Short term morphodynamics of an intertidal bar on megatidal ebb delta

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ABSTRACT

The morphodynamics of an intertidal bar located on an ebb delta of a megatidal inlet system in Normandy, France, was examined during four short experiments under low to high energy wave conditions and spring or neap tide contexts. Although there have been numerous studies on ebb-tidal bar morphology and on the processes affecting such bars, these concern only microtidal or mesotidal settings, and are mainly based on observations. No detailed work involving hydrodynamic conditions embracing the whole tidal cycle has been carried out so far on the mechanisms of onshore migration of these coastal accumulation features, especially along macro and megatidal coasts. In this study, the morphological response of the bar was coupled with the residence times and intensities of each hydrodynamic process (swash, surf, shoaling waves) over a representative bar cross-shore profile, and sediment transport patterns deduced from fluorescent tracer. The results show that the bar migrated exclusively shoreward during moderate to storm conditions (Hs > 0.7 m at the bottom of the bar seaward slope). During low energy wave conditions, no bar movement was observed. Swash action was not the dominant process, mainly due to its duration, which did not exceed 8 min in the course of a semi-diurnal tidal cycle. The movement of sediments and the bar morphology is induced mainly by surf processes and their associated currents. The increase in the significant wave height disturbed the general mean current behaviour, which was parallel to the bar crest during low energy conditions. Under surf conditions, mean flows are directed onshore, with an absence of bed return flow; this allows sediment to be transported towards the bar crest causing a landward bar migration. An offshore-directed cross-shore current (not favourable for bar migration) is recorded with larger water depths and no breaking waves (shoaling conditions). This study also highlights the influence of the tidal water level fluctuations in such a large tidal range setting, which induce a rapid shift in processes (such as bed shear and sediment re-working) across the shore-normal profile. These conditions explain the relative low rate of migration of the bar over the delta platform (about 33 m/year). This rate is much less than those reported from micro-mesotidal environments. Calculations of bed shear stress also show that the mean currents alone are not responsible for onshore bar movement, notwithstanding the megatidal character of the field site.

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1. Introduction

Individual swash bars commonly occur in ebb-tidal deltas in micro-mesotidal settings (Hayes, 1975) and are built by wave-induced accumulations of sand in the distal portions of these deltas (Hine, 1975). These bars tend to migrate landward on the downdrift coastal sectors at rates that can be quite high, ranging from 64–86 m/year (Smith and FitzGerald, 1994), to 133–327 m/year (FitzGerald, 1984; Gaudiano and Kana, 2001), and up to 46 m/month (Balouin et al., 2001, 2004a). Generally, in such mixed-energy (wave-tidal) settings, swash bars coalesce during their landward migration, thus, resulting in the development of large complex bars just before welding to the shoreline (Hine, 1975; Aubrey and Speer, 1984; FitzGerald, 1984, 1988; FitzGerald et al., 1984, 2000a; Kana et al., 1999; Borrelli and Wells, 2003). This welding mechanism can constitute an extremely important natural form of beach nourishment that can, in some cases, attain several million m³ in the course of a single welding event (Kana et al., 1999). Although ebb delta bars are a major component of the inlet morphology and of the shoreline sediment budget, their morphodynamics are rather poorly understood. Notwithstanding the various literature reports on onshore swash bar migration, no detailed work has been carried out so far on the mechanisms of migration of these coastal accumulation features. Conclusions also vary concerning the dominant process controlling migration. FitzGerald et al. (2000b) highlighted swash processes. Davis (1978) identified both swash and surf processes. Oertel (1975) and Gaudiano and Kana (2001) attributed bar migration to surf processes, while Oertel (1972) and FitzGerald (1984) recognised surf processes associated with tidal current asymmetry. These observations exclusively concern microtidal and mesotidal...
settings. Knowledge on the morphology and dynamics of these bars in very large tide-range settings (spring tidal ranges >8 m) is scanty, especially at short timescales.

Working in the large tide-range setting of the Normandy coast, in France, Robin et al. (2007a) highlighted a relationship between wave energy flux and bar migration rate. Although monitoring was restricted mainly to shoaling wave conditions and incorporated only a small part of the period of surf activity during the semi-diurnal tidal cycle in water depths greater than 0.8 m, a good correlation was found between wave energy and bar migration. Measurements in shallow water depths (in the swash and inner surf zones) are, however, required in order to quantify the relative effects of swash, surf, and shoaling wave processes on sand transport and bar dynamics. Shifting of these process domains over the bar profile is to be expected during a tidal cycle. Depending on the wave energy and the tidal range conditions (neap or spring tides), the intertidal profile will be affected by spatially and temporally variable ranges of wave shoaling, surf and swash processes (Masselink and Short, 1993). This influence becomes more pronounced with larger tidal ranges, as on megatidal beaches (the term ‘megatidal’ has been applied to beaches with mean spring tidal ranges >8 m; Levoy et al., 2000). These environments show a large variation of wave heights and of currents due to both tides and storm activity during a tidal cycle (Robin and Levoy, 2005; Robin et al., 2007a). Moreover, tidal and wind-induced currents, generally of minor to moderate importance on wave-dominated microtidal environments, may also play a significant role in sediment transport processes, especially on the lower foreshore (Levoy et al., 2000; Reichmüth and Anthony, 2007; Sedrati and Anthony, 2007). The aim of this paper is to investigate the relative importance of the different hydrodynamic processes on ebb-tidal delta bar migration on a very high tidal range environment. Detailed morphological and hydrodynamic measurements in shallow water associated with fluorescent tracer analysis were conducted during two spring and two neap tides in both storm and low energy wave conditions in order to determine the relative activity of surf and swash processes, as well as the ancillary contribution of currents in bar morphodynamics.

Fig. 1. Location of the study area.
2. Study area

2.1. Regional characteristics

The study was conducted at Regnéville inlet, located on the west Cotentin coast in Normandy, bounding the Channel Islands embayment (Fig. 1). The western coast of Cotentin is sandy and rectilinear, and indented by eight small inlets (locally called “havres”). The study site covers the largest of these, Regnéville inlet (Fig. 2).

The offshore area is characterised by complex hydrodynamic conditions. The tidal wave, propagating eastward from the Atlantic Ocean, is strongly modified by the shoreface bathymetry of this area, which comprises the Channels Islands and numerous shoals and archipelagos. In the southern part of the west coast of Cotentin (Mont-Saint-Michel Bay), reflection generates a standing tidal wave, a consequence of which is the very large tidal range at the coast. Northward, the tidal wave is progressive. The M2 (lunar and semi-diurnal) harmonic, which dominates the tidal wave, is associated with a virtual amphidromic point located on land in southwest England north of Portland (Pingree and Griffiths, 1979). The tidal range shows a marked increase from the north to the south of the Channel Islands embayment. At exceptional spring tidal conditions, the range is about 5 m in Cherbourg but attains 15 m, one of the highest in the world, in Mont-Saint-Michel Bay.

