



1 **Tracing Water Masses and Particle Dispersion on the**
2 **Northern South China Sea Shelf Using POM Signatures**
3 **under Contrasting Wind Conditions: A New Perspective**

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13 Abstract

14 River-dominated shelf systems are shaped by complex hydrodynamic and biogeochemical
15 interactions, making source-to-sink (S2S) tracking a challenge. To explore the influence of
16 physical processes on particle distribution in the northern South China Sea, two research
17 cruises were conducted along the Guangdong coast in the summers of 2018 and 2020.
18 Hydrographic profiles and particle volume concentrations were measured using a CTD and a
19 laser *in-situ* scattering transmissometer (LISST). Seawater samples from the surface,
20 pycnocline, and bottom layers were analyzed for chlorophyll-a (Chl-a), particulate organic
21 matter (POM, including POC, PN, and $\delta^{13}\text{C}_{\text{POC}}$), and nutrients. Empirical orthogonal function
22 (EOF) analysis revealed distinct patterns of hydrodynamic control in both years. In 2018,
23 stratification was intensified by local rainfall from a cyclonic system and the subsurface
24 seawater, leading to the accumulation of larger particles at the pycnocline. In 2020, however,
25 the Zhujiang River plume (ZRP) played a dominant role in stabilizing the water column under
26 the southwesterly monsoon, entraining bio-particles enriched in $\delta^{13}\text{C}_{\text{POC}}$. This process
27 facilitated the northeastward transport of biogenic material into the Taiwan Strait, possibly
28 influencing sediment composition along the plume pathway. Although the ZRP and subsurface
29 chlorophyll maximum shared similar biogeochemical signatures, the ZRP exhibited higher
30 POC-to-Chl-a ratios and greater particle bulk densities, indicating more advanced POM
31 degradation. Notably, the significantly negative correlation between $\delta^{13}\text{C}_{\text{POC}}$ and salinity along
32 the ZRP highlights $\delta^{13}\text{C}_{\text{POC}}$ serves as a robust tracer of riverine water, more effective than the
33 traditional N/P ratio in this river-dominated shelf system.

34 Keywords: River-dominated shelf regions, Zhujiang River plume, subsurface chlorophyll
35 maximum, water stratification, particle bulk density, POC-to-Chl-a ratio, $\delta^{13}\text{C}_{\text{POC}}$.

36



37 1. Introduction

38 As one of the world's largest river-dominated ocean margins (RiOMar; Xie et al., 2020), the
39 northern South China Sea (NSCS) receives substantial inputs of particulate matter and
40 terrestrial nutrients from major rivers, most notably the Zhujiang (Pearl) River (Cai et al., 2004;
41 Lee et al., 2006; Liu et al., 2012; Ou et al., 2019; Xu et al., 2008). These riverine effluents
42 contribute to the diversity of water masses and suspended particle assemblages, resulting in
43 complex hydrographic structures in nearshore regions (Lan et al., 2009; Yin et al., 2004; Zhou
44 et al., 2012). The hydrodynamics and biogeochemical processes governing the dispersal of
45 these effluents play a critical role in shaping coastal ecosystems, contributing to phenomena
46 such as benthic hypoxia along the river plume pathway (Luo et al., 2023; Qian et al., 2018).

47 The distribution of the Zhujiang River plume (ZRP) on the continental shelf is highly
48 dynamic, shaped by factors such as river discharge, wind patterns, upwelling, and coastal flow
49 fields (Chen et al., 2016; Dong et al., 2004; Lee et al., 2021; Ou et al., 2009; Xu et al., 2019;
50 Zu et al., 2014; Zu et al., 2015). Satellite-based turbidity imagery has identified eight distinct
51 spreading patterns of the ZRP (Chen et al., 2017a). During the summer monsoon, southwesterly
52 winds drive a northeastward surface flow, facilitating the propagation of the ZRP along the
53 Guangdong coast (Chen et al., 2017a, b; Lee et al., 2021; Pan et al., 2014; Zu et al., 2014).
54 Monsoon-driven coastal upwelling further enhances this transport by generating baroclinic jet
55 currents at the interface between the freshwater plume and the underlying saltwater (Chen et
56 al., 2017b; Zu et al., 2015).

57 The ZRP is critical in regulating nutrient availability and supporting primary production in
58 the NSCS. (Liu et al., 2019; Tong et al., 2024; Yang et al., 2021; Yin et al., 2001, 2004). Strong
59 water stratification inhibits vertical mixing along the plume pathway, allowing the riverine
60 substances to be transported over long distances (Chen et al., 2017b; Harrison et al., 2008;
61 Horner-Devine et al., 2015; Lee et al., 2021; Shu et al., 2014). Underway salinity observations
62 and satellite imagery confirm the broad extent of the ZRP into the southern Taiwan Strait (Bai



63 et al., 2015). Various methods have been used to investigate hydrographic, hydrodynamic, and
64 biogeochemical responses associated with the ZRP (Gu et al., 2017; Harrison et al., 2008; Lan
65 et al., 2009; Yin et al., 2004; Zu et al., 2015). A distinctive biogeochemical characteristic of the
66 Zhujiang River is its high nitrogen-to-phosphorus (N/P) ratio, which contrasts with that of the
67 surrounding seawater in the NSCS (Lee et al., 2023; Xu et al., 2008; Yin et al., 2001). The
68 influx of nitrogen-rich riverine water into the nitrogen-limited NSCS significantly enhances
69 coastal biomass, as observed by ocean color satellite sensors (Chen et al., 2004; Xu et al., 2008).

70 This phytoplankton bloom not only modifies planktonic communities but also alters the
71 physicochemical properties of suspended particles in shallow waters (Jiang et al., 2015; Li et
72 al., 2018; Zhong et al., 2021). The signatures of particulate organic matter (POM) serve as
73 valuable proxies for understanding biogeochemical cycles in the global ocean system (SCOR
74 Working Group, 2007; Weaver, 1991) and the source-to-sink (S2S) transport mechanisms of
75 riverine materials (Fischer, 1991; Gu, 2009; Meyers et al., 1993; Sun et al., 2021). While
76 particulate matters are generally expected to retain its original characteristics during transport
77 (Allen, 2017), it can undergo significant transformations along the way (Allen, 2017; Lee et
78 al., 2023; Turner et al., 2002). Flocculation promotes particle aggregation, altering size
79 distribution and bulk density, which subsequently impacts the removal of substances from the
80 water column (Hill et al., 2000). Riverine nutrient inputs stimulate phytoplankton growth,
81 reshaping biological community composition (Jiang et al., 2015; Lu et al., 2009; Tong et al.,
82 2024; Zhong et al., 2021) and influencing POM characteristics, such as stable isotope
83 compositions and C/N ratios, which are commonly used as indicators for tracing particle
84 sources in routing systems. (Miller et al., 2008; Yin et al., 2001). For instance, phytoplankton
85 blooms often lead to $\delta^{13}\text{C}$ enrichment in POM due to the progressive depletion of ^{12}C in the
86 dissolved inorganic carbon pool of the surrounding seawater (Deuser, 1970; Nakatsuka et al.,
87 1992). Microbial degradation further alters POM composition, resulting in residual POM with
88 a relatively $\delta^{13}\text{C}$ -depleted signature (Close et al., 2020; Huang et al., 2021). Additionally,



89 coastal hydrodynamics add further complexity to the physicochemical properties of suspended
90 particles (Eisma, 1986; Manning et al., 2010). Turbulence from waves and currents enhances
91 mixing, incorporating materials from surrounding waters along dispersal pathways (Cross et
92 al., 2014; Jago et al., 2006; Petersen et al., 1998). As a result, the original characteristics of
93 riverine materials might not persist throughout the S2S system.

94 Our previous study near the Zhujiang River estuary (Lee et al., 2023) revealed distinct
95 differences in the particle characteristics between the proximal ZRP and surrounding marine
96 waters. However, the NSCS is influenced by strong physical processes, including basin-wide
97 circulation, upwelling, and nonlinear internal waves (Alford et al., 2015; Feng et al., 2021; Gan
98 et al., 2022; Guo et al., 2014; Jing et al., 2009; Lee et al., 2021; Su, 2004). It remains unclear
99 whether the biogeochemical distinctions associated with the ZRP are preserved as it spreads
100 across the broader NSCS shelf. To enhance our understanding of particulate matter transport
101 on the NSCS shelf, this study addresses three key questions:

- 102 1. How do hydrodynamic processes influence the distribution of particulate matter in a
103 river-dominated shelf system?
- 104 2. What biogeochemical signatures of the suspended particles are carried by the ZRP along
105 its dispersal pathway, and which ones are transported to the downstream regions, such as
106 the Taiwan Strait?
- 107 3. Given that dissolved tracers (e.g., salinity, dissolved inorganic carbon) have been widely
108 used to identify ZRP waters (Bai et al., 2015; Cao et al., 2011; Guo et al., 2008; Huang
109 et al., 2020), can particulate matter, despite its non-conservative nature, also serve as a
110 meaningful indicator of water mass influence and associated biogeochemical processes
111 (Bouillon et al., 2007, 2011; Cathalot et al., 2013)?

112 2. Materials and methods

113 2.1 Hydrographic measurements and water sampling



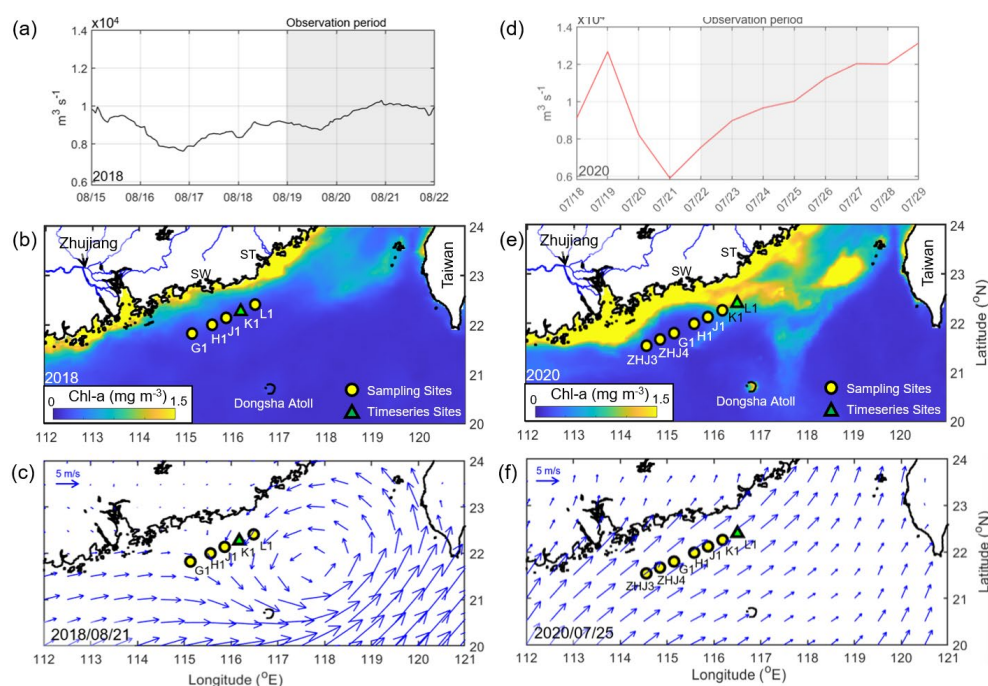
114 Two research cruises were conducted in the summers of 2018 (August 19-22, aboard R/V
115 Ocean Researcher III; ORIII) and 2020 (July 22–28, aboard R/V Legend) along the Guangdong
116 coast under varying river discharge conditions (Fig. 1a, d). Seven hydrographic stations (ZHJ3-
117 L1) were established to assess the spatial variability in hydrodynamics and the physicochemical
118 properties of suspended particles along the river plume dispersal pathway (Fig. 1b, e). To
119 capture temporal variability induced by internal waves and tidal flows (Lee et al., 2021, 2023),
120 24-hour time-series measurements with hourly sampling were conducted at Station K1 in 2018
121 and Station L1 in 2020 (Fig. 1b, e). However, due to technical issues, no data were collected at
122 the two southwest-most stations (ZHJ3 and ZHJ4) in 2018.

