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Cyclic behavior of sandy shoals on the ebb-tidal deltas of the Wadden Sea

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ABSTRACT

Ebb-tidal deltas are bulges of sand that are located seaward of tidal inlets. Many of these deltas feature shoals that cyclically form and migrate towards the coast. The average period between successive shoals that attach to the coast varies among different inlets. In this study, a quantitative assessment of the cyclic behavior of shoals on the ebb-tidal deltas of the Wadden Sea is presented. Analysis of bathymetric data and Landsat satellite images revealed that at the majority of inlets along the Wadden Sea migrating shoals occur. The average period between succeeding shoals correlates to the tidal prism and has values ranging between 4 and 130 years. A larger tidal prism favors larger periods between successive shoal attachments. However, such a relationship was not found for wide inlets with multiple channels. There is a positive relationship between the frequency with which the shoals attach to the coast and their migration velocity, and a negative relationship between the migration velocity of the shoal and the tidal prism. Finally, the data were too sparse to assess whether the longshore sediment transport has a significant effect on the period between successive shoals that attach to the coasts downdrift of the observed tidal inlets.

1. Introduction

Seaward of tidal inlets, ebb-tidal deltas are shaped by the joint action of waves and tides (Hayes, 1975; Oertel, 1975a). Their morphology is dynamic (Oertel, 1975b), alongshore transported sediment bypasses inlets from the updrift to the downdrift side through complex pathways involving the ebb-tidal delta and the inlet channels (FitzGerald et al., 2000). Part of the sediment bypasses the inlet as a coherent body, in general this is accomplished by (1) inlet migration and subsequent spit breaching or (2) the formation of large shoals on the ebb-tidal delta (often composed of multiple swash bars) that migrate to the coast (FitzGerald, 1988). The second process was categorized into multiple conceptual models by FitzGerald (1982) and FitzGerald et al. (2000), which discriminate between the impact of the shoal on the channels seaward of the inlet, i.e., stable inlet processes, ebb-tidal delta breaching, and outer-channel shifting. The attachment of a shoal to a barrier island is an episodic event that is observed at the downdrift side of many tidal inlets. The average period between successive attachments, P_S, shows a wide range of values. For example, at Teignmouth $P_S \sim 5$ yr (Robinson, 1975; Siegle et al., 2004), at Essex Inlet $P_S \sim 6$ yr (Smith and FitzGerald, 1994), at Deben estuary mouth $P_S \sim 30$ yr (Burningham and French, 2006), at New Inlet, Cape Cod $P_S \sim 2$ yr (FitzGerald and Pendleton, 2002), at Price Inlet, South Carolina $P_S \sim 5.5$ yr (FitzGerald, 1984; Gaudiano and Kana, 2001), and at Ameland Inlet $P_S \sim 55$ yr (Israel and Dunsbergen, 1999).

Various explanations were given for the different typical periods of bypassing events. Gaudiano and Kana (2001) investigated the cyclic behavior of shoals at nine inlets in South Carolina and found that for these inlets a positive relationship exists between the period between successive attachments of shoals and their tidal prism. Their conclusion is in line with the statement of FitzGerald (1988) that the time required for shoals to migrate onshore is typically shorter at smaller inlets because these generally have a smaller tidal prism, and usually also a smaller ebb-tidal delta (Walton and Adams, 1976). Consequently at smaller inlets shoals form closer to the coast. On the other hand, Hands and Shepsis (1999) and O'Connor et al. (2011) related cyclic behavior of the morphology seaward of other tidal inlets in the United States and Ireland to different climate phenomena that cause alternating periods with higher and lower wave energy. Burningham and French (2006) argued that the relatively long period between successive shoals at Deben Estuary is a result of the fact that the ebb-tidal delta is mainly composed of gravel, which leads to a lower sediment transport capacity.

Large shoals that migrate towards the coast are also observed at many tidal inlets along the Wadden Sea (Ehlers, 1988), an inland sea that is bordered from the North Sea by a chain of barrier islands that extends over Netherlands (West Frisian Islands), Germany (East and North Frisian Islands), and Denmark (Danish

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Table 1
Wave stations in the North Sea, local water depth (h), observed period, mean significant wave height ($\overline{H_s}$), and mean peak period ($\overline{T_p}$).

Station name	Short	h (m)	Period	$\overline{H_s}$ (m)	$\overline{T_p}$ (s)
IJmuiden	IJM	21	1990–2012	1.29	5.82
K13	K13	27	1990–2012	1.47	6.04
Eierlandse Gat	EIE	26	1990–2012	1.37	6.00
Schiermonnikoog	SCH	19.5	1990–2012	1.18	5.77
Fino1	FN1	29	2006–2009	1.49	6.99
Elbe	ELB	25	2006–2009	1.07	5.75
Helgoland	HEL	20	2009–2009	1.06	5.91
Sylt	SLT	13.2	2006–2009	1.02	6.64
Fanø Bugt	FNO	15.3	1998–2007	1.04	5.65

Wadden Islands). A better understanding of the periodically migrating shoals on the ebb-tidal deltas of the Wadden Sea is relevant, since they play an important role in the morphology of the islands and the sediment balance of the nearshore zone. For example, FitzGerald et al. (1984) recognized that the shape of the East Frisian Islands is strongly affected by the location at which these shoals attach to the islands. Also, the coasts of many of the barrier islands require high maintenance (e.g., RWS, 2014), while the attachment of a shoal to the coast can supply up to $O(10^7)$ m^3 of sand (Sha, 1989a; Hofstede, 1999b). Quantifying the migration of shoals on the ebb-tidal deltas of the Wadden Sea was done in several case studies, e.g., at Ameland Inlet (Israel and Dunsbergen, 1999). However, not all inlets were examined, nor were the characteristics of the migrating shoals at different inlets of the Wadden Sea compared.

Therefore, in this study it is assessed at which inlets of the Wadden Sea shoals migrate from the ebb-tidal delta to the coast, and what the typical time period between successive attachments of the shoals is. Also, it is investigated whether the relationship between this period and the tidal prism as found by Gaudiano and Kana (2001) is applicable to the ebb-tidal deltas of the Wadden Sea. This is not obvious, as the range of tidal prisms of the inlets

Table 2
Tidal prism (Q_P) and longshore sediment transport (Q_L) of the tidal inlets along the Wadden Sea coast. Part of this data was found in literature: (1) Elias and Van der Spek (2006), (2) Duran-Matute et al. (2014), (3) Sha (1989b) (after Postma 1982), (4) Biegel and Hoekstra (1995), (5) Niemeyer (1994), (6) Stanev et al. (2003), (7) Hofstede (1999b), (8) Dick and Schonfeld (1996), (9) Lumborg and Windelin (2003), and (10) Pedersen and Bartholdy (2007).

Inlet	No.	Q_P (10^6 m^3)	Q_L (10^6 m^3 yr^{-1})
Texel Inlet	1	700[(1)a]	0.2
Eierlandse Gat	2	180[(2)]	0.1
Vlie Inlet	3	934[(2)]	0.4
Ameland Inlet	4	383[(2)]	1.0
Pinkegat	5	100[(3)]	1.4
Zoutkamperlaag	6	320[(4)b] 200[(3)c]	1.4
Westerems	7	1000[(3)]	1.1
Osterems	8	525[(5)]	0.8
Norderneyer Seegat	9	163[(3)]	1.3
Wichter Ee	10	39[(6)]	1.2
Accumer Ee	11	174[(6)]	1.2
Otzumer Balje	12	145[(6)]	1.1
Harle Inlet	13	123[(6)]	1.0
Hever Inlet	14	835[(7)]	1.4
Schmaltief	15	183[(8)]	0.0
Amrum Inlet	16	906[(8)]	1.4
Hörnum Inlet	17	586[(8)]	0.4
Lister Dyb	18	620[(9)]	1.1
Juvre Dyb	19	155[(10)]	0.2
Knude Dyb	20	175[(10)]	0.0
Grå Dyb	21	138[(10)]	0.6

[a] Before 1932.
[b] Before 1969.
[c] After 1969.

Fig. 1. Map of the study area, including the names of the inlets considered in this study. Furthermore, the locations of the wave stations presented in Table 1 are indicated.