The central English Channel is an area of strong tidal current activity. Offshore mean currents measured at “Les Nattes” (Fig. 1) are parallel to the coast during most of the tidal cycle and can reach 1 m/s (Levoy, 1994). Maximum speeds are attained near high and low tide stages. These currents are directed northward around high tide and southward at low tide.

Open to the west, the Channel Islands Bay is exposed to North Atlantic Ocean waves. However, wave propagation is complicated due to the irregular shelf bathymetry, which results in decreasing wave heights on the shoreface (Levoy, 1994). Recorded offshore wave heights at “Les Nattes” (Fig. 1) are less than 0.5 m 65% of the time. Wave heights larger than 1.5 m are observed only 2% of the time. The waves are essentially from a west window (waves with southwesterly to northwesterly (230°–310°) directions represent more than 90% of the observations) in response to the prevailing synoptic winds in this region. Residual swell from the Atlantic Ocean occasionally complements the locally generated wind waves. The peak period is in the 5–9 s range. Near the coast, rocky platforms and tidal deltas locally modify the wave propagation patterns. The Channel Islands embayment may be viewed as a very large dissipative embayment.

2.2. Local characteristics

The field study site is characterized to the north by a complex spit, the Agon spit. This spit migrates to the south and its distal end exhibits eight recurves (Fig. 2) (Robin and LeRoy, 2007; Robin et al., 2007b). The ebb delta is large; the exposed zone at low spring tide extends more than 4 km offshore. Many ‘swash’ bars occur on its updrift shore, but are absent in its southern shore (Figs. 2 and 3). At Regnéville inlet, the tidal range attains 11 m at mean spring tides and 14 m during exceptional spring tides. These conditions produce a mean tidal prism of $15.10^6$ m$^3$ per tidal cycle.

The studied bar was located in the mid-tidal zone and its orientation was oblique to the beach (50° and the crest axis is 10°–190°), with the northern part located closer to the shoreline, consistent with the dominant wave direction and southerly longshore sediment transport (Figs. 2 and 3). The bar was 100 m wide, 250 m long, and 2 m high. The transverse profile of the bar was highly asymmetrical along the length of the bar. (Figs. 3 and 4). As reported by Hayes and Kana (1976) for this type of morphology, three distinct morphological sections were observed: a seaward slope, a slip face and a runnel. The seaward slope had a gentle gradient (tanβ = 0.02) and was characterised by sand with a mean D50 value of 0.5 mm and by numerous shells and gravel clasts. Plane beds generally prevailed, but wave ripples occurred during storm conditions. The slip face was steep with a gradient of 0.3 and exhibited waterline marks and drainage rills. The runnel was generally flat and characterised by finer sediment than the seaward slope. The D50 value was around 0.2 mm and shells were absent. High-tide water depths over the top of the bar varied significantly in the course of the fortnightly tidal cycle, ranging from 0.4 m at neaps to up to 4 m at springs.

The general hydrodynamic conditions in the study site and the corresponding bar migration patterns have been described by Robin (2007) and Robin and LeRoy (2005), and divided into 3 categories on the basis of the high-tide significant wave height: 1) low energy conditions (Hs < 0.7 m), with no bar movement; 2) moderate conditions...
(0.7 < Hs < 1.2 m), with an onshore bar migration rate of 0.2 m per day; 3) storm conditions (Hs > 1.2 m), exclusively characterised by onshore bar migration at a rate of up to 0.5 m per day.

3. Methods

Fieldwork was undertaken during four short experiments (29 January 2004, 22 March 2004, 2 and 9 May 2005) of one tidal cycle each. The methodology was identical, and consisted of the collection and analysis of topographic, hydrodynamic and tracer data. Given the difficulties inherent in conducting direct measurements on transport patterns in very small water depths (Masselink and Puleo, 2006; Hughes and Moseley, 2007) such as those that prevail over the bar, the tracer experiments and shear stress values, calculated from the hydrodynamic data and from the bar grain-size characteristics, were used to identify transport characteristics.
3.1. Collection and analysis of topographic data

Bar topography was monitored using a kinematic DGPS Trimble 4400 RS and referenced to benchmarks of the French National Geodesic Institute (IGN 69). Ten 250 m long profile transects spaced 25 m apart, transverse to the bar, were surveyed at low tide before and after each experiment (Fig. 2). The spacing between the measured points was less than 1 m and special attention was given to the slip face. Using the same instrument mounted on a platform and towed by a quad vehicle, the surrounding beach topography, and especially the 3D morphological evolution, was also monitored on a 600 m longshore × 700 m cross-shore zone encompassing the bar (Fig. 2). Using benchmarks located on the beach, the operational accuracy of individual surveys by both methods was estimated at ±3.2 cm including instrument, field measurement and interpolation uncertainties, thus resulting in a ±5 cm uncertainty margin on differentials between two surveys. The results reported here concern only the central instrumented profile. To study the bar movements, the middle position of the slip face was used as an indicator of the ridge position. The location of the crest of the ridge or the break in slope between the slip and the seaward faces, which is not always easy to determine due to the smooth profile, are indeed considered to be less valuable for this purpose.

3.2. Collection and analysis of hydrodynamic data

Hydrodynamic measurements were made with S4DW Inter-Ocean® self-recording electromagnetic current meters (S4) with a built-in pressure sensor (Directional Wave) to measure wave characteristics. The instruments were deployed about 40 cm above the bed, on the exposed face of the bar (29/01/2004 (D1, D2), 22/03/2004 (B1, B2), 02/05/2005 (C1, C2) and 09/05/2005 (A1, A2)) and in the runnel seaward of it (30/01/2004 (D4), 22/03/2004 (B4)), (Figs. 5 and 10). The data were collected in continuous mode at a 2 Hz frequency and mean currents were computed as 1 min averages. The recorded data were processed by Inter-Ocean Systems wave and current software packages supplied with the S4DW current meter.

