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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.

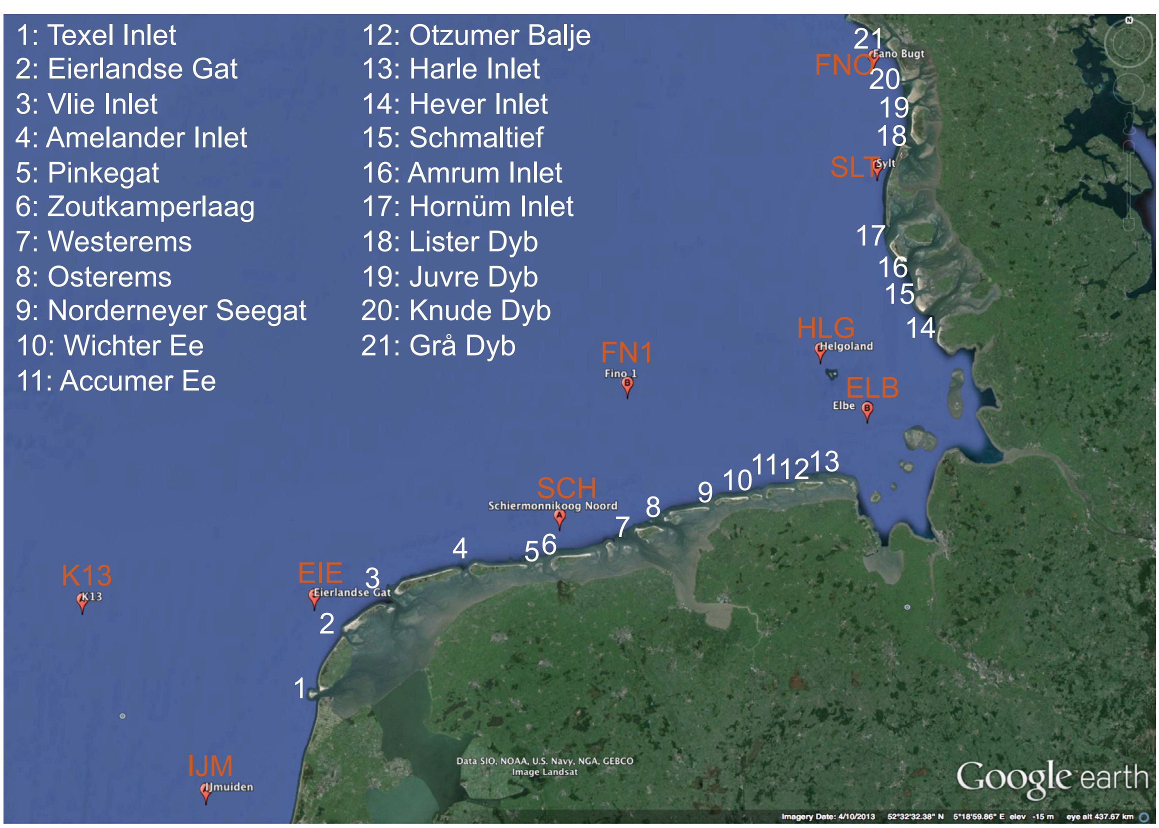

Fig. 1. Map of the study area, including the names of the inlets considered in this study. Furthermore, the locations of the wave stations presented in Table 1 are indicated.