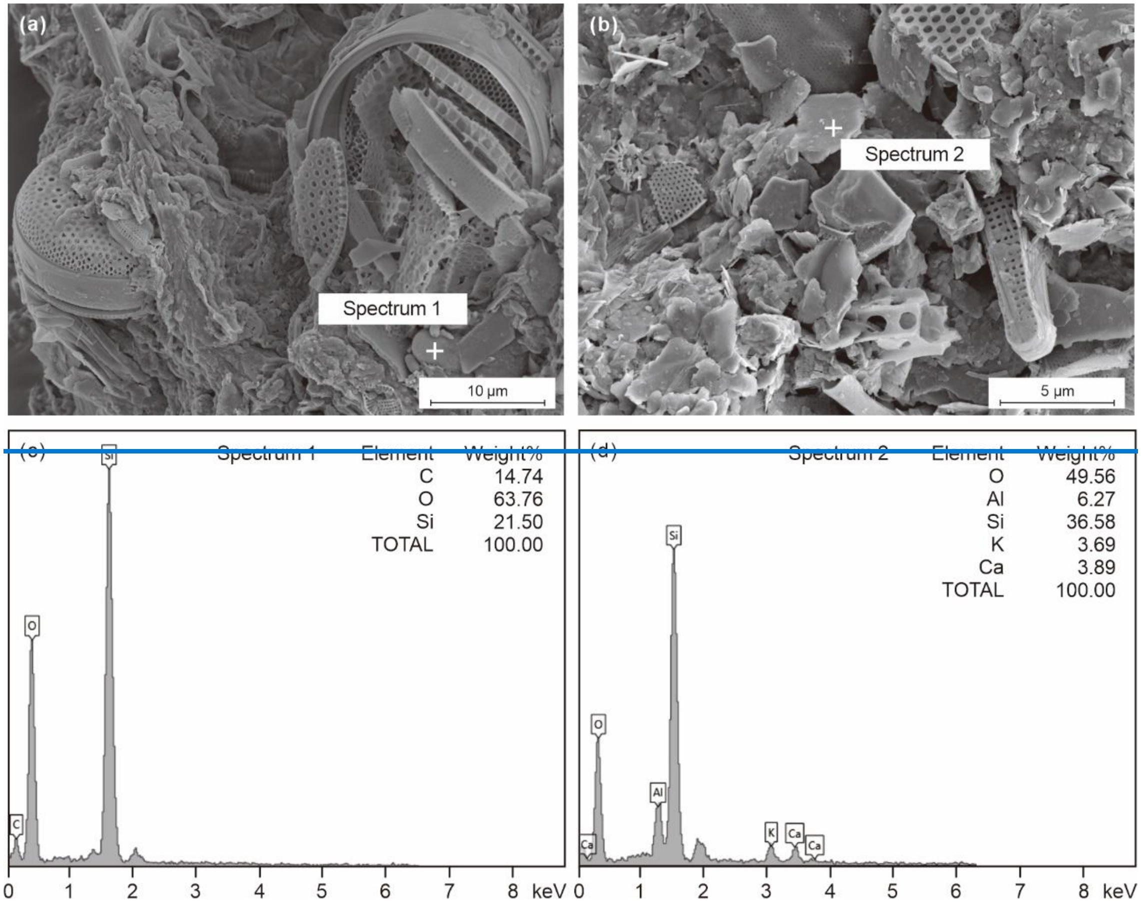



**Figure 4.** Scanning electron microscopy (SEM) observations of internal components of zooplankton fecal pellets and aggregates collected from the time-series sediment-trap mooring TJ-A1B in the northern SCS: (a, b) ellipsoidal pellet, (c, d) cylindrical pellet, (e, f) spherical pellet, (g, h) amorphous pellet, and (i) aggregates.



(a)
Spectrum 1
10 µm
(b)
Spectrum 2
5 µm
(c)
Spectrum 1
Element Weight%
C 14.74
O 63.76
Si 21.50
TOTAL 100.00
(d)
Spectrum 2
Element Weight%
O 49.56
Al 6.27
Si 36.58
K 3.69
Ca 3.89
TOTAL 100.00
keV

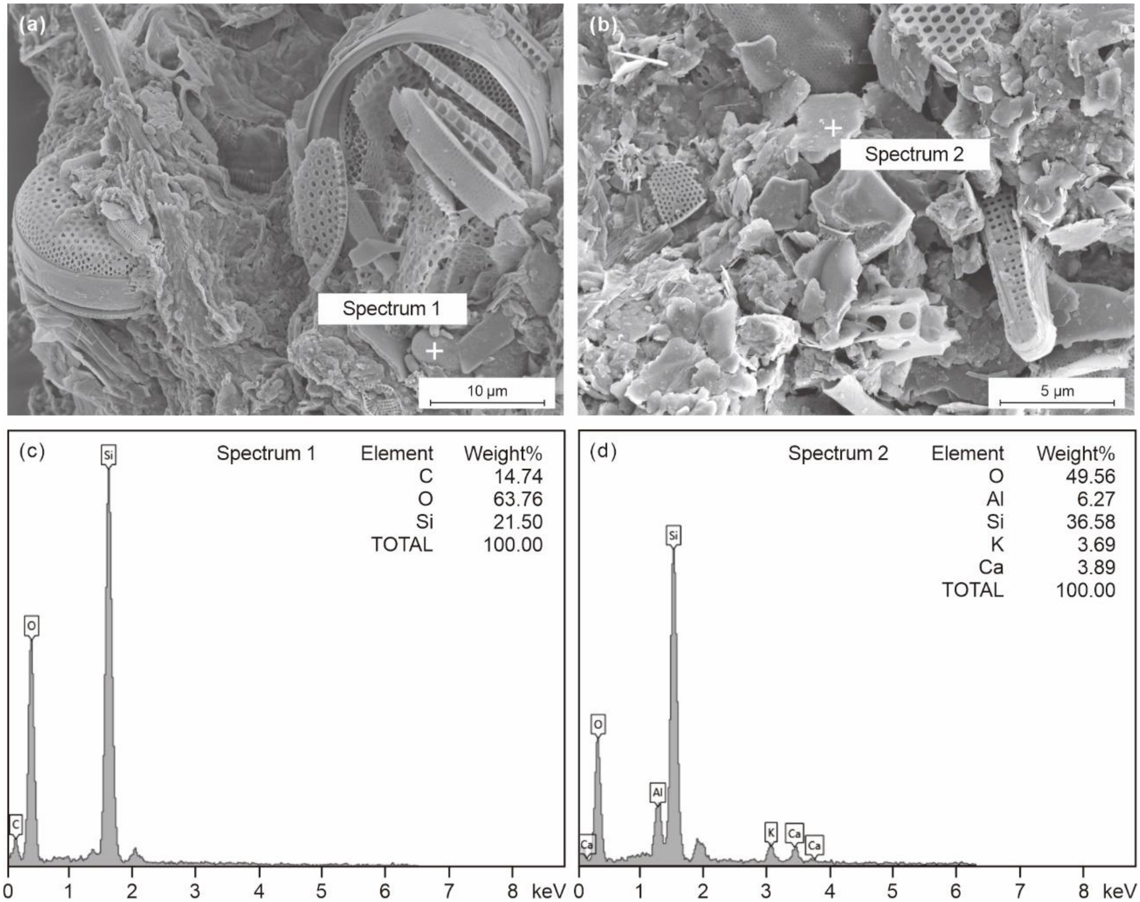



**Figure 5.** SEM coupled EDS analysis for internal structure and elemental composition of zooplankton fecal pellets in the time-series sediment-trap mooring TJ-A1B in the northern SCS. Panels (a) and (c) for one fecal pellet, and panels (b) and (d) for another fecal pellet.

