Wave-driven circulation over a double nearshore bar system during storm conditions

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ABSTRACT


Current profiles and waves were recorded from a multi-instrumented transect over a double nearshore bar system in the Gulf of Lions, NW Mediterranean Sea (France) during storm conditions with shoreface significant wave heights of up to 3.2 m. The results constitute a preliminary analysis aimed at constraining the 3D nearshore circulation in a microtidal system. Significant time changes in the vertical distribution of nearshore velocities were observed, forced by the wind/wave conditions. Such vertical changes have been highlighted by theoretical velocity profiles in the literature, but our study demonstrates much larger variability than has hitherto been shown. Another result obtained was that the hydrodynamic pattern observed in the inner trough was distinct from that observed along the seaward flank of the inner bar. For a well-defined threshold in wave height, velocities in the trough increased abruptly and earlier, and remained strong over a longer time than those on the seaward flank. The trough thus behaves essentially as a drain for water piled against the shore. This behavior is altered by the width of the surf zone (and not only by the significant wave height), which modulates the mean current velocity. These results are a useful preliminary step in improving numerical modeling of the complex surf-zone circulation over bar-trough systems.

ADDITIONAL INDEX WORDS: Current profile, longshore current, undertow, surf zone, ADCP, SHORECIRC

INTRODUCTION

Most sandy coasts display nearshore bars organized in single or multi-bar systems. Investigations of these nearshore bars are important in understanding wave breaking and hydrodynamic circulation on the shoreface because these features strongly influence the transformation and dissipation of waves that propagate to the shoreline, thus acting as a natural source of shoreline protection. Moreover, these features are important in terms of nearshore sand reservoirs (Certain et al., 2005). Thus, in an integrated management approach of coastal hazards on shorelines subject to high socio-economic occupancy, enhanced understanding of hydrodynamic processes prevailing over bars, especially during storm conditions, is of significant interest.

Nearshore bars display various morphological features that have been identified by Wright and Short (1984) in their beach state classification model. The bars are dynamic at different timescales, notably changing in response to variations in wave energy. Depending on the intensity and characteristics of storm events, bars can undergo temporary offshore migration (Winjberg, 1995) when strong seawards currents (undertow) dominate the sediment transport. Onshore bar migration may occur between storm events when wave energy is lower. At long timescales, this behaviour has been generally termed “Oscillation around a Position of Equilibrium” (OPE) (Certain and Barusseau, 2005). However, “Net Offshore Migration” (NOM), leading to long-term offshore bar migration and decay, has also been observed (Aleman et al., 2013).

The hydrodynamics of the inner surf zone in which bars develop have long been studied in the literature as they strongly control changes in sandy shoreline morphology. In particular, the evolution of nearshore sand bars was early related to low-frequency changes in the mean current. However, the influence of vertical modulations of the water velocity in the water column has, to date, not been deeply explored in the field, despite the possible effect of such modulations on the morphodynamics. Furthermore, because of this scarce knowledge, numerical modelling often ignores, or largely underestimates, the variety of vertical distribution of velocities, thus resulting in unrealistic results.

In this context, this preliminary study aims at monitoring and analyzing the 3D circulation over a system of double nearshore sand bars forced by waves, especially during a storm event. The objectives of this paper are: (1) to estimate temporal profile variations of currents inside and outside the surf zone, (2) to compare differences in current characteristics on the inner trough...
and the seaward flank of the inner bar, (3) to examine the importance of this type of in-situ data (2DV) in improving numerical models.

