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SPATIO-TEMPORAL VARIABILITY IN INTERTIDAL BEACH MORPHOLOGY ON A SEASONAL SCALE, MARIAKERKE, BELGIUM

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Abstract

The intertidal area is important regarding storm impact and post-storm recovery. Currently, knowledge on the morphodynamics of macro-tidal beaches without intertidal bars is still scarce. The aim of this study was to understand and quantify the spatial and temporal variability of the intertidal beach morphology on a monthly scale for a macro-tidal, sandy beach without bar morphology. To reach this aim, cross-shore beach topographic surveys were carried out monthly for 1.5 years at Mariakerke, Belgium. These surveys were compared to the hydrodynamics that were measured continuously near the research area. It appeared that significant morphological changes occurred within one month, independent of seasonal or long-term trends. Furthermore, it was found that there was a strong relation between hydrodynamic forcing and morphological response, but also that this relation strongly varied along the beach.

Key words: topographic profiles, hydrodynamic forcing, monthly morphological changes, autocorrelation

1. Introduction

The Belgian coast is densely populated and several areas are prone to coastal hazards such as erosion and marine flooding. The frequency and magnitude of these hazards are likely to amplify in the next decades due to sea level rise and climate change, resulting in increasing threats to the population living along the coast (Nicholls *et al.*, 2011; de Winter *et al.*, 2013). Getting a better understanding of coastal processes resulting in storm erosion and post-storm beach recovery is important to develop an efficient coastal management.

The intertidal area is an important area for storm impact and post-storm recovery. Wave impact is largest there and it is the pathway for sediment from the dry beach to the sub-tidal area. However, the combined action of waves and currents makes the intertidal area a complex area to study. For macro-tidal beaches, this complexity is further enhanced by the large variation in water level, which results in the movement of the different hydrodynamic zones across the intertidal area (Kroon and Masselink, 2002).

A number of studies were conducted on the morphodynamics of macro-tidal beaches characterized by a bar morphology (*e.g.* Cartier and Héquette, 2013; Masselink *et al.*, 2008; Sedrati and Anthony, 2007) or rip morphology (Austin *et al.*, 2010), but only a few have been dedicated to non-barred beaches. For barred macro-tidal beaches it is reported that landward sediment transport takes place under calm conditions and that seaward sediment transport occurs during storm events. Seasonal and storm-induced morphological behaviors were also observed on macro-tidal beaches with a rip morphology. For non-barred macro-tidal beaches, such as a large part of the Belgian beaches, the behavior of the intertidal area on a monthly to seasonal scale is unknown yet.

In general, detailed and high quality topographical data sets covering a long time span tend to be limited (Short and Trembanis, 2004). This limits the possibilities of understanding the morphodynamics at a monthly to seasonal scale. The aim of this study was to understand and quantify the spatial and temporal variability of the intertidal beach morphology on a monthly scale for a macro-tidal beach. Also the effect of the hydrodynamic forcing factors was investigated. The study site is at Mariakerke (Belgium): a macro-tidal sandy beach characterized by a flat intertidal area.

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Along the Belgian coast hydrodynamics have continuously been measured over the last decades. On the contrary, high frequency topographic data was lacking until now. Since September 2015 beach cross-shore profiles have been surveyed monthly with a Real Time Kinematic GPS (RTK-GPS). These high frequency, small scale topographic surveys allowed to determine the wide, range of morphological outcomes for different hydrodynamic conditions. In this study, monthly morphological changes were determined and related to the hydrodynamic conditions.

2. **Study site**

The study site is Mariakerke beach, near Oostende in Belgium (Figure 1). The tide is semi-diurnal and slightly flood dominant along the Belgian coast. The tide ranges from 3.5 m at neap to 5 m at spring tide, so the beach is in a macro-tidal regime. This results in significant tidal currents, of over 1 ms^{-1} in the nearshore area (Haerens *et al*., 2012). Wave energy is medium with an average wave height of 0.5-1 m, and a period of 3.5-4.5 s. Offshore waves are mainly driven by westerly (WSW-NW) winds and the incoming waves therefore generate a longshore drift towards the northeast. During storms with wind and waves from the north to northwest storm surges can occur with water levels of +5.5 m TAW (relative to the lowest astronomical tide; Haerens *et al*., 2012). The significant wave height with a 1 year return period is about 4.5 m.