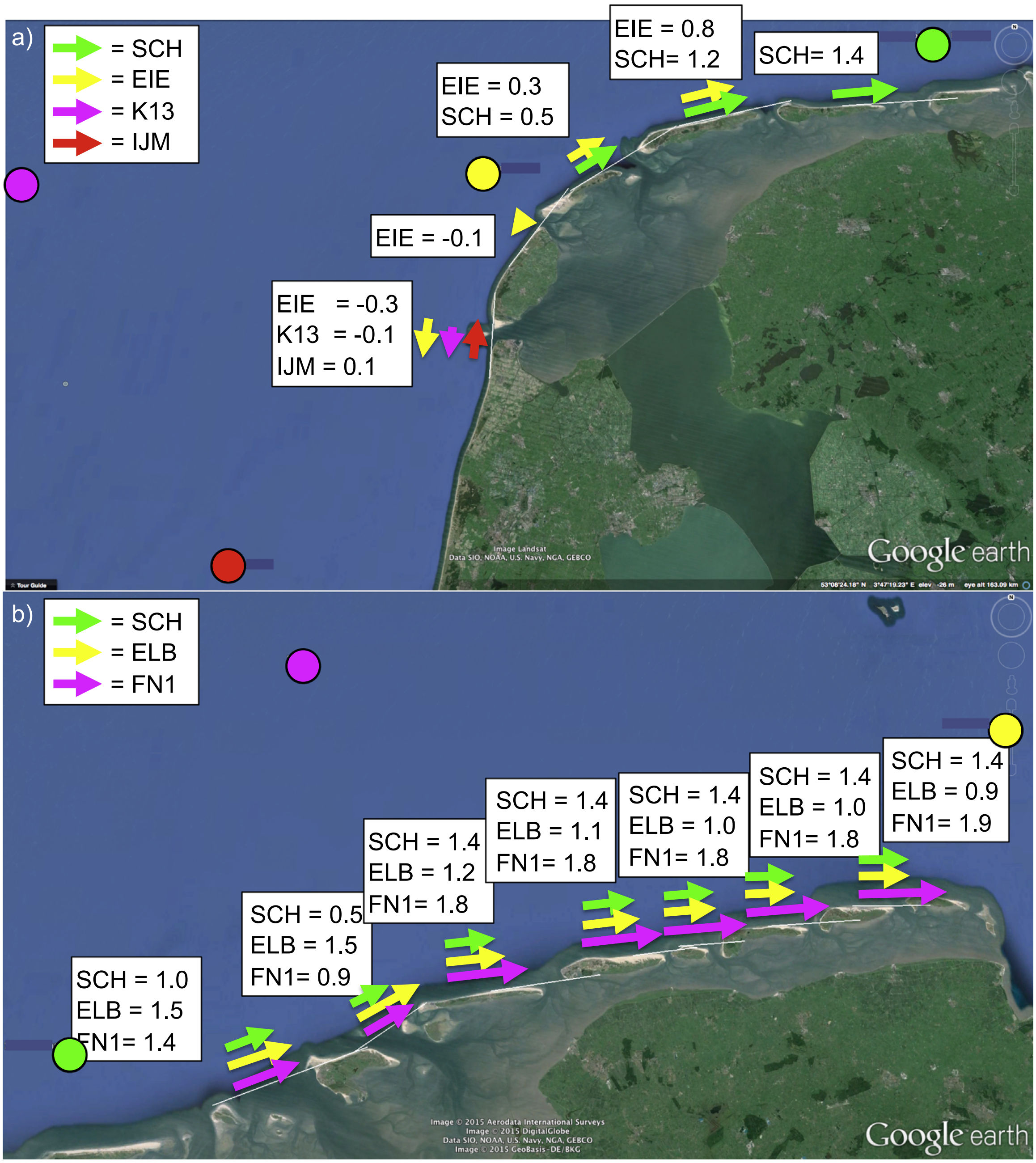

Fig. 2. Wave driven longshore sediment transport computed using the CERC formula, local orientation of the coastline, and the wave climate as observed at different wave buoys (indicated by the colored circles). Values indicate net longshore sediment transport in 10^6 m^3 yr^{-1}. The arrows indicate the direction of the longshore sediment transport, the colors correspond to the different wave stations (abbreviated as in Table 1). (a) West Frisian Islands. (b) East Frisian Islands. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this paper.)

considered in that study is much smaller than the range of tidal prisms of the inlets of the Wadden Sea. Since the migrating shoals are commonly related to the bypassing of sediment along inlets, the effect of the net wave-driven alongshore sediment transport on the period between successive shoal attachments is also investigated. Finally, it is established whether the velocity of migrating shoals is related to the period between successive attachments.

In the following section, first the data that were used for this study and the general characteristics of the study area are discussed. Next, in Section 3 the cyclic behavior of shoals at a number of exemplary inlets is presented. The shoal migration at all studied inlets is presented in the supplementary material. In Section 4, the characteristics of the migrating shoals observed on the ebb-tidal deltas of the Wadden Sea are discussed and compared to those observed by Gaudiano and Kana (2001). The final section contains the conclusions.

2. Material and methods

2.1. Data sources

The bathymetry of the West Frisian Islands and their ebb-tidal deltas are monitored by the Dutch government (*Rijkswaterstaat*) and these observations are made publicly available through *opendap.deltares.nl*. In this study, three different datasets were used to analyze the migration of shoals towards the West Frisian

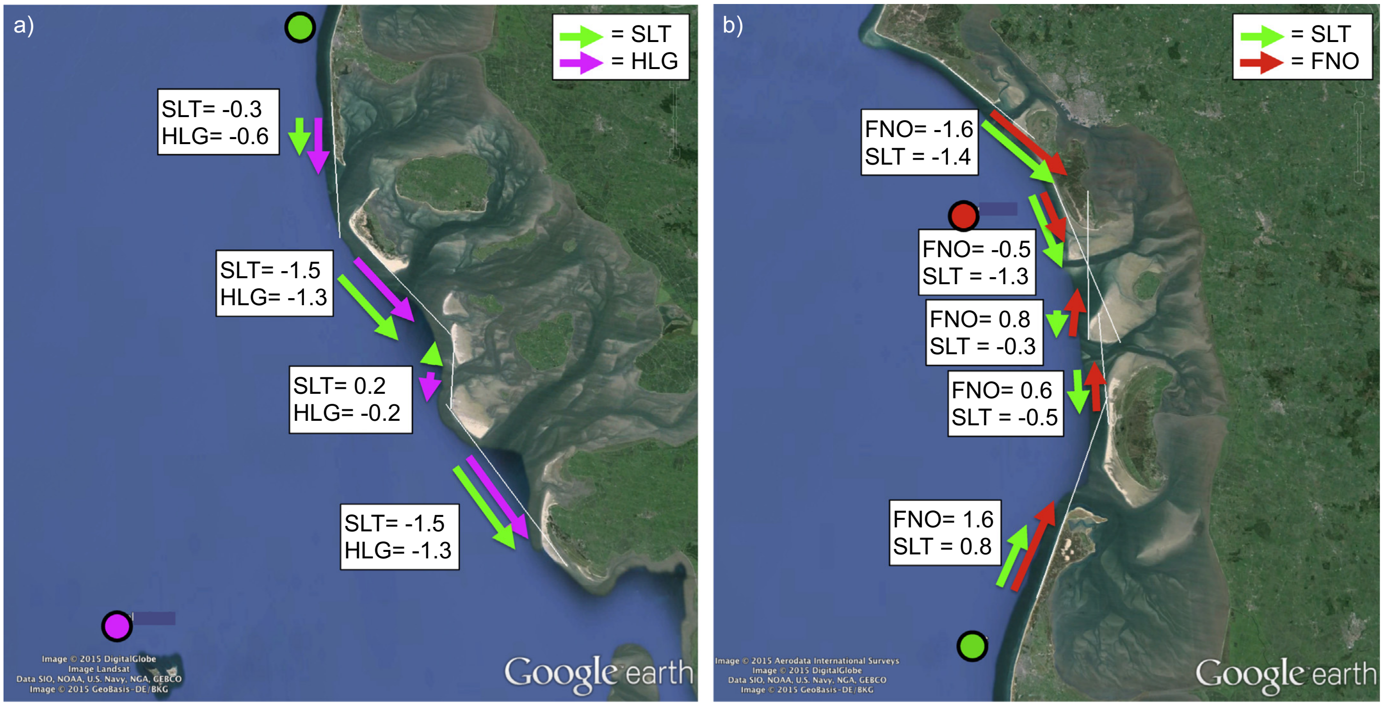

Fig. 3. As in Fig. 2. (a) North Frisian Islands. (b) Danish Wadden Islands.

Islands. The "Strandlijnen" dataset (Edelman, 1966) contains the position of the mean low water line on a yearly interval between 1843 and 1998, with an alongshore spacing of ~1 km. The "Jarkus" dataset contains bathymetric profiles along cross-shore transects on a yearly interval since 1965, with an alongshore spacing of ~200 m and a cross-shore spacing of 5 m. Finally, the "vaklodingen" dataset contains bathymetric profiles covering the entire Dutch coast with a 20 m spacing. The profiles are obtained at least every 7 years since 1981 and charts are available from 1926. Not all regions were monitored in the same year. Consequently, charts presented in this study were sometimes constructed from multiple surveys, which were conducted at most one year before or after the year that the chart represents.

