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Concentrations and sinking rates of transparent exopolymer particles (TEPs) in a coastal sea: the Changjiang River (Yangtze River) Estuary

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Abstract

Transparent exopolymer particles (TEPs) are ubiquitous throughout the oceans, and their sedimentation is considered an efficient biological carbon sink pathway. To investigate the role of coastal TEPs in sinking carbon from the upper layer, samples were collected in the spring and summer of 2011 in the Changjiang River (Yangtze River) Estuary, a typical coastal water. The concentrations and sinking rates of TEPs were measured, and potential sedimentation flux of TEPs was estimated. TEPs concentrations ranged from 40.00 μg/L to 1 040.00 μg/L (mean=(209.70±240.93) μg/L) in spring and 56.67 μg/L to 1 423.33 μg/L (mean=(433.33±393.02) μg/L) in summer, and they were higher at bloom stations than at non-bloom stations during both cruises. A significant positive correlation between TEPs concentration and chlorophyll *a* (Chl *a*) concentration was detected, suggesting that phytoplankton was the primary source of TEPs in this area. TEPs sinking rates ranged from 0.08 m/d to 0.57 m/d with a mean of (0.28±0.14) m/d in spring and 0.10 m/d to 1.08 m/d with a mean of (0.34±0.31) m/d in summer. The potential sedimentation flux of TEP-C ranged from 4.95 mg/(m^2·d) to 29.40 mg/(m^2·d) with a mean of (14.66±8.83) mg/(m^2·d) in spring and 6.80 mg/(m^2·d) to 30.45 mg/(m^2·d) with a mean of (15.71±8.73) mg/(m^2·d) in summer, which was ~17.81% to 138.27% (mean=65.15%±31.75%) of sedimentation flux of phytoplankton cells in the study area. Due to the increase of TEPs concentrations and their sinking rates, sedimentation fluxes of TEPs at the bloom station were obviously higher than at the non-bloom station during both cruises. This study indicates that TEPs serve as a carbon sink in the Changjiang River Estuary, especially during bloom events, and their sedimentation should be taken into account when we study the carbon sedimentation in the coastal sea.

Key words: transparent exopolymer particles, sinking rates, Changjiang River (Yangtze River) Estuary, coastal sea

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1 Introduction

Transparent exopolymer particles (TEPs) are transparent gel-like particles in the ocean that were first identified in the early 1990s (Alldredge et al., 1993). They are formed from polysaccharides mostly exuded by phytoplankton cells and bacteria (Stoderegger and Herndl, 1999; Passow, 2002a). TEPs were largely ignored before the method for visualization and quantification was established in the 1990s (Passow and Alldredge, 1995). Being stained with the polysaccharide specific dye Alcian Blue (Alldredge et al., 1993; Passow, 2002a), recent studies showed that TEPs are abundant in most marine ecosystems with concentrations of up to 8 000 mL^{-1} (Passow, 2002a).

TEPs are classified as particles, but exhibit gel-like properties, such as a high degree of adhesion, high flexibility, and the ability to swell/shrink depending on environmental conditions (Passow, 2002a). These properties allow TEPs to form aggregates with other particles, such as phytoplankton cells, bacteria, and detritus in the water column (Simon et al., 2002; Bar-Zeev et al., 2011), which could in turn enhance sinking fluxes and stimulate the biological carbon pump in the ocean (Koeve, 2005). The size and abundance of TEPs are on the same order of magnitude as phytoplankton cells, which suggests that they could contribute significantly to the total particulate pool in the ocean (Engel and Passow, 2001; Engel, 2002). The C:N ratio of TEPs is higher than the usual Redfield ratio (Mari, 1999; Engel and Passow, 2001), making the fast sedimentation of TEPs an efficient pathway of carbon sedimentation in the ocean (Passow et al., 2001; Engel, 2004).

Several studies have been carried out to study the sedimentation and export of TEPs in open oceans. Martin et al. (2011) found that 25%–43% of the TEPs-containing particulate carbon at 100 m depth was exported below 750 m during a spring phytoplankton bloom in the sub-polar North Atlantic. Bar-Zeev et al. (2009) found that during a diatom bloom in the Gulf of Aqaba, export flux of TEPs from surface waters to deeper waters (down to

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300 m) accounted for 24%–78% of total particulate organic carbon (POC) fluxes. Ramaiah et al. (2005) found that TEPs export flux ranged from 29 mg/(m^2·d) to 62 mg/(m^2·d), accounting for 8%–14% of total POC flux at 200 m depth in the western subarctic Pacific. Several other studies also suggested that TEPs could play an important role in the POC export in the ocean (Waite et al., 2005; Reigstad and Wassmann, 2007; Ignacio, 2015). However, to our knowledge, there has been no study carried out in coastal seas.

Coastal seas receive large amounts of riverine inputs and upwelled nutrients, sustaining a disproportionately high biological productivity in these areas (Chen and Borges, 2009). Despite their small surface area, coastal seas play an important role in the global oceanic carbon cycle (Cai, 2011; Bauer et al., 2013), and most of them serve as sinks of atmospheric CO_2 (Chen and Borges, 2009). TEPs levels are also high in coastal waters due to the high phytoplankton biomass there (Passow and Alldredge, 1994; Klein et al., 2011; Sun et al., 2012; Jennings et al., 2017). Despite their high levels and potential importance in carbon sedimentation in the productive coastal waters, few studies have examined the sinking dynamics of TEPs in the coastal sea, and their sinking behavior is quite unclear in these areas. This research gap hampers a more comprehensive understanding of carbon sedimentation in coastal seas.

The Changjiang River (Yangtze River) Estuary, located on the continental shelf at the western rim of the Pacific Ocean, is one of the most eutrophic coastal seas in the world with large amounts of nutrients input from the Changjiang River (Chen et al., 2010; Cheng et al., 2012). The high nutrient supply results in high phytoplankton biomass in this area, and phytoplankton blooms frequently occur during spring and summer, with *Prorocentrum dentatum* and *Skeletonema* cf. *costatum* being the most common bloom species (Tang et al., 2006; Liu et al., 2016; Xiao et al., 2018). Due to the high biological productivity and efficient export of particulate organic matter, the Changjiang River Estuary serves as a net sink of atmospheric CO_2 (Zhai and Dai, 2009). Several studies have been carried out to study the biological pump or carbon export in the Changjiang River Estuary, and these studies mainly focused the attention on the sedimentation of phytoplankton cells and zooplankton fecal pellets (Guo et al., 2016, 2019; Qiu et al., 2018). Until now, there has been no report that investigates TEPs concentrations and their sinking behavior in this area. In this study, samples were collected in the Changjiang River Estuary in spring and summer 2011, and sinking experiments were carried out aboard. The main goal of this study is to: (1) determine the concentration of TEPs in the Changjiang River Estuary, clarify their distribution pattern and evaluate the relationship between TEPs and environmental and biological parameters; (2) determine TEPs sinking rates, estimate their carbon sedimentation flux, and finally discuss the role of TEPs in carbon sedimentation in the Changjiang River Estuary.