Fecal pellets varied considerably in biovolume among the four types (Table 1). Ellipsoidal pellets had average biovolumes of 1.96 and 3.02×10$^6$ μm$^3$ at 500 and 1970 m depth, respectively. The average biovolumes of cylindrical pellets were 13.31×10$^6$ μm$^3$ at 500 m and 13.55×10$^6$ μm$^3$ at 1970 m, which were 10 times larger than other pellet types. Spherical pellets were the smallest, with a mean biovolume of only 0.90×10$^6$ μm$^3$. The biovolume of amorphous pellets ranged from 0.04 to 35.89×10$^6$ μm$^3$ and the average value was two times larger at 500 m (2.23×10$^6$ μm$^3$) than at 1970 m (0.92×10$^6$ μm$^3$). Two patterns of biovolume change from 500 m to 1970 m were observed for different fecal pellet types. Specifically, the average biovolume of ellipsoidal, cylindrical, and spherical pellets increased from 500 m to 1970 m, where the average biovolume of amorphous pellets decreased at 1970 m to only half of that at 500 m. At 500 m, the average biovolume of ellipsoidal, cylindrical, and spherical pellets was higher in June-August and December-February and those of amorphous pellets was elevated from December to April. Whereas, at 1970 m, the seasonal variation in biovolume for all shape was not significant.

**Table 1.** Biovolume, numerical flux, numerical percentage, carbon flux, and carbon percentage of four types of zooplankton fecal pellets in the time-series sediment-trap mooring TJ-A1B in the northern SCS.

| Depth (m) | Fecal pellet type | Number measured | Biovolume ($\times 10^6$ μm$^3$) | Numerical flux ($\times 10^3$ m$^{-2}$ d$^{-1}$) | Numerical percentage (%) | Carbon flux (mg C m$^{-2}$ d$^{-1}$) | Carbon percentage (%) |
|---|---|---|---|---|---|---|---|
| 500 | Ellipsoidal | 1278 | 0.03–49.56 | 0.05–1.42 | 20–58 | 0.0004–0.0184 | 3–47 |
| | | | **1.96 ± 4.53** | **0.38 ± 0.36** | **37 ± 11** | **0.0053 ± 0.0046** | **26 ± 11** |
| | Cylindrical | 501 | 0.09–118.39 | 0–0.21 | 0–19 | 0–0.1028 | 0–90 |
| | | | **13.31 ± 19.28** | **0.07 ± 0.06** | **8 ± 5** | **0.0103 ± 0.0217** | **29 ± 19** |
| | Spherical | 540 | 0.01–4.81 | 0–0.52 | 0–21 | 0–0.0032 | 0–9 |
| | | | **0.90 ± 1.02** | **0.11 ± 0.11** | **11 ± 5** | **0.0009 ± 0.0008** | **4 ± 2** |
| | Amorphous | 1331 | 0.04–35.89 | 0.15–0.74 | 15–75 | 0.0017–0.0138 | 7–82 |
| | | | **2.23 ± 4.27** | **0.34 ± 0.14** | **45 ± 16** | **0.0063 ± 0.0028** | **40 ± 18** |
| | Total | 3650 | 0.03–118.39 | 0.22–2.52 | 100 | 0.0021–0.1148 | 100 |
| | | | **3.46 ± 8.98** | **0.91 ± 0.59** | | **0.0228 ± 0.0238** | |
| 1970 | Ellipsoidal | 1981 | 0.05–96.19 | 0.28–2.51 | 36–62 | 0.0048–0.0802 | 35–82 |
| | | | **3.02 ± 8.01** | **1.15 ± 0.66** | **50 ± 6** | **0.0256 ± 0.0199** | **51 ± 11** |
| | Cylindrical | 628 | 0.07–294.90 | 0.04–0.45 | 3–12 | 0.0033–0.0681 | 14–53 |
| | | | **13.55 ± 25.97** | **0.19 ± 0.13** | **8 ± 2** | **0.0156 ± 0.0158** | **29 ± 12** |
| | Spherical | 897 | 0.04–10.92 | 0.08–0.91 | 7–21 | 0.0009–0.0075 | 1–15 |
| | | | **0.90 ± 1.47** | **0.34 ± 0.24** | **14 ± 4** | **0.0031 ± 0.0020** | **7 ± 3** |
| | Amorphous | 1481 | 0.04–12.68 | 0.20–1.19 | 14–43 | 0.0015–0.0191 | 2–26 |
| | | | **0.92 ± 1.84** | **0.60 ± 0.31** | **28 ± 8** | **0.0054 ± 0.0038** | **13 ± 6** |
| | Total | 4987 | 0.04–294.90 | 0.60–4.57 | 100 | 0.0108–0.1697 | 100 |
| | | | **3.34 ± 11.30** | **2.28 ± 1.24** | | **0.0497 ± 0.0360** | |

Bold values are the average and standard deviation of each above ranges.

### 34.2 Fecal pellet flux

Fecal-pellet-numerical (FPN) flux and fecal-pellet-carbon (FPC) flux at different depths were summarized in Table 1 and Fig. 6. FPN flux varied considerably throughout the year, from a minimum of 216 pellets m$^{-2}$ d$^{-1}$ in May to a maximum of 2518 pellets m$^{-2}$ d$^{-1}$ in December at 500 m, while at 1970 m, this value spanned a range of 597–4573 pellets m$^{-2}$ d$^{-1}$, with the minimum value occurring in October and the maximum in May. FPC flux varied between 0.0021 and 0.1148 mg C $m^{-2}$ $d^{-1}$ at 500 m (Table 1; Fig. 6b). At 1970 m, the range was 0.0108 to 0.1697 mg C $m^{-2}$ $d^{-1}$ (Table 1; Fig. 6d). The most apparent temporal trend in the FPN and the FPC fluxes was a distinct seasonal variation (Fig. 6). There was a double seasonal peak, with a primary (higher) peak in November-April and a secondary peak in June-August (Fig. 6). In particular, the FPC flux increased slightly in June 2021 before declining sharply over the next 3 months (Fig. 6), and then increasing again with a primary peak from November to April. An anomalously high value of FPC flux was detected at 500 m in April-May 2022, caused by a large increase in cylindrical pellets (Fig. 6b). Moreover, both FPN and FPC fluxes increased from 500 m to 1970 m, with values at 1970 m twice as high as those measured at 500 m (Table 1).

