

SAW-TOOTH BAR DYNAMICS ON THE AMELAND EBB-TIDAL DELTA

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Abstract

Ebb-tidal deltas are part of tidal inlet systems, and it is important to understand sediment transport processes and pathways that take place there. Sediment is transported along ebb-tidal deltas as both suspended load and bedload, and bedform migration is one of the processes by which bedload transport can take place. Saw-tooth bars are bedforms that are found regularly on ebb-tidal deltas, but they have not been studied thoroughly yet. The present study shows the characteristics of these bars, like bar height and length. Spatial correlation was used to find their migration speed. It was found that saw-tooth bars are approximately 2m high and have a wavelength of 500-1000m. Both bar height and migration speed appear to change in a cyclic way. The saw-tooth bars contribute substantially to the total sediment transport on the ebb-tidal delta.

Key words: ebb-tidal delta, sediment transport, morphodynamics, saw-tooth bars, bedforms, spatial correlation

1. Introduction

Ebb-tidal deltas are shallow features seaward of tidal inlets. They are important in dissipating storm waves and they are a (temporary) source of sediment for the backbarrier basin and barrier islands. Recently, many ebb-tidal deltas in the Dutch Wadden Sea face a loss of sediment (Elias et al., 2012). To maintain a safe coast line, it is considered to nourish the ebb-tidal deltas. However, the exact sediment pathways across the ebb-tidal deltas are still unknown, which makes it difficult to decide on an exact location for such nourishments.

Ebb-tidal deltas are morphodynamically complex areas: They have a large spatial variability in bathymetry, various grain size fractions can be present (Son et al., 2011) and they are exposed to both strong waves and tidal currents. Sediment is transported as both bedload and suspended load, and these two processes can take the sediment in different directions under different tidal and wave conditions (Herrling and Winter, 2014).

A part of the sediment on the ebb-tidal delta is transported as bed load through bedform migration. Many ebb-tidal deltas show cyclic patterns of shoal generation, followed by subsequent migration and attachment of these shoals to the downdrift barrier islands (e.g. Ridderinkhof et al., 2016). These shoals can be quite large (up to several km²) and they can migrate up to ~300 m/y, thus causing a large volume of sediment to be transported towards the coast. Other bedforms that are regularly found are migrating sand waves in tidal inlet channels (e.g. Buijsman and Ridderinkhof, 2008a,b).

The present study will focus on the characteristics of so-called saw-tooth bars, which have not been given much scientific attention yet. These bars can be found on the downdrift side of many ebb-tidal deltas in the Wadden Sea, several examples are shown in Figure 1. Modelling studies have shown that the sediment transport pathways in the bar area are in a downdrift direction along the adjacent barrier island (Cleveringa et al., 2005; Herrling and Winter, 2014). Herrling and Winter (2014) described these bars as shore-oblique sandbars, because their crests have an angle with the shore-normal. Usually, this angle decreases in a downdrift direction, meaning that the bar crests are more perpendicular to the shore when they migrate along the barrier island (see Figure 1). Figure 1 shows that saw-tooth bar lengths are in the order of hundreds of metres till a kilometre, and heights are in the order of metres. The typical migration speeds are unknown.

The goal of the present study is to characterize saw-tooth bars in terms of height and length, and to

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determine their typical migration speed and associated transported volume of sediment. We focus on the saw-tooth bars on the Ameland ebb-tidal delta because it is the least disturbed by human interventions (compared to other Dutch inlets), and because of the availability of bathymetric surveys.