For the (German) East and North Frisian Islands, yearly bathymetric data from 1982 to 2012 were made available by the *Bundesamt für Seeschifffahrt und Hydrography* (*BSH*) on a grid with a spacing of 50 m. The bathymetries were constructed by spatio-temporal interpolation on a high amount of survey data from German authorities and other sources. The quality of these data in the highly dynamic regions around tidal inlets did not allow for an analysis of the migration of individual shoals in front of the tidal inlets (except for shoals in front of Norderneyer Seegat between 1995 and 2012). It was nevertheless possible to use bathymetric data to determine the cross-sectional area of the inlets. No bathymetric data to study migrating shoals at the Danish Wadden Islands were available. Therefore, inspired by Capo et al. (2014), the migration of shoals on ebb-tidal deltas of the East and North Frisian Islands and the Danish Wadden Islands was extracted from satellite observations. For this, a total of 47 Landsat satellite images (*USGS*; available through http://earthexplorer.usgs.gov/) were selected (moments with little cloud cover and a low water level) in the period between 1973 and 2014, and subsequently analyzed using the open source geographic information system *QGIS*. It turned out that no satellite images were available in the period from 1991 to 1997 and only one satellite image before 1985 could be used. An additional 15 Landsat satellite images were used to determine the migration of shoals seaward of the West Frisian inlets from space. The total shoal area that is visible in satellite images depends on the water level and wave conditions on the ebb-tidal delta, hence the area of the migrating shoals could not be determined.

To obtain estimates of longshore sediment transport, a wave climate was constructed from hourly observations of wave characteristics at several stations in the North Sea (Table 1 and Fig. 1). The only exception concerns Fanø Bugt station that records wave characteristics on a three hourly interval.

2.2. Characteristics of the study area

The names and locations of the West (Nos. 1–6), East (7–13), North (14–17) Frisian and Danish (18–21) inlets that are considered in this study are indicated in Fig. 1. The tidal wave propagates along the coast from Texel Inlet towards Grå Dyb. The tidal range is minimal (1.35 m, Sha and Van den Berg, 1993) seaward of Texel Inlet, increases towards the Elbe mouth (3.0 m seaward of Hever Inlet, Hofstede, 1999a), and decreases again towards the north (1.5 m seaward of Grå Dyb, Vinther et al., 2004). The tidal prism of the different inlets was extracted from literature and presented in Table 2. Note that for some inlets multiple estimates are given. In such cases the most recent estimate is used. The evolution of the ebb-tidal deltas of Vlie Inlet, Texel Inlet and Zoutkamperlaag was strongly influenced by large interventions in the Wadden Sea in 1932 and 1969 (Biegel and Hoekstra, 1995; Elias and Van der Spek, 2006; Elias et al., 2012). The migration of shoals in the period prior to the interventions was studied on the latter two ebb-tidal deltas because it is possible that some of the shoals that attached to the downdrift coast afterwards formed as a result of the adjustment of the ebb-tidal delta to the new hydrodynamic conditions. Due to the lack of adequate data this was not possible for the migration of shoals on the ebb-tidal delta of Vlie Inlet.

The average significant wave height is largest seaward of the West Frisian Islands (Table 1). An estimate of the longshore sediment transport (including pores), Q_L, along the islands was derived using the CERC formula (CERC, 1984; Komar, 1998). This requires the wave height and propagation direction at the location of

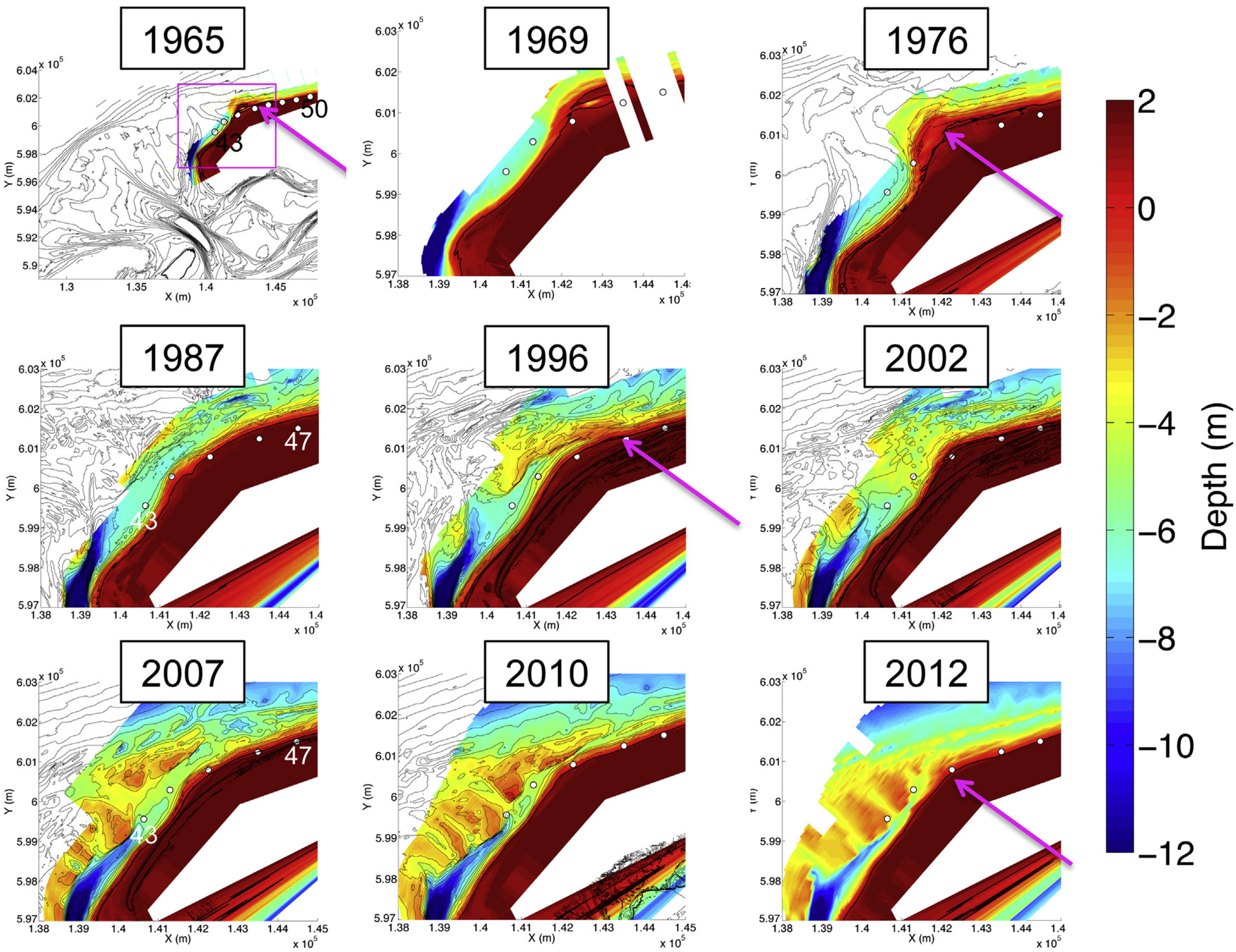

Fig. 4. Temporal evolution of the shoreline downdrift of the Vlie Inlet. The colored contours are constructed from the cross-shore depth profiles (Jarkus dataset). Contour lines obtained from the vaklodingen dataset are shown when available. A shoal attached to the coast in 1965, 1976, 1996, and 2012, as indicated by the magenta arrows. In the first frame the entire ebb-tidal delta and the region that is considered in the following frames is shown. The white dots indicate the location of the stations at which the position of the mean low water line was determined. The corresponding station numbers increase from 43 on the left to 50 on the right. Note that the contour lines that are shown in the frame of 1965 were obtained in 1971. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this paper.)

wave breaking, of which a climatology (consisting of 900 classes) was obtained by using the wave propagation model of Battjes and Janssen (1978) and the wave climate observed at the wave stations in the North Sea. Estimates of the wave driven longshore sediment transport along the islands are presented in Figs. 2 and 3 and Table 2. The values of Q_L presented in the table are based upon a weighted average (scaled with the distance between the buoys and the inlet) of the different estimates of Q_L that were found for the coast updrift of the inlets (Figs. 2 and 3). Data of the Fino 1 buoy were not used in the analysis because the observed wave climate was more energetic than that at the other buoys, which seems to lead to an overestimation of Q_L. Knude Dyb is special, as the longshore sediment transport along the coasts on both sides of the inlet is directed towards the inlet. The value in Table 2 results from averaging the estimates from both sides. It appears that there is an increase in the wave driven longshore sediment transport towards the east along the West Frisian Islands and a large and almost constant eastward longshore sediment transport along the East Frisian Islands. Furthermore, there is a southward longshore sediment transport south of the island Sylt, while north of Sylt the wave driven longshore sediment transport converges around Knude Dyb and Juvre Dyb. The estimate of the longshore sediment transport along the Skallingen peninsula (updrift coast of Grå Dyb) was obtained from literature (Aagaard and Sørensen, 2013). This was done because this coast receives more shelter from the shallow cape of Blåvands Huk than the wave stations that were used to construct a wave climate. A more detailed description of the computation of the longshore sediment transport is presented in the supplementary material.