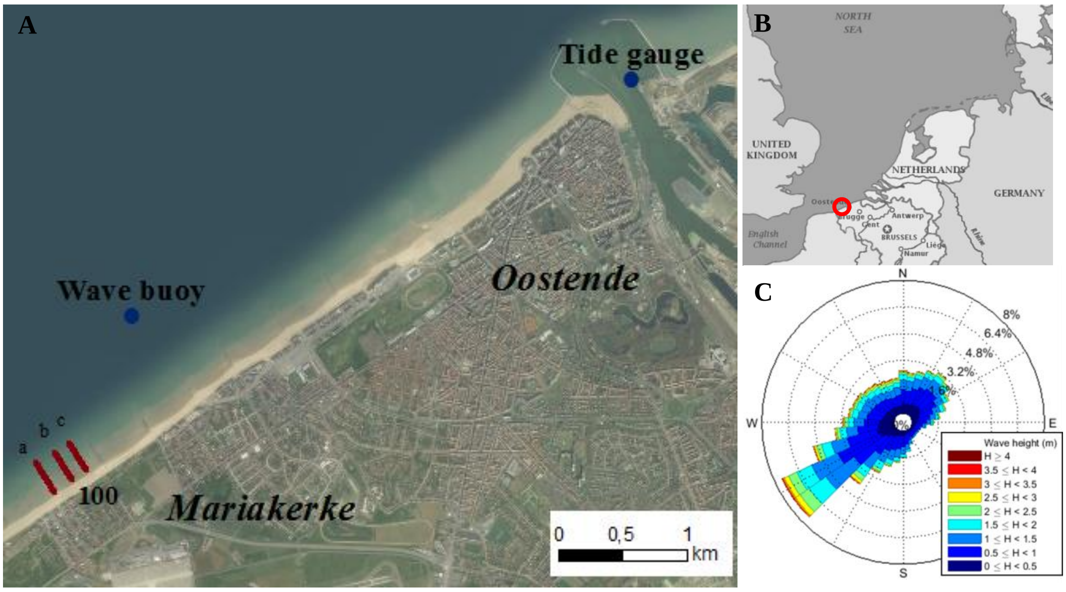

Figure 1. A) Map of the study area with cross-shore profiles and location of hydrodynamic measurements, B) Situation map of the Belgian coast, C) Annual wave climate.

The Belgian coast is oriented SW-NE (55-235°). More than 50% of the Belgian coast suffers from erosion (Deronde *et al*., 2004) and under natural conditions the beach at Mariakerke would also erode with -6 m^3/m/yr (Houthuys, 2012). Therefore protective measures have been taken and the beach is now protected with groins, a seawall and nourishments. Thanks to these measures the beach volume has increased by 8 m^3/m/yr since the 1980s (Houthuys, 2012). At Mariakerke, the beach is 200 m wide and ultra-dissipative without intertidal bars. The average grain size is 200 µm for natural conditions, but due to the nourishments this can locally be up to 300-400 µm. The groins have significantly altered the morphology, resulting in a smooth, gently sloping (1-2%) intertidal area and steeper (>5%) dry beach with a concave shape around the high water line (Deronde *et al*., 2008).

3. **Methods**

Beach topography of three cross-shore profiles (100a-c, Figure 1) was measured monthly with an RTK-GPS from September 2015 to February 2017, except for July and October 2016. Beach topography was measured before and after a storm in January 2017. In total 17 topographic surveys are available. The distance between the profiles was approximately 150 m. The profile length was up to 300 m from the seawall to the low water line. The accuracy of the RTK-GPS is 2-3 cm for the x, y and z coordinates combined. Also hydrodynamics were continuously measured close to the research area (Figure 1) over the study period.

The beach profiles a, b and c were analyzed separately for beach shape and were averaged for volume. The indicators for morphological change that were used in this study were beach width and beach volume. For each profile the intertidal area corresponds to the area between mean high water (MHW; +4.39 m TAW) and mean low water (MLW; +1.39 m TAW). The dry beach corresponds to the area above MHW (Figure 2; Houthuys, 2012). Beach volumes were calculated using trapezoidal rules.

