Kubicki, Adam; Kösters, Frank; Bartholomä, Alexander

Dune convergence/divergence controlled by residual current vortices in the Jade tidal channel, south-eastern North Sea

Erstveröffentlichung in Geo-Marine Letters; Vol. 37; Heft 1; Seite 47-58
Für eine korrekte Zitierbarkeit ist die Seitennummerierung
der Originalveröffentlichung für jede Seite kenntlich gemacht.

S. 47

Dune convergence/divergence controlled by residual current vortices in the Jade tidal channel, south-eastern North Sea

Adam Kubicki[1] Frank Kösters[2] Alexander Bartholomä[1]

Reference

doi:10.1007/s00367-016-0470-6 Electronic supplementary material
The online version of this article contains supplementary material,
which is available to authorized users. Published Online: 05. October 2016

Abstract

A field of large to very large subaqueous dunes was investigated in the Jade tidal channel, south-eastern North Sea, between January 2006 and October 2011. A ground-truthed sidescan sonar sediment map shows that the dunes, which are located on top of a consolidated clay surface, are composed of medium to coarse sand. A series of 35 consecutive high resolution bathymetric surfaces collected by multibeam echosounder revealed a complex migration pattern induced by the reversing tidal currents. Various parts of the dune field are under the influence of either ebb- or flood-dominated currents, as indicated by dune asymmetries. Although some dunes migrate at a pace exceeding 100 m/year, the majority are displaced by 30 m/year in the direction of the locally dominant current. In the deepest part of the channel, however, dunes were o bserved to converge head-on, resulting in practically zero net transport with minor oscillations of symmetrical dunes at the apex. Applying the numerical UnTRIM model for the simulation of the fair-weather hydrology, a simplified map of residual current vectors over the dune field was generated. The residual flow vectors are found to perfectly match the derived dune migration vectors, suggesting that dune convergence is controlled by two counter-rotating residual current vortices caused by the local shape of the tidal channel. As no sediment build-up is observed, a mechanism of sediment bypassing with potential recirculation must exist, but has not yet been identified.

Introduction

Subaqueous dunes, called also marine sand waves, are one of the most fascinating sediment ary features on continental shelves. They are defined as flow-transverse bedforms with wavelengths exceeding 0.6 m and heights greater than 0.075 m (Ashley1990). It is well documented that dune morphologies tend to adjust to changing hydrological conditions until a dynamic equilibrium is reached. Their shapes and dimensions reflect the interaction between critical current velocities, water depth, grain size and sediment availability, the relationships between these parameters applying equally to unidirectional currents (rivers, geostrophic flows) and reversing tidal currents (e.g. Flemming 1988, 2000; Mazumder 2003;Bartholomäetal. 2008; Carle and Hill 2009;Van Landeghem et al. 2012). In general the dune asymmetry indi-cates the direction of the prevailing current, but antiasymmetry migration has been also reported (Hanes 2012). In the case of periodically reversing flows, the symmetry/ asymmetry of the dunes is, in addition, controlled by the ratio between the local flood and ebb flow velocities which, in simplified form, is also expressed in the residual tidal flow pattern. Moreover, local seabed topography can greatly influence the flow pattern, especially in meandering channels (Hughes 2012).

The combination of complex topography, water level changes and reversing currents produces dune fields which are commonly separated into flood- and ebb-dominated regions (e.g. Belderson et al. 1978 ;Harris 1988 ; Harris et al. 1995 ; Gonzales and Eberli 1997 ; Fenies and Faugères 1998 ;

Kubicki, Kösters, Bartholomä: Dune convergence/divergence controlled by residual current vortices in the Jade tidal channel, south-eastern North Sea. S. 48
Geo-Marine Letters; Vol. 37; Heft 1; Seite 47-58

Bates and Oakley 2004; Carle and Hill 2009; Kubicki and Bartholomä 2011; Van Landeghem et al. 2012). The line separating the ebb- and flood-dominated parts is called the zone of zero net transport, also known as a bedload convergence zone. This line is mostly sharp and only in rare cases accompanied by symmetrical dune bodies (e.g. Le Bot and Trentesaux 2004; Barnard et al. 2006; Gómez et al. 2010; Fraccascia et al. 2016), let alone head-on dune convergence (e.g. Van Landeghem et al. 2012). The flow conditions triggering the head-on convergence has to date not been fully explained, potential control by local residual current vectors having been hypothesized but not verified in the field (Idier et al. 2011).

In the course of the present study, physically converging dunes discovered in the Jade tidal channel (Kubicki and Bartholomä 2011), south-eastern North Sea, presented an ideal opportunity to further investigate the underlying mechanisms of bedload convergence/divergence. The dune field was monitored for 6 years (January 2006–October 2011) by repetitive multibeam echosounding accompanied by sidescan sonar mapping calibrated by grab samples in the closing 12 months. In order to understand the characteristic distribution of residual current vectors, a numerical model was applied to simulate the local hydrology—a method already utilised in the 1970s (e.g. Tee 1976). Numerical modelling of local hydrology allows a physically consistent but spatially larger, synoptic view of residual current vectors than can be achieved by in situ measurements (Li et al. 2008). In the past, such modelling was not only limited because of insufficient computing power but often also tended to fail in reproducing true current magnitudes due to insufficient data on seabed topography (Hanes 2009). This situation changed dramatically as computing power increased and bathymetric data acquisition exploded by the development of multibeam echosounders for seabed mapping as well as LiDAR techniques for mapping the topography of intertidal areas. Nonetheless, in spite of the improvement in computing power and numerical models (e.g. Castro Díaz et al. 2008), there exists no universal modelling approach to reproduce accurately the interaction of fluid flow and sediment transport in dynamic shallow-water environments (Van Rijn et al. 2013). Therefore, numerical hydrological modelling often still acts as an aid in morphodynamic studies, rather than being the base of it (e.g. Fraccascia et al. 2016).

Investigations of seabed dynamics therefore still depend on repetitive in situ measurements of local topography. The monitoring period of subaqueous dunes commonly spans periods ranging from a few months (e.g. Whitmeyer and FitzGerald 2008) to at least 15 years (Zorndt et al. 2011). In view of this, the period covered in the present study can be considered as medium-term. The numerical modelling of the local hydrology was applied for a 2-week period to cover a complete spring–neap tidal cycle. The specific aims of the present study were (1) to document, for the first time, dune head-on convergence in a large tidal channel at high temporal and spatial resolution, and (2) to provide a plausible explanation of the mechanism controlling this phenomenon.

Physical setting

The Jade is a 50-km long, slightly meandering tidal channel located in the south-eastern German Bight. It is a natural waterway to the harbours of Wilhelmshaven, which include the largest German naval base and the easternmost deep-water container terminal in the North Sea, the Jade Weser Port. Due to its economic and military importance, the Jade fairway is monitored at monthly intervals by the German authorities to ensure the required water depth of 17.6 m below SKN_{LAT} (marine chart datum corresponding to the lowest astronomical tide; Götschenberg and Kahlfeld 2008). The time span between the surveys is never longer than 1 month. To maintain the design depth, the fairway is regularly dredged, the dredge spoil being subsequently deposed at designated dump sites near the mouth of the Jade in proximity to the study site. The semi-diurnal tides ranging from 2.8 m in the north to 3.8 m in the south (Götschenberg and Kahlfeld 2008)trigger maximum tidal current velocities exceeding 1.5 m/s (Grabemann et al. 2004). The tidal wave is uniformly distributed across the channel width, and no obvious stream core exists during either flood or ebb tide (Kahlfeld and Schüttrumpf 2006).

The area of interest covers ca. 14 km^2 and is situated in the northern part of the Jade between the islands of Minsener Oog and Oldoog in the west and the lighthouse Mellumplate in the east (Fig. 1). It covers a channel width of ca. 3.2 km and includes both channel flanks up to a water depth of 5 m below SKN_{LAT} . The eastern flank in the vicinity of the lighthouse is used as a dump site for the dredge spoil from the navigation channel. Over 11 million m^3 of sediment were disposed of here between 1994 and 2001 (BfG/WSA 2003). No official reports on dumping volumes are available after this period, although the site continued to be utilised. Kubicki and Bartholomä (2011) calculated that there has been a surplus of ca. 0.13 m/m^2 of sediment in the deepest investigated section of the channel of the Jade fairway between 2005 and 2010. If the value holds true for the entire area of interest, a further 1.8 million m^3 could have been dumped in this period.

