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The effect of wave-induced turbulence on intertidal mudflats: Impact of boat traffic and wind

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Abstract:

Semi-diurnal and fortnightly surveys were carried out to quantify the effects of wind- and navigation-induced high-energy events on bed sediments above intertidal mudflats. The mudflats are located in the upper fluvial part (Oissel mudflat) and at the mouth (Vasière Nord mudflat) of the macrotidal Seine estuary. Instantaneous flow velocities and mudflat bed elevation were measured at a high frequency and high resolution with an acoustic doppler velocimeter (ADV) and an ALTUS altimeter, respectively. Suspended particulate matter concentrations were estimated by calibrating the ADV acoustic backscattered intensity with bed sediments collected at the study sites. Turbulent bed shear stress values were estimated by the turbulent kinetic energy method, using velocity variances filtered from the wave contribution. Wave shear stress and maximum wave-current shear stress values were calculated with the wave-current interaction (WCI) model, which is based on the bed roughness length, wave orbital velocities and the wave period (T_S). In the fluvial part of the estuary, boat passages occurred unevenly during the surveys and were characterized by long waves ($T_S > 50$ s) induced by the drawdown effect and by short boat-waves ($T_S < 10$ s). Boat waves generated large bottom shear stress values of 0.5 N m^{-2} for 2–5 min periods and, in burst of several seconds, larger bottom shear stress values up to 1 N m^{-2} . At the mouth of the estuary, west south-west wind events generated short waves ($T_S < 10$ s) of H_S values ranging from 0.1 to 0.3 m. In shallow-water environment (water depth < 1.5 m), these waves produced bottom shear stress values between 1 and 2 N m^{-2} . Wave-current shear stress values are one order of magnitude larger than the current-induced shear stress and indicate that navigation and wind are the dominant hydrodynamic forcing parameters above the two mudflats. Bed elevation and SPM concentration time series showed that these high energy events induced erosion processes of up to several centimetres. Critical erosion shear stress (τ_{ce}) values were determined from the SPM concentration and bed elevation measurements. Rough τ_{ce} values were found above 0.2 N m^{-2} for the Oissel mudflat and about 1 N m^{-2} for the Vasière Nord mudflat.

These results demonstrate the advantages of combining the measurement of instantaneous velocity and bed elevation to determine in situ the erosion and deposition processes as a function of bottom shear stress variations.

Keywords: Wind waves; Boat waves; Bottom shear stress; Bed roughness length; Bed erosion; Intertidal mudflat; Seine Estuary

45

46 **Nomenclature**

47

48 A (m) : Semi-orbital excursion

49 C_{TKE} : Best fit coefficient for K - τ_{TKE} conversion

50 C_{SPM} ($mg\ l^{-1}$): Suspended particulate matter concentration

51 f (Hz) : Frequency

52 f_{NL} : Correction coefficient for non linear interaction between wave and current

53 f_W : Wave friction factor

54 H_S (m): Significant wave height

55 H_{RMS} (m): Root-mean-square wave height

56 h (m): Water height

57 k : Wave number

58 K ($m^2\ s^{-2}$): Turbulent kinetic energy

59 kp (km): Kilometric point, distance from Paris ($kp\ 0$: Pont Marie)

60 SNR (dB): ADV signal to noise ratio

61 T_S (s): Significant wave period

62 u, v, w ($m\ s^{-1}$): Instantaneous current velocity components following the coordinates East, North ,Up

63 $\bar{U}, \bar{V}, \bar{W}$ ($m\ s^{-1}$): Average current velocity components

64 u', v', w' ($m\ s^{-1}$): Fluctuating current velocity components

65 u'_t, v'_t, w'_t ($m\ s^{-1}$): turbulent component of the instantaneous velocity

66 u_w', v_w', w_w' ($m\ s^{-1}$): Orbital velocity component of the instantaneous velocity

67 $U(z)$ ($m\ s^{-1}$): Mean horizontal current velocity

68 U_w ($m\ s^{-1}$): Maximum orbital velocity

69 u^* ($m\ s^{-1}$): Friction velocity

70 z (m): ADV recording height above the bed

71 z_0 (m): Bed roughness length

72	
73	Greek letters
74	
75	κ : Von Karman constant
76	λ : ADV acoustic wave length
77	ρ (kg m^{-3}): Water density
78	ρ_b (kg m^{-3}): Sediment bulk density
79	τ_{ce} (N m^{-2}): Critical erosion shear stress
80	τ_{TKE} (N m^{-2}): Turbulent kinetic energy shear stress
81	τ_w (N m^{-2}): Maximum wave shear stress
82	τ_m (N m^{-2}): Mean bed shear stress integrating non linear wave-current interactions
83	τ_{wC} (N m^{-2}): Maximum wave-current shear stress
84	τ_{w-SW} (N m^{-2}): Wave shear stress for short-period boat-induced waves
85	τ_{w-LW} (N m^{-2}): Wave shear stress for long-period boat-induced waves
86	$\tau_{w-SW+LW}$ (N m^{-2}): Wave shear stress for boat-induced long waves and short waves
87	τ_C (N m^{-2}): Current shear stress
88	ν ($\text{m}^2 \text{s}^{-1}$): Kinematic viscosity of water
89	

90 **1. Introduction**

91

92 Estuarine intertidal mudflats, which store fine-grained sediment, represent key areas for the
93 investigation of sediment transport dynamics and estuarine water quality management. When
94 suspended particulate matter (SPM) settles, contaminants associated with it are deposited on estuarine
95 intertidal mudflats, which thus become the main areas of contaminants accumulation. Previous studies
96 have demonstrated that intertidal mudflats are subjected to successive periods of erosion and
97 sedimentation which are controlled by sediment supply and hydrodynamic forcing parameters such as
98 tides, fluvial discharge and wind (Dyer, 1994; Allen and Duffy, 1998; Uncles et al., 1998; O'Brien et
99 al., 2000). Therefore, the storage of fine sediment by intertidal mudflats may be temporary, as the
100 mudflats are subjected to erosion events of variable intensity and duration, from one millimetre per
101 day to several centimetres in a few minutes (Deloffre et al., 2005). When a major erosion event occurs,
102 the large amount of reworked sediments and the particle-associated contaminants released into the
103 water column increase the risk of localized pollution (Cundy et al., 2005), especially during periods
104 when fluvial discharge is low and there therefore is little dilution.

105

106 Erosion and resuspension processes occur when the bottom shear stress exceeds a critical threshold
107 value (Mitchener and Torfs, 1996; Black and Paterson, 1997). Extending our knowledge of the erosion
108 processes requires both accurate measurements of the hydrodynamic features near the bottom and a
109 good estimation of the properties of the surface sediment. Recent improvements in acoustic devices
110 allow accurate high frequency and 3D current velocity measurements and thus provide reliable and
111 consistent shear stress measurements (Kawanisi and Yokosi, 1997; Voulgaris and Trowbridge, 1998;
112 Talke and Stacey, 2003; Voulgaris and Meyers, 2004). A recent study carried out in the macrotidal
113 Seine estuary focused on the tidal-induced bottom shear stress variability (Verney et al., 2006): the
114 results demonstrated that tidal-induced shear stress measured at different location in the macrotidal
115 Seine estuary exceeded the calculated erosion threshold only during short high energy events (HEEs).
116 In estuarine areas, HEEs may be caused by waves generated by boat traffic and wind, which increase
117 the bottom shear stress (Grant and Madsen, 1979; Soulsby et al., 1993; Parchure et al., 2001).

118

119 The objective of this study is to focus on the HEEs observed on several intertidal mudflats in a
120 macrotidal estuary to identify and quantify the hydrodynamic factors causing the events, and to
121 investigate the impacts of HEEs on the mudflat dynamics. This study introduces a new approach for
122 determining the relationship between hydrodynamic parameters and mudflat erosion processes: the
123 coupling of accurate near-bed hydrodynamic measurements with bed elevation measurements.

124

125 **2. Field site**

126

127 Before reaching the turbidity maximum zone, the SPM entering into the macrotidal Seine estuary is
128 temporarily trapped in several fine-sediment storage areas sheltered from the strongest tidal-induced
129 hydrodynamics conditions (Fig. 1) (Guezennec et al., 1999; Lesourd et al., 2003; Deloffre et al.,
130 2005). Hydrodynamic conditions in the Seine Estuary are controlled by the semi-diurnal tidal cycle
131 and are modulated seasonally by fluvial discharge (Guezennec et al., 1999). During the highest spring
132 tides, the tidal range at the mouth of the estuary (kp 360) is up to 7 m and decreases upstream to 2 m at
133 the upper limit of the estuary (kp 202). During periods of low fluvial discharge, the estuary is divided
134 into two hydrodynamic compartments: a flood-dominated compartment downstream from kp 300 (Le
135 Trait) and an ebb-dominated compartment upstream from kp 300 (Verney et al., 2006). The influence
136 of wind on hydrodynamic features, i.e. wind waves and swell, is observed only at the estuary mouth
137 when the wind is from the west-south-west (Le Hir et al., 2000; Silva Jacinto, 2002).

138 Over the last century, the regional authorities have put an emphasis on facilitating economic
139 exchanges and in particular on encouraging sea-vessel traffic in the Seine estuary from its mouth to the
140 Port of Rouen (kp 245) (Lafite and Romana, 2001; Lesourd et al., 2001). This has resulted in the
141 construction of embankments and in heavy dredging activities to keep the main navigation channel
142 operational for sea vessels downstream from Rouen. Boat traffic within the Seine estuary is divided in
143 two sectors: upstream from Rouen the traffic consists exclusively of barges, which transport 3.5Mt
144 annually, whereas downstream from Rouen both barges and sea-going vessels travel the estuary, with

145 more than 3,400 sea-vessels sailing seaward (Data from the Port Authorities of Rouen). Such a high
146 amount of boat traffic has the potential to contribute to local changes in hydrodynamic conditions.

