

Boat wake effects on sediment transport in intertidal waterways

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Abstract

Boat traffic and resulting wakes are among the major human-mediated stressors on coastal ecosystems. Modulation of sediment transport by wakes and tides in an intertidal waterway with boat traffic is studied here. The hypothesis that boat wakes cause significant increases in sediment transport in intertidal settings is tested. Field observations of tides, currents, boat wakes and turbidity were collected on a transect within the Atlantic Intracoastal Waterway in Northeast Florida, USA. Hydrodynamic and sediment processes were evaluated by analyzing this field data set. A daily average of 60 wake events of varying energies were identified in the observations using time-frequency analysis methods. Due to differences in sediment suspension in response to each wake and unpredictable evolution of the bed state, decomposition of the effects of each individual wake on sediment is not possible. Therefore, the sediment dynamics during the periods of boat activity were compared in their entirety with the sediment dynamics during the periods of boat inactivity. Throughout the experiment, all periods of boat activity had consistently greater suspended sediment concentration near the bed compared to their preceding and succeeding periods of boat inactivity. In the first eight days of

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26 the experiment where tidal forcing was relatively similar between boat activity and inactivity
27 periods, sediment transport rates were estimated as 0.048 m³/m/hr and 0.043 m³/m/hr during
28 boat activity and inactivity, respectively, indicating a 12% increase in sediment transport due
29 to boat traffic. A larger increase in sediment transport rates during boat activity compared to
30 boat inactivity occurred over the last three days of the experiment. Volumes of sediment trans-
31 ported in low-tide, mid-tide and high-tide during boat activity were greater than their low-tide,
32 mid-tide and high-tide counterparts during boat inactivity. Therefore, the results confirm the
33 earlier mentioned hypothesis.

34 *Keywords:* boat wakes; waves; sediment transport; sediment flux; tides; erosion; intertidal; coastal
35 ecosystem; Florida; Intracoastal Waterway

36 1 Introduction

37 One of the major and growing human-mediated threats on coastal ecosystems is boat traffic that is
38 experiencing a significant growth worldwide (Tournadre, 2014). In intertidal settings, such as estu-
39 aries, shallow coastal bays and waterways that experience boat traffic, wakes of these boats create
40 an important hydrodynamic forcing, alongside tides, on coastal ecosystems (e.g., vanStraaten and
41 Kuenen, 1958; Green and Coco, 2007; Wiberg et al., 2015). Boats and their wakes have direct
42 negative impacts on coastal flora and fauna (e.g., Gabel et al., 2017). In addition, they pose threat
43 on shoreline and seafloor stability, light availability and water quality due to the potential of waves
44 to resuspend the sediment at the seafloor and make it available for advection by currents in inter-
45 tidal areas and shallow bays (e.g., Loosanoff, 1962; Schwimmer, 2001; Price, 2005; Lawson et al.,
46 2007; Mcloughlin et al., 2015). Although recreational boat activity for cruising and fishing can
47 also support coastal economies, boat traffic and resulting waves have been reported to significantly
48 enhance shoreline erosion in sheltered estuaries where waves would have relatively small impact
49 on shoreline in absence of this traffic (e.g., Bilkovic et al., 2019). Therefore, better understanding
50 of the impacts of boat wakes on fate of sediment is necessary to inform robust strategies for im-
51 proving ecosystem health, shoreline stability and efficient management of dredging, maintenance
52 and navigational needs in intertidal and intracoastal waters.

53 Investigations of boat wake effects on sediment transport have mostly been qualitative (Osborne
54 and Boak, 1999; Parnell et al., 2007) or focused on the physics of suspension of sediment during
55 individual wake events (Houser, 2011; Malej et al., 2019) and have not taken tidal stages or currents
56 into account (Bauer et al., 2002; Houser, 2011; De Roo and Troch, 2015). Studies on the effects of
57 tides and wakes on sediment processes (e.g., Styles and Hartman, 2019) focused on limited number
58 of wake events in data sets of relatively short periods (~40 hours) and neither integrated sediment
59 fluxes throughout the water column nor evaluated the wake impacts on cumulative sediment fluxes
60 within the studied systems. As a result, there is a strong need for research on the effects of boat
61 wakes on sediment processes in intertidal settings and modulation of these processes by tides.
62 It is hypothesized here that boat wakes could have significant effects on sediment transport in
63 intertidal waterways. To test this hypothesis, in this study, field observations of boat wakes, tides
64 and sediment processes were collected in an intertidal setting (Section 2.1) and analyzed (Section
65 2.2). The results obtained from the observations of tides and currents, boat wakes, and sediment
66 processes are evaluated (Section 3) and then used for discussing the impacts of wakes and tides
67 on sediment transport dynamics in intertidal areas (Section 4). The findings are summarized in
68 Section 5.

69 2 Method

70 2.1 Field experiment

71 The field observations were collected at the Tolomato River channel in Guana Tolomato Matanzas
72 National Estuarine Research Reserve (GTMNERR, hereafter GTM for brevity) within St. Johns
73 County in Northeast Florida, USA (Figure 1a) between 23 May and 3 June in 2019. The field site
74 (29.986391° Latitude North, 81.327358° Longitude West) is located 9 km north of St. Augustine
75 Inlet and 47 km south of St. Johns Inlet, where the Guana River connects to the Tolomato River
76 (Figure 1a). GTM is within the Atlantic Intracoastal Waterway and experiences year-round traffic
77 of navigational and recreational boats (FLHSMV, 2013; Montes et al., 2016; FDEP, 2018). Based
78 on the aerial photographs of 65-km-long intracoastal channel margin along GTM, it was found that
79 70 hectares of shoreline habitat (bars, marsh) eroded between 1970 and 2002 (Price, 2005). This
80 can be roughly converted into a shoreline erosion rate of 0.35 m/yr on average along the analyzed
81 section. This shoreline erosion rate is in the same order of magnitude as those that were recently
82 measured along the Intracoastal Waterway, at about 35 km south of our study site (Silliman et al.,
83 2019). The related analysis also revealed that exposure to boat wakes are likely the primary cause
84 of this erosion. For further details about the GTM and its boat traffic, wake climate and shoreline
85 habitat erosion rates, the reader is referred to Safak et al. (2020a) and Safak et al. (2020b).

86 The coastline at the location of the experiment is oriented $\sim 15^\circ$ counterclockwise from the North-
87 South orientation (Figure 1a). Based on the sediment samples collected, surficial sediment at the
88 study site is characterized as fine sand with a median diameter of $D_{50}=200 \mu\text{m}$ (Herbert et al.,
89 2018). The Tolomato River channel is about 400 m wide at the experiment location (Figure 1); a
90 sand bar, which emerges in low-tide, is located about 30 m offshore of the coastline. The hydro-
91 dynamic measurements were collected at two locations offshore of the sand bar (Figure 1b). An
92 acoustic velocimeter, Nortek Vector with 6 MHz frequency of acoustic signal transmission, was
93 located at each of the two points that were on a 13-m-long cross-channel transect. Point A, located
94 about 57 m from the shoreline, had a mean depth of 1.09 m averaged over the experiment duration
95 (Figure 1b). Point B, the shallow point that was located 13 m onshore of A, had an average depth
96 of 0.65 m and was dry during low-tide (Figure 1b). The cross-channel slope of the seafloor be-
97 tween the two measurement points was about 1/30. The velocimeters made point measurements of
98 pressure, flow velocity and acoustic backscatter continuously at 8 Hz sampling frequency. Qual-
99 ity control on the data sets was conducted. Data with along-beam signal correlations less than
100 90% were marked as low-quality and removed from the analysis (Nortek, 2018). Suspended sedi-

101 ment concentration was estimated using the calibrated acoustic backscatter (e.g., Ozturk and Work,
102 2016). The sampling volumes of the velocimeters were at 0.17 meters above bed (mab). Winds
103 were analyzed by using the meteorological data collected by the GTM at 29.6578° Latitude North,
104 81.2328° Longitude West, i.e., 39 km South of the experiment site (NERRS, 2019).

2.2 Data analysis

2.2.1 Hydrodynamic and sediment processes

Depth-integrated horizontal flux of sediment mass per unit width is obtained as

$$q = \int_{-h}^0 u(z) c(z) dz, \quad (1)$$

based on the measurements of currents (u) and suspended sediment concentration (c), and their estimated vertical structures. h is the water depth, z is the vertical coordinate which is equal to zero at the water surface and $-h$ at the bed. The vertical structure of horizontal currents, i.e., $u(z)$, is assumed to be logarithmic (Nielsen, 1992):

$$u(z) = \frac{u_*}{\kappa} \ln \left(\frac{z}{z_o} \right), \quad (2)$$

where u_* is the bottom friction velocity and $\kappa=0.41$ is the von Karman's constant. Furthermore, z_o is the zero-intercept level where the horizontal velocity is assumed to be zero and is related to the hydraulic roughness length (k_s) as $z_o = k_s/30$. Hydraulic roughness length is assumed to be related to a flat bed. Accordingly, $k_s = 2D_{50}$ where D_{50} is the median diameter of sediment (Nielsen, 1992) and $z_o=0.000013$ m. The shear stress at the bed is estimated as $\tau_b = \rho u_*^2$ where ρ is the density of water.

