

An integrated optic and acoustic (IOA) approach for measuring suspended sediment concentration in highly turbid environments

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1 **Combining optical and acoustic sensors to obtain accurate and high-resolution**
2 **profiles of suspended sediment concentration in highly turbid environments**

3
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12
13 **Highlights:**

- 14 (1) A combination of ASM, OBS and ADV resolves the ambiguity problem of two possible SSCs
15 for an OBS/ADV output.
- 16 (2) The integrated optic acoustic (IOA) approach enlarges the measurement range of OBS and
17 ADV to 100s g/L.
- 18 (3) The IOA approach provides high-resolution (1 cm) SSC profiles by ASM.
- 19 (4) The IOA approach was successfully applied in the Yangtze Estuary with SSC > 10 g/L.

20
21 **Abstracts:**

22 Accurate measurement of suspended sediment concentration (SSC) in highly turbid environments
23 has been a problem due to the signal saturation and attenuation. The saturation returns a limited
24 measurement range, and the attenuation raises the ambiguity problem that a low optical/acoustic
25 output could mean a low or high SSC. In this study, an integrated optic acoustic (IOA) approach is
26 therefore proposed to (i) overcome the ambiguity problem; (ii) increase the measurement range to
27 high SSC values; and (iii) obtain high-resolution SSC profiles. The IOA approach is a combination
28 of Argus Suspension Meter (ASM), Optical Backscatter Sensor (OBS) and Acoustic Doppler
29 Velocimeter (ADV). In this approach, ASM-derived SSC is preferred because of its lowest relative
30 error, followed by OBS and ADV. The ASM can produce high-resolution (1 cm) SSC profile when

31 it is not saturated (usually $SSC < 9 \text{ g/L}$). When the ASM is saturated, the missing SSC is recovered
32 by the OBS. Since the IOA approach solves the ambiguity problem in signal conversion, the
33 measurement range of OBS and ADV can be extended to 100s g/L. The best way to use an ADV,
34 however, is to have a rough estimation and assist in the OBS conversion. The IOA approach was
35 tested in the Yangtze Estuary during the wet and dry season, respectively. Comparison between the
36 SSC given by the IOA approach and in-situ water sampling indicates that the proposed IOA
37 approach is reliable with a relative error of 17–34%. The observed high SSCs were up to 63 g/L.
38 The measurements also show that the suspension is more concentrated in the benthic layer in the
39 wet season, whereas in the dry season, the suspension is better mixed throughout the water column.
40 To reduce the effects of particle size/composition, we suggest the usage of in-situ water samples or
41 mixed bottom sediment for the sensor calibration. Accurate calibrations with the particle
42 size/composition correction are expected to access a higher accuracy of the IOA approach in future
43 research.

44

45 **Keywords:** *suspended sediment concentration; Optical Backscatter Sensor; Argus Suspension*
46 *Meter; Acoustic Doppler Velocimeter; concentrated benthic suspension; Yangtze River Estuary*

47

48 **1. Introduction**

49 Suspended sediment concentration (SSC) is a critical parameter for understanding the transport
50 of sediment and associated contaminants (Manning et al., 2010; Liang et al., 2013; Huettel et al.,
51 2014; Burchard et al., 2018). SSC also limits the light availability and inhibits the primary
52 production in lakes, rivers, estuaries and coastal waters (Yoshiyama and Sharp, 2006; Van Kessel et
53 al., 2011). SSC can vary orders of magnitude over a small distance or a short period (Burchard et
54 al., 2018; Ge et al., 2018). Accurate SSC measurements with a high spatial and temporal resolution,
55 therefore, have significant implications for the management of ecology, biogeochemistry, and
56 geomorphology. However, measuring high-resolution SSC in a simple, robust and efficient way is
57 not straightforward, particularly in highly turbid environments.

58 Water sampling (e.g., suction/pumping) is a traditional, reliable and widely used method to
59 measure in-situ SSC. The SSC from the water sample is generally regarded as a reference for the
60 sensor calibration (Kineke and Sternberg, 1992; Fugate and Friedrichs, 2002; Gray and Gartner,

61 2010; Wang et al., 2013; Baeye and Fettweis, 2015; Druine et al., 2018). The SSC given by this
62 method contains a relative error of ~ 20% from sampling and later analysis (McHenry et al., 1967).
63 Point-integrating samplers can obtain SSC profiles of nearly the entire water column. However,
64 water sampling is labor-intensive, implying that both temporal and spatial resolutions are generally
65 limited. Accurate near-bed sampling (< 0.5 m) is furthermore challenging, although this region is of
66 high interest for understanding sediment exchange processes.

67 To obtain high-resolution SSC profile, especially in the bottom boundary layer, more advanced
68 technologies and sensors (optical or acoustic) have been developed in last decades(Wren et al., 2000;
69 Thorne and Hanes, 2002; Rai and Kumar, 2015; Rymszewicz et al., 2017).

70 Optical sensors measure SSC by the strength of back- or side-scattered light, e.g., Optical
71 Backscatter Sensor (OBS) (Campbell Scientific, 2018), Argus Suspension Meter (ASM) (Argus,
72 2014), YSI (YSI Incorporated, 2012), Fiber Optic In-stream Transmissometer (FIT) (Campbell et al.,
73 2005) and HHU-LIOS (Shao and Maa, 2017). They can measure SSC at a high frequency (1-25 Hz)
74 (Campbell Scientific, 2018), but their measurements are generally restricted to a single point in a
75 fixed deployment. Stacked optical sensors (e.g., Argus Suspension Meter, ASM) were later
76 developed and provide SSC profile with a vertical resolution of 1 cm (Vijverberg et al., 2011; Ge et
77 al., 2018). Although multiple or moving optical sensors increase the spatial resolution of SSC
78 measurements, they still require an intrusion in the flow, which may disturb the turbulence as well
79 as the distribution of suspended sediment. Particle-size dependency is another drawback of the
80 optical sensor. The reading of the same sensor may increase by as much as ten times for the same
81 SSC with a smaller particle size (Ludwig and Hanes, 1990; Campbell Scientific, 2018). Therefore,
82 continuous calibration against the in-situ SSC from water sampling is suggested (Maa et al., 1992;
83 Nauw et al., 2014). Additionally, the optical output has an upper limit, because of the signal
84 saturation (e.g., ASM) or attenuation (e.g., OBS). Within a low SSC (< 9 g/L), optical output
85 increases nearly linearly with increasing SSC (Fig. 1, see also Downing, 2006; Shao and Maa, 2017).
86 Beyond a threshold, however, ASM output maintains at its maximum, and OBS output decreases
87 with increasing SSC (Fig. 1). As a result, ASM has a limited measurement range, and OBS has an
88 ambiguity problem in conversion. A low OBS output could mean a low or high SSC. Recently, a
89 laser infrared optical sensor was developed by Hohai University (Nanjing, China, HHU-LIOS) with
90 a measurement range up to 30 g/L (Shao and Maa, 2017). This extension of SSC range is a

91 significant improvement, but it is still insufficient for the highly turbid environments, e.g., the
92 Yangtze Estuary (Wan et al., 2014) and the EMS Estuary (Winterwerp et al., 2017). A combination
93 of HHU-LIOS and OBS is therefore suggested by Shao and Maa (2017). However, their method
94 only gives SSC at a single point.

95 Acoustic sensors are utilized for measuring SSC profiles non-intrusively, e.g., Acoustic
96 Doppler Profiler (ADP) (Thorne and Hanes, 2002; Ha et al., 2011; Baeye and Fettweis, 2015) and
97 Acoustic Doppler Velocimeter (ADV) (Ha et al., 2009; Salehi and Strom, 2011; Shao and Maa,
98 2017). In addition to SSC, acoustic sensors also measure flow velocity synchronously. ADP (Moura
99 et al., 2011; Sahin et al., 2013; Fettweis and Baeye, 2015) and ADCP (Guerrero et al., 2011;
100 Anastasiou et al., 2015; Baeye and Fettweis, 2015), for example, concurrently obtain velocity and
101 SSC profiles over several meters. High-frequency acoustic signal (~ 10 Hz) can be used to estimate
102 turbulent water/sediment flux, e.g., ADV (Fugate and Friedrichs, 2002; Scheu et al., 2015; Yang et
103 al., 2016). Note that optical sensors cannot obtain synchronized high-frequency measurements of
104 velocity at the same location, though they also provide high-frequency SSC estimates (Guo et al.,
105 2018). The conversion from acoustic output into SSC also has the ambiguity problem and contains
106 significant uncertainties. First, acoustic output increases exponentially with increasing and low SSC
107 ($< 1-2$ g/L), so a small misalignment in acoustic output may introduce a significant error in its
108 estimate. For instance, 1dB misalignment in ADV output can cause an error of ~ 1 g/L in the
109 estimated SSC (Merckelbach and Ridderinkhof, 2006; Shao and Maa, 2017). Second, similar to
110 optical sensors, the acoustic signal also attenuates in high SSC ($> 1-10$ g/L) (Fig. 2, see also Ha et
111 al., 2009; Shao and Maa, 2017), which causes the ambiguity in SSC retrieval.

112 This study aims to solve the ambiguity problem that a low OBS/ADV reading could mean a
113 low or high SSC and access a broader measurement range. We propose an integrated optic acoustic
114 (IOA) approach to identify the “true” SSC and obtain high-resolution SSC profile by a combination
115 of OBS, ASM and ADV. This paper is organized in the following way. Section 2 describes the
116 calibration of sensors. Upon careful calibrations, we propose algorithms for each sensor to convert
117 their outputs into SSC in Section 3. Compared with the SSCs from the water samples obtained in
118 the Yangtze Estuary, these algorithms are evaluated. An optimal algorithm is then suggested in
119 Section 4. The accuracy and advantages of the proposed IOA approach are discussed in Section 5.
120 Section 5 also gives a discussion on the observed seasonal SSC profiles and intra-tidal bottom SSC

121 variation in the Yangtze Estuary. It is concluded in Section 6, that the IOA approach is reliable, and
122 it extends the measurement range to 100s g/L. The proposed IOA approach also provides high-
123 resolution (1 cm) SSC profiles by the ASM when it is not saturated. The application of the IOA
124 approach is beneficial for quantifying the sediment transport in the bottom boundary layer or highly
125 turbid environments.

126

127 **2. Sensor calibrations**

128 The OBS (turbidity in NTU) and the ASM (turbidity in FTU) were calibrated in a cylindrical
129 container (0.4 m diameter and 0.5 m height) with continuous and steady stirring at the bottom. First,
130 the container was filled with the water collected from the Yangtze Estuary. To determine different
131 SSC level, we gradually poured the slurry (an amalgam of bottom sediment collected every 2 hours
132 within a campaign) into the container. The OBS and one of the ASM sensors (88th sensor) were
133 mounted at 15 cm above the bottom with an outlet at the same height for water sampling. At each
134 SSC level, we took a water sample after the turbidity readings stabilized for 30 seconds.
135 Subsequently, the water sample was filtered through a 0.45 μm filter and dried at 40 $^{\circ}\text{C}$ for 48 h to
136 determine the SSC. Averaged turbidity during the sampling was then calibrated against the SSC of
137 water sample (Fig. 1).

138 The calibration of ADV (signal-to-noise ratio, SNR in dB) was carried out with the in-situ SSC
139 derived by ASM and OBS. The sampling rate of the ADV was 8 Hz, and the burst interval was 10
140 min. In each burst, the ADV sampled continuously for 90 seconds. In the signal processing, the SNR
141 from three receiving transducers were averaged to obtain the representative mean value, and burst-
142 averaged SNR was then calibrated with the in-situ SSC (Fig. 2).

143 Calibration results indicate that the response of each sensor (i.e., OBS, ASM and ADV) to
144 increasing SSC is quite different. ASM turbidity (T_{ASM}) increases linearly with SSC below a limit
145 of ~ 9 g/L (Figs. 1c and 1d). Beyond this limit, however, T_{ASM} maintains at the maximum (i.e.,
146 saturated). Figs. 1c and 1d also show that the sensors on the ASM behave roughly the same.