123 At each station, a Seabird SBE 19 plus CTD rosette was deployed to measure salinity,
124 temperature, water density, and fluorescence. The CTD was operated with a sampling rate of
125 0.04 seconds with a lowering rate of 0.5 m s⁻¹. To reduce high-frequency noise in the
126 hydrographic profiles, data points collected within 0.2 meters were averaged into a single
127 measurement. Additionally, a laser *in-situ* scattering transmissometer (LISST-200X, Sequoia
128 Scientific, Inc., Bellevue, USA) was mounted on the rosette to measure the volume
129 concentration (VC) of suspended particles across 32 grain-size classes, ranging from 2.5 to 500
130 μm.

131 Seawater samples were collected from three depths: 3 m below the surface, at the pycnocline,
132 and 3 m above the seabed, using 10 L water samplers on the CTD rosette (Niskin bottles in
133 2018 and Go-Flo bottles in 2020). After collection, 150 mL of seawater was filtered through a
134 0.45 μm Millex®-LCR syringe filter to analyze dissolved nutrients and was immediately frozen
135 in liquid nitrogen. Additionally, two 500 mL seawater samples were collected and stored in
136 HDPE opaque amber bottles. onboard water samples were filtered using pre-combusted glass
137 fiber filters (GF/F, Whatman; diameter: 25 mm; pore size: 0.7 μm; pre-combusted at 500°C for
138 6 hours) for subsequent analyses of suspended sediment concentration (SSC), chlorophyll-a
139 (Chl-a), and POM. Chl-a samples were wrapped in aluminum foil to prevent light exposure,



140 and the results were used to validate fluorescence measurements from the CTD profile
141 (Appendix Fig. A1). All filtered samples were stored at temperatures below -4°C during the
142 cruise before being processed in the laboratory.



143
144 **Figure 1:** Environmental conditions during the observation period. Panels from top to bottom
145 display Zhujiang River discharge (a, d), ocean color images from MODIS (b, e), and 10-meter
146 wind fields (c, f). Data from 2018 are shown on the left, and 2020 data are on the right. The
147 gray shading in the river discharge panel indicates the observation period during the cruise.
148 The color scale in the MODIS satellite image represents Chl-a concentration. To represent the
149 average Chl-a distribution in the NSCS during the cruise periods, satellite data collected over
150 the corresponding observations were averaged. The "SW" and "ST" shown in the image
151 represent Shanwei and Shantou. Arrows in the wind field panels indicate wind strength and
152 direction. Yellow circles and green triangles denote hydrographic stations, with green triangles
153 representing time-series stations. River discharge data were sourced from the Pearl River Water
154 Resources Commission, satellite data from NASA Worldview
155 (<https://worldview.earthdata.nasa.gov/>), and wind field data from ECMWF Reanalysis v5
156 (<https://www.ecmwf.int/en/forecasts/dataset/ecmwf-reanalysis-v5>).

157



158 2.2 Water stratification

159 Water column stability was quantified using a static stability index, E , a widely used metric
160 for assessing stratification influenced by freshwater input in nearshore environments (Boyer et
161 al., 2005; Du and Liu, 2017; Lee et al., 2016, 2023; Liu et al., 2018b; Lynn and Reid, 1968;
162 Neumann, 1966). The index is defined as:

$$163 E = (-1/\rho_0) \times (\partial\rho/\partial z) \quad (1)$$

164 where ρ_0 is the average water density during the observation; ρ is the measured water density
165 at the specific water depth, z . Higher values indicate stronger water stratification, while lower
166 values suggest weaker or well-mixed conditions.

167 2.3 Nutrient analyses

168 Nutrient samples collected in 2018 were analyzed at National Sun Yat-sen University,
169 Kaohsiung, while those from 2020 were analyzed at Academia Sinica, Taipei. Nutrient
170 concentrations were calculated using colorimetric methods: phosphate (PO_4^{3-}) and silicate
171 (SiO_4) by the molybdenum blue and silicomolybdic acid blue methods, respectively (Fanning
172 et al., 1973; Mullin et al., 1955; Murphy et al., 1962; Pai et al., 1990a; Rimmelin et al., 2005);
173 nitrite (NO_2^-) by the pink azo dye method (Pai et al. 1990b, 2021; Schnetger et al., 2014;
174 Strickland 1972); and nitrate (NO_3^-) by the cadmium-copper reduction method in 2018 and the
175 VCl_3 reduction method in 2020, (Pai et al., 2021; Schnetger et al. 2014). Calibration in 2018
176 used CSK standards (Wako Pure Chemicals Ltd., Japan) and certified reference materials
177 (KANSO Technos Co., Ltd., Japan), achieving precisions of $\pm 0.05 \mu\text{mol L}^{-1}$ for phosphate, ± 0.1
178 $\mu\text{mol L}^{-1}$ for silicate, $\pm 0.02 \mu\text{mol L}^{-1}$ for nitrite, and $\pm 0.08 \mu\text{mol L}^{-1}$ for nitrate, respectively. In
179 2020, Merck-certified standard solutions (Merck KGaA, Darmstadt, Germany) were used for
180 nutrient calibration: nitrite (catalog number 1.19899.0500), nitrate (catalog number
181 1.19811.0500), phosphate (catalog number 1.19898.0500), and silicate (catalog number
182 1.70236.0500). All calibration standards were prepared using Milli-Q water® to minimize



183 potential matrix effects. Analytical accuracy and consistency were validated by analyzing an
184 inserted CSK (Certified Standard for Nutrients in Seawater) reference standard during sample
185 runs. Calibration linearity ($R^2 > 0.997$) was confirmed prior to sample analysis. The analytical
186 precisions were $\pm 0.001 \mu\text{mol L}^{-1}$ for nitrite, $\pm 0.016 \mu\text{mol L}^{-1}$ for nitrate, $\pm 0.01 \mu\text{mol L}^{-1}$ for
187 phosphate, and $\pm 0.1 \mu\text{mol L}^{-1}$ for silicate.

188 **2.4 Identification of suspended particle characteristics**

189 **2.4.1 Physical properties of suspended particles**

190 LISST measured the VC of 32 size classes with non-uniform bin size increments (larger
191 increments in the coarser size classes). Therefore, VC records were normalized (VC_{nor} ; Jouon
192 et al. 2008) using the following equation to represent the particle size composition:

$$193 \quad VC_{\text{nor},i} = VC_{\text{mea},i} / \text{diff}(BS_i) \quad (2)$$

194 where i indicates each size class; VC_{mea} is the measured VC; BS is the corresponding bin size.

195 The SSC was determined by weighing the filter after freeze-drying for over 24 hours. The
196 SSC and VCs were then used to calculate the particle bulk density (ρ_{bk}) applying the following
197 equation (Hsu et al., 2010):

$$198 \quad \rho_{\text{bk}} = \rho_{\text{IW}} + (1 - \rho_{\text{IW}} / \rho_{\text{p}}) \times (\text{SSC} / \text{VC}) \quad (3)$$

199 where the ρ_{IW} is the average seawater density measured along the transect in two cruises ($1,023$
200 kg m^{-3} in this study); ρ_{p} is the assumed density of the solid part of the particle ($2,650 \text{ kg m}^{-3}$).

201 **2.4.2 Biogeochemical properties of suspended particles (POM and Chl-a)**

202 In the pre-processing of POM analysis, the weighed filter was treated with 2N HCl to
203 remove inorganic carbon, followed by rinsing with Milli-Q water[®] to eliminate residual acid.
204 POM analysis was conducted using an elemental analyzer coupled with an isotope ratio mass
205 spectrometer (Flash 2000 and Delta V Plus; both from Thermo Fisher Scientific). Calibration
206 of isotopic ratios and precision assessments were performed using internationally certified
207 standards (USGS40, USGS43, USGS64, USGS73, and NIST8542) and soil standards



(certificate number 341506; Thermo Fisher Scientific). The relative precision was maintained at $\pm 5\%$ for particulate organic carbon (POC; 1σ) and particulate organic nitrogen (PN; 1σ). The absolute precision was within $\pm 0.3\%$ for $\delta^{13}\text{C}_{\text{POC}}$.

Chl-a was extracted from the retained particles on the filter by immersing the filter in 90% acetone within a 15 mL centrifuge tube at 4°C for 24 hours. The Chl-a concentration was then quantified using a 10-AU Field Fluorometer (Turner Designs). To prevent photodecomposition of Chl-a, the procedure was conducted in a subdued light environment. The measured Chl-a concentration was used to calculate the PC ratio (particulate organic carbon to Chl-a concentration), which serves as an indicator of POM degradation (Guo et al., 2015; Jakobsen et al., 2016; Taylor et al., 1997). Guo et al. (2015) identified a PC ratio of 200 as the threshold between degraded and fresh POM. A lower PC ratio indicates fresh or newly produced POM, whereas a higher ratio suggests more degraded POM.

$$\text{PC ratio} = \text{POC/Chl-a} \quad (4)$$

2.5 River discharge and open-source data

River discharge from the Zhujiang River was measured at gauging stations on its three major tributaries: Samsui on the North River, Makou on the West River, and Bolou on the East River. Since data for Bolou was unavailable in 2018 and the East River's minimal contribution to total flow (Zhang et al., 2012), Bolou's measurements were excluded to ensure consistency between the 2018 and 2020 datasets. Daily average discharge values were used to filter out high-frequency variability. All data were obtained from the Zhujiang River Water Resources Commission (<https://www.pearlwater.gov.cn/>).

Ocean-color satellite imagery was obtained from NASA's Worldview application (<https://worldview.earthdata.nasa.gov/>), providing daily Chl-a data at a horizontal resolution of $1/24^\circ \times 1/24^\circ$. To represent the overall Chl-a distribution in the NSCS, satellite data collected during each cruise were averaged. Surface water samples provided ground truth data to validate



233 the accuracy of satellite-derived Chl-a measurements.

234 Precipitation data were obtained from the Integrated Multi-satellite Retrievals for Global
235 Precipitation Measurement (NASA), with a horizontal resolution of $1/10^\circ \times 1/10^\circ$ and daily
236 observation intervals (<https://disc.gsfc.nasa.gov/>; Huffman et al., 2023). Wind field data at 10
237 meters above the surface were sourced from the ECMWF Reanalysis v5 dataset
238 (<https://www.ecmwf.int/en/forecasts/dataset/ecmwf-reanalysis-v5>).