2.3. Methods

This study investigated the relationship between both the average period between successive shoal attachments at the downdrift coast and the migration velocity of the shoals and (1) tidal prism and (2) longshore sediment transport rate. Moreover, the relationship between the frequency with which the shoals attach to the coast and their migration velocity was investigated.

Shoals were visually identified in bathymetric charts and satellite images as coherent migrating shallow features on ebb-tidal deltas, with a typical scale of a few 100 m in both horizontal directions. The average period between successive shoal attachments was obtained by averaging the time between the moments

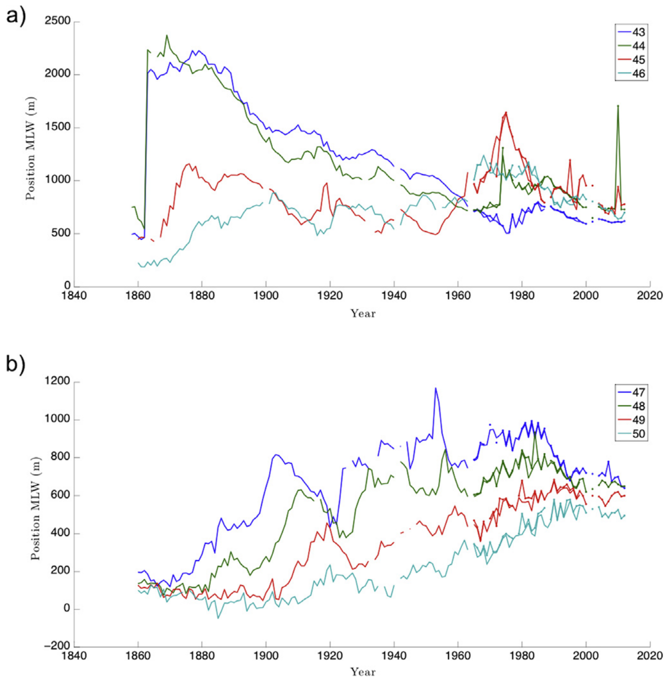

Fig. 5. Evolution of the position of the mean low water line at different stations on the downdrift coast of the Vlie Inlet in time. Station numbers are indicated in Fig. 4. The data suggest that shoals attached to the coast in 1865 (visible at stations 43 and 44), 1890, 1905, 1925, 1940, and 1955 (stations 47 and 48), 1965 (stations 45–47), 1976 (stations 44 and 45), 1996 (station 45), and 2012 (stations 44 and 45). Note the different scales of the vertical axis in the top and bottom panels.

that successive shoals for the first time attach to the coast. To obtain the average migration velocity of the shoals, first the edges of the shoals were manually selected in the bathymetric charts and satellite images. Subsequently, the centroids of the shoals (based on area) were computed, and their displacement was determined from successive images/charts. The displacement was divided by the time between successive charts to obtain the velocity. Finally, the average (and standard deviation) of the observed velocities was computed for each inlet. At some inlets shoals could only be identified close to the moment that they attached to the coast. As a consequence their migration velocity could not be determined.

3. Results

3.1. Cyclic shoal behavior at individual inlet systems

Cyclic events of migrating shoals are illustrated by a historical review of Vlie Inlet, Osterems, Accumer Ee, and Hörnum Inlet. Vlie Inlet is presented because the analysis of this inlet is exemplary for that of the West Frisian inlets. The observed shoal migration on the ebb-tidal delta of this inlet is characteristic for that on ebb-tidal deltas seaward of an inlet that consists of multiple channels. Shoal migration on the ebb-tidal delta of Osterems shows similar characteristics. This inlet is presented because, in contradiction to Vlie Inlet, it is not influenced by major changes in the back-barrier basin. The shoal behavior on the ebb-tidal delta of Accumer Ee is presented because of its high morphodynamic activity compared to the average over all inlets. Finally, shoal migration on the ebb-tidal delta of the Hörnum Inlet is discussed because this ebb-tidal delta is representative for ebb-tidal deltas with low morphodynamic activity. A complete analysis of shoal behavior on ebb-tidal deltas of all inlets, accompanied by an extensive amount of images, is given in the supplementary material.

3.1.1. Vlie Inlet

The Jarkus data reveal that shoals attached to the coast downdrift of Vlie Inlet in 1965, 1976, 1996, and 2012 (Fig. 4). From this, the mean period between successive attachments was established at 16 years (standard deviation (std): 4.5 yr). The events caused a displacement of the position of the mean low water line (MLWL), which is visible in Fig. 5. Peaks in the evolution of the MLWL at stations 47 and 48 suggest that also around 1865, 1890, 1905, 1925, 1940, and 1955 a shoal attached to the coast.

An estimate of the migration velocity of the shoals on the ebb-tidal delta of Vlie Inlet was established by tracking the yearly displacement of the shoal that is observed between 2005 and 2012 (Fig. 6). This resulted in a velocity of 212 m yr^{-1} (std: 69 m yr^{-1}).

Note that the morphology of the ebb-tidal delta of Vlie Inlet significantly changed as a result of changes in the local hydrodynamics due to the construction of a dike in the Wadden Sea in 1932 (Elias et al., 2012; Ridderinkhof et al., 2014). It is possible that some of the shoals that attached to the downdrift coast were formed during the adjustment period of the ebb-tidal delta to the new hydrodynamic conditions.

3.1.2. Osterems

Osterems is located between the islands Borkum and Juist. Three shoals attached to Juist in the period 1984–2014 (in 1990, 2000 and 2006; Fig. 7). From this, the period between successive shoals that attach to the coast of Juist was established at 8 years (std: 2.8 yr). No satellite images of the period from 1991 to 1997 are available. It was not possible to estimate the migration velocity of the shoals that attach to the coast of Juist. In addition, a second type of shoal migration is visible here. In the observed period, several shoals attached to a larger shoal that is located in the inlet and separates the channel closest to Juist (cross-sectional area ~$1.6{\cdot}10^3$ m^2) from the much larger main channel (cross-sectional area ~$4.4{\cdot}10^4$ m^2), the latter being located on the western side of the inlet. There is a third region where migrating shoals are observed on this ebb-tidal delta. Seaward of the main channel, two shoals that successively migrated towards the inlet center were identified. The first vanished before 1998, the second appears in the satellite image of 2000 and is still present in 2014.

3.1.3. Accumer Ee

Accumer Ee is located between the islands Baltrum and Langeoog. On the ebb-tidal delta of this inlet, a total of 10 shoals were identified that migrate towards Langeoog in the periods from 1984 to 1990 and 1998 to 2014 (Fig. 8). Some of these shoals already merged before they attached to the coast (e.g., Fig. 8: 2006). Based upon the successive attachments in 1986 and 1990, and in 2002 and 2006, 2010, a mean period between successive attachments of a shoal to the coast of 4 years (std: 0.8 yr) was established. Note that the time between the shoal that attached to the coast around 2010 and the moment that its successor will reach the coast (still seaward of Langeoog in 2014) will be considerably larger. Part of the shoals and centroids by which the shoal migration rates were determined are shown in Fig. 8. Additionally, the displacement of the centroids of the shoals with a *red contour* (from 1987 to 1990), *cyan contour* (from 1998 to 1999), *orange contour* (from 2000 to 2005), *yellow contour* (from 2002 to 2006), *red contour* (from 2002 to 2010), *green contour* (from 2006 to 2010), and *magenta contour* (from 2011 to 2014) that are shown in the supplementary material was considered. The velocity was established at 304 m yr^{-1} (std: 103 m yr^{-1}).