**STUDY AREA**

The sand barrier bounding Thau lagoon is a 13 km long low-lying linear feature in the Gulf of Lions in the Mediterranean Sea (Figure 1). The study site is located in the northern part of the barrier, near Sète and has been affected by persistent erosion over the last few decades. The barrier is characterized by the presence of a double nearshore bar system (Certain and Barusseau, 2005) and a cuspatc shoreline usually in phase with the inner bar (seaward bulges in the shoreline being located in front of the bar shoals) with a cusp wavelength of 400 m (Balouin et al., 2013). According to the Short and Aagaard (1993) classification, the field site is an intermediate beach ($\Omega = 5.5$) and displays a Rhythmic Bar and Beach (RBB) inner bar and a Longshore Bar and Trough (LBT) outer bar (Aleman et al., 2011).

Figure 1. Cross-shore profile of the field site and location of the equipment deployed to measure vertical current profiles in the nearshore.

The field site is a typical example of a microtidal environment characterized by a very low tidal range (< 0.30 m at mean spring tide). It is a wave-dominated system with very low mean energy, punctuated, especially during winter and autumn, by energetic storms. Just offshore of the study site, wave heights at the Dataswell Sète buoy (water depth of 32 m) are less than 0.3 m for 75 % of the time. Wave heights larger than 2 m are observed only 10 % of the time for short periods less than 48 hours. The dominant wave regime is short-fetched with peak periods in the 3-4 second range, and waves are mainly from azimuths 140-220°N generated by sea breezes.

**METHODS**

Several instruments were deployed on a cross-shore transect over the sand bars for over 2 months, from 15 December 2008 to 25 February 2009. This study focuses only on a single storm event that lasted for few days in early February 2009 with significant offshore wave heights of up to 3 m.

Hydrodynamic measurements were obtained from three stations across the sand bar system. The first and second stations were located in the inner trough (3.3 m water depth) and in the seaward flank of the inner bar (4.6 m water depth). Each station contained one Acoustic Doppler Velocimeter (Sontek ADV) and one Acoustic Doppler Current Profiler (RDI ADCP, 600 kHz). This combination allowed measurements through the entire water column. Indeed the ADV measure velocities at a point just above the seafloor (between 0.1 and 0.15 m) partly encompassing the blank space not covered by the ADCP. However, due to burial by sediment and corresponding bar morphological change, the ADV deployed on the seaward flank of the inner bar did not record starting from the peak of the storm. The data were collected at a frequency of 2 Hz during 1 minute with an interval of 3 or 6 minutes (inner trough and seaward flank of inner bar respectively) for the ADCP, and 20 minutes with an interval of 2h 40 minutes for both ADVs. In this study, mean currents were averaged over every minute. Velocity measurements from both the ADVs and the ADCP tended to display noise in highly turbulent or aerated flows. Signal correlation values recorded by the instruments were used to identify such potentially incorrect data. Each instrument has a pressure sensor that measured wave characteristics with a burst duration of 20 minutes every 3 hours. The wave characteristics were processed by standard spectral analysis. In addition to the Doppler sensors, a self-recording electromagnetic current meter comprising a pressure sensor (Inter-Ocean S4DW) was deployed offshore of the outer bar at about 40 cm above the bed. Only the wave characteristics of this instrument are used in this study. Data were collected at a 2-Hz frequency with a burst duration of 20 minutes every 3 hours. 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 with respect to the crests of the bars (140°N).

**RESULTS**

The 2DV current characteristics in the trough and the seaward side of the inner bar that prevailed in the course of a storm from 31 January to 4 February 2009 are described and analyzed with reference to nine key periods selected following three phases: waxing storm (1, 2, 3), storm peak (4), and waning storm (5, 6, 7, 8, 9).

