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1 **Sediment textural variability and mud storage on a large accreting**  
2 **sand flat in a macrotidal, storm-wave setting: the North Sea coast of**  
3 **France.**

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14

15 **ABSTRACT**

16 The North Sea coast of France is a macrotidal, storm-wave coast globally characterized by an  
17 erosional trend, except for the area of Calais which exhibits a large (approximately 12 km<sup>2</sup>),  
18 actively accreting sand flat formed following the onshore migration, over the twentieth  
19 century, of a shoreface sand bank. The sand flat and contiguous beach exhibit large variability  
20 in sedimentation, ranging from pure sand to significant fractions of mud, depending on the  
21 morphology (multiple intertidal bars and troughs, upper beach platform and foredune). In  
22 order to highlight the variability in sedimentation, *in situ* wave and current measurements,  
23 and sedimentary (samples and short cores) and topographic surveys were carried out along a  
24 cross-shore profile during three field experiments involving variable wave and tidal conditions  
25 and spanning different seasons. The results show an onshore decrease in current speeds and  
26 in wave heights compatible with a fining trend, from sand in the lower sand flat, to sand and  
27 interbedded mud layers towards the upper flat. Analysis of the sediment textural and spatial  
28 patterns over a one-year period show an increase in the mud fraction in the lower sand flat  
29 and the onshore migration of these fine sediments onto the upper sand flat, resulting in  
30 significant muddy sedimentation in this latter zone. This pattern shows that an accretionary  
31 context on sand-rich, storm-wave dominated macrotidal coasts offers conditions for the

32 significant trapping of mud, with implications for both contemporary management issues and  
33 the rock record.

34

35 **ADDITIONAL INDEX WORDS:** *beach profile, sand flat, muddy beach, macrotidal*

36

## 37 **INTRODUCTION**

38 Sandy tidal flats with heterogeneous sediments, an extremely flat morphology, and subject to  
39 variably strong tidal flows as the main hydrodynamic forcing agent are poorly documented in  
40 the literature on beaches (MALVAREZ *et al.*, 2004). Sand flats are commonly dominated by  
41 wave-induced sediment entrainment and combined wave-current interactions that are  
42 expressed as spatial distributions of complex sedimentary assemblages. The most studied in  
43 the literature are tidal flats displaying sediment heterogeneity (HOLLAND and ELMORE, 2008),  
44 such as those of the Wadden Sea (VAN STRAATEN and KUENEN, 1958; REINECK, 1967 and EISMA,  
45 1998), the Yellow Sea coasts of South Korea (WELLS *et al.*, 1990; YANG *et al.*, 2005) and the Bay  
46 of Fundy (KLEIN and SANDERS, 1964; AMOS, 1987; DASHTGARD *et al.*, 2006). Sometimes associated  
47 with such sand flats are beaches with intertidal bar–trough systems, the morphodynamic  
48 specificities of which have been highlighted in several recent studies (e.g., LEVOY *et al.*, 1998;  
49 MASSELINK and ANTHONY, 2001; KROON and MASSELINK, 2002; ANTHONY *et al.*, 2004, 2005;  
50 REICHMÜTH and ANTHONY, 2007, 2008a, 2008b; SEDRATI and ANTHONY, 2007). However, the  
51 association between sand flats and such intertidal bar-trough beaches has hardly been  
52 considered in the literature, excepting in two studies of the aeolian dynamics of sand flats  
53 associated with a large accreting beach in northern France (ANTHONY *et al.*, 2006, 2007).

54

### 55 **Study area**

56 The study area, a beach east of Calais on the North Sea coast of France (Fig. 1), is exposed to  
57 fetch-limited ( $T=4-6$  s), relatively low-energy waves (modal  $H_s < 0.6$  m) punctuated by storm  
58 activity ( $H_s$  up to 3 m). This environment is affected by semi-diurnal tides with a mean spring  
59 tide range of about 6.4 m in Calais, with flood-dominated residual flow towards the NE. The  
60 combination of storm winds and waves and large tidal ranges also generates strong longshore  
61 currents that affect both the shoreface and the beaches of the southern North Sea (ANTHONY  
62 and ORFORD, 2002; SEDRATI and ANTHONY, 2007; OBLINGER and ANTHONY, 2008). This site is one