2 Materials and methods

2.1 *Study area*

Two cruises were carried out in the Changjiang River Estuary during 22–31 May (spring) and 19–27 August (summer) 2011. During each cruise, five stations with varying chlorophyll *a* (Chl *a*) fluorescence levels were selected to collect the samples and carry out the sinking experiments. One bloom station (B3) and four non-bloom stations (C4, B5, A2, L1) were selected in spring and three bloom stations (F3, E3, D3) and two non-bloom stations (W3, O11) were selected in summer (Fig. 1). The detailed information and surface environmental parameters of these stations were shown in Table 1 of Guo et al. (2016).

2.2 *Sampling and analysis*

The vertical profiles of temperature (*T*), salinity (*S*) and fluorescence were recorded with a Seabird conductivity, temperature, and depth device (SBE 9/11 plus) complemented with a SeaTech fluorometer from surface to bottom at each station. Water samples were collected using a rosette sampler at 4 to 5 water depths at each station from the surface to the bottom, evenly distributed throughout the water column, for analysis of nutrients, Chl *a*, phytoplankton cell abundance and species composition, and TEPs concentration.

2.2.1 *Nutrient analysis*

Water samples for determination of nutrient concentrations

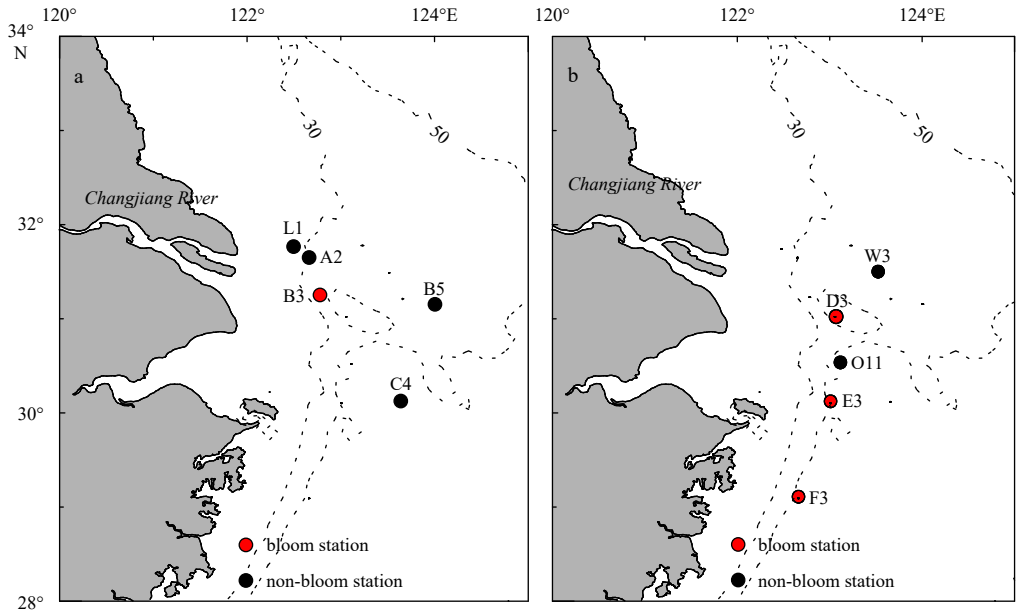

Fig. 1. Study sites in the Changjiang River Estuary during spring (a) and summer (b) in 2011. Dotted lines represent bathymetry (m).

Table 1. Correlation analysis between TEPs concentrations and environmental parameters at the survey stations

Cruise		Temperature	Salinity	Chl *a*	NH_4^+	NO_2^-	NO_3^-	PO_4^{3-}	SiO_3^{2-}
Spring	*R* (N)	−0.091 (22)	0.111 (22)	0.794** (22)	−0.586 (22)	0.209 (22)	−0.660 (22)	0.053 (22)	−0.316 (22)
Summer	*R* (N)	0.491 (25)	0.092 (25)	0.870** (25)	0.872 (25)	0.721 (25)	0.304 (25)	0.240 (25)	0.473 (25)
All	*R* (N)	0.726* (47)	−0.397 (47)	0.849** (47)	0.747 (47)	0.803 (47)	−0.151 (47)	0.435 (47)	−0.274 (47)

Note: * $P< 0.05$; ** $P< 0.01$. *N* indicates the number of samples.

were filtered through acid-cleaned acetate cellulose filters with a 0.45-μm pore size. After being poisoned by $HgCl_2$ solution, the filtrates were stored at 0–4°C in dark until analysis. In the laboratory, nutrients (NO_3^-, NO_2^-, PO_4^{3-}, SiO_3^{2-}, and NH_4^+) were determined with an autoanalyzer (model: SkalarSAN^{plus}, Skalar Analysis, Netherlands) according to Liu et al. (2011).

2.2.2 *Chl a analysis*

Samples for Chl *a* concentration analysis were filtered using 25 mm GF/F filters (Whatman™) and then stored at –20°C in dark until analysis. Chl *a* was then extracted with 90% acetone for 24 h at –20°C in dark, and samples were then analyzed with a Turner-Designs Trilogy™ laboratory fluorometer (Welschmeyer, 1994).

2.2.3 *Phytoplankton analysis*

Samples for phytoplankton analysis were preserved with 2% buffered formalin on board the vessel. In the laboratory, phytoplankton cells were identified and enumerated with an inverted microscope (Olympus, Japan) at a magnification of 200× or 400× according to the Utermöhl method (Utermöhl, 1958). The dominance of phytoplankton species was described by the dominance index (*Y*):

$$Y = (n_i/N) \times f_i, \tag{1}$$

where n_i is the sum of cell abundance for species *i* in all samples, *N* is the sum of cell abundance for all species, and f_i is the frequency of occurrence for species *i* in all samples (Guo et al., 2014).

The volume of phytoplankton cells was calculated from their linear dimensions using the geometric models (Sun and Liu, 2003). Thirty or more individual cells of each phytoplankton species were measured for their linear dimensions. Phytoplankton cell carbon (Phytoplankton-C) was then calculated from the cell volume with the equation formulated by Menden-Deuer and Lessard (2000).

$$C = 0.288 \times V^{0.811} \text{ for diatoms}, \tag{2}$$

$$C = 0.760 \times V^{0.819} \text{ for dinoflagellates}, \tag{3}$$

$$C = 0.216 \times V^{0.939} \text{ for other algae}, \tag{4}$$

where *C* is the carbon content of each species expressed in pg/cell, and *V* is the cell biovolume expressed in μm^3.

2.2.4 *TEPs and carbon analysis*

TEPs concentration was measured followed Passow and Alldredge (1995). Three replicated 150–200 mL samples were vacuum filtered (<20 kPa) with polycarbonate filters (Millipore; 25 mm diameter; 0.20 μm). Filters were first stained for <5 s with 1 mL of 0.02% Alcian Blue 8GX in 0.06% acetic acid (pH 2.5), and then samples were rinsed with 3 mL of deionized water. Alcian Blue-stained material in the filters was extracted with 6 mL of 80% sulfuric acid for 2 h on an oscillator, and the absorbance of the extracted material was then measured spectrophotometrically at 787 nm using a Varian Cary spectrophotometer. TEPs were quantified by a standard curve prepared with xanthan gum (XG) particles as described by Passow and Alldredge (1995), and concentrations are expressed in micrograms of XG equivalents per liter (μg/L). The detection limit of the measurements was 5.9 μg/L and the standard deviation of the replicate samples was less than 13% in all cases. Triplicate blanks (empty filters stained with Alcian Blue) were also prepared with every batch of samples. TEP-carbon (TEP-C, μg/L) was calculated with the slope (0.75) from the equation as follows (Engel and Passow, 2001):

$$\text{TEP-C} = 0.75 \times TEP_{\text{color}}, \tag{5}$$

where TEP_{color} is the TEPs concentration with the unit of μg/L.