An additional micro-Acoustic Doppler Sontek Velocimeter (two-dimensional sideways-looking microADV Sontek) and a pressure sensor were deployed on the bar crest (29/01/2004 (D3), 22/03/2004 (B3), 02/05/2005 (C3) and 09/05/2005 (A3), Figs. 5 and 10). The microADV was installed in order to measure currents, especially swash flows, very close to the bed, at heights of 10 cm (29 January 2004 and 22 March 2004) and 5 cm (2 and 9 May 2005) above the bed. The pressure sensor was installed 5 cm above the bed. The data were collected continuously at 4 Hz. Velocity measurements from the micro-ADV tended to become noisy in highly turbulent or aerated flows. Signal correlation values recorded by this instrument were used to identify such potentially spurious data. When signal correlation for a given acoustic beam was less than 80%, the data were discarded. Under swash conditions, when the sensor occasionally emerged, a signal-to-noise ratio of less than 100 was used to identify these occasions of undefined flow. In order to appreciate the current structure relative to the bar morphology, the mean currents were decomposed into cross-shore, onshore positive, and longshore, northward positive, components normalised relative to the crest line of the bar.

The vertical tidal excursion rate, or rate of vertical water-level change due to the tide, has been shown to be an important parameter in the translation of each process domain along the intertidal profile (Masselink, 1993). The vertical tidal excursion rate was determined from data obtained by the pressure sensor at the bottom of the seaward slope (A1, B1, C1 and D1). The vertical excursion rate, , at instant for each of the values obtained was calculated using the relation: where and are the water levels at and minutes, respectively. The vertical water level change can be converted to the horizontal water-level change by dividing by the beach gradient, for each point along a typical profile.

Wave data and water levels were used following the methodology of Kroon and Masselink (2002) in order to determine the periods and durations of operation of different hydrodynamic processes (shoaling waves, surf and swash) on the seaward slope of the bar. This methodology has been successfully employed in a number of studies (Reichmüth, 2003; Balouin et al., 2004b; Robin, 2007).

The Kroon and Masselink (2002) method is only valid for low wave energy because it does not take into account wave dissipation during propagation. For storm conditions, the duration of swash/surf/shoaling was calculated only for the point where the micro-ADV and pressure sensor were located (A3, B3, C3 and D3). However, the residence time of the swash on the whole seaward slope was also computed with the Kroon and Masselink (2002) method for comparison with the values at the instrument location. The bar slope seaward of the crest where the micro-ADV was deployed is weak and can consequently significantly influence the run-up height and hence the duration of swash action.

In order to identify the roles of waves and currents on sediment transport, the current- and wave-induced bed shear stresses at points A3, B3, C3 and D3 were calculated for each experiment. The critical bed-shear stress was computed from the sediment characteristics by:

\[ \tau_{cr} = (\rho_s - \rho) \cdot g \cdot D_{50} \cdot \rho \cdot \theta \cdot g \cdot \rho \cdot \theta \]

where \( \rho_s \) and \( \rho \) are the sediment and fluid densities, \( g \) the acceleration of gravity, and \( D_{50} \) the median bed-material diameter. The Shields parameter, \( \theta \), was computed by an approximation of the Shields curve proposed by Van Rijn (1993):

\[ \theta = 0.24 \cdot D_s^{-1} \cdot D_{50} \cdot \rho \cdot g \text{ for } D_s \leq 4 \]

\[ \theta = 0.14 \cdot D_s^{-0.14} \cdot D_{50} \cdot \rho \cdot g \text{ for } 4 \cdot D_s \leq 10 \]

\[ \theta = 0.04 \cdot D_s^{-0.19} \cdot D_{50} \cdot \rho \cdot g \text{ for } 10 \cdot D_s \leq 20 \]

\[ \theta = 0.013 \cdot D_{50}^{-0.28} \cdot D_{50} \cdot \rho \cdot g \text{ for } 20 \cdot D_s \leq 150 \]

\[ \theta = 0.055 \text{ for } D_s = 150 \cdot D_{50} \]

with particle diameter, \( D_s = \sqrt{(s - 1) \cdot g / \nu^2 \cdot D_{50}} \), where \( s = \rho_s / \rho \) is the sediment relative density, and \( \nu \) the kinematic viscosity. Currents

Fig. 4. Typical transect across the bar with horizontal lines indicating tidal levels (MHWS, mean high water spring; MHWN, mean high water neap; MSL, mean sea level. The beach elevation and the water levels are referenced to the French National Geodesic Institute level (IGN 69). The height of the slip face is approximately 2 m.
and wave-induced bed shear stresses were computed, following the Van Rijn (1993) model by:

\[
\tau_c = \left( \rho \cdot f_c \cdot (V \rightarrow r^2 + u \rightarrow r^2) \right) / 8 \quad \text{and} \quad \tau_w = \left( \rho \cdot f_w \cdot U^2 \right) / 4,
\]

where \(V\rightarrow r\), the depth-averaged velocity vectors in the main current direction, is obtained by numerical integration of a logarithmic velocity distribution over the depth inferred from the measured velocity and computed bed roughness heights (Van Rijn, 1993), \(u\rightarrow r\) is the time-averaged and depth-averaged return velocity due to wave action, \(U\) is the near-bed peak orbital velocity, and \(f_c\) and \(f_w\) friction coefficients due to currents and waves.

3.3. Collection and analysis of tracer data

Sediment tracer studies have been widely used to study sediment motion on straight beaches (e.g., Stépanian et al., 2001; Anthony et al., 2005; Tonk and Masselink, 2005; Sedrati and Anthony, 2007), and in more complex systems such as inlets (Oertel, 1972; Vila-Concejo et al., 2004). This technique has also been used to monitor transport on swash platforms by Balouin et al. (2001) and Robin (2007). In order to identify and quantify tidally-averaged sediment transport rates occurring on the seaward slope, four standard fluorescent tracer experiments were undertaken. The method employed here is based on the approach of White and Inman (1989a). Before each experiment, sand was collected in the study area, brought back to the laboratory, washed with fresh water to eliminate salt, dried and dyed with fluorescent paint in a concrete-mixer, and finally dried again. Before and after the dying process, samples were taken and the grain-size distributions compared to make sure that this process did not significantly alter the sediment characteristics. Using sand from the study area and verifying that the tagged and the native sands have similar grain-size characteristics usually ensures that the tracer will have the same hydraulic behaviour as the natural sediment, which is one of the fundamental assumptions of particle tracking methods (Black et al., 2004).