63 of the rare actively accreting sectors of coast in the southern North Sea, most probably due to  
64 sand supply generated by the onshore migration and coastal welding of a nearshore sand  
65 bank, in the twentieth century, leading to the accumulation of a shore-attached sand reservoir  
66 of 400,000 m<sup>3</sup> in nearly 80 years (GARLAN, 1990), and to the formation of the large upper beach  
67 sand flat fronting the dunes. The sand flat and contiguous beach exhibit large variability in  
68 sediment composition, ranging from pure sand to significant fractions of mud, depending on  
69 the morphology, which is a combination of multiple intertidal bars and troughs (IBT), an upper  
70 beach platform with lower, middle and upper sand flat segments (respectively LSF, MSF, USF  
71 in Figure 1), and a foredune. The IBT and LSF are characterised by unimodal fine to medium  
72 sand (mean grain size,  $X_m=0.19-0.33$  mm), the MSF by silt to fine sand ( $X_m =0.01-0.24$  mm)  
73 with most of the sediment being bimodal, and the USF by silt and clay ( $X_m= 0.01$  mm).

74

## 75 **MATERIELS AND METHODS**

76 A representative 1850 m-long cross-shore transect, covering the full range of surface textures  
77 from mud to sand, was set up on the sand flat and three field experiments (in March,  
78 September 2007, and in April 2008), involving variable wave and tidal conditions and spanning  
79 different seasons, were conducted. The transect was surveyed using a total station with errors  
80 within  $\pm 3$  mm for distance and  $\pm 0.0015^\circ$  for direction. An uncertainty band (5 cm) was  
81 determined as a margin of error of measurements of net change in profile morphology. All the  
82 surveys were referenced to a benchmark of the French National Geodesic Service (I.G.N. 69).  
83 Simultaneously, subsurface sediment samples (2 cm depth) were collected along this central  
84 transect from survey points spaced 10- 20 m apart. The grain-size distribution (sand-to-clay  
85 fraction) was analysed using a Laser Beckman-Coulter LS 230. Hydrodynamic data were  
86 collected during each experiment at three locations (Fig.1) along the transect (on IBT, LSF and  
87 USF). Directional wave and current data were obtained using an InterOcean S4  
88 electromagnetic current meter and two ADVs (*Acoustic Doppler Velocimeter*). Hourly wind  
89 data (speed and direction) were obtained from Meteo-France meteorological stations located  
90 a few kilometres inland of the experimental site.

91

## 92 **RESULTS**

### 93 **Energy conditions**

94 The experiments were conducted over twenty tides covering spring-to-spring cycles. The data  
95 presented concern only the first three days of each experiment, as the hydrodynamic  
96 conditions were sufficiently energetic as to influence the cross-shore morphology and the  
97 sediment distribution. The experiments were realised under similar tidal range conditions  
98 (between 6 and 6.37 m). The incident wave heights and the associated weather conditions  
99 during the considered periods of each experiment are displayed in Figure 2. The high-energy  
100 conditions in March 2007 were characterised by several strong wind events comprising NE to  
101 E winds (speeds of up to 13 m.s<sup>-1</sup>) that then slightly weakened on veering to W, then NW,  
102 regaining strength once again with speeds of more than 11 m.s<sup>-1</sup>. These wind events  
103 reinforced the mean current velocities on the sand flat (with peak current speeds exceeding  
104 1.9 m. s<sup>-1</sup>) and were responsible for waves with significant heights of about 2.58 m (Fig.2).  
105 Waves under low-energy conditions rarely exceed 1 m on average, and the mean current  
106 velocities never exceed 1 m.s<sup>-1</sup>. Such conditions are associated with wind speeds that do not  
107 exceed 5-6 m.s<sup>-1</sup> (Fig. 2).