Materials and methods

During the measuring campaigns in October 2010, April 2011 and October 2011, a Reson SeaBat 8125 multibeam echosounder was deployed simultaneously with a Benthos SIS-1624 sidescan sonar onboard RV Senckenberg

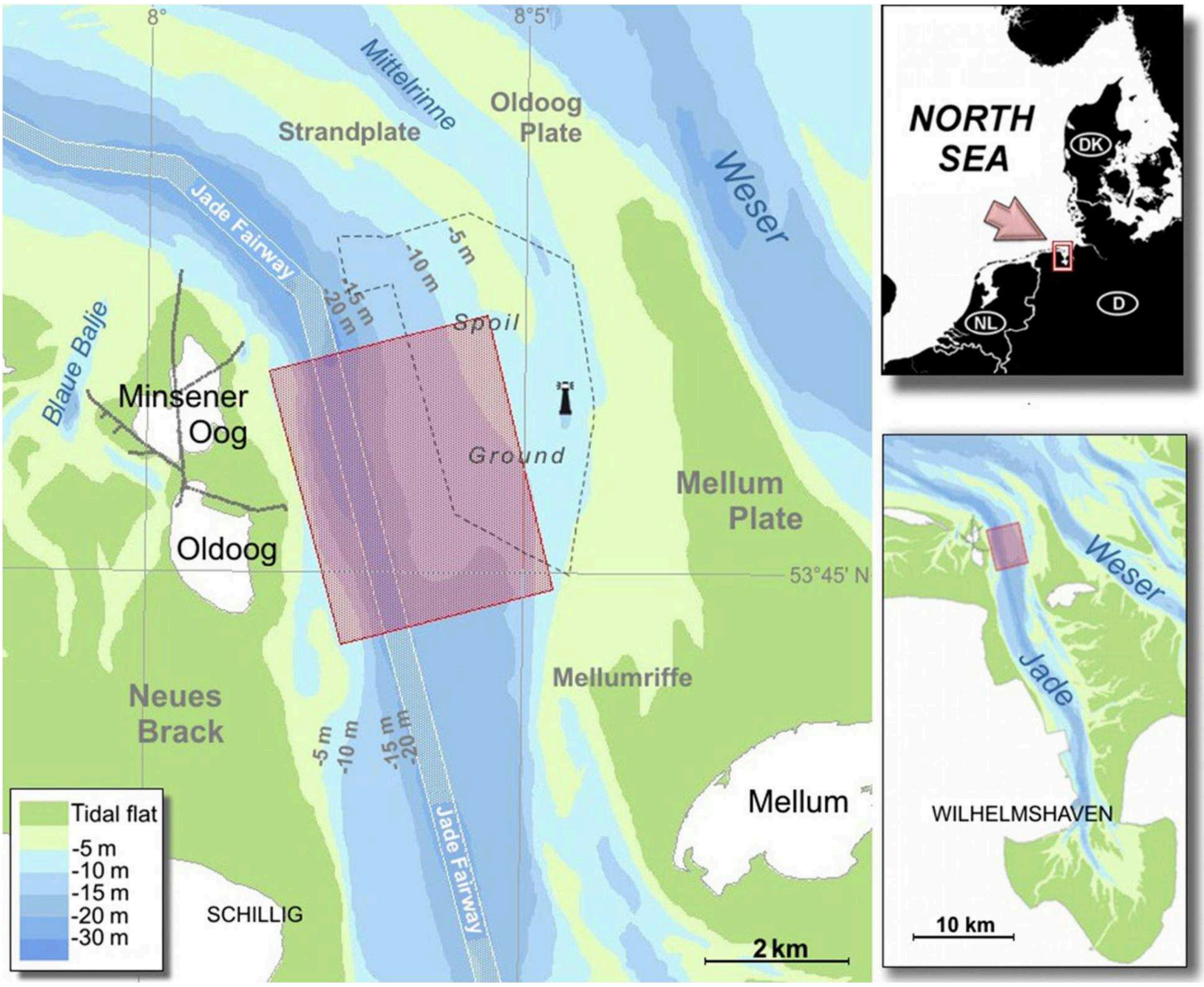

Fig. 1 Location of the study area in a meander of the Jade tidal channel

(Table 1). The survey area was expanded compared to earlier studies in this region (Kubicki and Bartholomä 2011) in order to also investigate the eastern flank of the Jade tidal channel and the vicinity of the Mellum lighthouse up to a water depth of 5 m, which is the vessel's safe under-keel clearance. The Reson SeaBat 8125 multibeam echosounder operating at 455 kHz was interfaced with a Magellan Aquarius 5002 Long Range Kinematic Global Navigation Satellite System. This configuration achieves vertical and lateral accuracies of better than 0.05 m (Ernstsen et al. 2006). The echosounder has a fixed recording swath width of about three times the water depth, which is considerably smaller than that recorded by sidescan sonar.

The Benthos SIS-1624 sonar, a dual-frequency system scanning at 123 and 382 kHz with along- and across-track resolution of better than 0.1 m, was set to record a 200-m wide swath. Full spatial coverage of the area was therefore achieved only by the sidescan sonar, whereas the bathymetric swaths were separated by regular gaps. This was visible especially in the shallow water, where many more multibeam tracks were needed to achieve full data coverage, but were not measured due to the limited timeframe of the campaigns. After each measuring campaign, the bathymetry and backscatter datasets were spatially matched in ArcGIS in order to manually delineate the crests of dunes higher than 1m, which are here referred to as large dunes sensu Ashley (1990). This dune height limit was arbitrarily chosen to ensure identification of individual dune crests even

Table 1 Summary of in situ data used in this study in various measuring campaigns (MBESmultibeamechosounder, SSS sidescan sonar, SES sediment echosounder)

	Atlas Fansweep 20-200 MBES	Reson SeaBat 8125 MBES	Benthos SIS-1624 SSS	Shipek sampler	Innomar SES-2000
January 2006–October 2010	32 pcs.				
February 2010 (Kubicki and Bartholomä 2011)				36 pcs.	
October 2010		1 pc.	1 pc.	51 pcs.	
April 2011		1 pc.	1 pc.	31 pcs.	
August 2011					1 pc.
October 2011		1 pc.	1 pc.		

Kubicki, Kösters, Bartholomä: Dune convergence/divergence controlled by residual current vortices in the Jade tidal channel, south-eastern North Sea. S. 50
Geo-Marine Letters; Vol. 37; Heft 1; Seite 47-58

after time intervals of 6 months. Smaller dunes migrate faster and individual crests can therefore no longer be traced at the chosen time interval. The crests of large dunes were also clearly recognisable on sonographs due to morphology-induced contrasts in backscatter records. This allowed delineating crests even where swath bathymetry lacked coverage.

The monthly bathymetric surveys for fairway monitoring performed by the WSAWilhelmshaven were carried out with an Atlas Fansweep 20-200 multibeam echosounder. This system operates with a frequency of 200 kHz and achieves a vertical accuracy of 0.05 m ±0.2 % of the water depth. These surveys were limited to the actual fairway width of ca. 300 m. In order to also monitor the area adjacent to the fairway, the lateral survey width was increased twice a year. After identifying sites requiring dredging, the bathymetric data were converted to a regularly spaced grid of 2 m and archived. For the purpose of the present study, 32 available datasets collected between January 2006 and October 2010 were used (see Fig. 2a, location A). Based on these data, digital terrain models (DTMs) were generated for time intervals spanning periods of 2 weeks to 7 months between individual surveys. After assigning the same colour scale to the bathymetry values, a 32-frame movie was generated which highlighted any changes in the lateral positions of the large to very large dunes in the survey area (see Electronic supplementary material available online for this article).

In addition, a sediment distribution map was compiled after calibrating the sidescan backscatter intensities recorded in October 2010 with 118 Shipek grab samples collected between February 2010 and April 2011 (Table 1). Such a calibration was adequate due to a surprising stability of the sediment distribution map observed in consecutive sonographs (Fig. 3). The sediment