![Fig. 5. Residual topographic change of the central profile during the 09/05/2005 experiment (low energy and spring tide conditions) (May 9 01h00 solid line; May 9 13h00 dashed line) (A) and 22/03/2004 (storm conditions during spring tide) (March 22 15h00 solid line; March 22 23h30 pm dashed line) (C). Cross-shore profile evolution during the 09/05/2005 (B) and the 22/03/2004 (D) experiments. Elevations in A and C are referenced to the French National Geodesic Institute level (IGN 69). Horizontal dashed lines on B and D denote the +/- 5 cm uncertainty in differentials between individual topographic surveys. The locations of instruments are indicated for each experiment.](image)
As an example, the median diameter of the tagged sand used during the 30 January 2004 experiment was coarser by only 0.03 mm (0.225 mm) than the initial sediment (0.196 mm), which is only slightly more than the 10% limit considered by White and Inman (1989a) as an acceptable difference for the experimental results not to be significantly altered. It is worth noting that Vila-Concejo et al. (2004) consider as acceptable much larger differences (85% – 125%) between the dyed and the natural mean grain size, and Black et al. (2007) note that wider limits seem to be accepted in most of the studies reported in the literature. At the beginning of the experiment, a mass of tracer is soaked with water and in a detergent solution to eliminate surface tension and thus reduce the floating problems. The tracer was then poured at low tide into a circular 1 m diameter × 0.1 m depth pit on the seaward flank of the bar near the crest. The mass of tracer used is fitted to the expected hydrodynamic conditions, and hence potential sediment transport conditions. In the present experiments masses between 22 kg and 50 kg were used (Table 1). During the following low tide, tracer concentrations were evaluated from visual counts under ultraviolet light of the tagged grains present at the beach surface. The spatial grid scheme is based on a polar coordinates system (Levoy et al., 1997) centred on the immersion point marked by a metal picket driven in the beach at the beginning of the experiment. The detailed method used to derive the tracer concentration from the number of grains present in surface is presented in Levoy et al. (1997). It is based on two principal assumptions: (i) the grain size distribution of the tracer is identical throughout the whole cloud and is similar to that of the natural sand and (ii) the content of tagged grains present on the surface is representative of that observed in depth on the entire mobile layer. Some preliminary tests, using sand from the west coast of Cotentin, have shown that, for a given grain diameter, the mass of a sample is proportional to the number of grains it contains and that the slope of this linear relation is also proportional to the grain diameter. Using those relations and assumption (i), the mass of tagged grain present in a superficial layer can be computed from the number of fluorescent particles counted in surface. The thickness of this superficial layer is deduced from the grain size distribution, and the total mass it contains can then be computed knowing the counting surface and the sediment density. The superficial fluorescent grains concentration can then be deduced from those two masses and finally the in-depth concentration using assumption (ii). As observed by Silva et al. (2007), as long as the tracer has not reached an equilibrium state with the transport system, a clear decreasing concentration of tracer with increasing depth exists, such that the latter hypothesis becomes invalid. But these authors recognize that, in such a non-equilibrium state, dispersive transport remains significant, thus calling into question another fundamental assumption on which are based all particle tracking experiments, and which stipulates that dispersion and diffusion should be dominated by advection transport (Madsen, 1989). The thickness of the mobile bed is estimated in the field from the depth of penetration of a significant amount of tracer measured in different points distributed in the tracer cloud. As mentioned by White and Inman (1989a,b), this approach is subjective in part because it depends on the amount considered as significant, and tends to overestimate the actual bedload thickness. The centroid location is then computed by integration (Levoy et al., 1997) following the spatial integration method, as described by Madsen (1989), and its motion expressed as longshore and cross-shore components with respect to the general bar crest orientation (Table 1). Tracer recovery rates are also computed to verify that the tagged sand motion has been correctly measured (White, 1998), thus satisfying the third assumption of particle tracking experiments. In the four experiments, the total recovery rates (including immobile sand) (Table 1) are larger than 80% during low energy conditions and between 60% and 70% during storm conditions, thereby validating the experiment (White, 1998). Due to globally low energy conditions along this coastal area, a significant amount a tracer did not move from the injection spot. The unmoved sand was recovered and weighed in the laboratory to calculate the total recovery rates. It is reasonable to assume that these experiments correctly highlight the sediment pathways. As sediment transport quantification, a hardy and uncertain task in itself given the present state of the art, was not the main objective of these experiments, exact values of the concentration and of the thickness of the mobile layer are not key issues here, because errors, if systematic, would not change the centroid location and hence the transport pathway. These values are only required in computations of tracer recovery rates.

### 4. Results

#### 4.1. Spring tide experiments

#### 4.1. General hydrodynamic conditions

The two experiments were undertaken during spring tides with tidal ranges of 11.4 m and 10.6 m (on 22 March 2004, and 9 May 2005). The location of the instruments is shown in Fig. 5. The tidal water level, nearshore currents, and wave characteristics are shown in Figs. 6 and 7.

On the 09/05/2005 campaign was characterised by low energy conditions with a significant wave height less than 0.35 m at the foot of the slip face of the next bar (A1) and 0.4 m on the bar crest (A3). Significant wave periods were 4 to 5 s and waves came, mainly from the 270°, almost normal to the bar crest (10° – 190°). On the bar crest (A3), mean current velocity reached 0.65 m/s, 30 min after high tide. Mean currents were mostly northward to north-westward (306° – 343°) typically induced by the regional tide circulation (for about 225 min, from 95 min before to 130 min after, high tide). Only over a very short period (20 min), at the

### Table 1

Pattern of tracer dispersal during the experiments (X and Y correspond respectively to the longshore (North positive) and cross-shore (onshore positive) components of the centroid migration) and bed shear stress characteristics.

