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Nearshore Waves and Currents over Crescentic Bars

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ABSTRACT

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The influence of crescentic sand bars on time and depth-averaged wave-induced currents is investigated. Crescent patterns are one of the most common features observed in the nearshore zone, but their morphological behavior and their influence on wave-induced currents and the intertidal zone morphology are still not well-understood. The two-dimensional coastal area model MORPHODYN is coupled with the random-wave model SWAN to compute the hydrodynamics over the French aquitan coast nearshore bars. Simulations of waves and currents are done for different tide and swell conditions on an idealized crescentic system bathymetry to investigate the influence of wave refraction over the crescentic bar on the wave focalisation in the intertidal domain and the current patterns induced. The sensitivity of our model to the tide level and the offshore wave characteristics is revealed, as the influence of the crescentic bars on the formation and the shape of a ridge and runnel system in the intertidal domain.

ADDITIONAL INDEX WORDS: *Rip current, circulation cell, ridge and runnel.*

INTRODUCTION

The sea bottom and the coastline are often characterized by three dimensional periodic patterns of different spatial and temporal scales (SONU, 1973; WRIGTH and SHORT, 1984). Crescentic bars are nowadays observed on lots of sandy coasts in the world, especially trough satellite images and the Argus video cameras system (LIPPMANN and HOLMAN, 1989). They contain a large amount of the mobile sand budget and are thought to have a strong influence on the beach morphology: irregularities or gaps in the bar can be responsible for local shoreline erosion. That's why the origin and the morphodynamics of these bars have been investigated for a few decades.

The two major hypothesis leading to the formation of crescentic patterns in the nearshore zone are the edge wave theory (BOWEN and INMAN, 1971; CARTER, 1988; KOMAR, 1998; SHORT, 1999) and the morphodynamic self-organization theory (FALQUES *et al*., 2000; CALVETE *et al*., 2002; COCO *et al*., 2002). More recently RENIERS *et al*. (2003) showed the formation of rythmic crescentic patterns is essentially the result of morphodynamic self-organization and that edge waves are a consequence and not the cause of the crescentic bar formation. Unfortunately, there is a lack of wave and wave-induced current measurements and detailed morphodynamical informations on this kind of bar.

The original feature of our paper is to investigate the influence of the refraction of the incoming waves over the crescentic bar on the intertidal zone morphology. The wave refraction over the crescentic bar induces wave energy focalization in some interidal zone areas, resulting horizontal circulations which are thought to shape the intertidal sand bars.

The purpose of the present paper is to investigate the influence of crescentic bars on wave refraction, energy focalisation in the intertidal zone and nearshore horizontal circulations with a modelling approach. Emphasis will be placed on the sensitivity of the rip current and the circulation cells to the sea level and wave conditions, and on the swell conditions which can promote the formation of a ridge and runel system.

STUDY AREA

The Aquitan coast is a 230km straight low sandy coast bordered by high dunes and exposed to high energy swells. The wave direction is predominantly W-NW, inducing a strong southerly longshore drift. The semidiurnal tides show a mean tidal range of 3.2 m, increasing to about 4.5m at spring tide. This coast is of the intermediate type 2e (following MASSELINK and SHORT, 1993) and exhibits crescentic nearshore bars (FROIDEFOND *et al*., 1990) with a year average wavelength of about 700m (See Figure 1). The average migration in the longshore drift direction is about 1 m per day (LAFON *et al*., 2002). In the intertidal domain ridge and runnel systems are observed (MICHEL and HOWA, 1999) with a mean wavelength of about 400m on a year average, and their longshore migration is of the order of 3 meters per day during summer. So the two systems do not seem to be linked on a year average point of view. But recent SPOT images showed that sometimes the two systems are strongly linked: on Figure 1 we observe that one nearshore crescentic bar is associated with two smaller crescentic bars shoreward, and each small crescent is connected with a runnel outlet. SPOT images can also show us irregularities in the shape of one crescentic as it was the case at Biscarosse South Beach on the Aquitan coast during the autumn 2001. These irregularities can lead to the formation of erosion or accretion spot in the intertidal domain, as it was observed during winter 2001 at Biscarosse South Beach where the coastline locally retreated by 15m and exhibited a cliff dune. Moreover each system seems to have its own morphodynamic time scales resulting a very complex behaviour of the bed forms.

