Net Offshore bar Migration variability at a regional scale: Inter-site comparison (Languedoc-Roussillon, France)

Nicolas Aleman†, Nicolas Robin†, Raphael Certain†, Jean-Paul Barusseau† and Mathieu Gervais†‡

†CEFREM (UMR5110)
CNRS/University of Perpignan
52 av. Paul Alduy
66860 Perpignan Cedex 9, France
nicolas.aleman@univ-perp.fr

‡ BRGM, Service Géologique Régional
1039 rue de Pinville
34000 Montpellier, France
www.cerf.jcr.org

ABSTRACT


The Languedoc-Roussillon coastline is a large unit stretching out over 200 km of sandy low coast in a wave dominated environment. The nearshore is characterized by a quasi continuous system of double sandbar that displays a wide range of typology. The interannual sandbar dynamic was investigated using 2D bathymetric profiles and 3D LiDAR imagery. This study has allowed determining the sandbar systems affected by the Net Offshore Migration (NOM). At a regional scale, conditions necessary to NOM development depend on the sandbars morphologies (crescentic or straight), the wave energy and the associated coastal orientation (low or high energy, sheltered area), the coastal structures (harbour and coastal defences) and the nearshore sedimentary budget. The areas where the NOM occurs show cycle dynamic differences. This regional inter-site comparison highlight that nearshore morphology and bar parameters seem to influence the nearshore bar behaviour. Interaction between the nearshore slope, width of the bar zone and the migration rate control the NOM duration. The sandbar volume and the regional wave climate influence also the migration rate of the system. On the Languedoc-Roussillon coast, the sediment grain size do not appear to influence the seaward bar migration.

ADDITIONAL INDEX WORDS: Net offshore migration, sandbars, regional scale, wave energy, coastal structures.

INTRODUCTION

Nearshore bars are common features of wave dominated sandy coast in micro to mesotidal environments. Their occurrence on the shoreface forms a natural protection for the coastline and represents an important sedimentary stock for the system. Thus, many studies focus on their morphodynamics. However, their evolution is complex due to many control parameters (hydrodynamical, geological, morphological…) giving rise to various movements with different temporal cycles and a large panel of feedback processes.

These studies have shown that, at multi-decadal scale, the straight bar systems are subjected to a cycle of seaward degeneration (Lippmann et al., 1993; Russink and Kroon, 1994; Wijnberg and Terwindt, 1995; Plant et al., 1999; Shand et al., 1999; Kuriyama and Lee, 2001). This behaviour is called “Net Offshore Migration” (NOM). Each bar goes through three successive stages (Kroon, 1991; Russink and Kroon, 1994) known as the “Dutch model”. On a multi-barred coast, the degeneration and disappearance of the outer bar at 5 to 7 m depth leaves sufficient accommodation and increases wave energy in the inner zone for the rapid seaward migration of the inner bar. The inner bar takes the place of the outer bar, while a new inner bar is created in shallow water. NOM observations are restricted at only a few areas in the world (New-Zealand (Shand, 2000), USA (Lippmann et al., 1993), Egypte (Khafagy et al., 1992), Japan (Kuriyama and Lee, 2001), Netherlands (Russink and Kroon, 1994; Wijnberg and Terwindt, 1995), Black Sea (Tatui et al., 2011), France (Certain and Barusseau, 2006) with a large panel of environmental parameters.

Literature exhibits disagreement as to whether bar migration is or not a continuous phenomenon; great inter-site variations can exist (Shand et al., 1999). Some field studies show that the seaward migration is triggered by a succession of high energy events (Russink and Terwindt, 2000; Certain and Barusseau, 2006). Observations seem to show that migration rates are linked to hydrodynamic conditions (Sallenger et al., 1985; Gallagher et al., 1998). However, bar volume can also influence this relationship; for example a large bar migrates slower than a smaller one (Smit et al., 2008; Russink et al., 2009; Tatui et al., 2011). According to Shand and Bailey (1999) an average life span ranging from 2.5 to 20 years can be noticed, as well as an average migration rate between 30 and 200 m.yr⁻¹ and an average return period from 1.2 to 15 years.