The vertical structure of suspended sediment concentration ($c(z)$) is obtained using the Rouse profile which is based on a balance between upward diffusion and downward settling of sediment (Rouse, 1937, 1961; Mofjeld and Lavelle, 1988)

$$c(z) = \frac{E}{w_s} \left[\frac{z}{z_o} \frac{(h-z_o)}{(h-z)} \right]^{-w_s/\kappa u_*}, \quad (3)$$

where E is the erosion rate and w_s is the sediment settling velocity taken as 0.03 cm/s for fine sand of $D_{50}=200 \mu\text{m}$. For each 10 minute measurement interval, q , u_* and E are obtained based on the Equations 1, 2 and 3 using the near-bed observations of mean currents and suspended

130 sediment concentration; then the vertical structures throughout the water column are constructed.
131 This procedure averages over the waves as well.

132 As demonstrated later in Section 3, sediment suspension and settling vary from one wake event
133 to another. This is due to both the variations in physical forcing (e.g., wake energy, tidal phase)
134 and the unremitting and unpredictable evolution of the state of the sea bed (whether it is consol-
135 idated or soft). Besides these variations, there are uncertainties associated with the background
136 levels of SSC and bed state in the absence of wakes which together make filtering the effects of
137 each individual wake on boundary layer processes, bed shear stresses, and, eventually, SSC levels
138 infeasible. Therefore, in this study, the sediment transport during the periods of boat activity and
139 the resulting wake energies is compared in its entirety with the sediment transport during the pe-
140 riods of boat inactivity. While the beginning and ending times of boat activity and boat inactivity
141 periods show small variations from one day to another, the periods of boat activity and inactivity
142 correspond to virtually equal 12-hr-long intervals on average from 7:30 AM to 7:30 PM, and from
143 7:30 PM to 7:30 AM, respectively. Modulation of sediment processes by tides is investigated by
144 comparing the sediment fluxes at varying water levels (low-tide, mid-tide, high-tide) and at parts
145 of the experiment with different tidal forcing (relatively small and relatively high tidal fluctuations
146 and resulting currents and bed stresses). The deployment period covered both neap and spring
147 tides.

148 **2.2.2 Boat wakes**

149 Due to their transient nature and relatively short timescales (seconds - minutes), boat wakes appear
150 in data as ‘*chirp*’ signals. Identification of boat wakes in field observations requires the use of
151 advanced methods of time-frequency analysis. First, the effects of tides in the pressure signal mea-
152 sured near the bed are filtered out. Applying a windowed Fourier transform and wavelet transform
153 to the de-tided data gives a spectrogram, in which the wakes are identified by the monotonically
154 increasing peak frequency where the energy is highest. To estimate the height of each wake, pres-
155 sure variation at the water surface is obtained from the de-tided pressure data measured near the
156 bed, by taking into account the vertical structure of pressure throughout the water column based on
157 the linear wave theory. Once the sea surface elevation is obtained, the height of the highest wave
158 and the corresponding period are recorded for each wake. For details of the identification of boat
159 wakes in the field observations and the related time-frequency data analysis methods, the reader is
160 referred to Sheremet et al. (2013).

3 Results

3.1 Tides and currents

The general conditions throughout the field experiment are summarized in Figure 2. Semi-diurnal tides dominated the water depth variations (Figure 2a) at both Station A (mean depth of 1.09 m during the experiment) and Station B (mean depth of 0.65 m). The average tidal range was about 1.2 m (Figure 2a). Station B was dry (i.e., the sensor was emerged during low tide) for 31% of the total duration of the experiment (Figure 2a), while Station A was submerged for the entire duration of the experiment. Current flow was along the North-South axis (Figure 3a). Wind climate was almost entirely northward in the North-South orientation during the experiment: north-northwestward winds between 3 m/s and 5 m/s, and north-northeastward winds between 1 m/s and 3 m/s (Figures 2b and 3b). Similar to the water depth variations, currents were also dominated by the tidal forcing (Figure 2c). As might be expected, bed shear stresses very closely followed current speeds (Figure 2d). The other feature apparent in the currents is the asymmetry such that northward flows and associated shear stresses at the bed were stronger than southward flows and associated bed stresses (Figures 2c-d and 3a). This difference is attributed to the wind climate (Figures 2b and 3b). The near-bed flows (0.17 mab) at Station A were about 35% stronger than those at Station B (Figures 2c and 3c). The concentrations of suspended sediment at 0.17 meters above bed at Station B were twice as high as those at Station A (Figures 2e and 3d).

3.2 Wakes

Spectrograms obtained by applying a windowed Fourier transform and wavelet transform to the de-tided data on two five-minute-long time segments – one that did not contain any boat wakes and one with boat wakes– are demonstrated in Figure 4. Within the time segment with boat wakes, monotonically increasing peak frequency where the energy is highest is evident and help identify the wakes in the data.

Based on the spectrogram analysis, a total of 661 wake events were detected during the experiment. Resulting waves most commonly had heights of ~0.1 m (Figure 5a) and periods of ~1.7 s (Figure 5b). In the most energetic events, wake heights and periods reached 0.5 m and 5 s, respectively (Figure 5). Contribution of winds to these observed waves and the wave climate of the study site is negligible considering the limited fetch and wind conditions during the experiment (Safak et al., 2020a).

191 3.3 Sediment processes

192 As an example, Figure 6 shows variations of water levels and suspended sediment concentration
193 (SSC) during the day (boat activity and resulting wakes) and night (boat inactivity; no wakes)
194 are shown for one day. The fluctuations in water levels and increases in SSC due to the boat
195 traffic during the day and resulting wakes are evident. To demonstrate the effect of individual
196 wakes, a 30-min-long time series of water levels, flow velocity and SSC are shown in Figure 7. As
197 previously explained in Section 2.2.1, different wakes are seen to cause sediment suspensions of
198 varying concentrations (enhanced by an order of magnitude in some wake events) due to varying
199 wave-induced orbital velocities and different behaviors of settling that occurs after the wake passes
200 by (Figure 7).

201 Based on the field observations (Section 2.1) and the analysis approaches detailed in Section 2.2.1,
202 vertical structures of currents, vertical structures of SSC, and finally the sediment transport at the
203 two points on the cross-channel transect are obtained (Figure 8). The higher SSC values throughout
204 the entire water column during the periods of boat activity compared to those during boat inactivity
205 are evident (Figure 8a and b). Between 23 May and 30 May, the peaks of horizontal sediment
206 transport per unit width were 0.1-0.15 m³/m/hr at both depths (Figure 8c); the period of 31 May -
207 2 June had evidently greater peaks that reached 0.4 m³/m/hr (Figure 8c). The horizontal sediment
208 fluxes estimated at Station A were consistently greater than those at B.

209 Variations of concentration of suspended sediment and volume of transported sediment integrated
210 separately over the periods of boat activity and boat inactivity are summarized in Figure 9. The
211 daily average of number of wake events is about 60. During weekdays, an average of about 45
212 wake events were observed. Saturday, Sunday and Memorial Day Monday had greater number of
213 wake events reaching 80 due to holiday traffic (Figure 9a). All boat activity periods are associated
214 with greater SSC and volume of sediment transported, compared to their preceding periods of boat
215 inactivity (Figure 9b and c). Throughout the experiment, average SSC during the periods of boat
216 activity is greater than the one during the periods of boat inactivity (Figure 9b). Total volume of
217 sediment transported per unit width (Figure 9c) throughout the experiment was estimated as 13.72
218 m³/m (Table 1), 60% of which was estimated to occur during boat activity (8.28 m³/m) and 40%
219 during boat inactivity (5.44 m³/m).