MODEL

Numerical model

The two dimensional coastal area model MORPHODYN developed by SAINT-CAST (2002) is considered. The wave driver SWAN (BOOIJ *et al*., 1999) is coupled with the hydrodynamic module of MORPHODYN which is a time and depth-averaged model integrating the equations of mass and momentum. The forcing is the result of gradients of mean momentum flux for both the organized wave motion and the roller contribution. The mean currents are calculated following Philipps decomposition (PHILLIPS, 1977) to take into account the undertow contribution. For more details on the coupling and the hydrodynamic module see CASTELLE *et al*. (2003a). The ability of our model to simulate waves and currents on a high energy barred-beach has been tested with field data during the one week field measurement PNEC 2001 at Truc Vert Beach

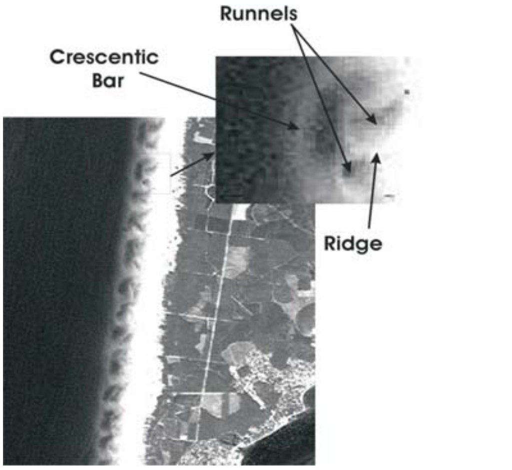

Figure 1. SPOT image of Truc Vert Beach, SPOT XS1, 15/05/01@CNES -DGO- UMR EPOC; Nearshore crescentic bar associated with a half-wavelength ridge and runnel system and intermediate crescentic system

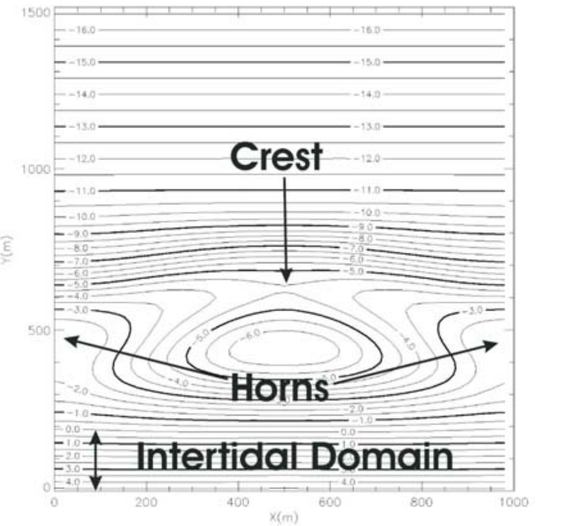

Figure 2. Periodic numerical bathymetry of nearshore crescentic bar, the shoreline is to the bottom.

(SENECHAL *et al*., 2002). After the calibration of the bottom friction coefficient and the lateral mixing, our model was in good quantitative agreement with field data during weak wind conditions (CASTELLE *et al*., 2003a). A qualitative study of the rip current occurring over the ridge and runnel system has been undertaken (CASTELLE *et al*., 2003b). The calculations are in a good qualitative agreement with the observations on the Aquitan coast. For example both observations and numerical simulations show a strong tidal modulation of the rip current, with maximum flow velocities occurring at mid-tide.

Periodic numerical crescentic bar bathymetry

For the calculations a numerical bathymetry of a crescentic bar has been created from a synthesis of bathymetric surveys and SPOT images. The computational domain ranges from 17m water depth at spring low tide to the shoreline, for a crescentic bar wavelength of 1 km. The crescent horn is connected to a longshore uniform gently slope intertidal domain. The mesh of the uniform computational grid is 20 m in both the longshore and crosshore directions (See Figure 2), with periodic lateral boundary conditions.

METHODS

For the following simulations we will consider as the reference simulation the calculation using the mean annual wave characteristics measured by the Biscarosse buoy which is moored on the continental shelf in 26m depth. The mean annual significant wave heIght and significant wave period are respectively 1.36m and 6.5s (BUTEL *et al*., 2002), with normally incidence at high tide (referred in the following as the "Reference offshore wave conditions").