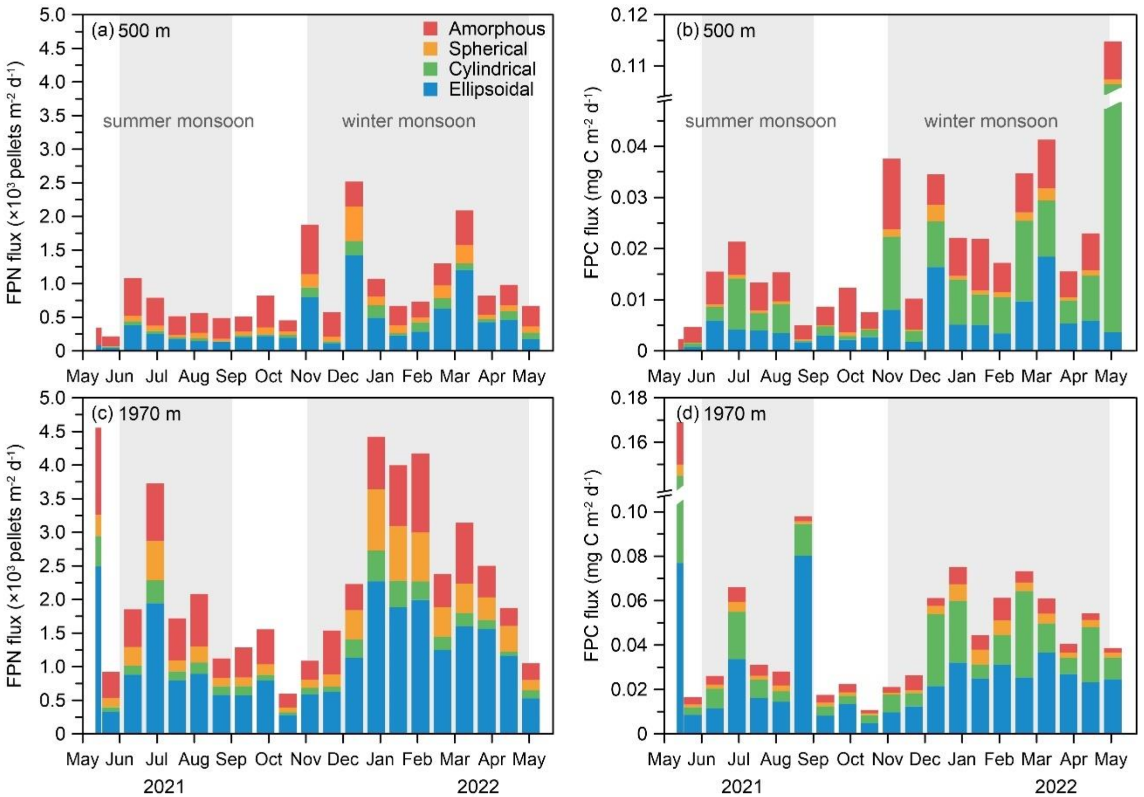



**Figure 6.** Temporal variations of FPN and FPC fluxes of fecal pellets at the time-series sediment-trap mooring TJ-A1B in the northern SCS. (a) FPN flux at 500 m; (b) FPC flux at 500 m; (c) FPN flux at 1970 m; (d) FPC flux at 1970 m.

The total fecal pellet flux consisted of four morphological pellet types, with each type making a distinct contribution to the total FPN and FPC fluxes (Table 1; Fig. 6). Typically, ellipsoidal and amorphous pellets dominated the numerical flux, accounting for 80% of the total FPN flux. Cylindrical and spherical pellets were minor contributors to the FPN flux. In terms of the dominance of different types of fecal pellets, there were notable differences between the two depths (Table 1; Fig. 6).

Amorphous pellets accounted for around 45% of the FPN flux at 500 m, while ellipsoidal pellets became most prominent at 1970 m. Cylindrical and spherical pellets had a relatively constant but low numerical percentage. Regarding FPC flux, amorphous pellets contributed on average 40% of the total FPC flux at 500 m, followed by cylindrical pellets (on average 29%) with larger size compared to the other types, despite their relatively low numerical flux. Ellipsoidal pellets contributed on average 26%, while spherical pellets contributed only 4%. At 1970 m, ellipsoidal and cylindrical pellets dominated the FPC flux throughout the time series. Carbon percentage of amorphous pellets declined to 2–26%, while spherical pellets still remained the lowest (1–15%) (Fig. 6b, and 6d). Notably, ellipsoidal, cylindrical, and spherical pellets exhibited higher FPN and FPC fluxes at 1970 m than at 500 m. However, amorphous pellets had lower carbon fluxes and carbon percentages at 1970 m due to their significantly lower biovolumes.

### 34.3 Contribution of fecal pellets to total POC flux

The POC flux in the northern SCS ranged from 0.11 to 5.31 mg C $m^{-2}$ $d^{-1}$ at 500 m, while it varied between 1.08 and 8.19 mg C $m^{-2}$ $d^{-1}$ at 1970 m (Fig. 7). A high seasonal variability of the POC flux was observed, with maxima in the winter monsoon period and minima in the inter-monsoon period at two depths (Fig. 7). This seasonal variation of the POC flux matched that of the FPC flux, with a higher peak from November to April, a lower peak from June to August, and a minimum value from September to October (Fig. 7). In addition to the temporal variation, the POC flux also varied significantly at different depths. On average, the POC flux at 500 m was only ~50% of that measured at 1970 m, and the minimum POC flux at 1970 m was one order of magnitude higher than that observed at 500 m.

The contribution of fecal pellets to the POC flux (FPC/POC ratio) ranged from 0.3% to 15.7% at 500 m, with the highest contribution occurring in April-May (Fig. 7). The FPC/POC ratio was generally low from May to July (<4%) and fluctuated between 1%–8% from August to December. During the winter monsoon period, this ratio remained fairly constant (~2%), and then it increased sharply in April-May. At 1970 m, the FPC/POC ratio varied from 0.5% to 5.7%, with a smaller range compared to that of 500 m. It was generally low except for May and August 2021(5.7% and 4.8%, respectively), and the minimum occurred in January 2022. In general, the FPC/POC ratio is relatively higher at 500 m and lower at 1970 m, with average percentages of 3.4% and 1.9%, respectively (Fig. 7).

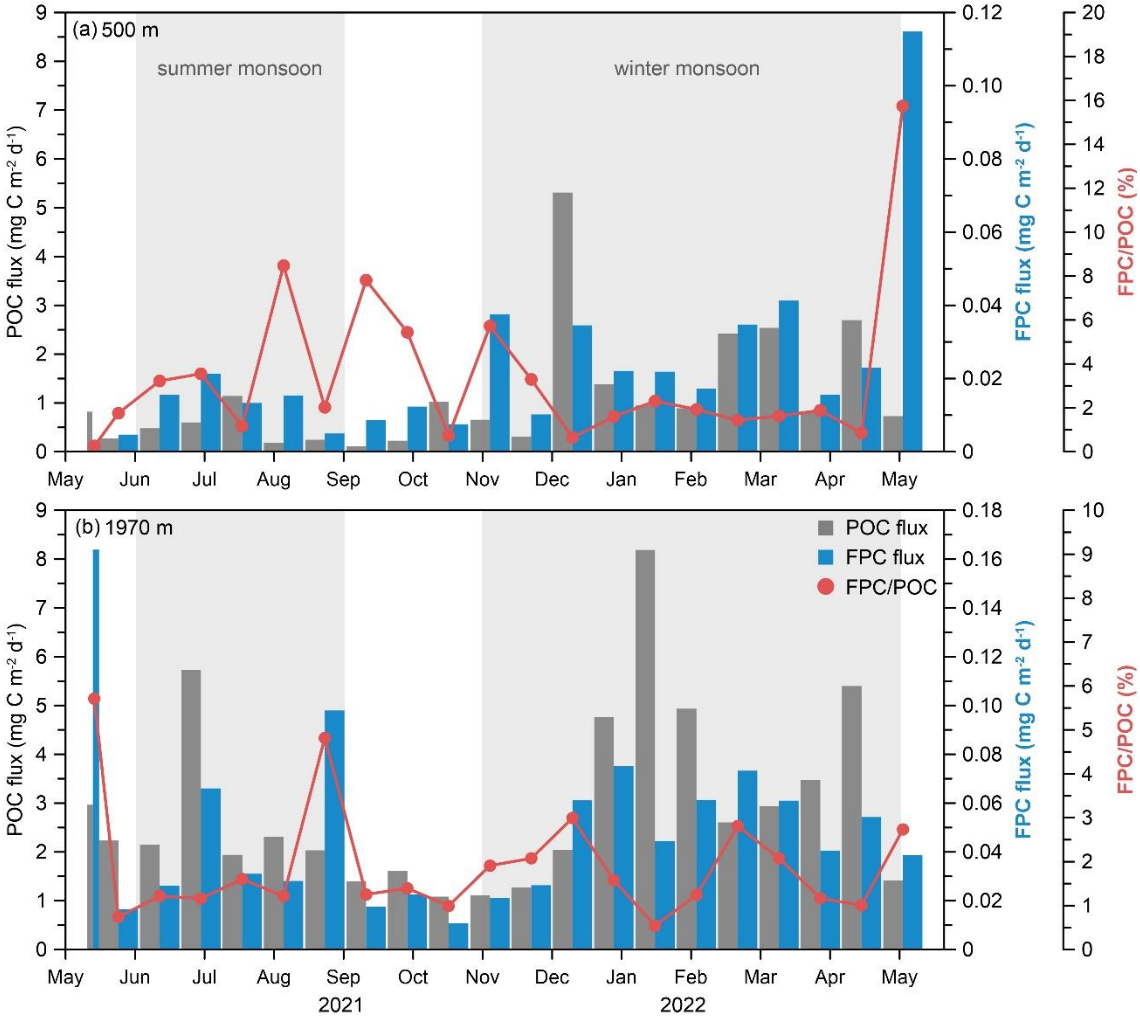



**Figure 7.** POC flux, FPC flux and FPC/POC ratio at water depths of (a) 500 m and (b)1970 m at the time-series sediment-trap mooring TJ-A1B in the northern SCS.