3.1.4. Hörnum Inlet

The ebb-tidal delta seaward of Hörnum Inlet is characterized by relatively low morphodynamic activity. In the period from 1973 to 2014, the shoals on this delta barely migrated (Fig. 9). The

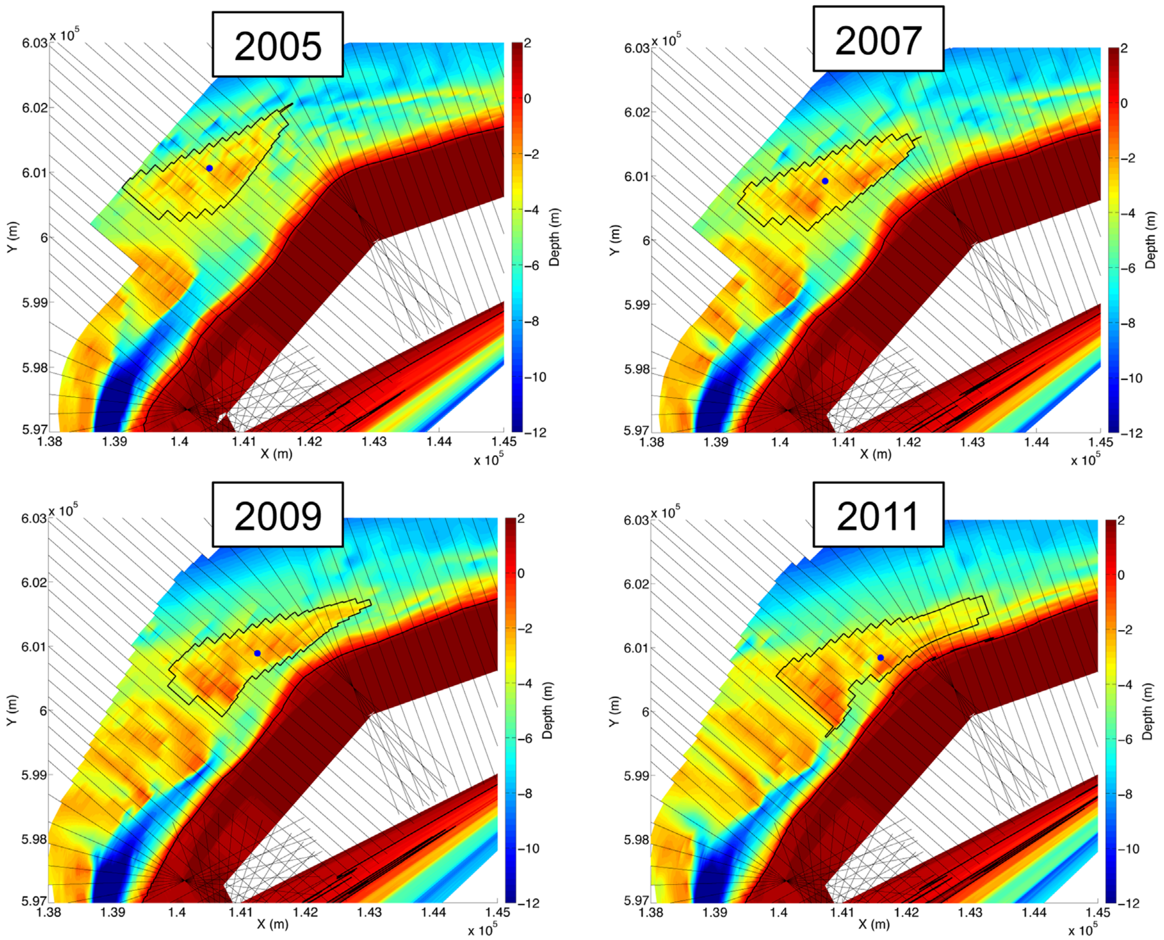

Fig. 6. The displacement of a shoal that attached to the downdrift coast of the Vlie Inlet in 2012 was manually tracked from 2005 to 2012; here four frames are shown. Its velocity was determined from the yearly displacement of its centroid (blue circle). (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this paper.)

attachment of shoals to the coasts adjacent to the inlet is not visible in the observed period. Therefore, the period between successive attachments is larger than 40 years.

3.2. *Relationships between morphodynamic and hydrodynamic characteristics*

The average period between successive attachments of shoals (P_S) observed on all ebb-tidal deltas is presented in Table 3. The number of bar migration events (N) that were used to compute this average is also presented. A value of P_S could not always be obtained because at some inlets less than two migrating shoals were observed within the period that observations are available. Table 3 also shows the average velocity of migrating shoals, V_S, and it is indicated whether the inlet consists of a single channel or multiple channels.

In Fig. 10 the average period between attachments of successive shoals is plotted against the tidal prism. This is done for all inlets for which a typical period was obtained in this study, as well as for the inlets considered by Gaudiano and Kana (2001). There is no significant relationship between P_S and the tidal prism when all observed inlets are considered ($R^2 = 0.28$), despite the fact that the best linear fit through all data points is close to the relationship that was found by Gaudiano and Kana (2001). A higher correlation coefficient ($R^2 = 0.88$) between P_S and the tidal prism is found when only considering inlets with a single channel in the inlet (dashed line in Fig. 10). This is because shoals that attach to the coast are generally formed close to the most downdrift channel on the ebb-tidal delta. This channel is located relatively close to the coast (considering the tidal prism) on ebb-tidal deltas that are located seaward of inlets that are composed of multiple channels (e.g., Osterems; Fig. 7). Consequently, shoals on such deltas travel a shorter distance and attach to the coast more frequently.

Fig. 11 shows P_S for the different inlets (in colors and numbers), together with their tidal prism and the local longshore sediment transport. Inlets with a single channel are indicated by circles. Surprisingly (given the fact that all shoals migrate in the downdrift direction), there is not a clear effect of the longshore sediment transport on P_S. However, it should be mentioned that variation in inlet geometries obscures the picture. The underlying problem is that there are not enough data to distinguish between the effects of all different parameters that possibly affect P_S, such as the tidal prism, longshore sediment transport, number of channels in the inlet, and offset of the downdrift islands.

In Fig. 12a the mean migration velocity of the shoals is plotted against the frequency at which the shoals attach to the coast ($1/P_S$). This velocity is larger at inlets where shoals attach to the coast more frequently, but the R^2 of the linear fit through these points is not high. The fastest migrating shoals are found on the ebb-tidal deltas of the East Frisian inlets. The circle that represents the migration velocity of shoals on the ebb-tidal delta of Knude Dyb is an outlier in this figure. Note that these shoals did not migrate to the coast, but to a large shoal located in the inlet (see supplementary material). Furthermore, the observed velocity of the shoals at Norderneyer Seegat in the period from 2002 to 2011 (246 m yr^{-1}) is relatively small, also compared to the 406 m yr^{-1}

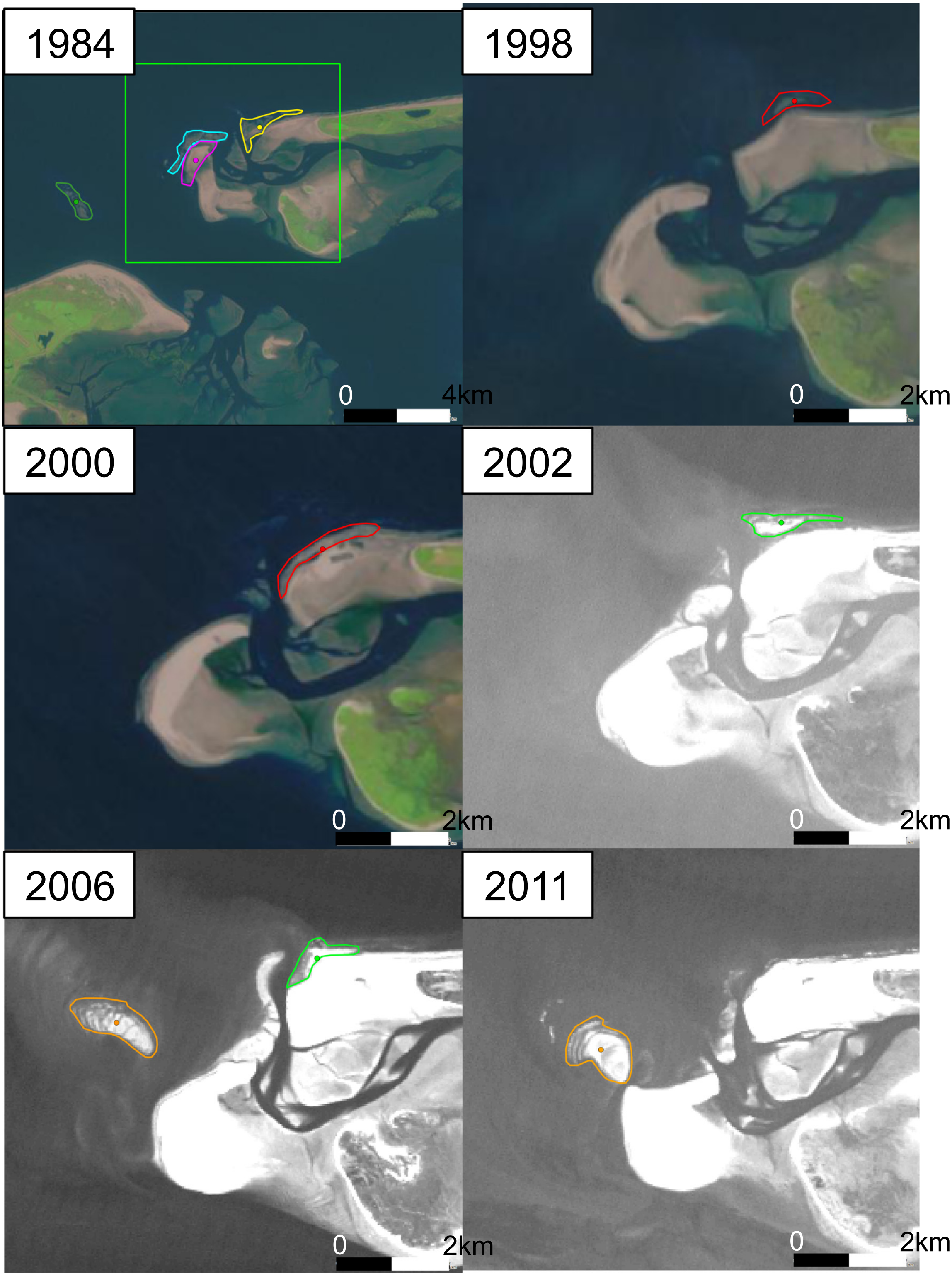

Fig. 7. Landsat images of the ebb-tidal delta seaward of Osterems, in different years. They reveal migrating shoals that originate from the ebb-tidal delta, which are marked by colored polygons. Their centroid is indicated by circles in corresponding colors. The green rectangle in the first frame indicates the region that is visualized in the subsequent frames. In the observed period, shoals attached to the island Juist around 1990 (*yellow contour*), 2000 (*red contour*) and 2006 (*green contour*). Meanwhile, also shoals that migrate towards the inlet are observed. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this paper.)