4 Discussion

4.1 Modulation of sediment transport by tides and wakes

Based on the results presented in Section 3, the impacts of tidal variations and boat wake activity in modulating sediment transport processes are investigated in detail here. There are two major differences in sediment transport dynamics between the last three-day-period of spring tides (31 May - 2 June; annotated with *LT* in Figure 2) and the first eight-day-period of the experiment (23 May - 30 May). First, the *LT* period is characterized by greater sediment flux peaks over the tidal cycles (Figure 8c). Second, within *LT*, the peak fluxes and integrated fluxes within the boat activity periods are evidently greater than those within the boat inactivity periods, in contrast to the comparable peaks and integrations over the periods of boat activity and inactivity during the previous part of the experiment (Figures 8c and 9c). These two features are attributed to the difference in the dynamics of tides and currents between these two intervals: First, the *LT* period had larger tidal fluctuations (1.5 m on average) compared to the previous part of the experiment (1.1 m on average; Figure 2a). These amplitudes of tidal fluctuations during these two periods are consistent with the data reported by the closest tidal gauge of the National Oceanic and Atmospheric Administration (NOAA; Station ID: 8720218) located near St. Johns Inlet. These larger tidal fluctuations during the *LT* period triggered stronger currents of 0.35 - 0.40 m/s (versus 0.27 - 0.29 m/s; Figure 2c) and higher bed stresses (>0.2 Pa reaching 0.32 Pa; versus ~ 0.15 Pa; Figure 2d). Second, there is a tidal-phase-induced asymmetry in bed stresses between the periods of boat activity and inactivity during *LT*: the stresses are much greater during the boat activity periods in contrast to the relatively similar bed stresses during boat activity and inactivity periods within the previous part of the experiment (Figure 2d). Note also that there is no comparable peak in stress in the boat inactivity period of 1 June but there are two peaks in the boat activity period of 2 June.

As a result, the sediment transport processes are evaluated separately for these two parts of the experiment. Total sediment volumes per unit width are obtained by integrating the depth-averaged sediment fluxes separately over the boat activity and inactivity periods. These volumes are standardized by taking into account the durations of these periods; and the sediment transport rates are obtained. For *LT*, the average sediment transport rate for the boat activity periods ($0.085 \text{ m}^3/\text{m}/\text{hr}$) is about twice as much as the one for the boat inactivity periods ($0.040 \text{ m}^3/\text{m}/\text{hr}$; Table 1). For the first eight days, when there was no such asymmetry between the periods of boat activity and inactivity in terms of currents, sediment transport was still more abundant during the boat activity periods ($0.048 \text{ m}^3/\text{m}/\text{hr}$ vs $0.043 \text{ m}^3/\text{m}/\text{hr}$; Table 1). In spite of the smaller difference compared

252 to the *LT* period, this 12% enhancement in sediment transport rates during the boat activity period
253 shows that boat activity and resulting wakes are significant factors controlling sediment dynamics
254 in intertidal waterways.

255 Modulation of the sediment transport by water levels is shown in Figure 10 separately for the first
256 eight-day-period and the last three-day-period of the experiment. During both the boat activity and
257 inactivity periods in these two sections of the experiment, volume of transported sediment shows
258 an overall increasing trend with increasing water levels (Figure 10). Average volumes of sediment
259 transported at low-tide, mid-tide and high-tide conditions during the periods of boat activity are
260 estimated to be greater than their low-tide, mid-tide and high-tide counterparts during the periods
261 of boat inactivity (Figure 10). Although the difference appears to be more evident in the second
262 part of the experiment due to the current-related effects detailed above (Figure 10b), the sediment
263 transport during boat activity is greater on average than the one during boat inactivity at all water
264 levels in the first part of the experiment as well (Figure 10a).

265 **4.2 Effect of ripples**

266 In settings where wind waves (assumed to be stationary over time scales of hours) are prominent,
267 ripples could form at the bed and affect the hydraulic roughness, bottom friction, and, eventually,
268 the vertical structures of flow and sediment transport. Boat wakes could affect these processes
269 as well, however, how they affect and whether ripples can form and sustain under these wakes are
270 unknown due to the transient nature and much shorter time scales (seconds - minutes) of the wakes.
271 Despite these uncertainties and instrumentation-related limitations on observing these processes
272 (i.e., measurements at a single point in the vertical throughout the water column), possible effect
273 of ripples on sediment transport rates here is investigated. Ripple height (η) and ripple length (λ)
274 are estimated by using the following relationships (Styles and Glenn, 2002)

$$275 \quad \frac{\eta}{A_b} = \begin{cases} 0.30X^{-0.39}, & X \leq 2 \\ 0.45X^{-0.99}, & X \geq 2 \end{cases}, \quad (4)$$

276

277

$$\frac{\lambda}{A_b} = \begin{cases} 1.96X^{-0.28}, & X \leq 2 \\ 2.71X^{-0.75}, & X \geq 2 \end{cases}, \quad (5)$$

278

279 where A_b is the bottom wave excursion amplitude, and X is the ratio of the nondimensional mobility
 280 number (θ_m) to the nondimensional sediment parameter (S_*)

$$281 \quad A_b = \frac{u_b T}{2\pi}, \quad u_b = \frac{H\pi}{\sinh(kh)T}, \quad (6)$$

$$282 \quad X = \frac{\theta_m}{S_*}, \quad \theta_m = \frac{u_b^2}{(s-1)gD}, \quad S_* = \frac{D}{4\nu} \sqrt{(s-1)gD}, \quad (7)$$

284
 285 where u_b is the bottom wave orbital velocity, T is wave period, H is wave height, k is wave number,
 286 s is the specific gravity of sediment (2.65), g is the gravitational acceleration, D is the sediment
 287 diameter taken equal to the median diameter of 200 μm here, and ν is the kinematic viscosity of
 288 water. For each wake event detected, the ripple geometry was estimated using this methodology.
 289 Then, ripple-induced hydraulic roughness (k_{s-r}) was estimated using the following relationship
 290 based on the observations of ripple formation under oscillatory flow (Nielsen, 1992)

$$291 \quad k_{s-r} = 8 \frac{\eta^2}{\lambda}. \quad (8)$$

292
 293 The corresponding z_{o-r} , equal to $k_{s-r}/30$, is added to the z_o , which is related to a flat bed, in
 294 Eqs. 2 and 3 to estimate the modified flow, sediment concentration, and sediment transport rates.
 295 Wave and flow conditions in more than two-thirds of the detected wake events here resulted in an
 296 estimated ripple height of $\eta=0.6-0.8$ cm, a ripple length of $\lambda=4-6$ cm, and a $z_{o-r} \sim 0.0003$ m, the
 297 last of which is an order of magnitude greater than the one for a flat bed. The sediment transport
 298 rates obtained by using this z_{o-r} that takes the boat-wake-induced ripple effects into account over
 299 the boat activity periods are calculated to be 6% greater than those obtained by assuming a flat bed
 300 over those boat activity periods. This indicates the possibility that estimates of sediment transport
 301 rates during boat activity could be subject to an even further increase in case of wake-induced
 302 rippled formation, however, it has to be noted that whether and how boat wakes form ripples can
 303 not be fully determined due to the aforementioned uncertainties. Evaluation of this possible further
 304 enhancement in sediment transport and the overall impact of boat wakes on sediment processes can
 305 be improved by collection of high-resolution data on bottom boundary layer and bed state.

306

307 5 Conclusions

308 In this study, the modulation of sediment transport by boat wakes, tides and currents in an intertidal
309 waterway setting with boat traffic was investigated by analyzing field observations. Although be-
310 ing transient and associated with relatively short time scales of minutes, waves that are generated
311 in the wakes of vessels were observed here to resuspend sediment and enhance the sediment con-
312 centration by an order of magnitude in some wake events. As a result of an analysis that compares
313 the periods of boat activity/inactivity and takes into account the effects of varying water levels and
314 currents, boat traffic and resulting wakes were shown to cause a significant increase in sediment
315 transport rate in intertidal waterways, even in fetch-limited conditions. Within the first three-
316 quarters of the experiment when the periods of boat activity and inactivity experienced relatively
317 similar tidal forcing, rates of sediment transport per unit cross-channel width were estimated as
318 $0.048 \text{ m}^3/\text{m}/\text{hr}$ and $0.043 \text{ m}^3/\text{m}/\text{hr}$ during boat activity and inactivity, respectively. This indicates a
319 12% increase in sediment transport due to boat traffic. In the last quarter of the experiment which
320 was modulated by both tides and wakes, twice as much sediment transport rate was estimated for
321 the period of boat activity compared to the one for the period of boat inactivity. Wake-induced
322 increase in sediment transport was detected at all tidal levels. To the best of the authors' knowl-
323 edge, this study has been the most comprehensive evaluation, so far, of boat wakes on sediment
324 processes in intertidal areas. A large-scale implication of our results is that boat activity, which
325 can contribute to coastal economies, is also a major anthropogenic impact on sheltered estuaries
326 and intertidal waterways due to its influence on hydrodynamics and resulting potential to erode
327 sediment, increase turbidity, decrease water quality. Another large-scale implication of the results
328 here is that reducing the anthropogenic impact on geomorphic evolution and mitigating shoreline
329 erosion in these estuaries and intertidal areas, and management of the stability and functionality of
330 coastal wetlands, reef and mudflat habitats require regulations on boat traffic. It needs to be noted
331 that the observed contribution of boat traffic and resulting wakes in sediment transport is affected
332 by seasonality in traffic and the time of the year the observations were collected (spring season);
333 therefore, there will be periods (i.e., summer season) when the effect of wakes will be even greater
334 than the observed effect here.