Positive linear correlations were observed between the POC flux and the FPC flux (Fig. 8a). Sample TJ-A1B21-UP21, which contained a substantial quantity of cylindrical fecal pellets measuring up to 1.5 mm in size but low POC flux, was removed from the fitted relationship. Meanwhile, there were negative linear relationships between the POC flux and the FPC/POC ratio (%) (Fig. 8b). However~~Besides~~, the negative linear relationship was weaker at 1970 m compared to 500 m.

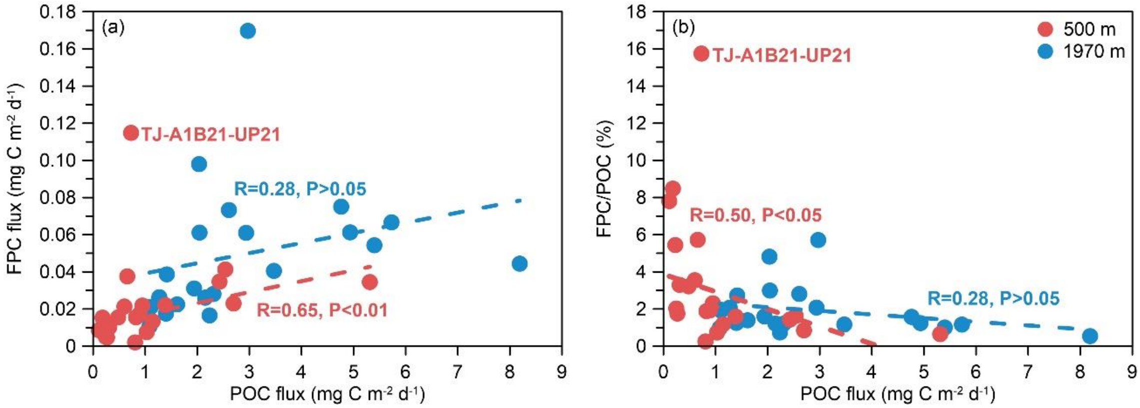



**Figure 8.** Correlation plots of (a) POC flux versus FPC flux (b) POC flux versus FPC/POC ratio of the time-series sediment-trap mooring TJ-A1B in the northern SCS.

### 3.4 Hydrological conditions

Southwest winds prevailed in the study area from June to September and northeast winds from late October to May (Fig. 9a). During the observation period, wind speed ranged from 0.2 to 19.8 m $s^{-1}$. Wind speed was low during the inter-monsoon period (6.4 ± 3.2 m $s^{-1}$) and increased in late October, reaching up to 8–10 m $s^{-1}$ in winter (Fig. 9a). Sea surface temperature (SST) varied between 24 to 31°C, with an average of 27 ± 2°C, and showed distinct seasonal variation (Fig. 9b). SST was generally high during summer and autumn (>28°C), declined continuously after November, reaching a minimum (24°C) in January and March. Mixed layer depth (MLD) ranged from 11 to 95 m, with an average value of 35 ± 22 m (Fig. 9c). MLD was typically shallow (<40 m) during spring and summer, increased in autumn and reached its maximum (95 m) in late December (Fig. 9c). Primary productivity (PP) varied between 4 to 34 mg $m^{-3}$ $d^{-1}$ with an average value of 12 ± 6 mg $m^{-3}$ $d^{-1}$ (Fig. 9d). PP showed a weak peak in December (25 mg $m^{-3}$ $d^{-1}$) and a strong peak in February. Precipitation ranged from 0 to 32 mm $d^{-1}$ with an average value of 3 mm $d^{-1}$ (Fig. 9e). Precipitation throughout the year was concentrated in June-October (7 ± 8 mm $d^{-1}$), with a maximum value occurred in August and low precipitation during winter (1 ± 2 mm $d^{-1}$). Sea water velocity fluctuated throughout the year (0.01–0.38 m $s^{-1}$), averaging 0.17 ± 0.07 m $s^{-1}$ (Fig. 9f). The maximum value occurred during the winter monsoon period.