All the numerical simulations were processed similarly. The parameters we tuned are the tide elevation (η), the significant wave height (Hs), the wave direction (θ) and the significant wave period (Ts). For each run we computed the wave field, the forcing, and the time and depth-averaged current on a crescentic bar with periodic lateral boundary conditions. The position and the shape of the rip current in the intertIdal zone and the circulation cells in the nearshore zone are then investigated and compared with the reference simulation.

RESULTS

The wave refraction over crescentic bars will generate an alongshore variation of wave heights in the intertidal domain resulting radiation stress gradients. The set-down and set-up longshore variations respectively outside and inside the surf zone will drive the mean-current and lead to the formation of circulation cells associated with rip currents (seaward oriented), and onshore flows.

For the reference simulation at high tide, the wave focalization and the horizontal circulations pattern are as follow. For a frontal 1.36m offshore wave height, the wave refraction over a crescentic bar will generate a wave energy focalization behind each crescent horn and a wave energy minimum behind the crescent through, inducing radiation stress gradients (see Figure 3). It results a set of large eddies with rips (see Figure 4). Two circulation cells in the intertidal domain are observed, associated with two offshore oriented rip current of $0.25m.s^{-1}$ approximately 500m spaced out. In the subtidal region two circulation cells are also observed, associated with a broad offshore rip current of about $0.15m.s^{-1}$. The two intertidal rips are though to bring some sediment from the intertidal zone to the nearshore area. Then, these regular offshore wave conditions for a long time seem to be a condition conductive to the formation of rip channels in the intertidal domain.

In the following we will show that the location and the intensity of the breaking zones strongly depend on the tide level and the wave characteristics. We will focus on the sensivity of the forcing and the horizontal circulations to each wave and tide parameter. The simulations were carried out for a large range of parameter values, a synthesis is presented here' after.

Sensitivity to the offshore wave direction

The wave direction is the leading wave characteristic controlling the shape and the location of the circulation cells in the foreshore and the nearshore zones. Elsewhere the rip areas, the wave-induced current magnitude is strongest when the offshore wave incidence increases while the rip just turns in the longshore current direction. For offshore wave directions up to about 10° all the circulations cells are replaced by a longshore current oscillation, but for frontal or near-frontal swell each circulation cell has its own behavior. The first circulation cells which desappear with the increasing wave direction are the down-current crescent horn side circulations. For the reference offshore wave conditions they disappear for an offshore wave direction of about 5° (see Figure. 5), while the up-current crescent horn circulations disappear for an offshore wave direction of about 10°. This distinct behaviors of the nearshore eddies can give an explanation for the rare dissymmetric shape of the nearshore crescentic bars which has been sometimes observed trough SPOT images.

In the following tests we will define the "Stability" As the sensitivity of the circulation cells to the offshore direction: a circulation cell is more stable when a bigger offshore wave direction is required to transform the circulation cell into a longshore current oscillation.

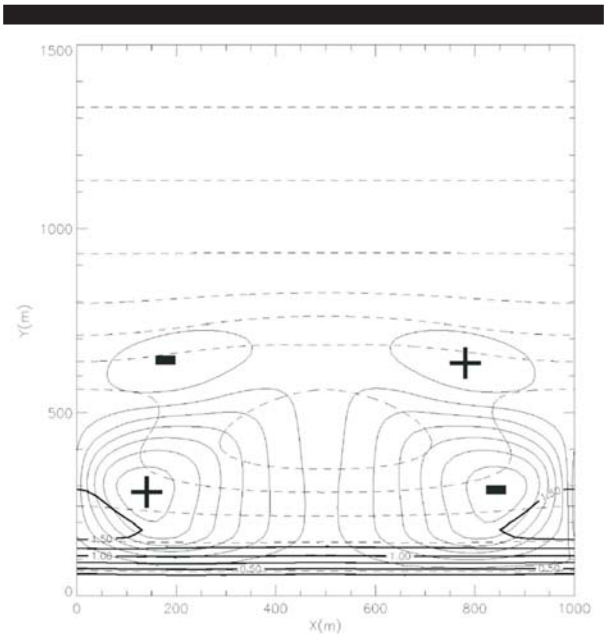

Figure 3. Radiation stress Sxy. Offshore wave conditions: Hs=1.36m, T=6.5s, θ=0°, η=4m. Dashed lines: bathymetry; Thick lines: iso value of Hs (m). Black lines: iso value of Sxy

