Multi time-scale morphological evolution of a shell sand, dune bank in a shallow mesotidal environment.

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ABSTRACT: Dune banks are ubiquitous systems in coastal areas. Understanding their morphodynamics and the associated sediment fluxes is still scientifically challenging. To address these questions, we use a multi time-scale bathymetric dataset of a dune bank located in a very shallow area inside a semi-enclosed bay, where the tidal current is strong and unsteady. The bank is composed of coarse shell sand, has a steady sediment volume, and is not migrating. The bank can be seen as a two-component system, featuring a ridge oriented along the bank, and a series of dunes orthogonal to the ridge. These two types of bedforms exhibit different dynamics. The transverse dunes are migrating toward SW (ebb current orientation) with a mean migration distance on the order of a meter over a month. At multiyear time scale, the orientation of the ridge is stable except for the central area of the bank, where the bedform configuration is quite variable.

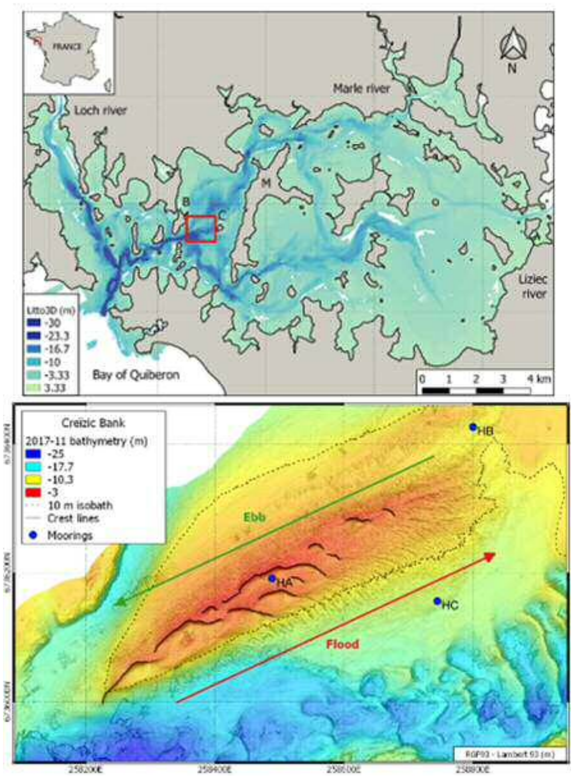
1. INTRODUCTION

Submarine banks and dunes are ubiquitous sedimentary systems in coastal areas (Ernstsen et al., 2006; Horrillo-Caraballo et al., 2008; Ferret et al., 2010). Understanding their morphodynamics, and the associated sediment fluxes and sediment transport pathways, is crucial for various applications such as the safety of navigation, the exploitation of marine resources, or the conservation of benthic and pelagic species (Trentesaux et al., 1999; Hequette and Aernoust, 2010; Todd et al., 2014). However, due to the lack of monitoring data and the difficulty in measuring or evaluating sediment transport for these systems, dune morphodynamics still poses some scientific challenges. Here, we focus on a very shallow sand bank, consisting of shell sand, and that is only subject to tidal forcing, the wave climate being characterized by very small significant wave heights. The bank is located on a narrow margin between two channels near the inlet of a large, semi-closed gulf. While tidal currents are strong and unsteady in this shallow area, and the dunes located in the central area of the bank are highly dynamic, the bank exhibits a very low migration rate and its sediment volume is conserved. Using bathymetric datasets covering multiple time scales, both multi-annual and over a month, this paper aims to study the morphodynamic behavior and sediment transfer of the bank and dunes.

2. STUDY SITE

The study site, the *Creïzic* submarine dune bank (fig. 1), is located in the western part of the Gulf of *Morbihan* (South Brittany, France). This gulf is connected to the Atlantic Ocean by a very narrow inlet. Due to this configuration, the semi-diurnal tide generates a residual current above the seafloor, with the ebb current being predominant in the outer part of the Gulf (Marcos et al., 1996). The Gulf of *Morbihan* is a bedrock-controlled lagoonal basin with low sediment supply, incised by a complex network of tidal channels (Menier et al., 2011). The last marine transgression led to the infilling of the incised palleo-valleys, with erosion at the entrance of the Gulf and sediment deposition (lithic and biolithic material) inside the Gulf. On the outer part of the Gulf (between its entrance and the island *Île aux Moines*) hydrodynamics conditions were highly energetic, leading to sediment deposits on the margins of the tidal channels only, such as the *Creïzic* bank (Menier et al., 2011).