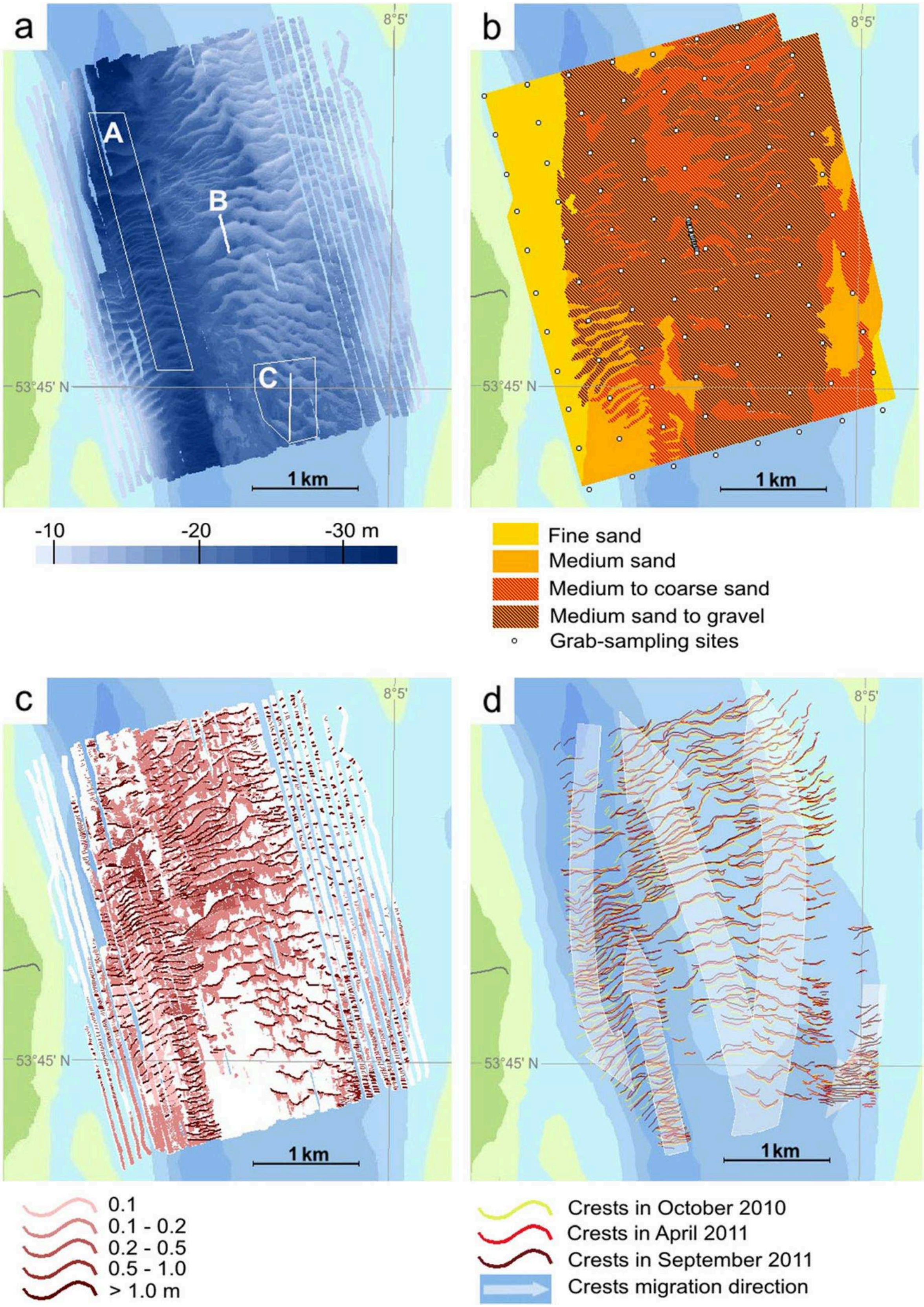

Fig. 2 Sedimentological and morphological data from October 2010 overlain by simplified bathymetry (cf. Fig. 1). a Highresolution bathymetry recordedby multibeam echosounder. B Sediment map derived from sidescan sonar records. C Bedforms with crests of different heights

marked by different colours. d Crest positions of the largest dunes in October 2010, April 2011 and September 2011, and vectors marking the change

Kubicki, Kösters, Bartholomä: Dune convergence/divergence controlled by residual current vortices in the Jade tidal channel, south-eastern North Sea. S. 51
Geo-Marine Letters; Vol. 37; Heft 1; Seite 47-58

samples were analysed in the laboratory after standard desalting by dialysis and separating the volume into gravel, sand and mud fractions. Gravel fractions (grain size >2 mm) were sieved mechanically, whereas the sand fractions (grain sizes between 2mm and 63 µm) were analysed by a settling tube (MacroGranometer; Brezina 1979) and the mud fractions (grain sizes <63 µm) by a Sedigraph III (Micromeritics, Inc.). The results were combined into grain-size distribution plots at quarter-phi intervals. Sediment patches identified on sonographs were classified according to the primary composition of the majority of sediment samples collected within given patch areas following the Udden-Wentworth classification scheme (Wentworth 1922).

Water levels and flow velocities of the Jade-Weser estuary were simulated with the UnTRIM modelling system. UnTRIM (Casulli and Zanolli 2005) uses a finite volume–finite difference method which solves the momentum and transport equations on a horizontally unstructured grid. It was set up threedimensionally with a spatial resolution of about 200 m by 300 m over the study area and a vertically constant resolution of 1 m. Thus, individual dunes are not resolved by the model, which instead simulates the overall flow regime of the Jade. Roughness is taken to be mainly due to spatially uniform small-scale ripples. The overall model topography represents the year 2002 based on echosounding and LiDAR data (data provided by the Federal Waterways and Shipping Administration, BAW, and the Federal Maritime and Hydrographic Agency, BSH) but was updated in the study area with more recent measurements from October 2010. Themodel is set up as a process study with application of realistic forcing. Wind stress at the surface was obtained from the operational German National Meteorological Service (DWD) weather forecast model (COSMO/LM, e.g. Doms et al. 2002). At the lateral open sea boundaries, water levels from a BAW measurement campaign in June 2002 were prescribed.

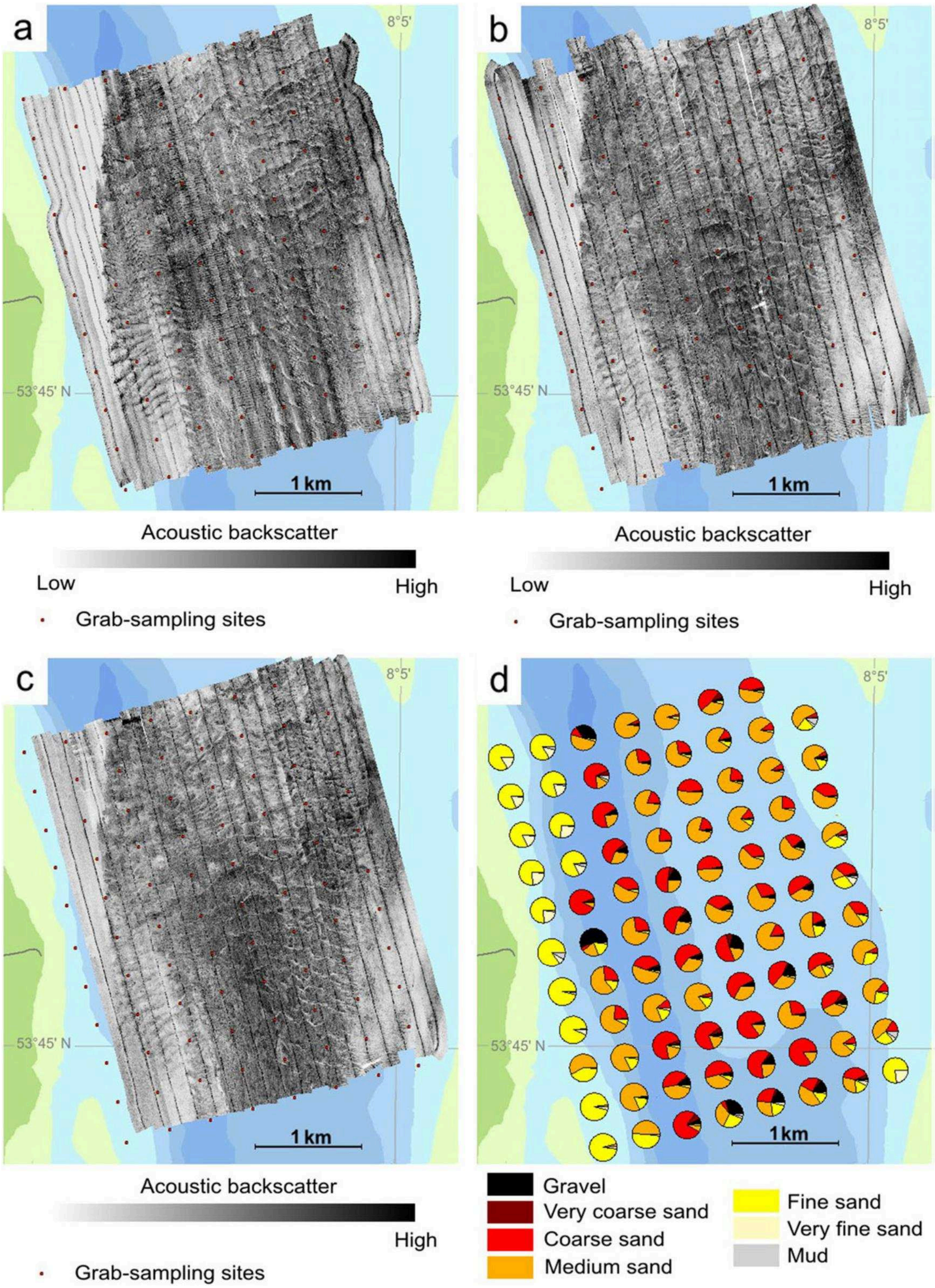

Fig. 3 Sidescan sonar mosaics collected in a October 2010, b April 2011 and c October 2011. d Sediment distribution charts of grab samples used for calibration of the sonographs

The model was run for 4 weeks of fair-weather conditions (only 2 days with winds reaching 7 Bf at the AlteWeser offshore gauge), and the last 2 weeks were used for analysis of a characteristic spring–neap cycle. Salt transport was taken into account

by the model but baroclinic flow is of less importance in the Jade due to very low inflow of fresh water (Reineck and Flemming 1990). In the model, river discharge was only considered for the Weser river. Validation of the model was successfully performed on the basis of the original 2002 setup (BAW 2009) and also included sediment transport (Kösters et al. 2014)which, however, was not analysed for this study. For each computational node in the model, the flood and ebb tides were determined and an average flood and ebb tidal current velocity was calculated. In addition, the current velocity for each node was summed over a full tidal cycle and subsequently averaged for the modelled springneap cycle. The resulting vector field describes the Eulerian residual flow field physically consistent over the model domain.