Sensitivity to the tide level

During spring low tide, the intertidal domain is uncovered, and the nearshore circulations are controlled by the crescentic bar. From mid tide to spring high tide, two intertidal horizontal circulations are observed for the reference offshore wave conditions. The higher the sea level is the stronger and the bigger the intertidal eddies are and the less strong the nearshore circulations are. The longshore location of the intertidal rips is the same during a tide cycle, which confirms the possibility that the reference offshore wave conditions for a long time can easily generate an intertidal ridge and runnel system. Therefore the sea level seems to have an influence just on the size and the intensity of the intertidal eddies for the reference offshore wave conditions. But in the following, we will notice it is wrong for bigger offshore wave heights.

Sensitivity to the offshore wave period

The influence of the wave period on the circulation cells is weak, but simulations show the longest periods tend to strengthen the stability of the circulation cells. For short swells, the circulation cells are quickly transformed into a longshore current oscillation when the wave direction increases, while the longest swells make the circulations stay for a longer time. This can be an explanation for the smoothing of the intertidal domain during some big storms: the shortest very oblique swells are the conditions liable to smooth the intertidal domain while the frontal swells produce very stable eddies which can not smooth the intertidal domain. The longest swells also induce stronger and narrower rip currents (see Figure 6), which is in agreement with observations on the aquitan coast.

The depth-averaged currents are very sensitive to the wave height. The bigger the offshore waves are, the strongest the wave-induced currents are, and the more stable the subtidal circulations are. But the shape and the direction of the intertidal circulation cells are much more sensitive to the wave height. For example at high tide and for reference offshore wave conditions, the refraction over the crescentic bar will generate a maximum wave height behind each crescent horn resulting an onshore flow and a minimum wave height behind the crescent through resulting an offshore flow associated with two circulation cells. This horizontal circulation behavior is observed within the range of Hs from 0.1m to approximately 2m. As a matter of fact, for the same tide level, wave period and direction but offshore wave height up to 2m, an increasing

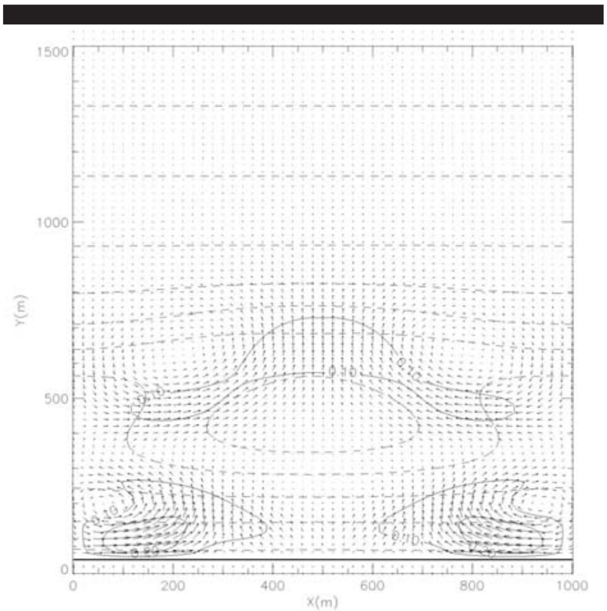

Figure 4. Wave-induced current vector plot over a crescentic bar for the reference offshore wave conditions at high tide: Hs=1.36m, T=6.5s, θ=0°, η=4m. Dashed line: bathymetry; Black line: iso-value of wave-induced currents (m.s^{-1}).

fraction of breaking wave will occur over the crescent horn. It results a movement of the intertidal location of the maximum wave height from behind the crescent horn to behind the crescent through, resulting intertidal circulation in the opposite direction (see Figure 7). We must also notice the critical wave height leading to this changement of circulation direction depends on the sea level: at high tide we need bigger offshore wave conditions to reverse the intertidal horizontal circulation direction than at mid tide. This changement of intertidal circulation cell direction during one tide cycle may have a strong influence on the intertidal area morphodynamics and could lead to the formation of irregular ridge and runnel systems.