**Waxing storm:** At the beginning of the storm, mean currents in the inner trough were weak (< 0.15 m.s⁻¹), in relation to the moderate wave energy (Figure 3A, 3B). They intensified starting from $H = 0.9$ m (in the trough) with strengthening of a pre-existing but weak longshore current (Figure 2D1). This first threshold corresponds to the inception of a surf zone over the inner bar-trough couplet (Figure 2A). Thereafter, mean currents became stronger, exceeding 0.5 m.s⁻¹ and up to 0.8 m.s⁻¹. The longshore current was therefore the principal flow component (Figure 2D2, 2D3) compared to the cross-shore current (less than 0.1 m.s⁻¹). As wave energy increased, the vertical distribution of the mean current direction became more uniform, and progressively tended to be parallel to the main axis of the bar-beach system (Figures 2F2, 2F3). On the seaward side of the inner bar, currents displayed characteristics influenced by the wind (mean velocity less than 0.2 m.s⁻¹ and relative heterogeneity of directions) (Figures 2E1, 2F1, 2E2, 2F2). Only the first metre of the water column was affected by stronger velocities of up to 0.4 m.s⁻¹ (Figure 2E1). This behavior was observed up to a significant wave height of 1.8 m on the inner bar. Starting from this second threshold corresponding to the inception of surf on the outer system, the current profile underwent a change with an increase in vertical homogeneity of the longshore current (up to 0.4 m.s⁻¹), (except for the ADV near the bed which recorded lower velocities) (Figure 2C3). The cross-shore velocity was associated with an undertow that appeared as the threshold observed above (i.e., $H > 1.8$ m on the inner bar) was attained. However, this current was of very low velocity (less than 0.1 m.s⁻¹) and was not constant over time.
Figure 2. Meteorological forcing and hydrodynamic response during a storm in February 2009. (A) Significant wave height; (B) wind velocity and azimuth; (C) cross-shore/longshore components of the burst-averaged velocity profiles observed at different times on the flank of the inner bar; (D) same measured features in the trough itself; (E) burst-averaged velocities in the trough and the flank of the bar; (F) burst-averaged azimuth of the current in the trough and the flank.
behavior corresponded to an original profile of mean currents with relatively lower velocities at the surface and at the bottom (0.25 m.s\(^{-1}\)), and a maximum in the middle of the water column (0.55 m.s\(^{-1}\)) (Figure 2E3). During waxing of the storm, the current direction was relatively uniform throughout the water column in relation to the increase in significant wave height.

**Storm peak:** During the peak of the storm (Hs = 2.25 m on the bar crest), the intensity and direction of the current were uniform throughout the water column (0.8 m.s\(^{-1}\) on average) on the seaward side of the inner bar (Figure 2F4). The longshore current was largely dominant and attained a maximum during this phase (0.7 m.s\(^{-1}\)). A weak return current (0.15 m.s\(^{-1}\)) was observed from 0.7 m depth to the bottom (Figure 2C4). In the inner trough, the current was also at its recorded maximum (0.93 m.s\(^{-1}\)) and almost totally longshore (0.9 m.s\(^{-1}\)) (Figure 2D4, 2E4). An undertow was also observed from a depth of 0.7 m, but with a weaker velocity (0.1 m.s\(^{-1}\)). The vertical velocity distribution in the water column was not as homogeneous as it was on the seaward side of the inner bar and reached a maximum at a depth of 1.2 m, whereas the current direction was uniform and parallel to the mean orientation of the bar-beach system.

**Waning storm:** The waning of the storm was characterized on the seaward side of inner bar by a high velocity which decreased down to the first threshold observed during the waxing stage. Velocities and directions were homogeneous throughout the water column up to about Hs = 1.5 m, which corresponded to the disappearance of the undertow, throughout of lower intensity than the longshore current (Figure 2B6 and 2B7). Currents in the inner trough were always stronger than those on the seaward side of the inner bar, and they remained strong up to burst 8 (Hs = 1.2 m in the trough, 0.5 m.s\(^{-1}\)) (Figure 2E8). They then started getting weaker during burst 9 (Hs = 0.9 m in the trough 0.1 m.s\(^{-1}\)), corresponding to the second threshold previously observed.