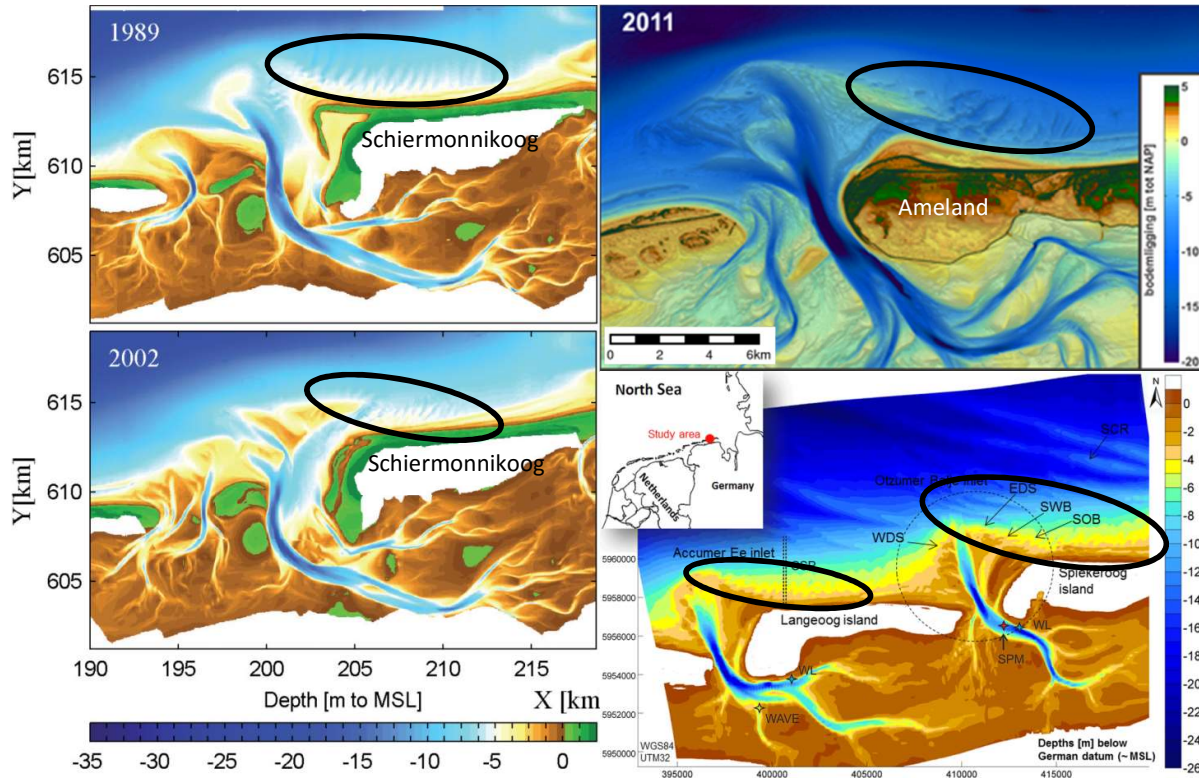


Figure 1. Occurrence of saw-tooth bars on various ebb-tidal deltas in the Wadden Sea area (circles). Left: from Elias et al. (2012); Upper right, from Vaklodingen (from zeeweringenwiki.nl); lower right: from Herrling and Winter (2014).

2. Methods

2.1. Bathymetries

The bathymetry of the Ameland ebb-tidal delta has been measured by Rijkswaterstaat (part of the Dutch Ministry of Infrastructure and the Environment) approximately every three years since 1989, and yearly since 2005. On top of that, the bathymetries of 1981, 1975, 1971 and 1926 are available, but the accuracy of the datasets before 1989 is less certain. In this paper, the bathymetries between 2002 and 2014 are discussed. The data were recorded using a singlebeam echosounder and were subsequently interpolated to a 20x20m grid. According to Perluka et al. (2006) the vertical accuracy of the measurements is between 0.11-0.40 m after interpolation with DIGIPOL (a linear interpolation method developed by Rijkswaterstaat). Although the data sets will contain errors, the morphological features we are interested in are relatively large and errors are mainly local in space in and time.

A first estimation on saw-tooth bar height, length and migration is obtained by analysing the bathymetry along a cross-section through the bar area (Figure 2, line AB). This will yield reliable information as long as the saw-tooth bars have a constant orientation, migrate in a relatively constant direction and the cross-section is normal to the troughs and crests of the bars. However, because orientation or migration direction of saw-tooth bars might change we also perform a 2D analysis.