that was observed for the period from 1926 to 1957 by Homeier and Kramer (1957) (in Nummedal and Penland, 1981). Finally, note that the velocity of the shoal migrating to Borkum (84 m yr^{-1}) is not displayed in Fig. 12a because P_S could not be determined for this inlet. In Fig. 12b the velocity of the migrating shoals is plotted against the tidal prism of the inlets. It appears that the migration velocity of shoals decreases with an increasing tidal prism. This relationship is more convincing when only inlets that consist of a single channel are considered. The shoals migrating seaward of Texel Inlet and Westerems migrate significantly slower than the other shoals observed. This was already recognized by Ehlers (1988), who referred to them as mega shoals.

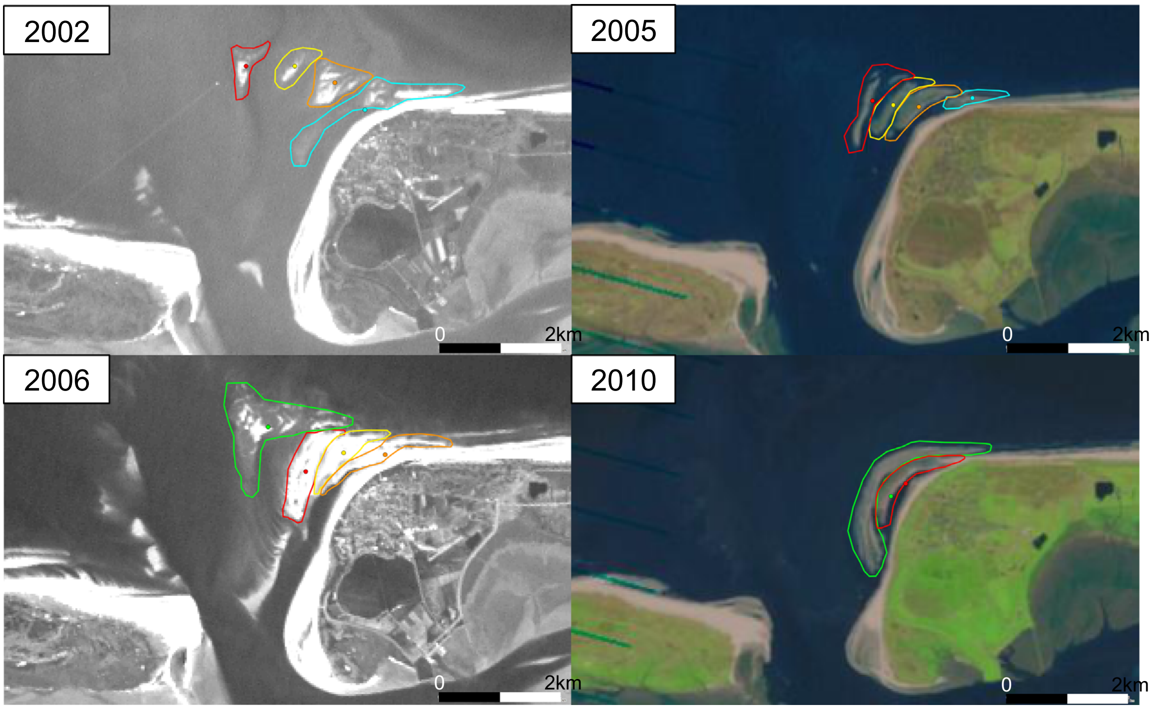

Fig. 8. Landsat images of the ebb-tidal delta seaward of Accumer Ee, in different years. They reveal migrating shoals that attached to the coast of Langeoog in the period from 2003 to 2010, which are marked by colored polygons. Their centroid is indicated by the circles in corresponding colors. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this paper.)

4. Discussion

Many ebb-tidal deltas seaward of inlets along the Wadden Sea exhibit migrating shoals. The associated inlets can be divided into two categories. The first involves shoal behavior that is described by the conceptual models presented by FitzGerald (1982). Shoals that migrate to the coast downdrift of the inlet form in the vicinity of the dominant ebb-channel on the ebb-tidal delta (e.g., Accumer Ee). This channel is often the extension of the only channel present in the inlet. The second category covers shoals that form in the vicinity of a secondary channel that is located closer to the downdrift coast (e.g., Vlie Inlet and Osterems). The latter occurs at tidal inlets that contain multiple channels.

Compared to the inlets studied by Gaudiano and Kana (2001), the inlets of Wadden Sea have a larger tidal prism (except Wichter Ee). Furthermore, the average period between successive attachments of shoals to the downdrift coasts is similar at the East Frisian inlets and larger at the other inlets. In agreement with that study, the data suggest that a larger P_S occurs for inlets with a larger tidal prism, but only for inlets that are composed of a single channel. At inlets with multiple channels the period seems to be smaller than at inlets with a single channel. This is because sand is temporarily stored in between the channels, and the presence of a secondary channel in the inlet causes shoals to form closer to the coast. The inlets with multiple channels are characterized by a relatively high width-to-depth ratio compared to the single channel inlets. Other parameters, such as the offset of the downdrift islands (large at e.g., Accumer Ee and Otzumer Balje), and the longshore sediment transport probably also affect P_S. However, to discriminate between the effects of all different parameters more data than presently available are required. Therefore, the results of this study call for a modelling study of migrating shoals on ebb-tidal deltas, in which the effects of the tidal prism, aspect ratio of the inlet, local sand supply, and the longshore sediment transport on P_S can be studied independently. The findings support the theory of FitzGerald (1988), who noted that the time required for shoals to migrate onshore is strongly affected by the distance between the location at which the shoals form and at which they attach to the coast.

Consecutive migrating shoals were not observed along the North Frisian inlets. This also holds for Hever Inlet, where shoals are only visible close to the moment that they attach to the coast. Due to the local large tidal range, the North Frisian inlets are located relatively close to each other (Hayes, 1975). As a consequence, their ebb-tidal deltas partly overlap and the region in which shoals could potentially form and migrate to the coast is influenced by tidal currents of adjacent inlets. Also, the local incident wave energy is considerably lower than that at the West and East Frisian inlets and the ebb-tidal deltas have a tide dominated morphology (Carr-Betts et al., 2012). Such systems are not captured by conceptual models for sediment bypassing in the form of migrating shoals because these models consider mixed energy inlets (FitzGerald, 1988; FitzGerald et al., 2000). Furthermore, Hörnum and Amrum Inlet have a large tidal prism, and the absence of migrating shoals within the observed period could thus be because the local hydrodynamics is tide dominated or because the period between successive shoals is larger than the period observed.

Time gaps in bathymetric data and satellite images are a cause of uncertainty in determining the exact moment of shoal attachment, hence in P_S. But, the impact of this uncertainty on P_S decreases when multiple shoals are considered. The time gaps have a smaller impact on the computed migration velocity, since the speed is determined each time slice and only the average of all observed velocities is considered. Note that in cases that a standard deviation could not be determined, an error bar of 30% was added to Figs. 10 and 12 and that some shoals were omitted from the analysis to decrease the uncertainty. More details on which shoals were considered to obtain P_S and the migration velocity are presented in the supplementary material.