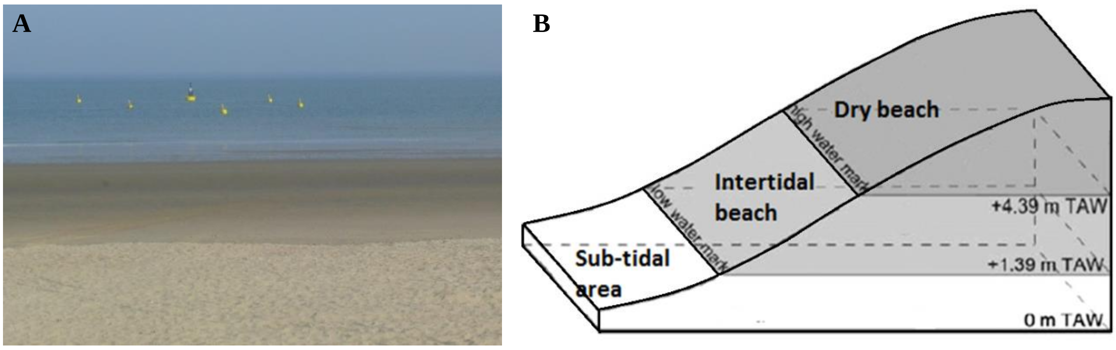

Figure 2. A) Ground picture of the study area taken from the seawall showing the elevated dry beach and the featureless intertidal area, B) Definition of the beach zones relative to the lowest astronomical tide (modified from Haerens *et al*., 2012)

Autocorrelation analysis was used to assess the temporal variability of the beach, because time series of topography were too short to analyze them with harmonic or spectral analysis. With autocorrelations the time after which significant morphological changes occur was determined. Autocorrelation is defined as the linear correlation coefficient between the data series and a lagged version of itself. The sample estimate of the autocorrelation r_k is defined as (Davis, 2002):

$$r_k = \frac{\frac{1}{(N-k)}\sum_{i=1}^{N-k}(\chi_i-\bar{\chi})(\chi_{i+k}-\bar{\chi})}{\frac{1}{N}\sum_{i=1}^{N}(\chi_i-\bar{\chi})} \tag{1}$$

Where N is the number of data points in the time series, $\bar{\chi}$ is the average of all values in the series, χ_i is the value at time i, and k is the lag for which the autocorrelation is calculated.

Morphological changes were compared to the average and maximum hydrodynamic conditions for each month using linear regression. Differences in morphological behavior between the three profiles were assessed using linear regression and standard deviations. The morphological behavior of the three profiles was compared for calm and energetic hydrodynamic periods. The definition of an energetic period was based on Haerens *et al.* (2012), who defined five thresholds for significant erosion along the Belgian beach: an off-shore maximum significant wave height of 4 m; a maximum water level of +5 m TAW; a storm duration of 12 hours; a total wave energy of 6.5 $e^{0.5}$ Jm^{-2}; and a wave direction between W and NW. In this study, a period was characterized as energetic, when at least three of these thresholds were exceeded.

4. Results

4.1. *Hydrodynamics*

Figure 3 shows the time series of maximum water level, wave height and wave directions. The hydrodynamic conditions clearly indicate a seasonal cycle. The wave height was generally smaller than 1 m between April and October, whereas in winter it was mostly larger reaching up to 3.6 m. The wave direction was mainly from the west to the northwest over the entire research period. In winter higher maximum water levels were observed than in summer.

The events exceeding one of the defined storm thresholds are indicated in red in Figure 3. Four clear storm events with wave heights exceeding 3 m were observed: in November 2015, January 2016, June 2016 and January 2017. The storms in November 2015 and June 2016 were characterized by low maximum water levels (4.1 and 4.4 m TAW respectively), while during the storms in January 2016 and 2017 the water level was high (5.3 and 5.7 m TAW respectively). Four other months (February, March, April and September 2016) were also identified as energetic and seven months were identified as calm.