#### 108 **Wave and current attenuation during typical rough weather**

109 Wave height attenuation (see locations of current meters in Figure 1) between the IBT and  
110 the LSF is very important (approximately 90 %), and still remains significant at 23 % between  
111 LSF and USF (Fig 3b). During the storm event in march 2007 strong winds exceeding 14 m.s<sup>-1</sup>,  
112 were associated with significant wave heights that exceeded 2.5 m on the beach, but that did  
113 not exceed 0.5 m at the same time on the LSF or USF (Fig. 3b). Over the bare sandy surface of  
114 the sand flat, the incoming waves were reduced in height due to breaking processes and  
115 bottom friction over the flat gradient, and the significant wave height over USF remained less  
116 than 0.3 m in spite of the storm event. The mean overall current velocities (U, sum of  
117 longshore and cross-shore currents) exhibited similar behaviour (Fig 3d). The largest velocities  
118 were, as expected, recorded on the beach, with currents becoming particularly strong (0.8–1  
119 m. s<sup>-1</sup>) when flows were forced during the storm. Velocities decreased slightly towards the LSF  
120 (0.42–0.49 m.s<sup>-1</sup>), except during slack water just before 01:00 (Fig.3d), when the currents were  
121 reinforced (0.55 m.s<sup>-1</sup>) by the wind notably under the very shallow water depths. Currents  
122 became very weak on the USF (0.4–0.2 m.s<sup>-1</sup>). During high tide, longshore-dominant currents  
123 did not exceed 0.6 m.s<sup>-1</sup> on the IBT, and decreased towards the LSF (0.2 m.s<sup>-1</sup>) and the USF  
124 (0.06 m.s<sup>-1</sup>). At the same time, cross-shore currents (0.4 m.s<sup>-1</sup> on the IBT, 0.3 m.s<sup>-1</sup> on the LSF  
125 and 0.2 m.s<sup>-1</sup> on the USF), were dominantly offshore. This large upper beach platform results

126 in quasi-complete attenuation of waves and currents even during storm conditions. This  
127 dissipation of energy over the intertidal sand flat encourages sediment deposition.

### 128 **Cross-shore morphological change**

129 The topographic changes recorded on the central profile are depicted in Figure 4. Much of the  
130 beach profile under mean highwater neaps was affected by significant change ( $>0.2$  m)  
131 between two survey profiles, with accretion and an onshore migration of IBT. Alternating  
132 zones of erosion and deposition occurred across the seaward slope of the bar, and there is  
133 some evidence for a landward movement of these zones, which could be analogous to the  
134 onshore migrating bed oscillations described by GREENWOOD *et al.*, (2004). The largest relative  
135 variations of topography on the beach were associated with IBT (0.39 to 0.45 m) and highlight  
136 a regular onshore supply of sand between the beginning of the survey in March 2007 and the  
137 end in April 2008. The net topographic differential over the survey period shows that much of  
138 the change is above the 5 cm uncertainty band (Fig. 4). The LSF was relatively stable. The  
139 topographic variations of the MSF over these experimental periods are moderate ( $<0.1$  m) and  
140 globally correspond to a progressive filling of the depression at the landward end of the MSF.  
141 The USF variations are not depicted here, but this zone showed relative morphological  
142 stability.

### 143 **Analysis of surface sediment change and temporal variation**

144 Surface sediments along the transect are composed of three grain size fractions representative  
145 of the local sediment stock: fine sand (250–125  $\mu\text{m}$ ), very fine sand (125–63  $\mu\text{m}$ ), and silt and  
146 clay (Figure 5). Medium and coarse sand fractions are not included in this study because they  
147 represented a weak but constant proportion ( $<10$  %) of the total sediment during the three  
148 experiments. Mud (grain sizes below 63  $\mu\text{m}$ ) is further subdivided into silt (63–2  $\mu\text{m}$ ) and clay  
149 ( $< 2$   $\mu\text{m}$ ). With the exception of the USF (exhibiting 15 to 90 % of silt and clay), the sediments  
150 of the beach and sand flat are dominated by fine sand which forms more than 70 % of the  
151 stock. Muddy areas are relatively sheltered from wave action and fine material is generally  
152 found trapped in a topographic depression (landward end of the MSF). On the USF, in March  
153 2007, the mud content in the superficial sediments increased, attaining up to 50%, at a  
154 distance of 1100 m landward of the IBT. This implies that mud is supplied to the sand flat when  
155 the small topographic depressions are flooded, because the area is protected from waves by  
156 the uppermost intertidal bar, a swash bar. Mud was found in two locations in September 2007  
157 and April 2008. The mud fraction attained up to 90% at the landward limits of the MSF in