Results

Bathymetry and sediments

The Jade channel topography was investigated at water depths larger than 5 m (SKN_{LAT}). The cross-section of the channel in the study area shows the trough of a channel orientated NNW–SSE with the deepest point located 35 m below SKN_{LAT} (Fig. 2a). The trough is located closer to the western channel flank off Minsener Oog and Oldoog, resulting in a steeper western flank (ca. 1°) in comparison to the eastern flank (ca. 0.5°), which has more the character of a terrace.

Both flanks of the channel are covered by sandy deposits with a broad grain-size spectrum (Fig. 2b). The shallowest parts of both flanks are composed of fine sand (2–3 phi), in each case coarsening towards the channel thalweg up to grain sizes ranging between mediumsand and gravel. Bedforms were present in each of the sediment types (Fig. 2c). Largest dunes reaching 9.4 m in height and 300 m in length had grain sizes ranging from fine sand to medium gravel. The primary large to very large dunes were covered by secondary dunes of smaller dimensions, which appeared to be less stable over time. Some of the dune bodies were up to several km in lateral extent, connecting both channel flanks with crests aligned normal to the shore.

Sonographs recorded during the three measuring campaigns in October 2010, April 2011 and October 2011 show little changes in the overall sediment pattern (Fig. 3) but the migration of individual dunes reached several tens of metres (Fig. 2d). Sediment classification uncertainties were mostly associated with large volumes of shell hash passing through the area. Shells trapped in dune troughs are recorded as coarse

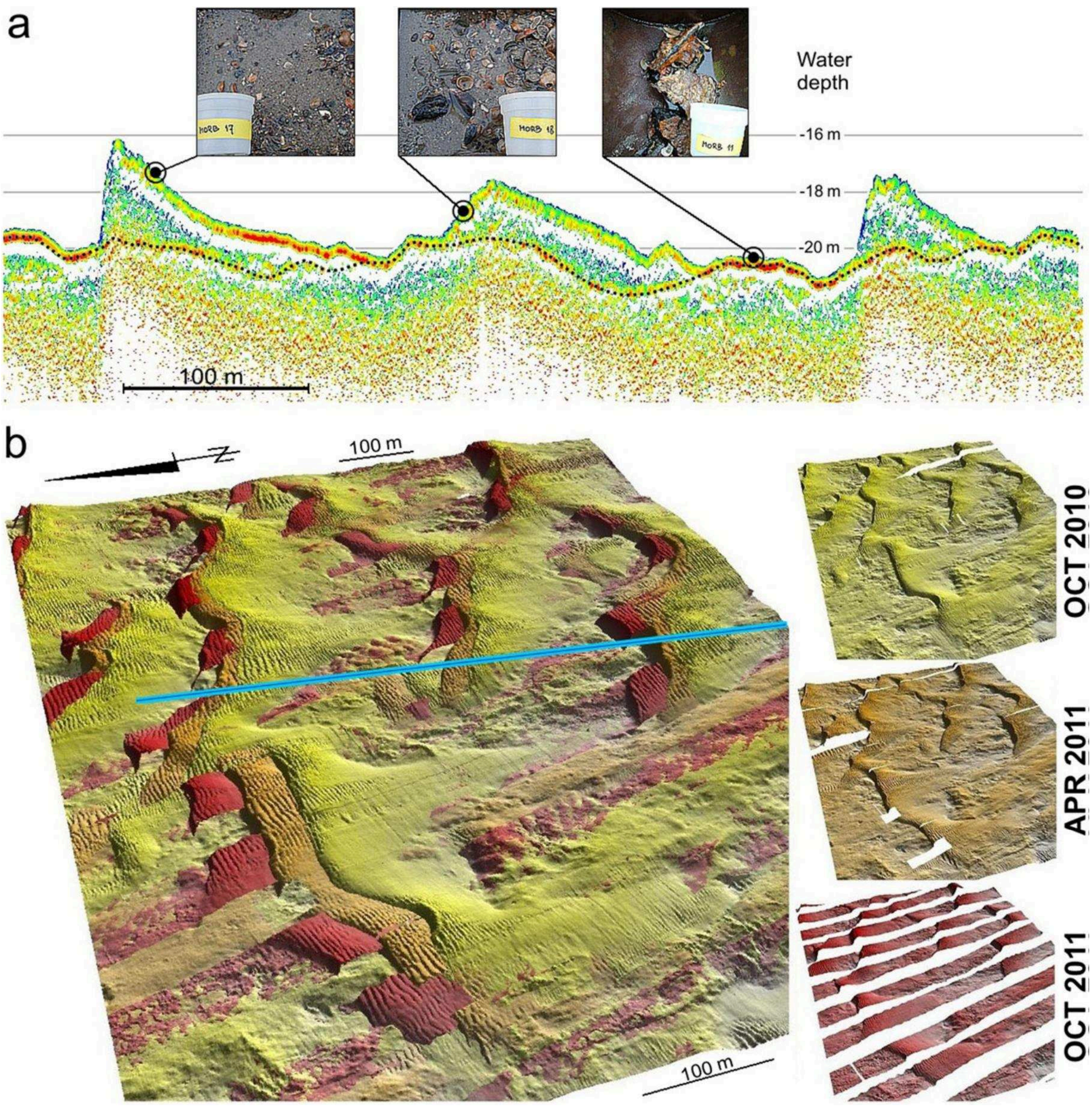

Fig. 4 a Innomar SES-2000parametric sub-bottom profiler record of three dunes located on a consolidated clay surface (dots)collected in August 2011 (see Fig. 2a, location C). Sediment samples are from February 2010and the plastic container are10 cm high. Vertical exaggerationof the cross-section ~15×. b 3Dview of these dunes recorded bymultibeam echosounder inOctober 2010 (yellow), April 2011 (orange) and October 2011(red). Note incomplete coverage of different datasets, and northward migration of dunes inall cases. Blue line marks the position of cross-section in a

Kubicki, Kösters, Bartholomä: Dune convergence/divergence controlled by residual current vortices in the Jade tidal channel, south-eastern North Sea. S. 53
Geo-Marine Letters; Vol. 37; Heft 1; Seite 47-58

material on acoustic backscatter images. In addition, grab sampling showed that shells seemed to be easily transported up the stoss side of the dunes, thereby Bcorrupting the groundtruthing of the sonographs at large spatial scales (Fig. 4a). Another characteristic feature of the area is the presence of a consolidated bed beneath the dunes, exposed parts having been identified in dune troughs at several locations (shown as dotted line in Fig. 4a). Successfully recovered samples consist of irregularly shaped cracked fragments of consolidated clay with barnacle shells attached (Fig. 4a). This type of channel bed often outcrops between dune bodies and, due to its rough texture, can also easily be mistaken for a gravelly seabed. It was therefore not always easy to unequivocally identify the material constituting different generations of dunes.

In order to resolve this issue, one of the largest dunes was investigated across its entire length with a series of 31 sediment samples recovered in April 2011 (Fig. 5). In general, a high content of medium to coarse sand was recorded. Sediment coarsening towards the crest of the dune and its lee side is visible in the contents of coarse sand, very coarse sand and gravel. There were also several sites along the stoss slope at which the medium sand content was over 10%higher than at neighbouring sites, thereby replacing the content of coarse sand. The successive samples may have been recovered from either crests or troughs of secondary bedforms superimposed on the large dune. The increase in medium sand content may thus be associated with smaller dunes 6–7 mlong and ca. 0.5 m high (Fig. 5c).

Seabed dynamics

In order to identify probable paths of dune migration, dune asymmetries were analysed even though a study by Hanes (2012) shows that results of such an approach are not always straightforward. Based on the lee-side exposition, flood- and ebb-dominated bedforms had been identified on earlier occasions (Kubicki and Bartholomä 2011). In October 2010 the survey area was expanded, which also allowed a larger coverage of derived migration vectors. The same area was scanned consistently in April 2011 to trace any changes in dune positions and to verify the assumption that asymmetries are induced by modern hydrological conditions. Once the migration paths were verified, it was essential to check whether the migration was perhaps temporarily induced by storm events in the winter of 2010/2011, or whether the observed vectors were the effect of the constantly acting tidal forces. In this manner the October 2011 survey confirmed that the dunes were migrating independently of high-energy events and that the migration rate could be calculated quite reliably (Fig. 4b).