335 One major remaining challenge in understanding the effects of boat traffic on sediment transport in
336 field conditions is that filtering the individual effects of each boat wake on bottom boundary layer
337 processes and sediment transport is not possible. This is because the sea bed state is continuously
338 evolving due to a plethora of processes; i.e., the sediment resuspension potential of a wake is
339 different when it propagates over a bed (i) that is consolidated after periods of relatively low energy,

340 or (ii) which has been softened due to recent high energy conditions. Accordingly, collecting and
341 analyzing observations on bed state simultaneously with data on wake effects on bottom boundary
342 layer (e.g., ripples) and sediment processes can be a potential focus on future studies. Another
343 research gap is within the investigation of the wake structure and resulting sediment transport as a
344 function of vessel properties (type, draft, size, speed). Ongoing efforts include the analysis of the
345 co-located video imagery data, collected for this goal, on the vessel traffic during this experiment,
346 in concert with the hydrodynamic observations.

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357 **Conflicts of interest**

358 The authors declare no conflicts of interest.

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Table 1: Volumes and rates of sediment transport

Days	Boat activity	Volume (m ³ /m)	Rate (m ³ /m/hr)
1-8	Yes	4.58	0.048
	No	4.27	0.043
9-11	Yes	3.70	0.085
	No	1.17	0.040
Total	Yes	8.28	0.059
	No	5.44	0.042

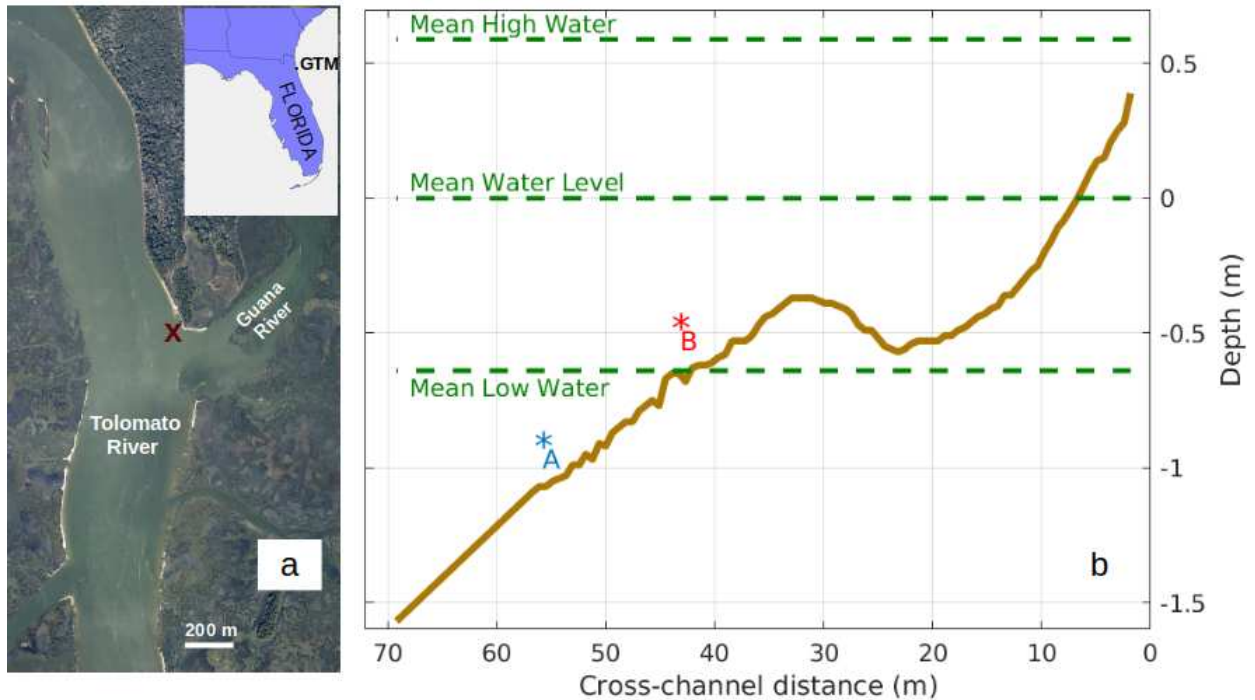


Figure 1: (a) The aerial view of the location of the cross-channel transect (marked with an ‘x’) of the instrumented platforms (A and B), and (b) the cross-channel bathymetry (dark brown). Inset panel at the top right of the aerial view shows where the site is located in Northeast Florida, USA; the aerial view shows the location of the experiment (29.986391° Latitude North, 81.327358° Longitude West) along the Tolomato River within the Atlantic Intracoastal Waterway. The river channel is about 400 m wide at the location of the transect. In the bathymetry figure in panel (b), mean high, mean and mean low water levels during the experiment are indicated with dashed green lines; vertical scale is exaggerated for clarity. The aerial view is obtained from the United States Geological Survey EarthExplorer database.

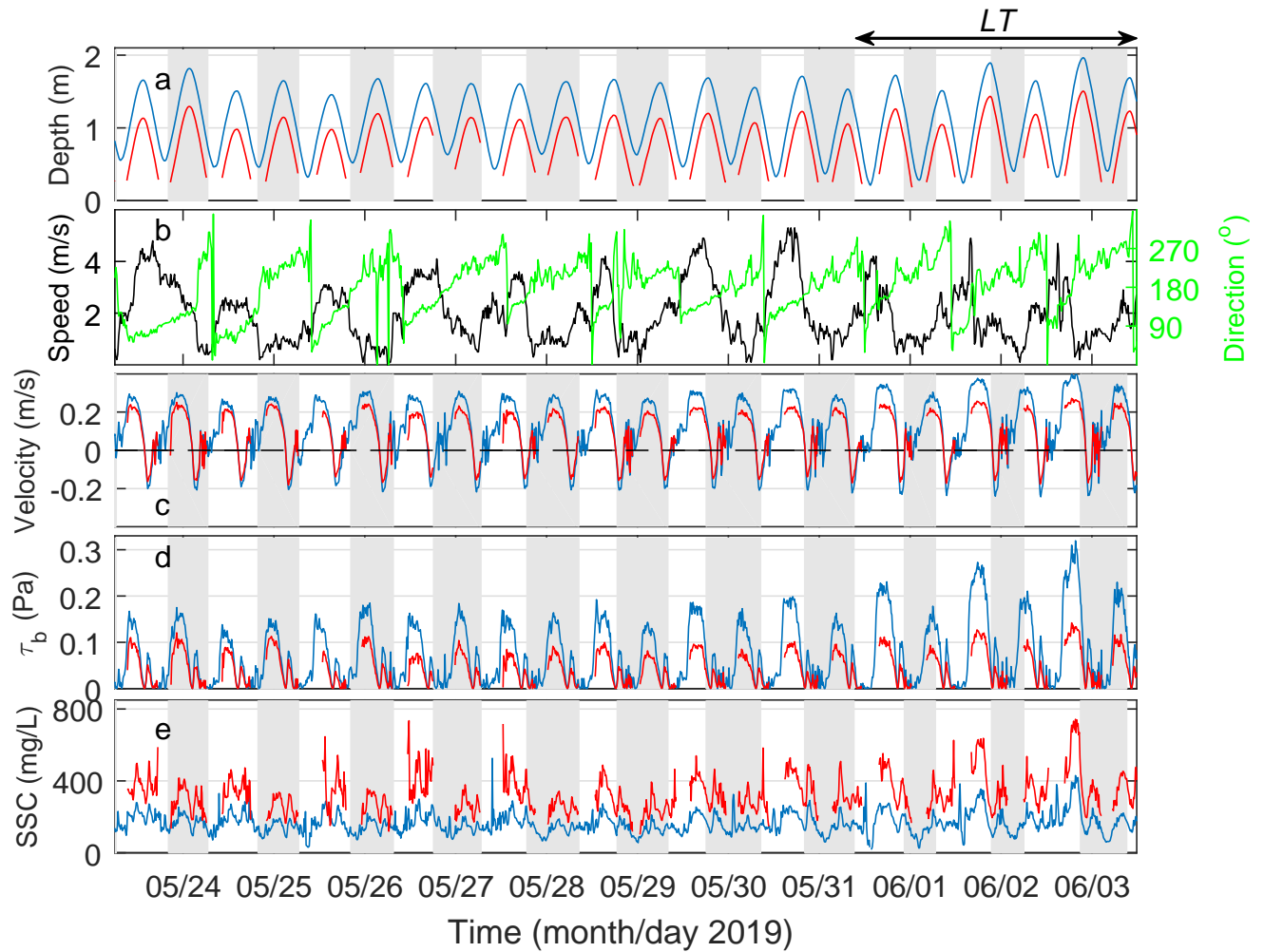


Figure 2: Time evolution of general conditions throughout the experiment: (a) water depth at Station A (blue) and Station B (red), (b) wind speed and direction, (c) current velocity at 0.17 meters above bed (mab) at Station A and Station B (positive and negative velocities indicate ~northward and ~southward flows, respectively), (d) shear stress at bed, and (e) suspended sediment concentration at 0.17 mab at Station A and Station B. The values are 10-min averages. The gaps in the data from Station B correspond to the low-tide periods when the data quality was low at very shallow water or the sensor volume at that point was out of the water. The grey shaded areas indicate the night periods of boat inactivity. The ‘LT’ annotation at the top panel indicates the spring tide period with relatively large tidal fluctuations and current speeds in the last part of the experiment.