In the 2D analysis, the bar area (Figure 2, square) will first be studied to find saw-tooth bar heights and lengths through time. For this, the area is detrended with the local (running) mean. Assuming that the bars are approximately sinusoidal, their height is given by $2\sqrt{2}\sigma$, with σ being the standard deviation (Smith, 1997). The wave length is estimated from visual observations.

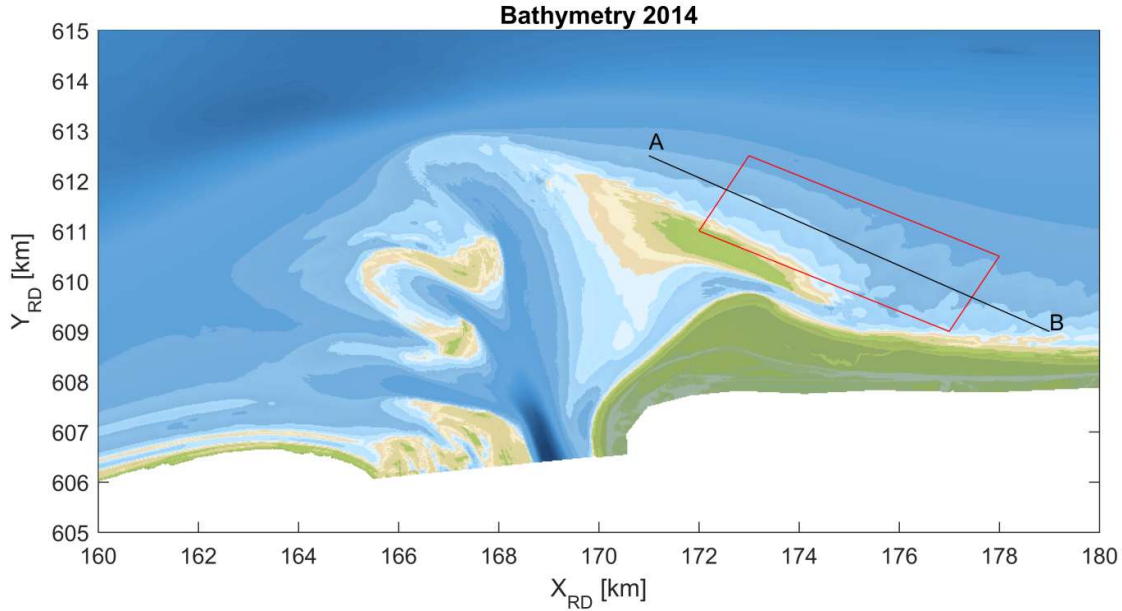


Figure 2. The location of the transect (black line) and the saw-tooth bar area (red square) on the bathymetry of 2014.

2.2. Spatial correlation

The bedform migration speeds can be obtained by calculating the spatial correlation of two bathymetries at different moments in time. However, actual bathymetries cannot be used in this case, because bedforms migrate along the sloping faces of the ebb-tidal delta. Duffy and Hughes-Clarke (2005) performed spatial correlation using the local gradient of the bathymetry, whereas Buijsman and Ridderinkhof (2008a) chose the difference with the local mean. For the present study the use of the gradient gave the most robust results.

The spatial correlation method of Duffy and Hughes-Clarke (2005) will be explained briefly below. For each location in the domain, a fit matrix $f(x,y)$ is created, containing the bed level gradients in a square area around this point at time T1 (Figure 3). A second fit matrix ($g(x+\Delta x, y+\Delta y)$) is created by taking the bed levels at time T2 from locations that are shifted Δx and Δy with respect to x and y of fit matrix f . For each displacement Δx_k and Δy_l , the correlation between f and g is calculated. The result is a matrix of correlation values $r(k,l)$ (Equation 1).

$$r_{k,l} = \sum_{k=0}^M \sum_{l=0}^N f(x,y)g(x + \Delta x_k, y + \Delta y_l), \quad (1)$$