147 The OBS turbidity (T_{OBS}) shows three responses (Figs. 1a and 1b). (1) At low SSC where T_{ASM}
148 is unsaturated, T_{OBS} increase is approximately linear. A critical OBS turbidity (T_{C}) can be
149 determined when T_{ASM} just saturates (Fig. 3a). (2) Within a range of moderate SSC, where T_{ASM}
150 saturates and $T_{\text{OBS}} \geq T_{\text{C}}$, T_{OBS} remains roughly the same and begins to decrease after reaching the

151 maximum ($\max T_{OBS}$). A parabolic function fits in this range. To relate the turbidity to SSC more
152 directly, we divide the curve into two sections (Fig. 3a, curves 3 and 4). (3) T_{OBS} decreases linearly
153 in high SSC where T_{ASM} saturates and $T_{OBS} < T_C$. After a process of trying to match the transition
154 from one range to the next as continuous as possible, four curves are suggested as representative
155 (Fig. 3a). Table 2 shows the equation for each calibration curve and their correlation coefficients.

156 The SNR from ADV also has three responses to different SSC level (Fig. 3b), i.e., increasing,
157 constant and decreasing region. For convenience, parabolic fitting with SSC on a logarithmic scale
158 is applied in this study, and it returns a high coefficient of determination (Table 2). Note that the
159 max SNR occurs in a critical SSC ($SSC_C = 2 \text{ g/L}$) (Fig. 2, see also Ha et al., 2009; Shao and Maa,
160 2017). It means that SNR decreases monotonically with SSC when ASM is saturated.

161

162 3. Conversion algorithms

163 Based on the different responses of ASM, OBS and ADV, algorithms are developed to convert
164 their outputs into SSC (Fig. 4). To explain the conversion process, we take the OBS-633, ASM and
165 ADV deployed in July 2014 as examples (Fig. 3).

166 The conversion of ASM is relatively simple. Before the conversion, whether the ASM is
167 saturated or not needs to be identified. The ASM only provides estimates under unsaturated
168 condition. Once the ASM saturates, no valid estimate is given by ASM. Fortunately, the missing
169 high SSC can be recovered by the OBS or ADV.

170 The accurate conversion of OBS requires the assistance of ASM and ADV. Critical OBS
171 turbidity (T_C) and SNR (SNR_C) need to be determined before the conversion (Fig. 3). When the
172 T_{ASM} is not saturated, a second-order polynomial is applied (Fig. 3a, curve 2). For saturated T_{ASM}
173 and $T_{OBS} < T_C$, the estimate is given by a negative and linear relationship (Fig. 3a, curve 5). For
174 saturated T_{ASM} and $T_{OBS} \geq T_C$, however, the estimate is taken as the smaller solution to the parabolic
175 equation when $SNR \geq SNR_C$ (Fig. 3a, curve 3) and the larger solution when $SNR < SNR_C$ (Fig. 3a,
176 curve 4).

177 The SSC derived by ASM and OBS serves the conversion of ADV. High-frequency SSC (c) is
178 a sum of burst-averaged (\bar{c}) and turbulent (c') components. Assuming that c does not change much
179 within a sampling burst of 90 s (i.e., $c \approx \bar{c}$), we can identify the correct estimates of c by the \bar{c}
180 given by ASM and OBS. Upon the determination of critical SSC (SSC_C), the estimate is taken as

181 the smaller solution to the parabolic equation when $SSC \leq SSC_C$, (Fig. 3b, curve 6) and the larger
182 solution when $SSC > SSC_C$ (Fig. 3b, curve 7).

183

184 **4. Application and evaluation**

185 To test and evaluate the proposed IOA approach and algorithms, we conducted field
186 measurement campaigns in July 2014 and January 2016, respectively. Upon the comparison
187 between the SSC given by each sensor and water sampling, an optimal algorithm is suggested within
188 the IOA approach. This section also shows measured SSC profiles with and without such an
189 algorithm and thus highlights the importance of using the IOA approach.

190

191 **4.1 Field campaigns in the Yangtze Estuary**

192 Since the surface SSC is up to 1 g/L and bottom SSC up to 10s g/L (He et al., 2001; Shi et al.,
193 2006; Wan et al., 2014), the Yangtze Estuary is an excellent example of highly turbid water,
194 particularly in the estuarine turbidity maximum (ETM). Two measurement campaigns were
195 conducted in the ETM of the North Passage (Fig. 5). For each campaign, both tripod- and ship-
196 borne systems with multiple sensors were employed. Table 3 shows the operated instruments and
197 their sampling schemes.

198 A sketch of the bottom-mounted tripod system is given in Fig. 5d. An ASM measured turbidity
199 profiles from 0.11 to 1.06 meter above the bed (mab here-after) with a vertical resolution of 1 cm.
200 An OBS simultaneously measured turbidity, salinity, and temperature at 0.35, 0.55 and 1.06 mab,
201 respectively. A downward-looking ADV recorded high-frequency 3D velocities and SNR at 0.35
202 mab. The sensors in the ADV were also used to monitor the heading, pitch and roll state of the tripod.

203 Ship-borne observations included measurements of turbidity, salinity and velocity profiles, and
204 water sampling. Turbidity and salinity profiles were hourly measured by the OBS moved from water
205 surface to near-bed (~ 0.5 m). The OBS stayed for 30 seconds at each relative depth layer, i.e.,
206 0.05H (near-surface), 0.2H, 0.4H, 0.6H, 0.8H, and 0.95H (near-bed), where H is the total water
207 depth. A water sample of 1.2 L was concurrently collected at each layer. These water samples were
208 used for laboratory analysis of SSC, salinity and primary-particle-size distribution (PPSD). The
209 PPSD was measured by the Coulter Counter analyzer after removing organic material and
210 destroying flocs by sonification. An LISST-100 (type C) hourly recorded the in-situ floc-size

211 distribution (FSD) and volume concentration at each layer. Bottom sediment was collected every 2
212 hours for the calibration of tripod-borne sensors.

213 To avoid interference between tripod- and ship-borne sensors, the tripod was deployed about
214 200 m upstream of the vessel. Compared with the distance between the two groins (~ 5 km), this
215 distance is negligible. For safety reasons, it is not allowed to deploy an instrument tripod or mooring
216 vessel in the Deepwater Navigational Channel (DNC). In our cases, both tripod- and ship-borne
217 measurements were conducted at the south to the channel, about 200 m away from the DNC (Fig.
218 5c). Due to significant differences in cross-channel hydrodynamics and topography (Song et al.,
219 2013; Wan et al., 2014; Ge et al., 2015), the tripod and the vessel should keep the same distance
220 from the DNC. Therefore, we can assume that the tripod- and ship-borne measurements are
221 representative for the same site, although they are actually in different locations.

222 Both temporal and spatial variations of temperature were small during the campaigns in July
223 2014 (24.7-27.0 °C) and January 2016 (3.5-6.1 °C). Hence the impact of temperature on the sensors
224 was negligible within a campaign. Water temperature during the two campaigns, however, were
225 significantly different from each other. The sensitivities of optical/acoustic sensors to SSC may
226 change due to such a temperature difference. Therefore, we calibrated the sensors at the temperature
227 similar to the on-site water temperature.

228

229 **4.2 SSC from in-situ water samples**

230 To evaluate the performance of each sensor, we regard the SSC from in-situ water sampling as
231 the reference. During both campaigns, the water depth (H) ranged from 9 to 13 m (Figs. 6a and 7a),
232 so the bottom SSC (at 0.95H) represented the SSC at 0.45-0.65 mab which can be used for the
233 evaluation of tripod sensors. The SSC from water sample can only be verified by comparing samples
234 taken closely in time and location. Unfortunately, such samples were not available in our study, so
235 we cannot prove that an SSC from water sample is right or wrong. Note that the SSC may be
236 incorrect due to sampling and analysis errors.

237 The SSC ranged 0.4-39.8 g/L during the campaign in July 2014 (Fig. 6d) and 1.4-5.1 g/L in
238 January 2016 (Fig. 7d). High SSC and broad range in July 2014 are suitable to evaluate the
239 performance of the proposed IOA approach in highly turbid environments. As a return, this approach
240 benefits the detection of concentrated benthic suspension (CBS) where $SSC > 10$ g/L.

241 Concerning intra-tidal variation (Figs. 6d and 7d), the SSC increased directly after low water
242 slack (LWS). An SSC peak occurred around the max flood, and the SSC decreased slightly then.
243 After high water slack (HWS), the SSC increased rapidly again, reaching another peak on the early
244 ebb. Subsequently, the SSC dropped and reached the minimum at LWS. Such an intra-tidal variation
245 pattern is similar in the wet and dry season, except the higher SSC in the wet season and postponed
246 peak in the late flood of the dry season.

247 On July 14, 15:00-17:00, the SSC from the water sample was more than 10 g/L (Fig. 6d).
248 During this period, the ASM was saturated, and both the OBS and ADV outputs decreased
249 significantly. It suggests that the observed high SSCs were reliable, and they caused optical/acoustic
250 attenuation in the field, as reproduced by the in-lab calibration. On July 15, 2:00-5:00, however, the
251 SSC decreased suddenly to ~ 1 g/L when the ASM was saturated. Meanwhile, the bottom turbidity
252 was over 3000 NTU, validated by both tripod- and ship-borne OBS, indicating an $SSC > 10$ g/L.
253 There are chances that the SSC from water sampling is underestimated during this period. This
254 underestimation could be the result of (i) sampling not close enough to the bed; (ii) error of analysis
255 in the laboratory; and (iii) a combination of both of the above. The underestimated SSC (only one
256 sample) is therefore removed in the evaluation.

257

258 **4.3 SSCs from OBS, ASM and ADV**

259 During the observation in July 2014, the T_{ASM} saturated (with a reading around 4000 FTU) on
260 the early ebb, which suggests a high $SSC > \sim 9$ g/L. Meanwhile, a significant reduction occurred in
261 the T_{OBS} and SNR. Such responses of T_{ASM} , T_{OBS} and SNR to high SSC can be reproduced in the
262 laboratory experiments (Figs. 1 and 2). It indicates that the response of each sensor is stable and
263 reliable either in the lab or field.

264 By the proposed algorithms (Section 3), T_{ASM} , T_{OBS} , and SNR were converted into SSC. Figs.
265 6d (July 2014) and 7d (January 2016) show the time series of ASM-, OBS- and ADV-derived SSC
266 at 0.35 mab. Note that the estimates given by the ASM are missing when it is saturated. All SSCs
267 given by sensors follow the intra-tidal variation pattern of the SSC from the water sample. By the
268 collaboration, OBS and ADV get access to higher SSC (> 60 g/L), although ASM only provides
269 reliable estimates of $SSC < 9$ g/L.

270 The ADV also provides estimates of turbulent sediment flux ($\overline{w'c'}$). The observed $\overline{w'c'}$ had a

271 tidally averaged magnitude of 10^{-4} kg/m²/s and reasonable intra-tidal variation, similar to the
 272 theoretical calculations $(\frac{\nu_t}{\sigma_t} \frac{\partial c}{\partial z})$ (Fig. 8). ν_t is the eddy viscosity given by

$$273 \quad \nu_t = \left(\overline{u'w'} \frac{\partial \bar{u}}{\partial z} + \overline{v'w'} \frac{\partial \bar{v}}{\partial z} \right) \left[\left(\frac{\partial \bar{u}}{\partial z} \right)^2 + \left(\frac{\partial \bar{v}}{\partial z} \right)^2 \right]^{-1}. \quad (1)$$

274 where σ_t is the turbulent Prandtl–Schmidt number, relating eddy viscosity (ν_t) to eddy diffusivity
 275 (K_t), as $K_t = \nu_t / \sigma_t$. A common assumption is that $\sigma_t = 0.7$. In highly turbid environments (e.g., the
 276 Yangtze Estuary), however, $\sigma_t = 2.0$ gives the optimal modeling of currents and SSC (Winterwerp
 277 et al., 2009). Direct comparison between the calculations $(\frac{\nu_t}{\sigma_t} \frac{\partial c}{\partial z})$ and in-situ measurements $(\overline{w'c'})$,
 278 verifies that $\sigma_t = 2.0$ gives a better estimate than $\sigma_t = 0.7$ (Fig. 8).

279

280 **4.4 Optimal algorithm in the IOA approach**

281 The performance of each sensor is evaluated by an averaged relative error:

$$282 \quad \text{Relative error} = \frac{|C_{\text{calculated}} - C_{\text{observed}}|}{C_{\text{observed}}} \times 100\% \quad (2)$$

283 where $C_{\text{calculated}}$ is the SSC estimated by sensors based on the calibration curves (Table 2); C_{observed}
 284 denotes to the SSC from the filtration of water sample (Druine et al., 2018).