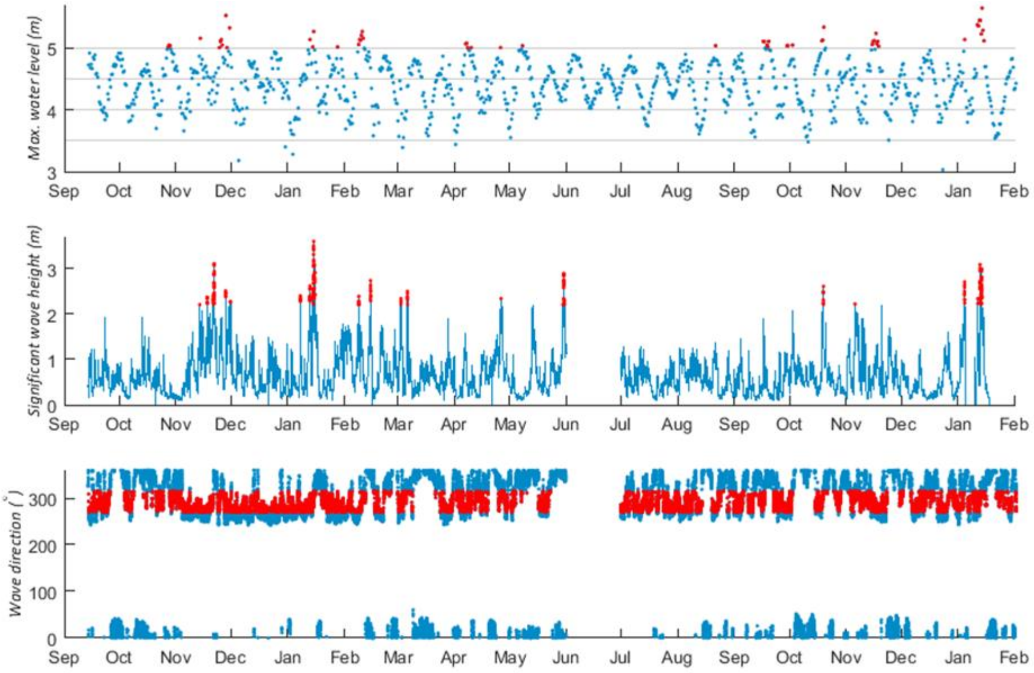

Figure 3. Time series of 12-hourly averaged maximum water level (TAW), significant wave height and wave direction from September 2015 to January 2017 with the hydrodynamic conditions meeting the storm thresholds of Haerens *et al.* (2012) indicated in red.

4.2. *Morphology*

4.2.1. *Cross-shore variability*

Beach topography of profiles a, b and c is shown in figure 4. The shape of the profiles was concave, with a gently sloping (2°) featureless intertidal beach (*i.e.* absence of bar and/or berm). The highest part of the dry beach (elevation > 7 m TAW) was relatively flat, however, its slope located around 40 m was steep (maximum slope of 16°). Profiles a, b and c showed a similar morphology, although the two extreme profiles (a and c) indicated a wider beach. Also their slopes were less steep and the flat part of the dry beach was narrower here.