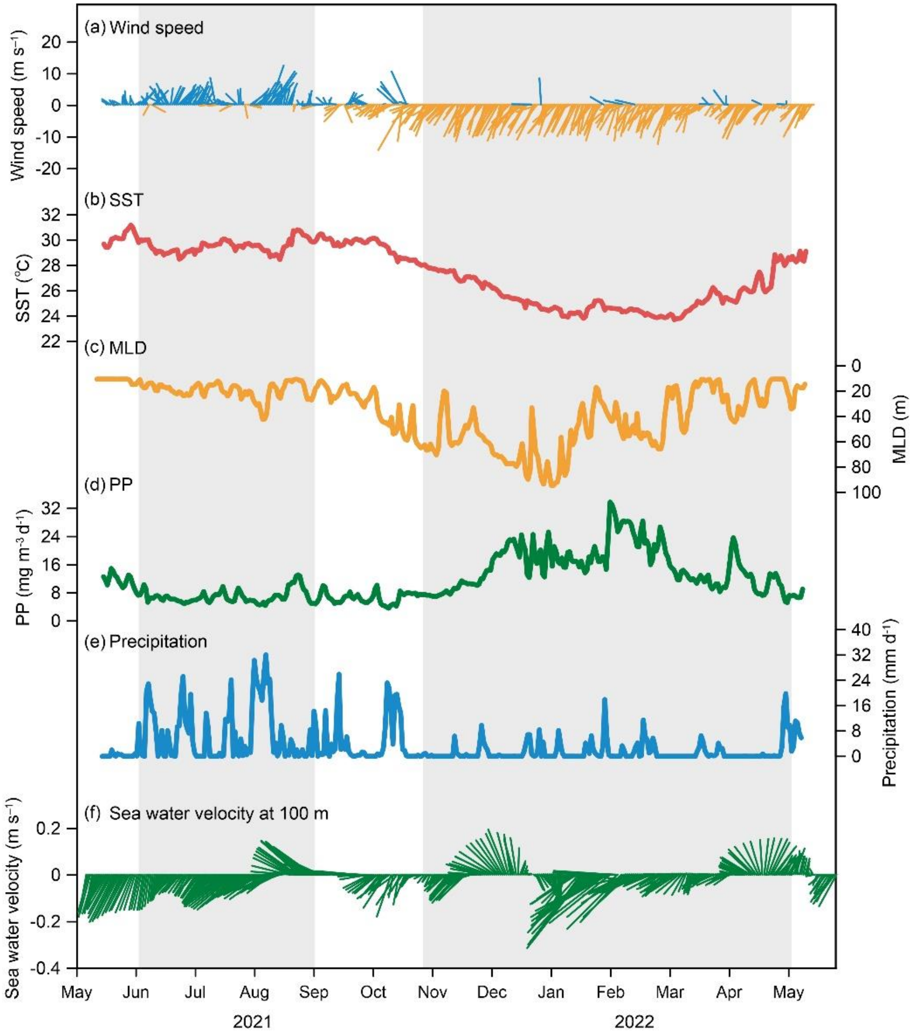


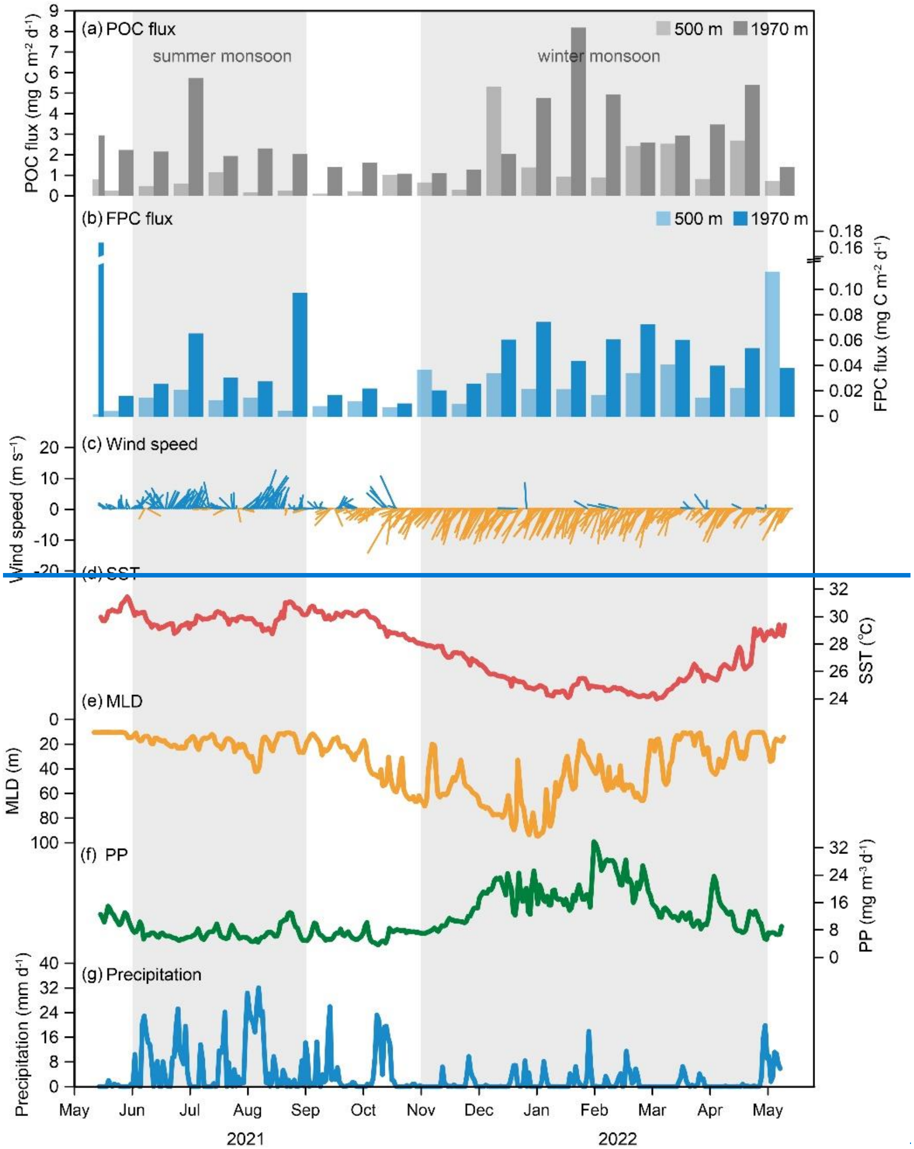

**Figure 9.** Hydrological parameters at the time-series sediment-trap mooring TJ-A1B in the northern SCS. (a) wind speed; (b) sea surface temperature (SST); (c) mixed layer depth (MLD); (d) net primary production (PP) of biomass; (e) precipitation; (f) sea water velocity at 100 m.

## 45 Discussions

### 45.1 Seasonal variation of POC and FPC export

Temporal patterns of the POC and the FPC fluxes in the northern SCS exhibited clear seasonal signals with well-defined winter peaks (November-April). The POC flux during this period constituted over 75% of the total annual POC flux (Fig. 109a). The FPC flux was also elevated, and the average flux during this period was 2 to 4 times higher than the average flux over the whole deployment period (Fig. 109b). Wind speed was also the highest during this period, reaching 8–10 m $s^{-1}$ (Fig. 9c).

~~Meanwhile, the sea surface temperature (SST) declined continuously after November, reaching a minimum (24°C) in January and March (Fig. 9d).~~ During the winter monsoon period, cooling of surface water, along with the strong northeasterly winds resulted in the enhanced vertical mixing, which can be reflected in the variation of the ~~mixed layer depth (~~MLD~~)~~ (Fig. 10c). ~~MLD was typically shallow (<40 m) during spring and summer, increased in autumn and reached its maximum (95 m) in late December (Fig. 9e),~~ MLD was the highest during this period, reaching 95 m, even deeper than the upper nutricline (Wong et al., 2015; Du et al., 2017). High concentrations of ~~primary productivity (~~PP~~)~~ also indicated that the subsurface water provided adequate nutrients to the upper layer, which stimulated the growth of phytoplankton (Fig. 10d~~9f~~). In the northern SCS, Chen et al. (2009) also reported a winter phytoplankton bloom (including *Picoeukaryotes*, *Synechococcus*, and *Prochlorococcus*). The significant increase in PP provided an enhanced food supply and supported high zooplankton biomass, thus resulting in twice the average zooplankton abundance compared to the other seasons (Fig. 2; Li et al., 2004; Tseng et al., 2005; Li et al., 2021). This pattern was consistent with studies in the southern SCS, where higher FPN and FPC fluxes were recorded during the East Asian winter monsoon (Li et al., 2022). Therefore, changes in phytoplankton community structure and zooplankton abundance influenced by the northeast monsoon resulted in a significant increase in the POC and the FPC fluxes. Similarly, in the northern Arabian Sea, fecal pellets were the dominant contributor to particulate matter during the northeast monsoon (Roman et al., 2000; Ramaswamy et al., 2005). In the northeastern Mediterranean Sea, the FPC flux also showed spring peaks during phytoplankton blooms (Carroll et al., 1998). Therefore, although in ~~the~~ oligotrophic seas, the monsoon system can increase the primary~~sea surface~~ productivity, which allows for increased zooplankton biomass and promotes the export of carbon from their fecal pellets.


(a) POC flux
500 m
1970 m
summer monsoon
winter monsoon
POC flux (mg C m-2 d-1)
(b) FPC flux
FPC flux (mg C m-2 d-1)
(c) Wind speed
Wind speed (m s-1)
(d) SST
SST (°C)
(e) MLD
MLD (m)
(f) PP
PP (mg m-3 d-1)
(g) Precipitation
Precipitation (mm d-1)
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Jan
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Mar
Apr
May
2021
2022