285 Table 4 summarizes the relative error and measurement range of each sensor. ASM-derived
 286 SSC contains the lowest relative error ($\sim 25\%$), though it has limited measurement range (< 9 g/L).
 287 The ASM also provides high-resolution SSC profiles when it is not saturated. Our proposed
 288 algorithms successfully extend the measurement range of OBS to ~ 60 g/L, and OBS-derived SSC
 289 has a relative error of about 30%. Although the ADV has the most extensive measurement range (\sim
 290 360 g/L), its estimates contain the lowest accuracy (relative error $> 80\%$), so the best it can be used
 291 is to have a rough estimation and assist in the conversion of OBS. According to the sensor
 292 performances, we suggest an optimal algorithm for the IOA approach (Fig. 4). ASM-derived SSC
 293 is preferred as long as the ASM is unsaturated. Under ASM-saturated condition, the missing ASM
 294 estimates can be recovered by the OBS. The main contribution of the ADV is to provide rough
 295 estimation and reduce the uncertainty in the OBS conversion.

296

297 **4.5 Performance of the IOA approach**

298 To highlight the importance and advantages of using the IOA approach with the optimal
 299 algorithm, Fig. 9 shows the estimated SSC profiles with and without the IOA approach. The classical

300 method (i.e., without IOA approach) means that the SSC is estimated only by three OBSs at three
301 different heights. By the OBS itself, the high-SSC-induced attenuation cannot be identified, so we
302 can only conduct the conversion by the first stage of the calibration curve (e.g., curve 2 in Fig. 3).
303 Therefore, the classical method may cause underestimation in high concentration.

304 Within low SSC (< 10 g/L), the two methods give similar SSC estimates (Fig. 9a). Closer to
305 the bed, with increasing SSC, a difference appears between them (Figs. 9b and 9c). The SSC is
306 significantly underestimated and generally less than 10 g/L without the IOA approach, whereas that
307 estimated by the IOA approach is up to 63 g/L.

308 The ASM not only identifies the reliable estimates given by OBS but also provides high-
309 resolution SSC profiles when it is not saturated (Figs. 9d, 9e and 9f). Ninety-six estimates are given
310 in a profile with a vertical resolution of 1 cm. Without the IOA approach, however, only three
311 estimates are given by the OBS at three layers (i.e., 0.35, 0.55 and 1.06 mab). When the near-bed
312 high SSC appears, the IOA approach provides a more reasonable and reliable SSC profile. At 01:40
313 am, July 12 (Fig. 9d), for example, the proposed IOA approach gives an SSC of ~ 40 g/L at 0.35
314 mab, while an SSC of ~ 4 g/L is obtained without the IOA approach. The reliable SSC profile given
315 by the ASM within 0.5-1.06 mab, suggests a sudden increase at 0.55 mab. Based on this trend, the
316 SSC profile estimated by the IOA approach is more reasonable.

317 Upon careful calibration and conversion, the IOA approach with the optimal algorithm allows
318 high temporal and vertical resolution of SSC variability. Particularly on the early ebb in July 2014,
319 the CBS was successfully captured and measured. The observed CBS lasted 3-4 hours, and its
320 thickness was ~ 1 m (Fig. 10c). The seasonal SSC variation was also observed in the Yangtze Estuary.
321 In the wet season (Fig. 12a), the SSC profile is L-shaped with a much higher bottom SSC (up to 63
322 g/L). A significant SSC gradient is thus present in the lowest 0.2H. In the dry season (Fig. 12e),
323 however, the SSC profile is more uniform over the entire water column. The SSC shows the highest
324 value just above the bed and decreases almost linearly to the surface.

325

326 **5. Discussion**

327 **5.1 Sources of relative errors**

328 In this study, the SSC estimates given the ASM, OBS and ADV are evaluated by comparing
329 with that from water sampling. Their relative errors are, therefore, not only determined by the sensor

330 accuracy but also contaminated by the errors in water sampling and filtration.

331 The error from the sensor accuracy is unavoidable and accumulates in the relative error of the
332 SSC estimate. OBS/ASM outputs, for example, have an accuracy of $\pm 10\%$ (Argus, 2014; Campbell
333 Scientific, 2018). Since a linear regression is applied for the ASM calibration, this accuracy causes
334 a relative error of 10% in the ASM-derived SSC. For the OBS, this accuracy also leads to a relative
335 error of 10% in the linearly increasing and decreasing region (i.e., curves 2 and 5 in Fig. 3a), and
336 up to 90% around the turning point (i.e., curves 3 and 4 in Fig. 3a). The SNR is calibrated against
337 the SSC on the logarithm scale, the relative error caused by its accuracy therefore increases with
338 increasing SSC. Near the turning point (SSC = 2 g/L), for example, the SNR accuracy of $\pm 1\%$
339 (Nortek, 2005) causes a relative error of 30%. The relative errors in Table 4, however, are higher
340 than those caused by the sensor accuracy, which suggests additional sources for the given relative
341 errors.

342 Note that no in-situ water sample was collected at the elevation (0.35 mab) where the ASM,
343 OBS and ADV deployed, so we can only evaluate their SSC estimates with the water samples hourly
344 obtained by a ship-borne sampler in the bottom layer (0.95H, i.e., ~ 0.45 -0.65 mab). The relative
345 errors could be thus overestimated because of the height difference between sensors and water
346 samples, particularly when a large near-bed SSC gradient presents (e.g., July 2014). To obtain a
347 more accurate relative error, we should employ a reliable in-situ water sampling system and collect
348 water samples at the same elevation of sensors. Besides, the ADV was calibrated by the OBS-/ASM-
349 derived SSC. Part of its relative error, therefore, may accumulate from those of the OBS/ASM. In
350 other words, the relative error of ADV-derived SSC is also overestimated. We suggest an individual
351 calibration for each sensor in future research.

352 Since the grain size and composition of suspended sediment can affect the responses of both
353 optical and acoustic sensor (Conner and De Visser, 1992; Gibbs and Wolanski, 1992; Green and
354 Boon, 1993; Merten et al., 2014; Su et al., 2016; Druine et al., 2018), their tidal variation could also
355 introduce errors in the SSC estimates. In the Yangtze Estuary, characteristics of primary particles
356 and flocs (e.g., size and density) continuously change in response to the complex advection,
357 resuspension, deposition and flocculation processes (Guo et al., 2017). During the campaign in July
358 2014, the median grain size of primary particles (D_{p50}) ranged 4-20 μm , with an average of $\sim 10 \mu\text{m}$.
359 Both the range and average enlarged in January 2016 (Table 5). Sediment composition, i.e.,

360 percentages of clay (P_{clay}), silt (P_{silt}) and sand (P_{sand}), varied with time and depth (Fig. 13 and Table
361 5). Table 5 also shows tidal averages of median floc size (D_{F50}) and floc density ($\rho = \bar{c}/V_c$, where \bar{c}
362 is the sediment concentration of water sample and V_c is the volume concentration measured by
363 LISST) at each relative depth. In July 2014, for example, both D_{F50} (15-90 μm) and ρ (80-800 kg/m^3)
364 had a broad range. Such strong variations in grain size and floc density could be one of the sources
365 for the relative error of SSC estimates.

366 In this study, we reduce the effects of particle size/composition by using a mixture of bottom
367 sediment for the sensor calibration. To a certain extent, the mixed bottom sediment represents the
368 tidally averaged condition of suspended sediment in the bottom layer (Fig. 13). The calibration thus
369 returns a representative curve for the averaged particle size/composition condition. Upon these
370 calibrations, the proposed IOA approach gives SSC estimates with a relative error of 17–34%. This
371 error is acceptable for in-situ SSC measurement and the quantification of sediment transport.

372 To access higher accuracy, one can introduce the particle size/composition correction in the
373 calibration (Conner and De Visser, 1992; Fugate and Friedrichs, 2002; Green and Boon, 1993; Su
374 et al., 2016). There are two basic methods, i.e., the “median grain size” method (Conner and De
375 Visser, 1992) and the “mixture of linear component response” method (Green and Boon, 1993; Su
376 et al., 2016). The former suggests corrections on the sensitivity coefficient as a function of the
377 median grain size, but this method is highly empirical due to the controversial suggestions on
378 empirical coefficients. By assuming that the total sensor output for mixtures is a linear sum of the
379 output for each composition, the latter suggests to derive the sensitivity coefficients for different
380 sediment compositions. Therefore, the “mixture of linear component response” method is
381 recommended, because it thoughtfully considers the sensitivity of sensor response to each sediment
382 composition.

383

384 **5.2 Advantages and disadvantages of the IOA approach**

385 By a combination of ASM, OBS and ADV, the proposed IOA approach successfully solves the
386 ambiguity problem in conversion. Therefore, both OBS and ADV extend their measurement range
387 of SSC (Table 4). Upon careful calibration, the OBS can provide estimates even up to 300 g/L
388 (Kineke and Sternberg, 1992). Note that the estimation by ADV is not reliable, because of the rather
389 scatter of data and the low SNR (Fig. 2). Although its measurement range can be extended to 100s

390 g/L, the best way it can be used is to give a rough estimation and identify the true value from OBS-
391 derived estimates. With the proposed optimal algorithm, we successfully captured and measured the
392 CBS in the Yangtze Estuary.

393 In addition to solving the ambiguity problem and extending measurement range, the IOA
394 approach also provides high-resolution SSC profiles by the ASM. In this study, the ASM was
395 deployed on a tripod and measured the SSC profiles in the bottom boundary layer. These profiles
396 have a higher resolution (0.01 m) than those measured by acoustic sensors (0.25-1.0 m), e.g., ADCP
397 (Anastasiou et al., 2015; Baeye and Fettweis, 2015) and ADP (Fettweis and Baeye, 2015). Note that
398 the ASM can produce valid high-resolution SSC profile only when it is not saturated. Once the ASM
399 sensor is saturated, the estimate given by ASM is missing. These missing values, however, can be
400 recovered by the OBS.

401 The IOA approach also provides direct and reliable measurements of turbulent sediment flux
402 ($\overline{w'c'}$) by the ADV. Unlike optical sensors, the ADV provides estimates of turbulent velocity (w')
403 and SSC (c') directly at the same position. In this method, the low-frequency SSC (\bar{c}) given by the
404 ASM and OBS help to identify the reliable high-frequency estimate (c) by assuming $c \approx \bar{c}$ (i.e.,
405 $c' \approx 0$). This assumption is reasonable within a sampling burst of 90 s. Fig. 8 shows the ADV-derived
406 $\overline{w'c'}$ with and without the IOA approach, as well as the theoretical calculations with $\sigma_t = 0.7$ and
407 2.0. Without the IOA approach, the $\overline{w'c'}$ is significantly underestimated (Fig. 8a). the $\overline{w'c'}$ with the
408 IOA approach, however, maintains close to the theoretical calculation with $\sigma_t = 2.0$, which is
409 consistent to the observations by Cellino and Graf (1999) and modeling results by Winterwerp et al.
410 (2009).

411 The IOA approach and the proposed optimal algorithm, however, have the following
412 shortcomings. First, sensor responses to SSC are not entirely the same in the field and laboratory
413 experiments. The OBS-633 employed in July 2014, for example, had a small amount (< 1%) of
414 outputs during the field campaign that exceeded the maximum turbidity (3418 NTU) obtained in
415 the in-lab calibration experiment. Part of the SSC given by the IOA approach is therefore missing.
416 The tests by Maa et al. (1992) indicate that both clay mineralogy and salinity are important factors
417 in the OBS calibration, whereas the scanning rate, the color of water and additional light source are
418 not important. In our study, sediment samples used in the calibration were collected from the bed

419 surface at the survey site. Their clay mineralogy thus did not change too much compared with the
420 near-bed suspensions. The salinity, however, ranged 0-12‰ during the field measurement in July
421 2014, whereas the mixture of water samples returned a representative mean salinity of 5‰ in the
422 in-lab calibration. Therefore, the salinity of ambient water is likely the main reason for the difference
423 between the in-lab and in-field response of an OBS. In-situ calibration is therefore recommended.
424 Second, the effects of particle size/composition are not taken into account in the proposed algorithm.
425 To improve the accuracy, careful calibrations with the particle size/composition correction are
426 expected in future research.

427

428 **5.3 Seasonal SSC profiles**

429 The two studying periods (wet and dry seasons) show very different vertical SSC profiles (Figs.
430 12a and 12d). In the wet season, the SSC is higher in the benthic layer, but lower higher up in the
431 water column; in the dry season, the opposite is found. Such a seasonality may correlate with the
432 seasonal location of salinity wedge and ETM, estuarine stratification, floc size and settling velocity.