To prevent biases due to potential outliers, the correlation r is normalized to R , by subtracting the mean from each dataset, and subsequently dividing r by the standard deviation (Equation 2).

$$R_{k,l} = \frac{\sum_{k=0}^M \sum_{l=0}^N [f(x,y) - \bar{f}] [g(x + \Delta x_k, y + \Delta y_l) - \bar{g}_{k,l}]}{\sqrt{\sum_{k=0}^M \sum_{l=0}^N [f(x,y) - \bar{f}]^2 \sum_{k=0}^M \sum_{l=0}^N [g(x + \Delta x_k, y + \Delta y_l) - \bar{g}_{k,l}]^2}} \quad (2)$$

The values in the resulting correlation matrix R are only taken into account in further calculations when their value is above 0.3. This threshold was chosen based on visual interpretation of several correlation matrices, and is used to exclude migration vectors resulting from areas that actually have no correlation with each other. In the remaining correlation matrix, the peak is defined as an area instead of one value, to prevent the selection of a random peak. Duffy and Hughes-Clarke (2005) found that $R_{\max}/\sqrt{2}$ optimally describes the plan view of the base of the cross-correlation maximum. Of this area of maximum correlation ($R > 0.3$ & $R > R_{\max}/\sqrt{2}$) the weighted centroid is taken, which is multiplied by the bathymetry grid cell size to determine the actual displacement of the bedform.

To determine the migration speed of bedforms, it is important to take the right size of the fit matrix and search area. The fit matrix should be large enough to contain a unique area of sea floor, which is in this case the typical wave length of a saw-tooth bar. The search area is approximately equal to the area represented in the fit matrix multiplied by 1.5. If the search area is too small, the new location of the saw-tooth bar cannot be found, but if it is too large, other new locations are also found at twice the bar wave length. Several sizes were tested for the search area and fit matrix, and optimum values were found to be 1000 m by 1000 m for the fit matrix and 1600 m by 1600 m for the search area.

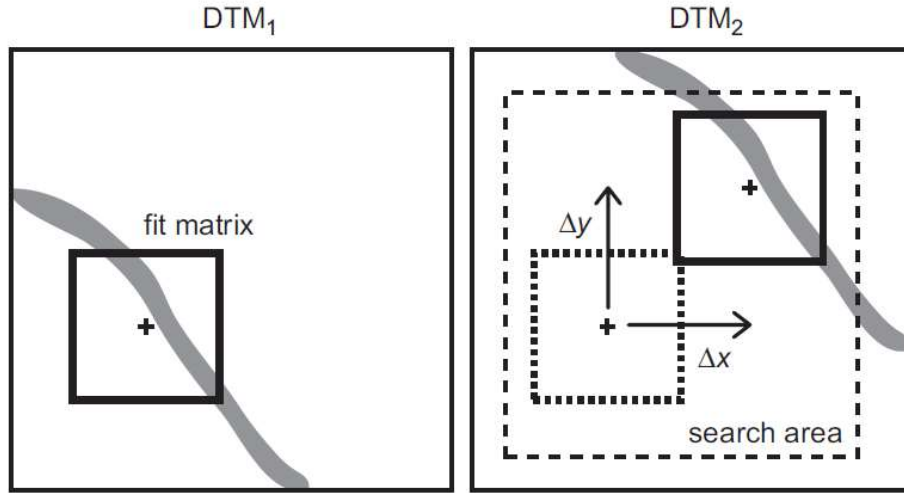


Figure 3. Illustration of the spatial correlation method (Buijsman and Ridderinkhof, 2008a)

2.3. Sediment transport

When the height h , width and migration velocity U of the saw-tooth bars are known, the volumetric sediment transport per unit width per unit time (q_b in m^2/y) can be calculated using Simons et al. (1965):

$$q_b = 0.5 \cdot U \cdot h \cdot (1 - \phi) + C_1 \quad (3)$$

In this equation, ϕ denotes the porosity of the sediment, which is generally taken to be 0.4. C_1 is a constant, representing the part of the bed load that is not transported by bedforms. For now, C_1 is assumed to be 0. When q_b is multiplied with the bedform width (in m), the volumetric sediment transport in m^3/y is obtained. This width was estimated from Figure 2 to be 1500-2000m.

