ELSEVIER

Marine Geology 245 (2007) 141 – 159

MARINE GEOLOGY
INTERNATIONAL JOURNAL OF MARINE GEOLOGY, GEOCHEMISTRY AND GEOPHYSICS

www.elsevier.com/locate/margeo

Double bar beach dynamics on the high-energy meso-macrotidal French Aquitanian Coast: A review

Bruno Castelle *, Philippe Bonneton, Hélène Dupuis, Nadia Sénéchal

UMR CNRS EPOC 5805, Université Bordeaux 1, Avenue des Facultes, 33405 Talence Cedex, France

Received 6 June 2006; received in revised form 23 April 2007; accepted 3 June 2007

Abstract

The French Aquitanian Coast is an approximately 250 km long straight low coast exposed to high energy conditions in a meso-macrotidal setting. Offshore wave conditions are seasonally modulated, predominantly with a WNW incidence, with offshore significant wave height likely to reach 10 m during winter. Truc Vert Beach, representative of most of the Aquitanian Coast beaches, commonly exhibits two distinct sandbar systems. The inner bar can go through all the states within the intermediate classification and usually exhibits a Tansverse Bar and Rip morphology. After a few weeks of lower energy conditions during summer, the inner bar commonly becomes a Low Tide Terrace with a mean wavelength of 400 m and a mean southerly migration rate of about 2–3 m/day. Crescentic bars have been reported in the literature in nontidal to microtidal settings. Long term persistent crescentic patterns are, however, exhibited at a narrow range of wavelength (mean of 700m) by the outer bar at the meso-macrotidal Truc Vert Beach. Most of the time, the outer bar is inactive and stagnates as offshore waves of $H_s > 3$ m are required to induce a significant morphological change. The crescent shape varies from a symmetric shape to a strongly asymmetric shape, likely to be the result of a long period of NW wave conditions. A strong, and rarely observed elsewhere, morphological coupling between the inner and outer bars can sometimes be observed, and may be the result of the combined effects of the initial presence of a well-developed outer crescentic bar and a long period of shore–normal low energy conditions. A synthesis of all the data available on the area combined with observations on other environments leads to a Truc Vert Beach state model ranging from a modal double bar configuration to an occasional triple bar configuration. This work also identifies knowledge gaps to be explored by further numerical and field studies in tidal double sandbar environments.

Keywords: crescentic bar; transverse bar and rip; low tide terrace; morphological coupling; field measurements; numerical modelling; satellite imagery

Contents

* Corresponding author.
E-mail address: b.castelle@epoc.u-bordeaux1.fr (B. Castelle).

0025-3227/$ - see front matter © 2007 Elsevier B.V. All rights reserved.
doi:10.1016/j.margeo.2007.06.001

1. Introduction

Coastal systems are highly variable due to temporally variable inputs of wave and tidal energy forcing. Wave-dominated sandy beaches are one of the most variable and unpredictable coastal systems. Many conceptual models have been designed to predict variations in beach morphology in terms of environmental conditions. The sequential morphologic state models (Wright and Short, 1984; Wright et al., 1985; Lippmann and Holman, 1990) predict the temporal and spatial evolution of single bar beaches under varying incident wave conditions. These models rely on a small number of environmental parameters, commonly the breaker height, the wave period, the sediment fall velocity and the local beach slope. From these parameters, three main beach states were identified as dissipative, intermediate and reflective states (Wright and Short, 1984). Intermediate beaches were further divided into four sub-states. Immediately below the high energy dissipative state is the Longshore Bar and Trough (LBT), then the Rhythmic Bar and Beach (RBB), next Transverse Bar and Rip (TBR) and finally the Low Tide Terrace (LTT) or ridge and runnel system (Short, 1979; Wright and Short, 1984; Short, 1999). Bauer and Greenwood (1988), (Anthony, 1998) and (Ranasinghe et al., 2004) showed that the environmental parameters were sufficient to discriminate between reflective and dissipative extreme beach states but not adequate to characterize inter mediate situations. Furthermore, the processes associated with morphological changes within the intermediate beach state transitions are still poorly understood. Only recently, with a numerical approach, Ranasinghe et al. (2004) gave a better understanding of the morphodynamic processes governing the down-state transition from idealised RBB and TBR morphologies. This down state transition was also only surveyed by Brander (1999) during a 12day field measurement.

Multiple bar beaches have long been investigated (King, 1972) and are present on a large range of sandy coastlines. Their behaviour is much less understood than single bar beach dynamics. Generally speaking, the bar number increases as the beach gradient and/or the wave period decrease (Short and Aagaard, 1993). Multiple bars are also more prevalent in tideless environments with the inner bar always being the most mobile (King, 1972). Indeed, each bar can go through the same states within the intermediate classification with a hierarchy of bar type, i.e. with the outer bar being of the highest energy type (Short, 1999). The outer bar can be dissipative only during high waves and is commonly quasi-inactive during low energy conditions, while the inner bar(s) can occasionally be reflective (Short, 1999). Among the multiple bar systems, triple bar beaches (Short, 1992; Short and Aagaard, 1993) and double bar beaches (Short and Aagaard, 1993; Short, 1999; Van Enckevort et al., 2004) were particularly focussed on. Short and Aagaard (1993) proposed a double bar model with indication of the observed frequency for each double bar configuration on the open, swell-dominated New South Wales coast (Australia). In other environments, changes in beach slope, sediment grain size or wave forcing may produce additional bar combinations and different frequencies of occurrence (Short, 1999), or produce the occurrence of single bar (Van Enckevort et al., 2004) or triple bar (Ruessink and Terwindt, 2000) configurations. Interaction between the outer and inner bars are not taken into account in this kind of model, neither is directly the tidal range. Indeed, despite tides contributing to beach morphodynamic processes and types (Short, 1991; Masselink and Short, 1993), such studies occurred in rather micro-mesotidal environments.

The Aquitanian Coast commonly displays double bar beaches with very dynamic rhythmic features in a high energy meso-macrotidal environment. Since 1998, most of the field experiments along the Aquitanian Coast took place at Truc Vert beach, located a few kilometres northward of the Cap Ferret sand spit (Fig. 1). It is considered as being representative of most of the Aquitanian Coast beaches. Different approaches have been undertaken: hydrodynamic data (Sénéchal et al., 2001, 2003; Butel et al., 2002; Bonneton et al., 2004; Castelle et al., 2006b); sedimentary and topographic data (Howa and De Resseguier, 1994; De Melo Apoluceno et al., 2002); satellite imagery (Lafon et al., 2002, 2004, 2005); and numerical

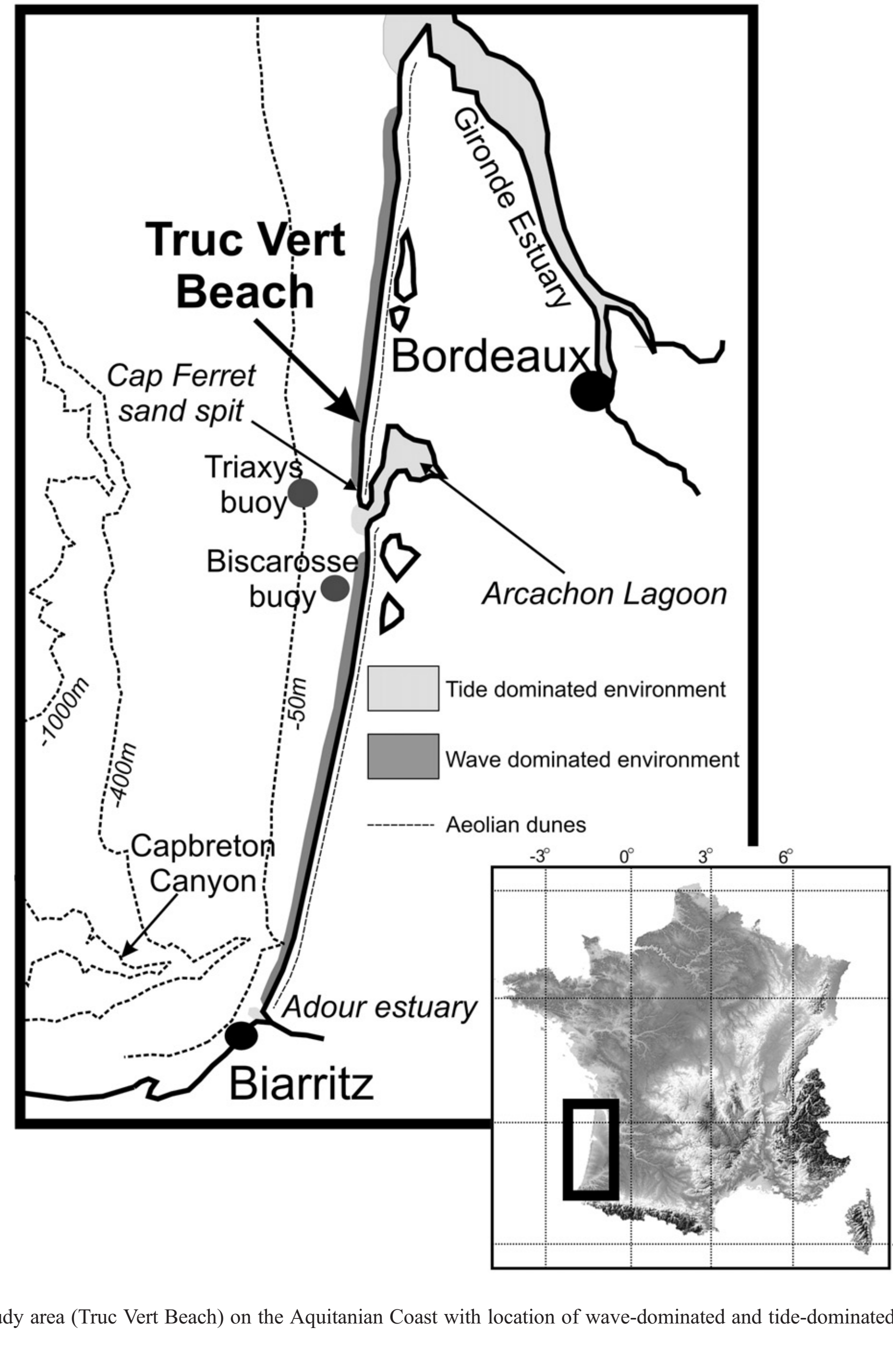

Fig. 1. Study area (Truc Vert Beach) on the Aquitanian Coast with location of wave-dominated and tide-dominated environments.

modelling exercises with direct application to the Aquitanian Coast beaches (Bonneton et al., 2004; Castelle et al., 2006a,b; Castelle and Bonneton, 2006).

The present paper aims at providing a synthesis of our knowledge about the meso-macrotidal high energy Aquitanian double bar beach system and to improve our understanding of double bar system dynamics. Knowledge gaps on the Aquitanian Coast beaches are identified and discussed. We begin with a description of the field site in Section 2. A review of previous works done on Truc Vert beach double bar dynamics is given in Section 3. In Section 4, a Truc Vert Beach state model is proposed, and the different findings are discussed. The findings are summarized and conclusions are stated in Section 5.