This study attempts to clarify the environmental conditions required to establish a NOM cycle and its characteristics with a regional scale approach. As mentioned by Shand et al. (1999) “an inter-site quantitative analysis may provide further conceptual information on the morphodynamics of NOM systems”. For this, a large set of bathymetric data and a topo-bathymetric LiDAR survey are compared to identify regional areas with or without NOM. A comparison of various environmental parameters is then used to define the optimal conditions for NOM triggering. In a second step, we try to explain the variability of NOM cycle at regional scale. Different morphological parameters of the NOM

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were calculated and then connected to the environmental context to explain the differences.

STUDY SITE

The Languedoc-Roussillon is located in the Gulf of Lions, south-western part of the French Mediterranean coast. The sandy coast extends over 200 km intersected by some rocky headlands (fig. 1). Many harbours and breakwaters were built along the coast. The nearshore zone is characterized by a well developed double bar system. In the southern part of the gulf, the inner and outer bars are crescentic. In the central part, the inner bar is crescentic and the outer bar is straight. Finally, in the north-eastern part, the bars are straight (fig. 1). The description of these systems can be more complex with a large set of patterns (Aleman et al., 2011).

The field site is classified as a wave dominated system (Certain, 2002). The tide is microtidal with tidal range < 0.30 m at mean spring. The annual significant wave height is low (0.80 m). However, Hs may exceed 3 m during storms with high water level variations which can cause surge > 1 m near the shore (Certain, 2002). The impact of these energetic events on the coast is highly variable due to the wave direction (E-SE and S-SE) and the coast orientation (curvilinear) (fig. 1). The energy of the storm is strongest in the central part of the gulf while the southern part is protected by the rocky coast (Gervais, 2012).

The geological context induces a longshore variability of the sediment grain size. In the southern area, deltaic mouths are responsible for the presence of coarse sand (D50 up to 1850 μm). Fine sands (around 200 μm) in the northern part come from ancient inputs of the Rhône River which no longer provides this kind of material in the area nowadays. Some irregularities are caused by localized rocky outcrops in the nearshore zone. In the cross-shore direction, the size of the sediment decreases seawards (Jago and Barusseau, 1981; Barusseau, 2011). The littoral drift is influenced by the coastal orientation. Along the southern part, it is directed northward and toward the south-west in the northern part (Certain, 2002; Brunel, 2010) (fig. 1). Rocky headlands and harbours may cause partial or total interruption of sediment transport.

METHODS

2D bathymetric profiles were performed by the SMNLR (Maritime and Navigation Service of Languedoc-Roussillon) every one or two years from 1984 to 2004. These profiles cover the entire study area with a random spacing from 200 m to 5 km and an offshore extends of 700 m, limit of the annual closure depth.

These data were completed by a topo-bathymetric LiDAR survey. The flight occurred in summer 2009 and covered the entire coast of the Languedoc-Roussillon. It provided a continuous longshore view of the coastal morphologies that allow inter-profile connexion.

Additional information was brought by a large set of aerial photographs taken at different years. They were georeferenced and analyzed with ArcGIS 10 software. They enable to digitalize the position of nearshore bars by water transparency and allow a longshore control. This reduces the lack of information between bathymetric profiles.

The table 1 summarizes the dynamic and the morphological characteristics of the nearshore bars of ten areas identified in the Gulf of Lions (fig. 1). For each area is given the observation duration (Pobs) giving the total time of the field survey, the return period (T) defined as the time interval between two successive occurrences of same nearshore profile, the NOM duration (D) that correspond to the duration of the migration between the generation and degeneration zones, the migration rate (M) computed only for the migration zone, the bar zone width (Xb) identified by its landward (inner trough) and seaward boundaries (annual closure depth), the estimated bar volume (Vb), the slope (β) between the shoreline and the closure depth, the mean grain size (D50) on the inner bar and the geological context.