3. Results

3.1. Saw-tooth bar characteristics

From the cross-sections, the saw-tooth bars are clearly visible (Figure 4). From this figure, the wavelength of the bars was estimated to be 500-1000 m. Their height ranges from 0.5-3.0 m. In the years 2008-2012, the bars decrease in height, and especially in the northern part (km 0 - 4.5) they seem to disappear.

From Figure 4, it is also possible to make a first estimation of the migration speed of the saw-tooth bars. Especially between 2006-2007 and 2007-2008, the bars in the cross-section do not change in shape, and their troughs and crests can be easily tracked (black arrows in Figure 4). Between 2006 and 2007 the bars migrate approximately 174 m, and between 2007 and 2008 the displacement is approximately 219 m.

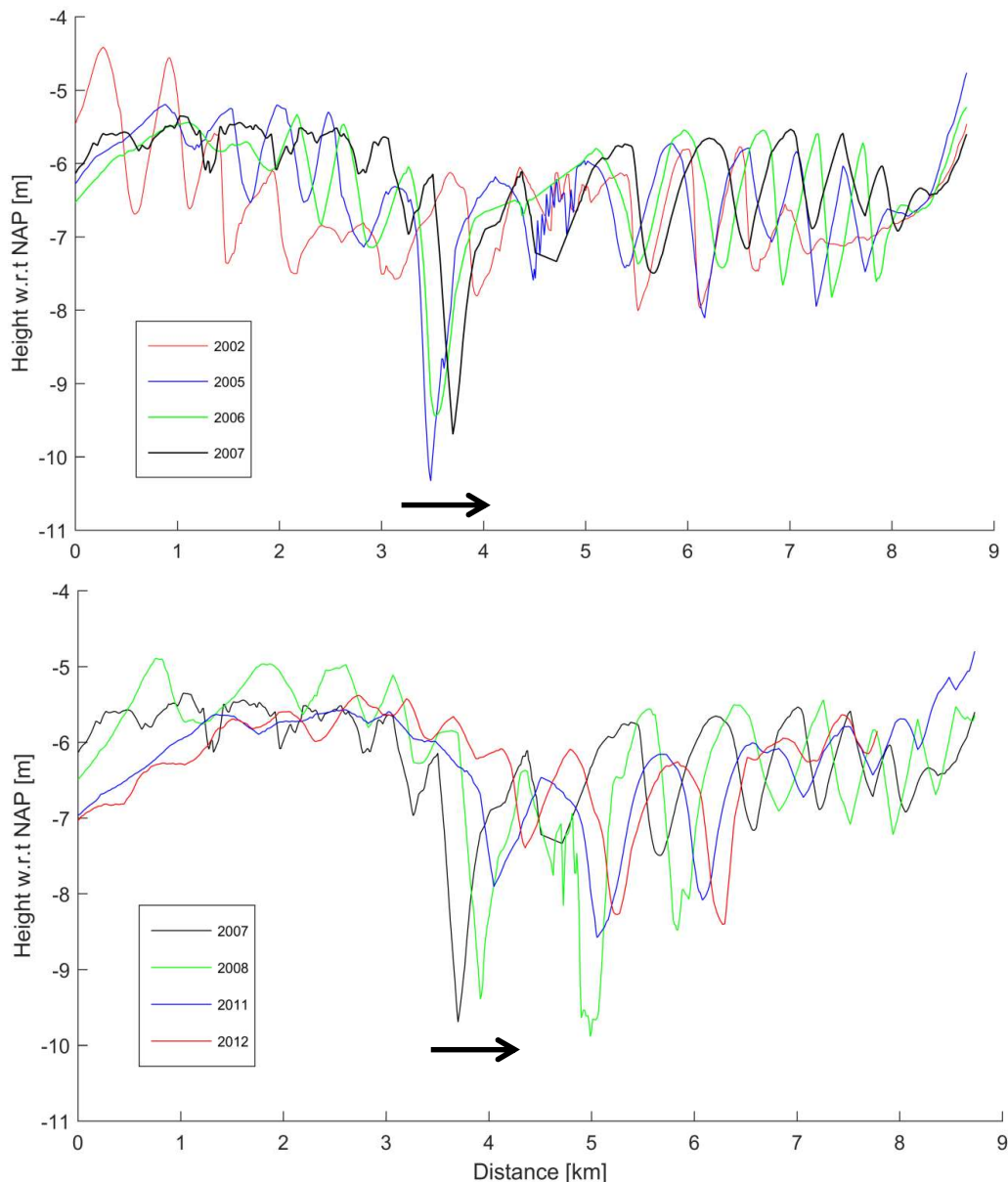


Figure 4. Depth along the transect AB between 2002 and 2012. Arrows indicate bedform migration direction.

Figure 5 shows the detrended bathymetry in the bar area. The saw-tooth bars are easily visible. The bar height (given in the upper right part of each plot) is stable between 2005 and 2008, but is lower in the years before and after this period. The 2D analysis shows a similar decreasing bar height from 2008 onwards as in the 1D plot (Figure 4). In 2012, the bars are still visible, but they are more than 50% smaller than their peak height of 2.1m in 2008.

From Figure 5 a wavelength of 500-1000 m is observed, similar as based on Figure 4.