239 3. Results

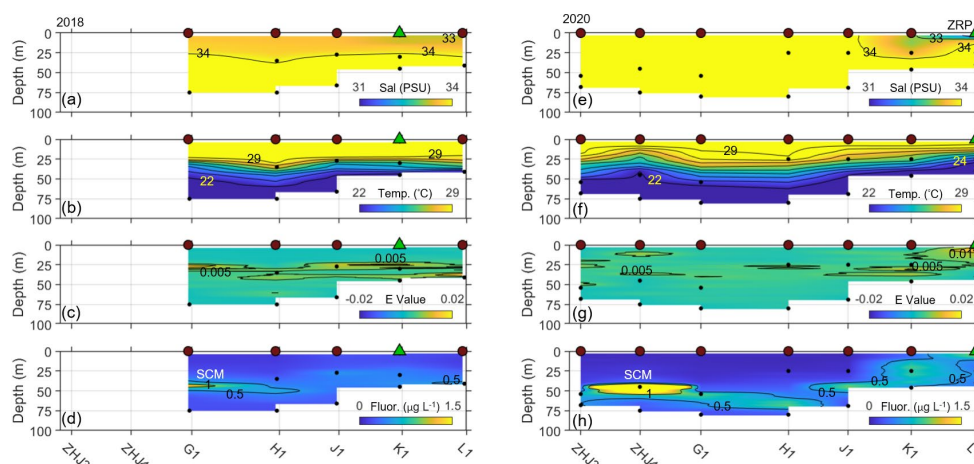
240 3.1 River runoff and hydrographic changes on the NSCS shelf

241 Our gauging station data are consistent with historical records showing that the average river
242 runoff during the wet season typically ranges between 1 and $2 \times 10^4 \text{ m}^3 \text{ s}^{-1}$ (Hong et al., 2020;
243 Zhang et al., 2012; Fig. 1a, d). During the sampling periods, river discharge conditions were
244 generally comparable between 2018 and 2020, with average values of $0.96 \times 10^4 \text{ m}^3 \text{ s}^{-1}$ and
245 $1.02 \times 10^4 \text{ m}^3 \text{ s}^{-1}$, respectively. Although differences were observed, they are unlikely to fully
246 account for the greater offshore extent of the ZRP in 2020 (Fig. 1b, e). Instead, contrasting
247 wind forcing played a dominant role in shaping the plume dispersal patterns. Enhanced
248 southwesterly winds during the 2020 summer monsoon (Fig. 1c, f) promoted stronger
249 northeastward propagation of the ZRP, facilitating its spread toward the southern Taiwan Strait,
250 as evidenced by satellite imagery (Fig. 1e). Additional mechanisms, such as variability in river
251 discharge influenced by dam operations and climatic oscillations (ENSO and PDO; Gu et al.,
252 2017; Liu et al., 2018a; Ouyang et al., 2014; Zhou et al., 2021), may have also contributed to
253 long-term variability but were likely secondary factors during our observation periods.

254 The dispersal of the ZRP created distinct hydrographic structures in the shallow water
255 environment in 2018 and 2020 (Fig. 2). Salinity profiles in 2018 indicated the presence of fresh
256 water (salinity 33–34) in the upper water column, primarily due to heavy precipitation induced
257 by a tropical depression (Fig. 1c, Fig. 2a, and Appendix Fig. A2). Despite lower offshore
258 rainfall in 2020, a water mass with salinity below 33 was observed at depths shallower than 7



259 m from Stations K1 to L1 (Fig. 2e). Temperature profiles in both years exhibited a typical two-
260 layer structure with warm water ($>25^{\circ}\text{C}$) restricted to depths shallower than 50 m (Fig. 2b, f),
261 consistent with previous observations in the NSCS (Lee et al., 2021; Wong et al., 2015; Zeng
262 et al., 2016). Vertical water stability revealed a continuous stratified layer around 25 m on the
263 shelf in 2018 ($E > 0.005$; Fig. 2c), attributed to low-salinity, warm surface water. In contrast,
264 the stratification structure in 2020 was discontinuous along the transect, despite the presence
265 of a warm surface layer. With the ZRP input, strong stratification was observed on the eastern
266 side of the transect (Fig. 2g).

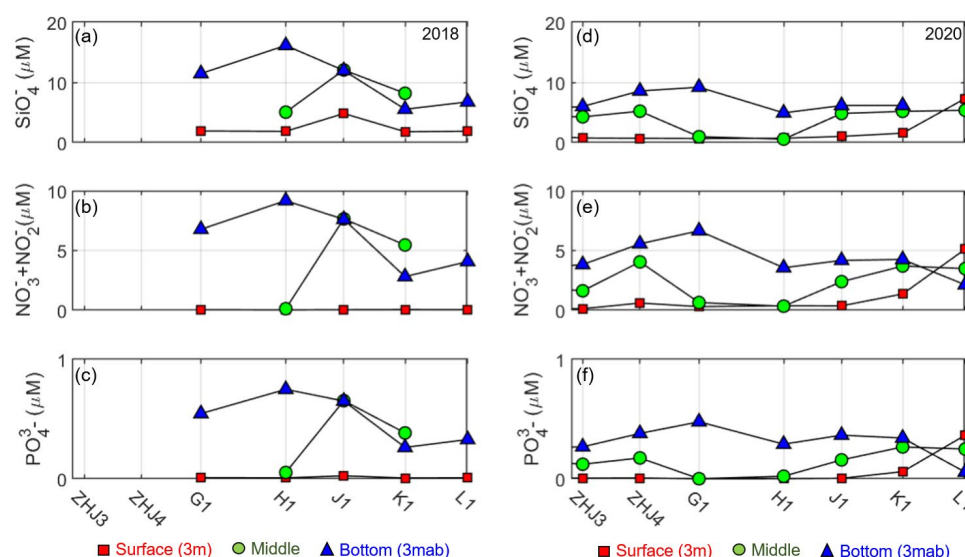


267 **Figure 2:** Hydrographic profiles along the transect in 2018 (left) and 2020 (right). Panels from
268 top to bottom show salinity, temperature, E values, and fluorescence. Brown circles and green
269 triangles mark hydrographic stations (as in Fig. 1), while black dots indicate sampling depths.
270 "SCM" represents the subsurface chlorophyll maximum, and "ZRP" denotes the Zhujiang
271 River plume.

273 Dissolved nutrient distributions also showed distinct patterns in both years, with
274 concentrations generally increased with depth, displaying lower values near the surface (Fig.
275 3). In 2018 (2020), silicate concentrations ranged from 1.8 (0.6) to 16.1 (9.2) μM , nitrate +
276 nitrite (N) from 0.03 (0.13) to 9.18 (6.65) μM , and phosphate from 0.01 (<0.01) to 0.75 (0.48)
277 μM . Bottom concentrations in 2018 were nearly double those measured in 2020. However,



278 surface nutrient concentrations at Station L1 significantly increased in 2020, reaching 7.32 μM
 279 for silicate, 5.11 μM for nitrate + nitrite, and 0.37 μM for phosphate, indicating shifts in water-
 280 mass composition. The N/P ratio, a conventional indicator of the water mass, generally
 281 remained below 15 along the transect for both years (Table 1). Exceptionally high N/P values
 282 were observed in 2020 (e.g., 88.43 at Station ZHJ4 and 89.47 at Station J1). Conversely, the
 283 surface water at Station L1 exhibited relatively lower N/P values (14.01 in 2020), despite the
 284 ZRP being characterized by significantly high N/P ratios due to low phosphate concentrations
 285 in river runoff (Yin et al., 2001).



286 **Figure 3:** Nutrient concentrations along the transect in 2018 (left) and 2020 (right). Panels
 287 show (a, d) silicate, (b, e) nitrate + nitrite, and (c, f) phosphate. Colored points represent
 288 samples collected at different depths (red square: surface; green circle: middle; blue triangle: 3
 289 meter above bottom).
 290



Table 1: Calculated N/P ratios for 2018 (top table) and 2020 (bottom table) at each hydrographic site.

2018							
N/P Ratio	ZHJ3	ZHJ4	G1	H1	J1	K1	L1
Surface	-	-	4.20	3.75	1.72	8.14	4.89
Middle	-	-	12.26	2.42	11.70	14.23	12.19
Bottom	-	-	12.40	12.25	11.69	10.70	12.39

* "-" symbol indicates missing or error data.

* Gray value indicates the N or P under the detection limit.

2020							
N/P Ratio	ZHJ3	ZHJ4	G1	H1	J1	K1	L1(ZRP)
Surface	22.18	88.43	-	368.31	89.47	22.69	14.01
Middle	13.29	23.18	626.08	15.59	15.10	13.87	13.99
Bottom	14.28	14.64	13.93	12.26	11.43	12.44	38.02

* "-" symbol indicates missing or error data.

* Gray value indicates the N or P under the detection limit.

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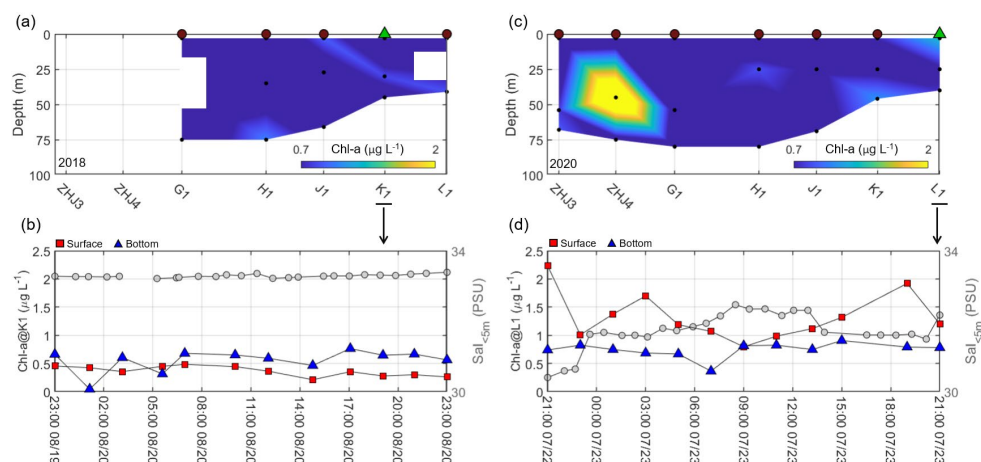
294 3.2 Contrasting POM Features in the Shelf System

295 The subsurface chlorophyll maximum (SCM) was observed at depths of 40–75 m from
296 Stations ZHJ3 to H1 in both years (Fig. 2d, h). Peak fluorescence reached $1.26 \mu\text{g L}^{-1}$ in 2018
297 and $5.43 \mu\text{g L}^{-1}$ in 2020. Chl-a measurements followed a similar trend (Fig. 4), with a maximum
298 concentration of $2.79 \mu\text{g L}^{-1}$ recorded at Station ZHJ4 in 2020. These findings suggest a
299 significant presence of phytoplanktonic biomass within the SCM, further supported by elevated
300 POC concentrations (Appendix Fig. A3). POM analysis revealed significantly lighter $\delta^{13}\text{C}_{\text{POC}}$
301 values (below -30‰ ; Fig. 5c) in the SCM water relative to ambient seawater, indicating distinct
302 isotopic fractionation during phytoplankton uptake and biodegradation (Close et al., 2020;
303 Tuerena et al., 2019; Zhang et al., 1999). Similar $\delta^{13}\text{C}_{\text{POC}}$ depletion has been reported on the
304 East China Sea shelf, attributed to phytoplankton size composition and the intrusion of the
305 offshore water having a low $\delta^{13}\text{C}_{\text{POC}}$ value (Liu et al., 2018c).