433 In the dry season, both the salinity wedge (Figs. 11b and 12f) and ETM (Wan, 2015; Fig. 7-12)
434 locate further upstream, and thus the lower half of the water column may have a more uniform SSC
435 profile, because of the thick salinity wedge and better mixing capability, especially the lowest 0.2H
436 (Fig. 12e). In the wet season, the wedge moves to downstream, and only its head can reach the
437 survey station (Figs. 10b and 12b). The observed wedge is therefore relatively thin, and the near-
438 bed mixing is weak. As a result, the vertical SSC gradient is high near the bed. The thickness of this
439 wedge is more than 2 m so that a high SSC gradient was observed at the experimental site. In other
440 words, the near-bed SSC in the channel could be higher than that observed at the survey station.

441 In addition to wedge and ETM movement, the increasing freshwater discharge also enhances
442 the strain-induced stratification (Simpson et al., 1990) and therefore estuarine circulation (Wan,
443 2015). The enhanced stratification benefits sediment trapping near the bottom (Geyer, 1993), while
444 the circulation accumulates sediment in the convergent zone (i.e., ETM). As an overall result, both
445 the SSC and its gradient are high near the bottom in the wet season. Although a stronger residual
446 current (Figs. 12c and 12g) occurs in the wet season, depth-integrated sediment flux (Figs. 12d and
447 12h) is roughly the same. Because of the increasing sediment supply from the upstream (Guo et al.,
448 2018), sediment accumulation therefore accelerates in the wet season, reaching a higher SSC.

449 The seasonality of SSC profile may also be the result of the changes in floc size and settling
450 velocity. Both floc size and settling velocity are large in the wet season, and thus the suspension is
451 more concentrated in the near-bed layer, because of the low turbulent shear (Wu et al., 2012) and
452 high chlorophyll concentration (Fettweis and Baeye, 2015; Deng et al., 2019); and vice versa in the
453 dry season. The quantification of the above processes should wait for the flocs, turbulence, and ETM
454 data.

455

456 **5.4 Intra-tidal SSC variation**

457 Based on many in-situ and laboratory measurements, Maa and Kim (2002) and Ha and Maa
458 (2009) found that erosion only occurs when the tidal current is in acceleration phases. This process
459 may be used in this study to explain the observed intra-tidal SSC variation. Besides, the survey site
460 locates on the land side to the tidally-averaged ETM (Wan, 2015; see Fig. 7-12), and thus horizontal
461 advection may also contribute to the change of SSC time series, because of the large longitudinal
462 and lateral SSC gradient.

463 During the flood periods in the wet season, the SSC increases with a reasonable pace whenever
464 the current is accelerating (Fig. 6d). This slight increase may be attributed to the re-dispersion of
465 new deposit from previous slack tides and the landward ETM movement. The SSC decreases
466 slightly when the current starts decelerating. The cut-off of sediment supply from the bed and
467 deposition in the late flood are responsible for this decrease. During ebb periods, the SSC jumps (or
468 increases quickly) right after tidal current changes to acceleration phases. It suddenly decreases and
469 recovers in 1-2 hours during this phase. There is a strong shoal-to-channel flow (Fig. 6b) for the
470 decreasing SSC, and vice versa for the increase. It suggests that lateral flow controls the rapidly
471 increasing or decreasing SSC during these periods. The SSC drops significantly right after the
472 current starts decelerating, and remains about the same then. The withdrawal ETM (i.e., seaward
473 movement) may predominate the rapid decrease, while the constant SSC is the result of limited
474 sediment supply from the seabed.

475 In the dry season (Fig. 7d), the changes of SSC during the accelerating flood and the
476 decelerating ebb have a similar pattern to those in the wet season. When the flood currents change
477 to deceleration phases, however, the SSC first keeps increasing and then decreases gradually. During
478 the accelerating ebb, a slight increase occurs in the beginning, followed by a slight decrease. Such

479 variations during these two phases cannot be explained only by the asymmetric erosion/deposition,
480 and longitudinal ETM movement may predominate these changes. Because of the low freshwater
481 discharge, both salinity wedge and ETM can intrude further upstream. The ETM may even pass the
482 observation station, leading to the increasing SSC during the decelerating flood. The decrease during
483 the accelerating ebb may be the result of withdrawal ETM.

484 The difference between these two survey periods is probably caused by the different location
485 and distribution of ETM. The ETM appears as a concentrated undercurrent in the wet season, and a
486 low concentration sediment cloud in the dry season (Wu et al., 2012). A larger horizontal SSC
487 gradient thus occurs in the wet season, especially in the cross-channel direction. In the branched
488 Yangtze Estuary, the cross-channel current is caused by the barotropic force induced by the cross-
489 shoal flow (Zhu et al., 2018). Although the cross-channel current is roughly the same during these
490 two seasons (Figs. 6b and 7b), it provides a much stronger advective transport of SSC in the wet
491 season, because of the larger SSC gradient. Such cross-channel transport of SSC is even stronger
492 than that from the erosion of bottom sediment. At the ETM, both along- and cross-channel advection
493 contribute significantly to the change of SSC, and thus, the observations of asymmetric
494 erosion/deposition are not as clear as those observed by Maa and Kim (2002). More
495 discussion/studies on the dominant process that controls intra-tidal SSC variation are needed, which
496 should include detailed data on longitudinal and lateral distributions of ETM and current.

497

498 **6. Conclusions**

499 Due to the signal saturation, the ASM has a limited measurement range of SSC; both the OBS
500 and ADV have an ambiguity problem in conversion because of the attenuation. By a combination
501 of ASM, OBS, and ADV (i.e., the IOA approach), we successfully solve the ambiguity problem and
502 access a broader measurement range and high-resolution SSC profiles. With this approach, the
503 ASM-derived SSC is preferred because it has the lowest relative error (~ 25%). The ASM also
504 provides high-resolution (1 cm) SSC profiles when it is not saturated ($SSC < 9$ g/L). Once the ASM
505 is saturated, the estimates given by ASM is missing. These missing values, however, can be
506 recovered by the OBS. Since the ambiguity problem is solved, both OBS and ADV extend their
507 measurement range up to 100s g/L. Although the ADV has a more extensive SSC range, the best it
508 can be used is to have a rough estimation and assist in the conversion of OBS output. To reduce the

509 effects of particle size/composition, we suggest using in-situ water samples or mixed bottom
510 sediment for the sensor calibration. Alternatively, one can take particle size/composition correction
511 into account in the calibration to access a higher accuracy.

512 The application of the IOA approach successfully captured and measured the concentrated
513 benthic suspensions (SSC > 10 g/L) in the Yangtze Estuary. Comparison between estimates and the
514 SSC of the in-situ water sample indicates that the IOA approach is reliable and gives estimates with
515 a relative error of 17–34%. The observed SSC profile in the Yangtze Estuary shows a notable
516 seasonal variation. In the wet season, suspended sediment accumulates in the benthic layer, forming
517 a non-uniform L-shaped profile, whereas a uniform and linear profile appears in the dry season.

518

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710 **Table 1**

711 Measurement techniques of suspended sediment concentration

Technology	Operating principle	Advantages	Disadvantages
Water sampling	Water-sediment sample is taken and later analyzed	Reliable Informative (SSC, salinity, PSD* etc.)	Flow-intrusive, Labor-intensive Low frequency Poor spatial resolution, Near-bed data missing
Optical	Light backscatter through water-sediment sample is measured and translated to SSC with calibration	High accuracy, Good spatial resolution High frequency	Flow-intrusive, Particle-size dependent, Limit measurement range Uncertainties in high SSC
Acoustic	Echo strength from sample determines SSC based on calibration	Nonintrusive, Good spatial resolution, High frequency synchronous SSC and velocity	Low accuracy, Limit measurement range Uncertainties in high SSC

712 * SSC and PSD denote suspended sediment concentration and particle size distribution, respectively.

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Table 2

C-R relationship for calibrated sensors. C denotes suspended sediment concentration in g/L, and R represents the readings of OBS (turbidity in NTU), ASM (turbidity in FTU) and ADV (SNR in dB).

Time	Instrument	Conditions	C-R relationship	Number of samples	Correlation index (R ²)	
201407	ASM	Unsaturated	$C=2.0 \times 10^{-3}R$	42	0.99	
	OBS-633	Unsaturated	$C=3.5 \times 10^{-7}R^2+1.6 \times 10^{-3}R+0.2$	42	0.99	
		Saturated, $T_{obs} \geq T_c$, $SNR \geq SNR_c$	$C=19.2-\frac{\sqrt{41734.0-12.2R}}{6.1}$	13	0.92	
		Saturated, $T_{obs} \geq T_c$, $SNR < SNR_c$	$C=19.2+\frac{\sqrt{41734.0-12.2R}}{6.1}$	7	0.97	
	OBS-636	Saturated, $T_{obs} < T_c$	$C=-1.2 \times 10^{-2}R+66.0$	7	0.97	
		Unsaturated	$C=3.0 \times 10^{-7}R^2+1.5 \times 10^{-3}R+0.2$	42	0.99	
		Saturated, $T_{obs} \geq T_c$, $SNR \geq SNR_c$	$C=18.7-\frac{\sqrt{42531.8-11.7R}}{5.9}$	13	0.93	
	OBS-638	Saturated, $T_{obs} \geq T_c$, $SNR < SNR_c$	$C=18.7+\frac{\sqrt{42531.8-11.7R}}{5.9}$	7	0.97	
		Saturated, $T_{obs} < T_c$	$C=-1.1 \times 10^{-2}R+65.9$	7	0.97	
		Unsaturated	$C=3.9 \times 10^{-7}R^2+1.4 \times 10^{-3}R+0.1$	34	0.99	
	ADV	Saturated, $T_{obs} \geq T_c$, $SNR \geq SNR_c$	$C=10.2-\frac{\sqrt{104937.2-35.0R}}{17.5}$	4	0.98	
		Saturated, $T_{obs} \geq T_c$, $SNR < SNR_c$	$C=10.2+\frac{\sqrt{104937.2-35.0R}}{17.5}$	10	0.97	
		Saturated, $T_{obs} < T_c$	$C=-1.6 \times 10^{-2}R+59.2$	10	0.97	
	201601	ADV	$SSC \leq SSC_c$	$\lg C=0.3-\frac{\sqrt{2623.2-43.3R}}{21.7}$	685	0.70
		ADV	$SSC > SSC_c$	$\lg C=0.3+\frac{\sqrt{2623.2-43.3R}}{21.7}$	685	0.70
ASM		Unsaturated	$C=1.8 \times 10^{-3}R$	43	0.99	
OBS-278	Unsaturated	$C=6.9 \times 10^{-7}R^2+6.5 \times 10^{-4}R+0.2$	43	0.99		
	Saturated, $T_{obs} \geq T_c$, $SNR \geq SNR_c$	$C=11.5-\frac{\sqrt{80551.5-27.5R}}{13.7}$	9	0.99		
	Saturated, $T_{obs} \geq T_c$, $SNR < SNR_c$	$C=11.5+\frac{\sqrt{80551.5-27.5R}}{13.7}$	14	0.99		
OBS-279	Saturated, $T_{obs} < T_c$	$C=-1.6 \times 10^{-2}R+61.1$	14	0.99		
	Unsaturated	$C=3.2 \times 10^{-7}R^2+8.2 \times 10^{-4}R+0.2$	43	0.99		
	Saturated, $T_{obs} \geq T_c$, $SNR \geq SNR_c$	$C=11.6-\frac{\sqrt{176062.0-45.0R}}{22.5}$	9	0.99		
OBS-570	Saturated, $T_{obs} \geq T_c$, $SNR < SNR_c$	$C=11.6+\frac{\sqrt{176062.0-45.0R}}{22.5}$	9	0.99		
	Saturated, $T_{obs} < T_c$	$C=-1.1 \times 10^{-2}R+57.0$	14	0.99		
	Unsaturated	$C=6.0 \times 10^{-7}R^2+9.1 \times 10^{-4}R+0.2$	43	0.99		

Saturated, $T_{obs} \geq T_c$, $SNR \geq SNR_c$	$C = 11.4 - \frac{\sqrt{81988.4 - 28.0R}}{14.0}$	9	0.99
Saturated, $T_{obs} \geq T_c$, $SNR < SNR_c$	$C = 11.4 + \frac{\sqrt{81988.4 - 28.0R}}{14.0}$		
Saturated, $T_{obs} < T_c$	$C = -1.5 \times 10^{-2}R + 56.1$	14	0.99

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Table 3

762 Shipboard and tripod instruments and their sampling schemes

Carrier	Instrument deployed	Distance above bed (mab)	Sampling interval (min)	Sampling duration (sec)	Sampling frequency (Hz)	Survey parameter	Profile resolution (m)
Vessel	ADCP	> 1.5	continuously	continuously	0.1	upper velocity	0.5
	OBS	> 1.0	60	30	1	SSC, salinity, temperature	0.1
	LISST	*	60	30	1	FSD	-
	Water sampler	*	60	30	-	SSC, salinity, PPSD	-
Tripod	ACP	< 0.8	5	60	1	near-bed velocity	0.05
	ADCP-wave	> 2.0	5	60	1	upper velocity, wave	0.5
	RBR	1.1	5	60	1	wave	-
	ADV	0.35	10	60	8	near-bed velocity, SSC	-
	ASM	0.11-1.06	5	60	1	SSC	0.01
	OBS	0.35, 0.55, 1.06	5	60	1	SSC, salinity, temperature	-

763 * data or samples collected at six relative depth layers, i.e., 0.05H (near surface), 0.2H, 0.4H, 0.6H,
764 0.8H, and 0.95H (near-bed), where H is the total water depth. FSD and PPSD denote the flocculated
765 and primary particle size distribution, respectively.