At Accumer Ee and Otzumer Balje it was sometimes difficult to discriminate successive shoals from each other, as they overtake

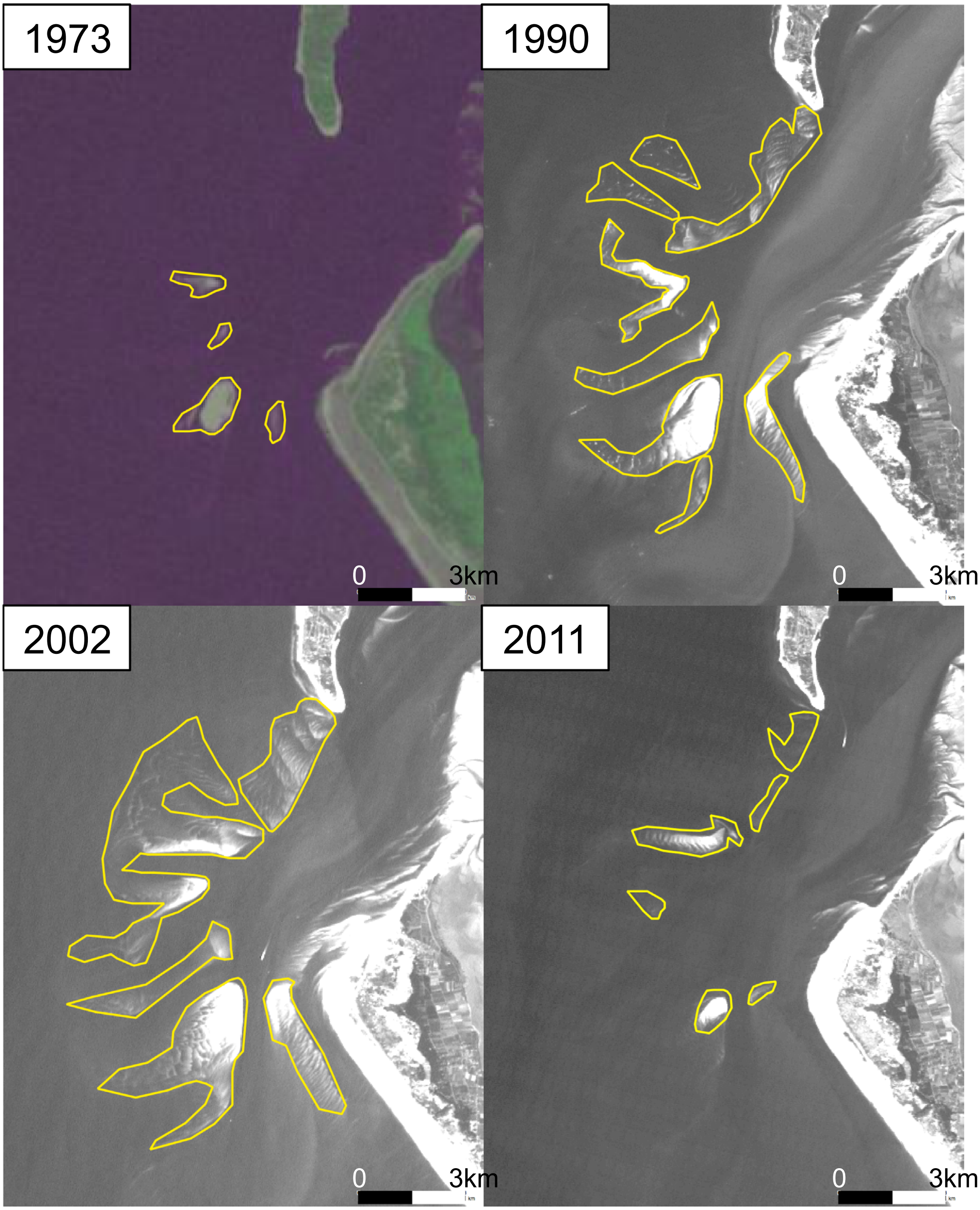

Fig. 9. Landsat images of the ebb-tidal delta seaward of Hörnum Inlet, in different years between 1973 and 2011. Shallow areas are indicated by yellow polygons. In the observed period, migrating shoals that attach to the coast are not observed. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this paper.)

each other, merge, and attach to the shore simultaneously. This is a result of the short time-span between successive shoals and the fact that their migration velocity often decreases when the shoals get closer to the coast. The latter was already recognized by FitzGerald (1988), who stated: "As swash bars move up the shoreface, they gain a greater intertidal exposure. Thus, flood tidal and wave-generated currents, which cause the bars' onshore migration, operate over an increasingly shorter period of the tidal cycle. This decelerates the bars' onshore movement leading to a stacking and coalescing of individual bars."

The longshore transport rates presented in this study are rough estimates calculated with the CERC formula. This formula assumes a straight coast without interruptions, and does not account for the slope of the beach or the sediment grain size (e.g., Kamphuijs, 1991). Also, note that the presented estimates strongly depend on the defined orientation of the coast. More details on how the estimate of the longshore transport rate are obtained is given in the online supplementary material.

In addition to tidal prism and wave energy, ebb-tidal deltas can also be effected by dredging activity. For example, the inlet channel at Grå Dyb is heavily dredged to provide access to Esbjerg Harbor. Furthermore, seaward of Harle Inlet the bathymetry is

Table 3
For each Wadden Sea inlet the average period between successive shoal attachments (P_S), velocity of the migrating shoals (V_S), their respective standard deviations [std], number of bar migration events observed (N), and if the inlet consists of a single (S) or multiple (M) channels is given. Part of this data was found in literature: (1) Elias and Van der Spek (2006), (2) Sha (1989a), and (3) Israel and Dunsbergen (1999).

Inlet	P_S [std] (yr)	V_S [std] (m yr^{-1})	N	S/M
Texel Inlet[a]	130 [42][(1)]	67 [–][(2)]	2[(1)]	S
Eierlandse Gat	6 [0.9]	230 [85]	3	M
Vlie Inlet	16 [4.5]	212 [69]	3	M
Ameland Inlet	59 [–][(3)]	226 [68]	1[(3)]	S
Pinkegat	9 [2.6]	292 [93]	4	M
Zoutkamperlaag	26 [4.6][b]	314 [144][c]	3[b]	S
Westerems	>28 [–]	84 [32]	0	S
Osterems	8 [2.8]	–	2	M
Norderneyer Seegat	5 [–]	246 [59]	2	M
Wichter Ee	4 [1.5]	351 [83]	3	S
Accumer Ee	4 [0.8]	304 [103]	4	S
Otzumer Balje	10 [0]	186 [100]	2	S
Harle Inlet	5 [–]	340 [147]	1	S
Hever Inlet	21 [7]	–	2	M
Schmaltief	>20 [–]	–	0	M
Amrum Inlet	>20 [–]	–	0	M
Hörnum Inlet	>40 [–]	–	0	S
Lister Dyb	?	–	0	S
Juvre Dyb	>15 [–]	–	0	S
Knude Dyb[d]	8 [2.1][d]	103 [31][d]	3	M
Grå Dyb	8 [1]	–	3	M

[a] Before 1932.
[b] Before 1969
[c] After 1969
[d] Observed shoals attached to a shoal inside the inlet.

affected by the Elbe mouth, which affects the local hydrodynamics. Moreover, the ebb-tidal deltas of Texel Inlet, Vlie Inlet, and Zoutkamperlaag were strongly affected by human interventions in the Wadden Sea (Elias et al., 2012; Biegel and Hoekstra, 1995). The presented characteristics of Texel Inlet represent pre-intervention conditions. Except for the shoal velocity, the same applies to Zoutkamperlaag. Interestingly, in contradiction to what was stated by Oost (1995), after the intervention migrating shoals are still present on the ebb-tidal delta of Zoutkamperlaag. The morphology of Harle Inlet is affected by a ~1.5 km long jetty located in the inlet that was constructed to protect the western coast of Wangerooge. Finally, some channels on ebb-tidal deltas are more or less fixed at their position because they are scoured into resistant sediment layers. It is known that this affected the morphology of Norderneyer Seegat, Accumer Ee and Lister Dyb (FitzGerald and Penland, 1987; Lindhorst, 2007). It is not known to what extent this influences the channels and shoals on the ebb-tidal deltas.

Similar shoals as those which periodically attach to the large shoal in Osterems and Knude Dyb, periodically attach to the mega shoal located seaward of Texel Inlet. Such shoals that attach to larger shoals on ebb-tidal deltas are also observed at Arcachon Inlet where shoals periodically migrate from the upper to the lower delta (Capo et al., 2014). A crucial difference between the ebb-tidal deltas seaward of Texel Inlet and Knude Dyb on the one hand, and Osterems and Arcachon Inlet on the other hand is that only at the latter two deltas, also shoal migration from the mega shoals to the adjacent coast is observed ($P_S \sim 8$–10 yr). This difference is possibly related to the much smaller net longshore sediment transport at Knude Dyb and Texel Inlet compared to that at the other two inlets. It is possible that larger shoals migrate on the ebb-tidal deltas on longer time scales. In this respect, FitzGerald (1988) stated that “at inlets that bypass sand through ebb-tidal delta breaching, small bar complexes may form and migrate onshore between major ebb-tidal delta breaching events”.

