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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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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 km²),
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 m³ 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 ± 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⁻¹) that then slightly weakened on veering to W, then NW,
102 regaining strength once again with speeds of more than 11 m.s⁻¹. These wind events
103 reinforced the mean current velocities on the sand flat (with peak current speeds exceeding
104 1.9 m. s⁻¹) 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⁻¹. Such conditions are associated with wind speeds that do not
107 exceed 5-6 m.s⁻¹ (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⁻¹,
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⁻¹) when flows were forced during the storm. Velocities decreased slightly towards the LSF
120 (0.42–0.49 m.s⁻¹), except during slack water just before 01:00 (Fig.3d), when the currents were
121 reinforced (0.55 m.s⁻¹) by the wind notably under the very shallow water depths. Currents
122 became very weak on the USF (0.4–0.2 m.s⁻¹). During high tide, longshore-dominant currents
123 did not exceed 0.6 m.s⁻¹ on the IBT, and decreased towards the LSF (0.2 m.s⁻¹) and the USF
124 (0.06 m.s⁻¹). At the same time, cross-shore currents (0.4 m.s⁻¹ on the IBT, 0.3 m.s⁻¹ on the LSF
125 and 0.2 m.s⁻¹ 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 μm), very fine sand (125–63 μm), 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 μm) is further subdivided into silt (63–2 μm) and clay
149 (< 2 μm). 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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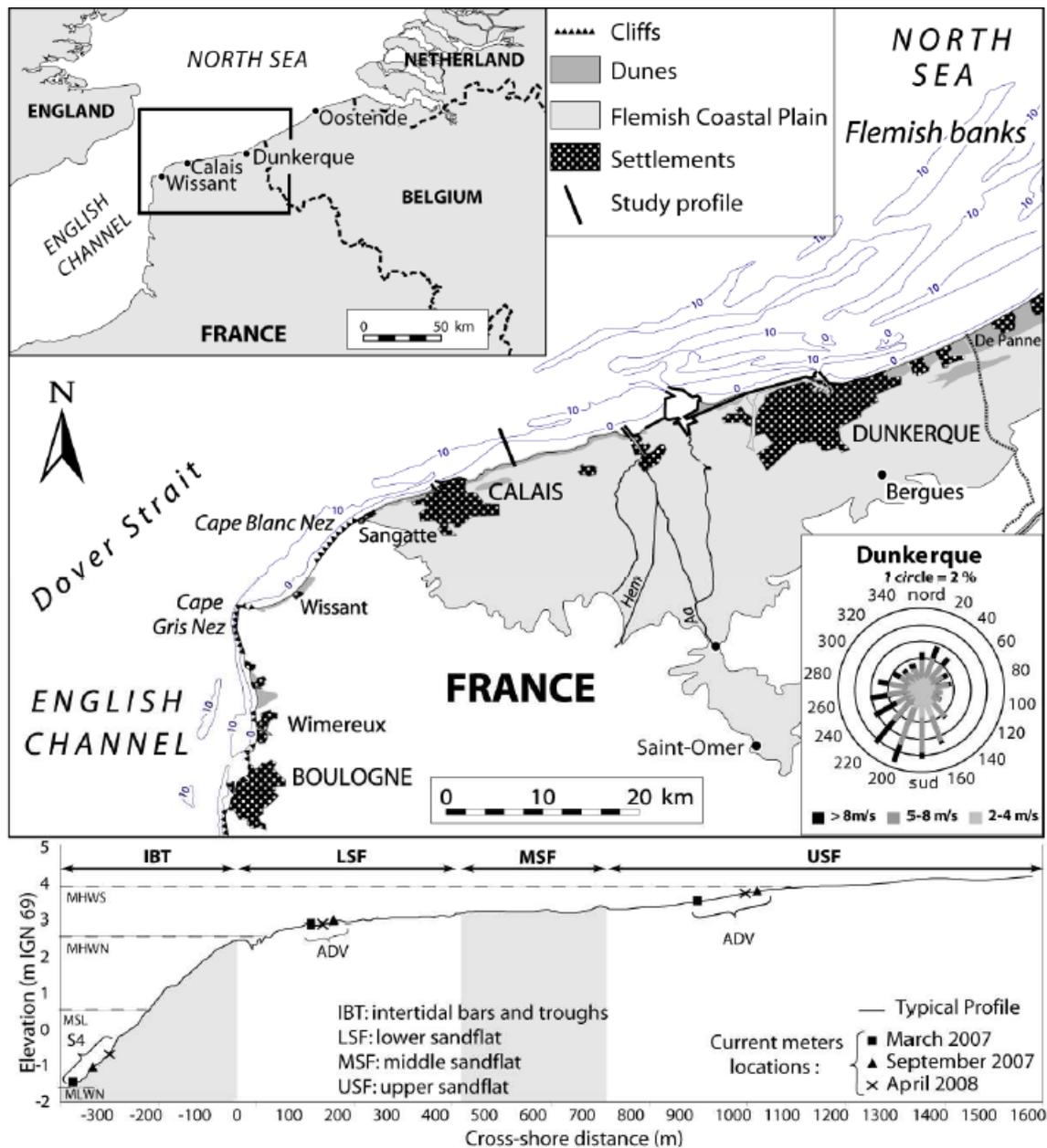
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316