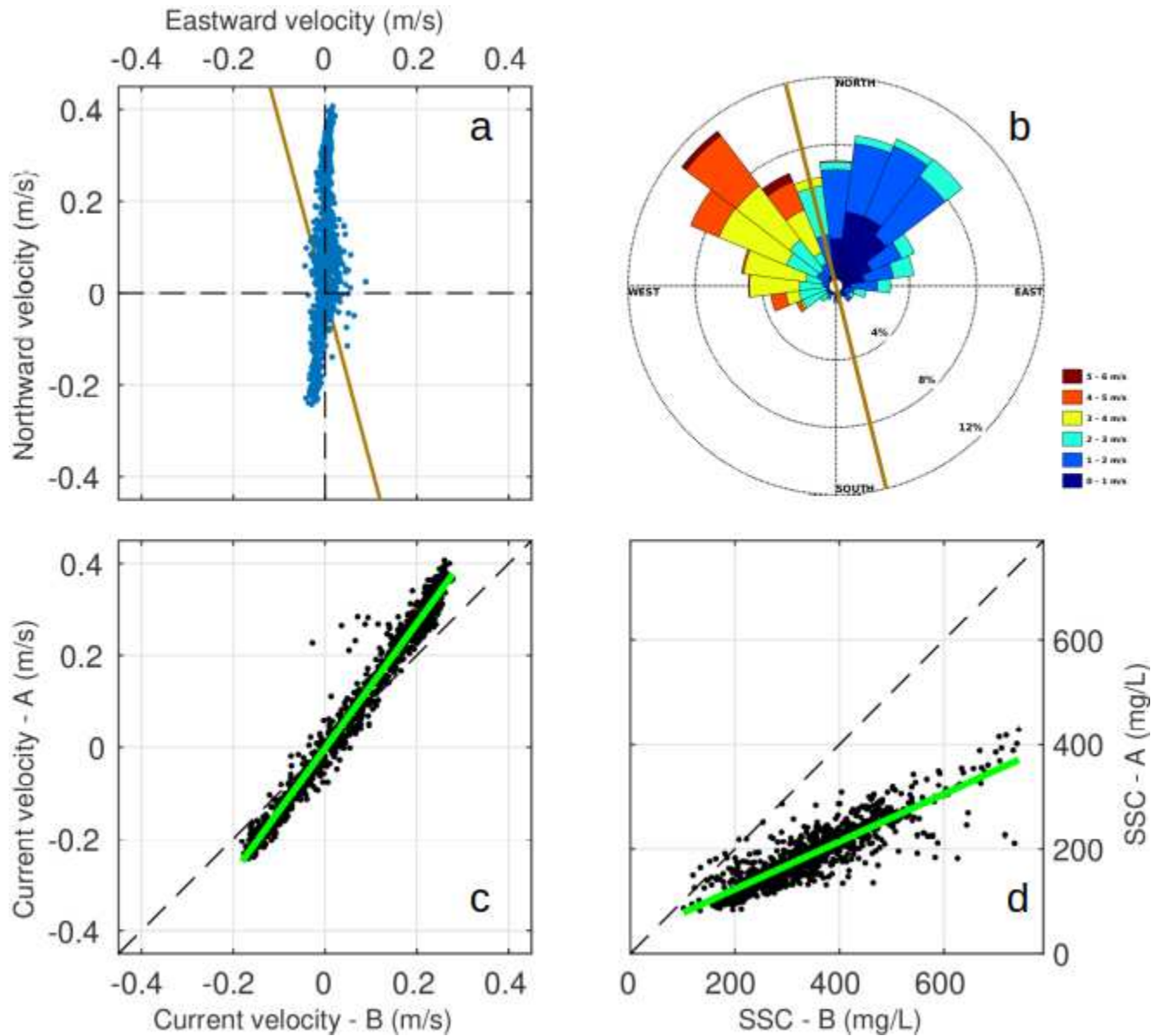


Figure 3: (a) Variation of northward current velocities with eastward current velocities at Station A, (b) wind rose during the experiment, (c) variation of current velocities at Station A with those at Station B, and (d) variation of suspended sediment concentrations at Station A with those at Station B. The current velocities and suspended sediment concentrations are 10-min averages. The wind rose in panel (b) shows where the winds were blowing to. The thick brown lines in panels (a) and (b) indicate the approximate orientation of the shoreline onshore of the transect. The thick green lines in panels (c) and (d) indicate the linear least square regressions (with r^2 of 0.97 and 0.79, respectively). The dashed black lines in panels (c) and (d) indicate the one-to-one relationships.

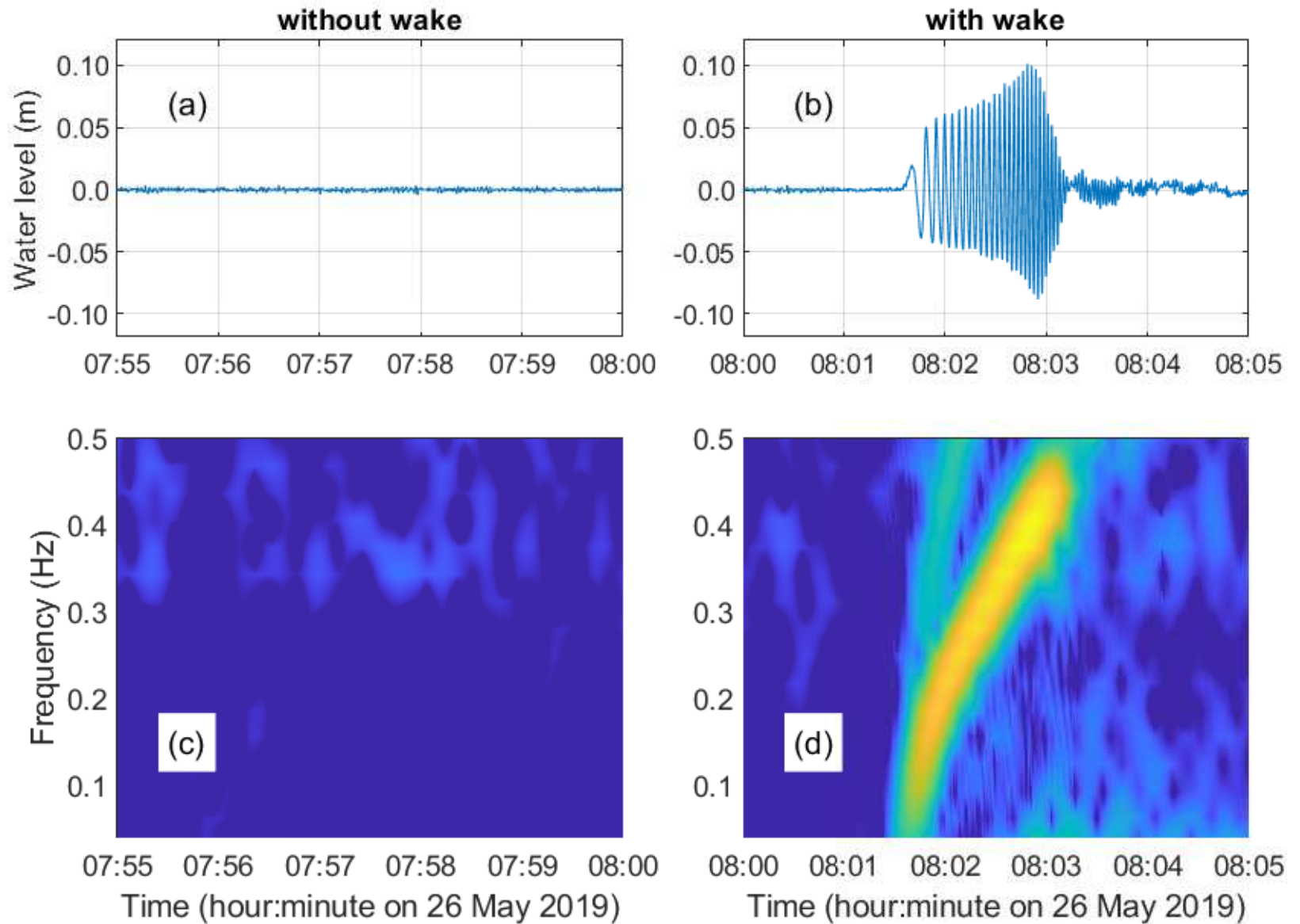


Figure 4: De-tided water levels (a-b) and normalized spectrograms (c-d) of two five-minute-long segments measured at Station A on 26 May 2019. Warm colors in (c-d) indicate high energy. The panels on the left and the right sides correspond to conditions without wakes and with wakes, respectively.