The *Creïzic* bank is situated in water depths ranging from 3 m to 25 m (fig. 1). It is about 1200 m long, 600 m wide, with a mean sediment thickness over the bed-rock



estimated to 11 m (Perez-Belmonte, 2008).

The volume of the bank is about $1.7*10^6$ m^3 and has been quasi steady over the last decade (sediment volume variations inferior to 1 % from 2003 to 2014) (Moal, 2015). The sand bank features large superimposed bedforms, with dune wavelengths up to 116 m and dune heights up to 3.8 m. The bank is mainly composed of shelly, coarse sand comprising both shell fragments and whole shells of the species: *Bittium*, *Littorina*, *Spisula elliptica* amongst others. The median sediment diameter is 1 mm for the central area of the bank. The Creïzic bank used to be exploited as a sand resource for oyster farming in the gulf until 2003.

Figure 4. The *Creïzic* bank (Gulf of *Morbihan*, France) with the main orientation of the tidal current.

The main hydrodynamic forcing factor at play on the bank is a strong and unsteady tidal current, typically 50cm/s and up to 2m/s, with a tidal range of about 3 m at spring tide. The ebb current is directed toward the SW and the flood current toward the NE. The eastern channel exhibits a classical bidirectional tidal current with a short reversal time; the western channel features a unidirectional, ebb orientated current. On the central area of the bank where active dunes are found, the flood current varies in direction, whereas the current ebb has stable direction and is stronger than the flood in magnitude. Fourteen other sand banks are located in the Gulf, all in the outer part. Hence, sediment exchanges might potentially occur between the *Creïzic* bank and these other sedimentary systems.

3. DATASET AND METHOD

The dataset used for this study consists of a series of Digital Elevation Models (DEM) obtained from Multibeam echo sounder bathymetric surveys from 2003, 2010, 2011, 2014, October 2017, and November 2017, with resolution from 1 m for 2003 to 25 cm for the two 2017 DEM, allowing diachronic analyses at different time scales. In addition, instrumented moorings were deployed on the bank during one month in the fall 2017, with the objective of measuring the hydrodynamic forcing. Sediment samples were collected in spring 2015 and June 2017 using an orange peel bucket. The collected samples were rinsed, dried off and sieved.

The picking of dune crest lines was performed manually on a GIS, using slope rasters to help visualize the crests (Franzetti et al., 2013). Using the bathymetry of November 2017, representative profiles drawn perpendicular to the crest lines were extracted for each dune in the central area. The profiles were analysed using Matlab in order to estimate the morphological parameters of the dunes: height *H*, stoss side length *a*, lee side length *b*, dune length *a*+*b*, stoss side angle *α*, lee side angle *β*, aspect ratio *H*/*L* and asymmetry *a*/*b* (Berné et al., 1989; Le Bot, 2001).

On a monthly time scale the bedform configuration remains relatively unchanged, so that bedforms can be individually identified and tracked between successive DEM. Therefore, two complementary methods were used to compute the distances and rates of bedform migration between the October and November 2017 surveys: 1) the migration distances from crest lines were computed using an algorithm implemented in Python for two consecutive datasets. A raster of Euclidian distances is generated for the crest lines of the first dataset, giving for each pixel of the raster the distance to the crest (within a range and resolution selected by the user). The distance raster of the first dataset is then intersected with the crest lines of the second dataset, directly giving the corresponding migration distances. The sampling step along the crest line is also chosen by the user ; 2) the migration distances and directions were also derived directly from two consecutive DEMs using the image correlation algorithm implemented by Stumpf et al. (2018) with a search radius of 10 m, degrading the DEM resolution to 1 m so that the algorithm could properly match features.

4. RESULTS

4.1 Morphological parameters

The *Creïzic* Bank comprises three main sectors: a central dune field featuring dunes with heights between 1 m and 3.8 m for wavelengths between 23 m and 116 m, and two dune fields on either side of the bank with dunes of decimetric lengths and metric wavelengths. A field of stable fossil mega ripples is located SE of the bank with a mean height of 5 m and a mean wavelength of 60 m (Moal, 2015).