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Hydrodynamic conditions</th>
<th>Injected mass</th>
<th>Estimated immovable sand</th>
<th>Mobile tracer recovery</th>
<th>Layer thickness</th>
<th>Estimated total tracer recovery</th>
<th>X/Y</th>
<th>Centroid migration</th>
<th>Bar migration</th>
<th>Bar crest immersion period</th>
<th>Duration of swash/surf/shoaling processes when the critical bed shear stress is exceeded and the mean current is towards the bar crest</th>
</tr>
</thead>
<tbody>
<tr>
<td>9 May 2005</td>
<td>Spring tide/fair weather H&lt;sub&gt;s&lt;/sub&gt; max 0.4 m</td>
<td>50 kg</td>
<td>34 kg</td>
<td>7.8 kg</td>
<td>2.0 cm</td>
<td>41.8 kg (83.6%)</td>
<td>2.3 m/– 0.7 m</td>
<td>2.5 m/353°</td>
<td>0.0 m</td>
<td>4 h 25 mn</td>
<td>2 mn/38 mn/0 mn</td>
</tr>
<tr>
<td>22 March 2004</td>
<td>Spring tide/storm condition H&lt;sub&gt;s&lt;/sub&gt; max 1.4 m</td>
<td>45 kg</td>
<td>34 kg</td>
<td>19.7 kg</td>
<td>4.0 cm</td>
<td>28.7 kg (63.7%)</td>
<td>16.7 m/10.3 m</td>
<td>19.5 m/43°</td>
<td>9.7 m</td>
<td>4 h 45 mn</td>
<td>2 mn/86 mn/0 mn</td>
</tr>
<tr>
<td>2 May 2005</td>
<td>Neap tide/fair weather H&lt;sub&gt;s&lt;/sub&gt; max 0.2 m</td>
<td>35 kg</td>
<td>32 kg</td>
<td>3.8 kg</td>
<td>1.5 cm</td>
<td>32.8 kg (93.8%)</td>
<td>0.6 m/3.4 m</td>
<td>3.5 m/90°</td>
<td>0.8 m</td>
<td>2 h 30 mn</td>
<td>5 mn/58 mn/0 mn</td>
</tr>
<tr>
<td>30 January 2004</td>
<td>Neap tide/moderate conditions H&lt;sub&gt;s&lt;/sub&gt; max 0.8 m</td>
<td>22 kg</td>
<td>9 kg</td>
<td>5.5 kg</td>
<td>4.0 cm</td>
<td>14.5 kg (65.9%)</td>
<td>17.7 m/7.2 m</td>
<td>19.3 m/34°</td>
<td>5.5 kg</td>
<td>3 h 00 mn</td>
<td>8 mn/85 mn/0 mn</td>
</tr>
</tbody>
</table>

Bed shear stress during swash/surf/shoaling processes when the mean current is towards the bar crest

- 2 N/m²/2–4 N/m²/0 N/m²
- 9 N/m²/9–25 N/m²/0 N/m²
- 2–3 N/m²/2–4 N/m²/0 N/m²
- 3–4 N/m²/3–6 N/m²/0 N/m²
beginning and at the end of the tidal cycle when the relative wave height increased, were mean currents directed towards the bar crest (10°–92°), but with mean velocities always less than 0.2 m/s (flood tide) and 0.1 m/s (ebb tide). Overall, the crest of the bar was submerged during about 259 min and the maximum water depth was 3.0 m.

The 22/03/2004 campaign was characterised by storm conditions with high tide significant wave heights reaching 1.3 m (point B1) and decreasing with the water level. Significant wave periods were 5 to 6 s and waves came from the west (270°), also almost normal to the bar crest. Significant attenuation occurred between the bottom of the seaward slope and the top of the bar at the beginning and at the end of the tidal cycle when the water depth was less than 2 m. Above this threshold, no significant attenuation was observed and the wave height at high tide was close to the value at point B1 (1.4 m at point B3). On the bar crest (B3), maximum mean velocities were observed at the beginning and at the end of the tidal cycle (0.56 m/s) when cross-shore currents were strong and onshore-directed and longshore currents weaker (below 0.15 m/s). This spatial current distribution clearly indicates strong wave activity versus a small tidal contribution related to the low water depths at the beginning and at the end of the tidal cycle. At high tide, mean current speeds were also strong and reached 0.4 m/s. The duration of northward-directed mean currents (326°–342°) during these storm conditions was shorter than during the 09/05/2005 campaign, lasting 198 min (from 80 min before, to 118 min after, high tide). Mean currents directed towards the bar crest in shallow water occurred the rest of the time (68 min). The total duration of submersion of the bar crest was about 290 min, with a maximum water depth at high tide of 4.1 m.

4.1.2. Morphological and tracer patterns

During low energy conditions (09/05/2005), the bar showed no significant movement. Topographic variations were small, and within
the error margin (Fig. 5b). In storm conditions (22/03/2004), a shore-ward migration of 0.7 m was observed during one tidal cycle. The seaward slope experienced significant erosion of up to 15 cm (Fig. 5d), while the slip face underwent accretion, leading to the landward migration of the bar. The advection of the fluorescent tracer confirms this trend, evincing northward sediment transport (353°), away from the bar crest (10°–190°, Fig. 6), under strong mean currents and low-energy wave conditions (a movement of 2.5 m of the centre of gravity of the cloud of fluorescent grains) and towards the slip face of the bar during storm conditions (movement of 16.7 m of the centroid of the tracer in a direction of 42° N) (Fig. 7). During a spring tide with low energy conditions, the cross-shore vector indicated a seaward displacement of 0.7 m of the tracer centroid (Table 1). Longshore transport exceeded cross-shore transport, but rates were very low. During storm conditions, cross-shore advection of 10.3 m occurred towards the crest of the bar, contributing to its onshore movement (Table 1).

4.1.3. Processes

Under low energy conditions (09/05/2005), the wave-induced shear stress was of the order of 1–3.5 N/m² (Fig. 8a) and was always larger than the critical threshold of sediment movement (0.37 N/m²). The current-induced shear stress was close to the critical value at the beginning and at the end of the tidal cycle, and reached 13 N/m² at high tide when the currents flowed northward (330°). On the basis of the mean current direction, the potential duration of sediment transport towards the crest of the bar was restricted to 20 min at the beginning of the flood (sediment motion may be initiated jointly by waves and currents during the first 10 min, and by the waves only during the last 10 min) and to 20 min at the end of the ebb tide (solely under wave action). This potential transport was efficient during both the swash, which had a very short duration (2 min), and at the beginning and the end of the surf (38 min) (Table 1). Nevertheless, the high-resolution topographic measurements show that this transport was not enough to
Fig. 8. Wave and current shear stresses during the 09/05/2005 (A) and 22/03/2004 (B) experiments. Solid lines indicate a bed shear stress exceeding the critical bed shear stress with current direction oriented towards the bar crest. Vertical line delimits the influence of processes (shoaling, surf, swash) measured at the micro-ADV point.

Fig. 9. Relative occurrence of swash, surf and shoaling wave processes over the bar profile during the 09/05/2005 (A) and 22/03/2004 (only swash) (B) experiments.
lead to significant migration of the bar. The direction of dispersal of the tracer indicates that sediment transport occurred during the shoaling phase, mainly under the effect of the northward tidal currents, parallel to the bar crest, probably with a weak contribution by waves.