**DISCUSSION**

**Vertical shearing of surf-zone currents**

This study has examined the response of a current profile over a double nearshore sand bar system during a storm event. This type of in-situ data obtained inside or outside the surf zone is rare in the literature. It shows that the vertical distribution of nearshore velocities is strongly hinged on wind/wave conditions, as reported by Yamashita et al., (1998) and Ferrer et al., (2011), and the temporal variability of which can lead to significant changes in time distribution. During fair weather or moderate wave energy conditions, the velocity profile can exhibit numerous declinations, with, for instance, maximum velocities at the top, bottom, or middle of the water column, probably as a function of changing wind stress and wave conditions. Furthermore, the velocity distribution is of high heterogeneity, with values that can reach 0.3-0.4 m.s\(^{-1}\) (Figure 2). This quite complex representation can be erroneously interpreted when a depth-averaged velocity, a single point measurement, or lagrangian measurements are used to interpret the hydrodynamic circulation as well as the direction and intensity of sediment transport over bar systems. During the peak of the storm, velocities are higher and relatively uniform throughout the water column as reported in the literature (Yamashita et al., 1998; Ferrer et al., 2011). Only near the bottom are currents relatively weak, a kink observed by Aagaard et al., (2012) on cross-shore velocities and which they attributed to bottom boundary layer streaming. In our study, this kink is essentially observed in the structure of the longshore current, which is much stronger than the cross-shore current, and is probably due to bed friction. Thus, however energetic the conditions are, there seems to be a difference between bottom processes implied in sediment transport and the rest of the water column, and this has important implications regarding the interpretation of bar morphological response time to storms.

**Surf-zone control on current velocities**

The system was mainly influenced by the longshore current as observed in other field sites (Greenwood and Sherman, 1986; Smith et al., 1993). A distinctive hydrodynamic behavior is observed between the trough and the seaward flank of the inner bar involving the following characteristics. (1) The longshore velocities, which reach 0.8 m.s\(^{-1}\), are slightly higher in the inner trough than over the bar during the waxing and peak phases of the storm. (2) The cross-shore velocities are weak and an undertow, fairly uniform over the water column, is observed mainly on the seaward flank of the inner bar. In the inner trough, the undertow is weaker and affects only the bottom of the column. The values of
the undertow (0.1 to 0.2 m s\(^{-1}\)) are similar to those described in the literature for similar wave energy conditions (Masselink and Van Heteren, in press). (3) A velocity increase is observed when the system is influenced by the surf zone (Figure 3A, 3B). The triggering of the longshore current is relatively synchronous in the different parts of the inner bar couplet. However, two thresholds in the increase of the velocities can be detected, with a first one when only the inner trough is affected by breaking waves (\(H_s = 0.9 \text{ m}\) in the trough) and a second one, even more intense, when the entire inner system is in the surf zone (\(H_s = 1.8 \text{ m}\) on the seaward flank of the bar). (4) Despite the difference in significant wave height over the inner system, mean velocities in the trough are relatively similar to those recorded on the seaward flank of the bar (Figure 3C). This behaviour is observed during the waxing and peaking of the storm but not during the waning period when breaking waves affect only the inner trough. During this period, mean velocities are higher in this part of the profile, notwithstanding the fact that this condition was not observed during the waxing period. This is probably due to the inner trough acting as a privileged drain for the water masses piled up on the shoreline.

**Input in terms of numerical modeling**

The third objective of this preliminary study is to examine the utility of the type of in-situ data (2DV) we have reported here in enhancing the output of numerical modeling. The understanding of wave-driven nearshore hydrodynamics since the late 1960s, following the seminal work of Longuet-Higgins & Stewart (1962), has benefited from several major refinements regarding nearshore wave/current interactions. These include, in particular, the impact of a homogenous current on wave dispersion (Burrows and Hedges, 1985), the combination of wave refraction and diffraction in the possible presence of a current (Kirby and Dalrymple, 1983; Holthuijsen et al., 2003), and the calculation of quasi-3D current profiles forced by nearshore waves (Putrevu and Svendsen, 1999).