2. Field site description

2.1. General settings

The Aquitanian Coast (Fig. 1) is an approximately 250 km long straight low coast bordered by high aeolian dunes (Pedreros, 2000). This coast is located between the Gironde and Adour estuaries, and is interrupted by the approximately 5 km wide Arcachon lagoon tidal inlet, containing complex sandbar and inlet systems (Michel et al., 1995; Cayocca, 2001). The sediment consists of fine to medium quartz sand with mean grain sizes ranging from 200 to 400 μm (Pedreros et al., 1996). The tide is of meso-macro type, with a tidal range of 3.2 m on average which can reach 5 m during spring tides. Tidal currents are intense close to the Arcachon lagoon inlet. Flow velocities can reach 2m/s southward of the Cap Ferret sand spit (Cayocca, 2001). Outside of the Arcachon lagoon inlet, Adour and Gironde estuary influence, tidal currents are not significant in comparison with wave-induced currents (Castelle, 2004).

The coast is exposed to high energy North Atlantic swells travelling mainly from the W–NW sector (Butel et al., 2002), generating a strong southerly longshore drift of approximately 700,000 m^3 of sediment per year (Michel and Howa, 1994). During the past few years, a mean erosion of 1 to 2m/year has been observed (Aubié and Tastet, 2000). Beaches are mainly intermediate double-barred following the classification of Short (1992), Short and Aagaard (1993). Periodic sandbar features are observed in the intertidal domain and in the nearshore zone, which migrate southward at different rates (Lafon et al., 2004). Fig. 2 shows a typical double sandbar configuration at Truc Vert Beach. The inner bar in the intertidal domain commonly exhibits a TBR morphology (Fig. 2) with a mean alongshore averaged wavelength of about 400 m (Lafon et al., 2002). Most of the time, the bars are not shore–normal oriented but skewed, also referred to as oblique (Ribas et al., 2003). The outer bar exhibits crescentic patterns (Froidefond et al., 1990; Lafon et al., 2005), i.e. a RBB morphology, with a yearly averaged wavelength of about 700 m (Lafon et al., 2004). A berm often forms on the upper part of the beach after fair weather conditions, sometimes displaying beach cusps.

2.2. Wave climate

Waves arriving on the Aquitanian Coast are generated by W–E tracking subpolar deep low pressure

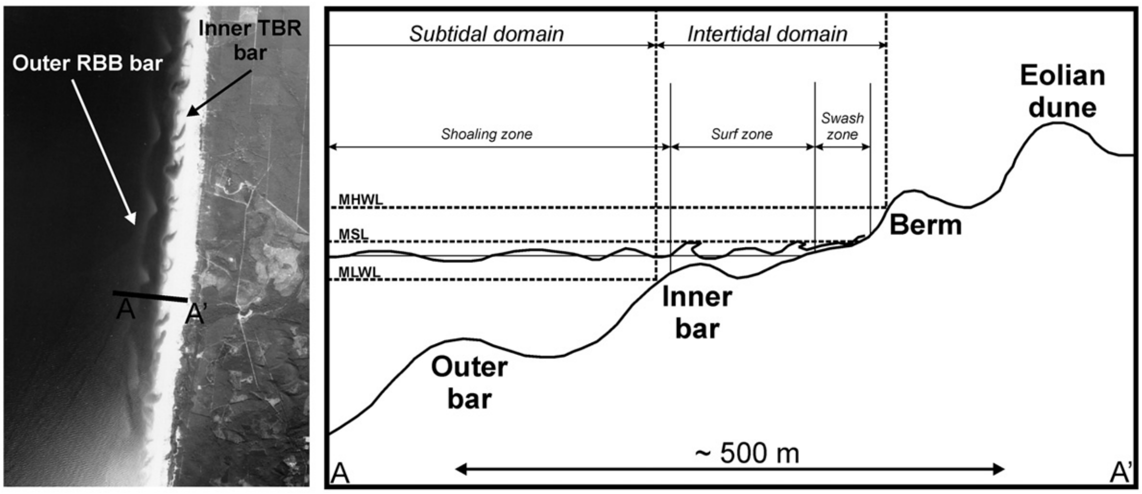

Fig. 2. Aerial photograph (IGN) of a section of the Aquitanian Coast displaying a double bar system, with typical Aquitanian Coast beach profile.

Table 1
Simulated annealing classification for Biscarosse

N	Occurrence	H_s	T_m	θ	Sea state
1	13.92	0.87	5.76	302.01	Summer WNW swell
2		12.14	7.87	296.41	Annual WNW swell
3	11.04	0.65	4.24	328.43	Summer NW swell
4	9.91	0.58	3.84	51.58	Annual E swell
5	9.88	1.58	5.90	286.58	Annual W swell
6	9.48	2.42	6.85	289.56	Annual WNW swell
7	9.05	0.99	5.42	8.87	Annual N swell
8	7.31	0.88	3.96	277.24	Summer W wind wave sea
9	5.52	1.75	10.36	294.76	Winter WNW swell
10	5.20	3.29	8.55	288.26	Winter WNW swell
11	5.09	0.81	5.25	192	Annual S swell
12	1.39	4.66	12.66	291.8	Winter big swell, WNW

The class 4 does not affect the coast (modified from Butel et al. (2002)).

systems over the North Atlantic Ocean and are, therefore, strongly seasonally modulated. A significant interannual variability of the wave climate also exists and could be related to the NOA Index (Dupuis et al., 2006). Recently, Butel (2000) developed a statistical toolbox to undertake a wave classification on the Aquitanian Coast (Butel et al., 2002) from the Biscarosse Buoy moored in 26 m water depth (Fig. 1). It was shown that significant wave height ranges from 0.1 to about 10 m, with the most energetic conditions occurring during winter with 25% of significant wave height larger than 2 m (Butel et al., 2002). Table 1 displays the 12 wave classes obtained with the toolbox (Butel et al., 2002). This classification shows that the Truc Vert beach area is mainly concerned with very low steepness waves associated with long distance swell travelling from the W–NW direction. The forcing varies from summer NW lower waves and occasional storms with a mean NW direction to very high energy winter W to WNW swells. Winds are generally weak in summer with a NW sea breeze in the afternoon. During winter, gusty W to NW winds are common. There is a significant spatial variability of the wave climate along the Aquitanian Coast as wave incoming directions are mostly about 290° around Biscarosse, while they are about 300° at the southern end of the coast with a narrower angular sector (Abadie et al., 2005, 2006).

2.3. Nearshore hydrodynamics

The field measurements of wave-induced currents along the Aquitanian Coast were predominantly obtained from a cross-shore array (Bonneton and Dupuis, 2001; Bonneton et al., 2004; Sénéchal et al., 2002). More recently, further field measurements were undertaken to assess the horizontal circulation behaviour in the intertidal domain (Sénéchal et al., 2003; Castelle et al., 2006b). According to fishermen, lifeguards and surfers, strong tidally modulated rip currents are observed over the intertidal TBR morphology, causing drownings each summer. Fig. 3 shows an aerial photograph of a TBR morphology downdrift oriented (oblique bars) in the intertidal domain on the Aquitanian coast (Castelle et al., 2006b). Two rip currents are easily observed associated with two sediment plumes. Maximum rip current flows occur from mid-tide for lower waves to high tide for high energy conditions, with no significant difference between ebb and flood (Castelle et al., 2006b; Castelle and Bonneton, 2006). This behaviour differs from other environments reported in the literature on both low-energy environments (Aagaard et al., 1997; Brander, 1999) and high energy environments (Brander, 2000) where maximum flow velocities occurred around low tide. Very low frequency (VLF) motions associated with those rip current circulations were observed during 6 day PNEC 2001 field measurements (Castelle et al., 2006b; Bonneton et al., 2007), with temporal scales of approximately 25min.

Due to the predominant W–NW wave direction, an intense longshore current is often observed. For example, during PNEC 2001 field measurements, a 2 m incidence swell at about 8° to the shore generated a southward mean longshore current ranging from 0.5 to 1m/s over a tidal cycle Castelle et al. (2006b). Given that offshore significant wave height can reach 10 m on the Aquitanian Coast, it is reasonable to assume that the longshore current velocity can reach very high values.

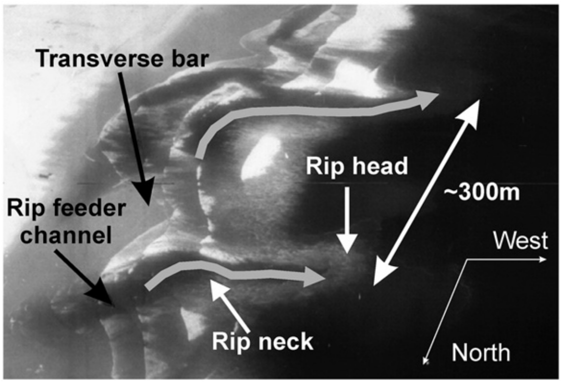

Fig. 3. Aerial photograph of the inner bar exhibiting a TBR morphology with regular downdrift oriented rip channels on the Aquitanian Coast. Visualisation of two rip current associated with two sediment plumes (Castelle et al., 2006b).

3. Sandbar systems

3.1. Inner bar

3.1.1. Morphology

Many previous studies on the French Aquitanian coast referred to the intertidal bar system as a ridge and runnel system (Michel and Howa, 1999; De Melo Apoluceno et al., 2002; Lafon et al., 2002; De Melo Apoluceno, 2003; Castelle and Bonneton, 2006), i.e. LTT, because these investigations were often undertaken after fair weather conditions. Actually, a TBR morphology is observed most of the time in the intertidal domain. Fig. 4 displays an example of 3 different inner bar morphologies from aerial photographs taken around low tide on the Aquitanian Coast. Fig. 4.A displays a LTT morphology. The bar is cut every several hundreds of meters by shallow shore–normal rip channels. On Fig. 4.B, a TBR morphology is observed with bars perpendicular to the shore and regularly spaced every few hundred meters. In the lower part of this photograph, the morphology almost looks like a LTT morphology as rips are very shallow. Fig. 4.C shows a typical Aquitanian Coast TBR morphology observed after a period of high energy conditions. Rip channels are deep and oriented with no preferred direction. Complex breaker patterns reveal that the inner bar is connected to alongshore irregular rip head bars.