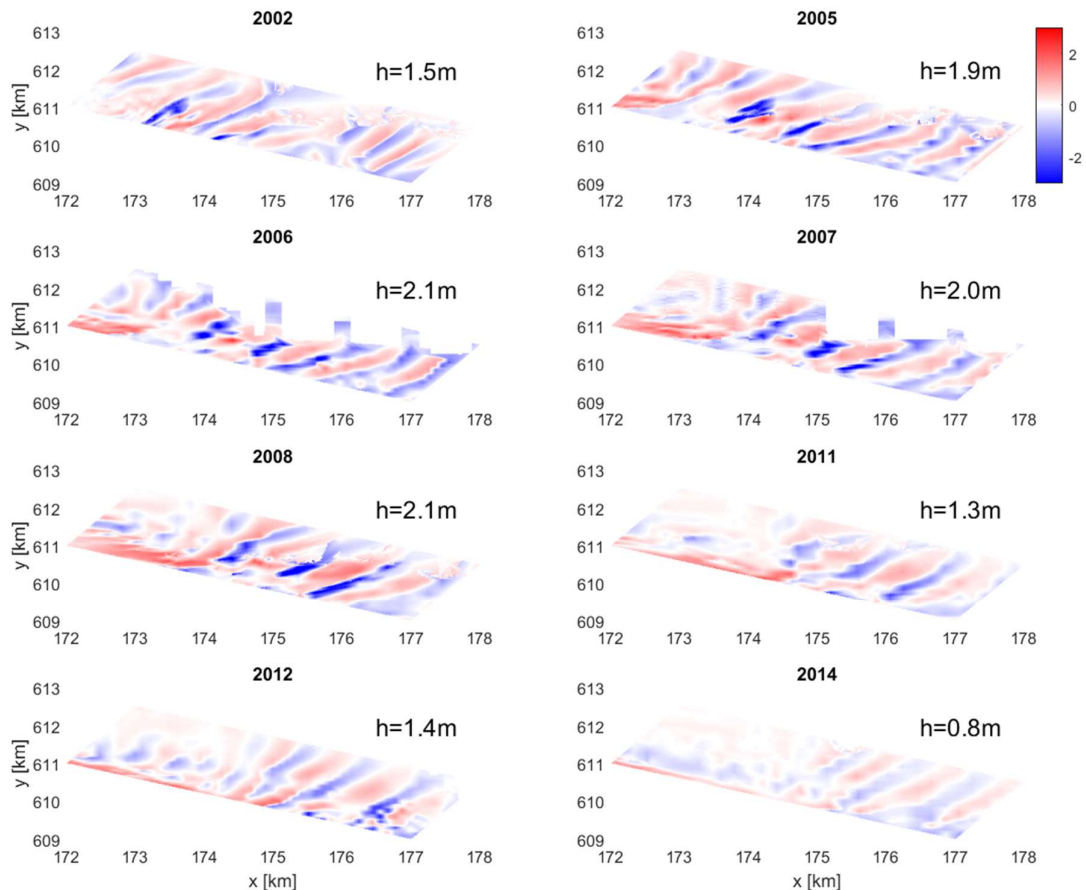


Figure 5. Detrended bathymetry in the bar area between 2002 and 2014. Bar height per year is given in the upper right part of each plot.

3.2. Saw-tooth bar migration speed and sediment transport

Figure 6 shows the migration vectors in the bar area as calculated with spatial correlation for the years between 2002 and 2014. It is visible that spatial correlation works best when the bathymetries are from two consecutive years. In the upper left part of Figure 6, which displays the migration for 2002-2005, some of the vectors are pointing towards the northwest, while all other figures show migration in the saw-tooth bar area taking place in the south-eastern direction. The period 2002 – 2005 might be too long to determine migration speeds because bedforms might migrate one wavelength in three years. Also from the 1D analysis it is difficult to track the crests and troughs for this period.

In the saw-tooth bar area, average migration speeds of 181.5 m/y for the period 2006-2007 and 197 m/y for the period 2007-2008 were found, which are relatively similar to the migration that was found through the cross-sections. Furthermore, the vector sizes and directions are relatively uniform in each plot, showing

that migration takes place towards the southeast with a constant speed for each year.