2.2.5 *Sinking rates*

Sinking rates of TEPs were determined at each station, and the SETCOL method (Bienfang, 1981) was used to measure the sinking rates. For analysis, a Plexiglass column (height=0.45 m and volume=750 mL) was filled completely with a homogeneous water sample within 10 min after sampling, and a cover was then placed on the set-up. The content in Plexiglass column was allowed to settle undisturbed for 2–3 h aboard the vessel, and the temperature was maintained by pumping water from a thermostatically controlled water bath with water jackets. In order to minimize the effect of vibrations of the vessel body, the SETCOL column was put in opaque sleeves and fixed with soft foam during the incubation as suggested by Mei et al. (2003). The settlement experiment was terminated by successively draining the upper, top, and bottom compartments of the Plexiglass column via taps in the wall of column. The TEPs concentration was measured before and after the settlement in all three compartments. These measurements were combined to calculate the sinking rate of TEPs according to the formula:

$$V = (B_s/B_t) \times L/t, \tag{6}$$

where *V* is sinking rate, B_s is the amount of TEPs settled into the bottom compartment, B_t is the total amount of TEPs in the column, *L* is length of the column, and *t* is settling interval. Three replicates of the settlement columns were filled with seawater collected from each sampling depth, and the mean of the three sinking rate values was calculated to represent the sinking rate at a particular sampling depth. Sinking rates of phytoplankton cells were also determined with the SETCOL method, with the Chl *a* being measured to calculate the sinking rates. Carbon flux of TEPs and phytoplankton cells estimates were provided by the product of the SETCOL-determined sinking rates mentioned above and the TEP-carbon or phytoplankton-carbon at the bottom layer. As the effect of water turbulence was not considered in the estimation on flux of TEPs and phytoplankton cells, the sedi-

mentation flux in this study was treated as the "potential sedimentation flux".

2.3 *Data analysis*

SPSS 14.0 was applied to carry out the Pearson Correlation Analysis between TEPs concentrations and various environmental parameters. Significant differences of environmental parameters and TEPs concentrations between different stations were tested using one-way ANOVA analysis. A probability of $p<0.05$ was considered significant in all statistical analyses.

3 Results

3.1 *Hydrographic conditions and phytoplankton community structure*

Vertical profiles of temperature, salinity, and Chl *a* concentration at each station are presented in Fig. 2. Surface temperatures ranged from 16.70°C to 20.87°C (mean=(18.23±1.45)°C) in spring, which was lower than that in summer, ranging from 24.79°C to 28.13°C (mean=(26.13±1.12)°C). Surface salinity ranged from 30.84 to 32.15 (mean=31.56±0.55) in spring, which was higher than that in summer, ranging from 24.92 to 31.88 (mean=28.70±2.50). During both cruises, the upper layers were dominated by warm and low salinity water and the deeper layers were dominated by cool and high salinity water. In spring, the highest surface Chl *a* concentration (17.15 μg/L) was observed at Station B3, and a *Prorocentrum dentatum* bloom was observed here with cell abundance exceeding 10^6 cells/L. At this station, *P. dentatum* accounted for over 95% of total phytoplankton cell abundance. Surface Chl *a* concentrations at the other four stations were generally low (<2.0 μg/L), and cell abundances at these stations were less than 20×10^3 cells/L. In summer, high surface Chl *a* concentrations (>20 μg/L) were observed at Stations F3, E3 and D3, which was more than 10 fold of that at Stations W3 and O11 (<2 μg/L). A *S.* cf. *costatum* bloom was observed at Stations F3, E3 and D3 with cell abundance exceeding 10^6 cells/L. At other stations (W3 and O11), phytoplankton cell abundance was less than 15×10^3 cells/L. The detailed composition of dominant phytoplankton species at each station was shown in Fig. 4 of Guo et al. (2016), and the phytoplankton community was dominated by dinoflagellates in spring and diatoms in summer in the study area. In the vertical direction, Chl *a* concentrations at each station were always higher in upper layers than in underlying layers, and this was most apparent at the bloom station during both cruises.

3.2 *TEPs concentrations*

Concentrations of TEPs at each station are shown in Fig. 3. TEPs concentrations ranged from 40.00 μg/L to 1 040.00 μg/L with an average value of 209.70 μg/L in spring, and they ranged from 56.67 μg/L to 1 423.33 μg/L in summer with an average value of 433.33 μg/L. In spring, surface TEPs concentration was highest with a value of 840.00 μg/L at Station B3, which was at least 3 fold of that at the non-bloom Stations C4, B5, A2 and L1. In summer, surface TEPs concentrations at the bloom Stations F3, E3 and D3 (>1 000 μg/L) were also higher than at non-bloom Stations W3 and O11 (<700 μg/L). In the vertical direction, the TEPs depth-profiles showed consistently higher concentrations in the upper layer than in deeper layers during both cruises.