766 **Table 4**

767 Measurement ranges (g/L) of ASM, OBS and ADV with their relative errors (%). Missing values
 768 are represented by the symbol NA (Not Available).

Time	Instrument	Range (g/L)	Relative error (%)
201407	ASM	0.0-8.0	33.6
	OBS-633	0.2-66.0	32.2
	OBS-636	0.2-65.9	NA
	OBS-638	0.1-59.2	NA
	ADV	0.1-457.3	88.6
201601	ASM	0.0-7.4	17.6
	OBS-278	0.2-61.1	28.2
	OBS-279	0.2-57.0	NA
	OBS-570	0.2-56.1	NA

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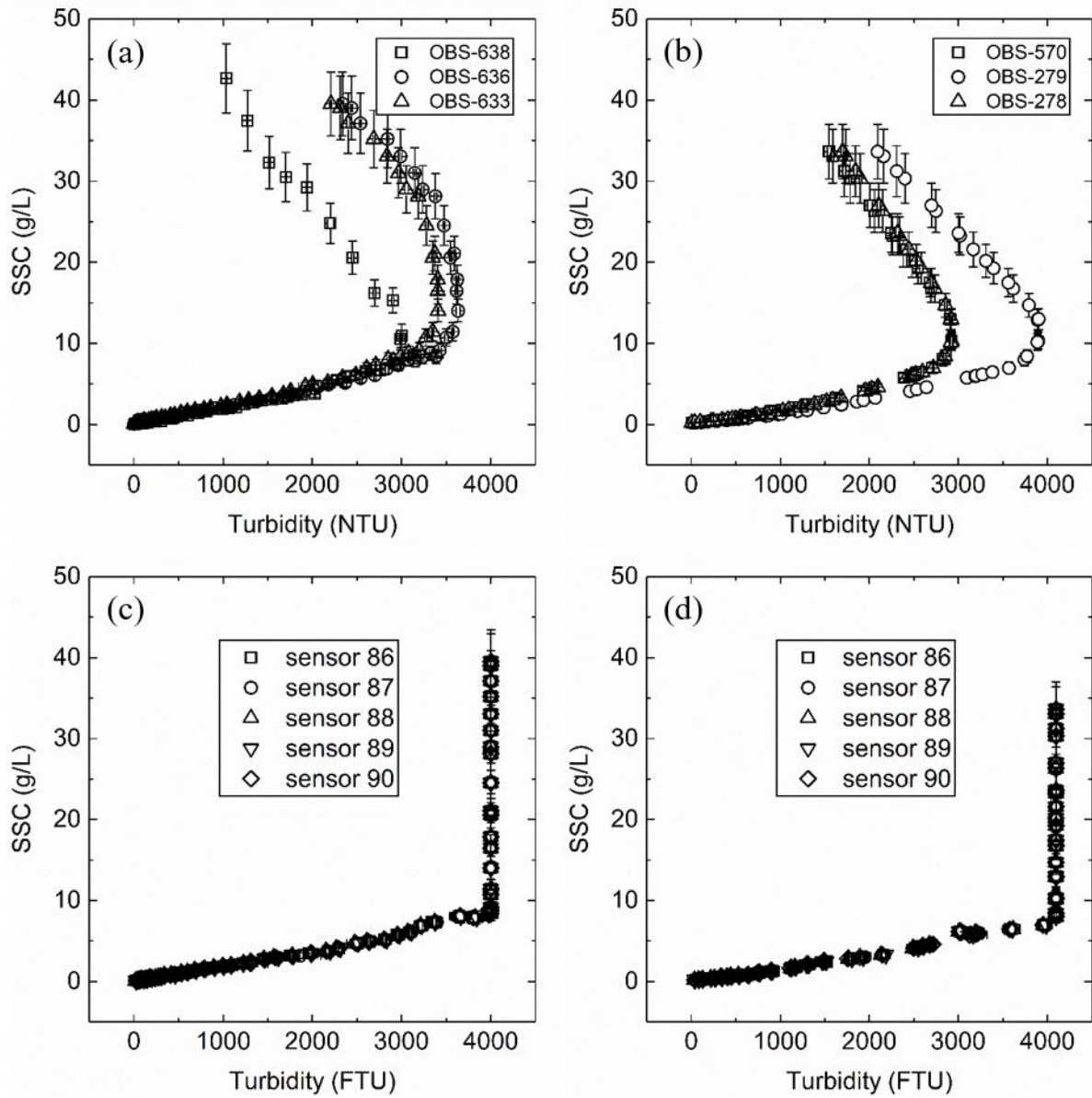
772 **Table 5**

773 Tidally averaged median grain sizes of primary particles (D_{P50}) and flocculates (D_{F50}), dry density
 774 (ρ) of flocculates and composition of suspended sediment in different layers with their standard
 775 deviations. Data are not available in the bottom layer as LISST does not work correctly in high
 776 turbidity. Missing values are represented by the symbol NA (Not Available).

TIME [yyymm]	Position	D_{P50} (std.) [μm]	D_{F50} (std.) [μm]	ρ (std.) [kg/m^3]	P_{clay} (std.) [%]	P_{silt} (std.) [%]	P_{sand} (std.) [%]
1407	0.05H	6.0(\pm 1.4)	26.3(\pm 8.8)	310(\pm 84)	39(\pm 6)	56(\pm 8)	5(\pm 6)
	0.2H	7.3(\pm 2.1)	24.7(\pm 7.4)	311(\pm 91)	35(\pm 6)	61(\pm 7)	4(\pm 4)
	0.4H	8.9(\pm 3.3)	25.7(\pm 10.7)	304(\pm 130)	32(\pm 6)	64(\pm 4)	4(\pm 4)
	0.6H	10.4(\pm 4.0)	27.5(\pm 16.3)	275(\pm 82)	30(\pm 5)	65(\pm 3)	5(\pm 5)
	0.8H	11.6(\pm 4.2)	33.9(\pm 19.5)	238(\pm 78)	28(\pm 5)	66(\pm 2)	6(\pm 5)
	0.95H	13.5(\pm 6.0)	33.3(\pm 6.3)	246(\pm 42)	27(\pm 6)	63 (\pm 3)	10(\pm 7)
	Bed	12.1(\pm 2.7)	NA	NA	27(\pm 3)	64(\pm 5)	9(\pm 3)
	All samples	9.8(\pm 4.5)	27.6(\pm 12.8)	288(\pm 97)	32(\pm 7)	62(\pm 6)	6(\pm 5)
1601	0.05H	9.4(\pm 4.0)	23.7(\pm 5.4)	502(\pm 339)	31(\pm 7)	66(\pm 6)	2(\pm 2)
	0.2H	12.6(\pm 5.8)	NA	NA	27(\pm 6)	69(\pm 4)	4(\pm 3)
	0.4H	14.6(\pm 5.2)	NA	NA	25(\pm 5)	71(\pm 3)	4(\pm 3)
	0.6H	16.2(\pm 5.0)	NA	NA	22(\pm 4)	72(\pm 2)	6(\pm 4)
	0.8H	18.6(\pm 5.4)	NA	NA	21(\pm 4)	71(\pm 3)	8(\pm 4)
	0.95H	21.1(\pm 5.9)	NA	NA	19(\pm 4)	71(\pm 3)	10(\pm 5)
	Bed	26.7(\pm 11.6)	NA	NA	17(\pm 5)	65(\pm 5)	18(\pm 10)
	All samples	16.2(\pm 7.6)	NA	NA	24(\pm 7)	70(\pm 4)	6(\pm 6)

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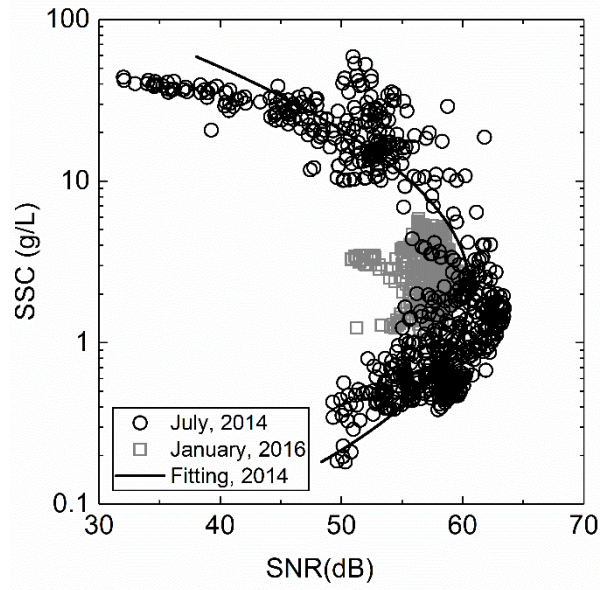


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781 **Figure 1.** Calibrations of OBS (turbidity in NTU) (a, b) and ASM (turbidity in FTU) (c, d) against
 782 SSC (in g/L) with bottom sediment collected in July 2014 (left panel) and January 2016 (right panel),
 783 respectively. Regression results are shown in Table 2.

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787 **Figure 2.** Calibration of ADV (SNR in dB) against the SSC (in g/L) given by ASM and OBS.

788 Regression results are shown in Table 2.

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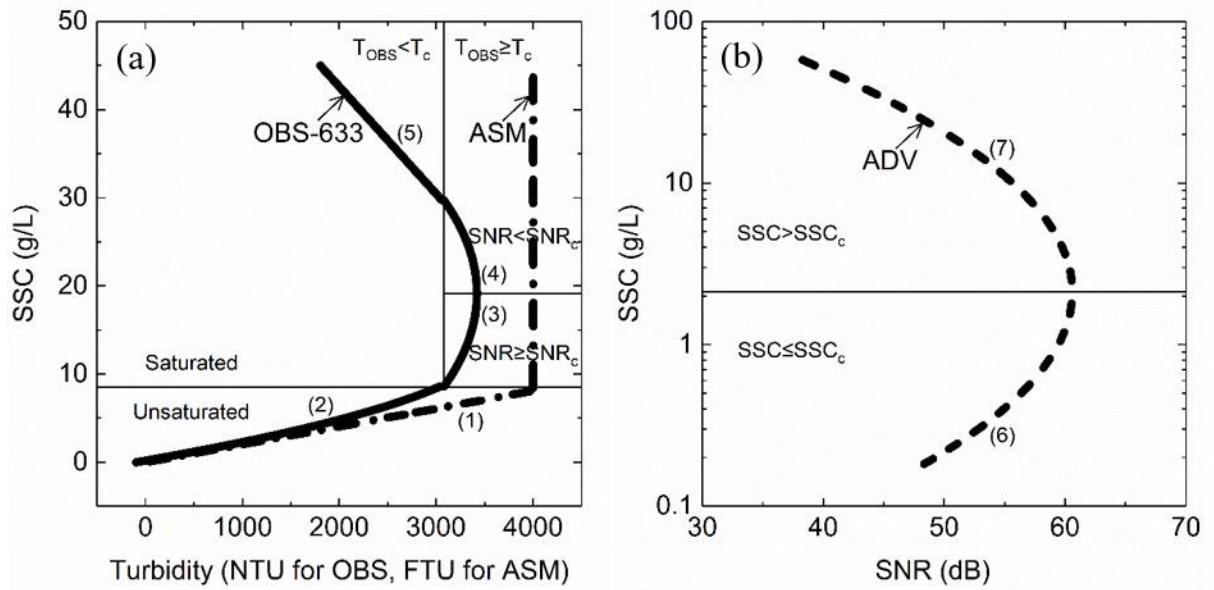
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803 **Figure 3.** Examples of calibration curve (ASM, OBS-633 and ADV employed in July 2014) for
 804 illustrating the conversion protocols of the IOA approach. T_c denotes the critical OBS turbidity
 805 (reading, i.e., $T_c = 3050$ NTU, corresponding to $SSC \sim 9$ g/L) where ASM just saturates (with a
 806 reading around 4000 FTU), and SNR_c (~ 61 dB) indicates the critical SNR corresponding to the
 807 max OBS turbidity (reading, i.e., 3400 NTU, corresponding to $SSC = 20$ g/L when using OBS.
 808 SSC_c indicates the critical SSC (i.e., $SSC_c = 2$ g/L) where the ADV returns the max SNR. The
 809 numbers in parenthesis, e.g., (4), is a shorthand of Calibration Relation (CR) 4 as shown in Table 2
 810 and Figure 4.