During storm conditions (22/03/2004), the wave shear stress was about seven times larger than the values calculated for low energy conditions, with maxima occurring at the beginning and at the end of the tidal cycle (20–25 N/m²) (Fig. 8b). The current shear stress was weaker, lower than 2 N/m², but regularly larger than the critical threshold of sediment movement. In all, the time of potential sand mobilization towards the crest was important. It lasted 45 min at the beginning of the flood (produced by the action of both waves and currents during the first 34 min, and then only by waves) and 43 min at the end of the ebb tide (both waves and currents during the last 26 min). The residence time of the swash was similar to that observed during low energy conditions (2 min). In contrast, the residence time of surf was longer (86 min), and sediment transport was caused by both waves and currents (Table 1). The duration of the potential movement of sediments in the direction of bar displacement was directly related to the increase in wave energy, and especially to the duration and intensity of potential surf action. Under these conditions, a landward displacement of the bar was observed.

The residence time of each process was also calculated for the whole seaward slope. During the 09/05/2005 campaign (low energy), the duration of shoaling increased at the bottom of the seaward slope, due to the progressive submergence of this part of the bar (Fig. 9a). Nevertheless, swash and surf durations were similar to those at the micro-ADV deployment point (A3). During 22/03/2004 (storm conditions), only the residence time of swash could be calculated using the methodology of Kroon and Masselink (2002), storm conditions not being amenable to analysis of surf residence times. The swash residence time was comparable to that of B3 (Fig. 9b).

Fig. 10. Residual topographic change of the central profile during the experiments: 02/05/2005 (low energy and neap tide conditions) (May 2 09h00 solid line; May 2 18h00 dashed line) (A) and 29/01/2004 (storm conditions during neap tide) (January 29 19h00 solid line; January 30 04h00 dashed line) (C). Cross-shore profile evolution during the 02/05/2005 (B) and 29/01/2004 (D) experiments. On A and C, elevations are referenced to the French National Geodesic Institute level (IGN 69). Horizontal dashed lines in B and D denote the ±5 cm uncertainty in differentials between individual topographic surveys. The locations of instruments are indicated for each experiment.
4.2. Neap tide experiments

4.2.1. General hydrodynamic conditions

The two experiments were undertaken under tidal ranges of 5.2 m and 5.0 m (on 29 January 2004, and 2 May 2005). The hydrodynamic conditions are illustrated in Figs. 12 and 11. The location of the instruments is shown in Fig. 10.

During the 02/05/2005 experiment, hydrodynamic conditions were relatively calm with waves from west (270°), and significant wave height and periods at the foot of the slip face of the next bar seaward (C1) of about 0.25 m and between 5 and 6.5 s. At the bar crest (C3), significant wave height reached 0.27 m at high tide. Throughout the tidal cycle, mean currents exhibited very low velocities, always below 0.08 m/s, closely related to the low tidal range and the absence of wave activity. Their directions were between east-southeast and west-southwest (111° to 249°). The time of submersion of the bar crest was about 130 min with a maximum water depth at high tide of 0.3 m.

The 29/01/2004 experiment was characterised by moderate conditions with high-tide significant wave heights reaching 0.76 m at the foot of the seaward slope (D1) and decreasing with the water level. Significant wave height attenuation occurred during wave propagation across the bar, so that at high tide at point D3, wave heights attained only 0.42 m. The significant wave period was 3.5 s and waves came from the west to south-west (270° to 225°). Mean current velocities attained 0.5 m/s at the beginning and at the end of the tidal cycle, when cross-shore currents were onshore and stronger than longshore currents, then decreased as the tidal level increased, as observed during the stormy conditions in the course of the spring tide experiment (22/03/2004). Currents flowing towards the bar crest lasted 75 min at the beginning and end of the tidal cycle.

Fig. 11. Spatial distribution of the sand tracer and hydrodynamic condition during the 29/01/2004 (storm and neap tide conditions) experiment. Tracer contents are expressed in grams of tagged grains per gram of natural sand and deduced from visual counts of fluorescent particles present on the surface. For the significant wave height, the grey line represents the pressure sensor installed near the micro-ADV (D3), and the solid line the S4DW (D1).
cycle). Only around high tide (from 42 min before, to 45 min after, high tide) did northwest to north currents (309° to 358°) prevail. In all, the time of submersion of the crest of the bar was 183 min, with a maximum water depth at high tide of 0.8 m.

4.2.2. Morphological and tracer patterns

During low energy conditions (02/05/2005), the bar showed no significant movement, and no noteworthy topographic variation was observed (Fig. 10b). Under moderate conditions (29/01/2004), a shoreward migration of 0.4 m was recorded. The seaward slope underwent erosion but this was only significant on the bar crest where it reached 6 cm (Fig. 10d). The advection pattern of the fluorescent tracer confirms this trend, with oblique sediment transport towards the crest of the bar (displacement of 19 m of the centre of gravity of the cloud of fluorescent grains in the direction 34° N) (Fig. 11). Under low wave energy, the sediment transport was also towards the slip face (direction of 90° N), but the movement of the centre of gravity of the cloud was only 3.5 m (Fig. 12). During this last campaign, the cross-shore vector of the tracer indicated an onshore advection of 3.4 m while during moderate condition, the displacement rose to 7.2 m (Table 1).

4.2.3. Processes

During low energy conditions (02/05/2005), the wave shear stress was between 1.8 N/m² and 3.8 N/m² (Fig. 13a). It was always larger than the critical bed stress value (0.37 N/m²). The current-induced shear stress was weak, always lower than 0.04 N/m². Current directions were between 111° north and 249° north. The direction of dispersal of the tracer was not representative of this general current pattern. It indicated, rather, a transport of sediment controlled by the

Fig. 12. Spatial distribution of the sand tracer and hydrodynamic conditions during the 02/05/2005 experiment (low energy and neap tide conditions). Tracer contents are expressed in grams of tagged grains per grams of natural sand and deduced from visual counts of fluorescent particles present on the surface. For the significant wave height, the grey line represents the pressure sensor installed near the micro-ADV (C3), and the solid line the S4DW (C1).
Fig. 13. Wave and current shear stresses during the 02/05/2005 (A) and 29/01/2004 (B) experiments. Solid lines indicate a bed shear stress exceeding the critical bed shear stress with current direction oriented towards the crest of the bar. Vertical lines delimit the influence of processes (shoaling, surf, swash) measured at the micro-ADV point.

Fig. 14. Relative occurrence of swash, surf and shoaling processes over the bar profile during the 02/05/2005 (A) and 29/01/2004 (only swash) (B) experiments.
wave direction. The time of potential movement of sediment towards the crest of the bar, which was due only to wave action, was 44 min at the beginning of the flood tide (2 min of swash and 42 min of surf) and 19 min at the end of the ebb (3 min of swash and 16 min of surf) (Table 1). This duration was not sufficient to induce significant movement of the bar as underscored by the short distance of tracer centroid displacement (3.5 m).