Particular attention was paid to the central area of the bank where 28 dune profiles (over 8 dunes) were extracted from the November 2017 DEM. These profiles were classified into 4 classes according to their shape (fig. 2): typical submarine dunes with a well-defined avalanche slope (TYP, 12 profiles), dunes with Milder slope at the Foot of Stoss side (MFS, 4 profiles), dunes with Wider Plateau at the Crest (WPC, 8 profiles) and dunes with both Milder slopes on the Stoss and Lee sides (MSL, 4 dunes). The mean morphological parameters of each class of dunes are presented in table 1. Except for the MSL class, all dunes do exhibit maximum lee-side slope angles consistent with avalanche mechanisms. The mean lee-side slope angles are rather small, as was observed dunes of similar shell sand composition in the Banc du Four (Franzetti et al., 2013). Lee-side angles of MSL dunes are even lower, which could be due to the tide reversal. There is a relationship between the location of the dunes and their class for some dunes types. The TYP dunes are located on the ridge with crest lines oriented along the bank. The WPC dunes have crest lines orthogonal to the axis of the bank and consequently to the ridge.

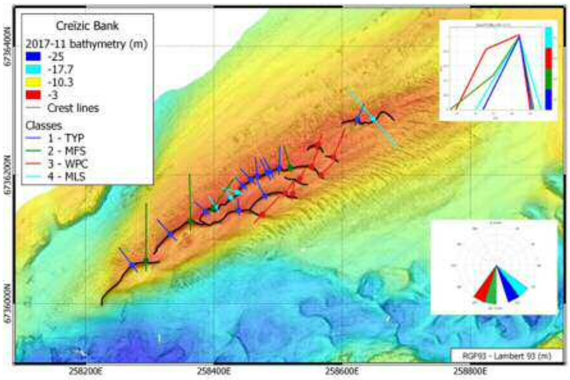


Figure 5. Bathymetric profiles extracted from the November 2017 DEM, categorized by morphological classes. The dots show the location of the dune profile highest points, chosen manually when analysing the profiles in Matlab. The characteristics of the four classes are sketched in the upper left insert; the mean orientation by class is displayed in the lower left insert.

A power law relationship between dune height and dune length has been investigated comparing the best fit for each dune class to the law $H=0.0677L^{0.8098}$ proposed by Flemming (2000). All classes are consistent with the maximum threshold given by Flemming, except for the WPC class where the morphological measurements were too scattered to determine a satisfying power law, so that no particular trend can be assessed. The TYP class is the closest to the Flemming relationship with an exponent of 0.85 against 0.81. Considering this classification, the central area of the bank can be seen as a two-component system, composed of the ridge on the western part (TYP dunes), oriented toward SE, almost parallel to the direction of the ebb current, and the series of dunes (WPC type) orthogonal to the ridge, with lee sides oriented to the SW.

As the asymmetry of the smaller, active bedforms is expected to adjust to the oscillating tidal currents according to the instantaneous direction of the flow (Winter et al., 2016), several terrain profiles have been examined at different steps of the tide throughout the bank to assess the bedforms' polarity. Bedforms on the eastern side of the bank are mainly symmetrical, or slightly changing their orientation with tidal current direction. Bedforms on the western side of the bank are all ebb oriented; indicating that sediment transport mainly occurs in ebb direction for that area. The smaller bedforms on the central area, located in the troughs of metric-size dunes, are also mainly ebb oriented, which is consistent with the orientation of the dunes that are orthogonal to the axis of the bank. Thus, the polarity of smaller bedforms has the signature of a main sediment transport pathway oriented toward SW, in the ebb current direction. The asymmetry of the ridge, with steeper slopes of the eastern side, is indicative of sediment transport in SE direction. Sediment transport is possibly occurring toward NE on the outer parts of the bank on the eastern side.

4.2 Multiyear evolution

The overall bank is very slowly migrating toward SE, with a migration of 40 m from 2003 to November 2017 for the Southern extremity of the bank.

Table 1: Mean morphological parameters for dune profiles extracted from the November 2017 bathymetric dataset.

	α_{mean}	α_{max}	β_{mean}	β_{max}	H/L	a/b
ALL	4.3	11.5	12.6	27.0	0.05	3.1
TYP	5.3	12.9	13.5	27.8	0.07	2.3
MFS	2.8	12.8	14.6	30.0	0.04	5.4
WPC	2.4	9.1	13.1	30.0	0.04	4.0
MSL	4.8	10.9	6.6	15.1	0.04	1.7

The configuration of the central area of the bank and the position of the primary dunes have been significantly evolving over the 2003-2017 period. Different dynamics were identified depending on the sectors of the bank. In the southern part of the bank, the orientation of the ridge is slightly changing with time, turning to North from 2003 to 2011 and going back to South thereafter. On the contrary, on the central area of the bank the ridge orientation is significantly changing. On the northern part of the bank, the ridge exhibits a stable orientation over time.