158 autumn, and in the middle of the USF in spring 2008, thus highlighting an onshore migration  
159 (450 m) of these fine sediments onto the USF. The other location of mud concentration was  
160 the LSF in September 2007 and only below the MSL mark in April 2008. Mud temporarily  
161 deposited on the beach (important supply during calm conditions in September 2007) seems  
162 to be easily resuspended during winter storms, and migrates onshore onto the USF.  
163 Analysis of the sediment textural and spatial patterns over a oneyear period show an increase  
164 in the mud fraction in the LSF, and the onshore migration of these fine sediments onto the  
165 USF (crossshore spatial fluctuations in the mud content), resulting in significant muddy  
166 sedimentation in this latter zone. The analysis of long-term satellite data (results not  
167 presented here) shows that the presence of mud on this uppermost part of the beach is rather  
168 unusual. This pattern shows, however, that in an accretionary context of a sand-rich, storm-  
169 wave dominated macrotidal coast with available mud, the morphodynamic conditions may  
170 favour the significant trapping of mud.

171

## 172 **DISCUSSION AND CONCLUSION**

173 As is common throughout the English Channel (LARSONNEUR *et al.*, 1982; ANTHONY, 2002;  
174 LESOURD *et al.*, 2003a), fine sediments are found in sheltered bays and estuaries where this  
175 grain-size fraction can easily be trapped. Two specificities of this study area are that it is one  
176 of the rare actively accreting sectors of coast in the southern North Sea, and it exhibits a  
177 significant fraction of mud for an open coast. The morphological system is composed of a  
178 beach with IBT succeeded by a large upper beach platform that ensures considerable wave  
179 and current attenuation (90 % by the IBT and 23 % by the sand flat) during typical rough  
180 weather affecting the southern North Sea. Energy attenuation by this system and local  
181 sediment availability explain the possibility for muddy sedimentation behind the uppermost  
182 swash bar. The system found associated with these flats thus differs from that of other mud-  
183 rich sandy beaches such as those of South America where active decadal-scale beach rotation  
184 is induced by Amazon-derived mud banks migrating alongshore (ANTHONY *et al.*, 2002;  
185 ANTHONY and DOLIQUE, 2004). Fine material is generally trapped in the topographic depressions  
186 (middle of MSF). The initial topography in March, 2007 influenced the future sediment  
187 distribution. During mean high water spring, the sand flat is flooded. At low tide, the very weak  
188 slope behind the swash bar and especially the topographic depression prevent water from

189 being drained. As a consequence, fine particles can accumulate. A demarcation zone (fig. 5)  
190 highlights the depositional boundary between the outer sand flats and the USF or mixed flats.  
191 The progressive filling of this depression (end of MSF) between March, 2007 and April, 2008,  
192 recorded in Figure 4, confirms the increase in proportion of settled fine particles depicted in  
193 Figure 5. The response of sediments to size-sorting processes has been discussed by several  
194 authors (e.g. MCLAREN and BOWLES 1985; GAO and COLLINS 1992; LE ROUX 1994; ANTHONY and  
195 HÉQUETTE, 2007). In many tidal systems, surficial sediment distribution shows distinct size-  
196 sorting patterns controlled by local energy gradients. The observed seasonal pattern  
197 demonstrates that mud is easily resuspended by currents and wave action in winter (CHANG *et al.*,  
198 *et al.*, 2006). As a consequence, the sand fraction becomes predominant on the upper beach and  
199 on the sand flat in the course of the winter season. Aeolian transport of sand is also facilitated  
200 as sand dries out (ANTHONY *et al.*, 2007). In response to the higher energy input by storm  
201 waves, sand is redistributed over the sand flat, resulting in the LSF and MSF, characterised by  
202 mixed sediment in September 2007, evolving into mud-depleted sand flats in April 2008, and  
203 thereby contributing to the bimodal grain-size distribution of the sediments. Mud deposition  
204 is controlled by very high tide levels and by the hydrodynamic regime, two parameters  
205 evincing a seasonal pattern. This study shows an increase in the mud fraction on the beach in  
206 one year. Several factors can explain this phenomenon: the specific morphology and its effect  
207 on wave attenuation, the availability of muddy sediment from the shoreface, a decrease in  
208 wave energy during summer, 2007, and notably surface drying with the formation of mud  
209 crusts with desiccation cracks that can be dispersed by wind. In this case, the in situ  
210 percentage of mud decreases on the surface. Fine sediments, as indicated earlier, had never  
211 been noticed (satellite observations) on the beach until September, 2007 demonstrating the  
212 recent appearance of the phenomenon. Analyses of short cores with interbedded mud and  
213 sand (layer <1 cm) and observation of muddy sedimentation on the USF (up to 5 cm thick)  
214 confirm, however, these sedimentological patterns. Facies analyses of short cores show a  
215 recurrent process of sedimentation and not an isolated event. The proximity of the port of  
216 Calais, the numerous shoreface sand ridges and the mud-rich sediments found in troughs  
217 between these ridges, increasing suspended particulate matter concentration in the Channel,  
218 or a cyclic modification of local or large-scale sediment transport may explain this input of  
219 mud. Mud has been observed on the shoreface and on parts of the intertidal beach in areas  
220 near the study site (ANTHONY *et al.*, 2004; OBLINGER and ANTHONY, 2008), as well as off the