Unfortunately, there is a significant lack of theoretical knowledge on wave transformation by vertically sheared currents (Booj, 1981; Liu, 1983). Thus, the dataset presented here and any other similar experiment in the field or in a wave flume, is of high importance to feed new theoretical insights regarding wave and sheared current interactions.

Over the last ten years, there have been a variety of numerical developments regarding the hydrodynamics of the nearshore zone that include the generalization of boundary conditions in coastal models (Haasa and Warner, 2009), the introduction of uncertainty in nearshore simulations (Mohammadi and Bouchette, 2013), and the elaboration of more robust numerical schemes (such as the so-called Green-Nagdi schemes; Marche, 2007). The present work demonstrates that these numerical refinements are of very limited use if a correct inclusion of wave-sheared current interactions is not achieved.

Another tendency in numerical modeling concerns simulations usually performed at the continental shelf-scale with models solving the primitive equations that tend to be downscaled to the nearshore zone. This enlargement of the use of these models requires robust 3D coupling with wave models such as WW3 (Bennis et al., 2011). The practical suitability of this methodology is under debate in the literature. For example, Michaud et al. (2013) modeled 3D nearshore hydrodynamics based on a comprehensive coupling between SYMPHONIE (Marsaleix et al., 2008) and WW3, and compared the results with a robust set of in-situ nearshore data. They obtained a correct agreement between simulations and measurements. However, although a lot of physics are embedded in the coupled model, waves and chiefly depth-dependent current patterns are altered by changes in the bottom elevation through time, especially via sand bars. As a consequence, the next step for the improvement of these full 3D-coupled models is to fully consider the complex interactions between waves and bars, which, in particular, includes what has been brought to the fore in this paper.

![Figure 4. Cross-shore profiles with a limited longshore thickening-extracted from SHORECIRC simulations. Top three: evolution of the spatial distribution of breaking waves with increasing wave height from 1.3 m to 4.2 m. Selected wave heights mark two thresholds where significant changes in the breaking wave distribution occur in the numerical results. Bottom: distribution of averaged velocities before (\(H_s=1.3\text{m}\)) and after (\(H_s=2.0\text{m}\)) the widening of the surf zone seaward of the inner trough.](image)

Nonetheless, present models, either based on primitive equations or on strict nearshore physics, are already of help in enhancing results acquired in the field. To illustrate this, we computed with a modified version of SHORECIRC (Svendsen et al., 2004), 3D velocity fields on a 800 x 600 m\(^2\) domain with a sea bottom very similar to that observed in the field study site in Sète (Figure 1), and forced by similar waves ranging from \(H_s = 0.5 \text{ m}\) to 5 m and corresponding similar periods. A very basic analysis of the results gives numerical evidence for the occurrence of thresholds in the distribution of the wave height (linked to the extension of the surf zone) that controls the 3D velocity patterns (Figure 4). Although SHORECIRC does not allow the computation of strongly sheared profiles (the model presupposes the profiles partly), these numerical results are encouraging because they suggest that there exists a physical interpretation of what was observed in the course of the field experiment.

**CONCLUSION**

The results presented in this study describe the complex configuration of current profiles over a double nearshore bar
system in a low microtidal setting, especially during fair weather and moderate wave energy. During storms, current profiles are vertically uniform, and the results further highlight the influence of breaking waves on the intensification of velocities and the establishment of undertow, which is confirmed by simple simulations dealing with 3D currents. However, the inner trough shows a peculiar behavior during storm waning probably due to its role as a privileged drain of the water masses accumulating over the bar-trough system during storm. These preliminary results will need to be confirmed by a fuller analysis of the extensive dataset obtained in the course of the > 2-month-long field experiment on the double bar system of the Gulf of Lions sand barrier coast, and which could lead to interesting insight into, and a better understanding of, the complex coupling between phases of waxing, peak and waning storm wave levels and sheared currents in the nearshore zone.

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LITERATURE CITED