RESULTS

The analysis of 2D bathymetric profiles shows that NOM does not affect all sectors of the Languedoc-Roussillon (fig. 2). In Roussillon, crescentic bars (fig. 3A) migrate both on the onshore and offshore directions without long-term trend. So, observations in crescentic bar area do not allow the detection of NOM (fig. 2A). Nevertheless, longshore oscillation of the crescent was observed at Leucate beach (Ferrer et al., 2009). This sector have coarser sediment (0.426 mm) associated with a steep slope (1:65) and a bar zone of 705 m (tab. 1). The bar systems of Cape of Agde, Aresquiers, Aigues Mortes and Espiguette are straight but are also not subject to NOM. Bars appear to oscillate around an equilibrium position (fig. 2A). Environmental parameters are quite different from Roussillon with finer sand sediment (between 0.148 and 0.178 mm), large zone of bars and gentler beach slope (tab. 1). Sector of Aigues Mortes forms a large bay sheltered by the Rhone delta. It has also the shortest bar zone (225 m) and a gentle slope (1:110). Cape of Agde is an area sheltered by the rocky coast and has many coastal defence structures. The bars zone is however larger and reaches 935 m for a slope of 1:140. In the Aresquiers beach, bedrock and beachrock outcrop at ~4 m depth and the bar zone is reduced to 415 m (tab. 1). The coast has many coastal defence structures (fig. 3B). The grain size is fine (0.161 mm) for a slope of 1:130. In the further north-east coast of Languedoc-Roussillon, Espiguette area has the widest bar zone (1400 m) but is disturbed by many groynes. The slope is low (1:120) associated with fine sand (0.178 mm).
Characteristics and dynamic of Net Offshore bar Migration at a regional scale: Inter-site comparison

The Net Offshore Migration affects the central and northern part of the Gulf of Lions. In the five areas identified, Port-la-Nouvelle, Gruissan, Agde, Sète and Maguelone, the sediment grain size is fine (0.154 to 0.196 mm) with a relatively gentle slope (from 1:105 to 1:125). These areas have the same NE-SW orientation. However, the migration rate of the bars, the return period of the cycle, the NOM duration, the bar volume and the width of the bar zone show significant differences (tab. 1). Return period and migration rate increase from SW to NW, while the NOM duration decreases (even if the return period in Sète and NOM duration in Agde were not fully observed). The bars volume is average to large with a bar zone width between 49.5 and 76.0 m. Maguelone is an exception with a return period, NOM duration and migration rate relatively low (8 years, 6 years and 19 m/year respectively). The bar volume and the slope are the lowest with the presence of a small bar.

The bar lifespan is composed to three stages identified in all areas (fig. 2). Bar appears near the shore with only oscillation around an equilibrium position (OPE in Certain and Barusseau, 2006) for several years (max : >19 years). Bar then migrates rapidly seaward in a few years (3-9 years). At last, the bar oscillates and degenerates offshore in a decade.

CONTROL FACTORS OF NOM OCCURRENCE

Specific conditions conducing to NOM have received little attention in the literature. In different inter-site comparisons, NOM is observed on beaches with fine sediment range from 0.16 to 0.21 mm and gentle slope between 1:225 and 1:75 (Shand et al., 1999; Ruessink et al., 2003). In the Languedoc-Roussillon, the NOM occurs in same conditions. The sediment is fine (0.15 to 0.20 mm) and the slope relatively gentle (~1:120). However, this study highlights other essential conditions for its formation:

1) The linear morphology of the bars. As seen above, the nearshore sandbar plan shapes vary from linear to crescentic in the whole region. On one hand, long term persistent rhythmic bedform features observed in the Roussillon coast (fig. 3) are not submitted to the NOM. Field studies at Leucate Beach have demonstrated the temporal cross-shore stability of the crescentic outer bars (Ferrer et al., 2009). This relative stability can be reliable to the generation of three-dimensional sandbar patterns that are typically a mixture of self-organization (Coco and Murray, 2007) and morphological bar coupling (Ruessink et al., 2007; Almar et al., 2010; Castelle et al., 2010b, a). 3D patterns induce stable cellular hydrodynamics (Castelle et al., 2005) and would produce an irregular longshore pattern of seaward flow (Shand et al., 1999). On the other hand in the central and northern part where the outer bar is straight, NOM is observed. According to Shand et al. (1999) persistent longshore currents associated with linear sandbar systems can be responsible for this state due to the longshore uniformity of return flow occurrence and a laterally continuous offshore bar migration.