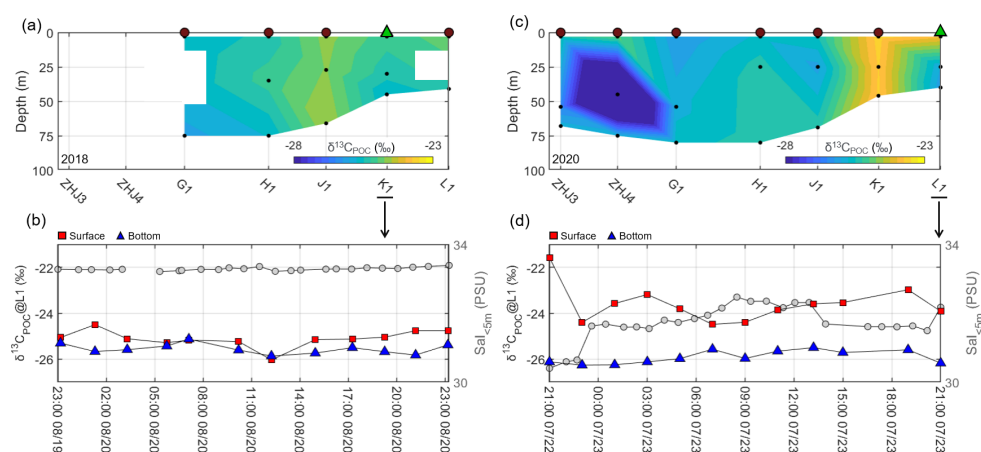
306 A significant increase in fluorescence was also observed in the upper water at Station L1 in
307 2020, which was absent in 2018 (Fig. 2d, h). This difference was attributed to the input of
308 nutrient-rich ZRP water, which stimulated phytoplankton growth (Fig. 1a, e and Fig. 3; Yin et
309 al., 2001, 2004; Yu et al., 2020). Consequently, surface waters in 2020 exhibited Chl-a
310 concentrations exceeding $1 \mu\text{g L}^{-1}$ (Fig. 4c), which led to altered POM properties, including
311 relatively enriched $\delta^{13}\text{C}_{\text{POC}}$ values ($> -24.5\text{‰}$; Fig. 5c). To rule out potential temporal aliasing
312 from hydrodynamic forcing (e.g., nonlinear internal waves or tidal flows; Alford et al., 2015;
313 Guo et al., 2014; Lee et al., 2021; Zu et al., 2015), a 24-hour continuous observation of Chl-a
314 and $\delta^{13}\text{C}_{\text{POC}}$ was compared with surface salinity (averaged within the top 5 m; Fig. 4b, d and
315 5b, d). In 2018, Chl-a and $\delta^{13}\text{C}_{\text{POC}}$ concentrations remained stable at approximately $0.5 \mu\text{g L}^{-1}$
316 and -25.4‰ , respectively, with an average salinity of 33.3. In contrast, surface Chl-a
317 concentrations in 2020 were more than twice those at the bottom, showing an inverse
318 correlation with salinity. Meanwhile, bottom Chl-a in 2020 remained stable at $\sim 0.74 \mu\text{g L}^{-1}$,
319 similar to 2018. The $\delta^{13}\text{C}_{\text{POC}}$ in 2020 followed the same trend as Chl-a, with constant bottom



320 values (around -26‰) and higher surface values (> -24.5‰).



321 **Figure 4:** Chl-a measurements along the transect in 2018 (left) and 2020 (right). Brown circles
322 and green triangles denote hydrographic stations (as in Fig. 1), and black dots indicate sampling
323 depths. White areas indicate missing data due to water sample unavailability or technical issues.
324 Time-series data are shown for Station K1 in 2018 (b) and Station L1 in 2020 (d). Red squares
325 and blue triangles represent surface and bottom samples, respectively, while gray dots indicate
326 salinity averaged within 5 m.
327



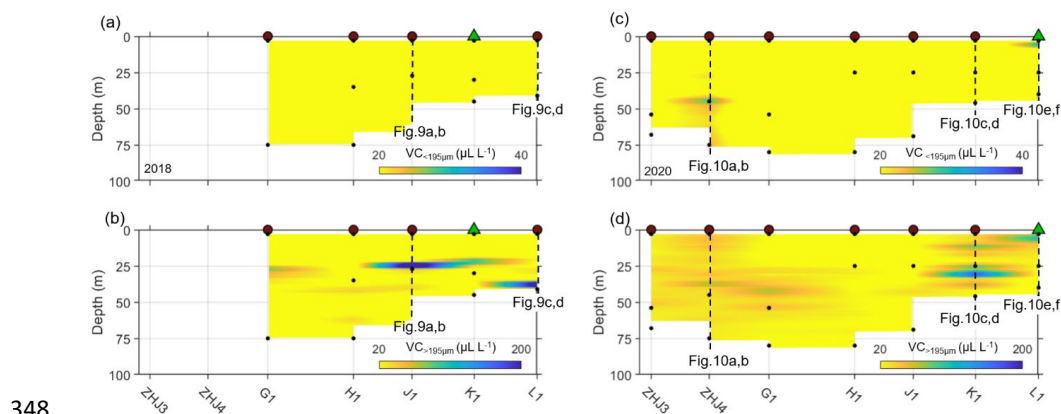
328 **Figure 5:** $\delta^{13}\text{C}_{\text{POC}}$ measurements along the transect in 2018 (left) and 2020 (right). Brown
329 circles and green triangles denote hydrographic stations (as in Fig. 1), with black dots
330 indicating sampling depths. White areas indicate missing data due to water sample
331 unavailability or technical issues. Time-series data are shown for Station K1 in 2018 (b) and
332 Station L1 in 2020 (d). Red squares and blue triangles represent surface and bottom samples,
333



334 while gray dots indicate salinity averaged within 5 m.

335 3.3 Variability in Particle Size and PC Ratios on the NSCS Shelf

336 Previous studies have documented significant spatial and temporal variability in particle
337 size across the NSCS (Li et al., 2018; Wang et al., 2022), noting that most phytoplankton in the
338 region are smaller than 200 μm (Dong et al., 2018; Liu et al., 2016). Therefore, the LISST
339 measurement threshold of 195 μm was adopted to distinguish biogenic substances from non-
340 biogenic and degraded particles. VC profiling in 2018 indicated that particles were
341 predominantly in the $>195 \mu\text{m}$ size class (Fig. 6a, b), with high values observed at 25 m at
342 Stations G1 and J1, as well as in the bottom water at Station L1. In contrast, VC profiles from
343 2020 showed distinct distribution patterns across various grain-size classes. High VC
344 measurements for particles $<195 \mu\text{m}$ were recorded at approximately 43 m at Station ZHJ4 and
345 at the surface at Station L1 (Fig. 6c). Conversely, high VC values for the $>195 \mu\text{m}$ size class
346 were found in the middle water column at Stations ZHJ4, G1, and K1, as well as in the surface
347 water at Station L1 (Fig. 6d).



348 **Figure 6:** Normalized VC measurements along the transect in 2018 (a, b) and 2020 (c, d).
349 Panels (a, c) display data for particles $<195 \mu\text{m}$, while (b, d) show data for particles $>195 \mu\text{m}$.
350 Brown circles and green triangles mark hydrographic stations (as in Fig. 1), with black dots
351 representing sampling depths. Dashed lines indicate VC profiling shown in Figs. 9 and 10.



353 4. Discussion

354 4.1 Co-variability among properties of water masses and particles

355 To better understand the complex interactions among vertical mixing processes, particle
356 sources, and biogeochemical responses in the coastal environment, an empirical orthogonal
357 function (EOF) analysis was conducted to quantify multivariable correlations of these variables
358 on the NSCS shelf. EOF analysis has been widely applied to various river-sea systems (Du et
359 al., 2022; Lee et al., 2016; Liu et al., 2019, 2021; Tao et al., 2022) and upstream regions of the
360 ZRP (Lee et al., 2021, 2023). Based on the EOF eigenvectors of independent variables, the co-
361 variability between intrinsic water properties and the biogeochemical characteristics of
362 transported particles was objectively identified for each eigenmode. The corresponding
363 eigenweightings represent the spatial signatures of these eigenmodes, hierarchically ordered
364 by their corresponding eigenvalues.

365 This study incorporated three groups of variables in the EOF analysis: (I) salinity,
366 temperature, and the E value, which represent water mass properties and mixing; (II)
367 fluorescence, Chl-a, and $\delta^{13}\text{C}_{\text{POC}}$, which indicate biogeochemical characteristics of suspended
368 particles; and (III) VC in two size classes ($<195\ \mu\text{m}$ and $>195\ \mu\text{m}$), reflecting the physical
369 properties of suspended particles (Fig. 7a-b, Fig. 8a-c). Variables having eigenvector values
370 below 0.1 were considered insignificant. Chl-a and $\delta^{13}\text{C}_{\text{POC}}$ were excluded from the 2018 EOF
371 analysis due to missing water samples but were included in 2020 to provide a more
372 comprehensive understanding of particle dynamics.

373 The first two eigenmodes of the 2018 cruise explained nearly 70% of the dataset's variability
374 (Fig. 7a, b), with both modes representing the influence of water stratification. The 1st
375 eigenmode (42.7%; Fig. 7a) showed a negative value for temperature in the eigenvector, while
376 all other variables were positive. This suggests that cold, saline water promoted vertical
377 stability and contained biogeochemical particles of various sizes, as indicated by the positive
378 fluorescence and VCs. In contrast, the 2nd eigenmode (26.4%; Fig. 7b) revealed an inverse

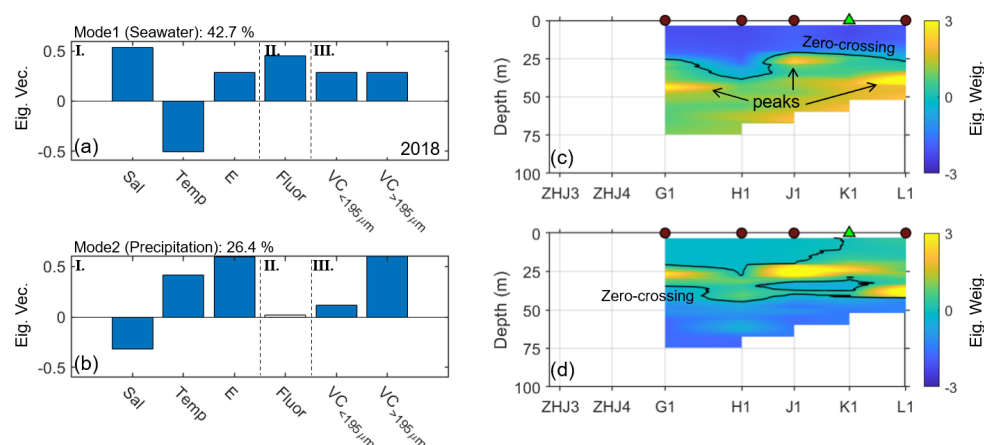


relationship between salinity and the E value, while all other variables had positive in the eigenvector values. This suggests that a diluted water mass (i.e., ZRP) contributed to water stratification and promoted larger suspended particles, as indicated by the strong positive eigenvector for $VC_{>195\mu m}$. The eigenweightings of the first two eigenmodes indicated that distinct water masses occupied different layers of the water column, with the 25-45 m depth range serving as a boundary, as marked by the zero-crossing in the eigenweightings (Fig. 7c-d). The cold seawater represented by the 1st eigenmode was confined to the lower water column (Fig. 7c), where peak positive eigenweightings indicating the accumulation of bio-particle, such as the SCM observed at Station G1. Meanwhile, the diluted plume water represented by the 2nd eigenmode occupied the upper water column (Fig. 7d), influenced by local precipitation (Appendix Fig. A2). Thus, the 2018 EOF analysis highlights how water stability, regulated by the interplay between subsurface seawater and surface-diluted water, shapes the distribution of suspended particles.