In the analysis presented in Section 3.2, data obtained for the

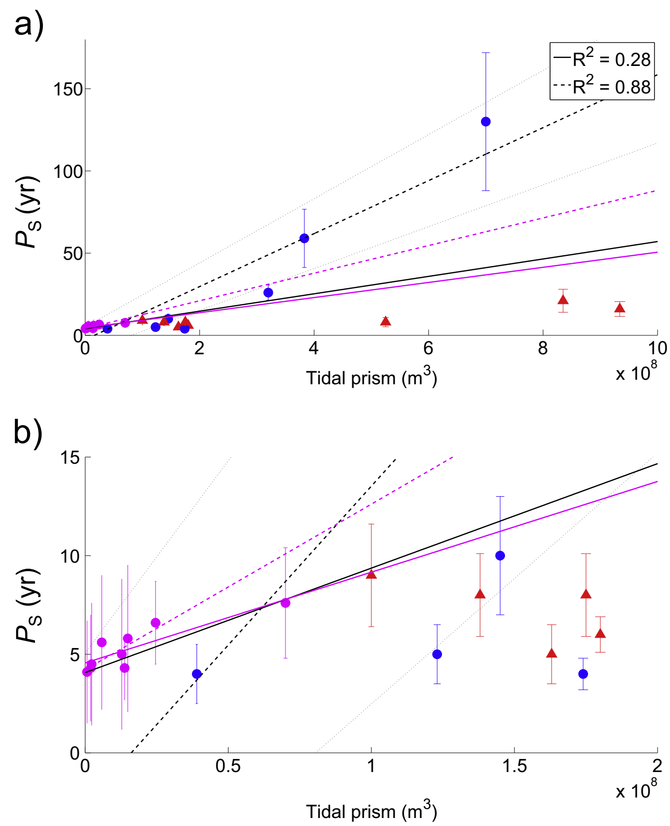

Fig. 10. Period between successive attachments of shoals plotted against the tidal prism. Panel (b) shows a zoom of the lower part of the domain displayed in panel (a). Error bars indicate the standard deviation. Wadden inlets with a single (multiple) channel(s) in the inlet are indicated by *blue circles* (*red triangles*). *Magenta circles* indicate the Gaudiano and Kana (2001) inlets. The *black solid line* gives the linear fit for all data points. The *black dashed line* gives the linear fit for the inlets with a single channel in the inlet, and the *black dotted lines* give the 95% confidence interval of this regression. Finally, the *solid* (*dashed*) *magenta line* shows the relationship found by Gaudiano and Kana (2001) including (excluding) Stono Inlet, which they identified as a possible outlier. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this paper.)

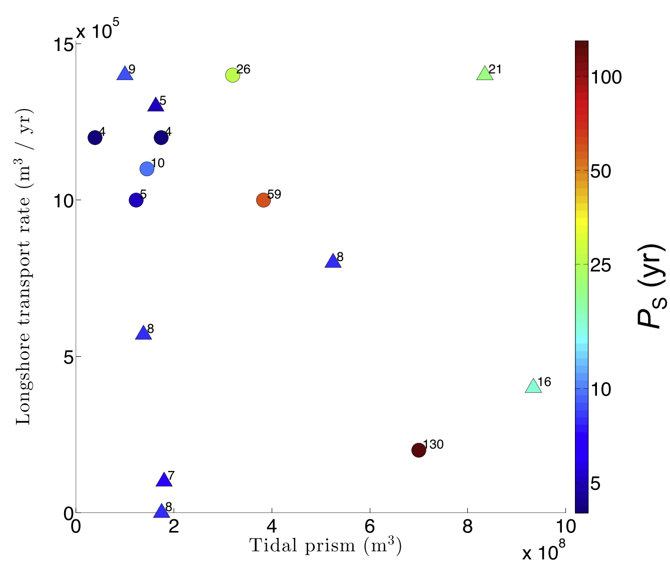

Fig. 11. Dependence of the period between successive attachments of shoals (indicated by the color of the symbols, and the numbers) on the tidal prism and the longshore sediment transport. Inlets with a single (multiple) channel(s) in the inlet are indicated by *circles* (*triangles*). (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this paper.)

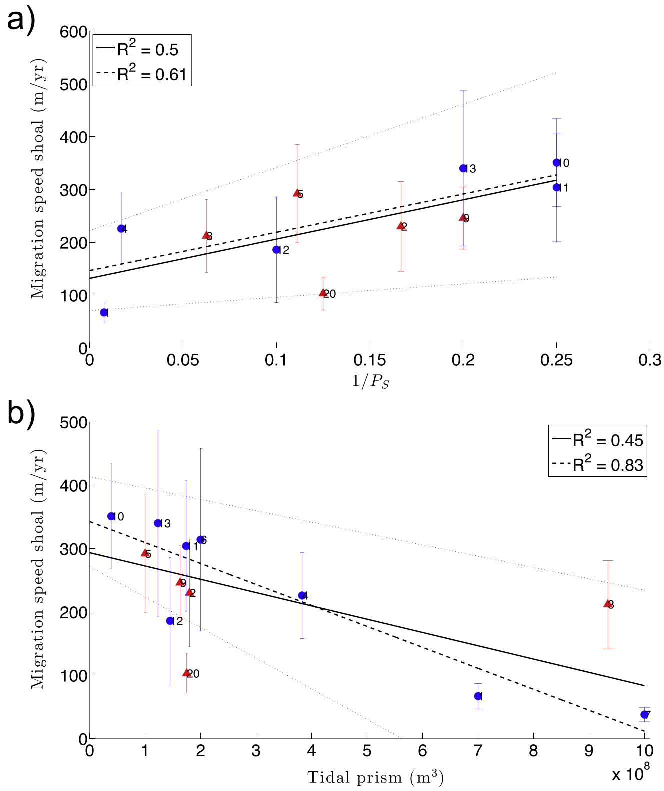

Fig. 12. Mean migration velocity of the shoals (error bars indicate the standard deviation) plotted against (a) the frequency at which shoals attach to the coast and (b) the tidal prism. The *solid* line shows the best linear fit through all data points. The *dashed lines* show the best linear fit through the data points that represent inlets with a single channel (indicated with blue circles). The *dotted lines* show the 95% confidence interval of the regressions that are shown by the *dashed lines*. The numbers indicate the representative inlets and correspond to Fig. 1. Note that the migration velocity of shoals at the Zoutkamperlaag is only plotted in panel (b) as it was determined for shoals migrating after the closure of the Lauwerszee in 1969. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this paper.)

ebb-tidal deltas of the Wadden Sea were combined with data obtained by Gaudiano and Kana (2001). For various reasons, it was decided not to include other ebb-tidal deltas for which a typical time scale between successive shoals was found in literature. These are, the ebb-tidal delta of Willopa Bay, where outer delta breaching occurs ($P_S \sim 16$ yr) (Hands and Shepsis, 1999), which was excluded because the bypassed sand does not form a shoal that attaches to the coast downdrift of the inlet (FitzGerald et al., 2000). The Irish ebb-tidal deltas described by O'Connor et al. (2011) and that of Teignmouth were excluded because their morphology is influenced by headlands, the effect of which is beyond the scope of this study. The ebb-tidal delta of Deben Inlet was excluded because it is built up of coarse sediment. New Inlet, Cape Cod could not be included because its tidal prism was not found. Finally, it was decided that adding only the ebb-tidal delta of Essex Inlet to Fig. 10 would make the analysis less clear. Of the above mentioned tidal inlet systems, only that of Essex Inlet and Teignmouth, which have a P_S and tidal prism that are both comparable to that of the inlets studied by Gaudiano and Kana (2001), would not significantly alter the results of the regression analysis that is presented in the previous section.

5. Conclusions

Bathymetric profiles and satellite images were studied to assess the cyclic behavior of shoals on the ebb-tidal deltas seaward of all inlets of the Wadden Sea. It was investigated whether there is a relationship between both the migration velocity of the shoals and the period between successive attachments of shoals to the coast downdrift of an inlet, and the tidal prism and longshore sediment transport.

Shoals that migrate towards the coast of the downdrift island were found on all studied ebb-tidal deltas of the West and East Frisian Islands and at some of the ebb-tidal deltas of the North Frisian Islands and Danish Wadden Islands. The average period between successive attachments of these shoals varies between 4 and 130 years.

Two distinctive classes of ebb-tidal deltas were identified that differ in the amount of channels that is present in the adjacent tidal inlets. For inlets with a single channel, the data analysis indicates that a larger tidal prism leads to a larger period between successive shoals and a slower migration velocity of shoals on ebb-tidal deltas. Shoals on ebb-tidal deltas seaward of wide inlets with multiple channels do not obey this relationship because these shoals are formed relatively close to the coast. Finally, there is a positive relationship between the migration velocity of the shoals and the frequency with which they attach to the coast. The data were too sparse to assess whether the longshore sediment transport has a dominant effect on the period between successive shoals that attach to the coasts downdrift of the observed tidal inlets.

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Appendix A. Supplementary data

Supplementary data associated with this paper can be found in the online version at http://dx.doi.org/10.1016/j.csr.2015.12.014.

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