147

148 For this study, two sites, representing the fluvial and marine parts of the estuary, were investigated: the
149 Oissel mudflat (kp 230) and the Vasière Nord mudflat (kp 355) (Fig 1). The sites were chosen on the
150 basis of recent work on the Seine estuary (Guezennec et al., 1999; Lesourd et al., 2003; Deloffre et al.,
151 2005; Deloffre et al., In press; Verney et al., 2006). The Oissel mudflat is one of the largest intertidal
152 storage areas of fine sediment in the fluvial part of the estuary, with a surface area of 9500 m². A two-
153 year high frequency survey of the bed elevation indicates that muddy sediments settle during high
154 river flow, with deposition rates up to 7.5 mm d⁻¹, and net deposits of 5 to 8.5 cm per episode
155 depending on the flux of suspended solids discharging at Poses (the upstream limit of the estuary). The
156 bed sediments are a mixture of sand and mud, and are characterised by modes of 20 and 200 µm
157 (Deloffre et al., 2005). During periods of low discharge, the previously-deposited material is eroded
158 continuously at the rate of 0.75 mm d⁻¹ and transported downstream. However, significant erosion
159 events of several centimetres are occasionally observed. Hydrodynamic surveys during periods of low
160 discharge have demonstrated that low tidal-induced bottom shear stress is lower than 0.2 N m⁻² and
161 thus not sufficient to explain the large erosion events, yet several HEEs that generated bottom shear
162 stress larger than 1 N m⁻² were observed (Verney et al., 2006).

163

164 The Vasière Nord mudflat, the largest mudflat in the estuary (3.2 km², (Lesourd et al., 2003)), and is
165 located in the northern part of the estuary mouth. Here, unlike the Oissel mudflat, the annual high
166 frequency survey shows that deposition occurs in bursts during periods of low fluvial discharge, and is
167 closely related to the highest spring tides and the presence of the turbidity maximum zone in the
168 estuary mouth (Deloffre et al., In press). These deposits are dominated by fine sediments (<50 µm),
169 which represent 70 to 90 % of the material (Lesourd, 2000). As in the upstream fluvial mudflat, HHEs
170 of several centimetres are observed, mostly after deposition. ADV current velocity measurements in
171 spring and neap tide conditions have revealed low tidal-induced bottom shear stress values, except
172 during the rising flood period of the highest spring tides (Verney et al., 2006). The sampling station

173 above the Vasière Nord mudflat is located at mid-cross-section and 6.6 m above the reference sea
174 level.

175

176 **3. Materials and methods**

177

178 In order to accurately identify HEEs, sedimentary and hydrodynamic parameters were monitored with
179 high frequency devices over tidal cycles. In addition, fortnightly cycle surveys were carried out to
180 investigate the mudflat response to HEEs. All surveys were carried out during periods of low fluvial
181 discharge.

182

183 **3.1. Bed-elevation measurements: the ALTUS altimeter**

184

185 The ALTUS altimeter is an autonomous 2 MHz acoustic transducer coupled with a pressure sensor
186 (Bassoullet et al., 2000). This device allows long term monitoring (Deloffre et al., 2005; Deloffre et
187 al., In press), but is also suitable for high-frequency surveys (sampling frequency up to 1 Hz) with a
188 data storage capacity of several weeks. The ALTUS provides bed elevation and water level
189 measurements with resolution of 0.2 mm and 20 mm respectively. For this study, the transducer was
190 positioned 20 cm above the bed, with a sampling frequency of one measurement every three minutes.

191

192 **3.2. Hydrodynamic characteristics: ADV measurements**

193

194 Stations were instrumented with a 6 MHz Nortek Vector Acoustic Doppler Velocimeter during
195 periods of low fluvial discharge ($<400 \text{ m}^3 \text{ s}^{-1}$). The apparatus was fixed on a rigid aluminium frame,
196 which was directed perpendicular to the main channel axis to minimize frame-induced noise. This set-
197 up has been found to be particularly suitable for turbulent intensity determinations (Kawanisi and
198 Yokosi, 1997; Talke and Stacey, 2003; Voulgaris and Meyers, 2004). ADV measurements give access
199 to the three directional components of the current velocity, 7 cm above the bed, and to the water level
200 variations, with a pressure sensor located 45 cm above the bed. Velocity measurements were recorded

201 in the East/North/Up coordinates, automatically compensating for any movement of the instrument
202 using data provided by the ADV internal compass. This minimizes errors due to ADV misalignment
203 with the vertical. For each tidal survey, the ADV ran continuously at the sampling frequency of 32 Hz.
204 For semi-lunar surveys, the ADV collected measurements at 2 Hz for 180 s bursts, every 13 min.
205 Mean current velocity and bottom shear stress were obtained by averaging instantaneous and
206 fluctuating components of the flow over the burst duration.

207

208 **3.2.1. Calculation of the bottom shear stress**

209

210 Various methods are presented in the literature for the calculation of bottom shear stress values from
211 measured instantaneous current velocities : the Logarithmic velocity Profile (LP) method (Fugate and
212 Friedrichs, 2002; Simpson et al., 2005), the Turbulent Kinetic Energy (TKE) method (Soulsby, 1983;
213 Williams et al., 1999; Talke and Stacey, 2003), the covariance (COV) method (Kim et al., 2000;
214 Voulgaris and Meyers, 2004) and the Inertial Dissipation (ID) method (Huntley, 1988; Kim et al.,
215 2000; Trembanis et al., 2004). The operational limitations for applying these methods in estuarine
216 environments have been discussed by various authors (Soulsby et al., 1993; Kim et al., 2000;
217 Hutnance et al., 2002). HEEs observed in the Seine estuary (Verney et al., 2006) are assumed to be
218 induced by wave events. Therefore, neither the LP nor the COV methods can be used, as the LP
219 method is based on time-averaged flow velocity and the COV method cannot separate tidal- and wave-
220 induced fluctuations.

221

222 The method best suited to the investigation of wave-current shear interactions is the TKE method, as a
223 spectral analysis of the instantaneous velocity provides both turbulent and wave characteristics
224 (Soulsby and Humphery, 1990). This method is based on the separation of the wave-induced ($u'_w, v'_w,$
225 w'_w) and turbulence-induced (u'_t, v'_t, w'_t) variances of each fluctuating velocity components u', v' and
226 w' . During wave events, the energy spectrum consists of the superposition of the conventional
227 turbulent spectrum featured by the Kolmogorov $-5/3$ roll off in the inertial subrange and a typical wave
228 spectrum, identified as a peak of energy in the wave frequency range (typically between 1 and 0.1Hz

229 for wind waves). According to Soulsby and Humphery (1990), the energy spectrum is split in two
 230 parts at the base of the wave peak. This method is performed automatically on the full u, v and w
 231 dataset where, according to the Kolmogorov theory, the separation line corresponds to an interpolation
 232 of the -5/3 slope (in log space), with a reference point at $f=0.1\text{Hz}$ (outside the wave frequency range).
 233 The area below the interpolation line therefore corresponds to the turbulent kinetic energy of the
 234 velocity component considered (respectively u'^2 , v'^2 or w'^2), and the area above the line to the wave
 235 variance contained in the fluctuating part of the velocity component.

236

237 The TKE shear stress (τ_{TKE}) is determined from the turbulent kinetic energy K:

$$238 \quad \tau_{\text{TKE}} = \rho C_{\text{TKE}} K = 0.5 \rho C_{\text{TKE}} \left(\overline{u_t'^2} + \overline{v_t'^2} + \overline{w_t'^2} \right) \quad (4)$$

239 Various C_{TKE} values are proposed in the literature for different estuaries, ranging from 0.18 to 0.21
 240 (Soulsby, 1983; Kim et al., 2000; Talke and Stacey, 2003). For the Seine estuary, Verney et al. (2006)
 241 found $C_{\text{TKE}}=0.19$ to be the best-fit constant for the tidal-induced shear stress on intertidal mudflats.
 242 τ_{TKE} is the best estimation of the bottom shear stress attributable to current in the presence of waves
 243 (Williams et al., 1999).

244

245 **3.2.2. Wave shear stress**

246

247 The significant wave height (H_S), root-mean-square wave height (H_{RMS}) and significant wave period
 248 (T_S) are calculated from the water level (h) time series over a 1 min burst. Significant wave orbital
 249 velocity U_w is calculated from the wave variances (u_w' and v_w') deduced from the turbulent spectrum
 250 analysis, such as (Myrhaug et al., 1998):

$$251 \quad U_w = 2 * \sqrt{\overline{u_w'^2} + \overline{v_w'^2}} \quad (5)$$

252 The wave shear stress τ_w is given by:

$$253 \quad \tau_w = 1/2 * \rho * f_w * U_w^2 \quad (6)$$

254 where f_w is the wave friction factor, which depends on the turbulent characteristics of the flow. In this
 255 study flow is turbulent, and the friction factor is obtained from the relation (Soulsby, 1997):

256 $f_w = 1.39 * (A/z_0)^{-0.52}$ (7)

257 where A is the semi-orbital excursion : $A = U_w T_s / 2\pi$ and z_0 is the bed roughness length.