221 Belgian coast (FETTWEIS and VAN DEN HEYDE, 2003; FETTWEIS *et al.*, 2006). In parallel, after this  
222 consequent supply of mud to the lower beach under low-energy conditions (September,  
223 2007), an onshore migration of fine sediments occurred in the central part of the MSF in 6  
224 months. During winter, characterized by high-energy events, cross-shore processes due to  
225 waves have certainly played an important role in spite of the significant contribution of  
226 longshore processes. The sediments also undergo progressive size sorting in the course of  
227 landward transport and onshore migration towards the sand flat. In summary, the results of  
228 this study show the possibility of muddy sedimentation on an open macrotidal storm-wave  
229 setting due to the influence of the beach morphology. Mud deposition is controlled by a  
230 seasonal hydrodynamic regime, and begins by an increase in the mud fraction on the beach,  
231 followed by onshore transfer and incorporation into the upper beach sand flat.

232

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308

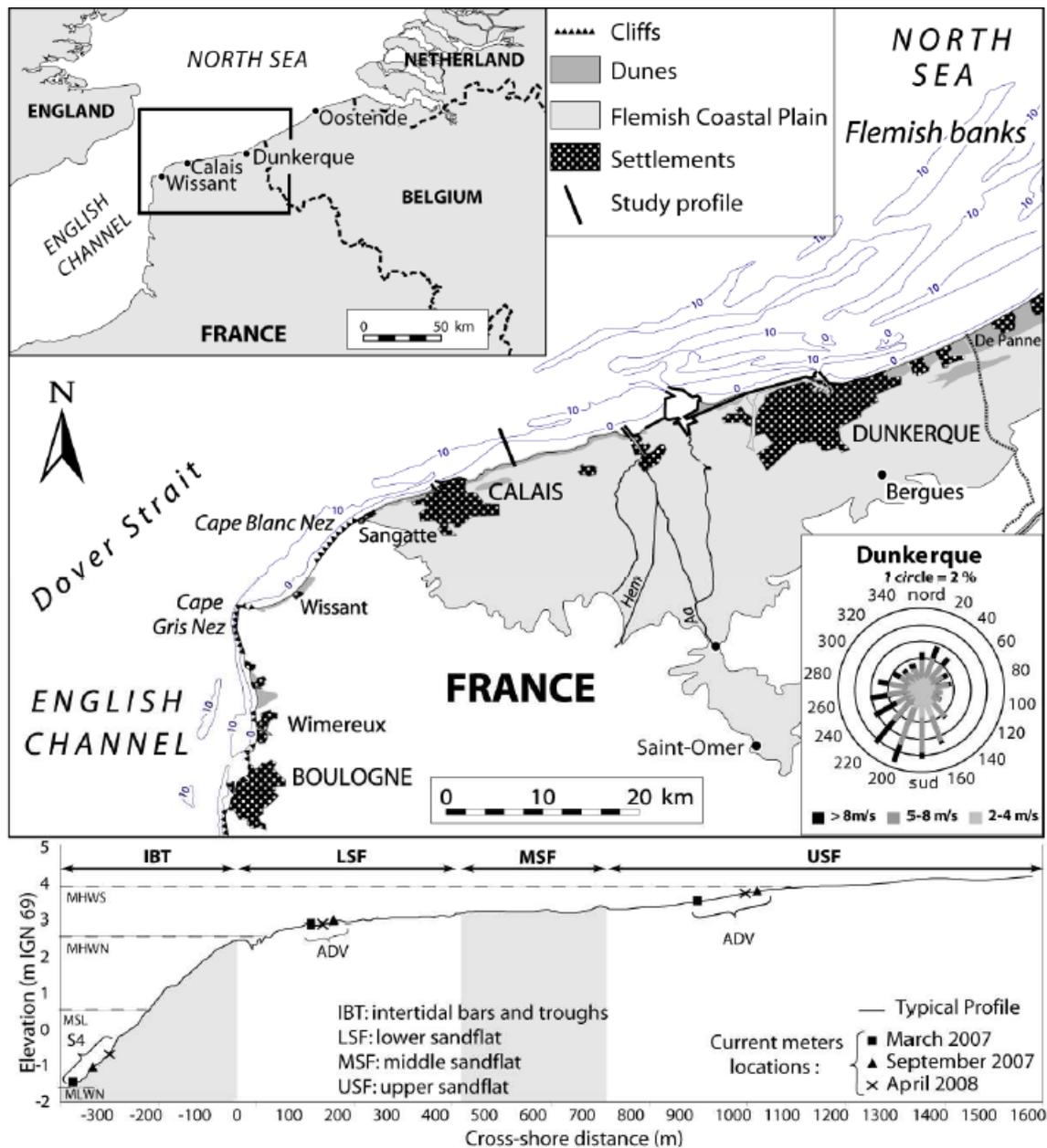
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316