3.1.2. Dynamics

In other environments reported in the literature, a few days of fair weather conditions are required to allow the formation of a LTT morphology. 46 surveys composed of high resolution topographic cross-shore profiles, shoreline maps (i.e. shoreline at low tide) and visual observation of the breaker zones were undertaken between 1998 and 2001 (De Melo Apoluceno, 2003). Fig. 5 shows a 5-phase conceptual model of the accretionary sequence of the inner bar proposed by De Melo Apoluceno (2003), associated with a downdrift migration of the system. The presence of the outer bar is

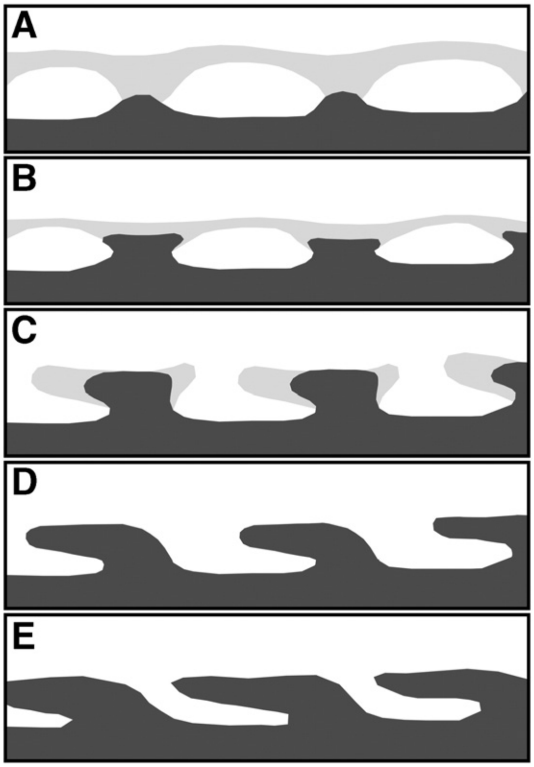

Fig. 5. Phases of a conceptual model for the LTT formation (modified from De Melo Apoluceno (2003)).

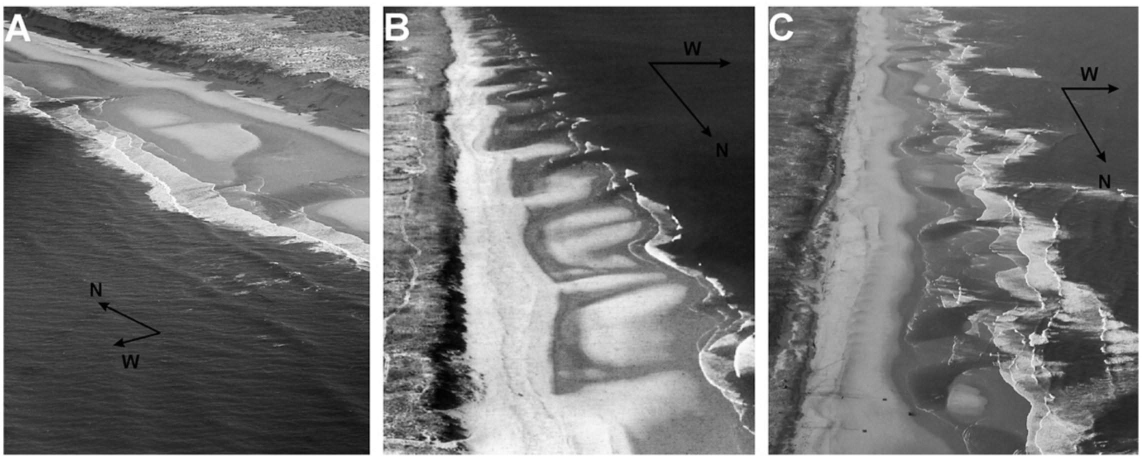

Fig. 4. Aerial photographs of different intertidal bar morphology during low-tide, Aquitanian Coast. (A) : Typical LTT morphology; (B) regular TBR morphology; (C) : TBR morphology with rip channels oriented in no preferred direction.

not taken into account. Starting from a LBT-RBB beach type, the morphology progressively reaches a TBR type associated with a shoreward migration of both the bar and the rip head bar (Fig. 5.A–B–C). Rip channels become well-developed, downdrift-oriented, resulting in an oblique bar configuration (Fig. 5.D). The rips progressively infill as the whole bar moves shoreward and the LTT morphology is eventually reached (Fig. 5.E). This conceptual model is actually similar to the conceptual model proposed by Brander (2000) which provides in more details of the mechanisms responsible for the accretive down-state transition. At Truc Vert Beach, it was found that 10 to 40 days of low energy conditions were required to reach a LTT morphology (Fig. 5.E) from the LBT TBR starting point (Fig. 5.A). It was also found that the LTT morphology could subsist for storm events with H_s<3 m, and that the TBR morphology could subsist during high energy storms with H_s>5 m.

A higher sample rate and higher resolution surveys of the inner bar were undertaken during 4days of the PNEC 2001 measurements during autumn (Fig. 6). At

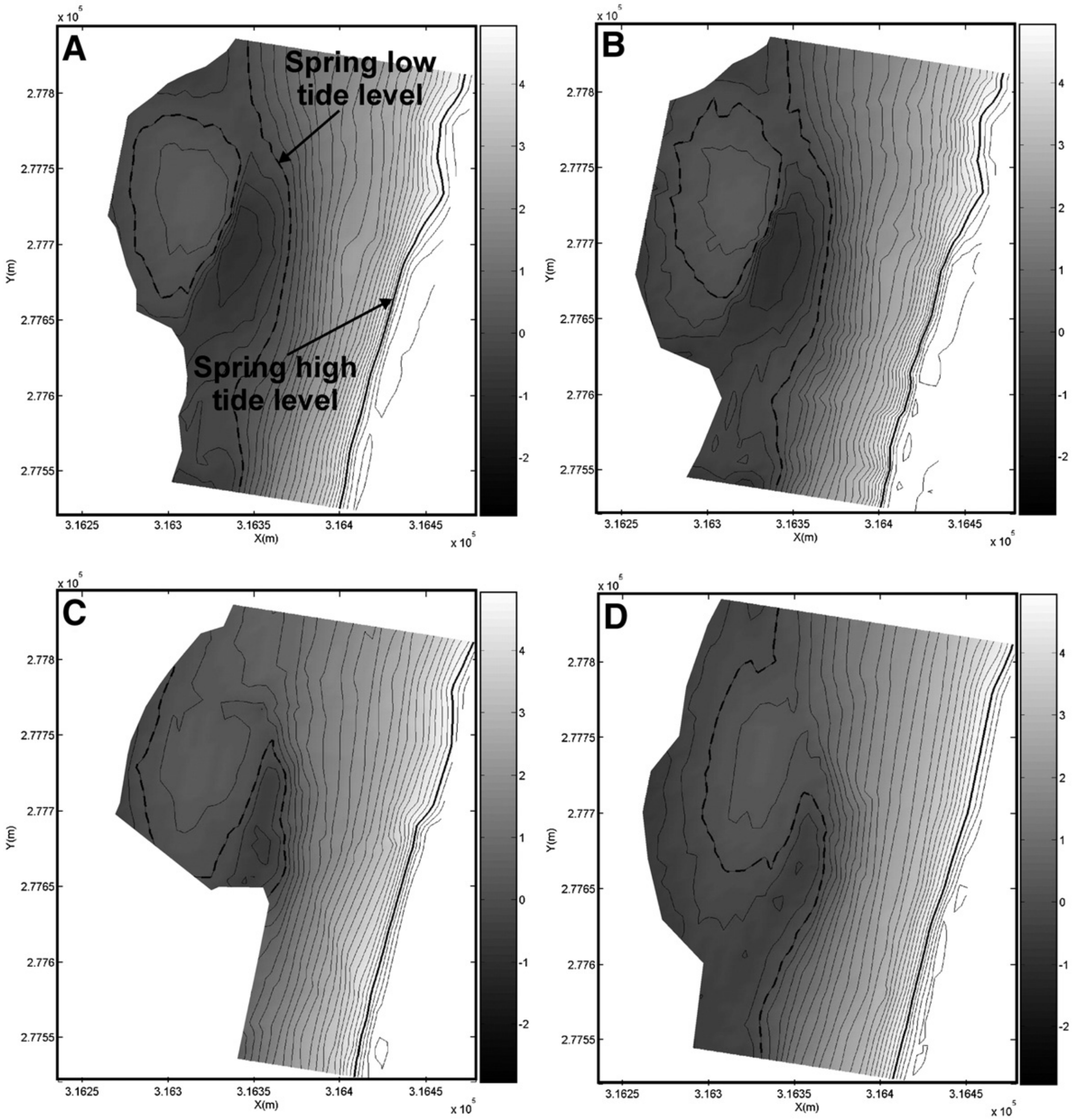

Fig. 6. Topographic surveys of the intertidal domain during PNEC 2001 field experiment showing the welding of the bar to the upper part of the associated with the opening up of a downdrift channel. A: October 15; B: October 16; C: October 17; D: October 18.

Table 2
Size distribution of the inner bar LTT morphology measured on SPOT image, after Lafon et al. (2004)

Date	Mean (m)	S.D. (m)	Med. (m)	Min. (m)	Max. (m)
16/07/86	370	146	342	102	852
02/09/86	427	131	401	146	840
29/07/89	435	211	389	142	1480
04/10/89	430	203	384	181	1303
04/10/90	390	166	343	127	1101
08/09/91	426	170	400	122	895
18/05/92	462	188	420	171	1315
05/10/94	419	150	385	181	849
28/06/95	421	149	406	158	697
23/08/97	440	144	417	197	858
24/06/98	404	136	369	165	948
16/07/99	410	170	400	90	866
01/08/00	463	205	436	85	1158

the starting point (Fig. 6.A), the bar is unwelded to the foreshore, with two channels. The bar was also welded to a rip head bar with a crescent shape (Castelle et al., 2006b). The day after (Fig. 6.B), the bar migrated a few meters onshore associated with a significant accretion of the upper part of the beach. During the third day (Fig. 6.C), the bar welded to the upper part of the beach, closing the northward oriented channel. On the last day (Fig. 6.D), the complete bar welded ashore. Prior to the field experiment, Truc Vert Beach was exposed to a 3 day storm with $H_s \approx 4$–4.5 m which can explain why the energetic wave conditions (1.2 m $< H_s <$ 3 m) resulted in an accretionary adjustment of the beach during the experiment, from a RBB TBR morphology to a TBR morphology. Two main findings can be deduced from those 4 days of observations. Firstly, rapid down-state transitions can be observed during high wave events. Secondly, the accretionary aspect of the commonly used accretionary conceptual models for intermediate beaches (Wright and Short, 1984) is not observed on Fig. 6: the main rip channel exhibits distinct sequential adjustments with a decrease in channel depth, an increase in the cross-sectional area available for rip flow and a reduction in the morphological relief. The lack of data on the morphological evolution of the crescent shape rip head bar connected intertidal system restricts the description of a conceptual model for the accretionary state, as rip head bars are thought to be a key component of rip system morphology evolution (Brander, 1999).

3.1.3. Wavelength and migration rate

Wavelengths and migration rates of the inner bar system were investigated using both shoreline maps (De Melo Apoluceno et al., 2002; De Melo Apoluceno, 2003) and satellite images (Lafon et al., 2002, 2004). The data was obtained during calm weather conditions, during the spring and summer periods, i.e. when the inner bar exhibited a LTT morphology. Based on satellite SPOT imagery from 1986 to 1999, and defining the wavelength as the average rip spacing, Lafon et al. (2004) showed that the inner bar alongshore averaged wavelength ranged from 370 to 463 m (Table 2). Using shoreline maps, De Melo Apoluceno et al. (2002) also found a ridge and runnel alongshore averaged wavelength ranging from 360 to 470 m.