The analysis of crest alignments in the three time steps showed a variety of directions of sediment transport as well as different migration rates throughout the area (Fig. 2d). The longest dunes located in the middle of the survey area weremigrating northwards with a slight bend towards the NNW following the general channel architecture. Some of the dunes were

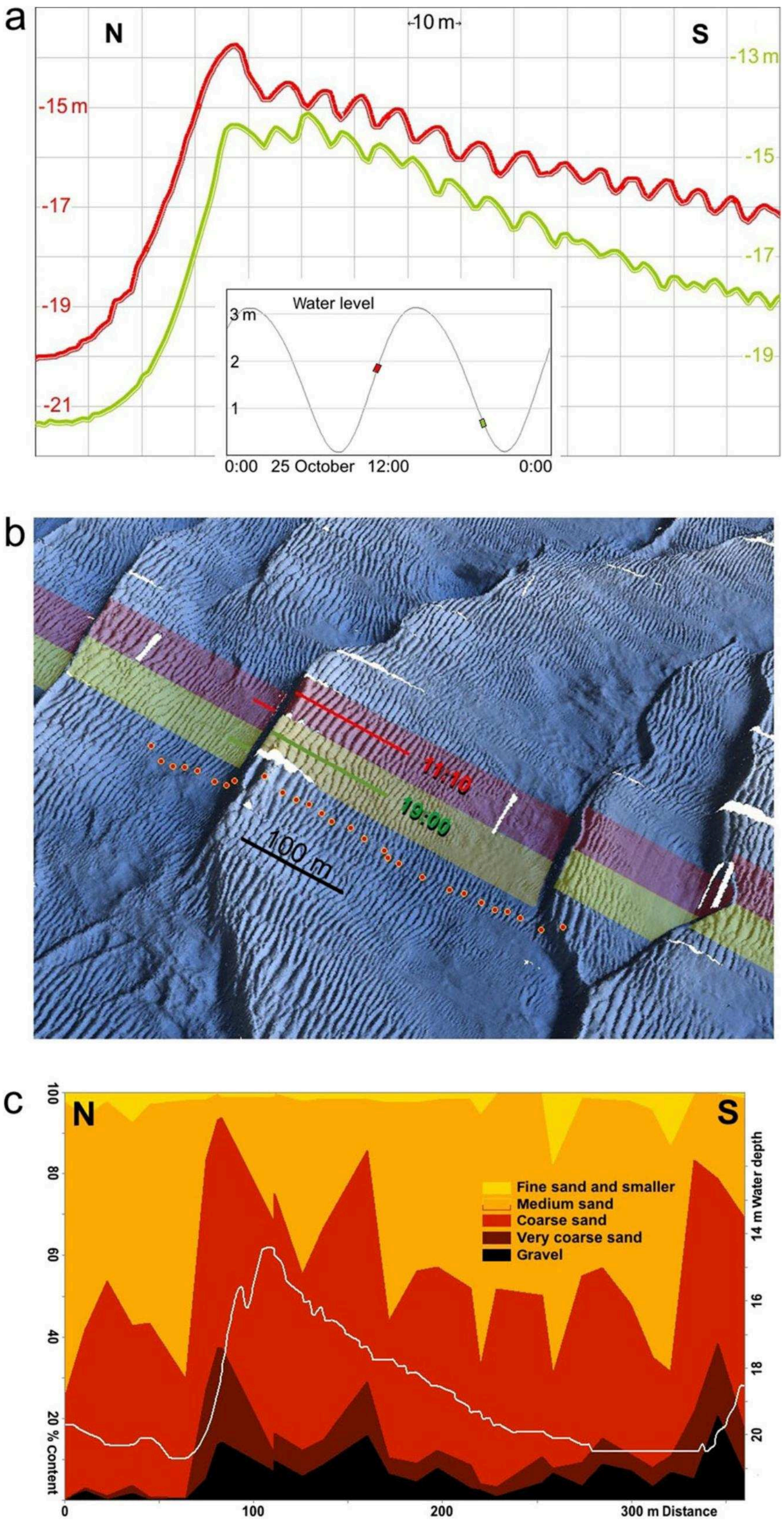

Fig. 5 a Cross-sections showing secondary bedforms recorded over the volumetrically largest dune (see Fig. 2a, location B) during the flood phase (red) and the ebb phase (green). Note a 1-m vertical shift of the plots to avoid overlapping. b Locations of cross-sections on 3D model.

Red dots 31 grab sampling sites used to plot panel c. c Grain-size composition based on grab samples across the dune. Bathymetric crosssection is delineated in white

migrating at a rate exceeding 100 m/year, but more typical values were around 30 m/year. Dunes on the western channel flank, by contrast, migrated southwards (at a rate of ca. 80 m/year) until they reached the channel thalweg where a dune field was propagating in the opposite direction (ca. 60 m/year). Another group of dunes, located in the SE of the eastern channel flank, was more stable at a SSW migration of only about 10 m/year.

Kubicki, Kösters, Bartholomä: Dune convergence/divergence controlled by residual current vortices in the Jade tidal channel, south-eastern North Sea. S. 54

Geo-Marine Letters; Vol. 37; Heft 1; Seite 47-58

Among all the bedform migration paths, those facing in opposite direction attracted special attention. The border between flood- and ebb-dominated dunes was delineated by connecting sections of dunes with symmetric stoss and lee angles. Such sections were frequently identified at the centre of dune bodies. As laterally adjacent sections were migrating in opposite directions, the opposing movement resulted in bending of crest lines and occasional calving of dunes. The zone of convergence of opposite migration paths was located exactly below the fairway. Bathymetric data from the fairway monitoring surveys further corroborated these observations. Thus, a series of 32 consecutive DTMs based on data collected between January 2006 and October 2010 confirmed constant movement of dunes in opposite directions, as illustrated in Fig. 6. Datasets from April and October 2011 were excluded from this figure due to insufficient coverage. With the aid of dune crest positions derived from sidescan sonar data, however, it was confirmed that the dunes continued to migrate along their consecutive paths for another year.

The convergence zone is characterised by little change over the 5 years covered by the data. Neither sediment accumulation nor bedform heightening were observed. In one case a section of a dune showed such small spatial oscillations that its position and dimensions could be taken as being stable over the entire 5-year period (Fig. 6).With lateral distance from the centre of convergence, the migration rates of bedforms increased. Within the fairway section the dune migration rate was up to ca. 50 m/year. Even though the latest datasets from 2010 and 2011 cover a larger area, they do not provide any clues as to the fate of the sediment in the convergence area. Due to the fact that the western channel flank was so steep, safe navigation was difficult and the pre-designed survey grid was thus rarely fully accomplished in this part of the Jade channel. Sediment transport on the western channel flank could therefore not be assessed based on bathymetry differences. For this reason the hydrodynamics of this section of the channel was simulated by numerical modelling in order to understand how tidal currents interact over this area, which could give indirect clues on forcing directions.

The modelling results showed that the tidal current exceeds 1 m/s in the middle of the channel during both flood and ebb phases (Fig. 7b, c), and that it progressively slows down towards both channel flanks. In addition, it was revealed that, at any one time, the tidal wave was of uniform height across the entire width of the channel, and that the turn of the tide from ebb to flood was abrupt with only a short slack-water period. The map with the Eulerian residual flow vectors shows that, due to the bending channel of the Jade, flood and ebb velocities are not perfectly symmetrical. Thus, averaging tidal velocities over a full tidal cycle reveals that the resulting residual current vectors show a complicated pattern of secondary circulation (Fig. 7d), which corresponds very well to the spatial pattern of dune migration (Fig. 2d).

The main vector of ebb dominance runs along the S–N axis and coincides with the greatest dune heights in the area. Flanking this vector, three tide-induced residual current vortices are identified, of which a clockwise vortex is located on the eastern flank in the SE of the survey area. The western flank, by contrast, is affected by a clockwise vortex in the north and a counter-clockwise one in the south which, in combination, produce a horizontal circulation pattern in the shape of an „8“. Since the two vortices rotate in opposite directions, the current vectors both face westwards at the centre of the “8“. This section precisely corresponds to the zone of dune convergence identified in the sedimentological data. The westward-facing vectors thus explain the lack of any dune heightening or sediment accretion in the convergence zone, although the precise mechanism of sediment bypassing and potential recirculation has not yet been identified.