317 FIGURES

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

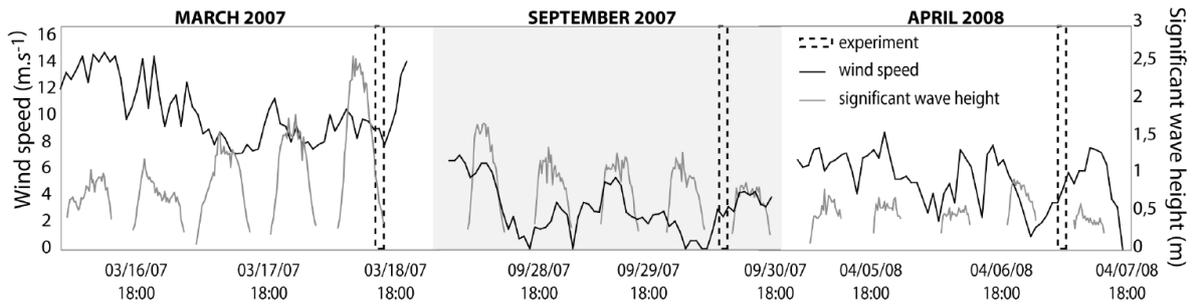
321 weather station of Dunkerque, and typical intertidal profile of Calais east beach with location

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

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

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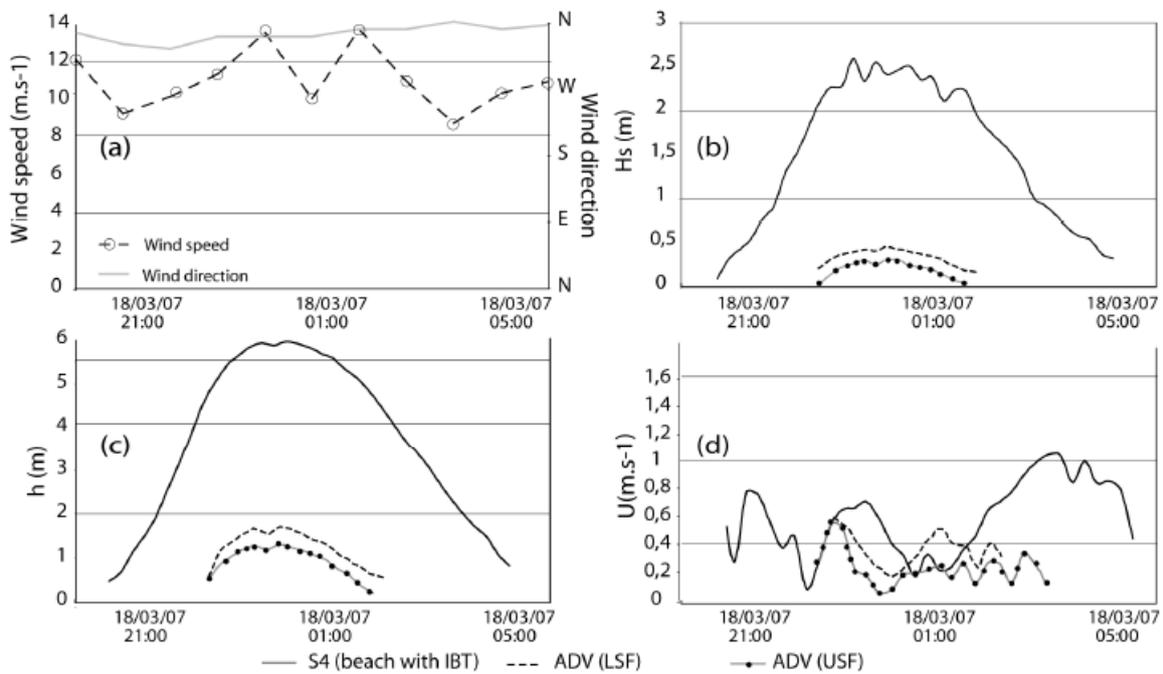
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327 Figure 2: Three-day incident wave height and wind speed records during the March,
 328 September 2007 and April 2008 experiments. The broken vertical bands indicate the time
 329 interval corresponding to sediment sampling.