Ridge and runnel alongshore movements were found to occur whenever fair weather conditions and oblique waves prevailed (De Melo Apoluceno et al., 2002; Lafon et al., 2004), which allows the persistence of the bar. Two pairs of SPOT images (16/07/86-02/09/86 and 29/07/89-04/10/89) were used to investigate the average longshore migration rate during low energy wave conditions with rare morphological changes. During the summers of 1986 and 1989, the southward migration rate of the inner bar was found to be respectively 3.1 m/day and 2.4 m/day. Based on 5 consecutive shoreline maps, De Melo Apoluceno et al. (2002) showed that, during the summer of 1999, the southward migration ranged from 0.5 to 4.3 m/day with an average of 1.7 m/day without relating these rates to wave forcing. Offshore wave data can be used to compute the longshore component of the offshore wave energy flux P_{long} which can be approximated (Ruessink and Terwindt, 2000) by:

$$P_{\mathrm{long}} = \frac{\rho g^2}{64\pi} H_s^2 T_p \sin\theta_0 \cos\theta_0 \tag{1}$$

where ρ is the water density, g the gravitational acceleration, H_s the offshore significant wave height, T_p the peak wave period and θ_0 the offshore wave angle to the shore. Results (Table 3) show that the longshore migration rates are weakly correlated to P_{long}, which was also the case at Egmond aan Zee for weak longshore migration rates (Ruessink and Terwindt, 2000). The

Table 3
Measured longshore migration rate of the inner bar measured by De Melo Apoluceno (2003) compared to the longshore component of the off shore energy wave energy flux P_{long}

Period	Longshore migration rate (m/day)	Mean P_{long} (W/m)
05/03/99–01/07/99	0.8	854.6
01/07/99–16/07/99	2.4	583.7
16/07/99–31/07/99	0.4	521.0
31/07/99–01/09/99	0.5	176.3
01/09/99–13/09/99	4.3	1031.7

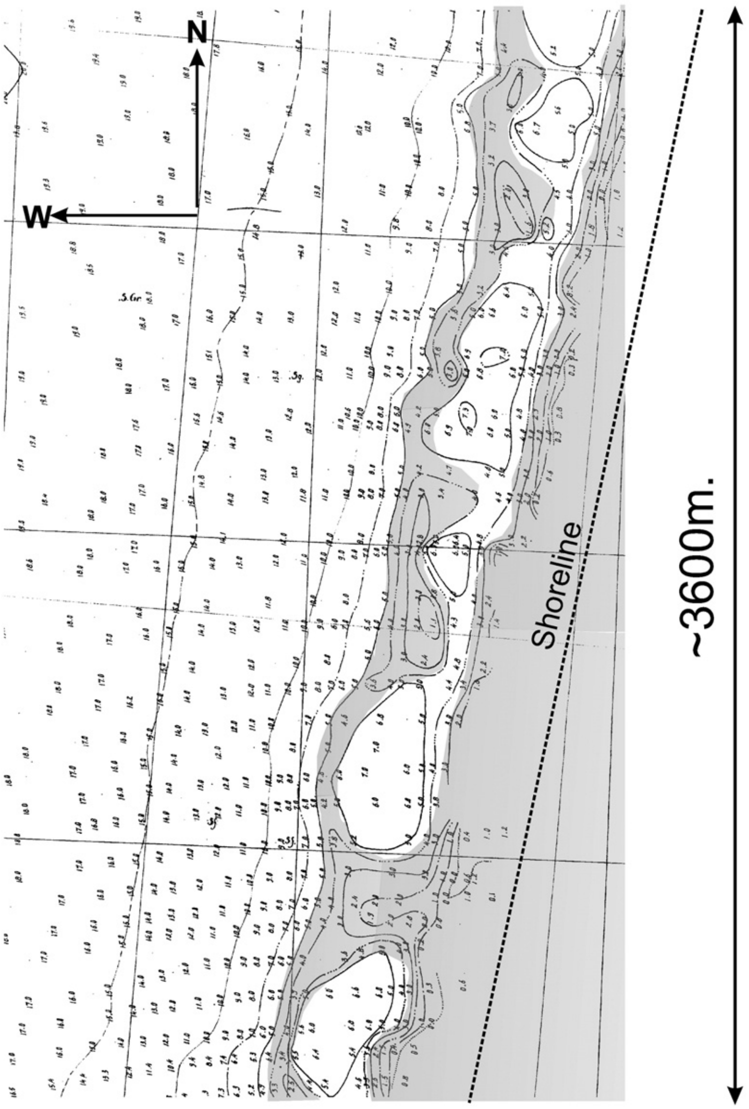

Fig. 7. Bathymetric chart deduced from a bathymetry survey carried out by the SHOM (1967) around Truc Vert Beach with a crescentic bar longshore averaged wavelength of about 700 m. The isobaths are given such as the Lowest Astronomical Tide (LAT) is 0.

measured longshore migration rates are of the same order of magnitude as those measured by Ruessink and Terwindt (2000) at Egmond aan Zee Beach for similar offshore wave conditions. Given that the longshore migration rate can reach 150 m/day at Egmond aan Zee, it is reasonable to assume that the Aquitanian Coast inner bar migration rate could reach such a value during energetic NW waves.

3.2. Outer bar

3.2.1. Morphology

Crescentic bars, also known as lunate bars (Shepard, 1952), are observed on a large range of sandy coasts all around the world (Van Enckevort et al., 2004). They can be found in embayed beaches (Short, 1979; Nafaa and Frihy, 1993) and along straight sandy coasts (Sallenger et al., 1985), and therefore play a key role in beach morphodynamics. These bars have been found in predominantly nontidal to microtidal settings (see for instance the listing in Van Enckevort et al. (2004)). However, on the meso-macrotidal Aquitanian Coast beaches, the outer bar commonly exhibits regular crescentic patterns (Froidefond et al., 1990; Lafon et al., 2005), i.e. a RBB morphology following Wright and Short (1984). Fig. 7 shows a bathymetric chart deduced from a bathymetric survey carried out by SHOM ("Service Hydrographique et Oceanographique de la

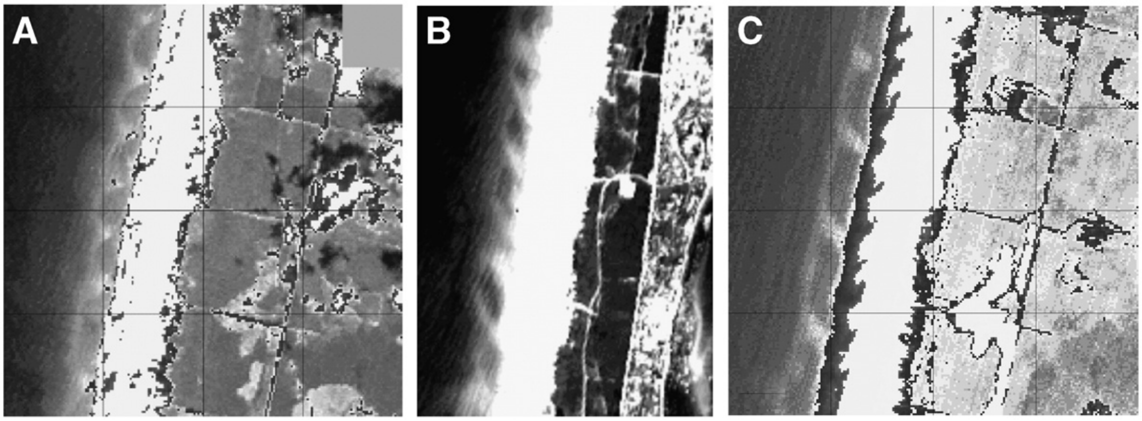

Fig. 8. Satellite SPOT images. Different nearshore crescentic bar morphologies are observed due to water transparency during fair weather conditions, Truc Vert beach area (Castelle et al., 2005). A: Symmetric shape; B: quasisymmetric shape; C: Asymmetric shape.

Marine") around Truc Vert Beach displaying an outer crescentic bar with an alongshore averaged wavelength of about 700m. On average, the shallower landward-protruding section of the bar, the deeper seaward-protruding section of the bar and the trough are respectively 2 m, 4.5 m and 6 m above the Lowest Astronomical Tide (LAT). These values are likely to vary a lot given the high energy highly variable wave conditions that the Aquitanian Coast is exposed to.

Fig. 8 shows that the crescentic bar shape can vary from a typical crescent shape (Fig. 8.A) to a strong asymmetric shape (Fig. 8.C) with the landward part of the bar being linear transverse oriented NW–SE. This asymmetric shape can also be referred as 'skewed' by Wright and Short (1984), Short (1999). Based on numerical wave model outputs and SPOT images, Lafon et al. (2005) suggested that an increased percentage of SW waves seemed to be able to alter the bar symmetry. However, in this particular case, asymmetric bars derived from the superimposition of SW and NW waves, with the NW waves always remaining dominant features. Based on numerical modelling, Castelle et al. (2005) showed that, starting from well developed crescentic patterns, long periods of oblique incidence swells were responsible for the nearshore crescentic bar shape, associated with a longshore migration of the system. Fig. 9 displays the asymmetric behaviour of nearshore crescentic bars and inner bar morphology as a function of the wave-induced current, circulation cell patterns and wave angle. It shows that long periods of NW swells on the Aquitanian Coast can result in the asymmetric shape sometimes observed around Truc Vert Beach.

3.2.2. Wavelength and migration rate

Table 4 shows the size distribution of the crescents measured on SPOT imagery by Lafon et al. (2005) around Truc Vert Beach area. The alongshore averaged wavelength ranges from 579 m to 818 m, with an average of 715 m. This suggests that the alongshore averaged wavelength covers a narrow range of wavelength around Truc Vert Beach, although previous studies on other sites suggest that crescents develop at a wide range of wavelengths after a storm event (Van Enckevort et al., 2004). Therefore, the outer bar behaviour after storm event at Truc Vert Beach remains an open question. Individual crescent wavelength ranges from 250 to 1570 m, with crescents longer than 1000 m observed on every SPOT image. This order of

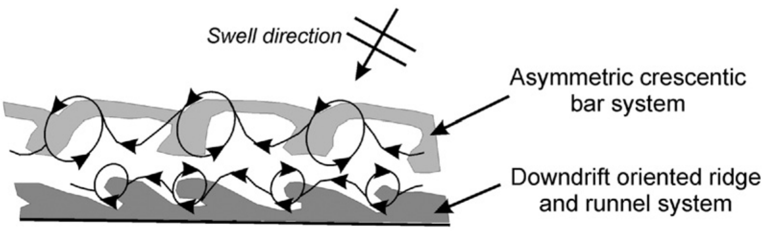

Fig. 9. Asymmetric behaviour of the outer nearshore crescentic bar and inner bar LTT morphology as a function of wave-induced currents, circulation cell patterns and wave angle (Castelle et al., 2005).