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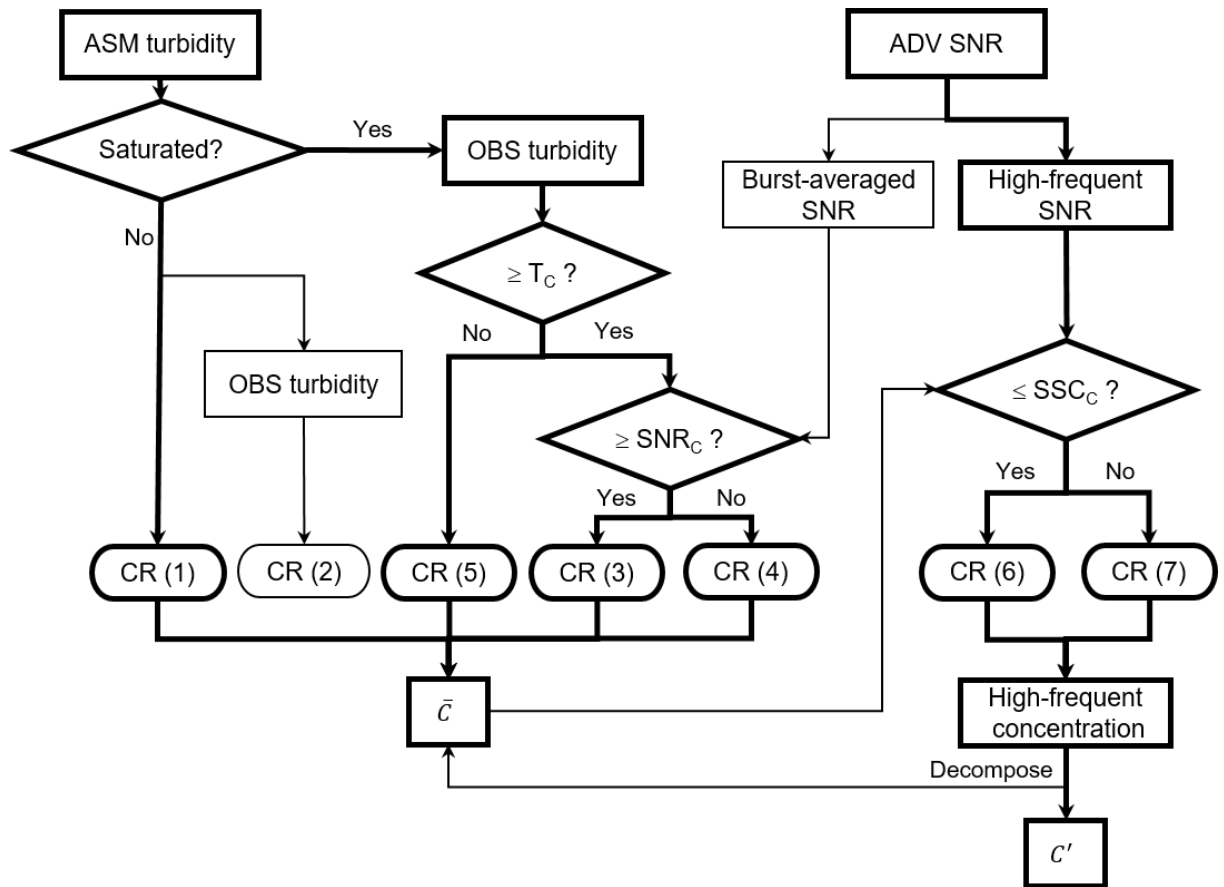
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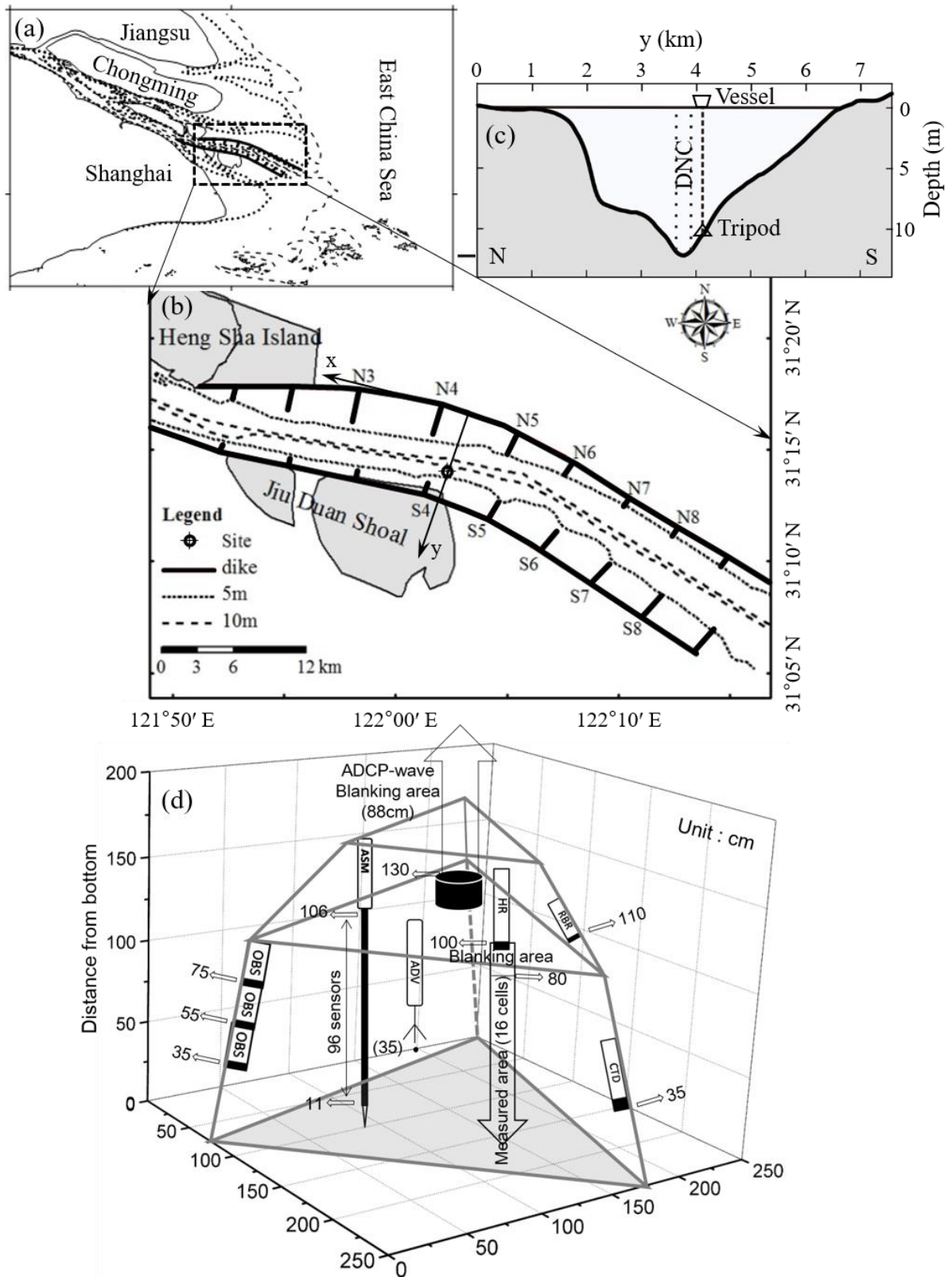
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Figure 4. Algorithms for ASM, OBS and ADV to estimate reliable SSC. CR denotes the calibration relationship between suspended sediment concentrations and readings of sensors (i.e., turbidity and SNR) given in Table 2. Highlighted flowcharts show the optimal protocol according to the performance of each sensor.



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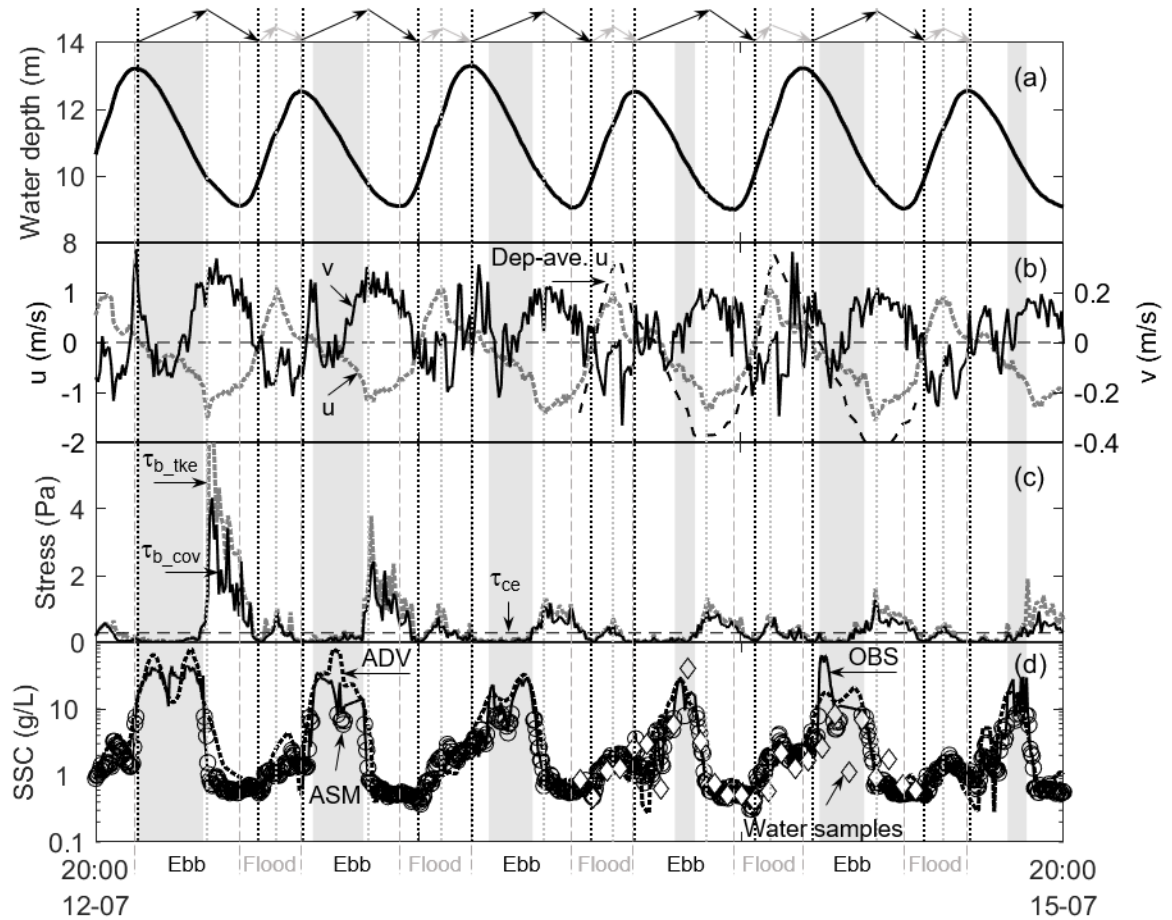
841 **Figure 5.** The Yangtze Estuary (a), the Deepwater Navigational Channel (DNC) at the North

842 Passage (b), the positions of the DNC and the moored tripod and shipboard observation systems in

843 an estuarine cross section (c), and the schematic of bottom-mounted tripod system with multiple