2) The shape of the coastline seems to be another parameter to be taken into consideration as it induces the degree of the system
exposition to the wave energy. The curvilinear orientation of the Languedoc-Roussillon coastline leads to a gradient of wave energy (tab. 2). On one hand, the southern part (NOM absent) is protected from SE storms by the rocky coast, only eastern waves are not attenuated (fig. 1). Thus, the significant wave height and extreme storms wave energy flux (WEF) are weaker (tab. 2). The frontal extreme storm may allow the development of 3D features (Wijnberg, 1995) that have been developed in (1). On the other hand, the central and the north-eastern parts (NOM present) are exposed to frequent SE storms and submitted to a "high regional exposition" (tab. 2). Consequently, only NE-SW oriented shorelines (fig. 1) with an angle of incidence of storm waves around 7° at 30 m depth (tab. 2) show NOM cycles. The succession of storms events is responsible for the seaward migration and degeneration of the outer bar (Certain and Barusseau, 2005; Gervais, 2012). Nevertheless, in sheltered areas (Cap d’Agde, Aigues Mortes) two-dimensional sandbar systems show small and relatively stable morphologies. These beaches form a large bay where wave energy seems to be sufficient to induce straight bars but not enough to trigger a NOM cycle. On the Espiguette beach, the NOM absence is possibly due to the high angle of incidence and strong littoral drift (tab. 2), inducing a very important longshore transport, emphasized by an exceptional accumulation against the harbour of Port-Camargue. These high sediment inputs and wide bar zone seem to be responsible for the absence of NOM or at least a very slow cycle unidentified on the time-series available.

3) The role of sedimentary stock is unclear. Maguelone and Aresquiers have older rocky outcrops on the shoreface (fig. 3), but the behaviour of these two systems is different. As such, the offshore limit between sand and substratum is further away (near 10 m depth) at Maguelone than at Aresquiers (2-3 m depth). Moreover, Aresquiers beaches are equipped by a lot of coastal structures (fig. 3). It therefore appears that low sediment stock does not prevent the occurrence of the NOM. The sediment budget seems rather control the parameters of the bars and therefore the properties of the cycle as developed below.

4) The results of this study have highlighted the influence of coastal structures on the no-NOM occurrence. Despite favourable environmental conditions, all areas equipped with extensive coastal defence structures (Cap d’Agde, Aresquiers, Espiguette) have a stabilized sandbar system where the NOM does not seem to occur. A large number of these hard structures intersect the nearshore bars and affect the sediment transport (Michel et al., 2011; Aleman et al., 2012). Local modifications of current patterns most likely explain this behaviour, as rip position controls by groynes (Short, 1992).

So at a regional scale, this study shows that the presence of NOM is not dependant on only one environmental parameter. It is the combination of several physical controls at different time and spatial scales that intervenes and consequently leads to difficulties in defining and assessing the influence level of each. However, this study highlights the limiting role of some of them (wave energy, coastal defences…).

**CONTROL FACTORS OF NOM REGIONAL VARIABILITY**

In the areas where it is present, the NOM characteristics are different from one site to another. These differences appear to be related to the morphology of the bars and the hydrodynamic conditions.

Regarding the differences of the NOM characteristics between sites, many authors suggest a relationship between the slope and the migration rate (Kroon, 1994; Wijnberg, 1995; Shand and Bailey, 1999; Shand et al., 1999; Grunnet and Hoekstra, 2004). In the Languedoc-Roussillon, the migration rate ($M_r$) increases with increasing $\beta$ despite its low variability (1:125 at Port-la-Nouvelle to 1:105 at Maguelone).

$X_{10}$ is a key geometric parameter that steer the inter-site and intra-site variation (Ruessink et al., 2003). Observations on beaches affected by NOM in Languedoc-Roussillon show that the NOM duration is modulated by the bar zone width ($X_{10}$). For a same migration rate, when $X_{10}$ is narrow, the NOM duration is shortened. Yet the relationship between $X_{10}$ and the external forcings are not clearly defined (Ruessink et al., 2003; Tatui et al., 2011).

In the literature, bars volume is usually considered as a parameter controlling the bar migration rate, small bars migrating faster than large bars (Grunnet and Hoekstra, 2004; Tatui et al., 2011). In the Gulf of Lions, a relationship between the migration rate and the nearshore bars volume is also observed. Surprisingly, it is the largest bars that migrate faster than the smallest ones. An enlightening observation is that areas with large bars receive more wave energy allowing a faster migration.