TEPs concentration showed significant positive correlation

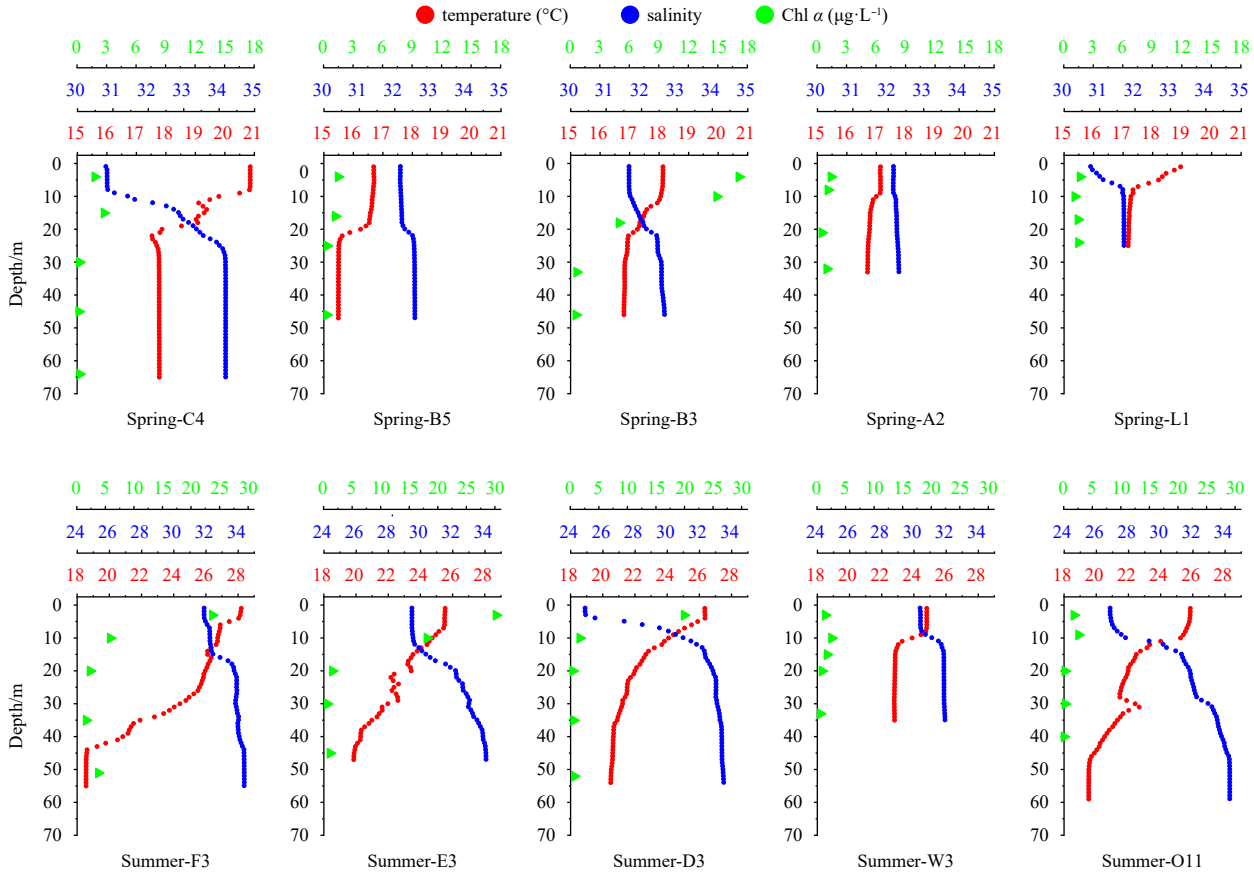

Fig. 2. Vertical profiles of temperature, salinity, and Chl *a* concentrations at each station during the two cruises.

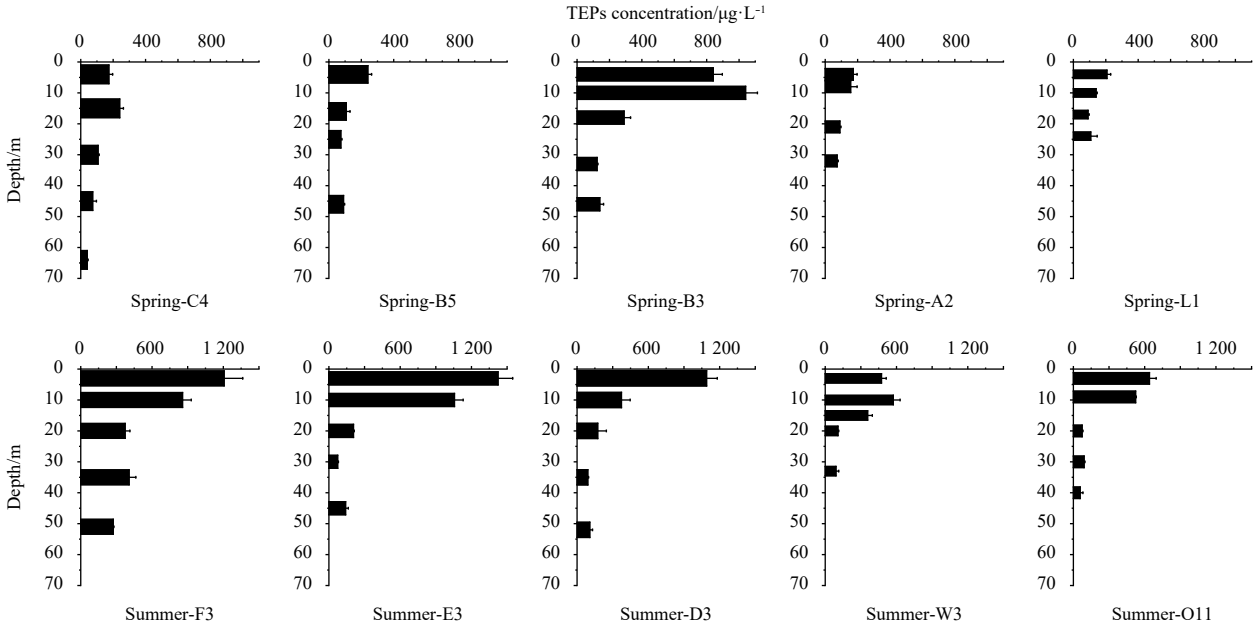

Fig. 3. TEPs concentrations (μg/L) at the survey stations during the two cruises.

with Chl *a* concentration during both cruises, and showed significant positive correlation with temperature with all the data of these two cruises (Table 1). No other environmental parameter was found to have a significant correlation with TEPs concentration. The equation obtained for the TEPs-Chl *a* relationship is lg TEPs = 2.13 + 0.59 × lg Chl *a* (n=22, r^2=0.81 and p<0.01) in spring and lg TEPs = 2.30 + 0.61 × lg Chl *a* (n=25, r^2=0.83 and p<0.01) in summer.

3.3 *Sinking rates of TEPs*

Sinking rates of TEPs are shown in Fig. 4. Sinking rates of TEPs ranged from 0.08 m/d to 0.57 m/d in spring with an average value of 0.28 m/d and from 0.10 m/d to 1.08 m/d in summer with an average value of 0.34 m/d. Except for the surface layer at Station F3 in summer, most of the sinking rates determined in the study area were below 1 m/d. For the surface layer in spring, the sinking rate of TEPs at the bloom Station B3 ((0.57±0.17) m/d) was the highest, followed by Stations B5, L1, and A2. Station C4 exhibited the lowest TEPs sinking rate. For the surface layer in summer, sinking rates of TEPs were obviously higher at the bloom Station F3, E3, and D3 (mean=(0.96±0.09) m/d) than at the non-bloom Stations W3 and O11 (mean=(0.24±0.03) m/d). In the vertical direction, TEPs sinking rates were higher in the surface layer than in underlying layers at most stations, and it is particularly apparent in summer (Fig. 5).