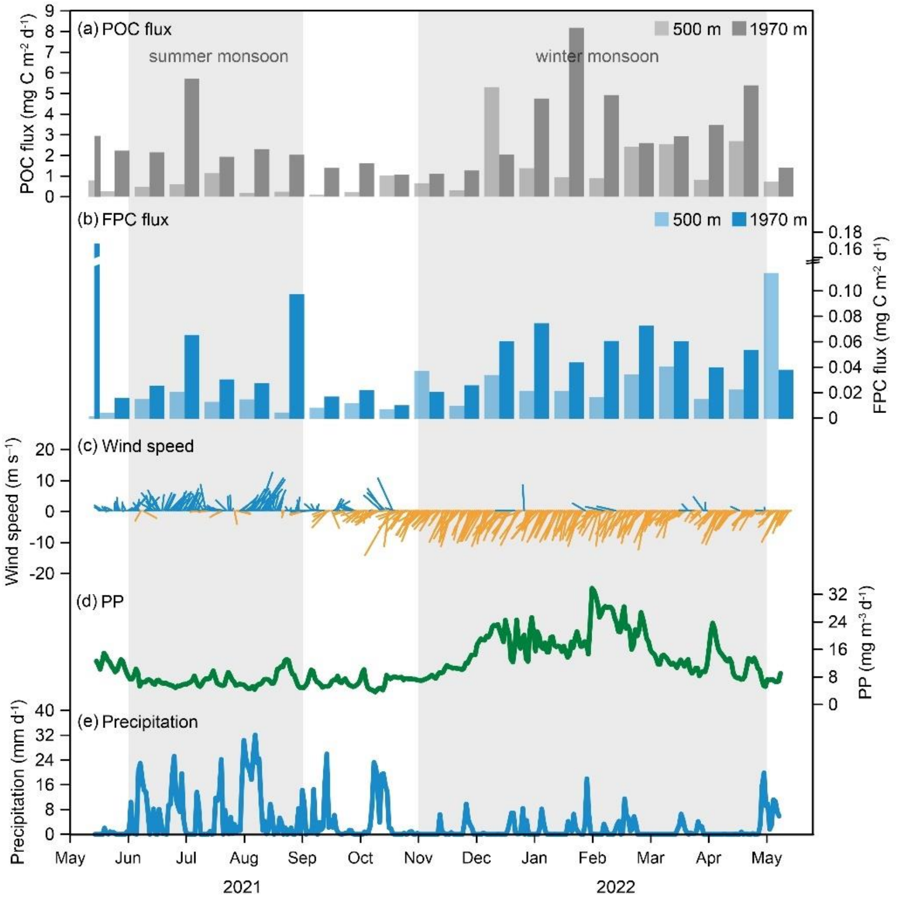


**Figure 109.** Seasonal variability of POC flux, FPC flux, and threefive hydrological parameters at the time-series sediment-trap mooring TJ-A1B in the northern SCS. (a) POC flux; (b) FPC flux; (c) wind speed; (d) sea surface temperature (SST); (e) mixed layer depth (MLD); (f) net primary production (PP) of biomass; (eg) precipitation.

Secondary peaks in the POC and the FPC fluxes occurred in summer (June-August) (Fig. 109a, and 9b). The southwest monsoon, typically accompanied by strong winds in the SCS, was a potential driver. However, from June to July 2021, mean wind speed decreased from 6.7 to 5.4 m $s^{-1}$ (Fig. 109c), with generally high SST (>28°C), which intensified the upper layer stratification. At this time, the MLD was less than 45 m, which was probably insufficient to transport subsurface nutrients to the epipelagiceuphotic layer. Therefore, the observed increase in the POC and the FPC fluxes cannot be attributed solely to the summer monsoon, but also to rainfall and terrestrial nutrient inputs. Indeed, precipitation in the northern SCS was highly seasonal, with up to 70% concentrated between June and September (Fig. 10e9g; Zhang et al., 2019). Summer precipitation can bring terrestrial organic matter from land into the ocean, resulting in the increased POC fluxes. These organic matters can also serve as a nutrient supply, contributing to the marine surface productivity, thus increasing zooplankton biomass and FPC fluxes~~through rivers, and theise additional nutrients can lead to an increase in zooplankton biomass~~ (Fig. 10b~~9g~~; Meyers, 1997; Vizzini et al., 2005~~; Chen et al., 2017~~). In addition, the notably high FPC fluxes at 500 m and 1970 m were observed in May 2021 and May 2022, respectively (Fig. 10~~9~~b). Previous studies have highlighted the annual occurrence of a diatom bloom peak in southwestern Taiwan waters in April (Chen et al., 2016). This may have led to a~~n~~ clear~~obvious~~ increase in zooplankton biomass, which produced a large number of fecal pellets~~ (Carroll et al., 1998)~~. These fecal pellets from southwestern Taiwan are likely ~~have been ~~transported to the northern SCS by deep-sea currents, which coincided with the previously reported high FPC flux recorded in May 2014 (Gao et al., 2020). In summary, the POC and the FPC fluxes in the northern SCS exhibited clear~~obvious~~ seasonal variations, which were primarily controlled by the East Asian monsoon system and seasonal precipitation.

## **4~~5~~.2 Role of zooplankton repackaginge in fecal pellet export**

Assemblage of different types and sizes of fecal pellets varied with depth, providing an indication of the repackaging by~~of~~ deep-sea dwelling zooplankton in the water column (Wilson et al., 2008). To better understand the FPC~~fecal pellet carbon~~ export to the deep sea, the biovolume of fecal pellets was converted into carbon content in the following discussion. Admittedly, using the same carbon conversion factor for the whole year and for all fecal pellet shapes and zooplankton producers could lead to uncertainty. Despite this uncertainty, our data still provide adequate information on FPC flux and its contribution to total POC flux in the northern SCS. Cylindrical pellets had the highest carbon content (on average 0.07 µg C pellet$^{-1}$), which was up to 10 times higher than other pellet types (Fig. 11b~~0~~). The maximum carbon content of cylindrical pellets at 1970 m was 10.62 µg C pellet$^{-1}$, which was 2.5 times higher than the maximum value recorded at 500 m (4.26 µg C pellet$^{-1}$). The average carbon content of ellipsoidal pellets increased from 0.01 µg C pellet$^{-1}$ at 500 m to 0.02 µg C pellet$^{-1}$ at 1970 m (Fig. 11a~~0~~). Spherical pellets were the smallest, and they also had higher carbon contents at 1970 m than at 500 m (Fig. 11c~~0~~). These larger pellets may result in a twofold increase in the FPC flux at 1970 m (Table 1; Fig. 10~~9~~b), which might come from the in-situ production of fecal pellets by deep-dwelling zooplankton communities. According to the literatures, ellipsoidal pellets could be attributed to copepods, pteropods, appendicularia, and larvae (González et al., 1994, 2004; Wilson et al., 2008; Wexels Riser et al., 2010; Gleiber et al., 2012). Cylindrical pellets are produced by copepods and euphausiids, and spherical pellets are produced by amphipods, ostracods and small copepods (Beaumont et al., 2002; Wexels Riser et al., 2007; Phillips et al., 2009; Köster et al., 2011). The origin of amorphous fecal pellets is still under debate, as they could be produced by chaetognaths (Wilson et al., 2008) or result from the fragmentation of other-shaped intact fecal pellets (Svensen et al., 2012). In the northern SCS, copepods are the dominant group, with some species (*Chiridius poppei*, *Heterorhabdus abyssalis*, *Scolecithricella valens*, and *Calanoides carinatus*) occurring only between 450 and 1000 m depth (Gong et al., 2017; Li et al., 2021). Larger individuals are mainly distributed in the deeper layers and produce larger fecal pellets (Paffenhöfer and Knowles, 1979; Li et al., 2021). This phenomenon of increased deep-sea fecal pellet flux due to mesopelagic and bathypelagic zooplankton is a common occurrence (Fowler et al., 1991; Wassmann et al., 2000; Belcher et al., 2017). Although zooplankton distribution is primarily concentrated within the epipelagic~~uphotic~~ zone (0–200 m), the total zooplankton abundance in the mesopelagic zones may still be substantial due to the large depth extent of these layers (Gong et al., 2017). Therefore, it is likely that a large amountnumber of fecal pellet production still occurs in the mesopelagic/bathypelagic zones to increase the export of fecal pellets to the deep sea, and these fecal pellets are characterized by strong cycling within the water column.