Under moderate conditions (29/01/2004), the wave shear stress was always larger than 3 N/m² and reached 7 N/m² at high tide (Fig. 13b). The current shear stress was smaller, with values between 0.39 and 0.61 N/m², but always larger than the critical bed shear (0.37 N/m²). In all, the time for potential movement of the sediment in the direction of the crest of the bar (due to both waves and currents) was significant and directly related to the increase in significant wave height. It lasted 42 min at the beginning of the flood tide and 51 min at the end of the ebb. The residence time of the swash was similar to that observed during low wave energy (8 min). In contrast, the surf duration was much more important (85 min) (Table 1). In these conditions, an onshore movement of the bar was observed.

The residence time of each process has been calculated for the whole seaward slope under neap tides. During the 02/05/2005 experiment (low energy), surf was not the only process acting on the bar as suggested by data from the micro-ADV site. The duration of shoaling increased with distance from the crest (Fig. 14a). Nevertheless, the residence time of swash remained small, lesser than 10 min. Only the residence time of swash can be determined for the 29/01/2004 experiment (storm conditions). It was similar to that of D3 (Fig. 14b).

5. Discussion

5.1. Duration of the swash

The recorded water levels and computation of run-up in shallow water during contrasting conditions show that the duration of the swash is very short. It lasts only 8 min during the neap tide under moderate wave and is more usually less than 3 min (i.e. less than 2% of the time of submergence of the bar); this pattern is the result of the large tidal excursion rates at the bar location. Vertical and horizontal tidal excursion rates are high in the mid-tidal zone in this megatidal environment, attaining excursion rates of 0.06 m/min during springs and 0.02 m/min during neap tides (Fig. 15).

**Fig. 15.** The vertical tidal excursion rate during storm conditions with a spring tide (A) and moderate conditions with a neap tide (B).
These speeds are larger than those found in the literature in field sites with large tidal ranges. Masselink and Anthony (2001) and Reichmuth (2003) observed vertical speeds less than 0.02 m/min, and Anthony et al. (2004) speeds of the order of 0.03 m/min for spring tides. The larger tidal range of the Regnéville area induces shorter swash duration than in these other field sites. The small slope on the bar crest also influences the duration of swash action by favouring fast horizontal translation rates (5.6 m/min during spring tides and 2.5 m/min during neap tides). Obviously, had the bar been located on the upper part of the beach, in a stage just prior to welding onto the coast, the duration of swash processes would have been greater.

5.2. Absence of bed return flow (undertow)

The mean cross-shore current exhibits specific intensity and directional patterns in the course of the tidal cycle. It is generally accepted in the literature and in sediment transport models that wave-induced currents are offshore in the surf zone and onshore in the shoaling zone (Osborne and Greenwood, 1992a,b). The bed return flow represents a mass conservation response to the associated drift of water under the crests of incident waves, and is often referred to as “undertow” in the surf zone (Svendsen, 1984). Its intensity increases linearly with incident wave height (Greenwood and Osborne, 1990; Hazen et al., 1990) and can attain up to 0.4 m/s (Miller et al., 1999; Garcez Faria et al., 2000; Aagaard et al., 2006), but is more frequently between 0.1 et 0.3 m/s (Davidson-Arnott and Mc Donald, 1989; Greenwood and Osborne, 1990; Masselink and Black, 1995; Aagaard et al., 2002; Anthony et al., 2004). The results obtained during this study show that at the beginning of the surf, flow velocity is onshore directed with velocities that can reach 0.6 m/s (22/03/2004, storm during a spring tide), then decreases with the increase in water depth. An offshore-directed cross-shore current is also recorded with larger water depths and non breaking waves (shoaling conditions). These results from the study site, thus, highlight the absence of bed return flow, a pattern that has been reported for breaking waves on the seaward slope of a bar in a number of studies (Greenwood and Davidson-Arnott, 1979; Wright and Short, 1984; Aagaard et al., 1998; Ruessink and Terwindt, 2000). These cases of ‘divergent’ behaviour can sometimes be explained by the presence of rip current circulation, although this is by no means an explanation for all cases of divergent behaviour, given the possible capacity for self-organised behaviour in surf zone circulation. Cell circulation will occur in cases of three-dimensional bar topography but not in cases of linear bars (Aagaard et al., 1998, 2004). Cell circulation was not observed on the Agon bar. Onshore flow occurs at the beginning and end of the tidal cycle when the top of the bar is not yet submerged. No transfer of water can take place at these phases between the seaward slope and the runnel. Three explanations are proposed to account for this original behaviour: (1) the contribution primarily of the tide and secondarily of the swell waves (Elgar et al., 2001; Hoefel and Elgar, 2003) is more important than the bed return flows. This hypothesis is supported by the small seaward slope of the bar (where a quasi-horizonal crest is often observed) which reduces the propensity for the development of bed return flows (Raubenheimer et al., 1996; Aagaard et al., 2002), and by the large vertical and horizontal tidal excursion rates; (2) the bar is composed of sand with a mean D50 value of 0.5 mm and incorporates numerous shells and gravel clasts. As a result, infiltration of swash and surf bores during the flood tide is important and reduces considerably the intensity of the return currents. The bar is unsaturated up to a water depth of 0.8 m and 0.3 m respectively during spring and neap tide (Robin, 2007). This is particularly the case during the swash, but also at the beginning of the surf. Nevertheless, this explanation does not hold for larger water depths; (3) finally, the northward-directed longshore current can also contribute to reducing bed return flow.

5.3. Processes involved in bar displacement

The results of these experiments highlight the influence of each hydrodynamic process on bar migration. The results bring out two salient points:

(1) Throughout each tidal cycle, the swash duration was less than 8 min. Because of this short duration, but also to the weak efficiency especially during fair weather conditions, swash can only induce movement of sand towards the crest of the bar, without this resulting in a significant displacement of the bar, and this in spite of current velocities that exceeded the critical value for sand movement.

(2) An increase in the significant wave heights in the surf zone induces potential sediment movement favourable to bar migration over a longer period of time. The wave shear stress may reach 60 times the critical value during storms at spring tides. Under these conditions, the current shear stress is also more intense and always exceeds the critical shear stress. This results in considerable sediment movement across the upper part of the seaward slope and crest of the bar, inducing shoreward bar movement. Although during low energy conditions the critical bed-shear stress was exceeded during the first 10 min of the flood tide, no bar movement was observed. There must, therefore exist a threshold in duration and intensity, in order for significant migration to occur.