Previous studies have shown that wave energy presents a very good relationship with the migration rate and NOM duration.
Characteristics and dynamic of Net Offshore bar Migration at a regional scale: Inter-site comparison

Table 2: Summary statistics on severe storms simulated by CFSR (46 cases since 1979) in the Gulf of Lions (after Gervais, 2012).

<table>
<thead>
<tr>
<th></th>
<th>Argelès</th>
<th>Leucate</th>
<th>Gruissan</th>
<th>Sète</th>
<th>Espiguette</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average $H_s$ (m)</td>
<td>1.08</td>
<td>1.26</td>
<td>1.23</td>
<td>1.39</td>
<td>1.38</td>
</tr>
<tr>
<td>Average Direction (deg)</td>
<td>106.8</td>
<td>119.7</td>
<td>125.4</td>
<td>144.4</td>
<td>165.9</td>
</tr>
<tr>
<td>Angle of incidence (deg)</td>
<td>+22.8</td>
<td>+17.7</td>
<td>+7.4</td>
<td>+6.4</td>
<td>-6.4</td>
</tr>
<tr>
<td>Sum WEF (KJ.m$^{-2}$)</td>
<td>178 900 000</td>
<td>240 400 000</td>
<td>227 400 000</td>
<td>266 000 000</td>
<td>233 300 000</td>
</tr>
<tr>
<td>Sum WEF longshore (KJ.m$^{-1}$)</td>
<td>6 800 000</td>
<td>16 700 000</td>
<td>-2 200 000</td>
<td>-27 200 000</td>
<td>-18 700 000</td>
</tr>
<tr>
<td>Direction of induced longshore drift</td>
<td>N</td>
<td>N</td>
<td>SW</td>
<td>SW</td>
<td>NW</td>
</tr>
</tbody>
</table>

Concluding remarks

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(Grunnet and Hoekstra, 2004). In fact, storms are responsible for the origin of the undertow involved in seaward bar migration (Lippmann et al., 1993). Sète where the migration rate is the fastest receive the highest energy during storms, while in Gruissan the reverse can be observe (tab. 1 and tab. 2). Eventually, the morphology of the Gulf of Lions and the direction of the major storms cause longshore variability of the wave energy and induced currents. This variability influences different patterns of migration rate at a regional scale.

Only Maguelone and Port-la-Nouvelle long time series allow a thorough analysis of NOM return period frequency. This frequency seems uniform for both sites (7-9 and 6-8 yrs respectively). For the duration at regional scale of the return period, a great inter-site variability exists (tab. 1). Certain (2002) and Gervais (2012) have demonstrated that the NOM is triggered by high energetic storms, and their impacts are very different according to the varying morphology and orientation of the coastline (Gervais et al., 2012). Relation between NOM cycles, storms frequency and orientation of the coastline need to be done to define $H_s$ threshold for migration triggering.

The case of Maguelone is particular with a very slow migration rate. Taking into account the morphology of this area and the NOM duration (tab. 1), the reverse should be observed since a narrow and steep shoreline occurred resulting in a narrow bar zone and limited sediment volume (fig. 2). However, as the offshore rocky plateau is wide and shallow (~10 m), the relative slowness could be explained by the attenuation of strong waves further offshore due to the outcropping bedrock (Sabatier et al., 2004).

CONCLUDING REMARKS

The Languedoc-Roussillon coastline is characterized by a well developed sandbar system that displays a great variety of typologies. On this regional scale, only straight sand bars systems exhibit the NOM. However, sufficient wave energy is required to trigger a NOM cycle, but contrarily some parameters can constrain its properties (coastal structures, sedimentary budget...).

Regional NOM differences suggest that each area is characterized by distinctive morphological and forcing parameters. NOM cycle characteristics are determined by a combination of several main dynamic and morphological parameters as hydrodynamics, nearshore slope, bar zone width. Moreover, the sandbar volume, the sediment budget, the coastline orientation and the regional hydrodynamic variability can also influence the NOM.

This study highlights that the regional sandbar morphodynamics is highly sensitive to the variability of the morphological and environmental parameters. Thus, Languedoc-Roussillon coastline is ideal for studying the behaviour of the sandbar systems. New data collection like high resolution hydrodynamical data in the surf zone and new LiDAR imagery will allow a better understanding of all the parameters involved in the NOM development and the role of each, and particularly explain the longshore variability along sedimentary cells.

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