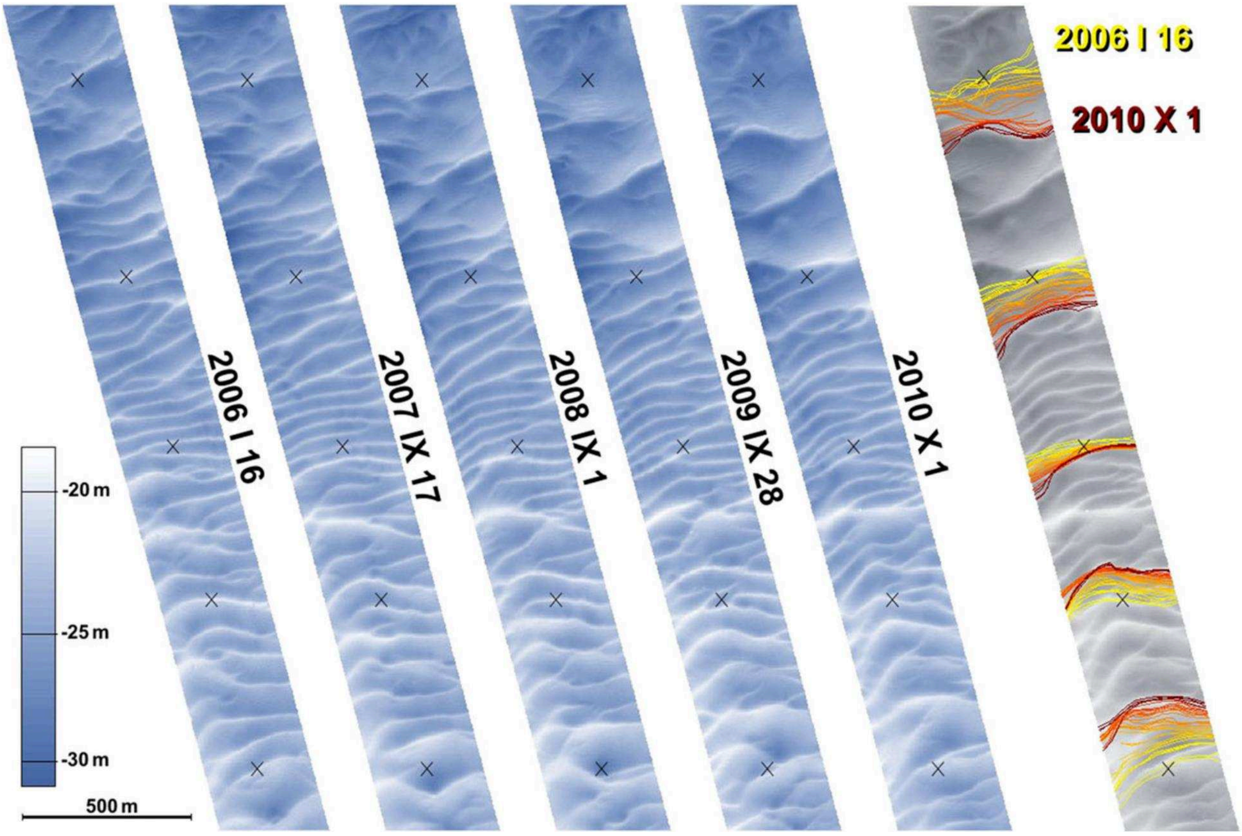

Fig. 6 Dynamics of the dune field below the Jade fairway highlighted by five examples of bathymetric records out of 32 analysed in this study. On top of the grey-scaled bathymetry of October 2010, a planimetric view of five selected large dune crests and the change of their position between January 2006 and October 2010 is presented in colours darkening from yellow to brown (see Fig. 2a, location A). The datasets are geographically Aligned

Kubicki, Kösters, Bartholomä: Dune convergence/divergence controlled by residual current vortices in the Jade tidal channel, south-eastern North Sea. S. 55
Geo-Marine Letters; Vol. 37; Heft 1; Seite 47-58

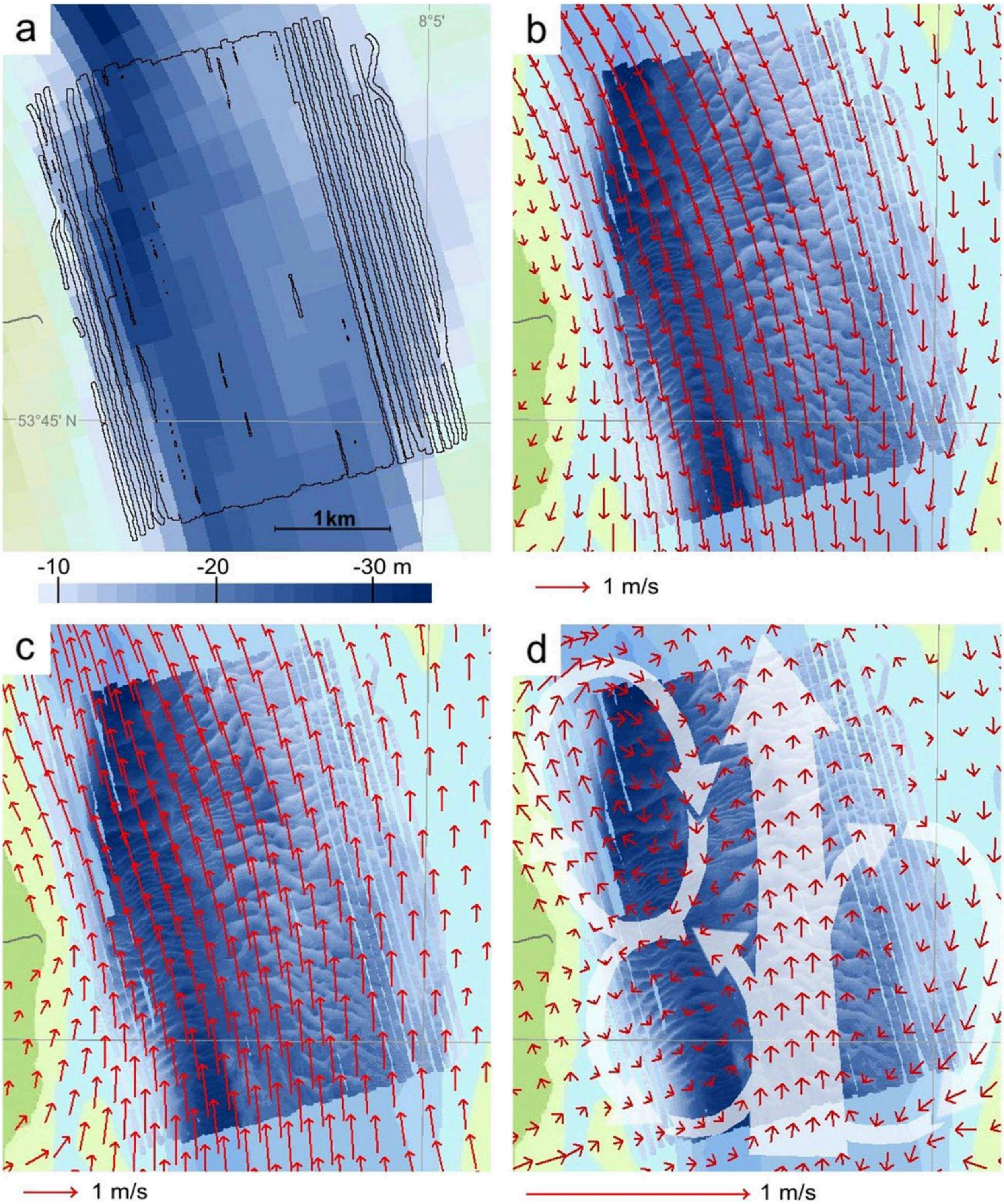

Fig. 7 Results of the numerical modelling of the hydrology in the study area. a Simplified bathymetry and model grid shapen compared to the extent of the October 2010 survey. b Depthand

time-averaged flood current vectors. c Depth- and timeaveraged ebb current vectors. d Residual current vectors with schematic interpretation (white arrows). Note exaggeration of vector magnitudes in panel d relative to panels b and c

Discussion

Seabed mobility and implications for dredging management

Without long time series of in situ current measurements, one can only speculate on critical velocities achieved at various tidal phases and under different weather conditions over particular seabed areas. In the present study, however, this shortcoming is compensated by a unique dataset of 35 highresolution bathymetric surveys spanning 6 years. These data show, without any doubt, that bedform migration occurs independently of storm events. The large to very large dunes in the study area migrate at rates of 30–100 m/year. These migration rates are faster than those recorded in similar tidal inlets also comprising medium to coarse sands (32 m/year in Bartholdy et al. 2002; 21 m/year in Cuadrado and Gómez 2011).

In addition, smaller bedforms were observed on numerous occasions to completely change direction in response to the reversing tidal currents. This phenomenon was noted when neighbouring echosounding transects crossing the same secondary dunes were scanned at different tidal phases (Fig. 5a). This observation strengthens the notion that the medium sand and finer fractions in the area are mobilised by tidal currents during any weather conditions on a daily basis. The experiment by Svenson et al. (2009) on a large dune located ca. 4 km south of the study area demonstrated that the measured friction velocities were able to mobilise even fine gravel. In that case, the dune responded to the daily tides by an up-crest coarsening trend in sediment sorting—a feature also observed over the largest dunes in the present study area (Fig. 5c). Moreover, bedforms of various sizes were identified in all sediment types ranging in mean diameters from fine sand to gravel. This suggests that the entire channel bed is regularly exposed to tidal currents exceeding critical velocities for sediment mobilisation.