(3) Shoaling was observed on the crest of the bar only during spring tides. During this period, sediment transport was jointly generated by waves and mean currents especially induced by tidal circulation parallel or away from the crest of the bar (10°) and directed northward. Shoaling did not lead to onshore bar movement. This behaviour, observed at the crest of the bar (micro-ADV position) can be extended to the whole of the seaward slope, as attested by the similar durations of each process, and particularly of the swash.

Topographic variations highlight the transfer of sediment from the seaward slope of the bar to the landward slope and slip face. This behaviour is observed in 2D cross-shore profiles (Figs. 5 and 10), but particularly in the 3D residual topographic evolution (Fig. 16), notwithstanding the fact that the spacing between DEMs is larger than that between the hydrodynamic datasets. During storm conditions, maximum mobility is observed on the seaward slope of the bar. This behaviour, due to surf bore transport, is similar to that described by Sunamura and Takeda (1984) for inner bars and by Kroon and Masselink (2002) and Anthony et al. (2004) for intertidal bars in multiple bar-trough (ridge and runnel) systems. The runnel in the case of the Agon bar showed no significant morphological changes. During low energy conditions, the intertidal area was fairly stable.

5.4. Influence of the neap-spring tidal cycle on bar migration

Kroon and Masselink (2002) found evidence for more effective wave action on the profile during neap tides due to relative stationarity of waves. Their study was, however, conducted under low-energy wave conditions. Anthony et al. (2004) deduced, from the study of a more energetic beach, that the effects of the neap-spring tidal range variation on wave activity are subordinate to those due to the random wave energy regime. Masselink et al. (2006) and Reichmuth and Anthony (2007) have also suggested that the variability in wave processes introduced by the neap-spring tide variation is mainly significant during persistent calm wave conditions but is obliterated by highly variable wave energy levels.

In the Regnéville area, bar morphological changes only appeared during increases in wave energy at the bottom of the seaward slope of the bar. Under low energy, the sediment transport is weak and insufficient to lead to significant change in the topography, notwithstanding strong strong
Tidal currents during spring tides (but only during a short time at high tide). The wave energy level, thus, appears as the main parameter responsible for movement of the bar or for topographic variations of the mid-tidal delta. The tidal range variation is, however, an important parameter that needs to be taken into account because it leads to very different water depths above the bar. During the 09/05/2005 (low energy and spring tide) and 29/01/2004 (moderate conditions and neap tide) experiments, despite a quite similar significant wave height observed at high tide on the top of the bar (0.4 m), the lower water depths during the neap tide (only 0.8 m above the bar) compared to those of the spring tide (3 m) imply stronger wave-induced shear stresses. In these conditions, the sediment transport was 16 times larger and at the origin of the observed morphological changes. In very large tidal range environments exposed to waves, wave action is the main factor leading to significant topographic change in the mid-tidal zone (Levoy et al., 2001). The tide plays, however, an important role in these variations, not so much through the action of currents (which are of secondary importance in the topographic changes in this part of the delta) but by the water depth variations it induces. This variation implies three phenomena: (1) the shifting of the processes and of the direction of the cross-shore current; (2) the intensity of the bed shear-stress for identical wave conditions; and (3) the duration of bar reworking.
5.5. Migration rate and duration of bar reworking

The hydrodynamic conditions and corresponding bar migration patterns were divided into low energy conditions (Hs < 0.7 m), with no bar movement including 02 and 09/05/2005 experiments and moderate to storm conditions (Hs = 0.7 m), with an onshore bar migration rate greater to 0.2 m per day including 29/01/2004 and 22/03/2004 campaigns. These migration rates are therefore small in comparison with environments with similar hydrodynamic conditions (FitzGerald, 1984; Balouin et al., 2004). In the study area, the tidal water level fluctuations control the duration of emergence and flooding. The net result of these tidal fluctuations is to reduce the duration over which sediment transport and morphological changes occur (Masselink and Short, 1993). This is illustrated by the findings of Davis et al. (1972) and Jago and Hardisty (1984) who show that bar migration rate decreases with increasing tidal range. As predicted by Kroon and Masselink (2002) for ridges and runnels in macrotidal environments, landward migration of intertidal bars is intermittent and controlled by the tidal water level. In the study area, the time of action of all the hydrodynamic processes during a tidal cycle is short. During storm events and neap tide conditions, wave and tidal processes potentially rework the Agon bar over a period of only about 130–183 min. In spring tide conditions, wave processes are active, during a relatively short period not exceeding 260–290 min. The low duration of the bar exposure to hydrodynamic processes during storm events contributes to the low migration rates in spite of mean significant wave heights similar to those of other sites (Robin et al., 2007a).

6. Conclusion

An intertidal bar on a megatidal ebb delta (mean spring tidal range of 11 m) was monitored during two spring and neap tidal cycles under both storm and low energy conditions. These experiments contribute to a better understanding of the morphodynamics of these coastal deposits, the study of which has been essentially limited to micro- and meso-tidal environments and at meso- to macro-timescales (1 year to decades). It appears that:

1. Despite a very large tidal range and a large dissipative tidal flat near the inlet, waves generated by local winds have the capacity to induce landward bar migration as in more energetic micro-mesotidal environments. However, the megatidal range induces a short duration of bar exposure to hydrodynamic processes, thus limiting bar reworking. These characteristics lead to weaker migration rates in comparison with micro-meso tidal environments.

2. The duration of each hydrodynamic process acting on the bar is the second factor contributing to slow bar migration. In this context of strong tidal currents, especially at high tide when such currents are parallel to the shore, periods of onshore bar migration are restricted to high wave conditions and only during short periods at the beginning and at the end of the tidal cycle. On the contrary, at high tide for spring-tide conditions or during low wave energy periods (spring and neap tides), the mean currents induced by the tidal circulation are dominant and cannot lead to landward bar migration.

3. The results from this study clearly demonstrate that onshore bar migration is mainly accomplished by surf zone processes (joint action of waves and their induced currents), with swash processes playing a secondary role. Thus, the term “swash bar”, used to define intertidal bars of tidal deltas in micro-mesotidal setting (Hayes, 1975), may be questionable in large tidal range environments. However, a study of the morphodynamics of the ebb delta bar on the upper beach profile, where high-tide depths are low, and where the bar is exposed to more intensive swash action, would be necessary to elucidate the real influence of swash.

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