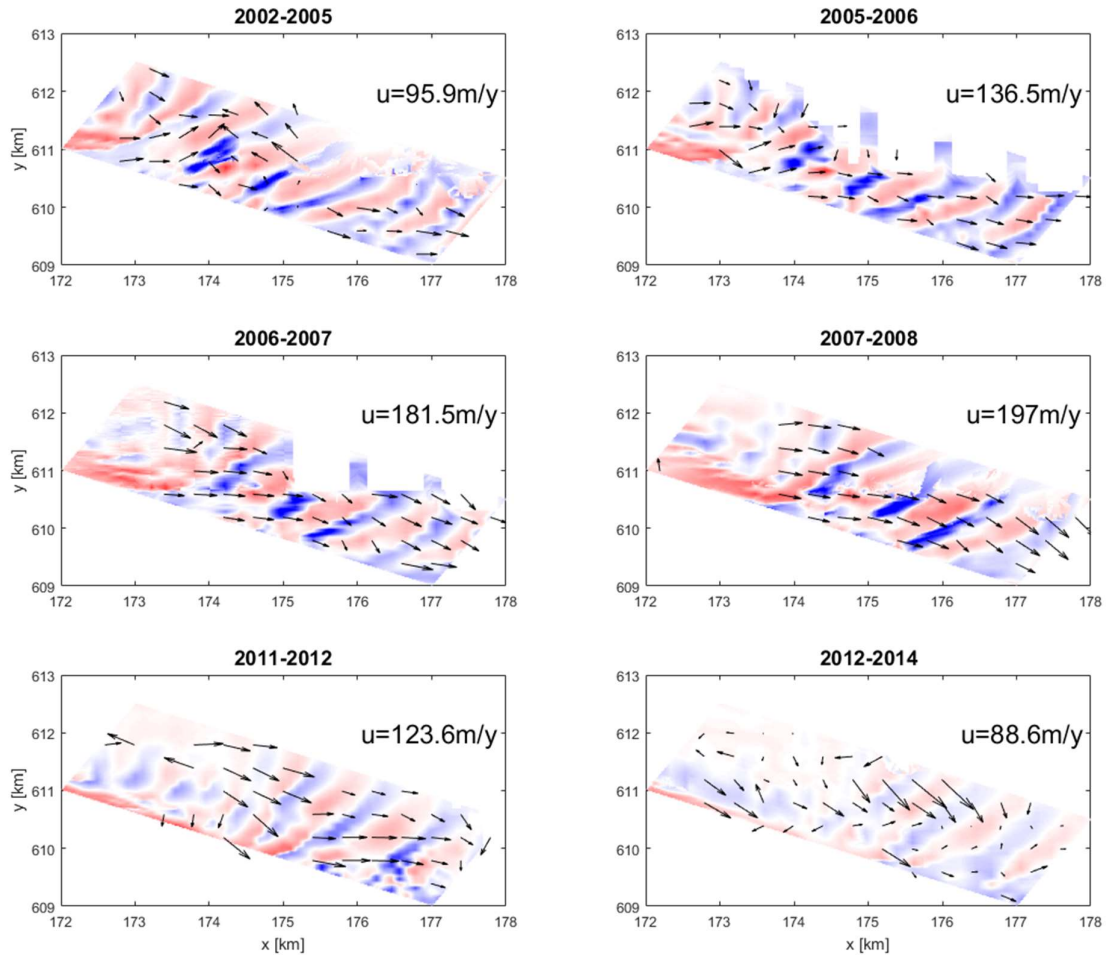


Figure 6. The migration vectors that result from spatial correlation of the bathymetries between 2002 and 2014, projected on the detrended bar area.

Furthermore, Figure 6 suggests a cyclic evolution of the migration speeds similar to the bar height evolution presented in Figure 5: migration speeds are increasing up to 2007, and decrease again from 2008 onward. The bar heights increase until 2005, and after 2008, their height decreases significantly.

On average, between 2002 and 2014 the saw-tooth bars migrated with 137 m/y. Using this value together with the average height of 2 m and width of 1500 m, Equation 3 results in an average volumetric sediment transport of 123.300 m³/y. Using maximum values of $U = 200$ m/y and $h = 3$ m leads to a maximum volumetric transport of 270.000 m³/y.

4. Discussion and conclusions

In the present study, saw-tooth bars have been characterized as downstream migrating shore-oblique bars on ebb-tidal deltas. Their characteristic height and length are 0.5-3 m and 500-1000 m, respectively.

Spatial correlation has been successfully used to determine migration speeds of the saw-tooth bars on the Ameland ebb-tidal delta. On average, these saw-tooth bars migrate with 137 m/y, but speeds of 200 m/y are also found. Migration takes place along the eastern edge of the shoal, and further downstream the bars