317 FIGURES

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319

320 Figure 1: Location map of the study area with representative wind conditions from the nearby

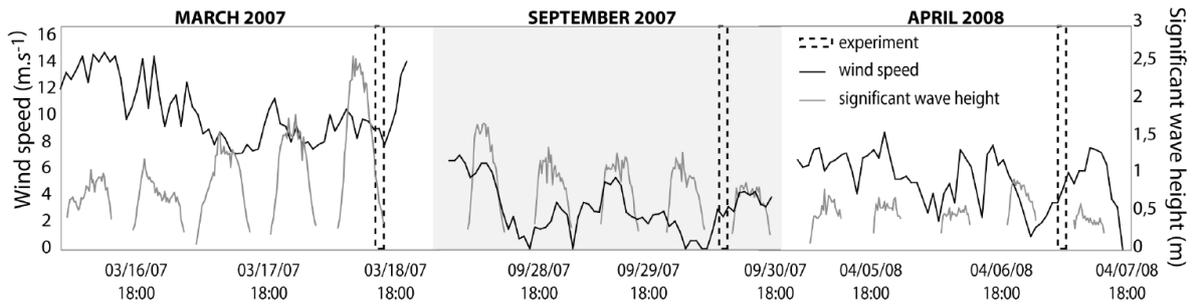
321 weather station of Dunkerque, and typical intertidal profile of Calais east beach with location

322 of current meters. MHWS = mean high water springs; MHWN = mean high water neaps; MSL

323 = mean sea level; MLWN = mean low water neaps.

324

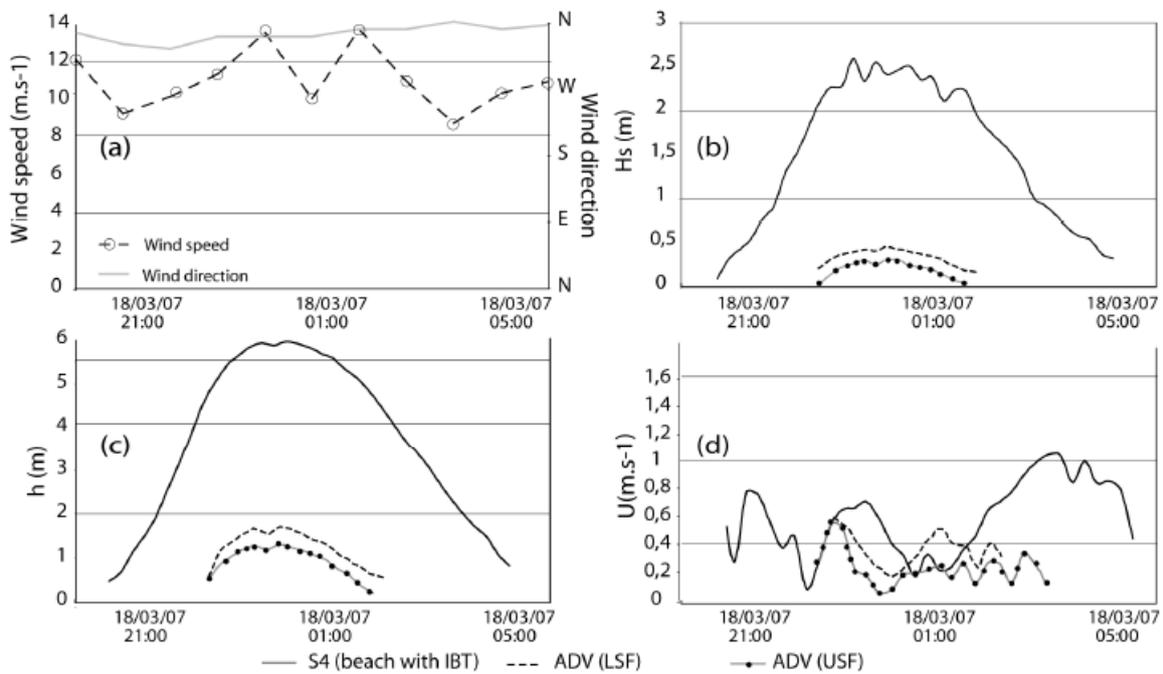
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326

