Dynamics of very-large dunes in sandbank areas subjected to marine aggregate extraction, Belgian continental shelf

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ABSTRACT: Dynamics of very-large dunes were investigated over sandbanks subdued to marine aggregate extraction in the Belgian continental shelf. In the Flemish Banks, six areas were regularly monitored with a multibeam echosounder (MBES) providing high resolution bathymetric data. An optimization procedure was set up to estimate the dune migration distance and direction between successive campaigns. These dune migration data were compared to simulated hydrodynamic forces and indicated that dune migration was mostly driven by tidal currents, with the direction and magnitude of migration being dependent on the relative position of the dunes on the sandbanks. Closer investigation in a heavily extracted area suggested a local reorganization of sediments in the area: an accretional trend in the extraction pit is observed at the expense of the surrounding very-large dunes which presented an erosive and flattening pattern.

1. INTRODUCTION

In the Belgian continental shelf, marine aggregate extraction occurs in legally defined areas over sandbanks. These sandbanks are covered with bedforms including very-large dunes (> 3 m height). Beyond human extraction, which can cause seabed depressions up to several meters in depth in intensively exploited sites (Degrendele et al., 2010), the migration of these very-large dunes is the main source of variability in the seabed morphology. In this study, high resolution bathymetric data are exploited in the period 2003-2013 in order to investigate the dynamics of these very-large dunes and to assess whether the extraction activity affected this natural variability. Approximating the dune migration within each area by a homogenous translation of the whole seabed, an optimization process was implemented to extract the migration distance and direction between successive monitoring campaigns over the 2003-2013 period in six exploited areas. The resulting migration data were compared to simulated hydrodynamic data (currents), and the seabed evolution in a recent extraction hotspot was more closely examined.

2. METHODS

2.1. Study area

In this study, data are exploited from the Flemish Banks area, located 20-30 km offshore the Belgian coast. In this region (Fig. 1), three extraction zones (red polygons) are present along different SW-NE-oriented sandbanks. In these extraction zones, six monitoring areas (black rectangles) are regularly surveyed: Monitoring zone A of the Oostdyck (ODMA); Monitoring zone A, B and C of the Buiten Ratel (BRMA, BRMB and BRMC respectively); and Monitoring zone A and B of the Kwintebank (KBMA and KBMB respectively).

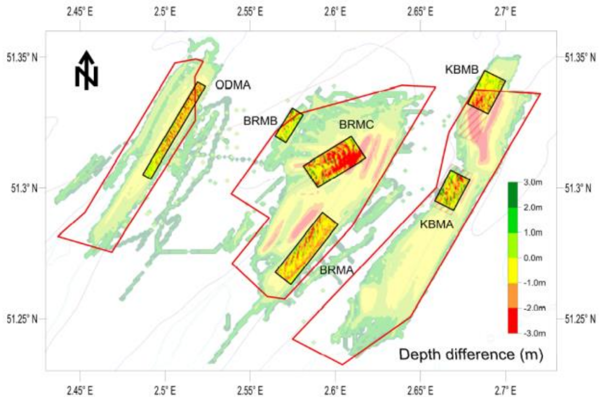

Figure 1. Study area in the Flemish Banks, Belgian continental shelf. Red polygons: marine aggregate extraction zones. Black rectangles: monitoring zones. Background color scale: extraction density. Color scale in monitoring zones: depth difference between recent surveys and a reference bathymetry.

2.2. Bathymetric data

High resolution depth measurements over the monitoring zone were acquired with a MBES (see Roche et al., 2011). Monitoring data started between 2003 (KBMA, KBMB) and 2010 (BRMC). The monitoring intensity ranged from 1 to 4 surveys per year.

2.3. Extraction data

Aggregate extraction activity was recorded through an Electronic Monitoring System (EMS) which was placed onboard of the extraction vessels. The EMS stored the time and location of the ship as well as the extraction activity and was used to build a spatio-temporal dataset of marine aggregate extraction (see Roche et al., 2011).