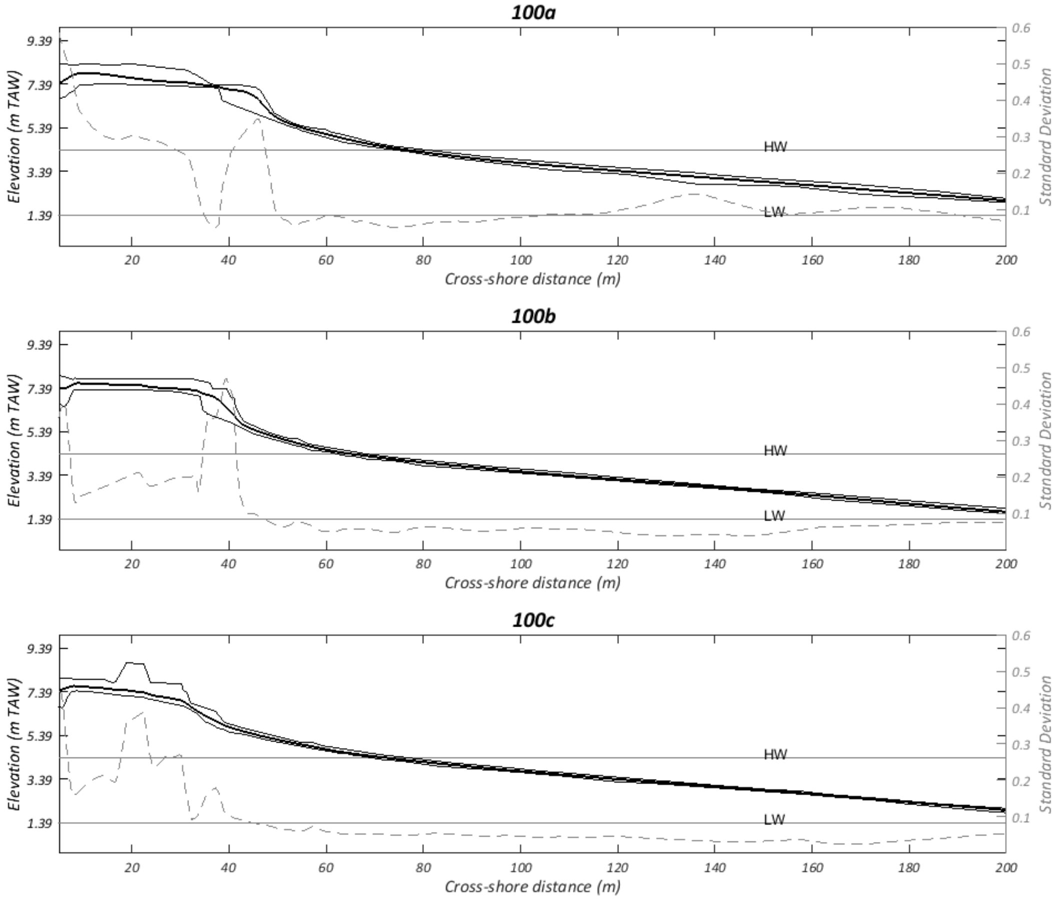

Figure 4. Mean (thick black line), envelope (small black lines) and standard deviation (dashed grey) of 17 measured cross-shore profiles.

Figure 4 reveals that the envelope of topographic variation was wider for the dry than for the intertidal beach. On the dry beach the average envelope was 0.8 m and the maximum was 1.6 m. The standard deviation was also the largest for the dry beach, with an average of 0.3 m. At the steep slope the standard deviation reached up to 0.5 m. In the intertidal area the variation was much smaller, with an average envelope of 0.2 m and a standard deviation of 0.1 m on average. Monthly changes in elevation were thus larger on the dry beach than on the intertidal beach and maximum on the steep slope.

Table 1. Autocorrelations of the indicators for morphological change. Values exceeding the significance level (0.5/-0.5) are in bold.

Time lag (months)	Total volume	Dry beach volume	Intertidal beach volume	Total beach width
0	**1.0**	**1.0**	**1.0**	**1.0**
1	**0.6**	-0.1	0.4	**0.9**
2	0.4	-0.2	0.0	**0.6**
3	0.0	-0.2	-0.1	0.3

Table 1 shows the autocorrelation of the total, dry beach and intertidal beach volume and the total beach width for a time lag of 0 to 3 months. If the autocorrelation is larger than the significance level (0.5 or smaller than -0.5), it means that the indicator is stable over the considered time lag. The autocorrelation analysis reveals significant variations in beach volume and width at a significance level of 5%. The total volume can be considered stable over 1 month, but from 2 months on significant changes occured. Beach width was most stable and significant changes in general occurred only after 3 months. However, significant changes in dry and intertidal beach volume often took place within one month.

Although the hydrodynamics showed a seasonal cycle, this was not obvious for morphological change (Figure 5). The beach volume showed large variations in autumn and winter, while in spring and summer the beach was relatively stable. However, in autumn and winter there were large differences between consecutive months and between the same months in a different year. The maximum volume change between two profile surveys was +13.4 m^3/m and the minimum -8.3 m^3/m. The standard deviation of the total volume changes was 5.7 m^3/m. Volumetric changes were larger for the intertidal area (standard deviation of 3.7 m^3/m) than for the dry beach (standard deviation of 2.6 m^3/m), but in general they showed the same pattern.