The potential sedimentation flux of TEP-C estimated with

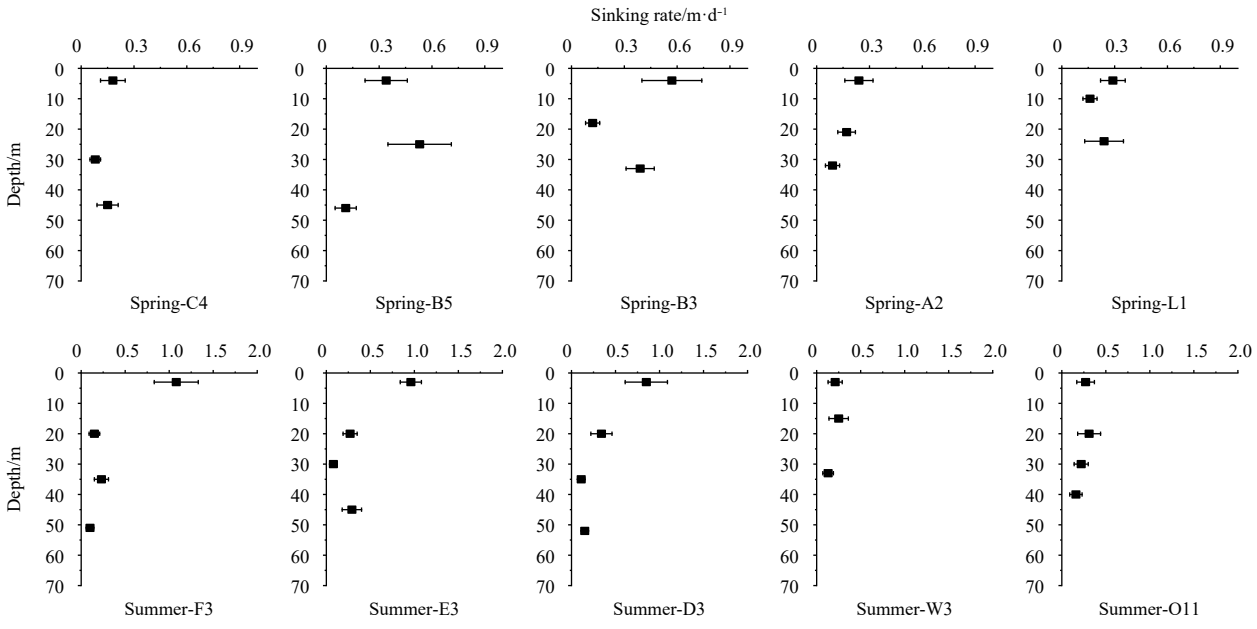

Fig. 4. Sinking rates of TEPs at each station during the two cruises as measured with the SETCOL method.

SETCOL-determined sinking rates at each station is shown in Fig. 6. In spring, the sedimentation flux of TEP-C ranged from 4.95 mg/(m²·d) to 29.40 mg/(m²·d) with an average value of (14.66±8.83) mg/(m²·d), and the flux at the bloom Station B3 was higher than that at the non-bloom Stations C4, B5, A2 and L1. In summer, the potential sedimentation flux of TEP-C ranged from 6.80 mg/(m²·d) to 30.45 mg/(m²·d) with an average value of (15.71±8.73) mg/(m²·d), and the flux at the bloom Stations F3, E3 and D3 were higher than that at the non-bloom Stations W3 and O11. The potential sedimentation flux of phytoplankton-C in the study area ranged from 10.13 mg/(m²·d) to 77.52 mg/(m²·d) in spring and from 8.50 mg/(m²·d) to 80.95 mg/(m²·d) in summer. Sedimentation flux of TEP-C equalled to 27.82%–138.27% (mean=65.15%±31.75%) of that of phytoplankton-C during the two cruises in the study area.

4 Discussion

4.1 *Correlation between TEPs and biological/environmental parameters*

In this study, TEPs concentrations in the 10 m layer at Station B3 during spring and within the surface layer at Stations F3, E3, and D3 during summer were high, exceeding 1 000 μg/L (Fig. 3). Phytoplankton biomasses at these stations were also high (Fig. 2). A *P. dentatum* bloom was observed at Station B3 in spring, and a *S.* cf. *costatum* bloom was observed at Stations F3, E3 and D3 in summer. The coincident maxima for TEPs and phytoplankton biomass at these stations are consistent with the concept that TEPs are mainly produced by growing and senescing phytoplankton cells (Passow et al., 2001; Passow, 2002b). The significant positive correlation between TEPs concentrations and Chl *a* concentrations in this study provides further support for this concept (Table 1).

Several studies have found that TEPs concentrations were high during phytoplankton blooms (Ramaiah and Furuya, 2002; Ortega-Retuerta et al., 2017). In particular, diatom blooms are always associated with high TEPs concentrations during their actively growing and/or senescent phases (Mari and Burd, 1998). This is consistent with the observed high TEPs concentrations at Stations F3, E3 and D3 in summer (Fig. 3). *Skeletonema* cf. *costatum* has already been proven to be a very important producer of TEPs (Engel, 2000; Beauvais et al., 2003), and the stations mentioned above represent only the stations where *S.* cf. *costatum* bloomed. In spring, TEPs concentration in the surface layer at Station B3 where *P. dentatum* bloomed was also higher than at other stations (Fig. 3). To date, there has been no report on the production of TEPs by *P. dentatum*. However, several studies have observed high TEPs levels during blooms dominated by dinoflagellates (Alldredge et al., 1998; Berman and Viner-

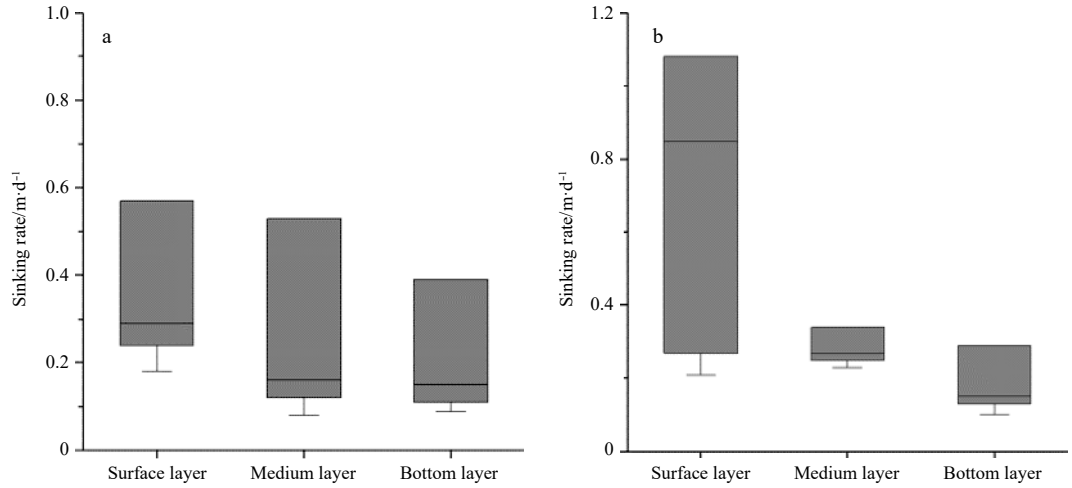

Fig. 5. Comparison of TEPs sinking rates at the surface, medium and bottom layer during the two cruises. a. Spring and b. summer. Box plots show the median value (mid-line), 25% and 75% quantiles (box), and 5% and 95% quantiles (whiskers).