Due to weak water stratification along the NSCS shelf in 2020 (Fig. 2g), the EOF analysis yields different results in the first two eigenmodes, which together explained 69.5% of the dataset's co-variability (Fig. 8a-b). The 1st eigenmode (39.1%; Fig. 8a) showed positive eigenvector values for salinity, fluorescence, Chl-a, and $VC_{<195\mu m}$, while the remaining variables were negative. This indicates that cold, saline water was associated with finer biogenic particles and relatively depleted $\delta^{13}C_{POC}$. The eigenweightings were significantly higher in the middle water at Station ZHJ4 (Fig. 8d), reflecting the characteristics of the SCM on the NSCS shelf. The 2nd eigenmode (30.4%; Fig. 8b) showed only salinity as a negative eigenvector, suggesting that a diluted water mass contributed to stratification and entrained biogenic particles with relatively enriched $\delta^{13}C_{POC}$ and a range of particle sizes. The 2nd mode's eigenweightings indicated that diluted water primarily occupied the surface layer at Station L1 (Fig. 8e), consistent with the ZRP pathway observed in 2020. While seawater-induced stratification dominated the 1st eigenmode in 2018, it appeared in the 3rd eigenmode in 2020

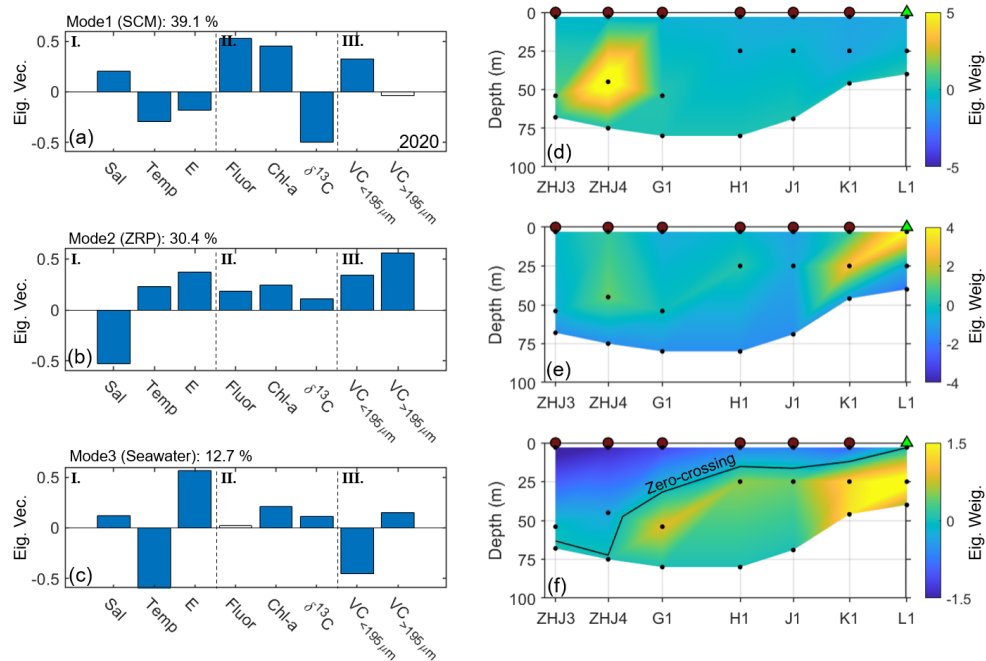


405 (12.7%; Fig. 8c, f), which displayed positive eigenvectors for all variables except temperature
406 and $VC_{<195\mu m}$. This suggests that cold seawater enhanced stability and carried coarser particles
407 with relatively enriched $\delta^{13}C_{POC}$ values to the SCM in the measurement. The 3rd eigenmode's
408 eigenweighting showed a zero-crossing, separating the shelf into upper and lower water
409 columns characterized by distinct water masses and particle properties (Fig. 8f), consistent with
410 the EOF results of the 2018 cruise (Fig. 7c).



411
412 **Figure 7:** First two modes of the 2018 EOF analysis. The 1st and 2nd modes are shown in the
413 top and bottom panels, respectively. Eigenvectors for each mode are in (a) and (b), while
414 eigenweightings are in (c) and (d). Eigenvalues and corresponding interpretations are listed in
415 the upper left corner of each eigenvector panel. The dashed line categorizes parameters into
416 three groups: (I) water mass properties, (II) biogeochemical features of transported particles,
417 and (III) physical characteristics of suspended particles. Gray bars indicate parameters with
418 eigenvector values <0.1 , excluded from EOF interpretation. The black line in the
419 eigenweighting represents the zero-crossing depth. Brown circles and green triangles denote
420 hydrographic sites (as in Fig. 1).

421



422
423 **Figure 8:** First three modes of the 2020 EOF analysis. The 1st, 2nd, and 3rd modes are shown in
424 the top, middle, and bottom panels, respectively. Eigenvectors for each mode are in (a), (b),
425 and (c), and eigenweightings in (d), (e), and (f). Eigenvalues and interpretations are in the upper
426 left of each eigenvector panel. The dashed line categorizes parameters into three groups: (I)
427 water mass properties, (II) biogeochemical features of transported particles, and (III) physical
428 characteristics of suspended particles. Gray bars indicate parameters with eigenvector values
429 <0.1, excluded from EOF interpretation. The black line in the 3rd mode represents the zero-
430 crossing depth. Brown circles and green triangles denote hydrographic sites (as in Fig. 1).
431



4.2 Particle distribution associated with water stratification on the NSCS Shelf

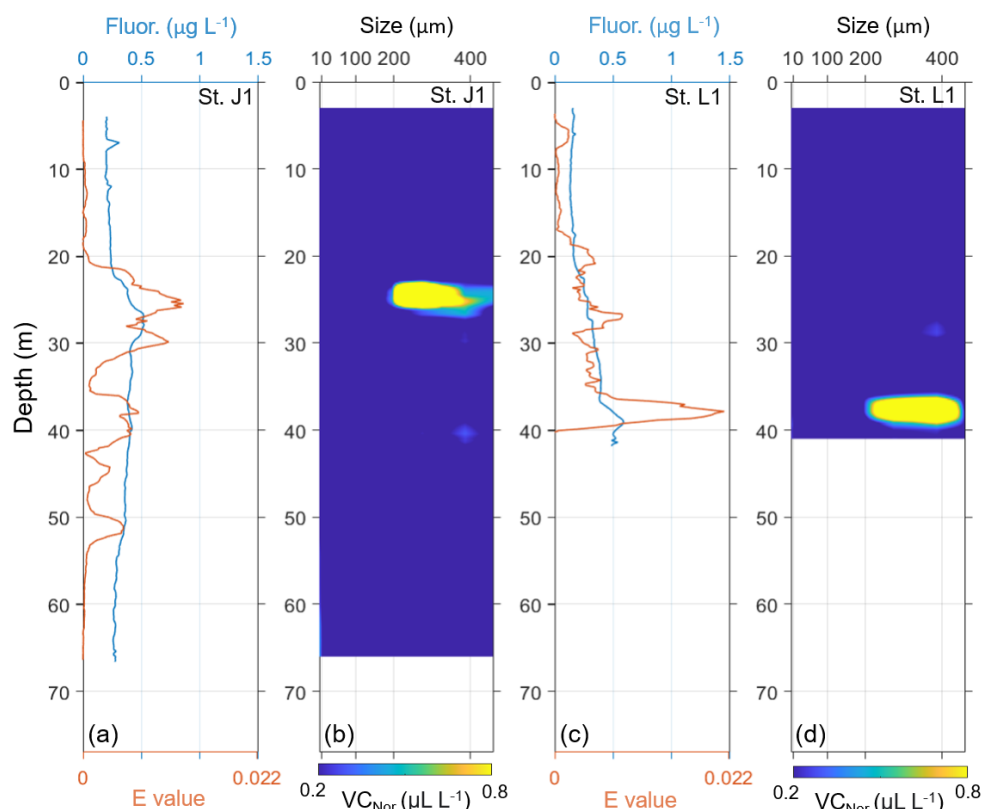
Salinity and temperature are key factors influencing water stability in coastal environments, with salinity serving as a primary driver of stratification (Maes et al., 2014). In 2018, stratification was notably enhanced due to the formation of a low-salinity surface layer across the shelf (Fig. 2a, c). Satellite data indicated that increased rainfall led to lower surface salinity in the region (Appendix Fig. A2). In contrast, stratification along the transect in 2020 was relatively weak ($E < 5 \times 10^{-3}$), despite the presence of warm surface water (Fig. 2f, g). Nevertheless, the ZRP transported low-salinity water along its pathway, enhancing stability at the surface of Station L1 (Fig. 2e, g) and causing the halocline to shoal to depths shallower than 25 m.

On the NSCS shelf, water stratification plays a crucial role in regulating the distribution of suspended particles. The highest concentrations of coarse particles ($>195 \mu\text{m}$) were observed within strongly stratified layers (Figs. 9, 10, and Appendix Figs. A4, A5). This phenomenon, known as the intermediate nepheloid layer (INL; Tian et al., 2022), has been documented in various coastal systems, including the East China Sea shelf (Guo et al., 2010), the Cariaco Basin (Lorenzoni et al., 2009), and the Taiwan Strait (Du and Liu, 2017). The INL can originate either from settling particles within a buoyant river plume (Du and Liu, 2017; Lorenzoni et al., 2009) or from resuspended seafloor sediments driven by high-energy processes, such as nonlinear internal waves (Feng et al., 2021; Lee et al., 2021). Material accumulates at the pycnocline due to strong vertical density gradients, which inhibit mixing caused by surface winds and bottom boundary currents (Du and Liu, 2017; Fortini et al., 2016; Franks, 1992; Lee et al., 2021).

In areas adjacent to the ZRP, such as Station K1, coarse particles were vertically redistributed throughout the water column due to a deeper stratified layer (Fig. 6d and 10c, d). This suggests enhanced vertical transport of particulate matter, and is consistent with the findings that the strength and spatial distribution of plume-induced stratification are key factors



458 in regulating the vertical exchange of marine substances (Cui et al., 2019; Luo et al., 2009).
459 The dispersal of the ZRP on the NSCS shelf is closely tied to river runoff. Although artificial
460 dams along the Zhujiang River regulate outflow at the river mouth, intense precipitation
461 associated with climate variability (e.g., ENSO) has caused flooding in the river basin,
462 potentially reinforcing vertical stability on the continental shelf (Bermúdez et al., 2021; Moser
463 et al., 2012; Peng et al., 2018; Voynova et al., 2012).



464 **Figure 9:** Hydrographic (a, c) and VC (b, d) profiles at Stations J1 and L1 in 2018, as shown
465 in Fig 6. The brown and cyan lines in hydrographic profiles represent the E value and
466 fluorescence, respectively. The grain-size spectrum shows normalized VC.
467
468



469 4.3 POM distribution on the NSCS Shelf

470 The SCM and ZRP were identified on the NSCS shelf based on their physical and
471 biogeochemical characteristics. While both exhibited similar features, such as high Chl-a
472 concentrations (Fig. 4), they differed in $\delta^{13}\text{C}_{\text{POC}}$ signatures, the VC size composition, PC ratios,
473 and particle bulk density (Fig. 5, 6, Table 2, Appendix Fig. A6). The lower PC ratio and particle
474 bulk density in the SCM suggest the presence of relatively fresher bio-particles compared to
475 those in the ZRP (Appendix Fig. A6). The depleted $\delta^{13}\text{C}_{\text{POC}}$ in the SCM may result from factors
476 such as phytoplankton size composition and biological metabolism under conditions of low
477 dissolved CO_2 concentration (Close et al., 2020; Law et al., 1995; Liu et al., 2018c; Miller et
478 al., 2008). Although low $\delta^{13}\text{C}_{\text{POC}}$ values are traditionally considered indicative of terrestrial
479 input (Cai et al., 1988), misidentification of POM sources can occur without multivariable
480 constraints (Lee et al., 2023).