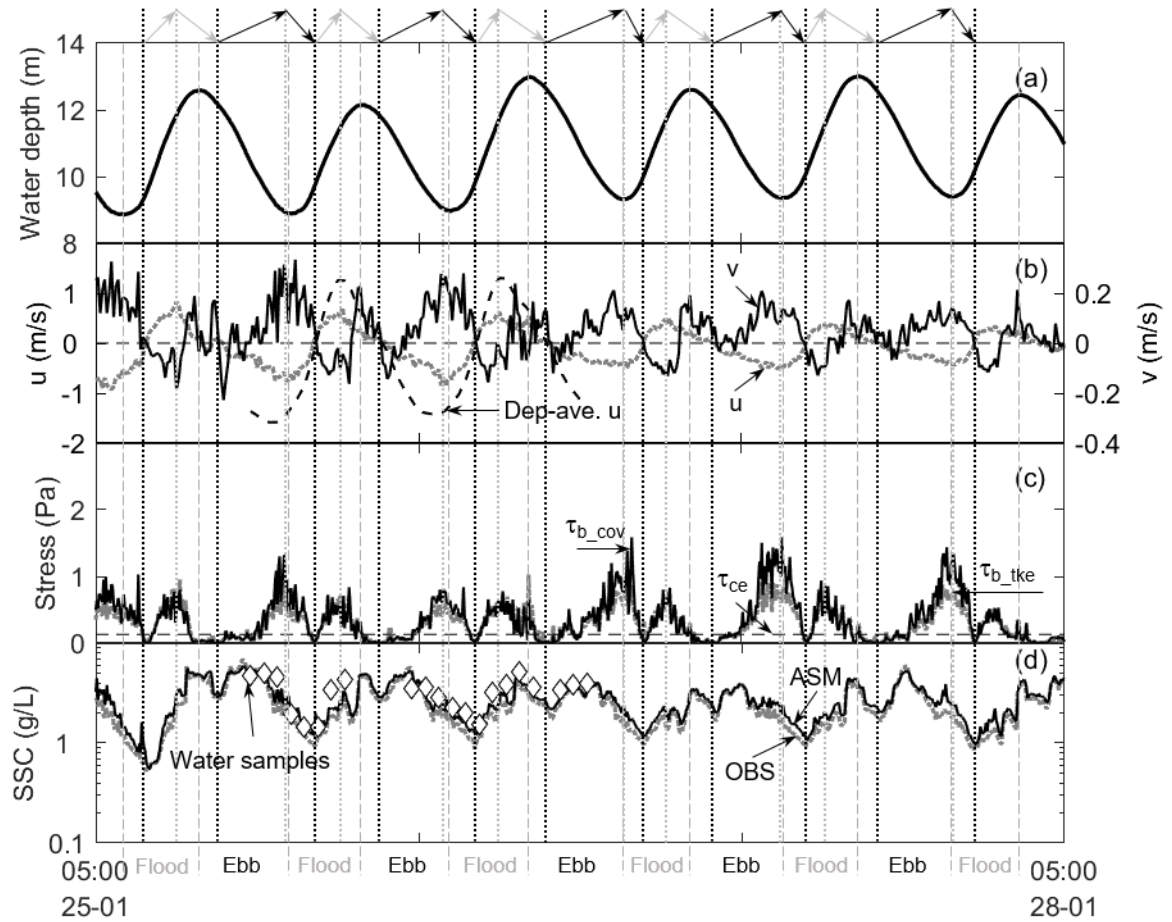
844 sensors (d). The numbers in (d) represent the distance of the sensor above the seabed.

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847 **Figure 6.** Time series of 2014 July (wet season) measurements in the North Passage, Yangtze
 848 Estuary. (a) water depth measured by the CTD, (b) along- (u , grey dot) and cross- (v , black solid)
 849 channel velocity measured by the ADV at 0.35 meter above bed (mab) and depth-averaged u (black
 850 dash); (c) bed stress calculated by TKE Method (τ_{b_tke} , grey dot) and COV Method (τ_{b_cov} , black
 851 solid) and critical stress for erosion (τ_{ce} , black dash); (d) SSCs from the filtration of water samples
 852 collected at the bottom layer (i.e., 0.95H, diamond), and ASM (circle), OBS (solid) and ADV (dot)
 853 at 0.35 mab. Positive u indicates the flood direction, and positive v represents the cross-channel
 854 velocity from the north to the south. Since the survey site locates at the south to the channel, positive
 855 v also indicates the channel-to-shoal flow. The time period for flood (grey) and ebb (black) are
 856 marked at the bottom. The tidal current acceleration phases are marked on top by arrows with a
 857 positive slope, and the deceleration phases are marked by arrows with a negative slope. The shadow
 858 area indicate the periods when SSC > 10 g/L. The tidal current phase between near-bed and depth-
 859 averaged velocity is roughly the same.



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861 **Figure 7.** Time series of 2016 January (dry season) measurements in the North Passage, Yangtze
 862 Estuary. (a) water depth measured by the CTD, (b) along- (u , grey dot) and cross- (v , black solid)
 863 channel velocity measured by the ADV at 0.35 meter above bed (mab) and depth-averaged u (black
 864 dash); (c) bed stress calculated by TKE Method (τ_{b_tke} , grey dot) and COV Method (τ_{b_cov} , black
 865 solid) and critical stress for erosion (τ_{ce} , black dash); (d) SSCs from the filtration of water samples
 866 collected at the bottom layer (i.e., $0.95H$, diamond), and ASM (solid) and OBS (grey dot) at 0.35
 867 mab. Positive u indicates the flood direction, and positive v represents the cross-channel velocity
 868 from the north to the south. Since the survey site locates at the south to the channel, positive v also
 869 indicates the channel-to-shoal flow. The time period for flood (grey) and ebb (black) are marked at
 870 the bottom. The tidal current acceleration phases are marked on top by arrows with a positive slope,
 871 and the deceleration phases are marked by arrows with a negative slope. The tidal current phase
 872 between near-bed and depth-averaged velocity is roughly the same.

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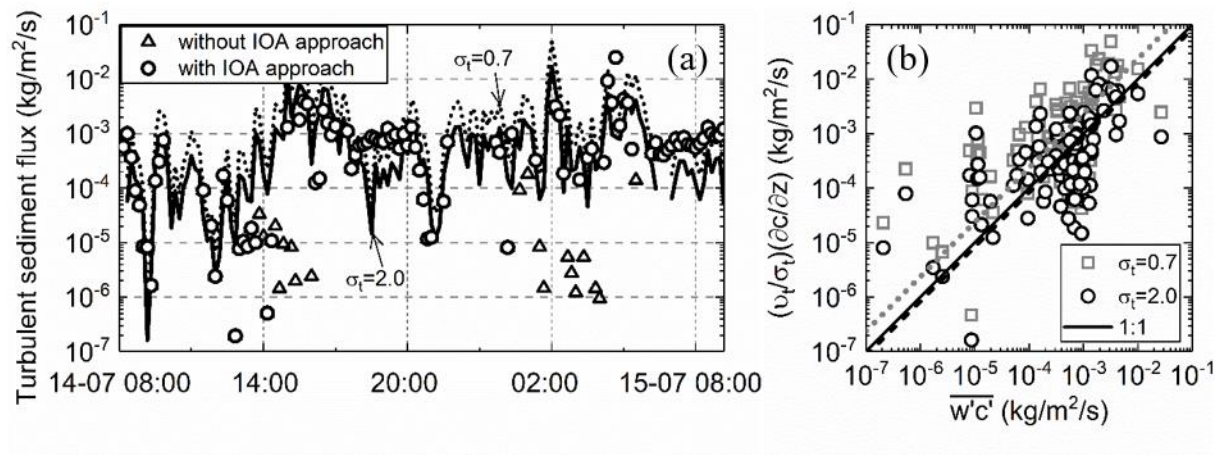
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882 **Figure 8.** Comparison between ADV-derived turbulent sediment flux ($\overline{w'c'}$) and the theoretical

883 calculations ($\frac{v_t}{\sigma_t} \frac{\partial c}{\partial z}$) with two classic values of turbulent Prandtl–Schmidt number, i.e., $\sigma_t = 0.7$ and σ_t

884 $= 2.0$. ADV-derived $\overline{w'c'}$ with and without the proposed algorithm are also presented (a).

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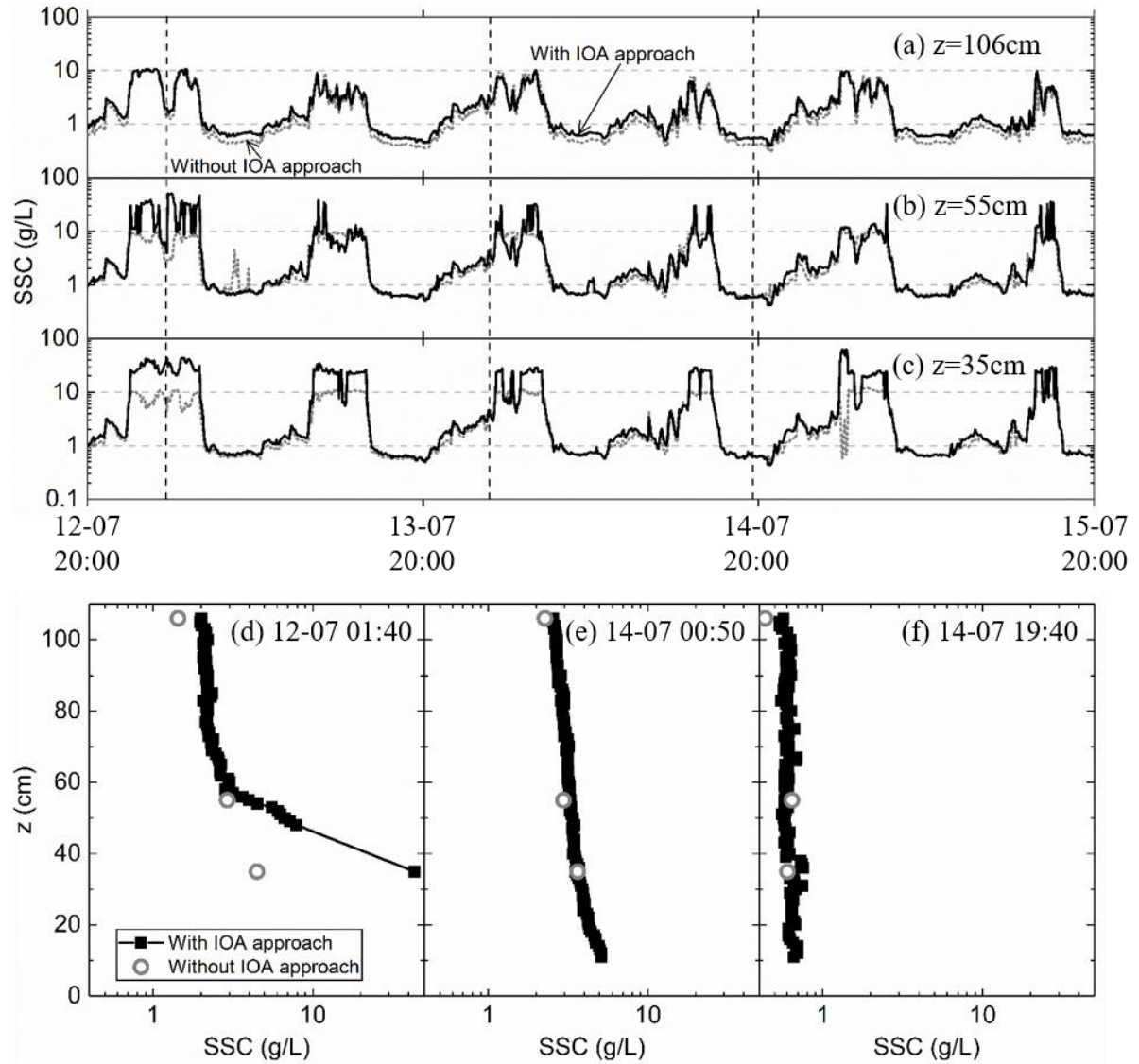
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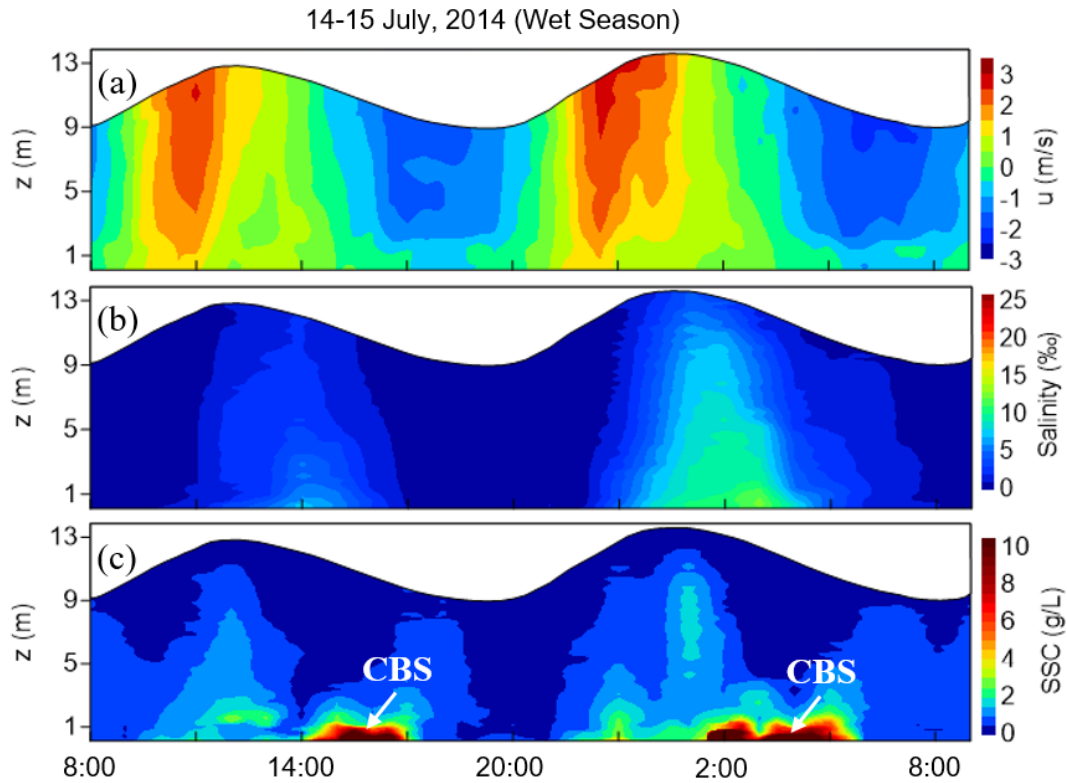
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893 **Figure 9.** Time series of SSC from three tripod mounted OBSs with (black solid) and without (grey
 894 dot) the IOA approach at 106 cm (a), 55 cm (b) and 35 cm (c) above bed, and three representative
 895 SSC profiles within high (d), mid (e) and low (f) SSC. The ASM readings below 50 cm from bed
 896 are saturated (d), and thus, removed, except the one at 35 cm above bed, which was recovered by
 897 the OBS reading at that time. A straight line between the SSCs from ASM at 35 and 50 cm is
 898 suggested as the possible SSC profile.