258

259 **3.2.3. Wave-current shear stress**

260

261 Waves and current both contribute to the bottom shear stress; various models have been developed to
 262 determine the combined wave-current shear stress (Grant and Madsen, 1979; Fredsoe, 1984). The
 263 method used in this study refers to the parametric Wave-Current Interaction (WCI) model proposed by
 264 Soulsby (1995). The equations used are based on theories previously developed and fitted to field and
 265 tank experiments. Soulsby introduced a correction coefficient f_{NL} that takes into account the non-linear
 266 interaction between the waves and the current in the mean bed shear stress:

267 $f_{NL} = 1.2 * (\tau_w / (\tau_w + \tau_C))^{3.2}$ (8)

268 The mean bed shear stress τ_m is:

269 $\tau_m = \tau_C (1 + f_{NL})$ (9)

270 In the present study, wave-current interaction is incorporated into the τ_{TKE} calculations, and therefore
 271 τ_m is equal to τ_{TKE} . Given that Ψ is the angle between the waves and the current, the total wave-current
 272 bed shear stress becomes:

273 $\tau_{WC} = \sqrt{(\tau_{TKE} + \tau_w * \cos(\Psi))^2 + (\tau_w * \sin(\Psi))^2}$ (10)

274

275 **3.3. Bed roughness calculation**

276

277 Bed roughness length is a key parameter that must be determined when calculating wave shear stress.
 278 At the tidal scale, however, bed roughness length varies rapidly, as it is a function of sediment grain-
 279 size distribution, bedforms present, and suspended sediment concentration (Collins et al., 1998;
 280 Trembanis et al., 2004; Voulgaris and Meyers, 2004). Moreover, in the presence of waves, the bed
 281 roughness length is greatly affected by the increase in eddy viscosity within the wave boundary layer
 282 (Grant and Madsen, 1979; Soulsby and Humphery, 1990) and no longer corresponds to the physical

283 bed roughness used in the WCI method to calculate wave-current shear stress. Therefore, the bed
 284 roughness length is calculated outside wave events from the drag coefficient $C_d(z)$ for each site at the
 285 tidal scale, and assuming the development of a logarithmic velocity profile (Soulsby and Humphery,
 286 1990):

$$287 \quad u^{*2} = C_d(z) * U(z)^2 \quad (11)$$

$$288 \quad \frac{U(z)}{u^*} = \frac{1}{\kappa} \log\left(\frac{z}{z_0}\right) \quad (12)$$

289 where u^* is the friction velocity calculated from τ_{TKE} such that:

$$290 \quad u^* = \sqrt{\frac{\tau_c}{\rho}} \quad (13)$$

291 and

$$292 \quad z_0 = z^* \exp\left(-\frac{\kappa}{\sqrt{C_d(z)}}\right) \quad (14)$$

293

294 **3.4. SPM concentration: estimation from the ADV backscatter**

295

296 In addition to current measurements, acoustic Doppler devices (ADCPs or ADVs) provide
 297 backscattered acoustic amplitudes and signal to noise ratios (SNR) for measurement validation.
 298 Calibrating the backscattered acoustic intensity with SPM concentrations is complex, but provides key
 299 information on sediment transport features, i.e. hydrodynamic and suspended sediment characteristics
 300 at high frequency (Kawanisi and Yokosi, 1997; Voulgaris and Meyers, 2004). The main difficulty is
 301 that the backscattered acoustic intensity depends on the SPM concentration, grain-size distribution and
 302 composition in the volume sampled. The optimal dynamical response of the ADV backscattered
 303 acoustic intensity is given for particle sizes D_{opt} where $D_{opt} * \lambda / 2 = 1$ and λ is the ADV unity for coarser
 304 particles, assuming that the entire emitted signal is returned to the transducers. For a 6 MHz ADV
 305 such as the one used for this study, the operational size range is estimated to be between 10 μm and
 306 200 μm , with the optimal size calculated to be 80 μm , similar to the mode value of the grain-size

307 distribution of the muddy material present in the estuary (Lesourd, 2000). This validates the use of the
308 ADV backscatter as an appropriate proxy for estimating SPM concentration.

309

310 In parallel to physical acoustic theories (Thorne and Hanes, 2002), Voulgaris and Meyers (2004)
311 proposed empirical calibrations to convert backscatter signal to SPM concentration. For this study,
312 calibration experiments were carried out in the laboratory using surface sediments collected at the two
313 sampling stations (Fig. 2). The calibration experiment is based on a classical calibration set-up, i.e.,
314 the ADV is immersed in a tank that is homogeneously filled step by step with surface sediments to
315 increase the SPM concentration (C_{SPM}). The ADV acoustic backscattered intensity is recorded for 30 s
316 and a water sample is collected to determine the weighted C_{SPM} . The burst-averaged SNR values are
317 used to quantify the backscattered acoustic intensity, and then compared with the measured C_{SPM} in the
318 tank for all sediments (Fig. 2). Log(SNR) is linearly correlated with $\log(C_{SPM})$ for both sites :

319

$$320 \quad \log(C_{SPM}) = -26.48 + 15.03 * \log(SNR) \text{ (Fig. 2 – Vasière Nord [1]) } (R^2 = 0.84) \quad (15)$$

$$321 \quad \log(C_{SPM}) = -28.02 + 15.91 * \log(SNR) \text{ (Fig. 2 – Oissel [2]) } (R^2 = 0.98) \quad (16)$$

322

323 For these two calibration sets, the operational concentration ranges from 10 to 5000 mg l^{-1} . At lower
324 concentrations, the backscattered intensity is highly variable and the calibration curve does not show a
325 consistent pattern. For C_{SPM} higher than 5000 mg l^{-1} , the ADV response no longer changes with
326 increasing C_{SPM} . However, in practice this upper limit is never reached as C_{SPM} rarely exceeds 3000
327 mg l^{-1} in the Seine estuary (Lesourd, 2000; Deloffre et al., 2005).

328

329 This empirical method for ADV-SPM calibration was used by Voulgaris and Meyers (2004) (Fig. 2).
330 However, it should be noted that these authors used a 10 MHz Sontek ADV that is more sensitive to
331 finer particles and lower C_{SPM} . This explains the difference between their calibration equation and that
332 presented here.

333

334 4. Results

335

336 4.1. High Energy Events and forcing parameters

337

338 4.1.1. The estuary mouth: the wind influence

339

340 A typical W-SW wind event occurred on May 5, 2004, with an average wind speed of 8 m s^{-1} and
341 gusts of 10 m s^{-1} (Fig. 3). W-SW wind events of similar intensities are known to increase wave action
342 in the estuary mouth (Silva Jacinto, 2002). The sampling station is located in the middle of the largest
343 mudflat in the estuary, at the height of 6.6 m above reference sea level, thus water heights above the
344 station rarely exceed 1 m during neap tide conditions. The water level fluctuations measured by the
345 ADV and filtered from the tidal amplitude are shown in Fig. 3a. Waves are observed continuously
346 during the tidal cycle, with significant wave periods varying from 3 to 8 s and significant wave heights
347 ranging from 0.1 to 0.35 m (Fig. 3b). Waves were present continuously during this survey, so the bed
348 roughness length was not calculated. Instead, the bed roughness calculated for the same site during the
349 fortnightly cycle was used ($z_0=0.37 \text{ mm}$) as well as the bed roughness lengths given by Soulsby (1997)
350 for mud and muddy/sandy sediment (i.e., 0.2 and 0.7 mm respectively) to investigate the variability of
351 the results.

352

353 The wave-current shear stress fluctuations are shown in Fig 3c and compared to the TKE shear stress.
354 During the survey, τ_{WC} values were twice to one order of magnitude higher than τ_{TKE} , with
355 characteristic values ranging from 0.6 to 4 N m^{-2} and 0.1 to 1 N m^{-2} , respectively, for τ_{WC} and τ_{TKE} .
356 This confirms that wind-waves are the dominant forcing parameter at the estuary mouth. The largest
357 waves ($>0.2 \text{ m}$) are associated with τ_{WC} values above 1 N m^{-2} . Comparing τ_{WC} values obtained for the
358 different bed roughness values (Fig. 3c – shadow area) demonstrates high sensitivity of the z_0
359 calculation: estimating τ_{WC} with $z_0=0.2 \text{ mm}$ or 0.7 mm results in discrepancies of up to 100%
360 compared with τ_{WC} calculated with $z_0=0.37\text{mm}$.

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4.1.2. The fluvial estuary: the influence of boat traffic

Representative water level recordings from the Oissel mudflat are shown in Fig. 4a. Examination of the water elevation time-series reveals the passage of at least five boats. These passages are identified by the boat-generated wave packets with amplitudes up to 0.16 m.

A ship passage is examined in detail in Fig. 4b and Fig. 4c; the figures show typical vessel-generated water-level and current-velocity variations. These boat-induced variations affect the local hydrodynamics and are characterised by one long wave followed by short wave packets as reported in previous studies (Schoellhamer, 1996; Fagerburg and Pratt, 1998; Parchure et al., 2001).

Long waves are caused by the drawdown effect, which is defined as an abrupt diminution of the water level caused by the displacement of the boat. The occurrence and amplitude of the drawdowns are controlled by the width of the channel, the local water depth and some boat-related features, such as the shape of the hull and the boat speed, e.g., the narrower the width, the larger the drawdown (Schoellhamer, 1996; Fagerburg and Pratt, 1998). Here, the drawdown shows a wave period of 50 s and an amplitude of 0.06 m. The wave is reflected several times by the river banks and its amplitude decays with time. The drawdown substantially affects the local current velocities, causing horizontal velocity variations of 0.2 m s^{-1} (Fig. 4 c). This type of long wave is observed before the arrival of short wave packets. In Fig. 4b, the boat-generated short waves have a period of 3 s, the first and largest wave height is 0.1 m and following wave heights decrease with time. Wave packets are observed several times as a result of reflections on embankments. The boat passage affects the mudflat for 2- to 5-min periods, and induces high flow velocity fluctuations: the largest fluctuation amplitude is 0.3 m s^{-1} and then decreases with time (Fig. 4 c).