481 The SCM is typically found near the pycnocline, where nutrient enrichment and optimal
482 light conditions favor phytoplankton growth (Lu et al., 2010). The VC profile (Fig. 10a, b and
483 Appendix Fig. A5) revealed that the SCM was positioned below the pycnocline and primarily
484 composed of finer particles ($<10\ \mu\text{m}$), consistent with previous findings (Chen et al., 2021; Liu
485 et al., 2016; Ning et al., 2004; Williams et al., 2013). However, Xu et al. (2022) reported that
486 in offshore areas deeper than 100 m, the SCM was located above the pycnocline, highlighting
487 the complexity of its distribution in the NSCS.

488 Previous studies on the upper reaches of the ZRP have shown that most entrained particles
489 in the river plume originate from marine biogenic sources, as substantial terrestrial particles
490 are either trapped upstream by dam operations or rapidly settle upon entering the Zhujiang
491 River Estuary (He et al., 2020; Lee et al., 2023; Wei et al., 2021; Xia et al., 2004). As a result,
492 the low bulk density and enriched $\delta^{13}\text{C}_{\text{POC}}$ observed along the river plume pathway, particularly
493 at the surface of Station L1 ($1288.64\ \text{kg m}^{-3}$ in particle bulk density and $> -24.5\text{‰}$ in $\delta^{13}\text{C}_{\text{POC}}$;
494 Fig. 5c, d and Table 2), reflect the dominance of biogenic sources. Despite both ZRP and SCM



495 being primarily composed of biogenic particles, distinct physicochemical differences were
496 observed. The high PC ratio in the ZRP suggests that POM was more degraded in the river
497 plume compared to that of the SCM (Table 2; Appendix Fig. A6), resulting to higher particle
498 bulk density ($1288.64 \text{ kg m}^{-3}$). Although the PC ratio can be influenced by biological
499 communities (Lee et al., 2020) and the contribution of transparent exopolymer particles (TEPs;
500 Passow, 2002), the low Chl-a concentrations in the ZRP support our interpretation (Fig. 4c).
501 Moreover, strong stratification within the plume suppressed the vertical mixing, allowing
502 degraded particles to remain suspended in the surface layer (Fig. 10e, f).

503 A bimodal particle size distribution (273 and $386 \text{ }\mu\text{m}$; Fig. 10f) in the ZRP could be
504 attributed to degradation of meso-sized POM (Chen et al., 2015). Additional processes,
505 including zooplankton grazing (Branco et al., 2019; Chen et al., 2015; Landry et al., 1982),
506 bio-aggregation (Mari et al., 2017; Michels et al., 2018), and interactions among various
507 biological communities (Ning et al., 2004; Tong et al., 2023; Zhou et al., 2015), may also
508 potentially contribute to the high VC of particles ranging from 200 to $400 \text{ }\mu\text{m}$ at the surface of
509 Station L1.



Table 2: Derived particle bulk densities (top two tables) and PC ratios (bottom two tables) at each hydrographic site in 2018 and 2020.

2018							
Bulk Den. (kg m ⁻³)	ZHJ3	ZHJ4	G1	H1	J1	K1	L1
Surface	-	-	-	2715.46	5019.05	2771.29	2229.94
Middle	-	-	-	2735.6	2126.07	2280.33	-
Bottom	-	-	-	2266.39	1934.63	1972.99	1905.94

* Bold type indicates Chla >1 µg/L

* "-" symbol indicates missing or error data, and gray value indicates VC <0.1 µL/L or SSC <1 mg/L.

2020							
Bulk Den. (kg m ⁻³)	ZHJ3	ZHJ4	G1	H1	J1	K1	L1 (ZRP)
Surface	1040.39	1077.85	1047.72	1160.09	1192.47	1447.45	1288.64
Middle	1127.11	1097.2	1130.36	1192.22	1307.08	1101.51	1496.24
Bottom	1103.01	1139.84	1171.27	1198.12	1302.8	1199.42	1655.39

* Bold type indicates Chla >1 µg/L

* "-" symbol indicates missing or error data, and gray value indicates VC <0.1 µL/L or SSC <1 mg/L.

2018							
PC Ratio	ZHJ3	ZHJ4	G1	H1	J1	K1	L1
Surface	-	-	579.99	514.81	190.82	673.68	424.27
Middle	-	-	-	558.47	476.45	168.04	-
Bottom	-	-	515.6	158.07	470.72	331.98	185.65

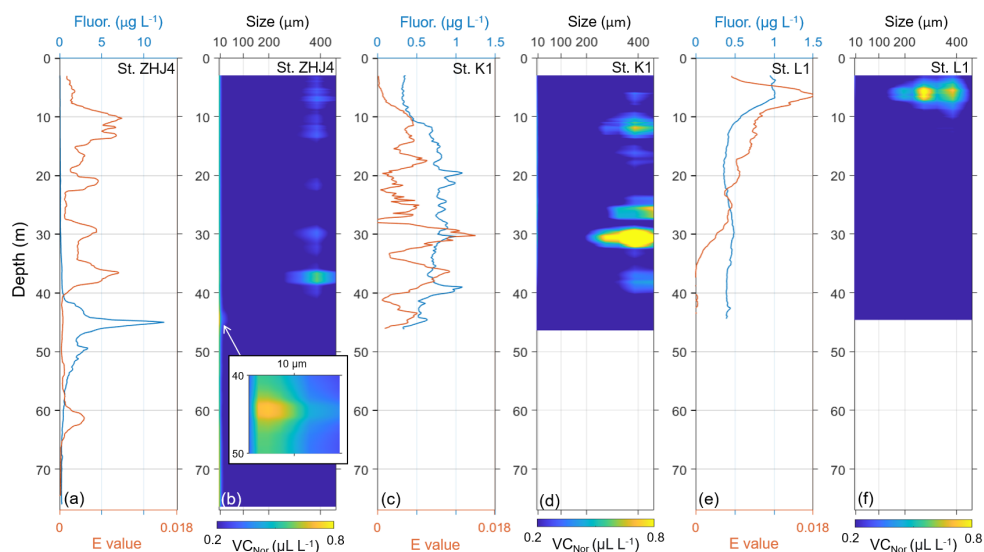
* Bold type indicates Chla >1 µg/L

* "-" symbol indicates missing or error data, and gray value indicates POC <0.1 mg/L or Chla <0.5 µg/L

2020							
PC Ratio	ZHJ3	ZHJ4	G1	H1	J1	K1	L1 (ZRP)
Surface	363.54	324.57	493.72	235.82	348.42	353.24	233.19
Middle	95.63	52.42	159.34	112.27	119.15	288.2	275.22
Bottom	103.59	160.17	212.61	834.76	181.14	163.04	248.4

* Bold type indicates Chla >1 µg/L

* "-" symbol indicates missing or error data, and gray value indicates POC <0.1 mg/L or Chla <0.5 µg/L



513

514 **Figure 10:** Hydrographic (a, c, e) and normalized VC profiles (b, d, f) at Stations ZHJ4, K1,
 515 and L1 in 2020, as shown in Fig 6. The brown and cyan lines in hydrographic profiles represent
 516 the E value and fluorescence, respectively. The inset in (b) provides a zoomed-in view of the
 517 finer VC size class.



518 4.4 Implications of biogeochemical signatures in transported particles

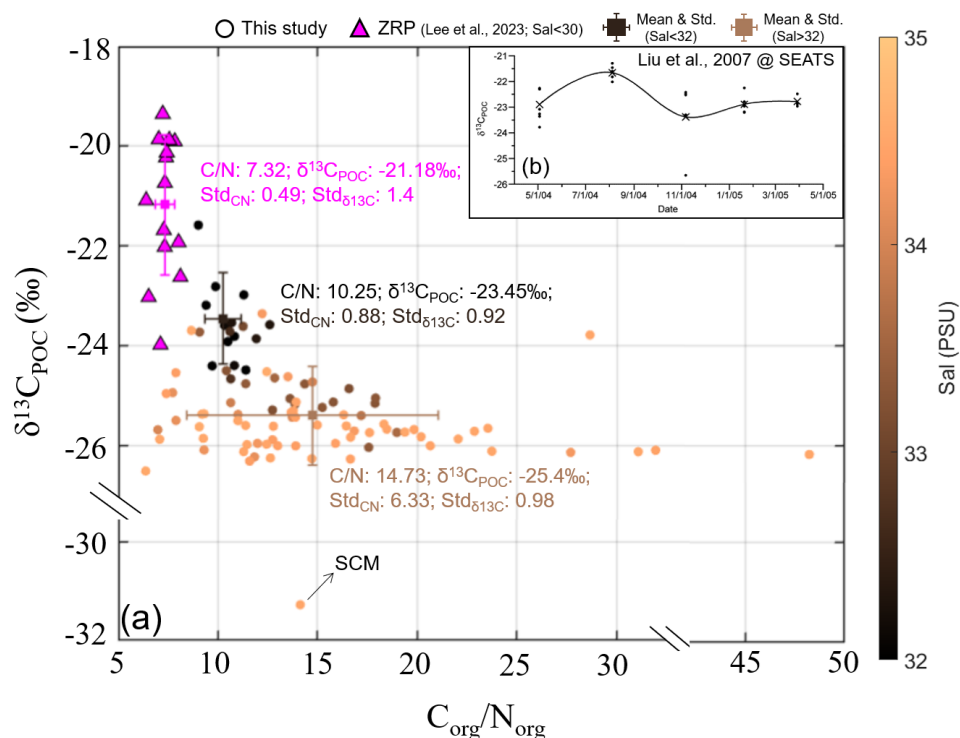
519 Annual sediment transport in the Pearl River Estuary predominantly follows a westward
520 trajectory, leading to significant sediment accumulation toward Hainan Island (Chen, 2006; Gu
521 et al., 2024; Hu et al., 2011; Tian et al., 2019; Wang et al., 2023). However, the eastward-
522 spreading ZRP, driven by the prevailing summer monsoon, offers an alternative pathway for
523 riverine materials to reach the NSCS shelf (Cai et al., 2023; Cao et al., 2019; Jia et al., 2023;
524 Liu et al., 2010). Our findings, consistent with Lee et al. (2023), indicate that particles
525 transported by the northeastward-flowing ZRP are primarily marine-derived biogenic
526 substances (Fig. 2, 4, 5, and Table 2). The presence of marine POM within the river plume
527 suggests a high carbon settling flux in the eastern NSCS shelf (Chen et al., 2022; Hung et al.,
528 2007; Wei et al., 2020), which influences sediment composition along the ZRP pathway (Cai
529 et al., 2023; Chen et al., 2022; Guo et al., 2019) and facilitates material transport toward the
530 Taiwan Strait (Tong et al., 2024).