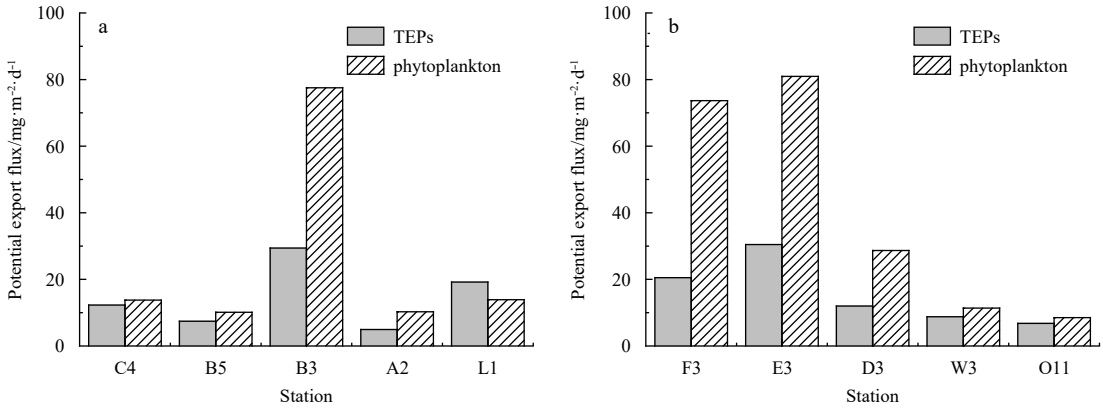

Fig. 6. Potential carbon sedimentation flux of TEPs and phytoplankton cells at each station in spring (a) and summer (b) as estimated by SETCOL-measured sinking rates.

Mozzini, 2001), and Han et al. (2016) found that *Prorocentrum* could produce copious amounts of mucous. Qiu et al. (2018) also found that *P. dentatum* could form aggregates during a spring bloom in the coastal East China Sea (ECS). Therefore, the ability of *P. dentatum* to produce TEPs and their precursors needs to be clarified in the future.

The TEPs profiles in the water column of this study presented maximum values in the upper layers and decreased as water depth increased (Fig. 3), which was consistent with that of Chl *a* (Fig. 2). Previous studies in other coastal waters have reported similar vertical distribution pattern (Bar-Zeev et al., 2011; García et al., 2002; Corzo et al., 2005; Zamanillo et al., 2019). These studies and our observations establish that this vertical distribution pattern of TEPs with higher concentrations in the upper layer decreasing with depth, is common in coastal seas during warm seasons, and this is mainly due to the higher phytoplankton biomass in the upper layer (Zamanillo et al., 2019). In most studies, the relationship between TEPs and Chl *a* was expressed with a potential function of the form lg TEPs=$\alpha + \beta \times$ lg Chl *a*, and the value of α and β obtained in this study fell in the range reported in historical studies (Table 2).

Besides phytoplankton biomass and species composition, TEPs formation and distribution are also controlled by several environmental factors, including temperature (Claquin et al., 2008; Fukao et al., 2012), salinity (Mari et al., 2012) and nutrient levels (Mari et al., 2005). In this study, TEPs concentrations showed a significant positive correlation with temperature (Table 1). Claquin et al. (2008) studied the effects of temperature on photosynthetic parameters and TEPs production in eight species of marine microalgae, and they found that temperature influenced TEPs production by affecting the photosynthetic activity of phytoplankton cells. Fukao et al. (2012) studied the effects of temperature on cell growth and production of TEPs by the diatom *Coscinodiscus granii*, and they found higher growth rates of *C. granii* at higher temperatures. This is likely responsible for the high production of TEPs at higher temperature. Therefore, temperature impacts TEPs production by affecting phytoplankton physiological activity. In this study, salinity and nutrient concentrations showed no significant correlations with TEPs concentration (Table 1), despite their reported effects on TEPs formation (Mari et al., 2005, 2012; Pedrotti et al., 2010). The limited sample data and insignificant variation in salinity and nutrient concentrations among sampling stations (refer to Table 1 of Guo et al. (2016)) may be responsible for the poor correlations between TEPs and these environmental parameters in this study.

4.2 *Comparison with other oceanic systems*

TEPs concentrations ranged from 40.00 μg/L to 1 423.33 μg/L in the study area, which is within the range reported in other coastal seas (Fig. 7). It has been found that coastal seas always present high TEPs concentrations (Passow, 2002a), which were higher than those reported in some open oceans (Kodama et al., 2014; Iuculano et al., 2017; Ortega-Retuerta et al., 2019). However, due to higher nutrient inputs and shallower mixing depths, phytoplankton biomass is also higher in coastal seas (Chang et al., 2003). For a better comparison, the ratio between TEPs concentration and phytoplankton biomass (Chl *a*) is considered here. Average TEP:Chl *a* ratios (w/w) in the study area ranged between 48.98 μg/μg and 380.95 μg/μg (mean=(148.83±90.47) μg/μg) in spring and 47.10 μg/μg and 385.19 μg/μg (mean=(182.84±103.60) μg/μg) in summer. These values are comparable to TEP:Chl *a* ratios determined in other coastal seas, such as the Ross Sea (~85 μg/μg) (Hong et al., 1997) and Subarctic Pacific (125–144 μg/μg) (Ramaiah et al., 2001), and lower than those in open oceans, such as the north-eastern Aegean Sea ((578±485) μg/μg) (Parinos et al., 2017) and the oligotrophic Pacific Ocean ((357.3±126.6) μg/μg) (Iuculano et al., 2017). These widely varying TEP:Chl *a* ratios imply that TEPs concentration, although associated with phytoplankton biomass, is also a factor of various physical and biological processes. The relatively high TEP:Chl *a* ratios in open oceans was most probably due to the strong nutrients limitation which promote TEPs production by phytoplankton cells (Pedrotti et al., 2010). Furthermore, as bacteria and other heterotrophic organisms also produce TEPs and its precursors (Sugimoto et al., 2007; Ortega-Retuerta et al., 2019), the active regeneration process in the open ocean (Capblancq, 1990) could also contribute to the high TEP:Chl *a* ratios there.

4.3 *TEP-C in the Changjiang River Estuary*

TEP-C calculated in this study ranged from 30.05 μg/L to 780.00 μg/L (mean=(157.27±180.70) μg/L) in spring and from 42.50 μg/L to 1 067.50 μg/L (mean=(325.10±294.77) μg/L) in summer. Phytoplankton-C were within the ranges of 6.84–293.17 μg/L (mean=(57.43±84.65) μg/L) in spring and from 1.33 μg/L to 595.52 μg/L (mean=(91.21±153.76) μg/L) in summer. Generally, TEP-C was at a similar level to phytoplankton-C and even slightly higher than phytoplankton-C during both cruises in the study area (Fig. 8). It should be noted that in the study of Guo et al. (2016), phytoplankton cell carbon was converted from cell volume with the equation in Eppley et al. (1970) in the Changjiang River Estuary. However, phytoplankton cell carbon was calculated from the cell volume with the equation formulated by Menden-Deuer and Lessard (2000) in this study. To our knowledge, the formula in Menden-Deuer and Lessard (2000) is more widely accepted in recent years compared to that of Eppley et al. (1970). Therefore, we calculated phytoplankton cell carbon with the equation in Menden-Deuer and Lessard (2000).