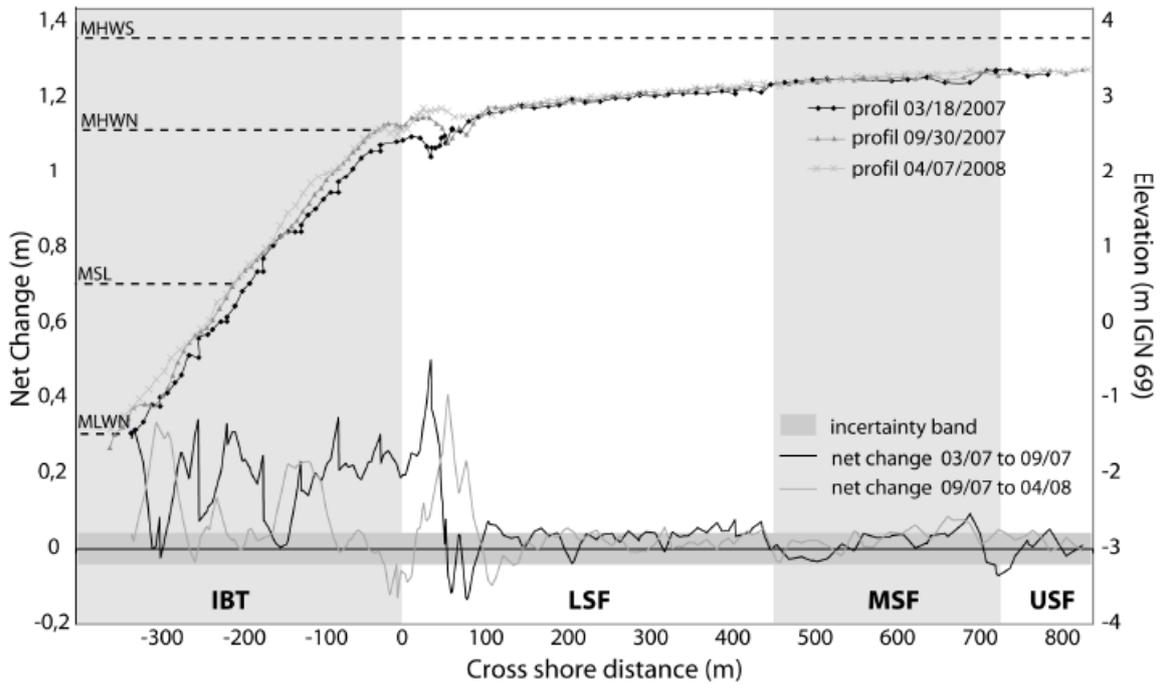
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332 Figure 3: Wind conditions (a) from a nearby station, and significant wave height H_s (b), local
 333 water depth h (c), and mean overall current U (d) recorded on the beach, sand flat and upper
 334 sand flat (see Fig. 1) during storm conditions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