531 Our results show an enriched $\delta^{13}\text{C}_{\text{POC}}$ signature in coastal regions influenced by ZRP,
532 highlighting a clear two-end-member mixing trend between riverine input and ambient
533 seawater (Fig. 11a; Appendix Fig. A7). POM in the proximal ZRP region near Hong Kong
534 (salinity < 30) exhibits a $\delta^{13}\text{C}_{\text{POC}}$ value of -21.18‰ and a C/N ratio of 7.32 (Lee et al., 2023).
535 In the distal region of the ZRP near offshore Shanwei, $\delta^{13}\text{C}_{\text{POC}}$ decreases to -23.45‰ with a
536 C/N ratio of 10.25, indicating a progressive dilution with a seawater end-member ($\delta^{13}\text{C}_{\text{POC}}$
537 value of -25.4‰ and a C/N ratio of 14.73). Although POM within the ZRP is considered
538 degraded in our study, the $\delta^{13}\text{C}_{\text{POC}}$ signature remains discernible after extended downstream
539 propagation from the river mouth, highlighting its potential as a tracer of riverine influence
540 over a broad spatial scale. Notably, the $\delta^{13}\text{C}_{\text{POC}}$ signature of the ZRP also aligns with values
541 observed in the upper 50 m at the SEATS (Southeast Asian Time-series Station; Fig. 11b; Liu
542 et al., 2007). This suggests that stable carbon isotope fractionation follows a similar mechanism
543 in both eutrophic (nearshore) and oligotrophic (offshore) environments, despite differences in



544 plankton communities across water masses (Ho et al., 2015; Huang et al., 2010; Li et al., 2018,
545 2021; Lu et al., 2015; Miller et al., 2008; Phillips et al., 2005; Quay et al., 2015; Yin et al.,
546 2001).

547 Climatic variability could further complicate particle distribution and biogeochemical
548 responses on the NSCS shelf, as rapid fluctuations in river discharge and sediment load from
549 the Zhujiang River impact the system (Liu et al., 2017, 2018a; Xiao et al., 2016; Zhang et al.,
550 2015). Increased flooding events in the river basin may extend the dispersal of terrestrial
551 effluents into the marine environment, blurring the distinction between inshore and offshore
552 waters (Brando et al., 2015; Ren et al., 2020; Shi & Wang, 2009). Physical mechanisms, such
553 as upwelling circulations and nonlinear internal waves (Feng et al., 2021; Gan et al., 2009; Gu
554 et al., 2012; Jing et al., 2009; Lee et al., 2021), further contribute to the mixing of particles
555 from different sources. This process leads to a decoupling of POM signatures between the water
556 column and surface sediments observed in the previous work (Lee et al., 2023). Given these
557 complexities, the multivariable approach applied in this study provides a framework for
558 accurately identifying particle sources and tracking their transport dynamics on the NSCS shelf.



559

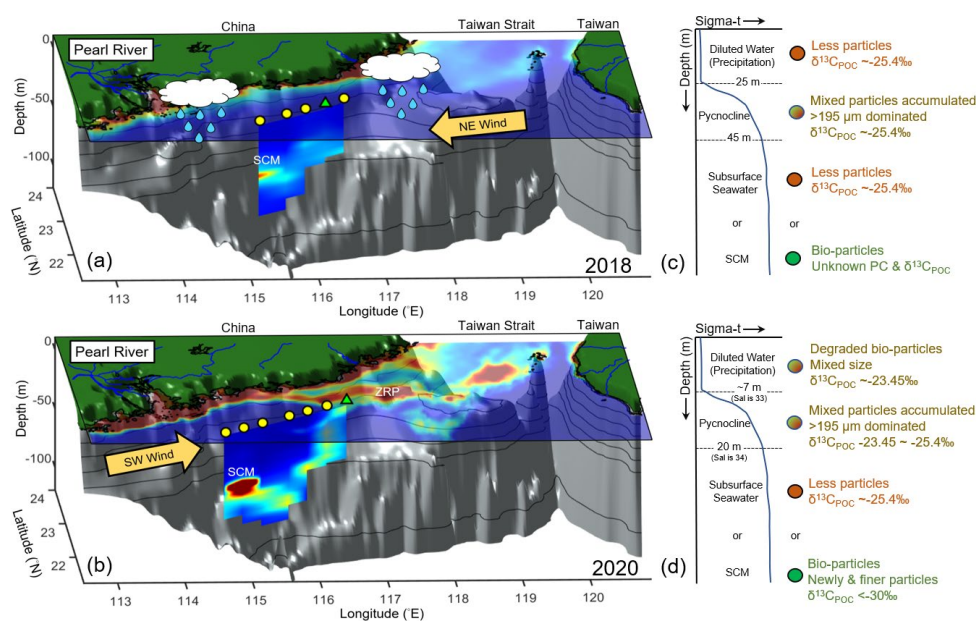
560 **Figure 11:** (a) $\delta^{13}C_{POC}$ and C/N ratio results for 2018 and 2020. Circles represent POM samples
 561 from this study, colored by corresponding salinity. Magenta triangles denote POM
 562 measurements from Lee et al. (2023) for waters with salinities <30. Squares indicate mean
 563 $\delta^{13}C_{POC}$ and C/N ratio values, with standard deviations noted beside them. (b) Time-series
 564 $\delta^{13}C_{POC}$ observations in the upper 50 m at SEATS from Liu et al. (2007). Cross symbols and a
 565 black curve in (b) indicate the mean trend during the observation period, while black dots
 566 represent raw data at each sampling.



567 **5. Conclusion**

568 This study underscores the critical role of water stratification in regulating particle
569 distribution on the NSCS shelf, particularly along the northeastward ZRP pathway (Fig. 12).
570 EOF analysis indicates that vertical water stability was shaped by local precipitation,
571 subsurface seawater, and the ZRP, which together governed particle accumulation at the
572 pycnocline. In 2018, strong water stratification induced by precipitation from a tropical
573 depression and subsurface seawater facilitated the retention of larger particles ($>195\ \mu\text{m}$)
574 between 25 and 45 m depth (Fig. 12a, c). In contrast, reduced offshore rainfall in 2020 shifted
575 the dominant stratification mechanism, with ZRP becoming the primary driver under the
576 influence of the southwesterly monsoon. This led to a shoaling of the halocline to depths
577 shallower than 20 meters (Fig. 12b, d), while subsurface seawater continued to contribute to
578 vertical water stability, as indicated by the third mode of the EOF analysis.

579 Our findings indicate that the ZRP plays a key role in transporting riverine nutrients and
580 marine-sourced biogenic particles toward the Taiwan Strait, potentially shaping sediment
581 composition and coastal biogeochemistry along its pathway. Although both the ZRP and SCM
582 exhibited high Chl-a concentrations, their POM characteristics differed markedly. The ZRP
583 transported more degraded organic material, as reflected by higher PC ratios and greater
584 particle bulk densities, while the SCM was dominated by fresher biogenic particles with lower
585 PC ratios and lighter bulk densities (Fig. 12d). These contrasts underscore distinct particle
586 transport processes, with the ZRP carrying relatively degraded material due to prolonged transit,
587 whereas the SCM reflects *in-situ* phytoplankton production. Furthermore, the distinct $\delta^{13}\text{C}_{\text{POC}}$
588 signatures observed among the ZRP, SCM, and ambient seawater highlight its potential as an
589 effective tracer for distinguishing water masses in the NSCS shelf environments. In contrast,
590 the N/P ratio exhibited minimal variability, limiting its effectiveness as a conventional tracer
591 of the ZRP spreading.

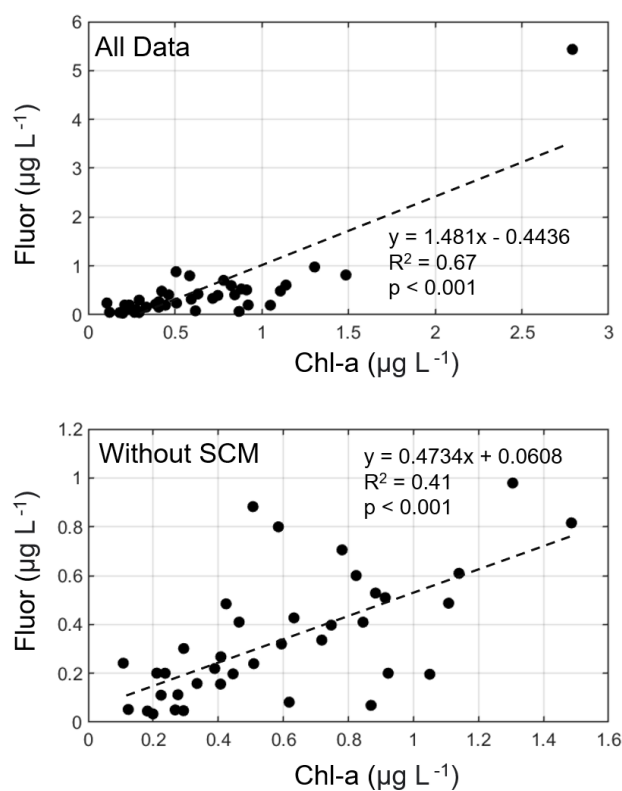


592

593 **Figure 12:** Schematic of particle distribution on the NSCS shelf. Panels (a, b) illustrate two
594 scenarios: local precipitation (2018) and ZRP influence (2020), enhancing vertical water
595 stability. Color images show satellite-derived Chl-a concentrations (horizontal view; same as
596 Fig. 1b, e). Yellow circles and green triangles mark hydrographic sites (as in Fig. 1). Panels (c,
597 d) display corresponding characteristics of suspended particles along the water density profile,
598 linked to water stratification in 2018 and 2020. Circles beside the density profile depict particle
599 signatures at different layers, including diluted water, pycnocline, and subsurface seawater (or
600 SCM).

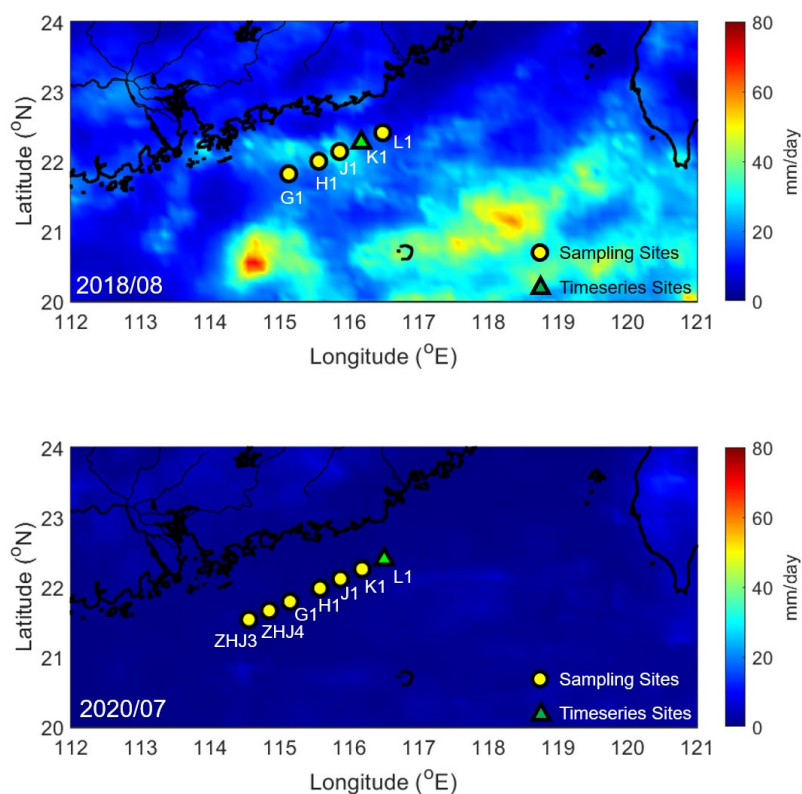


601 6. Appendices



602

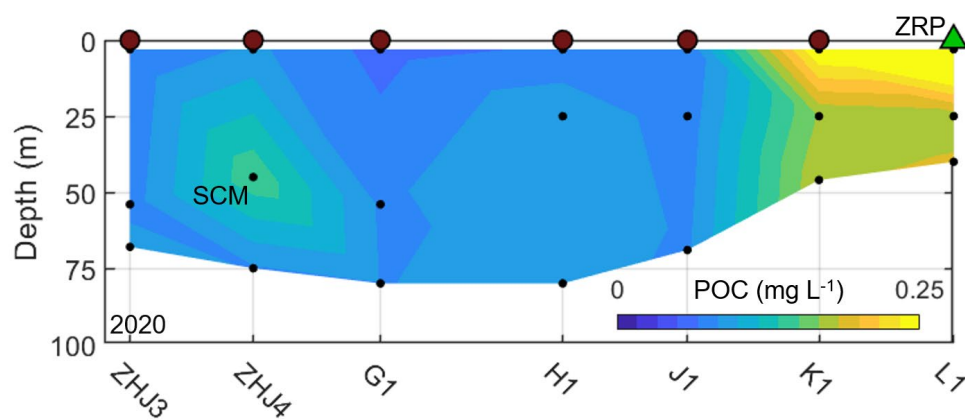
603 **Appendix Fig. A1:** Chl-a and fluorescence measurements from 2018 and 2020. The upper
 604 panel displays all collected data, while the lower panel excludes data from the SCM. Dashed
 605 lines indicate linear regression between Chl-a and fluorescence.