Several studies have revealed that TEPs could constitute an important part of the POC pool in coastal environments. Wetz et al. (2009) found that TEP-C averaged 16% of the total POC in the Neuse River Estuary of North Carolina. Sun et al. (2012) found that TEP-C could constitute 15% of the total POC in the Zhujiang River Estuary in China. Malpezzi et al. (2013) found that TEP-C

Table 2. Log-log relationship between TEPs (μg/L) and Chl *a* concentration (μg/L) in different areas: lg TEPs = $\alpha + \beta \times$ lg Chl *a*

Dominant species	Sampling site	α	β	Reference
Phaeocystis antarctica	Ross Sea	2.25	0.65	Hong et al. (1997)
Mixed diatoms	Baltic Sea	ND	0.33	Passow (2002a)
Diatoms	East Sound	2.25	0.45	Passow (2002a)
Diatoms	Bransfield Strait, Antarctica	1.63	0.32	Corzo et al. (2005)
–	Southern Ocean	1.08	0.38	Ortega-Retuerta et al. (2009)
Dinoflagellates	Changjiang River Estuary	2.13	0.59	this study
Diatoms	Changjiang River Estuary	2.30	0.61	this study

Note: – means none information, and ND no data.

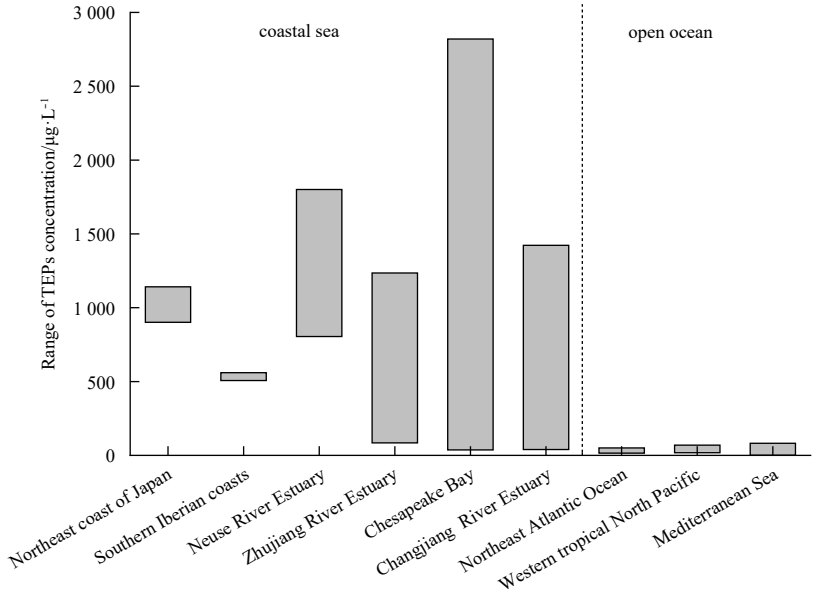

Fig. 7. Range of TEPs concentrations (μg/L) observed in coastal and open oceans around the world. The data are from the northeast coast of Japan (Ramaiah et al., 2001), Southern Iberian coasts (Prieto et al., 2006), Neuse River Estuary (Wetz et al., 2009), Zhujiang River (Pearl River) Estuary (Sun et al., 2010), Chesapeake Bay (Malpezzi et al., 2013), Changjiang River Estuary (this study), Northeast Atlantic Ocean (Engel, 2004), western tropical North Pacific (Kodama et al., 2014), and Mediterranean Sea (Ortega-Retuerta et al., 2019).

could constitute 32% of the total POC in the Chesapeake Bay. Ortega-Retuerta et al. (2017) observed that in early summer TEPs represented 77% of the POC on average in the coastal northwestern Mediterranean Sea. Ignacio (2015) estimated that TEPs would represent between one quarter and two fifths of the total POC of the epipelagic zone for the global ocean by studying TEPs concentrations across the tropical and subtropical regions of the Atlantic, Indian and Pacific Oceans. It is unfortunate that POC data are not available for this analysis. However, phytoplankton-C was calculated from the geometric model (Sun and Liu, 2003). We compared TEP-C and phytoplankton-C with the assumption that this kind of comparison would reflect the importance of TEP-C in the POC pool. TEP-C was at a similar level to phytoplankton-C or even higher than it during spring and summer (Fig. 8). As phytoplankton-C always constitutes a significant part of the POC pool in eutrophic coastal seas (Chang et al., 2003), TEPs would also most probably constitute a significant part of the POC pool in the Changjiang River Estuary. It should be noted that our calculations and conversion factors for TEP-C come from the only available theoretical concentration relationships. These relationships were determined from TEPs produced from a variety of pure diatom cultures as well as a natural assemblage of diatoms (Engel and Passow, 2001), ranging from 0.53 μg C (μg Xeq)$^{-1}$ to 0.88 μg C (μg Xeq)$^{-1}$ with an average value of 0.75 μg C (μg Xeq)$^{-1}$. Assuming that the production of exudates is likely to be species-specific for phytoplankton cells (Penna et al., 1999), the C con-

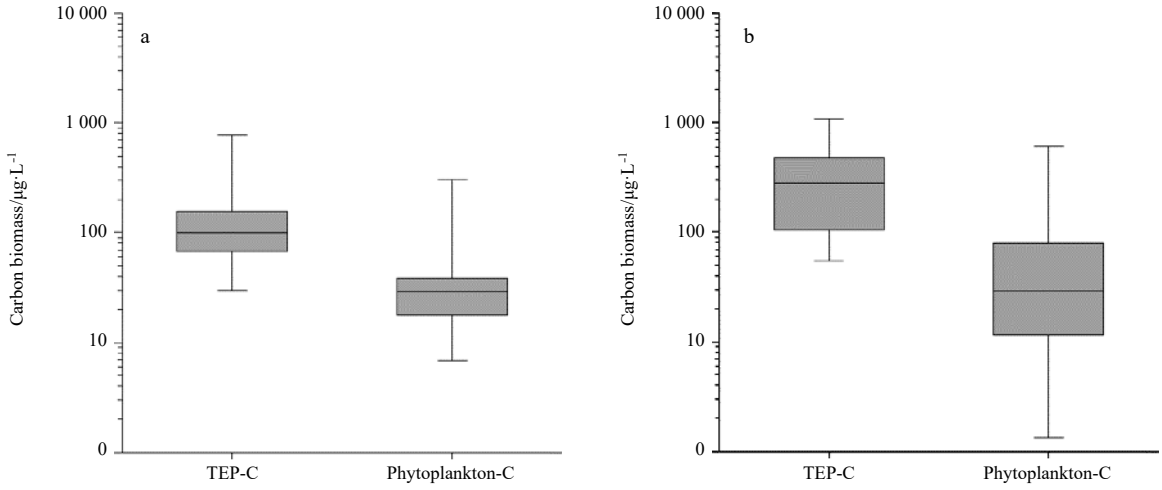

Fig. 8. Comparison of TEP-C (μg/L; data presented on a $\log_{10}$scale) and phytoplankton-C (μg/L; data presented on a $\log_{10}$scale) during two cruises. a. Spring and b. summer. Box plots show the median value (mid-line), 25% and 75% quantiles (box), and 5% and 95% quantiles (whiskers).

tent of TEPs would also change among species. Therefore, the conversion factors from Engel and Passow et al. (2001) may be inaccurate for estimating TEP-C in phytoplankton groups other than diatoms.