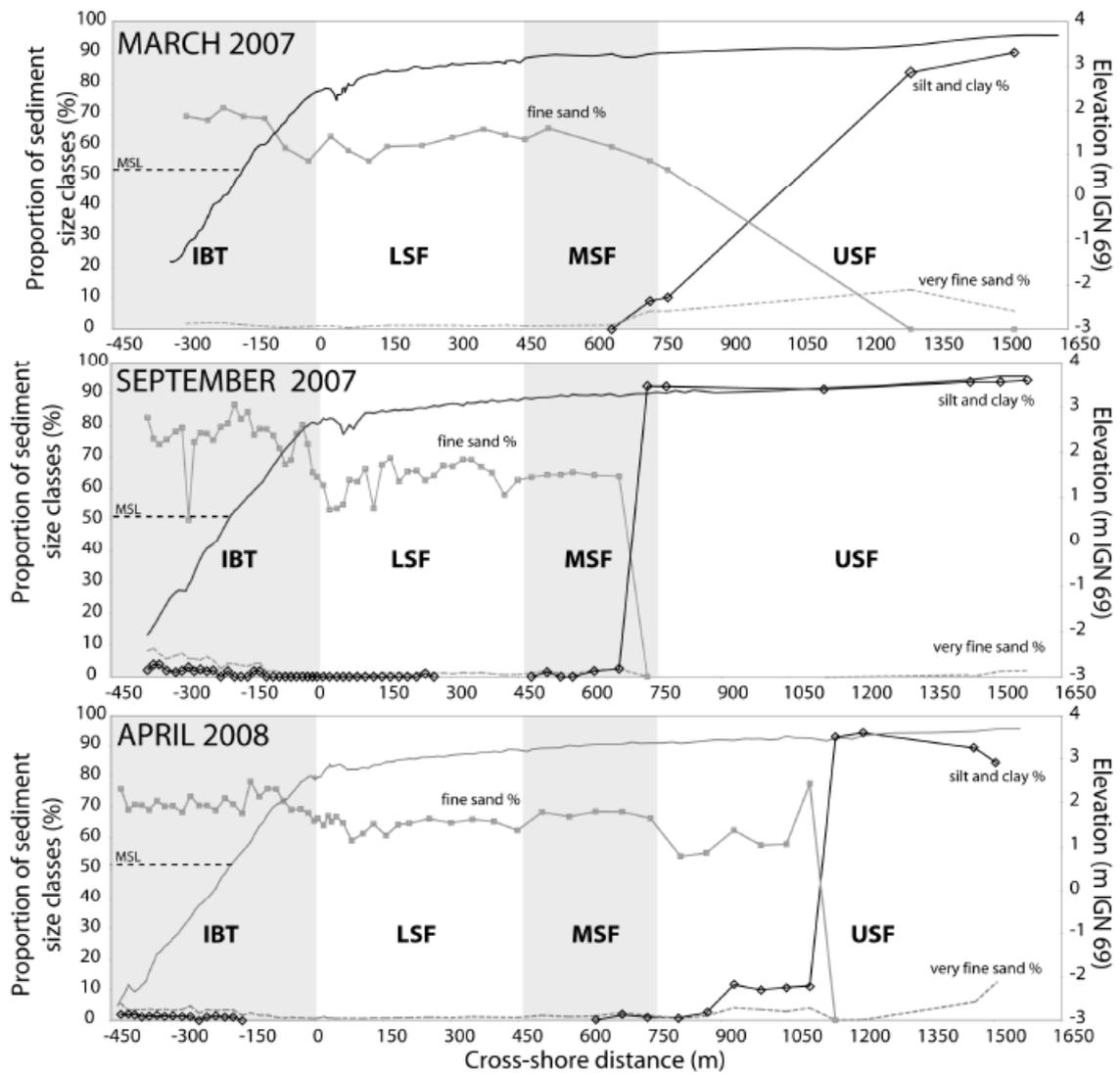
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337 Figure 4: Changes in profile morphology between the 3 experiments. Note that USF is not
 338 shown in full.

339



340

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