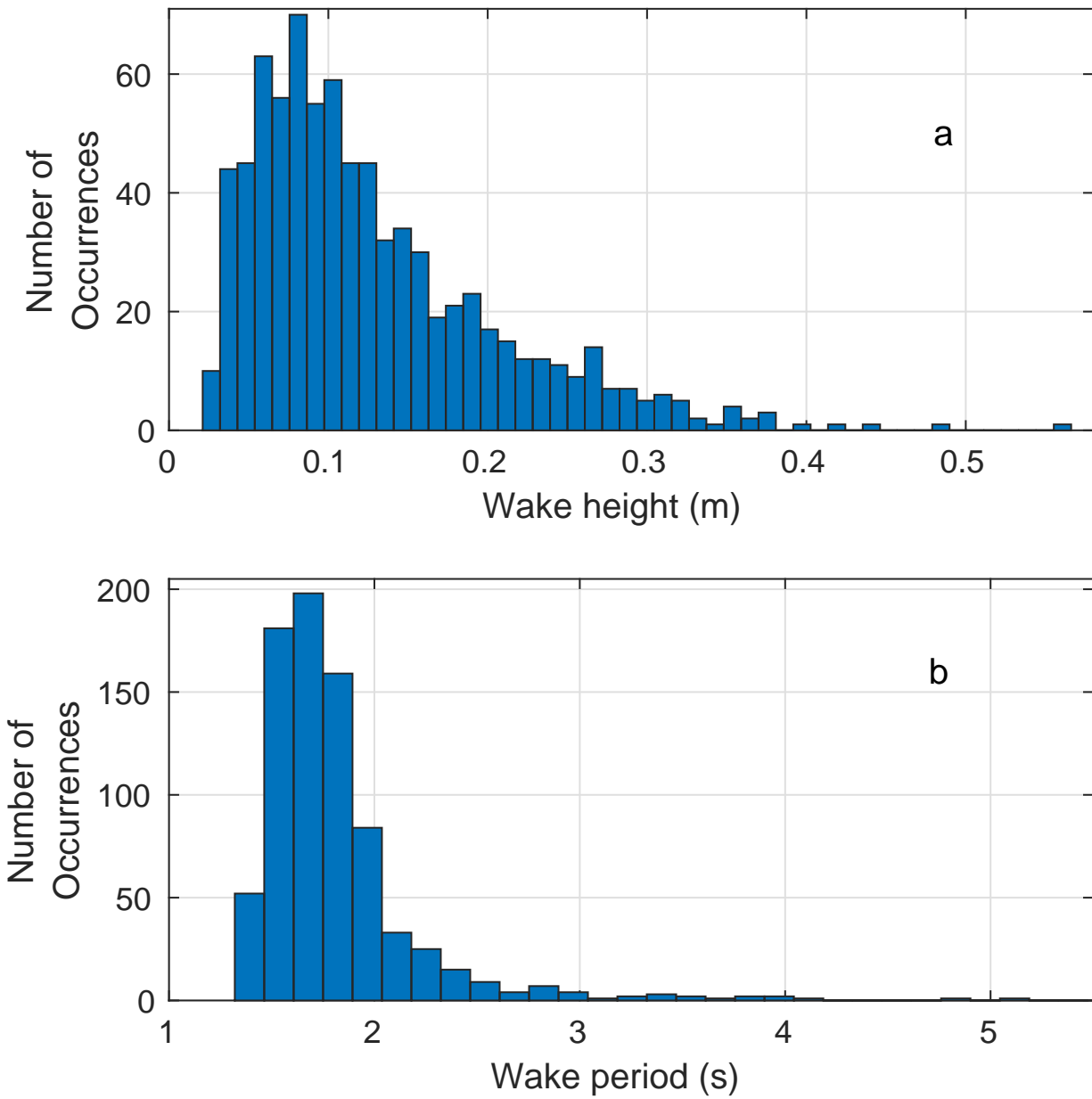


Figure 5: Histograms of (a) wake height, and (b) wake period at Station A.

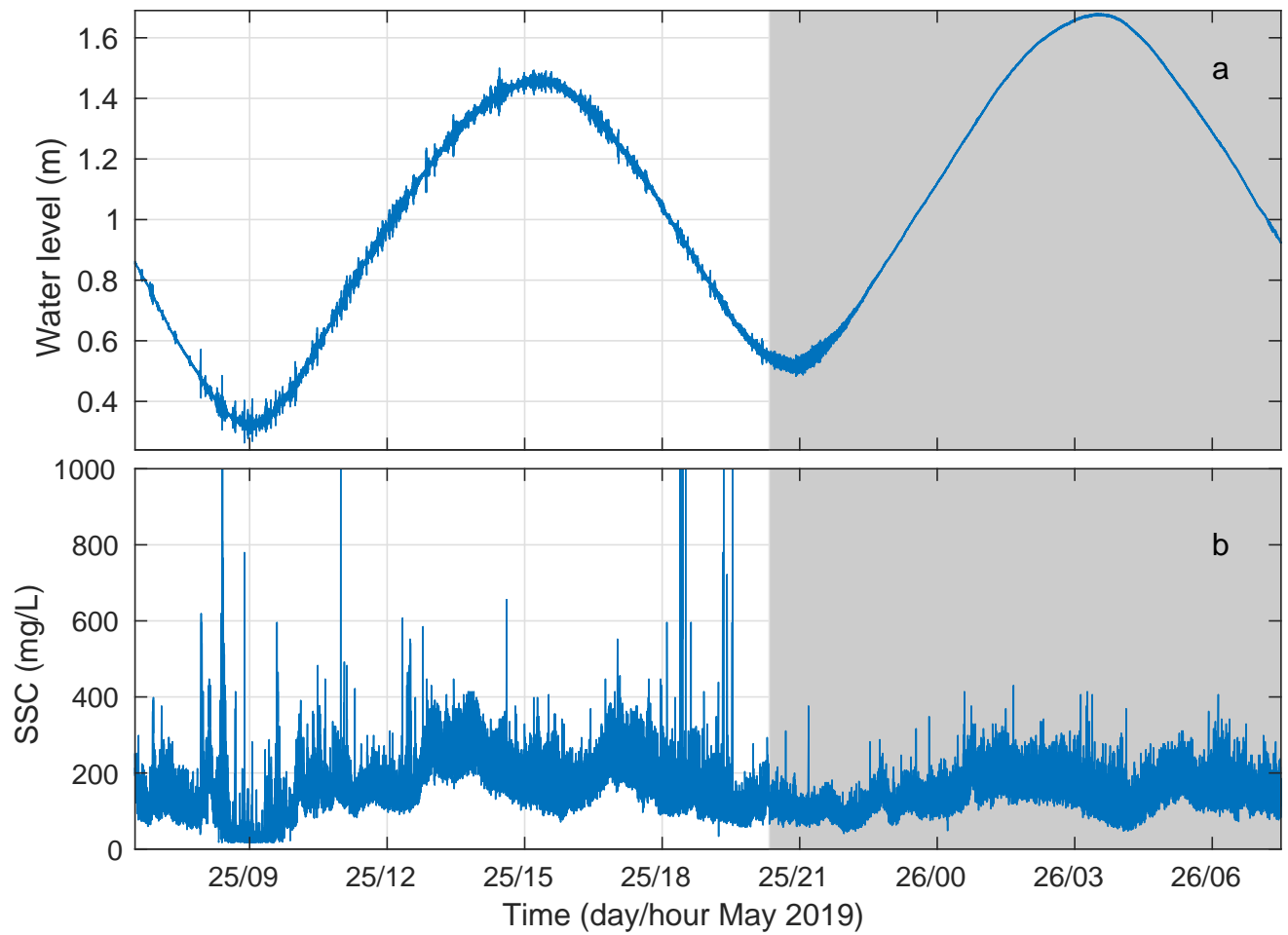


Figure 6: Time evolution of: (a) water level, and (b) suspended sediment concentration at 0.17 mab at Station A between 25 May and 26 May. The values are 8-Hz raw data. The areas shaded in gray indicate the night time of boat inactivity with no wakes.