Waves generated by barges or vessels contribute to the bottom shear stress. This contribution can be estimated using the WCI model detailed in section 3.2.3. The bed roughness length for the Oissel

389 mudflat was estimated by Verney et al. (2006) to be 0.3 mm, from the calculation of the drag
390 coefficient obtained by comparing mean current velocity U and friction velocity u^* in the absence of
391 waves. Wave height measurements revealed that the boat-generated waves are mono- or sometimes bi-
392 modal. As described in the previous section, the WCI model is applied for waves characterised by a
393 single period and a single height. Short and long waves were examined separately to estimate the shear
394 stress contribution of each type of wave and to determine the total boat-induced bottom shear stress.
395 Long and short waves were filtered by band-pass filters from the spectral analysis of the raw-water
396 level signal, with long and short wave frequencies assumed to range from 0.002 Hz to 0.1 Hz, and 0.1
397 Hz to 1 Hz, respectively. Fig. 5 focuses on a typical time series corresponding to Fig. 4b and details
398 the procedure applied to calculate τ_{WC} . Once extracted from the raw signal (Fig. 5 a, b and c), the long
399 and short wave signals are processed to calculate their respective wave periods and significant wave
400 heights. Long wave properties are calculated over a 1 min period. However, this calculation period is
401 too long to represent accurately the rapidly fluctuating short waves, and so the significant wave
402 heights, periods and orbital velocities for short waves were calculated over an 8 s burst period. Short
403 wave heights decay rapidly from 0.1 to 0.02 m in a few minutes. Significant long-wave heights up to
404 0.06 m are observed and the perturbations induced last for approximately 5 min with slight wave
405 height decay. Similar to short waves, long waves affect the turbulent spectrum in the low frequency
406 range (i.e. $f < 0.1$ Hz). In the absence of long waves, the energy spectrum shows a quasi-stationary
407 behaviour in this frequency range, while in the presence of long waves it greatly increases. A second
408 cut off therefore is applied to the low frequency regime ($f < 0.1$ Hz) to calculate the wave variance
409 associated with long waves, fixed to a constant variance calculated for $f = 0.1$ Hz. Wave shear stresses
410 for long (τ_{W-LW}) and short (τ_{W-SW}) waves are calculated from the WCI model equations (Eq. 5 to 10)
411 (Fig. 5 d). In this case, τ_{W-LW} presents a maximum value of 0.1 N m^{-2} as a result of the drawdown
412 effect, and τ_{W-SW} increases when short waves arrive, with a maximum value of 1 N m^{-2} . Low amplitude
413 short waves are observed during the drawdown period, generating a wave shear stress of 0.08 N m^{-2} ,
414 lower than the τ_{W-LW} value. τ_{W-SW} and τ_{W-LW} then are summed to obtain the overall wave shear stress
415 $\tau_{W-LW+SW}$, which is used to calculate the overall wave-current shear stress (τ_{WC}), from equations 8 to 10

416 (Fig. 5e). τ_{TKE} is one order of magnitude lower than τ_{WC} and non-linear wave effects on τ_{TKE} are
417 observed. This procedure is extended to the entire dataset (Fig. 6). During the tidal cycle, τ_{TKE} is well
418 correlated with the current velocity (Fig. 6: from 03h00 to 06h00).

419

420 All boat passages generate bottom shear stress with τ_{WC} values above 0.1 N m^{-2} and up to 2 N m^{-2} . The
421 boat traffic in the Seine estuary is dense, and occasionally boats must either follow each other closely
422 or pass each other with very little clearance in the narrow channel. This results in longer duration
423 HEEs, characterised by a succession of multiple wave packets, which can combine with each other and
424 generate larger waves and thus greater bottom shear stress (Fig. 6 – from 00h40 to 01h20). In this
425 case, the turbulent flow relaxes slightly and does not reach a steady state until more than 20 min after
426 the last barge passage.

427

428 **4.2. Impact of the HEEs on the dynamics of the intertidal mudflats of the Seine estuary**

429

430 The factors controlling the variability of the bottom shear stress intensity are identified by tidal
431 surveys as the tidal currents (Verney et al., 2006), the W-SW wind events (at the mouth of the Seine
432 estuary), and the passage of boats and barges (in the fluvial part of the estuary). Based on these
433 studies, surveys were carried out in the fluvial part of the estuary and at the mouth of the estuary to
434 monitor hydrodynamic and sedimentary processes during a semi-lunar cycle. The objective of this
435 work is to investigate the impact of HEEs on the mudflat dynamics, and in particular the erosion and
436 resuspension processes affecting the surface sediment.

437

438 **4.2.1. Wind impact on mudflat behaviour**

439

440 The Vasière Nord survey was carried out in spring tide conditions, which are reported as being
441 favourable for sediment accretion above the mudflat (Deloffre et al., In press). The variations of the

442 bed elevation of the Vasière Nord mudflat are compared to the time series of τ_{WC} , SPM concentration,
443 water surface elevation, and wind and wave conditions (Fig. 7).

444

445 Throughout the survey, the water level above the mudflat never exceeded 1.5 m (Fig. 7 a). Wind speed
446 above 10 m s^{-1} are observed unevenly; they generate wind waves with an average wave height of 0.15
447 m and wave periods ranging from 2 to 10 s. Waves are always observed above the mudflat and the
448 lowest wave heights are less than 0.1 m and correlated with wind speeds below 5 m s^{-1} (Fig. 7 b).
449 Periods of large amplitude waves, above 0.2 m, are observed in bursts.

450

451 The weakest wave event occurred during VN1, and this period there was chosen to calculate a z_0 value
452 (wave heights $>0.1\text{m}$ excluded), and estimated to be 0.37 mm. The combination of low water heights
453 and large wave amplitudes induces strong bottom shear stresses. Periods of wind-wave heights above
454 0.15 m are reported as HEEs and correspond to bottom shear stress values higher than 0.5 N m^{-2} for
455 periods lasting from the hour to the tidal scale (Fig. 7 c and d). The largest HEE (VN2) is correlated
456 with a SW wind event of 13 m s^{-1} , generating wave heights up to 0.3 m and τ_{WC} of 2 N m^{-2} . Calm
457 periods are associated with bottom shear stress values below 0.5 N m^{-2} .

458

459 The Vasière Nord mudflat underwent several periods of sedimentation and resuspension/erosion (Fig.
460 7f). A typical sedimentation/resuspension pattern is observed, characterized by a new deposit during
461 the flood period: VN1: +10 mm, VN3: +3 mm; VN4: +5 mm. Deposition events are correlated with
462 the weakest hydrodynamic conditions, i.e. $\tau_{WC} < 0.8 \text{ N m}^{-2}$ and wave heights below 0.15 m.
463 Resuspension and erosion periods are observed during HEEs characterised by τ_{WC} values greater than
464 1 N m^{-2} , induced by wind-wave heights above 0.15 m. These HEEs partly or entirely remove the
465 previously deposited sediment (Fig. 7f): VN1: -2 mm; VN2: -7 mm; VN3: -5 mm; VN4: -2.5 mm,
466 VN5: -7 mm, VN6: -2 mm. This material is re-enters the water column, as demonstrated by the
467 monitoring of C_{SPM} : every resuspension or erosion event is correlated with high C_{SPM} values above 100
468 mg l^{-1} , and occasionally as high as to 1500 mg l^{-1} (Fig. 7e)

469

470 At the scale of the survey, the total amount of deposited sediments is removed, and the net budget of
471 the erosion/sedimentation periods shows is an erosion of the bed of 5 mm. This erosion was confirmed
472 by field observation at the end of the survey: the surface of the mudflat was rippled, made up of hard
473 sandy-mud, and hard-mud pebbles were scattered over the mudflat as a consequence of strong
474 hydrodynamic conditions and erosion at the edge of the mudflat.

475

476 **4.2.2. Boat impact on mudflat behaviour**

477

478 The results of the bed roughness length calculation during the survey are shown in Fig. 8. They reveal
479 a variability of 30% around a mean value of 0.1 mm, and maximum value of 0.3 mm. These calculated
480 z_0 values are used for τ_{WC} calculations. The behaviour of the Oissel mudflat during a semi-lunar cycle
481 is examined in Fig. 9 in response to the variations in the bottom shear stress and the local C_{SPM} . The
482 average tidal-induced shear stress (boat passages excluded) is low (less than 0.1 N m^{-2}), which is
483 explained by the weak tidal currents in the upper reach of the estuary (Verney et al., 2006). C_{SPM} is
484 low, ranging from 10 to 50 mg l^{-1} (Guezennec et al., 1999; Deloffre et al., 2005). These low
485 hydrodynamic conditions are favourable for sedimentation: the altimetric survey shows a constant
486 sedimentation rate of 0.2 mm per tide.

487

488 Short HEEs ($\tau_{WC} > 0.5 \text{ N m}^{-2}$) are recorded only irregularly (OI1, OI3, OI5, OI7, OI10); and they are
489 associated with an increase in C_{SPM} above 200 mg l^{-1} (Fig. 9a, b and c). Among all the HEEs reported,
490 only one is correlated with a large and abrupt bed erosion (f 6 mm for OI10 - Fig 9d). This erosion
491 event is clearly correlated with a boat passage, as indicated by bottom shear stress values higher than
492 0.5 N m^{-2} . This event affected only a longshore line of the mudflat, where erosion is visible and
493 indicated by a change in the bed surface: near the bank, the bed is flat and soft, and near the river, the
494 bed is rough and scattered with muddy pebbles, typical of erosional events. All other HEEs observed
495 during the survey were associated with a C_{SPM} increase, but no net erosion was recorded by the

496 altimeter during this survey: because of the local effect of boat-induced waves, this could correspond
497 to erosion of another part of the mudflat, where bed shear stress exceeds the critical shear stress.

498

499 **5. Discussion**

500

501 **5.1. Processes of erosion: boat-induced waves**

502

503 Field measurements showed that barge passages in a narrow channel change the local hydrodynamics
504 by generating a drawdown and packets of waves, and sometimes causing sediment resuspension (Fig.
505 4; Fig. 5; Fig. 9; Table 1). The drawdown is a low frequency variation of the water level, and its
506 amplitude was reported to vary from 0.05 to 0.1 m. Short waves are grouped in wave packets of wave
507 height ranging from 0.05 to 0.15 m. Boat passages cause short duration HEEs, which never exceeded
508 10 min. These observations are in agreement with the results of the field surveys and laboratory
509 experiments reported by Parchure et al. (2001). These authors classified waves and drawdown
510 intensities by boat type. They concluded that large vessels generated large drawdowns but low short-
511 wave heights, contrary to leisure boats, which travel faster and thus generate small drawdowns but
512 large short-wave heights. They also reported that barges induced more resuspension, with C_{SPM}
513 varying from 100 to 500 mg l⁻¹ close to the bed. These concentrations are similar to those measured
514 from the ADV backscattered intensity on the Oissel mudflat after barge passages. This might reflect
515 the bed dislocation/liquefaction effect of the long waves, which would layer the first centimetres that
516 could then be removed by short waves (De Wit and Kranenburg, 1997).