A smooth channel bed composed of consolidated clay, as identified in the study area, would normally be an indication for a prolonged absence of any sediment cover. Instead, the area is covered by fully developed dunes when compared with global data on dune dimensions (Fig. 8; cf. Flemming 1988). This could mean that the observed dunes are a fairly recent phenomenon, being possibly related to the dumping of dredge spoil near the

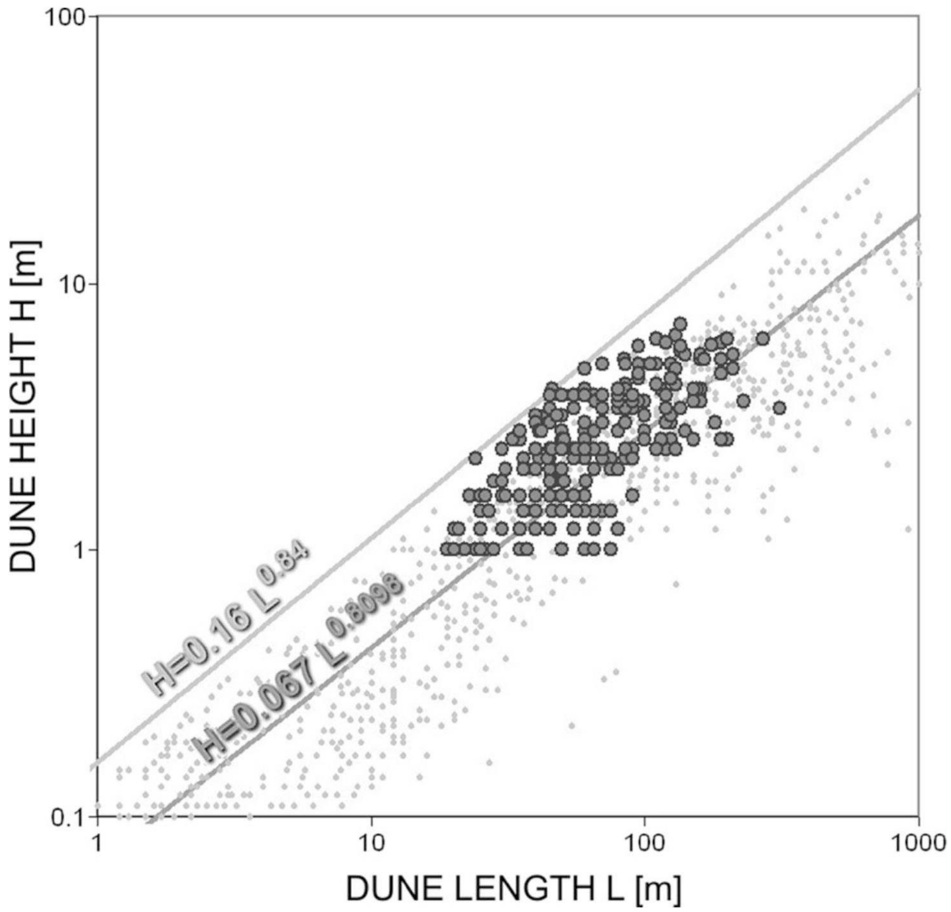

Fig. 8 Plot of dune height (H) vs. dune length (L) for the study area. Mean and maximum trend lines of subaqueous bedforms as well as the overall scatter of the global dataset are plotted in the background for comparison (extracted from Flemming 1988)

lighthousewhich has provided a newsediment source fromwhere the sediment has been redistributed by the tidal currents. This hypothesis is strengthened by the observation that dunes located south of the lighthouse, up-stream with respect to residual current vectors, are lower and shorter than the ones situated closer to the lighthouse (Fig. 2c). This finding may be useful to authorities striving for an optimisation of dredging and dumping strategies.

When evaluating the bathymetric changes over the past 6 years, it seems that the dunes are merely passing through this section of the channel and that the channel would once again become void of sediment if the source were to be cut off by, for example, closing the dumping site. If the sediment source were indeed the dump site (e.g. Wienberg et al. 2004), then one should be able to precisely calculate the time of natural redistribution of the exogenic material. One could also consider controlling dune dimensions by dumping only certain grain sizes and avoiding others. Thus, the availability of sediments coarser than fine sand would be conducive to forming large to very large dunes in the area. Decreasing the grain size of dumped material would result in the formation of smaller, more rapidly migrating dunes and thereby avoid navigational obstacles in the form of elevated crest heights.

Observed sediment transport pattern in relation to modelled hydrology

Due to the local channel topography, a complicated pattern of residual currents has developed, which was identified even on the relatively coarse grid of the numerical model compared to the dune lengths. It has to be kept in mind here that the simplified bathymetry used in the model does not resolve individual dunes. However, the required assumptions of the numerical model—e.g. averaging the variable topography within individual grid cells—were shown to be insignificant with respect to the advantage of a broader spatial view and the opportunity to analyse the flow field in a physically consistent way using characteristic tidal parameters. A major result of the study is the fact that the transport vectors derived from tracing the crest lines are in ideal agreement with the residual current vectorsmodelled for fair-weather conditions. Thus, the locations of the largest dunes coincide with the highest residual currents, which are locally ebb-dominant. Smaller dunes also clearly migrate in the direction of the residual currents. Because the modelled current velocities lack detailed validation for the 2010 bathymetry, they should in the interim be treated as an approximation. The sedimentological data, on the other hand, provide multiple indicators that critical velocities for mobilising coarse to very coarse sand are exceeded during everyday tidal action. Nevertheless, the model resolution is high enough to reproduce the residual current vortices at exactly the same locations as indicated by the observed dune pathways. Such residual current vortices are a natural phenomenon in environments characterized by reversing tidal currents, but it is a rare experience to be able to observe their effect in dune migration paths on the seabed in such detail.

In the study area, the neighbouring counter-rotating vortices have resulted in dunes converging along one axis. Interestingly, no sediment accretion is observed at the point of convergence in the course of the 6 years of monitoring (Fig. 6). Moreover, even a buffer zone of ca. 200 m radius around the convergence point remained relatively stable, being characterised by symmetrical dune bodies and only minor shifts in the positions of dune crests. In combination with the numerical model results, the westward-directed flow vectors at the centre between the two counter-rotating vortices suggest that the sediment bypasses in that direction, although this could not be verified on the ground by dune migration patterns. Unfortunately, it was not possible to establish the exact nature of the bypassing mechanism because detailed measurements on the western bank were not available to this study. While no evidence of an accreting western bank in the vicinity of the convergence zone is available, a clear depocentre was observed in the north-western corner of the study area (see animation in the Electronic supplementary material). This accumulation is spatially in perfect agreement with the residual current vortex which probably transports the sediment away from the convergence zone towards the north along the shore of the Minsener Oog island, before eventually bending eastwards precisely at the location of the depocentre (see Fig. 7d).

It can thus be hypothesized that the sediment trapped by the opposing residual current vortices over the western channel bank is constantly being recirculated. As this feature could not be confirmed by the available sedimentological data, the hypothesis should be tested by a coupled hydrodynamic–sediment transport simulation using a higher-resolution grid supported by more detailed ground-truthing in the area of interest

Conclusions

The meandering section of the outer Jade tidal channel, which is apparently being supplied with material derived from a nearby dredge-spoil dumping site, was monitored monthly over a 6-year period by means of high-resolution bathymetric mapping to trace dune migration rates and directions. The field investigations were complemented by numerical modelling of the fair-weather hydrology. The main results and implications can be summarized as follows:

- The model-derived residual current vectors are in perfect spatial agreement with data collected in situ.
- The main direction and highest velocity of residual ebbcurrent flow is associated with the largest dunes, which are composed of medium to coarse sand.
- Residual current vortices form on both sides of the channel. These are large enough to be traced on the seabed by dune asymmetries.
- Two counter-rotating vortices over the western channel bank result in dune convergence along one axis.
- The convergence zone remained stable over the entire 6- year monitoring period, suggesting equilibrium conditions between hydrology and morphology.
- It is hypothesized that sediment bypasses the convergence zone to be constantly recirculated.

Acknowledgements

This research was funded by the Federal Ministry of Education and Research (BMBF/KFKI) as part of the „Model-based analysis of long-term morphodynamic processes in the German Bight (AufMod)“ project (03KIS083 and 03KIS088). The authors wish to acknowledge Sandra Bülles and Axel Götschenberg from the WSAWilhelmshaven for enriching the study with archived bathymetric data. Our sincere thanks go to the captain Karl Baumann and the crew of the RV Senckenberg for their navigational skills during the measuring campaigns. ArnulfMöller is acknowledged for acquiring and post-processing themultibeam bathymetric data. Astrid Raschke is thanked for her help in sediment analysis. Last but not least Burghard W. Flemming, Daniel M. Hanes and an anonymous reviewer are deeply acknowledged for constructive critics and remarks that enriched the manuscript.

Compliance with ethical standards

Conflict of interest The authors declare that there is no conflict of interest with third parties.