Table 4
Size distribution of the nearshore crescentic bar systems measured on SPOT image, after Lafon et al. (2004)

Date	Mean (m)	S.D. (m)	Med. (m)	Min. (m)	Max. (m)
16/07/86	804	200	804	399	1155
29/07/89	777	211	793	380	1428
27/05/91	818	214	767	440	1569
08/09/91	706	169	688	441	1122
18/05/92	726	193	700	361	1050
24/06/98	579	200	539	362	1353
16/07/99	633	236	568	248	1313

wavelength is quite common for a straight beach, all around the world crescentic bar wavelength on straight coasts varies from 100 to 3000 m (Van Enckevort et al., 2004).

Estimating the crescentic bar longshore migration is a challenging task without both high spatial and temporal resolution imagery. The only available data comprises two pairs of SPOT images during the summers of 1991 and 2000 (Lafon et al., 2004). Between May and September 1991, the outer bar morphology did not significantly change except for a restricted zone showing the splitting of two crescents into three crescents. This splitting occurred where the longest crescents were observed, similar to the crescent splittings observed by Van Enckevort et al. (2004), which indicates once again the attempt of the crescentic bar systems to self-organize into a more uniform pattern. A 1 m/day southerly migration rate of the outer bar was observed over this period with no significant morphological change outside the splitting area. Between April and August 2000, neither modification of the crescent morphology nor significant longshore migration of the crescentic bar system was observed. During the summer 2000 period, H_s was always below 3 m, with a mean P_{long} of 799.2W/m and a maximum of 10,432.1W/m. During the summer of 1991, H_s exceeded 3 m for 2.3% of the time, but without accurate wave angle information, P_{long} cannot be computed. This suggests that only offshore wave conditions with H_s>3 m with a W–NW incidence are likely to induce a significant southerly longshore migration of the crescentic bar system.

3.3. Interaction

Crescentic bars have occasionally been associated with similar rhythmic protuberances in the shoreline (Sonu, 1973; Dolan et al., 1985; Thornton et al., 2007) and have been thought to have a strong influence on the location of erosion hot spots (Castelle, 2004; Thornton et al., 2007). Double-barred systems featuring inner bar spacings approximately half the spacing of the outer bar were already documented by Short and Aagaard (1993) and Van Enckevort et al. (2004). However, there is no existing aerial photograph or bathymetric survey showing evidence of complete coupling between each morphology. On the Aquitanian coast during the summer period and dominant NW low energy swells, average migration rates and wavelengths of each of the systems were different, suggesting uncoupled systems. Lafon et al. (2004) showed that for all the images, the mean number of ridge and runnel systems included in one single crescent ranged from 1.43 to 2.17. Between 65 and 90% of the crescents were associated with either one or two inner bar rip channel(s).

However, Fig. 10 shows 3 distinct evidences of a strong morphological coupling, suggesting a strong morphological control of the outer bar on the inner bar can sometimes occur. In the first configuration (Fig. 10.A), the inner bar exhibits TBR morphology welded to rip head bars with a crescent shape, typical of rip cell systems. Two rips are associated with one crescent wavelength and each rip is oriented in the opposite direction. On Fig. 10.B, the aerial photograph taken at low tide shows a LTT inner bar morphology with the uncovered part of the bar located just shoreward of the crescent crest. On the last configuration (Fig. 10.C), for one crescent wavelength, two small rip channels are observed in the intertidal domain, each one being oriented in the opposite direction. Their shape and length scales are completely different from those observed on Fig. 10.A.

Self-organization mechanisms (Falquès et al., 1996, 2000; Damgaard et al., 2002; Reniers et al., 2004; Calvete et al., 2005) or different mode edge waves (Bowen and Inman, 1971) cannot explain such a length scale factor as the aerial photographs presented in Fig. 10 show an obvious morphological coupling, suggesting that the inner bar rips did not form by themselves. The common point between each configuration is the presence of a well developed crescentic morphology of the outer bar, i.e. welded or almost welded to the inner bar with strong three-dimensional characteristics. This is in agreement with a recent investigation undertaken by Ruessink et al. (2006, 2007) using continuous wavelet and cross-wavelet transforms of a double sandbar system on the Gold Coast (Australia). They showed that, initially, inner and outer bar variability develops independently and that, eventually, the inner bar variability becomes slaved to the outer bar variability. Lafon et al. (2005) did not observe any morphological coupling despite the presence of well

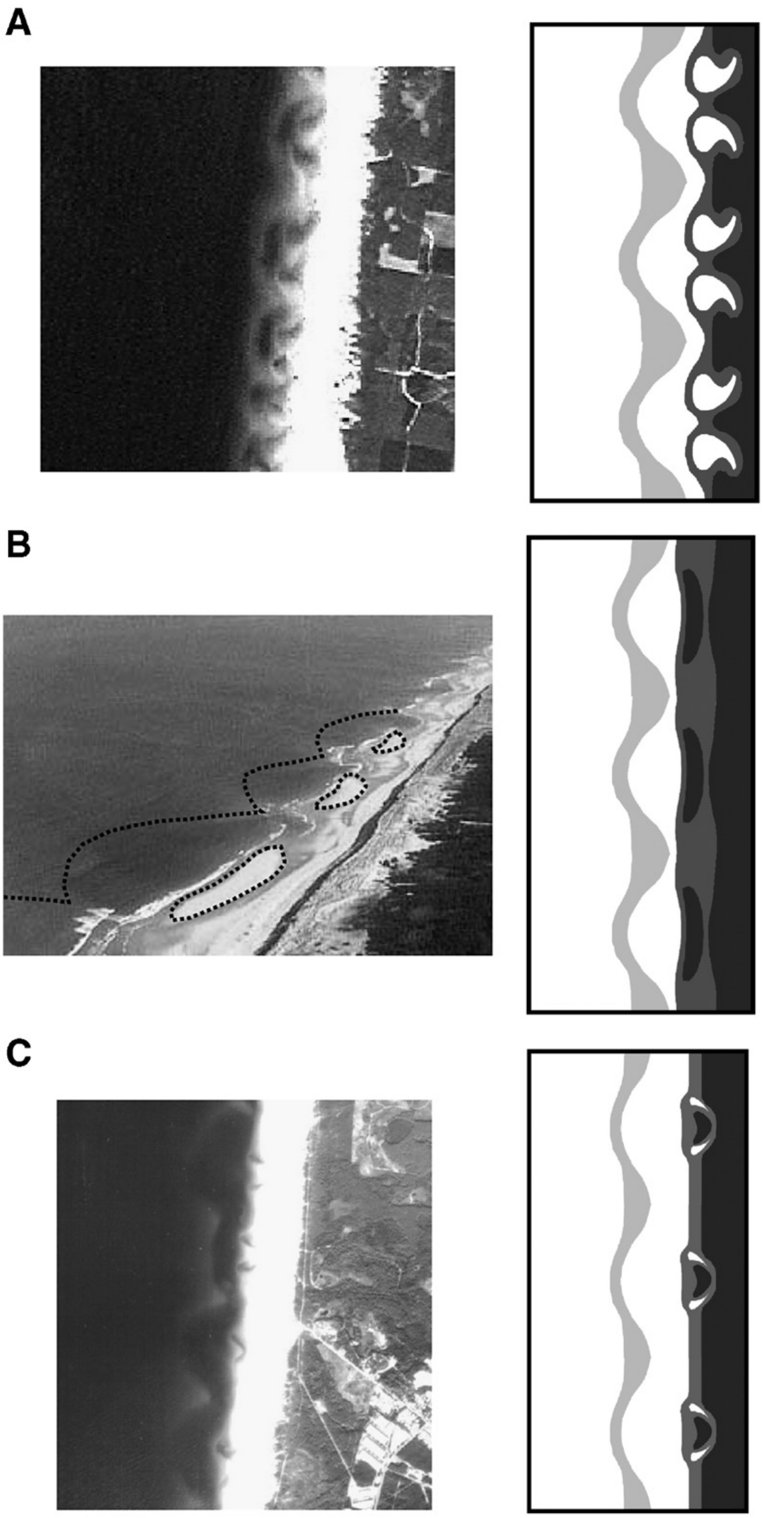

Fig. 10. Evidence of strong morphological coupling between the inner and outer bars (Castelle, 2004). A: Satellite SPOT image (15/10/2001@CNES UMR EPOC 5805); B: Aerial photograph (1999); C: Aerial photograph (IGN, 1978).