517

518 The water height time series indicate the passage of many boats. The most substantial events are
519 reported in Table I, along with their principal hydrodynamic features. Relations between boat-induced
520 flow variations, sediment resuspension, and bed erosion are difficult to establish, because they are
521 related to various criteria such as water level, wave amplitude and frequency, bed form, and bed
522 structure (Parchure et al., 2001). However, comparison of the local hydrodynamic variations and the
523 response of the bed sediments shows that resuspension processes mainly occur during both high and

524 low frequency velocity fluctuations (Table I, Boats 1, 5, 7 and 10). Low frequency current fluctuations
525 occasionally generated low intensity resuspension (Table I, Boats 2, 4, 6, 8 and 9). Moreover, the
526 erosion event observed by the ALTUS occurred when the average water height was the lowest, at
527 approximately 0.3 m, which suggests that water level is a critical parameter for erosion in the upper
528 part of the estuary. Despite the low probability of such HEEs (as they require both boat passage and
529 low water level), their amplitudes demonstrate that boat traffic plays an important role at the annual
530 scale in mudflat dynamics and sediment fluxes in the upper estuary. This is confirmed by Deloffre et
531 al. (2005), who reported three or four periods of abrupt erosion per year during a two-year survey
532 above the Oissel Mudflat. These large erosion processes occurred after a period of deposition of
533 several centimetres, when bed sediment bulk densities and critical erosion shear stress are the lowest.

534

535 This emphasizes the need for further examination of very shallow water processes. The influence of
536 boat-induced waves as they break on the mudflat, when the turbulent intensity is at its highest, is of
537 special interest.

538

539 **5.2. Bed sediment erodibility and critical erosion shear stress**

540

541 The turbulent threshold effect on mudflat sediment erosion processes has been researched extensively
542 over the last 30 years. This threshold effect is especially relevant for mathematical modelling of
543 sediment transport, which uses the critical erosion shear stress as a major controlling parameter
544 (Sanford and Maa, 2001). Many instruments have been developed to estimate this threshold in field
545 studies or in laboratory flumes (Mitchener and Torfs, 1996; Black and Paterson, 1997; Tolhurst et al.,
546 2000). All these instruments are based on the same experimental protocol, i.e. the shear stress applied
547 is controlled and increased stepwise, and the erosion threshold is reached when the operator observes
548 that C_{SPM} shows a substantial increase or exceeds a fixed level of C_{SPM} or turbidity. Similar
549 measurements of the critical erosion shear stress can be carried out in situ by comparing time series of
550 bottom shear stress values to erosion criteria, i.e. C_{SPM} and bed height measured by ADV and ALTUS
551 devices.

552 Those two methods are applied for the Oissel mudflat measurements. A comparison of C_{SPM} values
553 and τ_{WC} values (Fig. 9 and 10) shows that substantial resuspension occurred when τ_{WC} was above 0.2
554 $N\ m^{-2}$, except for OI1 where no concentration increase was observed. Based on bed elevation
555 measurements, bed erosion occurred abruptly and only once during the study, and was associated with
556 high τ_{WC} values (between 0.3 and 0.8 $N\ m^{-2}$). The bed sediments of the Oissel mudflat are sandy-mud
557 with a thin layer of newly deposited sediments, as observed by the altimetric survey (Fig. 9). The
558 critical shear stress value calculated from the relation provided by Mitchener and Torfs (1996) for
559 sandy-mud sediments is 0.6 $N\ m^{-2}$, which is in the range of the τ_{ce} value estimated. However, the
560 altimeter did not measure any variation of the bed elevation during these events. This could be either
561 because the erosion affected only the thin upper layer of fluid mud deposited at the surface, the erosion
562 thickness being smaller than the ALTUS vertical resolution, or more probably because erosion
563 occurred elsewhere on the mudflat. Unlike devices dedicated to erosion threshold determination that
564 work with a confined controlled volume of water, the C_{SPM} method used in situ to determine τ_{ce} is
565 subjected to variations in both the intensity of the hydrodynamic processes and in the bed sediment
566 properties. Therefore, an increase in C_{SPM} observed by the ADV may be the result of bed erosion away
567 from the sampling site and thus not measurable by the ALTUS altimeter, the resuspended sediment
568 being then advected through the ADV sampling volume as modelled and discussed by Brun-Cottan et
569 al. (2000).

570

571 Estimating critical erosion shear stress is more complex at the estuary mouth: this site is influenced by
572 the turbidity maximum zone, and so the background C_{SPM} is naturally highly variable, and ranges from
573 10 to 1000 $mg\ l^{-1}$ (Lesourd et al., 2003; Deloffre et al., 2005). The C_{SPM} method therefore cannot be
574 applied to determine τ_{ce} , and only the altimetric measurements are used (Fig. 7). The results
575 demonstrate that deposition periods correspond to τ_{WC} values below a critical value of 0.8 $N\ m^{-2}$, and
576 the lower the τ_{WC} , the higher the deposition rate. Erosion processes take place for τ_{WC} values higher
577 than 1 $N\ m^{-2}$. The relation between erosion rate and bed sediment properties is clearly observed: all
578 erosion events that occur after a period of deposition have an erosion rate that ranges from 0.1 to 0.165

579 $\text{g m}^{-2} \text{ s}^{-1}$ (VN2 to VN5). During VN5 and VN6, the erosion rate decreased from 0.1 to $0.035 \text{ g m}^{-2} \text{ s}^{-1}$,
580 whereas the mean shear rate was similar during these two tides (1.5 N m^{-2}). During VN5, the bed
581 surface sediment had been newly deposited during the previous tides, and should be characterised by a
582 lower bulk density and a lower critical erosion shear stress. During this tide, all newly deposited
583 sediments were removed and the bed level reached was lower than at any time during the previous
584 four days. Therefore, bed sediments during VN6 had been subjected to consolidation processes for
585 several days and should feature higher bulk densities and higher critical erosion shear stress, which
586 would explain the lower erosion rate during VN6. The critical erosion shear stress value of 1 N m^{-2} is
587 in the upper range of the critical erosion shear stress measured by Mitchener and Torfs (1996) for
588 newly-deposited muddy bed sediments and which ranges from 0.1 to 1.5 N m^{-2} .

589

590 The differences between critical erosion shear stress values calculated in this study and the values
591 proposed in the literature may be the results of differences in the hydrodynamic processes observed.
592 Most of the knowledge of erosion and deposition processes of muddy sediments is based on studies
593 that taking into account only the current velocities (Tolhurst et al., 2000). In contrast, this study
594 examined the impact of wave-induced shear stress on mudflat dynamics. Currently, our understanding
595 of the interaction between wave-induced shear stress, muddy sediment erodibility, and bed sediment
596 properties is limited to field observations (Winterwerp and van Kesteren, 2004). Thus, further research
597 is required to provide a better understanding of current only, wave only and current-wave erosion
598 processes in relation to muddy bed sediment properties.

599

600 **6. Conclusions**

601

602 The combined use of high frequency and high resolution altimetric measurements and near bottom
603 sediment hydrodynamic measurements during both tidal and semi-lunar surveys identified and
604 quantified wind and boat passage events and their impact on mudflats. The tidal surveys allowed
605 continuous recording of the current velocity and water height fluctuations. These measurements
606 allowed quantification of the boat- and wind- induced wave contributions to the bottom shear stress.

607 Bed elevation, bottom shear stress, and suspended particulate matter concentration measurements
608 close to the bottom were used to determine critical erosion and deposition shear stresses.

609

610 The fluvial part of the Seine estuary is affected by boat traffic. Boat-induced waves show a bimodal
611 pattern, with long and short waves, and generate bottom shear stresses stronger than 0.5 N m^{-2} for a
612 few minutes with peaks up to 1 N m^{-2} . In most cases, boat passages generate sediment resuspension
613 when bottom shear stress values exceeded 0.2 N m^{-2} . Large erosion processes (erosion of more than a
614 5 mm thickness) are observed under specific conditions such as low water height ($h < 30 \text{ cm}$) and high
615 amplitude waves. Low amplitude erosion processes are observed at very shallow water depths at the
616 beginning of the flood tide and at the end of the ebb tide, which could be caused by tidal currents or
617 boat passages. These observations highlight the need for further research on the effect of both very
618 shallow water processes and emersion/immersion processes on sediment dynamics.

619

620 At the mouth of the Seine estuary (Vasière Nord Mudflat), W-SW wind events generate waves with a
621 significant wave height of 0.1 to 0.3 m for wind speeds ranging from 7 to 15 m s^{-1} . Wind waves induce
622 bottom shear stress values higher than 0.5 N m^{-2} and up to 2 N m^{-2} . These results confirm that W-SW
623 wind events are the predominant forcing parameter for mudflat dynamics at the estuary mouth. Critical
624 deposition shear stress is estimated to 0.8 N m^{-2} and critical erosion shear stress to be 1 N m^{-2} .