propagate along the island. The average volume of sediment transported by the saw-tooth bars is $112.300 \text{ m}^3/\text{y}$.

Cheung et al. (2007) and Ridderinkhof et al. (2016) studied the behaviour of the large shoal on the Ameland ebb-tidal delta and found an average migration speed of 226 m/y . The associated volume of transported sediment is $1 \cdot 10^6 \text{ m}^3/\text{y}$ (Cheung et al., 2007). Buijsman and Ridderinkhof (2008b) found that sand waves in the channel of the Texel inlet transported a volume of $89 \cdot 10^3 \text{ m}^3/\text{y}$ between 1999 and 2002. The average transported volume by saw-tooth bars of $1.23 \cdot 10^5 \text{ m}^3/\text{y}$ as found in the present study indicates therefore that saw-tooth bars contribute substantially to the total sediment transport across the ebb-tidal delta.

It was found that both the saw-tooth bar height and migration speed increase after 2002 and decrease after 2008. This suggests a cyclic pattern, but not enough data are available to find an entire cycle of increasing and decreasing bar height and migration speed. Therefore, this process still has to be studied.

It is also not yet known how the values for bar height and migration speed on the Ameland ebb-tidal delta relate to the properties of saw-tooth bars on other ebb-tidal deltas. This will be a subject for further research as well.

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