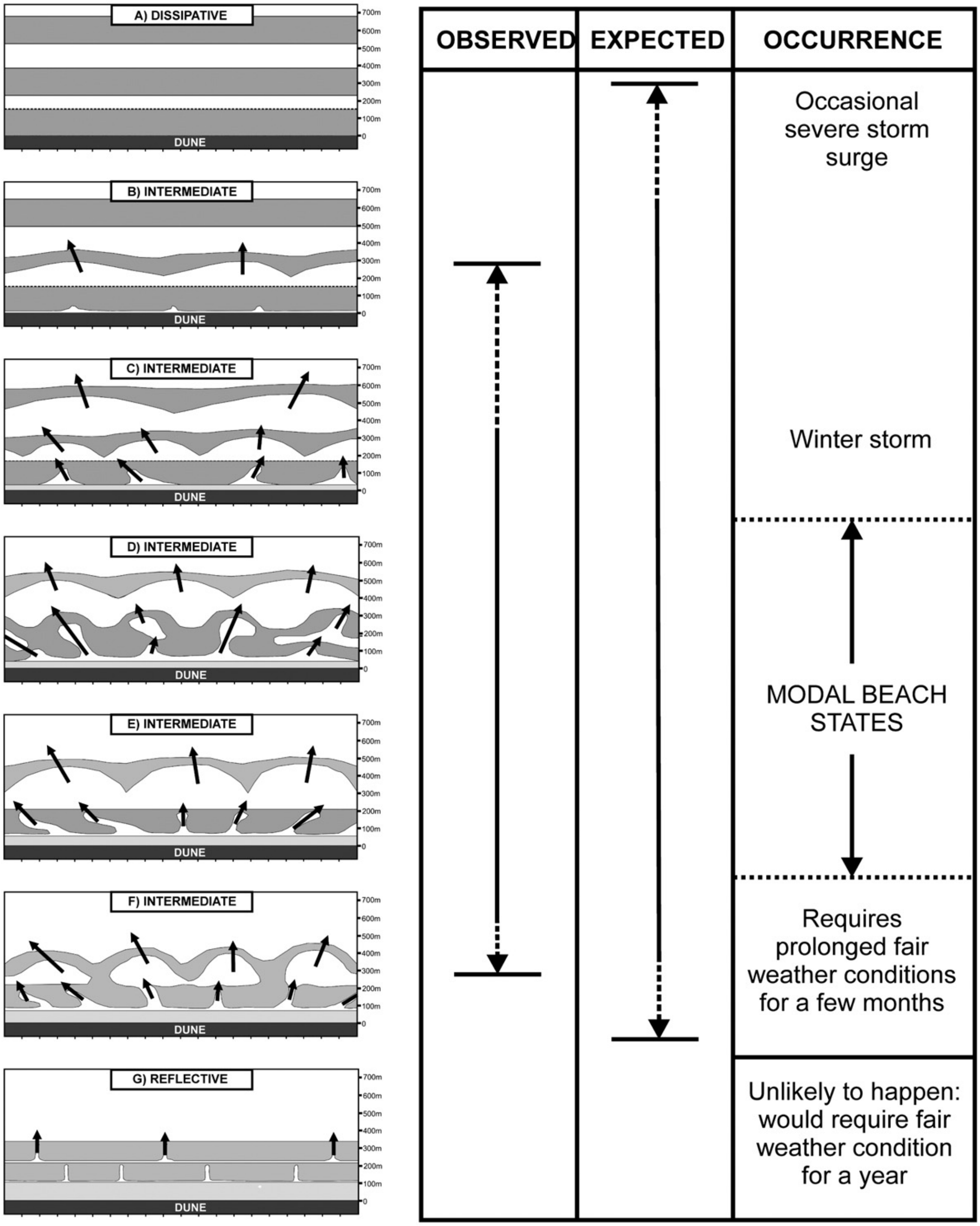

Fig. 11. Preliminary beach state model exhibiting the possible range of beach state around Truc Vert Beach area. Type (A) is expected following severe storms and storms surges, as type (B) after a sever winter storm. Type (C), (D), (E) and (F) were observed on aerial photographs and/or satellite images. Type (F) is only possible following extreme period of low energy conditions (≈year), and then impossible to occur on the Aquitanian coast. Arrows indicate rip current when active under sufficient wave energy conditions.

developed crescentic patterns, suggesting other key parameters for morphological coupling occurrence. Off shore wave conditions prior the morphological couplings on Fig. 10 have in common : more than 10days of low energy shore–normal swell just prior the photograph and high energy shore–normal swell a few weeks before the photograph. The fact that rip channels are almost shore–normal in Fig. 10 confirms that shore–normal waves may play a key role in this morphological coupling. Moreover, with a numerical approach, Castelle and Bonneton (2004) showed that, for H_s<1.5 m, wave refraction over an idealized Aquitanian coast near shore crescentic bar system and the resulting energy focalization shoreward could generate stable and regularly spaced rip currents in the intertidal domain over a tide cycle. Further investigations, including the use of a nonlinear morphodynamic model, may explain more rigorously this morphological coupling.

4. Discussion

4.1. Truc Vert Beach state model

All the sandbar investigations presented above are considered to build a beach model for the Truc Vert Beach area. Fig. 11 displays this beach model with 7 beach states. This beach model is restricted to the available database, and extended to expected configurations following previous works on beach morphology (Lippmann and Holman, 1990; Aagaard, 1991; Short, 1992; Short and Aagaard, 1993; Van Enckevort et al., 2004). Beach states range from a dissipative state (A) to a reflective state (G), with 5 intermediate beach states in-between.

The dissipative state (A) exhibits a dissipative beach system containing three shore-parallel bars, with rip circulations expected to be weak in comparison with the bed return flow. This shore-parallel nearshore bar configuration has never been observed at Truc Vert Beach, and should have therefore a very low occurrence frequency, i.e. would require a decadal storm. Truc Vert Beach usually exhibits an intermediate state. After individual extreme winter storms, the beach is likely to exhibit a high energy intermediate beach state (B) and (C), with a continuous outer bar either straight (LBT, (B)) or rhythmic (LBT RBB,(C)). These beach states could also be part of an accretionary state sequence, developing from straight shore-parallel bars (A) within a few hours or days following a period of severe storm waves and surges. Under continuing low or moderate energy conditions, the intermediate crescent horns weld to the inner bar (D), causing the disappearance of the alongshore continuous trough and the separation of the bays into isolated narrow channels with strong rip currents. This beach state configuration is commonly observed on the Aquitanian coast (for instance on Fig. 4.C), sometimes after a common storm type. Then, as the bars move shoreward under post-storm conditions increasing rhythmicity leads to (D), (E) and (F) Truc Vert modal beach states. The outer bar is located about 400–500 m from the shoreline and regularly broken by widely spaced rips (with a wavelength of about 600–800 m), which is the so-called nearshore crescentic bar commonly observed on Truc Vert Beach. The inner bar is highly rhythmic and attaches to the beach, with a wavelength of about 300–500 m. The inner bar is dominated by detached or attached (TBR-RBB) bars and rip systems (D). Under continuing low energy conditions, the inner bar attaches to the beach as TBR (E), and eventually welds to the beach as a ridge and runnel system (LTT, F). The intermediate beach state (E) can be observed on Fig. 2, and (F) on Fig. 8.C. For a long period of particular offshore wave conditions, a coupling between the inner and outer bars could be observed within the states (D), (E) and (F), as described in Section 3.3. An unusually long period of low waves could produce the fully reflective beach state (G) when all the bars weld to the beach. Such configuration would require a period of the order of a year of H_s < 1 m which is obviously impossible on the Aquitanian coast, but needs to be taken into account in this beach state model, as all the bars in a beach state model can theoretically go through all the states of a single bar (Short and Aagaard, 1993).

This beach state model is in-between the generalised two and three bar beach systems proposed by Short and Aagaard (1993), despite some significant differences. Firstly, the present model goes from a double bar to a triple bar configuration. This single-double or double triple bar configuration has already been observed (Ruessink and Kroon, 1994; Van Enckevort et al., 2004), while Short and Aagaard (1993) distinguished single, double and multi-bar beach systems. Despite the Truc Vert Beach morphology most of the time exhibiting double bar morphology, this triple bar configuration could play a key role during severe storms. Secondly, this model, for a meso-macrotidal environment, differs also in terms of frequency of outer and inner bar combinations. Indeed, an outer bar LBT morphology is observed about 40% of the time by Short and Aagaard (1993) on the east coast of Australia, while investigations at Truc Vert Beach suggest that it is an occasional configuration. Investigations in other environments suggested that crescentic bar lifetime was on the order of a few days to several weeks (Wright et al., 1985; Lippmann and Holman, 1990). For example, the outer bar on the Gold Coast (Australia) exhibited a LBT morphology during each high energy event, with typically $H_{\mathrm{rms}}>1.5\text{–}2$ m (Van Enckevort et al., 2004). It differs considerably for Noordwijk (The Netherlands) where crescentic features of the outer bar had a lifetime of 0.5–37months (Van Enckevort and Ruessink, 2003). Certain and Barusseau (2005) also showed that a decadal storm was required to straighten the outer bar at the microtidal Sètes Beach. Truc Vert Beach outer bar lifetime may be of the same order as the latest as crescentic patterns deduced from breakers were still clearly observed on an aerial photograph during high energy conditions with $H_s \approx 6$ m (Castelle, 2004), suggesting Hs on the order of 10 m (i.e. decadal storm) may be required to straighten the outer bar. An outer bar decay, as observed by Ruessink and Terwindt (2000), Castelle et al. (2007), may also occur during a decadal storm, which is not taken into account in the present Truc Vert Beach model.

Morphological coupling, as described in Section 3.3., may be observed for the states (D), (E) and (F) but is not included in this conceptual model due to significant

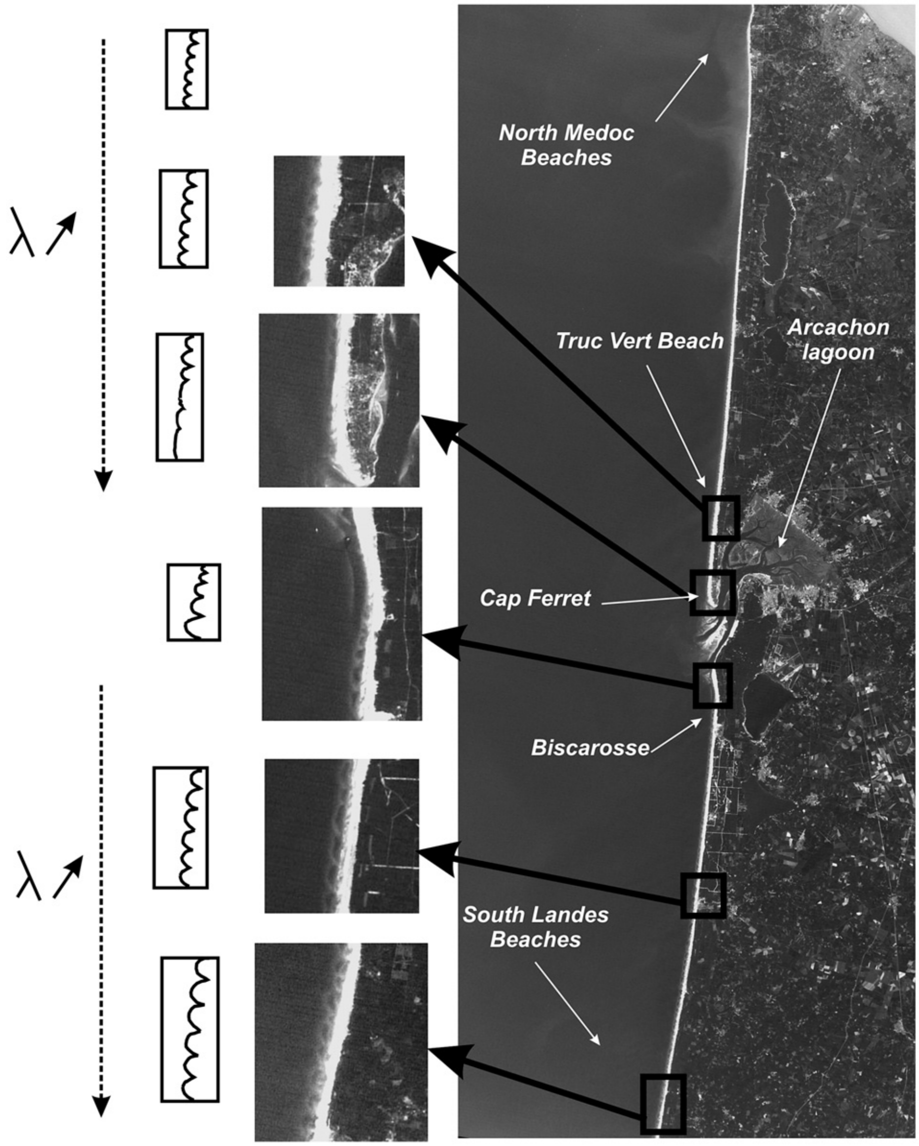

Fig. 12. Variation of the outer crescentic bar morphology along the Aquitanian Coast. Crescentic bars are not observed around the Arcachon lagoon inlet where tidal currents are intense, and the outer bar alongshore averaged wavelength Λ slightly increases to the south, after Castelle (2004).

knowledge gaps in this behaviour. This beach state model must be considered as a starting point for further investigations on the Truc Vert Beach morphodynamics. Video imagery and higher sample rate satellite imagery are likely to provide a more rigorous analysis. Conclusions reached in this study need to be rigorously discussed to build a more robust beach state model and to assess the impact of the meso-macrotial settings on the bar dynamics.