DISCUSSION

The results show that the wave-induced current over and behind nearshore crescentic bars in a semi-tidal environment

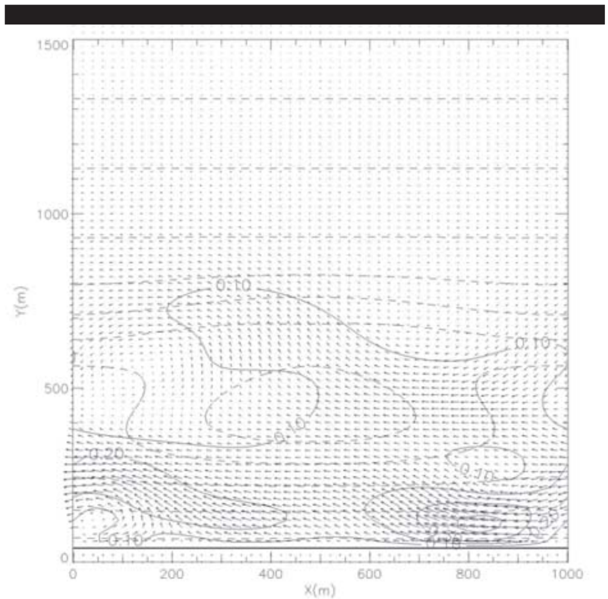

Figure 5. Wave-induced current vector plot over a crescentic bar. Offshore wave conditions: Hs=1.36m, T=6.5s, θ=5°, η=4m. Dashed line: bathymetry; Black line: iso-value of wave-induced currents (m.s^{-1}).

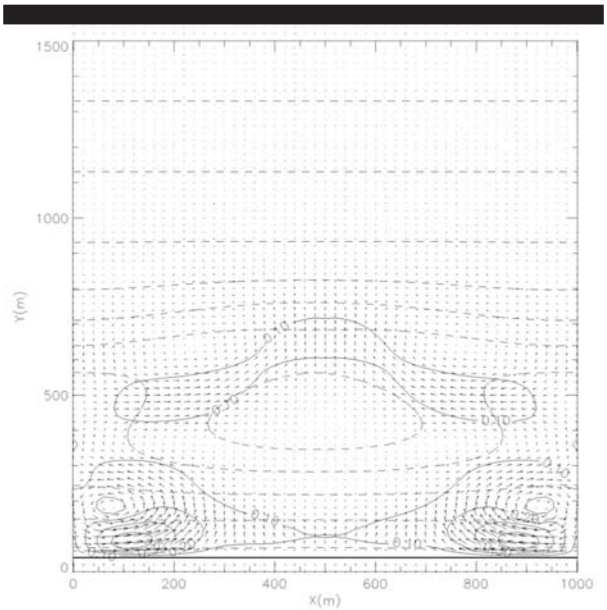

Figure 6. Wave-induced current vector plot over a crescentic bar. Offshore wave conditions: Hs=1.36m, T=19s, θ=0°,η=4m. Dashed line: bathymetry; Black line: iso-value of wave-induced currents (m.s^{-1}).

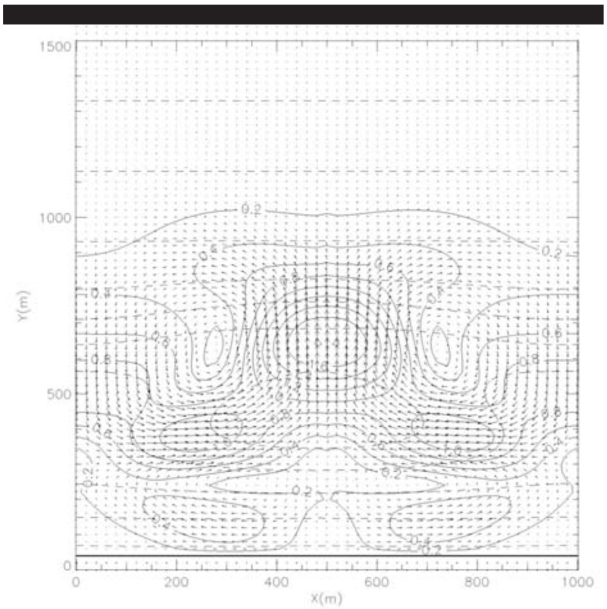

Figure 7. Wave-induced current vector plot over a crescentic bar. Offshore wave conditions: Hs=4m, T=6.5s, θ=0°, η=4m. Dashed line: bathymetry; Black line: iso-value of wave-induced currents (m.s^{-1}).