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900 **Figure 10.** Time-depth variability of (a) along-channel velocity (u), (b) salinity and (c) SSC during
 901 14-15 July, 2014. Positive u indicates the flood direction. CBS denotes the concentrated benthic
 902 suspension ($SSC > 10$ g/L).

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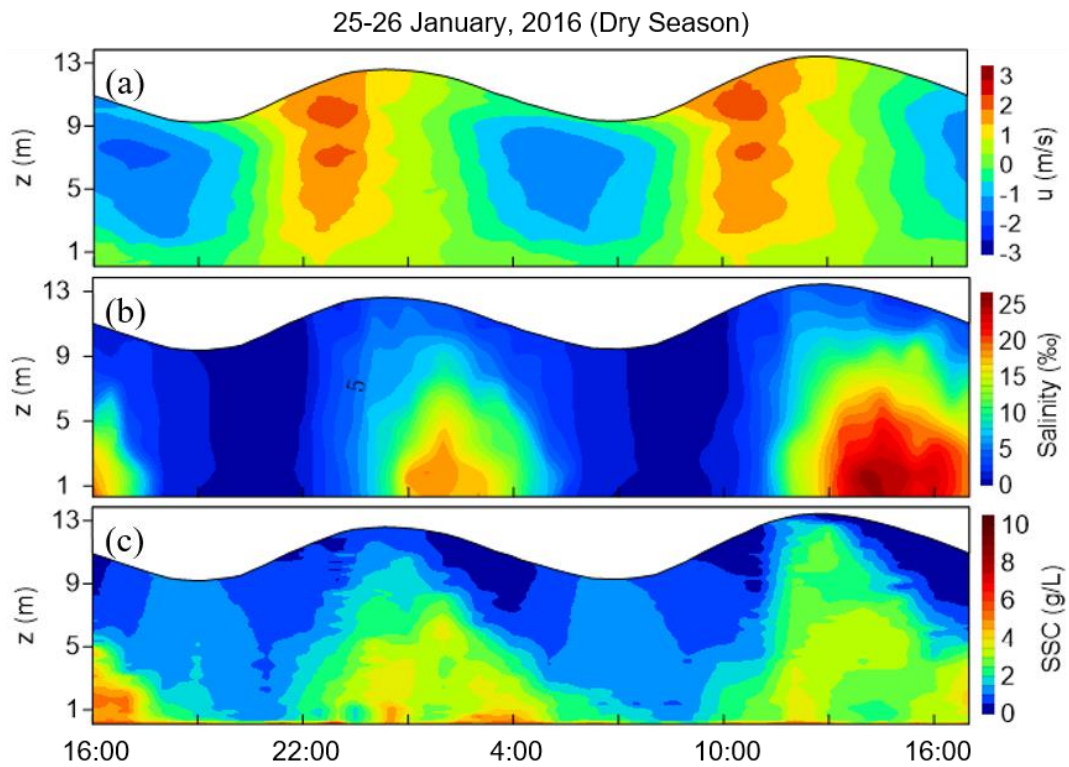
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Figure 11. Time-depth variability of (a) along-channel velocity (u), (b) salinity and (c) SSC during 25-26 January, 2016. Positive u indicates the flood direction.

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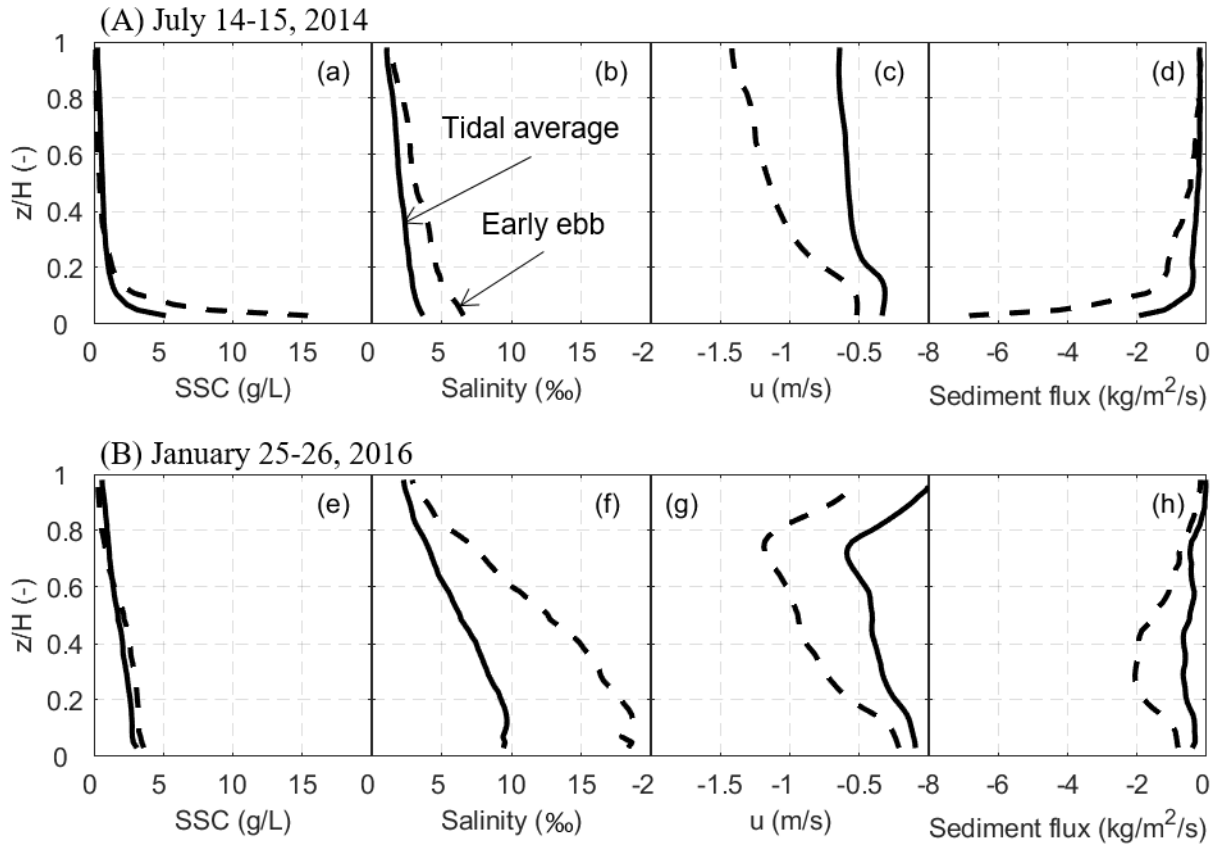
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Figure 12. Profiles of (a) (e) SSC, (b) (f) salinity, (c) (g) along-channel velocity (u) and (d) (h)

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along-channel sediment flux averaged over tidal cycles (solid line) and early ebb (dash line) of

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spring tide in July, 2014 (upper panels) and January, 2016 (lower panels). Negative u and flux

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indicate the direction from land to sea.

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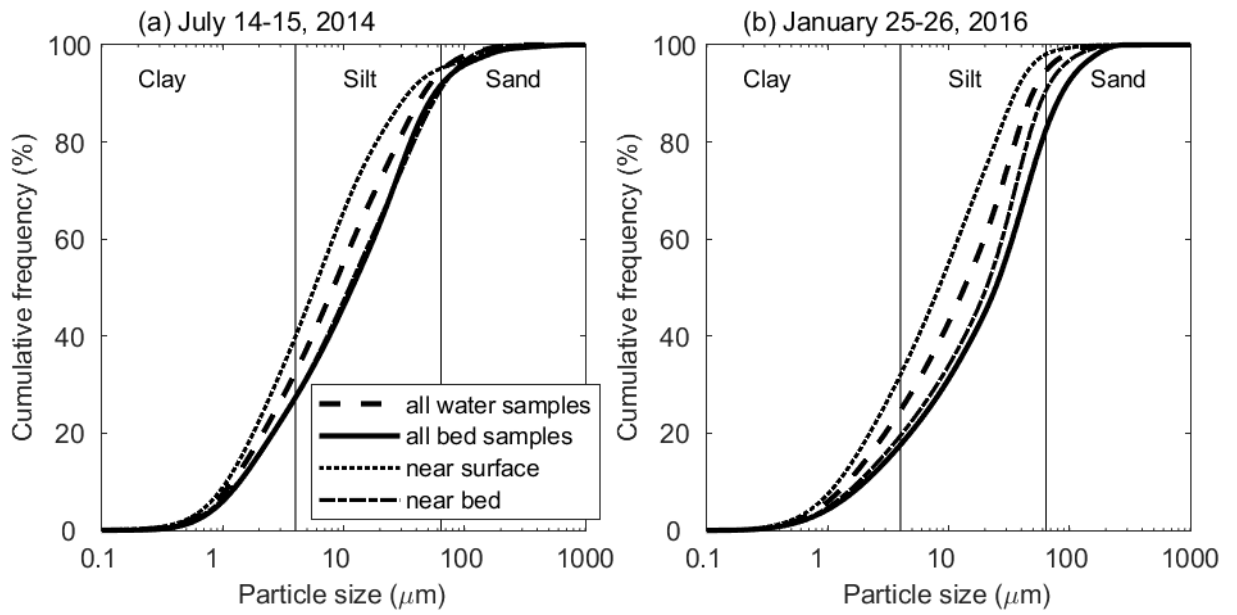
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953 **Figure 13.** The cumulative frequency distribution of the sediment samples collected near water
 954 surface (dot), near seabed (dash dot), and at seabed surface (solid) in July, 2014 (a) and January,
 955 2016 (b). The dash line represents the average of all water samples.

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