Apart from beach volume, monthly changes in beach width were also studied (Figure 5). The temporal behavior of beach width was different from that of the beach volume. Only in 9 of the 16 months they both showed erosion or accretion. In general the beach width was relatively stable, with changes up to 3 m, but in May 2016 and January 2017 the beach widened significantly (up to 7 m). The beach became narrower in again within one month. The standard deviation of the variation in beach width was 3.2 m.

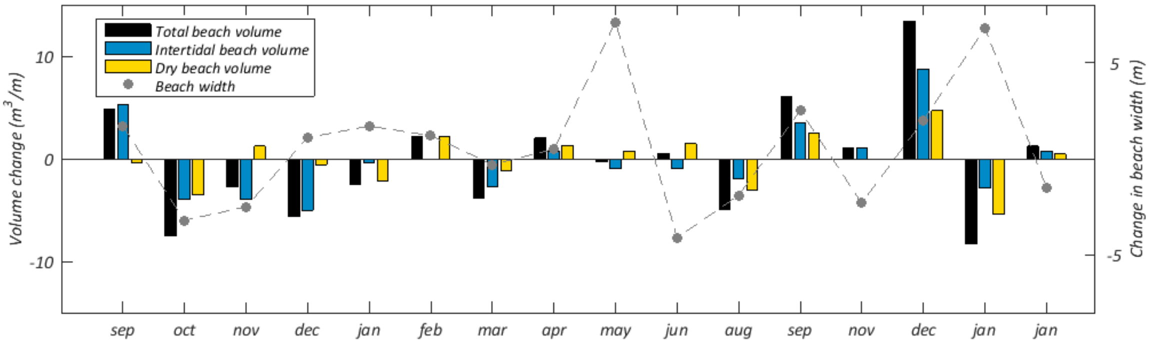

Figure 5. Monthly changes in beach volume and total beach width.

4.2.2. *Along shore variability*

The temporal variability was thus significant, but also the spatial variability was large. Table 2 shows differences in beach volume and width changes between the three profiles and thus it becomes clear that the along shore variability was large as well. Firstly, the correlation of the morphological changes between the three profiles was often small and even negative correlations occurred. This means that the three profiles showed a very different temporal behavior. Volume changes were up to 63% similar for profile b and c, while they were different between profiles a and b. During calm months, changes in the position of the mean low water line were very different for the three profiles, probably due to the small magnitude of these changes. During energetic conditions the mean low water line moved seawards for all three of the profiles. The mean high water line position behave similar for the three profiles during calm conditions, but showed different trends for the three profiles during energetic conditions.

Secondly, Table 2 shows the mean standard deviation of the variation in beach volume and width between the three profiles. For the volume the standard deviation was 2.0 m^3/m for the dry beach and 3.4 m^3/m for the intertidal area. This is almost as large as the standard deviation describing the temporal variability (2.6 and 3.7 m^3/m for the dry beach and intertidal area respectively). The difference in volume change between the three profiles was larger for calm months than for energetic months. The standard deviation for changes in beach width was smaller comparing the three profiles (along shore variability) than comparing the different months (temporal variability; 2.1 m versus 3.2 m). Changes in beach width, in contrast to volume, were more different between the three profiles for energetic than for calm conditions.

Table 2. Correlation and standard deviation (stdev) of changes in volume and width for the dry and intertidal beach comparing the three profiles (a,b and c) from September 2015 to January 2017. Crosses indicate a negative correlation.

Volume change	All months (n = 16)				Calm months (n = 8)				Energetic months (n = 8)			
	a-b	a-c	b-c	stdev	a-b	a-c	b-c	stdev	a-b	a-c	b-c	stdev
Dry beach	4 %	35 %	32 %	2.0	4 %	27 %	42 %	2.3	4 %	69 %	39 %	1.6
Intertidal beach	18 %	8 %	34 %	3.4	16 %	15 %	63 %	4.1	16 %	3 %	5 %	2.8

Beach width change	All months (n = 16)				Calm months (n = 8)				Energetic months (n = 8)			
	a-b	a-c	b-c	stdev	a-b	a-c	b-c	stdev	a-b	a-c	b-c	stdev
Mean high water	5 %	5 %	6 %	1.3	40 %	40 %	82 %	1.0	x	x	30 %	1.6
Mean low water	23 %	47 %	31 %	2.1	x	4 %	33 %	2.0	65 %	61 %	26 %	2.3