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626

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798 **9. Figure Caption**

799

800 Table I: Summary of hydrodynamic features (Significant wave height and maximum velocity
801 fluctuations), suspended particulate matter concentration and bed elevation measurements during boat
802 passages above the Oissel intertidal mudflat. (H_S LW: significant long-wave height; H_S SW:
803 significant short-wave height; ΔU LW : long-wave-induced velocity fluctuation; ΔU SW : short-wave-
804 induced velocity fluctuation)

805

806 Fig. 1: The Seine estuary and study sites: The Oissel Mudflat (kp 230) in the upper estuary and the
807 Vasière Nord mudflat (kp 355) at the estuary mouth. Position of the instrumented MAREL Buoy.
808 (Kilometric point (kp): distance from the Pont Marie, Paris) (Channel width exaggerated upstream kp
809 350 to clarify the figure)

810

811 Fig. 2: Calibration of the 6 MHz Nortek ADV backscattered amplitude with weighted suspended
812 sediment concentration: experimental results (this study) and data from Voulgaris and Meyer (2004)
813 from a 10 MHz Sontek ADV

814

815 Fig. 3: Hydrodynamic features during a W-SW 8 m s^{-1} wind event above the Vasière Nord intertidal
816 mudflat: (a) instantaneous wave height; (b) significant wave height (H_S) and period (T) over a one
817 minute period; (c) TKE shear stress (τ_{TKE}), and Wave-Current shear stress (τ_{WC}) for a bed roughness
818 length of 0.37 mm. The shadow area shows the τ_{WC} variability as a function of low (0.2mm) or large
819 (0.7mm) bed roughness length

820

821 Fig. 4: Boat passages above the Oissel intertidal mudflat: (a) Wave height during the tidal cycle and
822 zoom on one boat passage: (b) wave height (c) and 3D current velocity variations.

823

824 Fig. 5: Typical hydrodynamic signature of a boat passage above the Oissel intertidal mudflat : (a)
825 wave height ; (b) long wave height and (c) short wave height; (d) short waves (τ_{w-SW}), long waves (τ_{w-}
826 LW) and combined short-long waves ($\tau_{w-LW+SW}$) shear stresses and (e) bottom shear stress calculations :
827 combined short-long waves ($\tau_{w-LW+SW}$) shear stress, wave-current shear stress (τ_{WC}) and TKE shear
828 stress (τ_{TKE})

829

830 Fig. 6: Impact of boat passages on hydrodynamic features above the Oissel mudflat during a tidal
831 cycle: (a) mean water level and mean current velocity (U) and (b) wave-current shear stress (τ_{WC}) and
832 TKE shear stress (τ_{TKE}).

833

834 Fig. 7: Variability of hydrodynamic and sedimentary parameters during high spring tides above the
835 Vasière Nord mudflat. (a) water level; (b) wind speed and direction measured at the MAREL Buoy;
836 (c) significant wave height (H_s); (d) wave-current shear stress (τ_{WC}); (e) SPM concentration (C_{SPM})
837 and (f) bed elevation variations. Sedimentation periods are indicated by grey dots and the erosion
838 periods by black dots

839

840 Fig. 8: Variability of the bed roughness length during a fortnightly survey at the Oissel Mudflat.

841

842 Fig. 9: Variability of hydrodynamic and sedimentary parameters during a semi-lunar cycle above the
843 Oissel mudflat. (a) water level; (b) wave-current shear stress (τ_{WC}); (c) SPM concentration (C_{SPM}) and
844 (d) bed elevation variations

845

846 Figure 10: Comparison between bottom shear stress (τ_{WC}) and SPM concentration (C_{SPM}) values above
847 the Oissel Mudflat: determination of the critical erosion shear stress

848

849

Figure Caption

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Fig. 2: Calibration of the 6 MHz Nortek ADV backscattered amplitude with weighted suspended sediment concentration : experimental results (this study) and data from Voulgaris and Meyer (2004) from a 10 MHz Sontek ADV

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Table I

Boat Nb	Water height above the bed (m)	Hs LW (m)	Hs SW (m)	$\diamond U$ LW ($m s^{-1}$)	$\diamond U$ SW ($m s^{-1}$)	Resuspension ($mg l^{-1}$)	Erosion (mm)
1	0.7	0.1	0.15	0.15	0.2	500	NO
2	0.35	-	-	0.15	0	100	NO
3	0.35	0.1	0.08	0.05	0.15	100	NO
4	0.5	0.05	0	0.1	0	0	NO
5	0.55	0.2	0.05	0.5	0.1	500	NO
6	0.3	-	-	0.1	0	0	NO
7	0.4	-	-	0.1	0.2	450	NO
8	1.4	0.05	0.05	0.1	0.05	50	NO
9	0.5	0.05	0	0.1	0	0	NO
10	0.2	-	-	0.3	0.2	1500	6

Figure 1

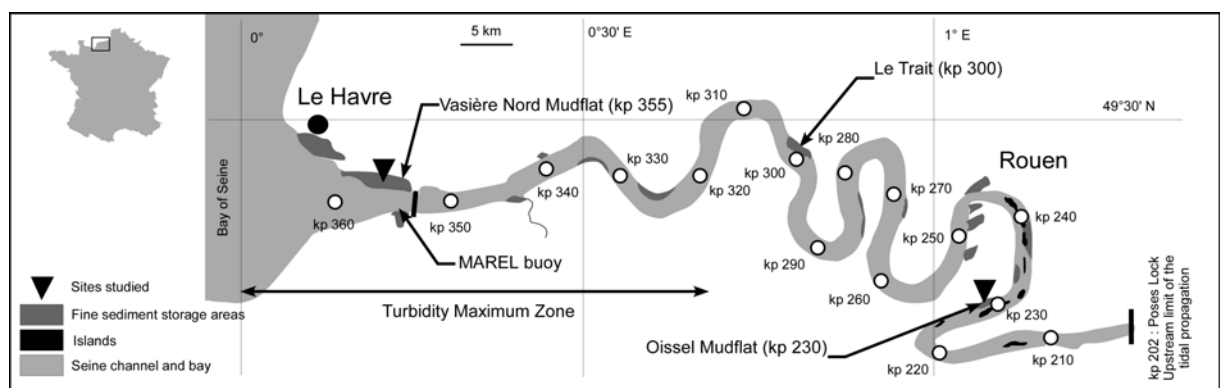


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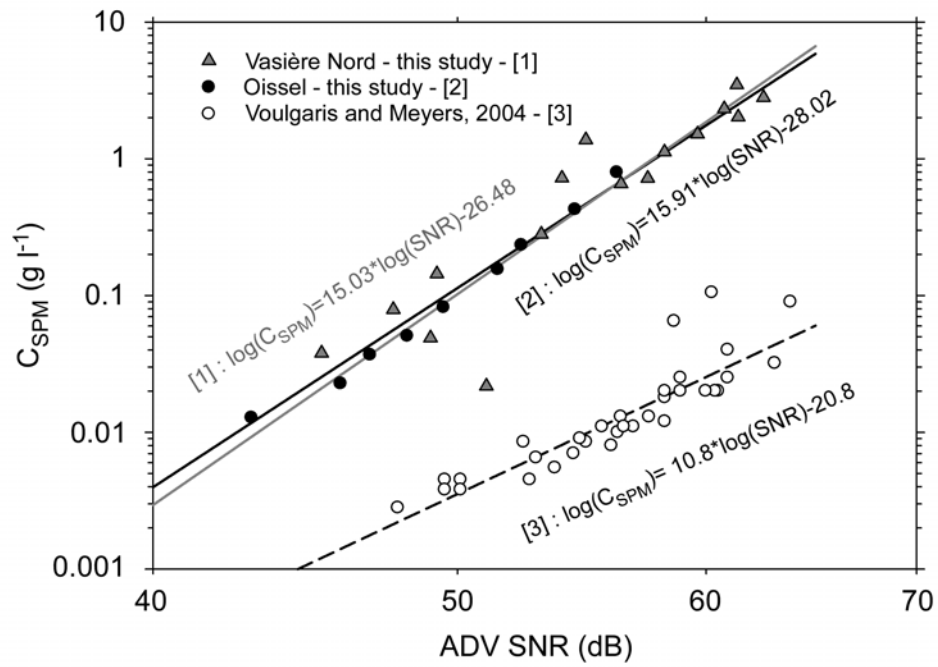


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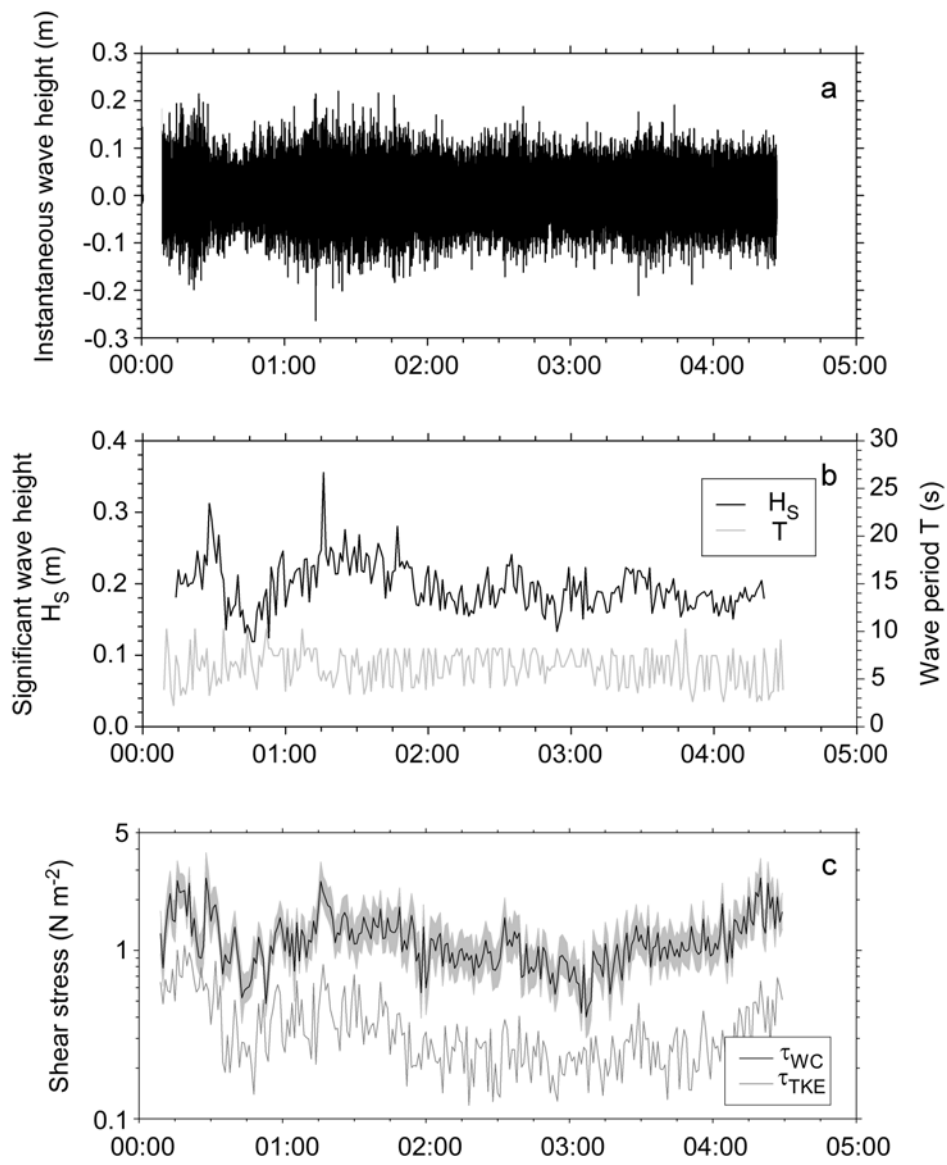