4.2. Extension to the whole Aquitanian Coast

Field measurements, satellite imagery and numerical works presented above focussed on Truc Vert Beach area. Truc Vert Beach is not entirely representative of all the other beaches of the Aquitanian Coast. Sediment grain size (Pedreros, 2000), seaward shelf width, wave climate (Abadie et al., 2005) and beach slope can be significantly different. It results in an alongshore variability of the sandbars which have not been discussed previously.

High energy swells have a peak direction of about 300° in the southern part of the Aquitanian Coast Abadie et al. (2005), while in Truc Vert Beach area swells are distributed on a wider angular sector, usually between 280° and 300° (Butel et al., 2002). This is because the southern part of the Aquitanian coast is more sheltered by Spain from the SW–W swells than for the northern Aquitanian coast. The continental shelf is also significantly narrower in the southern Aquitanian Coast, and ends in front of the Capbreton Canyon (see Fig. 1). It results in weaker wave attenuation on the continental shelf due to bottom friction, and significantly more energetic waves on the southern beaches.

Occasional satellite images cover the entire Aquitanian cost. Fig. 12 shows a LANDSAT image of the Aquitanian coast displaying alongshore variations of the nearshore crescentic bar morphology. Crescentic bars are present, with a significantly shorter mean wavelength than around Truc Vert Beach, in the far northern part of the Coast despite the high turbidity making the crescentic bar identification a challenging task. In the Southern part of the Cap Ferret sand spit, crescent patterns start straightening, and then are interrupted by the Arcachon inlet tidal banks. Tidal currents are thought to be responsible for the straightening of the crescent patterns, disturbing and interacting with the circulation cells in the surf zone which are a key component in the crescentic bar development. At the southern extremity of the Arcachon lagoon inlet, crescentic patterns start to form, with irregular wavelengths and shapes. Then, outside the influence of the tidal currents, crescentic bars become rhythmic down to the southern part of the Aquitanian coast. The most important feature is that the crescentic bar wavelength significantly increases from the northern to the southern part of the Aquitanian coast. A factor of about 2 exists between the two wavelengths. This would mean that the mean crescentic bar wavelength in the southern Aquitanian coast is of the order of 1500m. The whole Aquitanian Coast could then afford a natural laboratory to investigate crescentic bars. Further investigations must be undertaken to provide accurate data on the alongshore variability of the different parameters (the sediment grain size, mean beach slope, local wave climate, etc) in order to accurately explain this longshore variability of the nearshore crescentic bar morphology, and to quantify the sensitivity of the crescent wavelength to the various physical parameters.

5. Conclusion

Field measurements, satellite imagery and numerical modelling undertaken around Truc Vert Beach were combined to provide a synthesis of our knowledge on the Aquitanian coast high energy double sandbar system. The inner bar received considerable attention recently with many shoreline maps, topographic surveys and remote sensing. The LBT morphology requires at least 10days of fair weather condition, most of the time during summer, to reach a LTT morphology with an alongshore average wavelength of about 400m which migrates downdrift at a mean rate of 2–3 m/day. The outer bar system received less attention with just a handful of satellite images during the past 15years and occasional bathymetric surveys. Despite crescentic having been reported in the literature in nontidal to microtidal settings, the outer bar exhibits long term persistent crescentic patterns at a narrow range of wavelength (mean of 700m) at the meso-macrotidal Truc Vert Beach. The crescent shape varies from a symmetric to an asymmetric shape, likely to be the result of a long period of NW waves. The outer bar is inactive and stagnates for H_s<3 m, while its behaviour is still poorly understood during high wave conditions.

Various aerial photographs and visual observations suggest that a decadal storm may be required to straighten the outer bar, as it was observed in other sites (Van Enckevort et al., 2004; Certain and Barusseau, 2005). According to these findings, a beach state model is proposed for meso-macrotidal beach system of Truc Vert Beach which ranges from a modal double bar configuration to an occasional triple bar configuration. This model can be extended to the whole Aquitanian

Coast, despite some significant differences which may exist concerning the wavelengths and the morphological response times of the system.

The present beach state model, like all the other ones proposed in the literature (Short, 1999), does not take into account the occasional strong morphological coupling between the inner and outer bars, which may have an underestimated role on the entire system behaviour. At Truc Vert Beach, this coupling occurs when the outer crescentic bar is well developed i.e. welded, or almost welded, to the inner bar and, likely, after a significant period of shore–normal wave conditions. The requirement of a well developed outer bar is in agreement with Ruessink et al. (2006, 2007). As the distance of the bar crest to shore is a key parameter for the alongshore wavelength (Deigaard et al., 1999), this study also suggests that the distance between the outer bar and the inner bar may also be a key parameter for the morphological coupling. The role of tidal range may also have a significant influence on double sandbar system morphology which is still poorly understood. Indeed, previous studies on single or multiple alongshore rhythmic sandbar systems dealt with micro-mesotidal environments. Truc Vert Beach exhibits both strong and long term persistent rhythmic bedform features, which shows that intermediate beach state models have to be extended and developed to meso-macrotidal settings.

Significant knowledge gaps remain on Truc Vert Beach sandbar behaviour, such as the variation of the outer bar distance to the shore (particularly during storm events), the short-term variations of both sandbar systems during high wave events and post-storm events and the morphological time response to varying wave forcing. The model proposed on Fig. 11 also has to be tested rigorously. The frequency of occurrence of each morphological configuration (Fig. 11) is barely known and has to be explored through permanent video imagery and compared with other environments. Alongshore migration rates of both systems are poorly understood, particularly for $H_s > 3$ m, as alongshore migration rates of only 0 (1 m/day) were computed during low to moderate wave energy periods. Thus, field measurements and video imagery during high wave events will provide key information for the overall understanding of this high energy meso-macrotidal environment.

This study also results in numerous modelling work perspectives. The various recent advances in the understanding of the cross-shore sandbar dynamics (Drake and Calantoni, 2001; Elgar et al., 2001; Hoefel and Helgar, 2003) have to be implemented in nonlinear 2DH models as not only the distance of the bar to the shore but the distance between each bar may play a key role in the entire system dynamics. The numerical simulation of both the outer bar straightening and decay have to be explored as it remains, at the time of writing this paper, an open problem. Nonlinear modelling has been previously undertaken in tideless environments (Damgaard et al., 2002; Reniers et al., 2004; Calvete et al., 2005; Dronen and Deigaard, 2007) and now needs to be undertaken with varying tide level. Consequently, swash zone processes need to be accurately parameterized in the model to be able to simulate the inner bar dynamics which is often located in the intertidal domain.

The Aquitanian coast is a well developed high energy meso-macrotidal environment which deserves further field experiments combined with numerical modelling. It will be attempted during a 6 week international field campaign to be held at Truc Vert Beach in early 2008 including high quality bathymetric surveys, satellite and video imagery, and a large array of deployed pressure sensors and current meters. These measurements combined with numerical modelling and the implementation of a permanent video station at Biscarrosse Beach on the Aquitanian Coast may bridge some important knowledge gaps highlighted in this paper.

Acknowledgments

This study was initially performed within the framework of the “Programme National d’Envirronement Côtier” (PNEC), “Action de Recherche Thématique” (ART) 7 “Hydrodynamique sédimentaire en zone côtiere”, sponsored by the CNRS/INSU. This study was also supported by the ECORS program (Research contract SHOM no. CA/2006/06/CMO). The two anonymous reviewers are acknowledged for their expertise and constructive comments which substantially improved the content of this paper. Finally, we sadly dedicate this work to our colleague and friend Denis Michel, who was among the first ones to investigate the Aquitanian Coast beaches, and who tragically passed away during a recent field experiment at Biscarrosse Beach. We love and miss you Denis.

References

Aagaard, T., 1991. Multiple-bar morphodynamics and its relation to low frequency edge waves. J. Coastal Res. 7, 810–813.

Aagaard, T., Greenwood, B., Nielsen, J., 1997. Mean currents and sediment transport in a rip channel. Mar. Geol. 140, 25–45.

Abadie, S., Butel, R., Dupuis, H., Brière, C., 2005. Paramètres statiqtiques de la houle directionnelle au large de la côte sud aquitaine. C.R. Geoscience 337 (8), 769–776.

Abadie, S., Butel, R., Mauriet, S., Morichon, D., Dupuis, H., 2006. Wave climate and longshore drift on the South Aquitaine coast. Cont. Shelf Res. 26, 1924–1939.

Anthony, E.J., 1998. Sediment-wave parametric characterization of beaches. J. Coast. Res. 14, 347–352.

Aubié, S., Tastet, J.P., 2000. Coastal erosion, processs and rate : an historical study of the Gironde coastline, Southwestern France. J. Coast. Res. 16 (3), 756–767.

Bauer, B.O., Greenwood, B., 1988. Surf-zone similarity. Geogr. Rev. 78, 137–147.

Bonneton, N., Bonneton, P., Senechal, N., Castelle, B., 2007. Very low fre-quency rip current pulsations during high-energy wave conditions on a meso-macro tidal beach. In : Proc. 30th Int. Conf. on Coastal Eng.

Bonneton, P., Dupuis, H., 2001. Transformation of irregular waves in the inner surf zone. Proc. of the 27th Int. Conf. on Coastal Eng., vol. 1, pp. 745–754.

Bonneton, P., Marieu, V., Dupuis, H., Sénéchal, N., Castelle, B., 2004. Wave transformation and energy dissipation in the surf zone: Comparison between a non-linear model and field data. J. Coastal Res. SI 39, 329–333.

Bowen, A.J., Inman, D.L., 1971. Edge waves and crescentic bar. J. Geophys. Res. 76, 8662–8671.

Brander, R.W., 1999. Field observations on the morphodynamic evolution of low-energy rip current system. Mar. Geol. 157, 199–217.

Brander, R.W., 2000. Morphodynamics of a large-scale rip current system at Muriwai Beach, New Zealand. Mar. Geol. 165, 27–39.

Butel, R., 2000. Botido, une boîte à outils pour le traîtement et l'imagerie des données de bouées océanographiques. Internal Report D.G.O. 35pp.

Butel, R., Dupuis, H., Bonneton, P., 2002. Spatial variability of wave conditions on the French Aquitanian coast using in-situ data. J. Coastal Res. SI 36, 96–108.

Calvete, D., Dodd, N., Falquès, A., van Leeuwen, S.M., 2005. Development of rip channel systems: normal and near normal wave incidence. J. Geophys. Res. 110, C10006. doi:10.1029/2004JC002803.