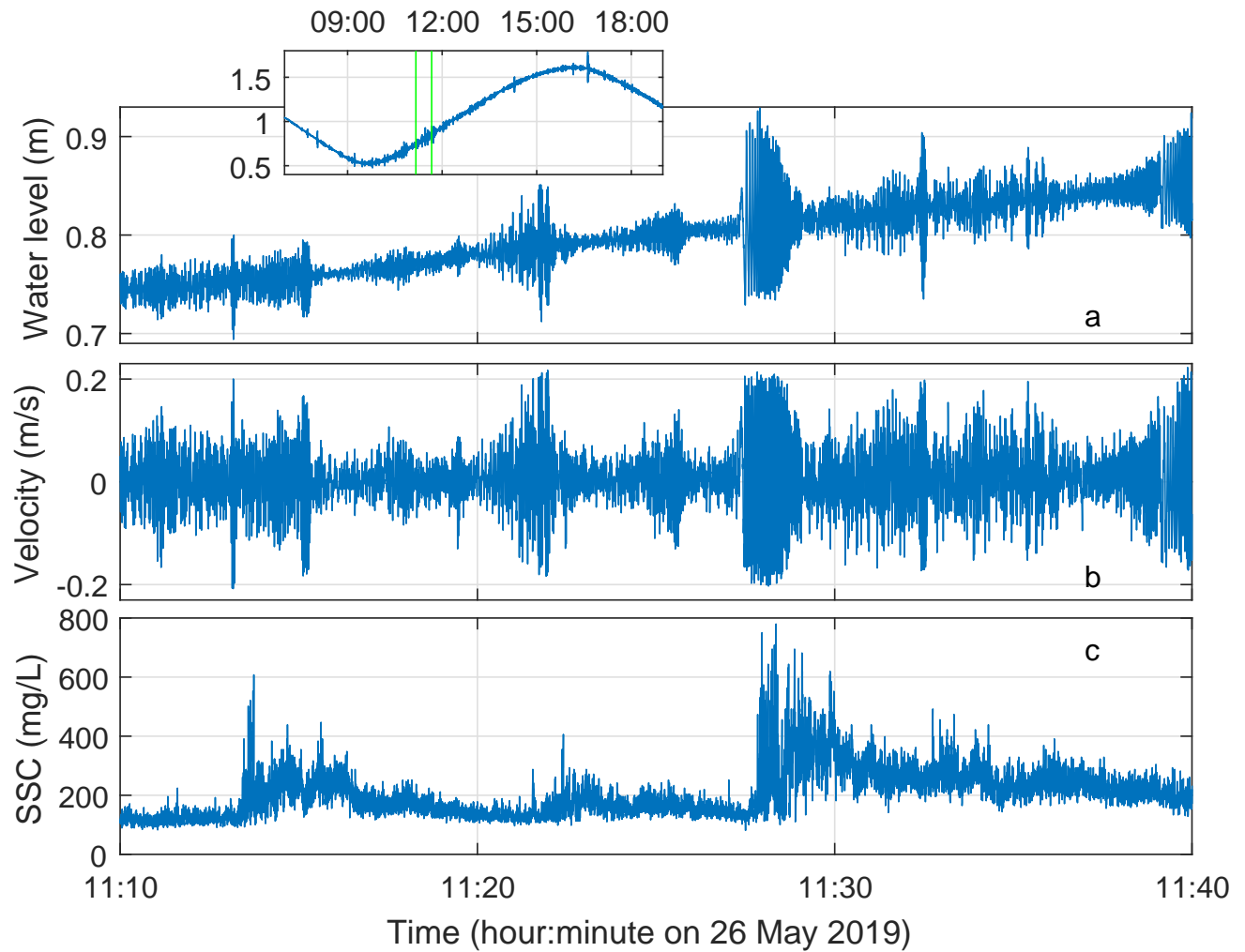


Figure 7: Time evolution of: (a) water level, (b) flow velocity, and (c) suspended sediment concentration at 0.17 m above bed at Station A during the wake events between 11:10 and 11:40 on 26 May 2019. The values are 8-Hz raw data. The green lines in the inset indicate the tidal phase that corresponds to the 30-min-long time-series in panels (a), (b), and (c).

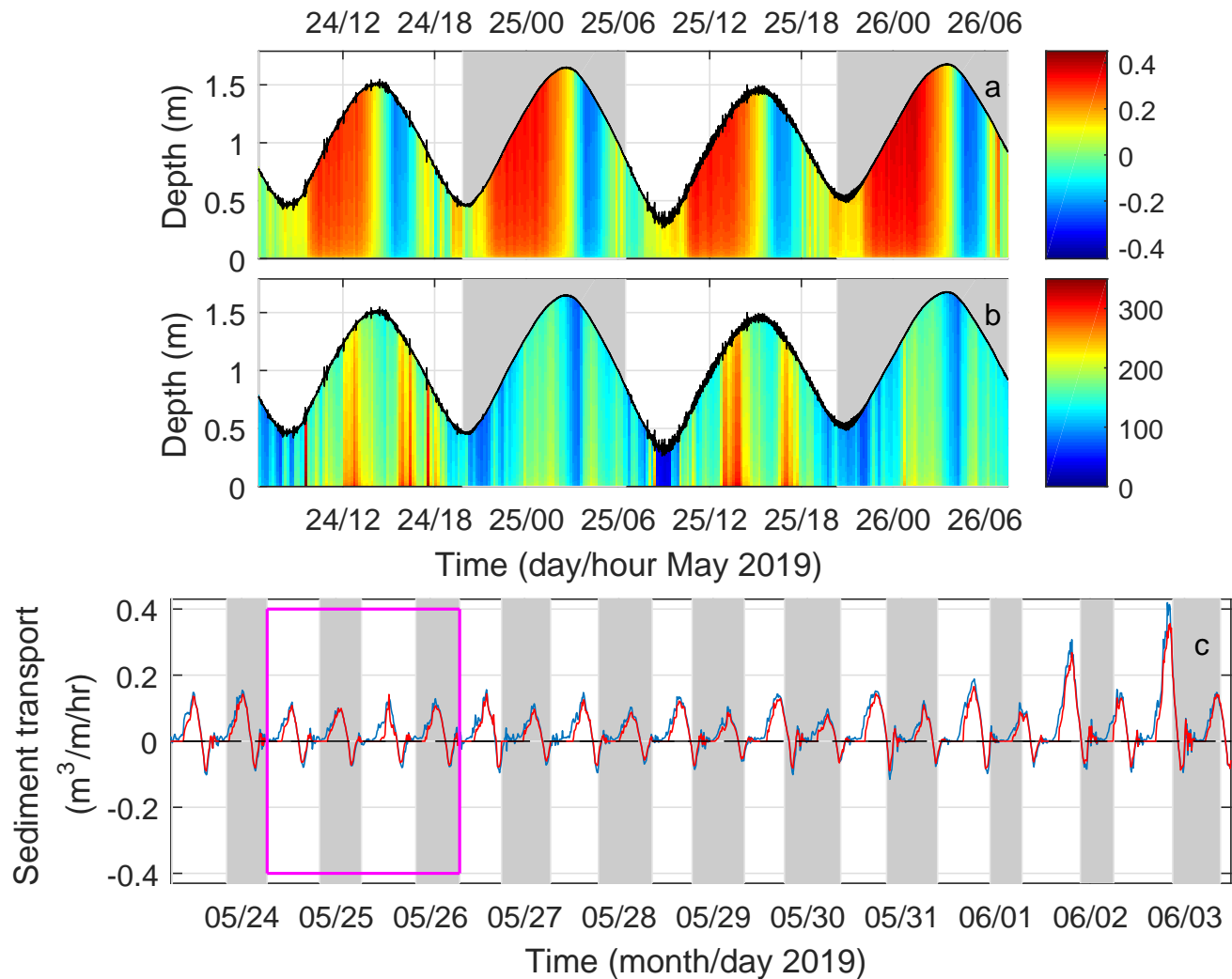


Figure 8: Time evolution of: (a) vertical structure of current velocity (m/s; positive and negative indicate ~northward and ~southward flow, respectively) at Station A between May 24th and 26th, (b) vertical structure of SSC (mg/L) at Station A between May 24th and 26th, and (c) depth-integrated horizontal sediment volume flux per unit width at Station A (blue) and Station B (red) throughout the experiment. The grey shaded areas indicate the night periods with no boat activity. The wake events are visible in the 8-Hz data (in black) inserted on the vertical structures of mean currents and SSC. The magenta rectangle in panel (c) indicates the time period for which the data of panels (a) and (b) are shown.