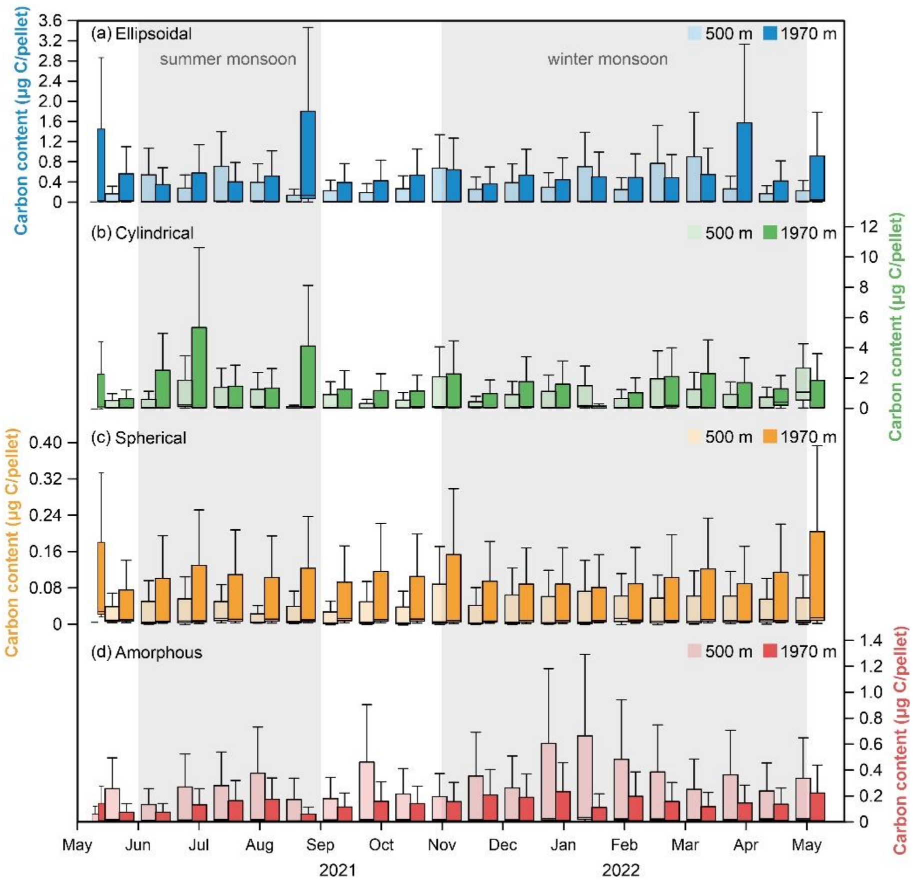


**Figure 1110.** Carbon content of four types of fecal pellets at water depths of 500 m and 1970 m at the time-series sediment-trap mooring TJ-A1B in the northern SCS. (a) Ellipsoidal pellet; (b) cylindrical pellet; (c) spherical pellet; (d) amorphous pellet.

In addition to the influence of mesopelagic and bathypelagic zooplankton, lateral input by deep-sea currents may also be a significant factor in the increasing export of fecal pellets to the deep sea. Analysis of the internal composition of fecal pellets identified the presence of terrigenous minerals like quartz and clay minerals, with an elemental composition characterized primarily by O, Si, C, Ca, Al, and K (Figs. 4, and 5). The weak correlation between the FPC flux and the POC flux at 1970 m (Fig. 8) also suggested that POC export in the deep northern SCS was influenced by multiple factors including the input from Taiwan rivers (Blattmann et al., 2018, 2019). Previous studies have demonstrated an increasing deep-sea POC flux in the northern SCS due to laterally--transported terrestrial organic carbon (Blattmann et al., 2018, 2019; Zhang et al., 2022).

Therefore, the significant increase in the POC flux and the FPC flux in deeper layers may be a result of lateral input via deep-sea currents along the continental slope. This phenomenon has also been observed in the Panama Basin, where Pilskaln and Honjo (1987) reported an increase in the FPC flux from 0.09 mg C m$^{-2}$ d$^{-1}$ at 1268 m to 1.50 mg C m$^{-2}$ d$^{-1}$ at 3769 m. They identified deep-sea currents as a possible driver of the increase in the FPC flux. In summary, lateral transport of deep-sea currents is also likely to lead to increased fluxes of deep fecal pellets.

Conversely, the biovolume and carbon flux of amorphous pellets were significantly reduced at 1970 m compared to the 500 m (Table 1). The average carbon content of amorphous pellets also showed a decrease from 0.02 μg C pellet$^{-1}$ at 500 m to 0.01 μg C pellet$^{-1}$ at 1970 m (Fig. 11d0), indicating the fragmentation of fecal pellets during the sinking process. Previous studies have shown that certain copepod species have distinct feeding behaviors on fecal pellets (Noji et al., 1991). For instance, the species *Oithona similis* is known to frequently engage in coprorhexy or coprochaly (González and Smetacek, 1994). This highly--adaptable species, which is widespread throughout the northern SCS and found in all water layers (Gong et al., 2017), and may play a critical role in fecal pellet fragmentation. In the eastern Fram Strait, higher copepod FPC fluxes were detected in the upper water column compared to the lower water column, indicating the effects of re-feeding and decomposition (Lalande et al., 2016). Similarly, studies conducted at K2 station K2 also provided evidence of fecal pellet fragmentation by repackaging of mesopelagic sinking debris (Wilson et al., 2008). These phenomena further support the idea that deep-dwelling zooplankton may play a significant role in the repackaging of fecal pellets. Additionally, increased current activity may also lead to fragmentation of fecal pellets. As shown in Fig. 121, the amorphous FPC flux showed a trend of winter peak and summer sub-peak, with the highest value occurring in May 2021. However, the temporal variation in amorphous pellet proportion to the total FPC flux did not show consistency with the amorphous FPC flux (Fig. 121b). Notably, as current velocity increased, the proportion of amorphous pellets to the total FPC flux was significantly higher (~40%), meaning that these pellets exhibited a higher degree of fragmentation (Fig. 121b, and 11c). Therefore, the fragmentation of fecal pellets in the northern SCS shows the joint effect of zooplankton reworking grazing and hydrodynamic changes.

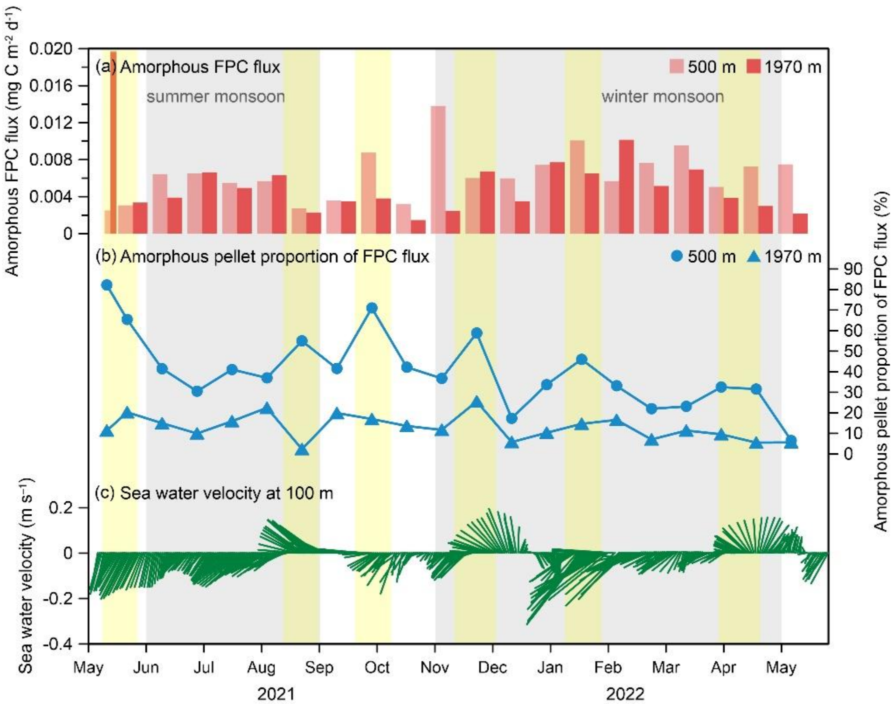


**Figure 1211.** Correlation between (a) amorphous FPC flux, (b) amorphous pellet proportion to the total FPC flux, and (c) sea water velocity at 100 m at the time-series sediment--trap mooring TJ-A1B in the northern SCS. Yellow shadows display the period with a relatively high proportion of amorphous pellets to the total FPC flux.

### 45.3 Sinking fate of zooplankton fecal pellets

In the northern SCS, variousable mechanisms affect the carbon export of zooplankton fecal pellets (Fig. 132). In the epipelagiceuphotic zone, zooplankton consume phytoplankton and egest sinking fecal pellets. Phytoplankton cells, zooplankton moults, and fecal pellets together form the larger aggregates. High FPC fluxes are observed during the northeast monsoon period and the summer rainy season. Presence of deep-dwelling zooplankton communities and lateral inputs from the slope into the deep basins tend to increase the export of fecal pellet to the deep sea. However, amorphous pellets are fragmented during the sinking process, indicating that surface-produced pellets are likely to be consumed and reworked by zooplankton grazing and fragmented by strong hydrodynamic activities. The evolving picture regarding the sinking fate of fecal pellets is therefore a coupling between the surface PPprimary production, repackaging and fragmentation by mesopelagic and bathypelagic zooplankton, lateral input by deep-sea currents and hydrodynamically--induced fragmentation.