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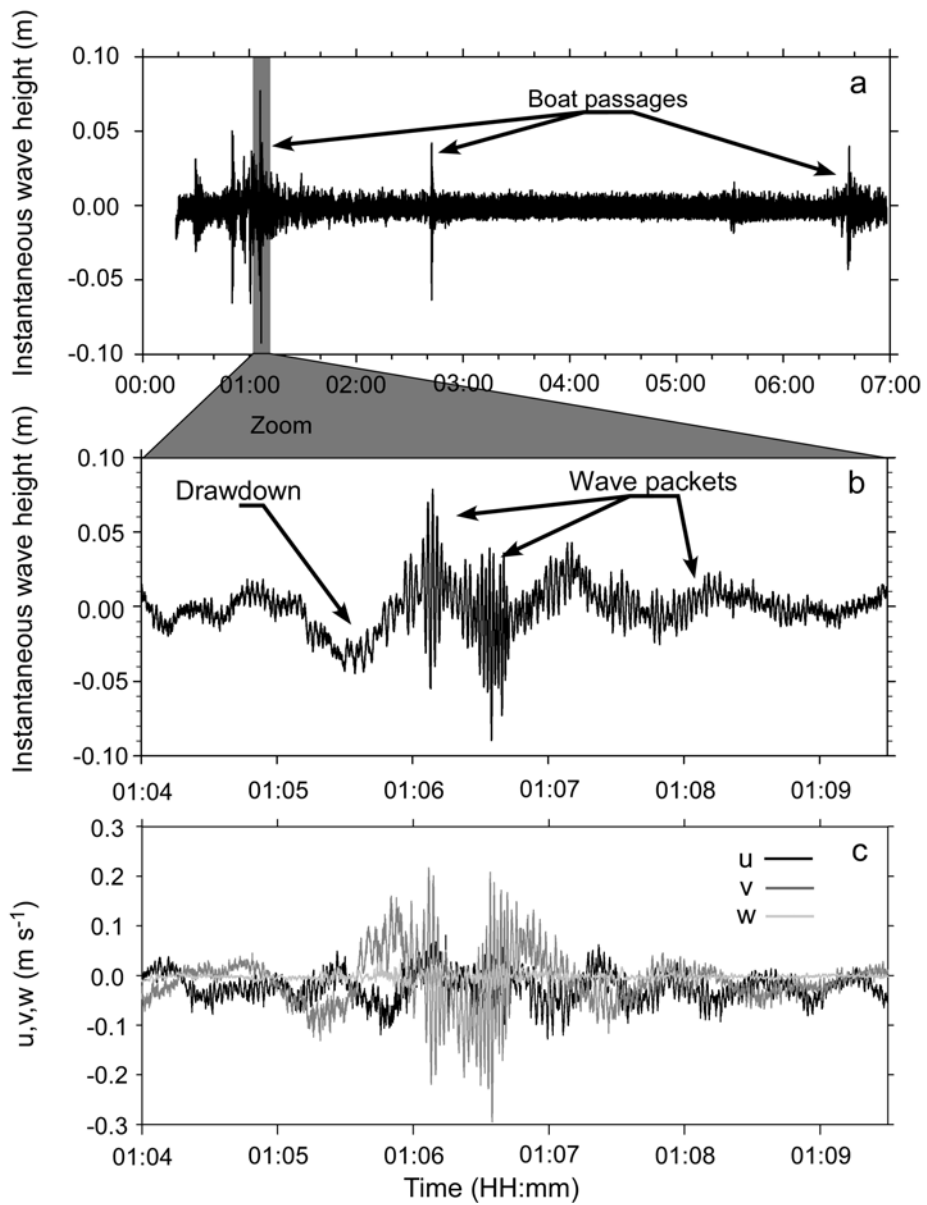


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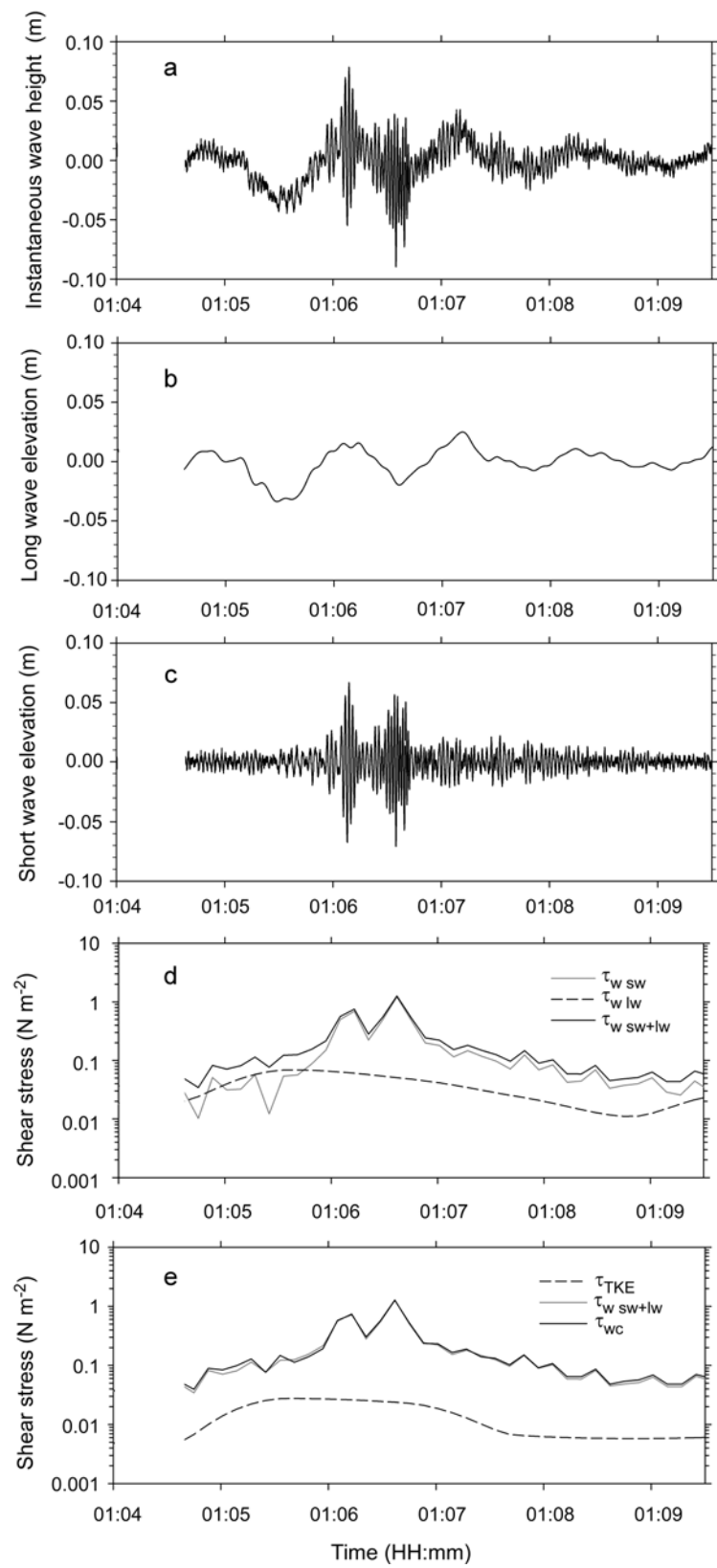


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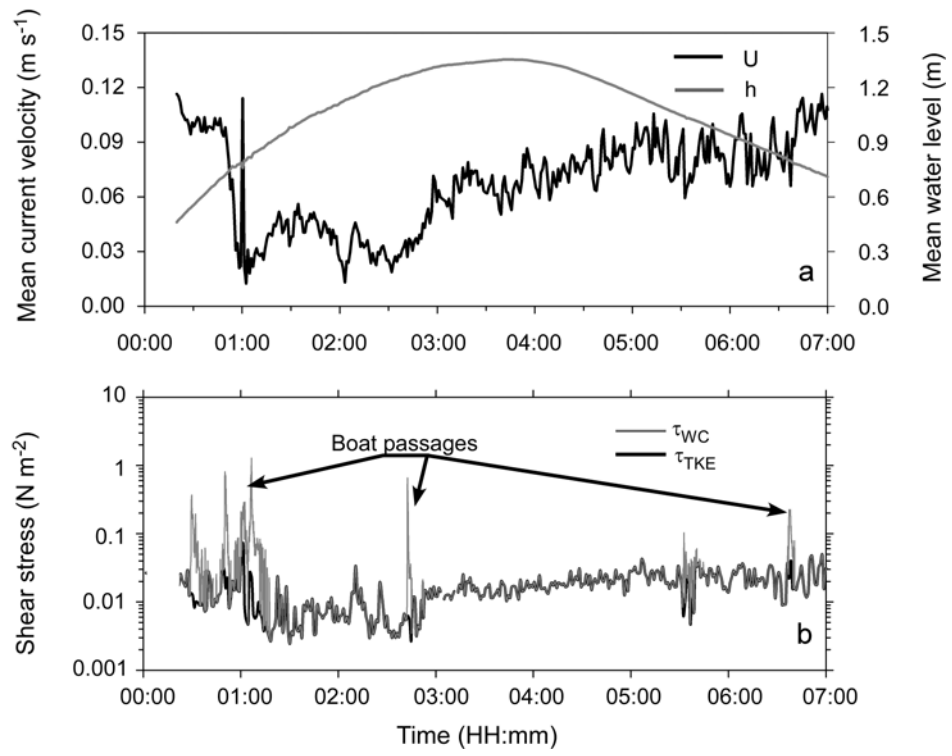