5. Discussion

5.1. *Relation hydrodynamic forcing and morphological response*

In this study the hydrodynamics clearly showed more energetic wave conditions in winter than in summer. However, time series of changes in beach volume and beach width did not reflect the same trend. Moreover, no significant erosion was observed during 2 out of the 4 storms. The storms in January and May 2016 resulted in only 0.3 m^3/m and 1.0 m^3/m of erosion. However, it is known from previous studies that in general small waves result in accretion while large waves result in erosion. The wave effect can quickly change from accretive to erosive (Coco *et al.,* 2013).

Table 3. Percentage of intertidal and dry beach volume change (converted to daily change) and total beach width change that can be explained by hydrodynamic forcing (n = 16) for the mean of the profiles and the minimum and maximum for the profiles separately in brackets.

	Dry beach volume change (%)	Intertidal beach volume change (%)	Change in beach width (%)
Mean significant wave height	7.5 (40-60)	10.1 (42-52)	69.5 (63-71)
Mean significant wave height highest 5%	30.8 (22-39)	28.0 (33-38)	51.2 (42-51)
Mean significant wave height highest 20%	45.2 (35-54)	38.9 (42-50)	67.0 (58-67)
Max. water level	31.0 (27-34)	26.4 (15-32)	29.0 (26-31)

Table 3 shows that there was a good relation between the hydrodynamic conditions and morphological change between two surveys. The average volume decreased and the average beach width increased for larger waves or a higher maximum water level. Especially the mean significant wave height of the highest 5-20 % of the waves was related to morphological change. The role of water level was also significant, although it was slightly smaller than the role of wave height. It should be noted that these effects are partly overlapping, as high water levels and high waves are both induced by northwestern winds. The relation between hydrodynamic forcing and beach width was stronger than the relation with beach volume.

In general, the relation between hydrodynamic forcing and morphological response becomes better analyzing the profiles separately (Table 3). Assuming similar hydrodynamic forcing over the research area, this means that the three profiles react differently to the same forcing. This assumption was made, the area is subject to the same incoming hydrodynamics and it is known that groins often only very locally around the groin affect the hydrodynamics (Rocha *et al.*, 2013). Regarding changes in intertidal beach volume, profile a and b react very similar, but under more energetic conditions accretion instead of erosion is observed for profile c. The beach width responds stronger to hydrodynamic forcing from south to north (a to c). Most likely this is partly due to local differences in morphology and partly due to the effect of the groins. Moreover, it was assumed the hydrodynamic forcing is similar for the three profiles, but the groins might affect waves and currents, resulting in different hydrodynamic forcing on the three profiles.

Although there is a reasonably good relation between hydrodynamics and morphological change, there are some months showing morphological changes that cannot be explained by hydrodynamic forcing. This is especially true for March and August, when there was erosion (-4 and -5 m^3/m respectively) while wave conditions were calm and the maximum water level was low. Such specific conditions might be due to variations in sediment input from along shore currents or aeolian transport. Human interference, such as reshaping of the beach, presence of beach cabins and infrastructure for tourism might have also affected the morphology.

Furthermore, not all storms resulted in the same morphological outcome. Partly this is caused by differences in hydrodynamic forcing, but for a large part this is also due to the time for the beach to recover. In January and May 2016 the storm happened almost one month before the next topographic survey and this probably explains why the observed erosion was small. Recovery was likely fast because the storm erosion was relatively small. For larger storms, when the upper beach is also significantly affected, recovery can take multiple years (Maspataud *et al.*, 2009). For this study, the effect of recovery time could not be measured, because between surveys multiple energetic periods might have occurred. Recently, some research has been done to clusters of storms, but their effect remains difficult assess (Coco *et al.*, 2013).

5.2. *Seasonal and long-term trends*

For macro-tidal beaches with an intertidal bar or rip morphology, seasonal and storm-induced morphological behaviors have been observed (Austin *et al.*, 2010; Quartel *et al.*, 2007). However, for macro-tidal flat intertidal beaches, such as the beach at Mariakerke the morphological behavior on a monthly to seasonal scale is not known yet. The cumulative volume changes over the research period, corrected for the long-term trend (Houthuys, 2012) are shown in Figure 6. From September 2015 to January 2017 there is a trend of erosion – stability – accretion – erosion. However, where in autumn 2015 the beach was eroding, in autumn of 2016 the beach is still accreting and erosion only starts in January. Although the time series might indicate a seasonal trend, the series is too short to draw any conclusions and more research is needed.