Tracking each dune from a DEM to another is not always feasible when the DEM are more than 1 year apart. When possible, migration distances have been computed using a profile along the main axis of the bank and crossing orthogonally the dunes. Migration distances are of decametric order (max. 54 m between 2011 and 2014). They vary from one dune to another and give different annual migration rates depending on the two DEM used within the series of datasets. For the ridge, the migration is toward SE but slower (max. 24 m between 2003 and 2010).

4.3 Monthly time scale migration

The migration of the crest lines of the central area of the bank between October and November 2017 has been investigated (fig. 3), with a range and resolution set to 10 m and 0.25 m respectively, showing a significant migration at the time scale of a

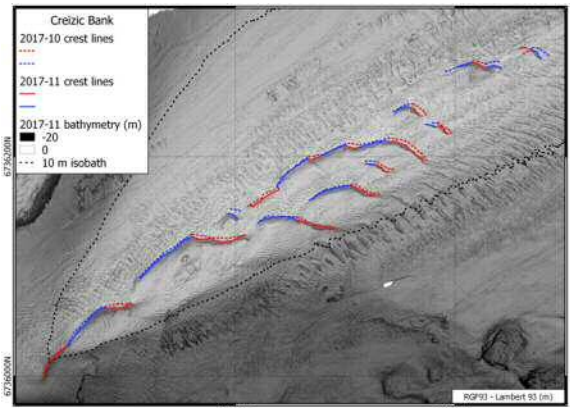


Figure 6. Crest lines of the central area of the *Creïzic* bank used for the computation of migration distances.

month. The dune crest line sections that are orthogonal to the ridge exhibit higher migration distances than the ridge itself, with the maximum migration distance up to 4.5 m and a weighted mean of 2 m for a same standard deviation of 0.5 m (mean value of the std for considered sections, table 2). Few migration distances were negative considering all the sections of orthogonal dunes, confirming that they are migrating toward SE. The dunes constituting the ridge are undergoing a deformation rather than actually migrating, since the weighted mean migration of the ridge line sections is low, close to the crest line picking error, and the percentage of negative values is higher.

Using the image correlation algorithm with the two 2017 DEMs, displacement ranges of several meters have been computed at the bank scale. On the central and northern area, migration distances are the highest, up to 7 m over the small dunes that are not connected to the ridge. On the southern part of the bank, around the extremity of the bank, migration is between 0 and 2 m, mainly oriented toward South. At the Northern extremity of the bank, beyond the 10 m isobath, a counter clock-wise motion is seen, going first to the North, then to the West and finally joining the general motion of the central area toward South-West. Migration distances close to zero on the western part of the bank are possibly an artefact due to the high degree of similarity of the small dunes in this area, which could prevent the algorithm from properly correlating objects. Altogether, a general motion of migration toward SW is observed. This global migration

Table 2: Migration distances of the crest lines. The mean was computed by weighting the migration distance with the ratio of the length of the line section and the length of all the line sections considered.

	Interval [m]	std [m]	% negative	Mean [m]	Total length [m]
All	|0 ; 4.5|	0.5	6.2	1	608
Ridge	|0 ; 3.5|	0.5	8.8	0.5	345
Orthogonal	|0 ; 4.5|	0.5	2.8	2	263

pattern could be seen as a recirculation pathway around the bank, the sediment being redistributed from the South of the bank to the North in a counter clockwise loop crossing the deeper parts of the eastern side of the bank.

5. CONCLUSION

This study focuses on the multiyear and monthly time scales, morphological evolution and dynamics of a submarine dune bank located in the Gulf of *Morbihan*, in a shallow area where the tidal currents are strong and unsteady. The bank exhibits a low migration rate and a steady volume, whereas the superimposed dunes are undergoing deformation and/or migration. The bank can be seen as a two-component system, featuring a ridge oriented along the bank, and a series of dunes that are orthogonal to the ridge. At the multiyear time scale, the orientation of the ridge is quite stable except for the central area of the bank, where it is quite variable, with the junction points between the ridge and the orthogonal dunes also changing rapidly. Migration distances for the orthogonal dunes are up to 54 m in three years, and display mean migrating distances of 2 m in one month, whereas the ridge is rather undergoing a deformation at monthly scale. The orthogonal dunes are migrating to the SW, in the direction of the ebb current which is dominant on the area. This migration direction is confirmed by results of an image correlation algorithm applied between October and November 2017. Furthermore, a recirculation pattern over the bank can be inferred from the migration directions of the smaller bedforms. Sediment could be recirculated from the South point of the bank to its North extremity in a wide counter clock wise loop in the tidal channel east of the bank. This hypothesis could be investigated, as well as the longitudinal orientation of the ridge dunes in the central and southern part of the bank, using a local hydrodynamic model.

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