are very complex and sensitive to the offshore wave conditions and the sea level. The simulations show that the wave refraction on the crescentic bar induces circulation cells in the subtidal and in the intertidal zone, the horizontal circulations seem to be realistic. For one crescentic bar and reference offshore wave conditions, four circulation cells are observed. The two nearshore circulation cells are associated with one strong offshore rip current facing the crescent through, and two stronger and narrower rip currents half crescent wavelength spaced out in the intertidal domain. Tuning the wave period weakly influence the longshore location of the intertidal rip currents, but does not significantly affect the horizontal circulations. Even if the wave period is not one of the most relevant parameter, the frontal or quasi-frontal long swells lead to stronger and the more stable horizontal circulations. The circulation cells disappear with increasing the incidence of the offshore waves, and then an oscillation of the longshore current takes place. The dissymmetric behavior of the horizontal circulations is pointed out: the circulations which are up-current the crescent horn are more stable. The direction and the strength of the circulation cells are very sensitive to the wave height: for example directions of the intertidal circulations change during one tide cycle for offshore significant wave height up to 2m, while subtidal circulations are strengthened. Moreover the tide level affects the stability of the nearshore circulation, resulting different behaviors of the circulation cells for obliquely incidence offshore waves during one tide cycle. But we must bear in mind our numerical bathymetry can not represent all the morphological configurations of crescentic bars that we can observe on the Aquitan coast. The horizontal circulations induced by the numerical bathymetry will be different from those induced by lunate shape cescentic bars, or systems which crescent horns are disconnected from the intertidal domain. Further investigations must be undertaken on this topic.

One of the main attempts of our paper was to investigate the link between the formation of ridge and runnel system and the wave refraction over the nearshore crescentic bars. The existence of strong rip currents is a condition conductive to the formation of rip channel in the intertidal domain if the hydrodynamics do not strongly change during a tide cycle. The simulations so show that the offshore significant wave height must not exceed 2m, with a normally to near-normally incidence. This is in agreement wIth the observations on the aquitan coast: the most of the time regular ridge and runnel systems are observed during summer after long period of low energy conditions. A constant direction of the intertidal circulations during a tide cycle is also observed for offshore wave height up to 4m. This can give an explanation for the strongly linked morphological configuration of the two systems as it is observed in Figure 1 even if this morphological configuration is rarely observed on the French aquitan coast. Most of the time it does not seem a morphological relation exists between the two systems. Another assumption commonly considered is the ridge and runnel system characteristics are controlled only by the offshore wave conditions. The feedback between hydrodynamics and the evolving topography can lead alone to the formation of oblique sand bars with a spacing of several times the surf zone width like those observed in the intertidal region of the aquitan coast, or other coasts which don'T exhibit crescentic patterns in the nearshore zone (RIBAS *et al*., 2003). The two mechanisms both can act and lead to the formation of a ridge and runnel system. Besides, another idea is the refraction over the crescentic bars can promote the formation of some bed form instabilities in the intertidal domain, and then these instabilities will grow according to the self-organization mechanisms and lead to the formation oblique bars. We have so to investigate what is the most relevant mechanism leading to the formation of regular ridge and runnel systems, using fully-coupled morphodynamic model to take into account both the "Bed-surf" Interaction and wave refraction over the nearshore bars.

CONCLUSION

A calibrated numerical model (MORPHODYN) has been coupled with the wave module SWAN to simulate the waves and the wave-induced currents over nearshore crescentic bars. The idealized bathymetry is typically the kind of morphology we observe on the French aquitan coast all year long. The simulations put forward the sensitivity of the horizontal circulations to the sea level and the wave characteristics. The nearshore and foreshore bars were commonly considered as unlinked but we showed the wave propagation over the nearshore crescentic bars are responsible for the formation of two rip currents in the intertidal region. Considering one crescentic bar, these rip currents are thought to lead to the formation of two rip channels, commonly called ridge and runnel system on the SW French coast. This morphological configuration is sometimes observed from SPOT images, but most of the time it is not. As a matter fact, another mechanism conductive to the formation of such bars is the self-organization mechanism which includes the bed-surf interaction. Further investigations must be undertaken with a fully coupled morphological model.

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