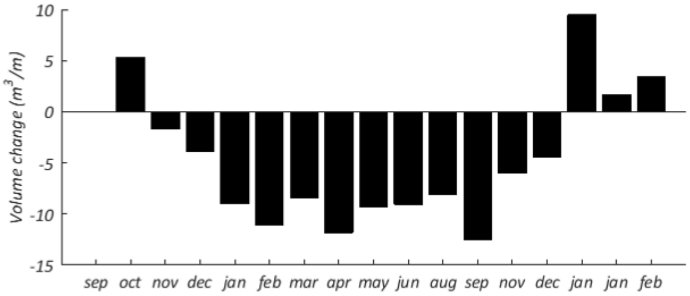

Figure 6. Cumulative changes in total beach volume with September 2015 as a reference corrected for the long-term trend.

The cumulative volume changes were up to ± 18 m^3/m/year, which is similar to the variation along the long-term trend for most other years. However, when major storm events occur, erosion can be up to 50 m^3/m/year (Houthuys, 2012). Between 1983 and 2009 five major storm events occurred that caused erosion in this range (Haerens *et al.*, 2012). For typical years without storm events, the variation along the long-term trend as found by Houthuys (2012) is similar to the magnitude of yearly volume changes found in this study. From previous studies it is known that a large yearly variation can be typical for beaches with human interference and that these beaches can be less stable than natural beaches (Senechal *et al.*, 2016).

5.3. *Future research*

In this study a relation between hydrodynamic conditions and morphological response was found. From the hydrodynamics it is known that they follow a seasonal trend, so this can also be expected for the (intertidal) beach morphology. However, the time series of 1.5 years in this study was too short to determine such a trend and therefore the time series should be extended. Furthermore, large along shore morphological differences in beach behavior were found. It was assumed that the hydrodynamic forcing was similar along the study area, but waves and currents might be affected by the groins. This assumption should be tested with field measurement and numerical modeling. In this study the general effect of hydrodynamics on beach morphology for a featureless intertidal beach was determined, but hydrodynamics and sediment transport should be studied more in-depth to improve this relation.

6. Conclusion

This study investigated the spatial and temporal variability of a macro-tidal non-barred beach at Mariakerke in Belgium. Three cross-shore topographical profiles were measured monthly over 1.5 year. The resulting small scale, high frequency topographical dataset allowed us to determine the range of morphological changes that can take place. It was found that significant morphological changes take place on a monthly scale, independent of seasonal and long-term trends. Especially in autumn and winter the monthly variation in morphology was large: ± 13 m^3/m/month, with a standard deviation of 5.7 m^3/m for the total volume and ± 8 m^3/m/month and a standard deviation of 3.7 m^3/m for the intertidal beach volume. Erosion and accretion were alternating between consecutive months. In spring and summer the beach morphology was relatively stable, except for August when significant erosion was observed. The results indicated that the range of morphological changes was ± 18 m^3/m/year, but this can be up to three times larger in years with major storm events.

A clear relation between hydrodynamic forcing (wave height and water level) and morphological response was found. However this relation was very different for the three profiles. For all profiles the beach became wider under more energetic conditions, but the response of beach width was much stronger for profile c than for a. Furthermore, the beach volume decreased under more energetic conditions in profile a and b, while it actually increased in c. The relation between hydrodynamic conditions and beach width was stronger than for beach volume. Changes in beach width could be explained for 70% by the hydrodynamic conditions, while for the intertidal volume change this was 52%. Largest morphological changes took place on the steep slope at the dry beach, especially when waves and water level were high. Although a large part of the morphological changes could be related to the hydrodynamic forcing, some morphological changes could not be explained by the waves or water level. For some months these changes could be related to the recovery time when the beach was re-build after an energetic event before the next survey. Other natural forcing factors (wind) and also human interference might have affected the relation between hydrodynamic forcing and morphological response.

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