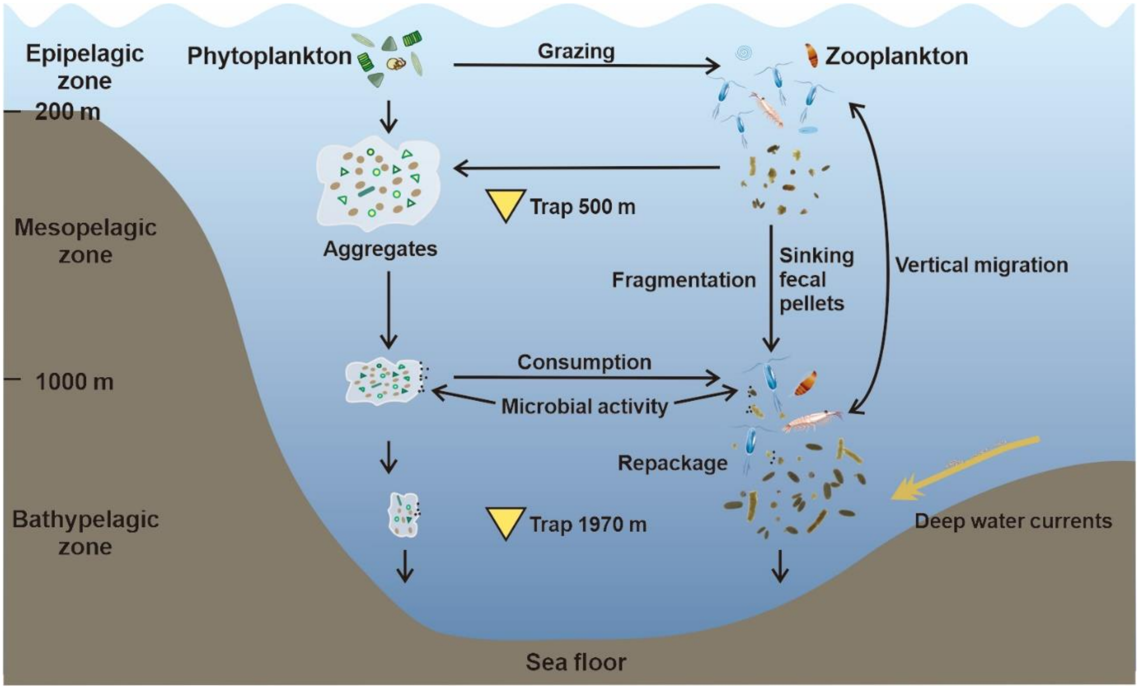


**Figure 13~~12~~.** Conceptual graph of the sinking processes regulating the carbon export of fecal pellets in the northern SCS. Yellow triangles show the locations of time-series sediment traps to collect fecal pellets in this study.

Zooplankton fecal pellets were a minor contributor to POC flux in the northern SCS. Fecal pellets contributed an average of 3.4% (range 0.3–15.8%) of the POC flux at 500 m, and 1.9% (range 0.5–5.7%) of the POC flux at 1970 m. These results are similar to those from several other oligotrophic seas (Urrère and Knauer, 1981; Pilskaln and Honjo, 1987; Wassmann et al., 2000; Wilson et al., 2008; Goldthwait and Steinberg, 2008; Shatova et al., 2012). ~~However, compared to the southern SCS (9.0%), t~~The contribution of fecal pellets to the total annual carbon flux was ~~comparatively~~ lower in the northern SCS compared to the southern SCS, possibly due to their higher degree of fragmentation and degradation (Li et al., 2022). Even though 87% of the sinking POC in the northern SCS was from marine biogenic~~spheric~~ origin, the majority may have come from phytoplankton cells such as *Prochlorococcus* and *Synechococcus*, zooplankton moults, zooplankton carcasses, and large aggregates (Zhang et al., 2019, 2022). Negative correlations between the POC flux and the fecal pellet contribution were observed, indicating that during periods of low POC flux, fecal pellets may play a proportionally larger role in deep-sea carbon export (Fig. 8). In contrast, during periods of high POC flux, aggregates composed of diatoms, dinoflagellate flocs, fecal pellets, and other debris appeared to be the major contributors (Fig. 3). Wilson et al. (2013) found that during periods of low POC flux in the northeast Pacific, fecal pellets also accounted for a greater proportion of deep-sea POC flux. This negative correlation between the FPC flux and the POC flux may be a common characteristic of particulate fluxes in the deep ocean (Wilson et al., 2013). In the northern SCS, the FPC flux was relatively low, with a high abundance of amorphous pellets and significantly low FPC/POC ratios, which may indicate a low efficiency BCP with a weak carbon sink effect.

Although the contribution of fecal pellets to the total carbon flux in the northern SCS is quantitatively low (0.3–15.8%), detailed analyses of the spatiotemporal variations in fecal pellet fluxes can provide significant insights into the processes controlling fecal pellet production, sinking, and reworking. Linking fecal pellet fluxes to seasonal and oceanographic dynamics can provide new insights for investigating the efficiency of BCP in the SCS, and greatly enhance our understanding of the biogeochemical processes that influence the export of organic carbon to the deep sea. Additional research is needed to determine the presence of fecal pellets at the sediment-water interface, and to further explore the sinking and burial processes of POC in the deep sea, from sinking particles to sediment cores.

## 5~~6~~ Conclusions

Characteristics, internal structure, quantity, and carbon content of zooplankton fecal pellets were investigated in the northern SCS to quantify the numerical and carbon fluxes of fecal pellets and to explore the process of fecal pellet sinking in the tropical marginal sea. Our conclusions are as follows:

1. Seasonal variations in the FPN and the FPC fluxes showed distinct peaks from November to April and from June to August. Strong northeast monsoon and surface water cooling led to the mixing of the upper water column, importing nutrients from subsurface into the epipelagic~~uphotic~~ layer, stimulating phytoplankton growth and increasing FPC flux in winter. Additionally, the FPC fluxes were also high in summer due to heavy precipitation that brought terrestrial nutrients into the sea.

2. Zooplankton fecal pellet fluxes were twice as high~~higher~~ at 1970 m than at 500 m. The occurrence of larger ellipsoidal, cylindrical, and spherical pellets at 1970 m provided evidence for repackaging and in-situ production of mesopelagic/bathypelagic zooplankton communities, and lateral input by deep-sea currents. Amorphous pellets were abundant and their biovolume decreased by half at 1970 m compared to 500 m, indicating that these fecal pellets were subject to fragmentation during sinking, possibly due to the impacts of zooplankton grazing and strong current disturbance.

3. The sinking process of fecal pellets is controlled by a combination of primary~~sea surface~~ productivity, mesopelagic and bathypelagic zooplankton repackaging, as well as current activities. Although the contribution of fecal pellets to the deep-sea carbon flux is relatively low in the northern SCS, fecal pellets still play a variable but indispensable role in the vertical carbon export.

### Data availability

The data involved in this study have been archived~~are underway of archiving~~ at the PANGAEA database (https://doi.pangaea.de/10.1594/PANGAEA.962713~~https://issues.pangaea.de/browse/PDI-35447~~).~~ They are provided as supporting materials during the reviewing process.~~

## Supplement

The supplement related to this article is available online.

## Author contributions

ZL designed the study and obtained the funding. HW carried out the measurements and wrote the original draft with helps of JL and BL. HW, ZL, JL, BL, and YZ contributed to data interpretation and manuscript writing. ZL, JL, BL, YZ, XZ, JC, JZ, HS, and WW participated in mooring deployment/recovery cruises.

## Competing interests

The contact author has declared that none of the authors has any competing interests.

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