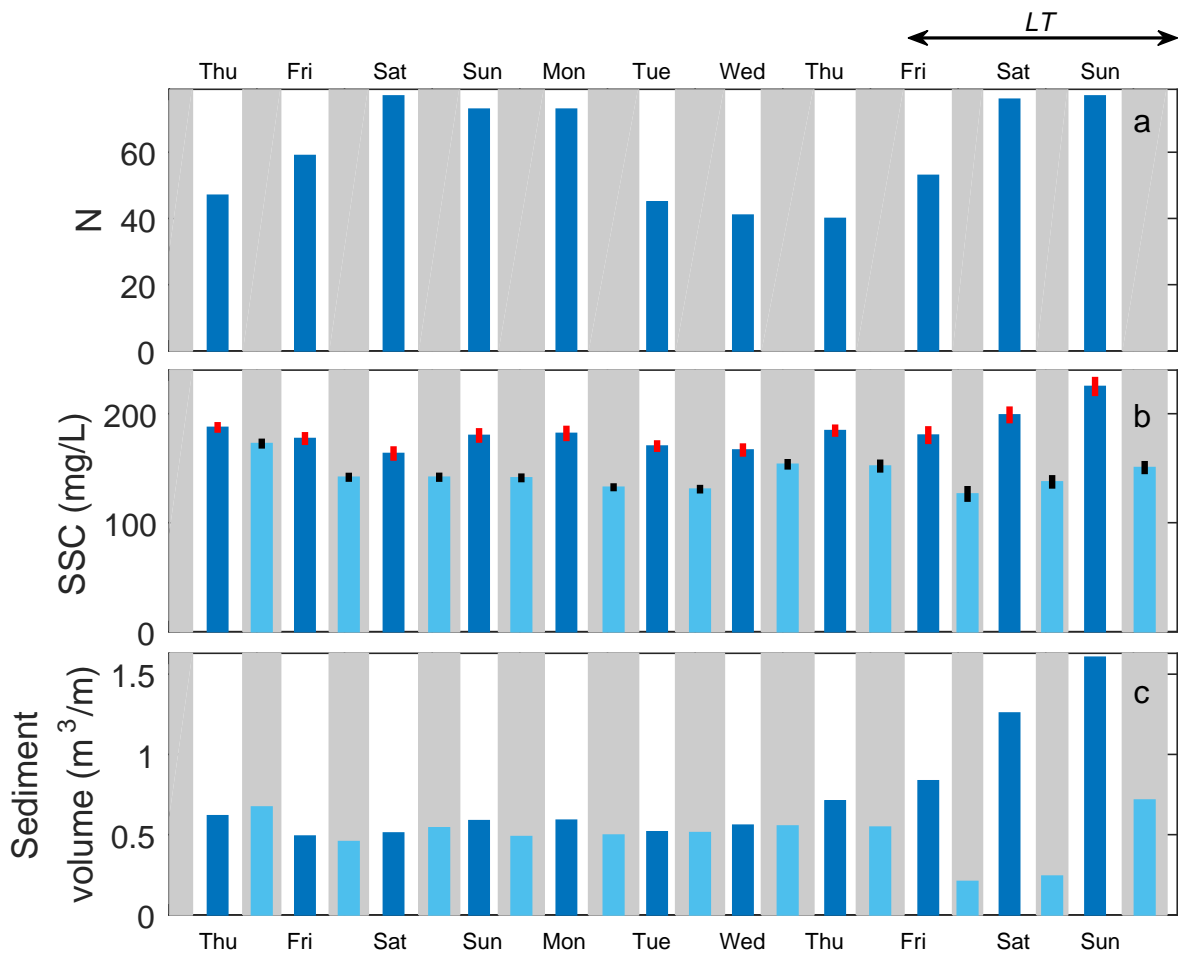


Figure 9: Variation of (a) total number of wake events during each boat activity period, (b) boat activity (dark blue) and boat inactivity period (light blue) averages of suspended sediment concentration at 0.17 mab, and (c) total sediment volume transported during boat activity (dark blue) and boat inactivity periods (light blue). Grey shaded areas highlight the boat inactivity periods. Vertical red and black bars in panel (b) show \pm standard error during boat activity and boat inactivity periods, respectively. The annotation at the top panel indicates the period with relatively large tidal fluctuations and current speeds in the last part of the experiment (Figure 2).

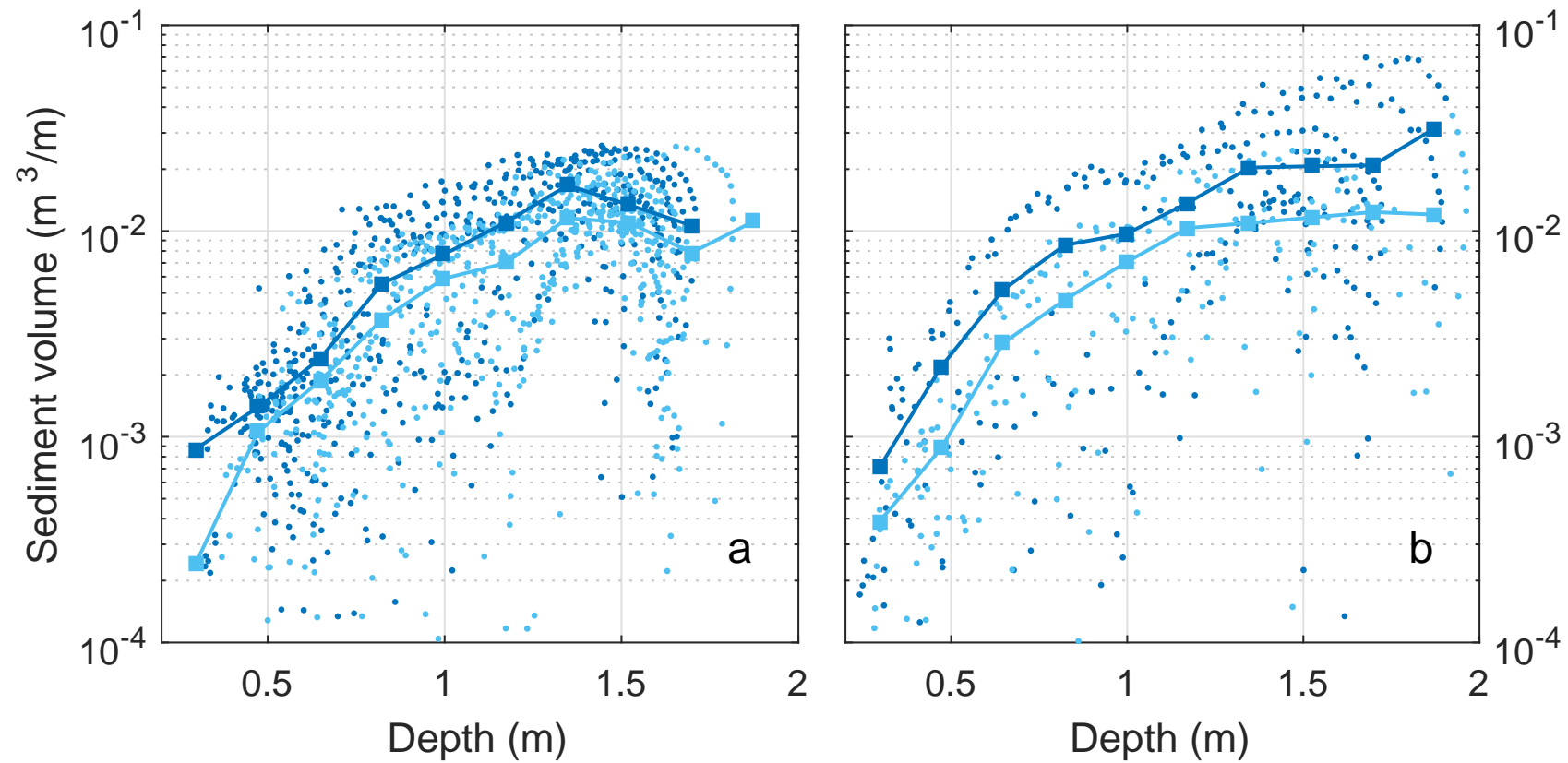


Figure 10: Volume of sediment transported at Station A during boat activity (dark blue) and inactivity (light blue), as a function of water depth. The two panels correspond to the results for (a) the first eight days, and (b) the last three days of the experiment. Dots show the volume estimates representing the 10-min intervals; the squares are averages over 18-cm-wide depth bins.