327 Figure 2: Three-day incident wave height and wind speed records during the March,  
 328 September 2007 and April 2008 experiments. The broken vertical bands indicate the time  
 329 interval corresponding to sediment sampling.

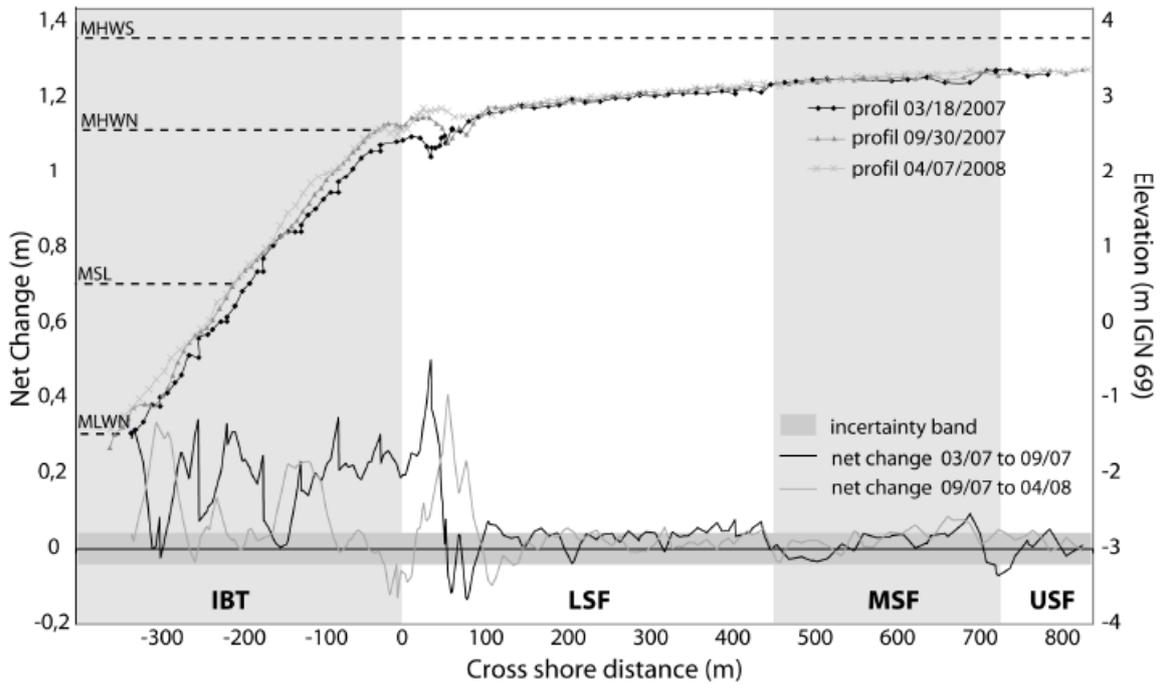
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331

332 Figure 3: Wind conditions (a) from a nearby station, and significant wave height  $H_s$  (b), local  
 333 water depth  $h$  (c), and mean overall current  $U$  (d) recorded on the beach, sand flat and upper  
 334 sand flat (see Fig. 1) during storm conditions in March 2007.