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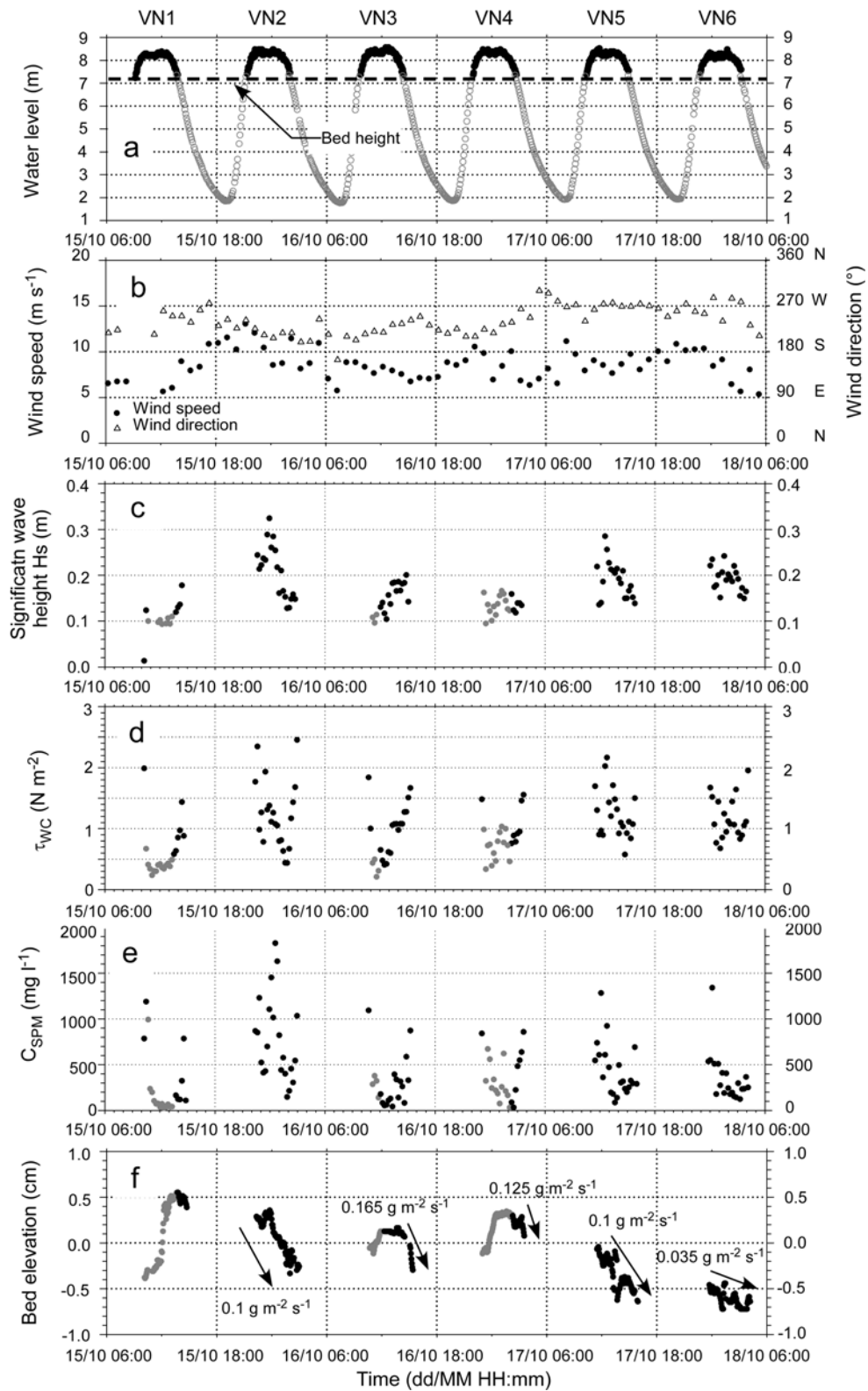


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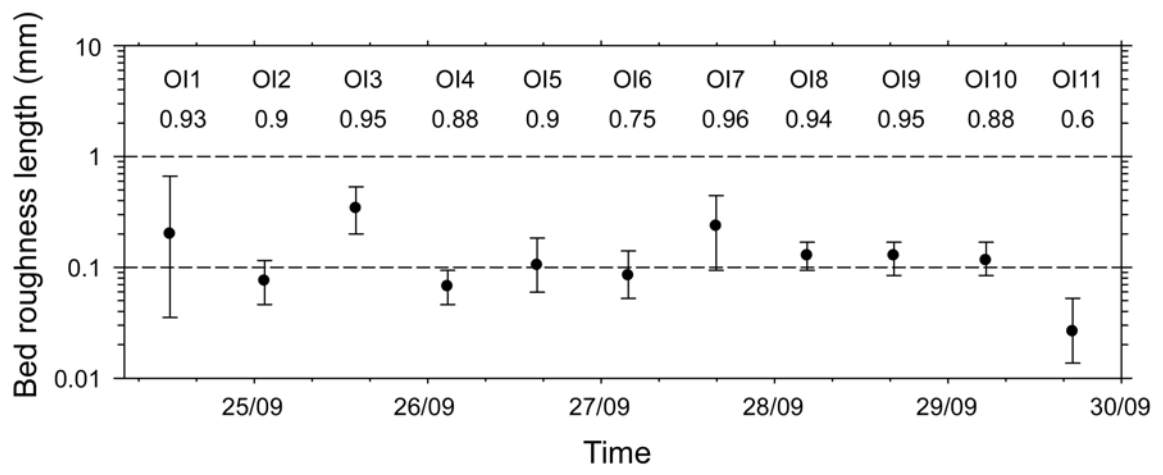


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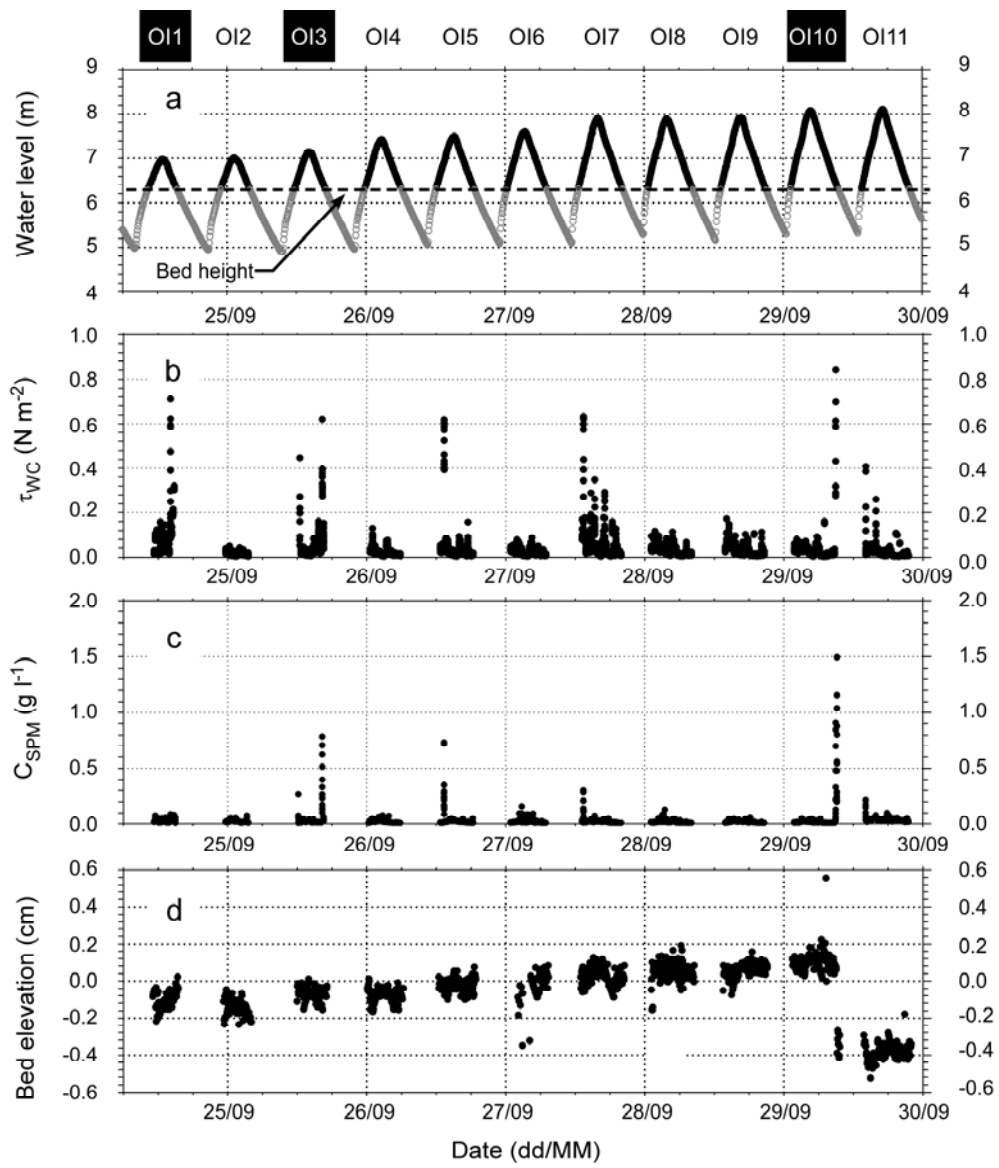


Figure 10