2.4. Analysis

The MBES data provided a succession of bathymetries for each monitoring zone. Two main sources of variation in the seabed were observed: the human extraction and the migration of the very-large dunes. Despite some peculiarities in the individual movements of the latter, they followed a motion close to a general translation. In order to estimate this dune migration between two campaigns ($MBES_1$ and $MBES_2$ for the earlier and later stage, respectively), an optimization procedure has been implemented as follows: (1) the sediments extracted during the period were restored to $MBES_2$ in order to build a state closer to $MBES_1$ without extraction; (2) $MBES_1$ was shifted laterally with different intensities and directions; (3) the best shift was selected as the one producing the highest log likelihood between the shifted $MBES_1$ and the reconstructed $MBES_2$, assuming a normal distribution of the residuals. This workflow was applied to the successive campaigns from all monitoring zones. The obtained migration distance between two campaigns was converted into a migration rate expressed per Spring-Neap cycle (SN) of 15 days. Dune migration data were compared to simulated tidal currents in the monitoring zone produced with the hydrodynamic model COHERENS under tidal and wind forcing (see Van den Eynde et al., 2010).

3. RESULTS AND DISCUSSION

3.1. Migration rates and directions

The migration rates and directions obtained by the optimization procedure are shown for each area in Fig. 2 (y and x axis, respectively).

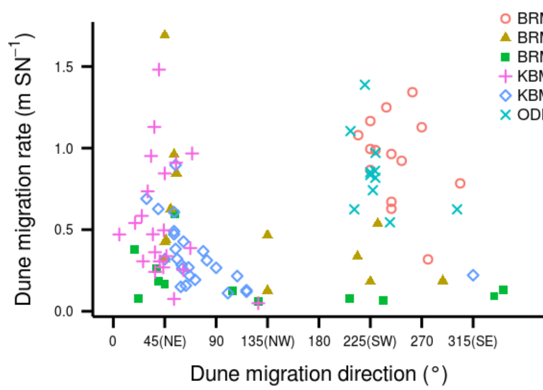

Figure 2. Dune migration rate *vs* direction.

Out of the six areas, BRMC was characterized by the smallest dune migration rates (< 0.6 m SN^{-1}). In contrast, BRMA and ODMA showed high migration rates (up to 1.4 m SN^{-1}). These two areas were also the only ones to exhibit a dominant SW-directed dune migration. These areas are indeed located on the SE flank of their sandbanks (Fig. 1), where ebb currents (directed towards the SW) predominate. On the contrary, KBMA and KBMB, which are located on the NW flank of the Kwintebank (Fig. 1), only experienced dune migration towards the NE (flood direction, with the exception of one observation towards the SE for KBMB; Fig. 2). Dune migration along the Buiten Ratel was less obvious. This is due to the peculiar shape of the head of the sandbank (Fig. 1): dune migration of BRMB, located at the NW edge of this head, displayed the fastest migration towards the NE, but also in the opposite direction (albeit at a lower rate). In the middle kink part of this head (BRMC), dunes migrated both in the flood- and ebb direction with generally lower rates.

3.2. Current-driven dune migration

In shallow marine environments, dune migration, and sediment transport in general, is mostly driven by tidal currents. To test this hypothesis, dune dynamics in the formerly defined areas were compared to the corresponding simulated residual currents. Fig. 3 shows the dune migration direction as a function of the simulated residual current direction. The diagonal dashed line marks the exact agreement between both (i.e. dune migration occurs in the same direction as residual currents). The size of the symbols in Fig. 3 is proportional to the dune migration rate, giving an indication of the migration intensity for each observation.

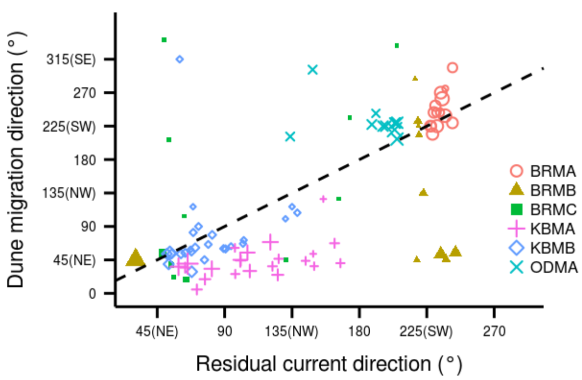

Figure 3. Dune migration direction *vs* residual currents direction.

BRMA and ODMA occupy a relatively narrow area in the upper right corner (SW-directed) around the diagonal, suggesting that the simulated residual currents explained the migration direction to a large extent. Similarly, but in the opposite direction (NE), the agreement between the direction of dune migration and residual currents was also high for KBMB, while residual currents in KBMA (towards the NE and NW) were more spread than the dune migration (mainly towards the NE). Finally, the agreement between dune migration direction and residual current direction was less good for BRMB and BRMC, indicating that the model was less able to simulate currents in this peculiar area (head of the Buiten Ratel).