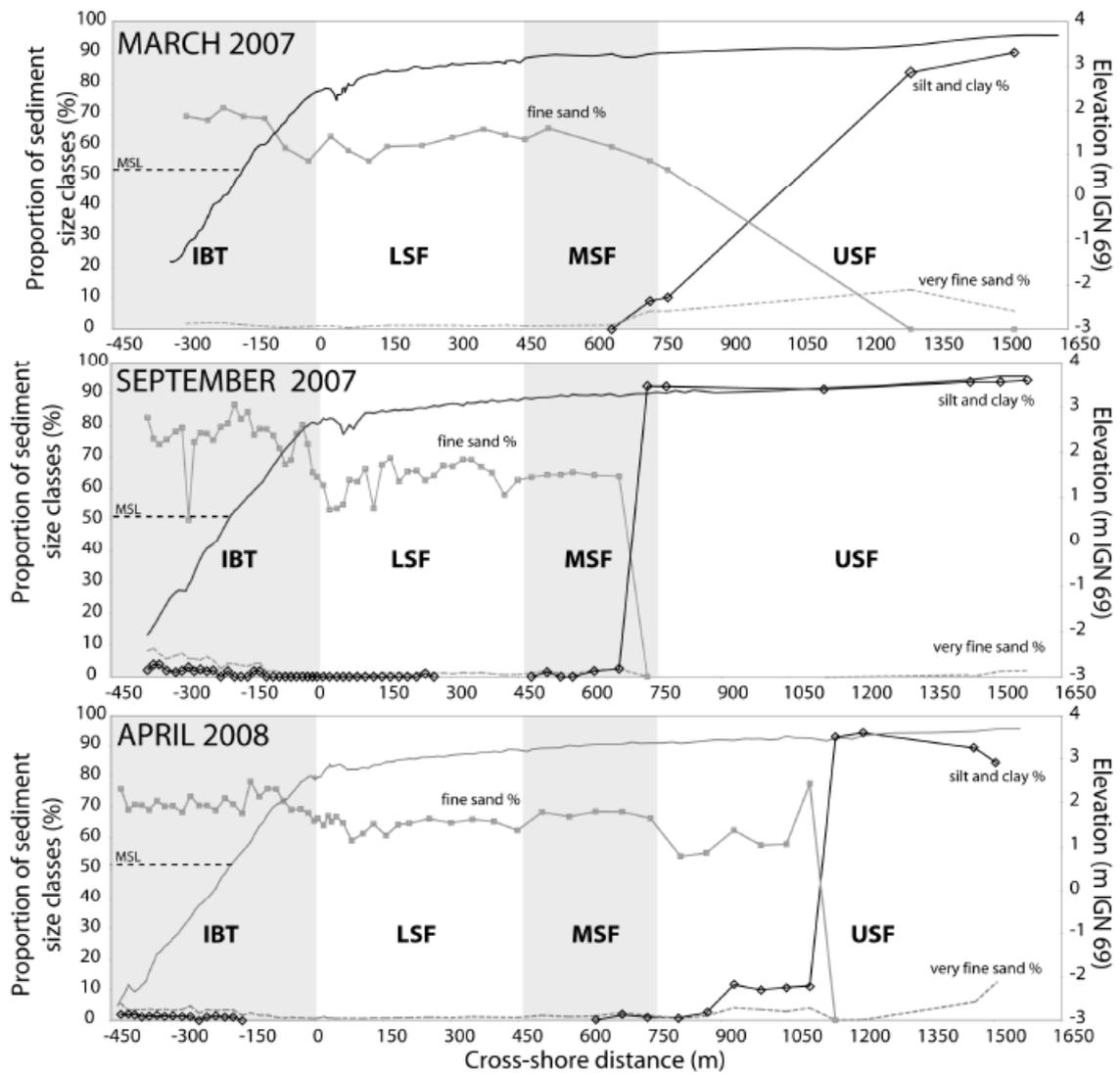
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336

337 Figure 4: Changes in profile morphology between the 3 experiments. Note that USF is not  
 338 shown in full.

339



340

341 Figure 5: Changes in proportion of sediment size classes and in spatial distribution of sediment  
 342 on the surveyed beach transect.