References

Ashley GM (1990) Classification of large-scale subaqueous bedforms: a new look at an old problem. J Sediment Petrol 60(1):160–172

Barnard PL, Hanes DM, Rubin DM (2006) Giant sand waves at the mouth of San Francisco Bay. Eos 87(29):285–289

Bartholdy J, Bartholomä A, Flemming BW (2002) Grain-size control of large compound flow-transverse bedforms in a tidal inlet of the Danish Wadden Sea. Mar Geol 188:391–413

Bartholomä A, Schrottke K, Winter C (2008) Sand wave dynamics— surfing between assumptions and facts. In: Parsons D, Garlan T, Best J (eds) Proceedings of Marine and River Dune Dynamics III. University of Leeds, Leeds, pp 17–24

Bates CR, Oakley DJ (2004) Bathymetric sidescan investigation of sedimentary features in the Tay Estuary, Scotland. Int J Remote Sens 25(22):5089–5104BAW (2009) Modellvalidierung von UnTrim/ SediMorph - Hydrodynamik und Schwebstofftransport des Jade-Weser Ästuars. Bundesanstalt für Wasserbau, Hamburg. http://www.baw. d e / d o w n l o a d s / w a s s e r b a u / m a t h e m a t i s c h e _ verfahren/Validierungsstudien/Modellvalidierung_Weser-GM_ UnTRIM2007_v1.3.pdf

Belderson RH, Johnson MA, Kenyon NH (1978) Bed-load partings and convergences at the entrance to the White Sea, USSR, and between Cape Cod and George's Bank, USA. Mar Geol 28:65–75

BfG/WSA (2003) Bagger- und Klappstellenuntersuchungen in der Jade. Bundesanstalt für Gewässerkunde & Wasser- und Schifffahrtsamt Wilhelmshaven, Bericht BfG-1349, Koblenz-Wilhelmshaven

Brezina J (1979) Particle size and settling rate distributions of sandsized materials. In: Partec 79 (eds) Papers 2nd European Symp Particle Characterisation, 24–26 September 1979, Nürnberg. Partikel Technologie, Nürnberg

Carle L, Hill PR (2009) Subaqueous dunes of the upper slope of the Fraser River Delta (British Columbia, Canada). J Coast Res 25(2): 448–458

Castro Díaz MJ, Fernández-Nieto ED, Ferreiro AM (2008) Sediment transport models in Shallow Water equations and numerical approach by high order finite volume methods. Comput Fluids 37: 299–316

Casulli V, Zanolli P (2005) High resolutionmethods for multidimensional advection-diffusion problems in free-surface hydrodynamics. Ocean Modell 10(1-2):137–151

Cuadrado DG, Gómez EA (2011) Morphodynamic characteristics in a tidal inlet: San Blas, Argentina. Geomorphology 135:203–211

Doms G, Steppeler J, Adrian G (2002) Das Lokal-Modell LM. Promet 27(3-4):123–128

Ernstsen VB, Noormets R, Hebbeln D, Bartholomä A, Flemming BW (2006) Precision of high-resolution multibeam echosounding coupled with high-accuracy positioning in a shallow water coastal environment. In: Bartholomä A, Winter C (eds) Coastal dynamics and human impact: south-eastern North Sea. Geo-Mar Lett 26(3): 141–149

Fenies H, Faugères J-C (1998) Facies and geometry of tidal channel-fill deposits (Arcachon Lagoon, SW France). Mar Geol 150:131–148

Flemming BW (1988) Zur Klassifikation subaquatischer, strömungstransversaler Transportkörper. Bochumer geol geotech Arb 29:44–47

Flemming BW (2000) The role of grain size, water depth and flow velocity as scaling factors controlling the size of subaqueous dunes. In: TrentesauxA, Garlan T (eds)Marine Sandwave Dynamics (MARID 2000). International Workshop, 23–24 March 2000, University of Lille 1, Lille, France, pp 55–60

Fraccascia S, Winter C, Ernstsen VB, Hebbeln D (2016) Residual currents and bedform migration in a natural tidal inlet (Knudedyb, Danish Wadden Sea). Geomorphology 271:74–83

Gómez EA, Cuadrado DG, Pierini JO (2010) Sand transport on an estuarine submarine dune field. Geomorphology 121:257–265

Gonzales R, Eberli GP (1997) Sediment transport and bedforms in a carbonate tidal inlet, Lee Stocking Island, Exumas, Bahamas. Sedimentology 44:1015–1030

Kubicki, Kösters, Bartholomä: Dune convergence/divergence controlled by residual current vortices in the Jade tidal channel, south-eastern North Sea. S. 58

Geo-Marine Letters; Vol. 37; Heft 1; Seite 47-58

Götschenberg A, Kahlfeld A (2008) The Jade. In: Heyer H (ed) Estuaries and fairways. Die Küste 74:263–274

Grabemann H-J, Grabemann I, Eppel DP (2004) Climate change and hydrodynamic impact in the Jade-Weser area: a case study. In: Schrenewski G, Dolch T (eds) Geographie der Meere und Küsten. Coastline Reports 1, pp 83–91

Hanes DM (2009) Recent technologies usher in new era of coastal geomorphology research. Eos 90(23):198–199

Hanes DM (2012) The genesis of an inter-field marine sandwave and the associated anti-asymmetry migration of neighboring crests. Geophys Res Lett 39, L04402. doi:10.1029/2011GL050641

Harris PT (1988) Large scale bedforms as indicators of mutually evasive sand transport and the sequential infilling of wide-mouthed estuaries. Sediment Geol 57:237–298

Harris PT, Pattiaratchi CB, Collins MB, Dalrymple RW(1995)What is a bedload parting? IAS Spec Publ 24:3–18

Hughes ZJ (2012) Tidal channels on tidal flats and marshes. In: Davis RA, Dalrymple RW (eds) Principles of tidal sedimentology. Springer, Heidelberg, pp 269–300

Idier D, Astruc D, Garlan T (2011) Spatio-temporal variability of currents over a mobile dune field in the Dover Strait. Cont Shelf Res 31: 1955–1966

Kahlfeld A, Schüttrumpf H (2006) UnTRIM modelling for investigating environmental impacts caused by a new container terminal within the Jade-Weser Estuary, German Bight. In: ICHE (eds) Proc 7th Int Conf HydroScience and Engineering, 10–13 September, Philadelphia, USA. Drexel University, Philadelphia

Kösters F, Grabemann I, Schubert R (2014) On SPM dynamics in the turbidity maximum zone of the Weser Estuary. Die Küste 81:393– 408

Kubicki A, Bartholomä A (2011) Sediment dynamics in the Jade tidal channel prior to port construction, southeastern North Sea. J Coast Res SI 64:771–775

Le Bot S, Trentesaux A (2004) Types of internal structure and external morphology of submarine dunes under the influence of tide- and wind-driven processes (Dover Strait, northern France). Mar Geol 211:143–168

Li C, Chen C, Guadagnoli D, Georgiou IY (2008) Geometry-induced residual eddies in estuaries with curved channels: observations and modeling studies. J Geophys Res 113, C01005. doi:10.1029/2006 JC004031

Mazumder R (2003) Sediment transport, aqueous bedform stability and morphodynamics under unidirectional current: a brief overview. J African Earth Sci 36:1–14

Reineck H-E, Flemming BW (1990) Salzgehalt der Restnässe auf oder in der obersten Sedimentschicht und der Porenwässer im Eu- und Supralitoral der Jadewatten in Relation zu denen des Jadewassers. Senck marit 21:33–54

Svenson C, Ernstsen VB, Winter C, Bartholomä A, Hebbeln D (2009) Tide-driven sediment variations on a large compound dune in the Jade tidal inlet channel, southeastern North Sea. J Coast Res SI 56: 361–365

Tee KT (1976) Tide-induced residual current, a 2-D nonlinear numerical tidal model. J Mar Res 34(4):603–628

Van Landeghem KJJ, Baas JH, Mitchell NC,Wilcockson D,Wheeler AJ (2012) Reversed sediment wave migration in the Irish Sea, NW Europe: a reappraisal of the validity of geometry-based predictive modelling and assumptions. Mar Geol 295–298:95–112

Van Rijn LC, Ribberink JS, Van der Werf J, Walstra DJR (2013) Coastal sediment dynamics: recent advances and future research needs. J Hydraul Res 51(5):475–493

Wentworth CK (1922) A scale of grade and class terms for clastic sediments. J Geol 30:377–392 Whitmeyer SJ, FitzGerald DM(2008) Episodic dynamics of a sand wave field. Mar Geol 252:24–37 Wienberg C, Dannenberg J, Hebbeln D (2004) The fate of dumped sediments monitored by a high-resolution multibeam echosounder system, Weser Estuary, German Bight. Geo-Mar Lett 24:22–31 Zorndt AC, Wurpts A, Schlurmann T (2011) The influence of hydrodynamic boundary conditions on characteristics, migration, and associated sand transport of sand dunes in a tidal environment. Ocean Dyn 61:1629–1644