606

607 **Appendix Fig. A2:** Satellite-derived precipitation data during the observation period in 2018
 608 (upper panels) and 2020 (lower panels). Yellow circles and green triangles mark hydrographic
 609 stations, with green triangles representing time-series stations. Colors indicate precipitation
 610 levels obtained from the Integrated Multi-satellite Retrievals for Global Precipitation
 611 Measurement (NASA, <https://disc.gsfc.nasa.gov/>; Huffman et al., 2023).

612

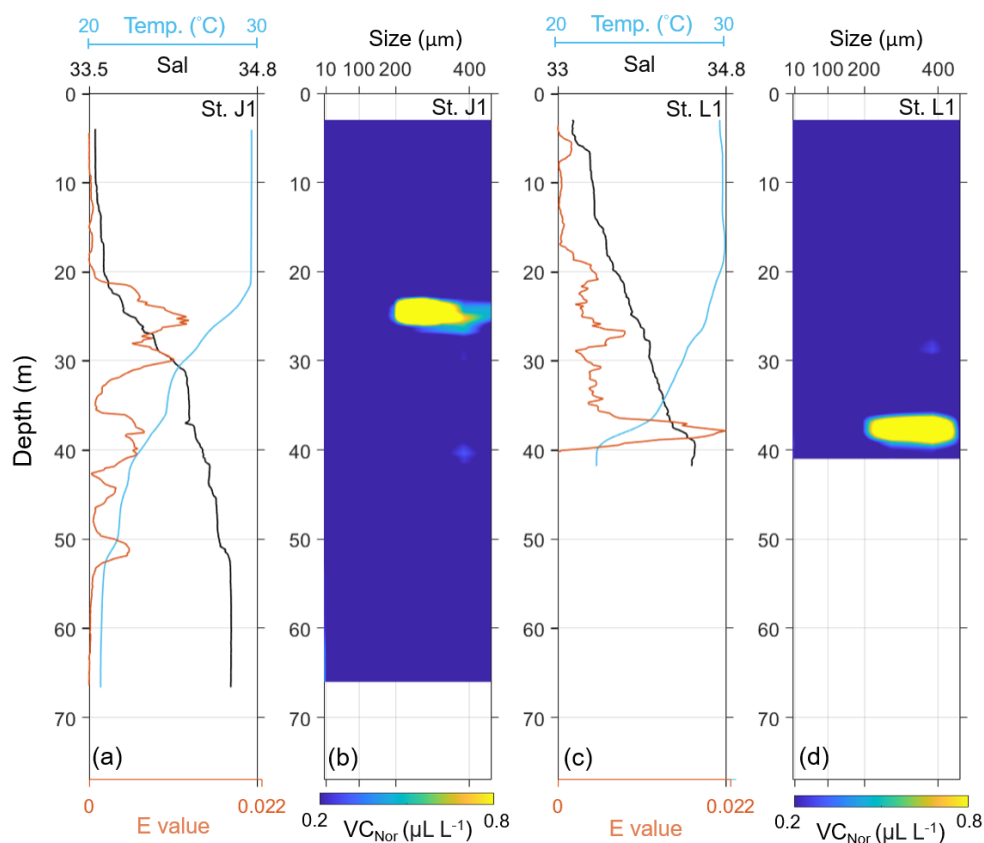


613

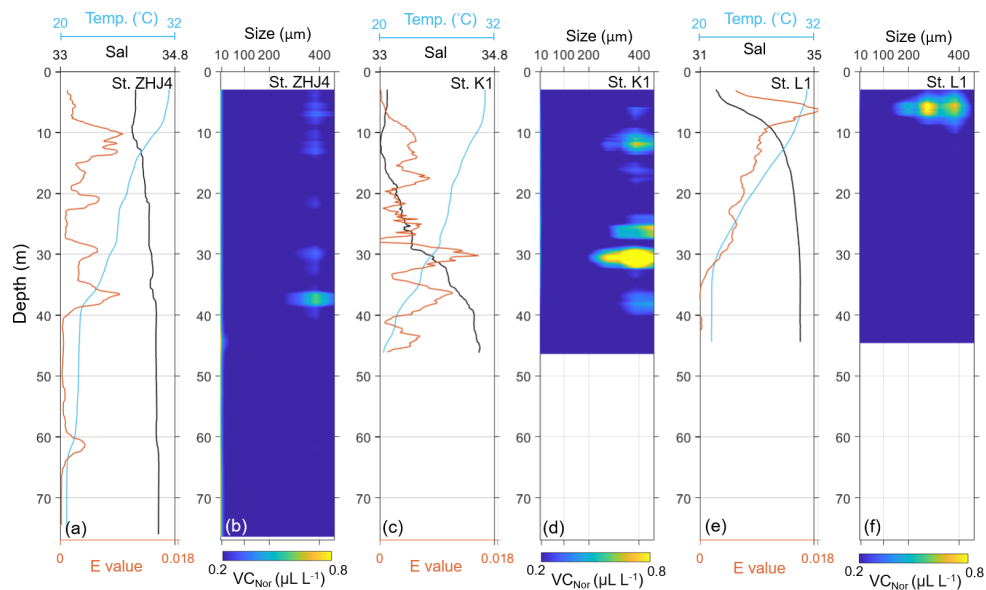
614 **Appendix Fig. A3:** POC concentration along the transect in 2020. Black dots indicate sampling

615 depths, while brown circles represent hydrographic stations from the cruise.

616



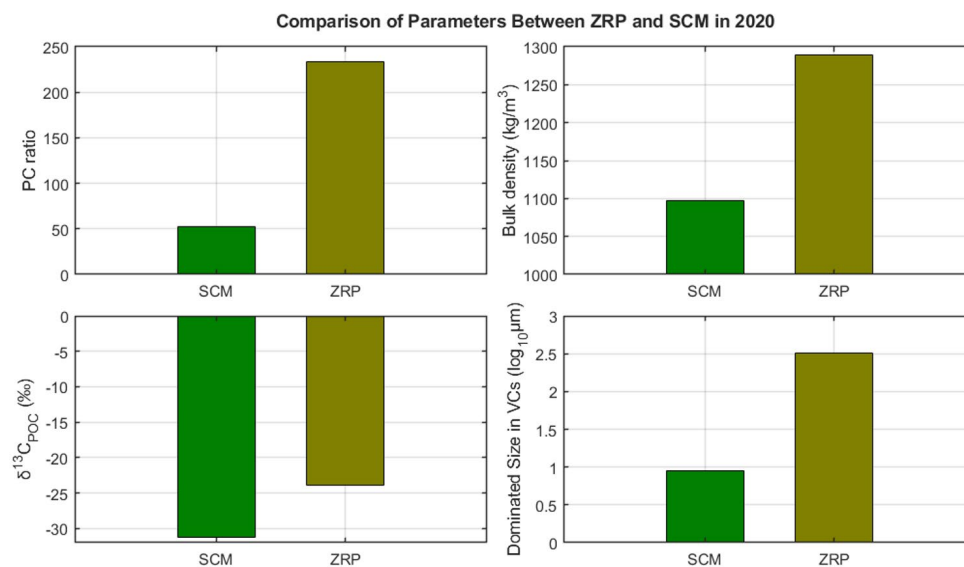
Appendix Fig. A4: Hydrographic (a, c) and VC (b, d) profiles at Stations J1 and L1 in 2018. Black, cyan, and brown lines in the hydrographic profile represent salinity, temperature, and E values, respectively. The spectrum illustrates the normalized volume concentration.



622

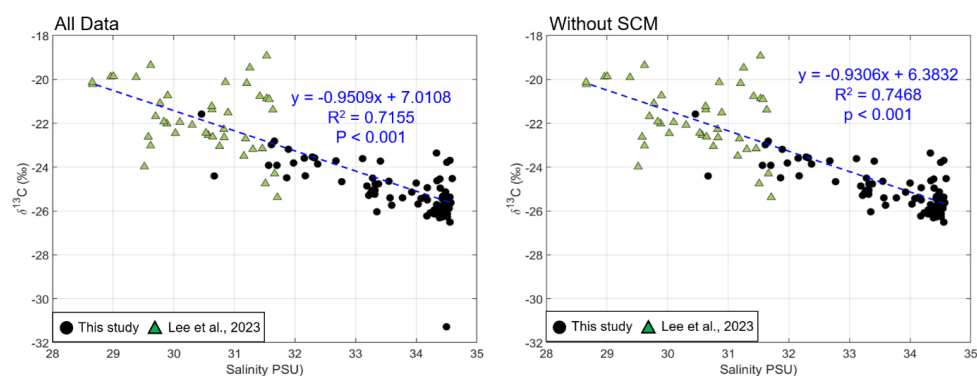
623 **Appendix Fig. A5:** Hydrographic (a, c, e) and normalized VC (b, d, f) profiles at Stations ZHJ4,
624 K1, and L1 in 2020 (from left to right). Black, cyan, and brown lines in the hydrographic
625 profiles represent salinity, temperature, and E values, respectively.

626



627

628 **Appendix Fig. A6:** Physicochemical characteristics of POM measured in 2020, including the
 629 PC ratio, $\delta^{13}\text{C}_{\text{POC}}$, particle bulk density, and dominant particle size based on VC measurement.
 630 The bar chart shows the SCM in green and the ZRP in olive green



631

632 **Appendix Fig. A7:** Salinity and $\delta^{13}\text{C}_{\text{POC}}$ measurements from 2018 and 2020. The left panel
633 presents all collected data, while the right panel excludes the SCM. Blue dashed lines indicate
634 linear regression between salinity and $\delta^{13}\text{C}_{\text{POC}}$.

635



636 **7. Code availability**

637 The code used in this study are available from the corresponding author on reasonable request.



638 **8. Data availability**

639 The datasets used and analyzed in this study are available from the corresponding author on

640 reasonable request.



641 **9. Author Contributions**

642 JL and JTL designed the field observations, with contributions from YSL. Sample analyses
643 were primarily supported by YSL, TYH, and CTAC. WG provided the data resources of the
644 Zhujiang River. JL prepared the initial draft of the manuscript under the supervision of JTL.
645 CRW contributed to manuscript revision. All authors contributed to data interpretation and final
646 manuscript editing.



647 10. **Competing interests**

648 The authors declare that they have no conflict of interest.



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663 12. **References**

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