Preliminary investigations suggested that the dune migration rate was also positively related to the magnitude of simulated residual currents (not shown), and that winds alone were not able to explain dune migration rate and direction (not shown). Consequently, these results indicate that dune migration over the sandbanks was mainly driven by currents, which essentially have a tidal origin. The agreement between simulated currents and estimated migration parameters also suggests that both approaches produce valid results.

3.3. The effect of aggregate extraction

The optimization procedure set up to determine the dune migration can be used to remove most of the variability in the seabed due to these dune movements in order to examine the remaining pattern. This application was exploited here for the BRMC area, which was a hotspot of aggregate extraction from 2009 to 2014. A comparison was made between the oldest (early 2010) and latest (late 2013) campaigns as follows (Fig. 4): the optimal dune migration was applied as a general translation to the original bathymetry which was then subtracted from the recent bathymetry to produce a difference map showing the evolution of the seabed over this nearly 4-year period; in order to keep the natural accretion and erosion signal, human extraction during this period was removed (Fig. 4). This resulted in a global difference map between late 2013 and early 2010 showing areas where accretion (in blue) or erosion (in red) occurred (Fig. 5).

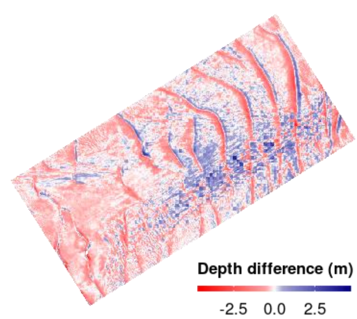

Figure 5. Seabed dynamics in the BRMC area shown as a difference map between late 2013 and early 2010. Note that accretion is observed where extraction took place, whilst the surrounding very-large dunes have flattened.

Overall, in BRMC, the dune migration between 2010 and 2013 occurred in the NE direction. Some remaining patterns indicate that the dune migration effect was not entirely removed: especially at the northern corner of the map, positive accretion fronts (blue bands) showed that the actual position of the new dune crests is further to the East. This effect was sensibly more pronounced and ubiquitous when the dune migration was not accounted for (not shown). Another pattern related to these very-large dunes can be observed: the difference map show wide negative bands over them (red bands in Fig. 5), revealing a global erosional pattern. Indeed, a comparison of the 2010 and 2013 transects across the dunes located in the northern half of the area showed that, in addition to migration towards the NE, they decreased in height over time (not shown). In parallel, the zone where extraction was concentrated in BRMC, located at the East of the map (see Fig. 4), showed a general accretion trend (Fig. 5). The extraction pit (locally deepened with 5 m compared to the reference level) thus experienced a possible refilling while the neighboring dunes exhibited a general flattening.

4. CONCLUSION

The optimization procedure, set up to automatically determine the dune migration, generated valid and valuable data to investigate dune dynamics in different locations over sandbanks. Comparison with simulated currents showed that dune migration over these sandbanks was mostly driven by tidal currents with the position of the dunes over the sandbank determining whether they shifted in an ebb- or flood direction. In a heavily exploited area, there was a general erosive pattern over the very-large dunes surrounding the intensively extracted site, which on the contrary showed an accretional trend. From this, there seems to be a local reorganization of the sediments in the area at the expense of the very-large dunes which are decreasing in height over time. This calls for further investigation to determine whether this affects the behavior of the sandbank, the hydrodynamics in the surrounding area, and the sustainability of the extraction activity.

5. ACKNOWLEDGMENT

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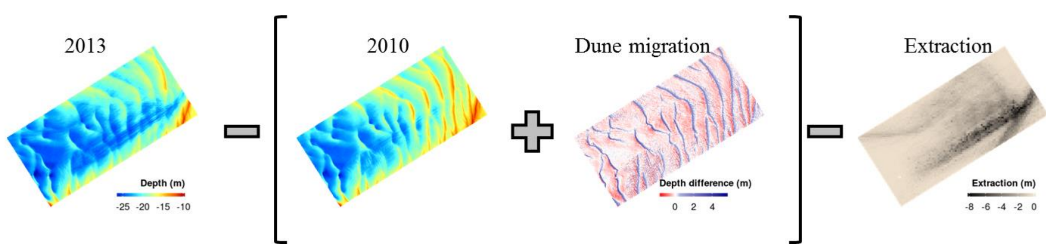

Figure 4. Workflow to produce the difference map in Figure 5. See text for explanations.

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