Castelle, B., 2004. Modélisation de l'hydrodynamique sédimentaire au-dessus des barres sableuses soumises à l'action de la houle : application à la côte aquitaine. Ph.D. thesis, University Bordeaux I, in French, unpublished, 340p.

Castelle, B., Bonneton, P., 2004. Nearshore waves and currents over crescentic bars. J. Coast. Res. SI 39, 687–691.

Castelle, B., Bonneton, P., 2006. Modeling of a rip current induced by waves over a ridge and runnel system on the Aquitanian Coast, France. C.R. Geosciences 338 (10), 711–717.

Castelle, B., Bonneton, P., Butel, R., Dupuis, H., 2005. Nearshore modeling of nearshore crescentic bar dissymetry on an open coast, france. In : Proceeding of Coastal Dynamics '05, [CD-ROM], Barcelona, Spain.

Castelle, B., Bonneton, P., Butel, R., 2006a. Modeling of crescentic pattern development of nearshore bars: Aquitanian coast, france. C.R. Geosciences 338 (11), 795–801.

Castelle, B., Bonneton, P., Sénéchal, N., Dupuis, H., Butel, R., Michel, D., 2006b. Dynamics of wave-induced currents over a multiple-barred sandy beach on the Aquitanian Coast. Cont. Shelf Res. 26 (1), 113–131.

Castelle, B., Turner, I.L., Ruessink, B.G., Tomlinson, R.B., 2007. Impact of storms on beach erosion: Broadbeach (Gold Coast, Australia). J. Coast. Res. SI 50, 534–539.

Cayocca, F., 2001. Long-term morphological modeling of a tidal inlet: the Arcachon Basin, France. Coast. Eng. 42, 115–142.

Certain, R., Barusseau, J.-P., 2005. Conceptual modeling of sand bars morpho-dynamics for a microtidal beach (Sètes, France). Bull. Soc. géol. Fr. 176 (4), 343–354.

Damgaard, J.S., Dodd, N., Hall, L., Chesher, T.J., 2002. Morphody-namic modeling of rip channel growth. Coast. Eng. 45, 199–221.

De Melo Apoluceno, D., 2003. Morpho-hydrodynamique des plages à barres en domaine méso macro-tidal : exemple de la plage du Truc Vert, Gironde, France. Ph.D. thesis, Université Bordeaux I, in French, unpublished.

De Melo Apoluceno, D., Howa, H., Dupuis, H., Oggian, G., 2002. Morphody-namics of ridge and runnel systems during summer. J. Coastal Res. SI 36, 222–230.

Deigaard, R., Dronen, N., Fredsoe, J., Hjelmager Jensen, J., Jorgensen, M.P., 1999. A morphological stability analysis for a long straight barred coast. Coast. Eng. 36, 177–195.

Dolan, R., Vincent, L., Hayden, B., 1985. Crescentic coastal landforms. Z. Geomorphol. 18, 1–12.

Drake, T.G., Calantoni, J., 2001. Discrete particle model for sheet flow sedi-ment transport in the nearshore. J. Geophys. Res. 106 (C9), 19859–19868.

Dronen, N., Deigaard, R., 2007. Quasi-three-dimensionnal modelling of the morphology of longshore bars. Coast. Eng. 54, 197–215.

Dupuis, H., Michel, D., Sottolichio, A., 2006. Wave climate evolution in the bay of biscay over two decades. J. Mar. Syst. 63, 105–114.

Elgar, S., Gallagher, E.L., Guza, R.T., 2001. Nearshore sandbar migration. J. Geophys. Res. 106 (C6), 11623–11627.

Falquès, A., Montoto, A., Iranzon, V., 1996. Bed-flow instability of the long-shore current. Cont. Shelf Res. 16, 1927–1964.

Falquès, A., Coco, G., Huntley, D.A., 2000. A mechanism for the generation of wave-driven rhythmic patterns in the surf zone. J. Geophys. Res. 105 (C5), 24071–24088.

Froidefond, J.-M., Gallissaires, J.-M., Prud'homme, R., 1990. Spatial variation in sinusoidal on a crescentic nearshore bar: application to the Cap Ferret Coast. J. Coastal Res. 6, 927–942.

Hoefel, F., Helgar, S., 2003. Wave-induced sediment transport and sandbar migration. Science 299 (5614), 1885–1887.

Howa, H., De Resseguier, A., 1994. Application of a fluorescent grain detector/counter for sand transport evaluation in the littoral zone. Proc. Int.Conf. Ocean Osates '94, vol. 3, pp. 254–257.

King, C.A.M., 1972. Beaches and Coasts. Edward Arnold, London.

Lafon, V., Dupuis, H., Howa, H., Froidefond, J.-M., 2002. Determining ridge and runnel longshore migration rate using spot imagery. Oceanologica Acta 25, 149–158.

Lafon, V., De Melo Apoluceno, D., Dupuis, H., Michel, D., Howa, H., Froi-defond, J.-M., 2004. Morphodynamics of nearshore rhythmic sandbars in a mixed-energy environment (Sw France):i. mapping beach changes using visible satellite imagery. Estuar. Coast. Shelf Sci. 61 (2), 289–299.

Lafon, V., Dupuis, H., Butel, R., Castelle, B., Michel, D., Howa, H., De Melo Apoluceno, D., 2005. Rhythmic sub-tidal and inter-tidal bar morphology and dynamics in a mixed-energy environment. part II: physical forcing analysis. Estuar. Coast. Shelf Sci. 65 (3), 449–462.

Lippmann, T.C., Holman, R.A., 1990. The spatial and temporal variability of sand bar morphology. J. Coast. Res. 95, 575–590.

Masselink, G., Short, A.D., 1993. The effect of tide range on beach morpho-dynamics and morphology: a conceptual model. J. Coast. Res. 9, 785–800.

Michel, D., Howa, H., 1994. Morphological evolution of a littoral sand bank, modelisation of its dynamics. Annals Geophysical, Europe-an Geophysical Union, Part II, 12, p. 240.

Michel, D., Howa, H., 1999. Short-term morphodynamic response of a ridge and runnel system on a mesotidal sandy beach. J. Coast. Res. 15, 428–437.

Michel, D., Howa, H., Tastet, J.-P., 1995. Essai de modélisation de l'évolution morphologique d'un banc sableux intertidal (sud du Bassin d'Arcachon, France). C.R.A.S. 321, 497–504.

Nafaa, N., Frihy, O.E., 1993. Beach and nearshore features along the dissipative coastline of the nile delta. J. Coastal Res. 9, 423–433.

Pedreros, R., 2000. Quantification et modï£¡isation du transport éolien au niveau des zones côtières-application au littoral aquitain. Ph.D. thesis, University Bordeaux I, in French, unpublished.

Pedreros, R., Howa, H., Michel, D., 1996. Application of grain-size-trend analysis for the determination of sediment transport pathways in intertidal areas. Mar. Geol. 135, 35–49.

Ranasinghe, R., Symonds, G., Black, K., Holman, R., 2004. Morphodynamics of intermediate beaches: a video imaging and numerical modelling study. Coast. Eng. 51, 629–655.

Reniers, A.J.H.M., Roelvink, J.A., Thornton, E.B., 2004. Morphodynamic modeling of an embayed beach under wave group forcing. J. Geophys. Res. 109, C01030. doi:10.1029/2002JC001586.

Ribas, F., Falques, A., Montoto, A., 2003. Nearshore oblique sand bars. J. Geophys. Res. 108 (C4), 3119. doi:10.1029/2001JC000985.

Ruessink, B.G., Kroon, A., 1994. The behavior of a multiple bar system in the nearshore zone of terschelling, the netherlands. Mar. Geol. 21, 187–197.

Ruessink, B.G., Terwindt, J.H.J., 2000. The behaviour of nearshore bars on the time scale of years: a conceptual model. Mar. Geol. 163, 289–302.

Ruessink, B.G., Coco, G., Ranasinghe, R., Turner, I.L., 2006. A cross-wavelet study of alongshore nonuniform nearshore sandbar behavior. In : Proc. of the 2006 International Joint Conference on neural networks [DVD-ROM], Vancouver, Canada. pp. 8743–8750.

Ruessink, B.G., Coco, G., Ranasinghe, R., Turner, G., 2007. Coupled and noncoupled behavior of three-dimensional morphological patterns in a double sandbar system. J. Geophys. Res. 112, C07002. doi:10.1029/2006JC003799.

Sallenger, A.H., Holman, R.A., Birkemeier, W., 1985. Storm-induced response of a nearshore-bar system. Mar. Geol. 64, 237–257.

Shepard, F.P., 1952. Revised nomenclature for depositional coastal features. Bull. Am. Assoc. Petrol. Geol. 36, 1902–1912.

Short, A.D., 1979. Three-dimensional beach-stage model. Journal of Geology 87, 553–571.

Short, A.D., 1991. Meso-macro tidal beach morphodynamics—an overview. J. Coast. Res. 7 (2), 417–436.

Short, A.D., 1992. Beach systems of the central netherlands coast: processes, morphology and structural impacts in a storm driven multi-bar system. Mar. Geol. 107, 103–137.

Short, A.D., 1999. Handbook of Beach and Shoreface Morphodynamics. Wiley.

Short, A.D., Aagaard, T., 1993. Single and multi-bar beach change models. J. Coast. Res. SI 15, 141–157.

Sénéchal, N., Bonneton, P., Dupuis, H., 2002. Field experiment on secondary wave generation on a sbarred beach and the consequent evolution of energy dissipation on the beach face. Coast. Eng. 46, 233–247.

Sénéchal, N., Dupuis, H., Bonneton, P., Howa, H., Pedreros, R., 2001. Observation of wave transformation in the surf zone over a gently sloping beach. Oceanologica Acta 24 (6), 545–546.

Sénéchal, N., Dupuis, N., Bonneton, P., 2003. Preliminary hydrodynamic results of a field experiment on a barred beach, truc vert beach on October. Ocean Dynamics 54, 408–414.

Sonu, C.J., 1973. Three-dimensional beach changes. J. Geology 81, 42–64.

Thornton, E.B., MacMahan, J., Sallenger Jr., A.H., 2007. Rip currents, mega-cusps, and eroding dunes. Mar. Geol. 240, 151–167.

Van Enckevort, I.M.J., Ruessink, B.G., 2003. Video observations of nearshore bar behaviour. Part 2: alongshore non-uniform variability. Cont. Shelf Res. 23, 513–532.

Van Enckevort, I.M.J., Ruessink, B.G., Coco, G., Suzuki, K., Turner, I.L., Plant, N.G., Holman, R.A., 2004. Observations of nearshore crescentic sandbars. J. Geophys. Res. 109, C06028. doi:10.1029/2003JC002214.

Wright, L.D., Short, A.D., 1984. Morphodynamic variability of surf zone and beaches: a synthesis. Mar. Geol. 56, 93–118.

Wright, L.D., Short, A.D., Green, M.O., 1985. Short term changes in the morphodynamic of beaches and surf zones: an empirical predictive model. Mar. Geol. 62, 339–364.