4.4 *TEPs sinking rates and their potential role in the carbon sedimentation in the Changjiang River Estuary*

There have been already several studies on carbon sedimentation in the Changjiang River Estuary and adjacent coastal ECS. Hung et al. (2013) estimated that POC export fluxes are 486–785 mg/(m^2·d) in the coastal ECS with sediment trap measurements and vertical mixing models. Guo et al. (2016) studied sinking rates of phytoplankton cells in the Changjiang River Estuary and estimated that export flux of phytoplankton cells was (26.10±26.25) mg/(m^2·d) in spring and (63.13±48.16) mg/(m^2·d) in summer. Qiu et al. (2018) reported simultaneous estimates of the POC fluxes from phytoplankton cells and zooplankton fecal pellets in the coastal ECS, and found that POC fluxes at the bloom station could be as high as 24 g/(m^2·d), which was about 100 times the rate at non-bloom stations (0.26 g/(m^2·d)). Until now, there has been no study on TEPs sinking rates and their export flux in this area.

To our knowledge, we present here the first data of TEPs sinking rates in the Changjiang River Estuary, and the 0.08–1.08 m/d range of TEPs sinking rates measured with the SETCOL method in this study fell within the range reported in other studies (Table 3). It has been reported that TEPs are less dense than seawater, with an estimated density between 0.70 g/cm^3 to 0.84 g/cm^3 (Azetsu-Scott and Passow, 2004). Therefore, ballast-free, "pure" TEPs would ascend in the seawater. This is consistent with the results of Azetsu-Scott and Passow (2004) and Mari (2008) that the sinking rates of TEPs could be negative (Table 3). However, ballast-free TEPs are unlikely to exist in large numbers in coastal seas due to high concentrations of suspended inorganic and organic particulate matter in these areas. As TEPs are extremely sticky (Rochelle-Newall et al., 2010), they can form aggregates with ambient phytoplankton cells, bacteria, mineral clays, and detritus (Prieto et al., 2002). This aggregation probably increases the weight of TEPs and allows them to sink to deeper waters (Mari et al., 2017). De Vicente et al. (2009) calculated TEPs sinking rates in an oligotrophic reservoir via sediment trap results. They found that TEPs sinking rates ranged from 1.12 m/d to 1.31 m/d, which is slightly higher than our results. In the Vincente study, they found large phytoplankton aggregates in the sediment traps, and these aggregates containing TEPs are likely responsible for the higher TEPs sinking rates reported in their study. However, these large phytoplankton aggregates containing TEPs might be lost during the discrete sampling of the SETCOL method. Therefore, this study underestimated TEPs sinking rates by excluding the effect of large phytoplankton aggregates.

Table 3. Comparison of the TEPs sinking rates in this study with results from other studies

Location	TEPs form	Sinking rate/m·d^{-1}	Reference
Seawater from Santa Barbara Channel	particle-free TEPs	–0.22 to 0.04	Azetsu-Scott and Passow (2004)
Water from New Caledonia	aggregates of TEPs and latex beads	–0.29 to 0.49	Mari (2008)
Oligotrophic reservoir (Quéntar)	natural TEPs	1.12–1.31	De Vicente et al. (2009)
Changjiang River Estuary	natural TEPs	0.08–1.08	this study

During both cruises, sinking rates of TEPs at the bloom station were obviously higher than at the non-bloom station (Fig. 4). In the vertical direction, TEPs sinking rates were higher in the surface layer than in underlying layers (Fig. 5). Therefore, sinking rate of TEPs in this study was high at sites where phytoplankton biomass was high. According to coagulation theory, aggregation of particles depends on collision rates and their sticking coefficients (Burd and Jackson, 2009). The higher abundance of phytoplankton cells would result in the higher collision rates between TEPs and phytoplankton cells, further leading to the enhanced formation of fast sinking phytoplankton-TEPs aggregates (Jackson and Burd, 1998). Qiu et al. (2018) found that phytoplankton sinking rates at the bloom event was more than 10 times the rate at non-bloom stations during a *P. dentatum* bloom in the ECS, and the microscopic observation indicated that the formation of phytoplankton aggregates was responsible for the high sinking rates during the bloom. Therefore, there is a larger probability for TEPs and phytoplankton cells to collide and form aggregates at the bloom station in this study, which should be responsible for the higher TEPs sinking rates there.

It has been reported that TEPs disappear from the euphotic zone via two main pathways: degradation by bacteria and sinking processes associated with other particles (Prieto et al., 2006). Researchers have concluded that the former pathway is less important than the sinking process due to the refractory nature of TEPs (Obernosterer and Herndl, 1995). Therefore, sedimentation of TEPs represents the dominant pathway of their removal in the ocean. As the concentration and carbon content of TEPs is sometimes within the same order of magnitude as that of phytoplankton cells (Passow, 2002a), export of carbon via sedimentation of TEPs is significant. In the Santa Barbara Channel, the sedimentation flux of TEPs at 500 m was found to range from 7 mg/(m^2·d) to 70 mg/(m^2·d), contributing roughly 30% to the POC flux in this area (Passow et al., 2001). In an oligotrophic reservoir in southern Spain, the sedimentation flux of TEPs ranged from 0.51 mg/(m^2·d) to 177.04 mg/(m^2·d) at the bottom layer, contributing between 0.02% and 31% to the carbon sedimentation to sediments (Mari et al., 2017). In this study, the potential sedimentation flux of TEPs was calculated within the range of 4.95–29.40 mg/(m^2·d) in spring and 6.80–30.45 mg/(m^2·d) in summer (Fig. 6). It is unfortunate that no data regarding the sedimentation flux of POC was obtained for this study. However, we estimated the potential sedimentation flux of phytoplankton cells with the SETCOL-determined sinking rates in this study, and found that the sedimentation flux of TEPs could be equalled to 27.82%–138.27% of sedimentation flux of phytoplankton cells in the study area. Because phytoplankton cell sedimentation is always considered an important pathway of carbon sedimentation in the coastal sea (Turner, 2002, 2015), the results of this study indicate that sedimentation of TEPs should also be an important pathway of POC export in the Changjiang River Estuary. As TEPs are types of transparent gel-like particles found in seawater, they have been largely ignored and have received much less attention in studies on POC export when compared with phytoplankton cells and zooplankton fecal pellets (Turner, 2002, 2015). The results of this study suggest that they should be taken into account when studying sinking POC in eutrophic coastal seas around the world.

5 Conclusions

This study reported concentrations and sinking rates of TEPs in the Changjiang River Estuary during the spring and summer of 2011, and the potential sedimentation flux of TEPs was also estimated and compared with phytoplankton cells to reveal their importance in the carbon sedimentation in the eutrophic coastal sea. TEPs concentrations ranged from 40.00 μg/L to 1 423.33 μg/L in the study area, which is within the range reported in other coastal seas around the world. TEPs concentrations exhibited a significant positive correlation with Chl *a* concentrations, with high values being observed at the bloom station during both cruises. TEP-C was at a similar level to phytoplankton-C or even higher than it during both cruises, indicating that TEPs would most probably constitute a significant part of the POC pool in the study area. The sedimentation flux of TEPs was estimated with the SETCOL-determined sinking rates, and it equalled to 27.82%–138.27% (mean=65.15%±31.75%) of sedimentation flux of phytoplankton cells in the study area, indicating that TEPs play a significant role in the carbon sedimentation in the Changjiang River Estuary.

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