Processes controlling the behaviour of sandwaves and megaripples in the North Sea

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Abstract

The morphology and morphodynamics of the seabed are crucial to understanding the behaviour of harmonic bedforms, which is important for modelling sediment transport. Previous research has mainly focussed on the type and distribution of bedforms, but area-covering data and time records are scarce. Multibeam and sidescan sonar data of 4 journeys reveal the contrasts between a coastal site with asymmetric and flattened, compound 3D sandwaves on a shoreface-connected ridge, with migration rates of 6.5 - 20 m a^{-1}, and an offshore site with asymmetric and sharp-crested, compound 2D sandwaves, with migration rates of -3.6 - 10 m a^{-1}. In the respective areas, megaripples crests are parallel and under a 20º angle to sandwave crests and vary little and strongly in appearance and orientation over the length of the sandwave. The dominance of (longshore) currents or wave activity is held responsible for the behaviour and development of the variation in bedforms at the two North Sea sites. These field data provide parameters and boundary conditions for sand transport modelling and the empirically-derived behaviour may be used to test sand transport models.

Introduction

Harmonic bedforms are important seabed features, characterising large parts of the North Sea bed, both at one point in time, for example their morphologic effect on benthos habitats (Baptist and others, 2001; 2002; Van Heteren and others, 2003), and as dynamic elements, for example for predicting seabed changes, coastline development and the effects of man-made structures. Modelling sediment transport is the key to these predictions. To date, however, sediment transport models are unacceptably inaccurate. The comparison of various sediment transport models to field data reveals that model outputs of total sediment transport may vary up to several orders of magnitude (Davies *et al.*, 2002). Prediction inaccuracies are largest for rippled beds with high surface roughness coefficients. Davies et al. (2002) identify the necessity for more field measurements in order to make sand transport models more accurate. Presently, especially the long-term dynamics are poorly understood, due to the lack of data. Where data exist, they are primarily point measurements whilst timeseries are scarce. This study provides a time series of full-coverage imagery of sites several km^2 in size, of in total five journeys over a period of 1.5 years, in order to explain the behaviour of marine bedforms.

This paper aims (1) to present new field data of two sites with harmonic bedforms in the North Sea of both a morphologic nature, which may serve as detailed input parameters of surface roughness for sediment transport models, and of a mophodynamic nature, which may be used to test the model predictions of seabed change of rough beds with harmonic bedforms, (2) to identify the processes that are responsible for the dynamic behaviour of these bedforms under the ruling conditions of the North Sea, and (3) to formulate hypotheses which may explain the development of these bedforms.

This will lead to improved sediment transport models which are applicable to predicting the effects on seabed changes, either natural or due to human intervention.

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Methods

Two sites were selected in the North Sea: a coastal site (1770*1625m) in an area with shoreface-connected ridges with 14-18 m waterdepths 6-8 km offshore southwest of IJmuiden and a site (5510*1100m) in a sandwave field at 27-30 m waterdepths 50 km offshore from Bergen (Figure 1). The area-wide morphology of the seabed was determined with a hull-mounted SIMRAD ED3000 D multibeam echo sounder and a shallowly-towed Dowty 310 sidescan sonar. The multibeam operates at a frequency of 300 kHz and the sonar at 325 kHz. The seabed was sampled using a box corer with a diameter of 32 cm, from which cores of 10 cm diameter were resampled. Data were aquired on 4 journeys in March, June/July and September/October 2001 and April 2002, and for the offshore site also in September 2002.

Lengths and heights of bedforms were measured manually off the corrected multibeam images (1:2500) and profiles, whereby the wavelengths of megaripples always is an average of 7 to 10 adjacent ripples. Bathymetric profiles approximately normal to the crests of the bedforms were compiled from the multibeam data. The comparison of profiles of different data sets over time provides the migration rates of the sandwaves, also measured manually with a linear scale. Hereby, migration rates were measured on lee slopes rather than at the crests of sandwaves, because the crest variability due to megaripple variation may be larger than that due to sandwave displacement. In the offshore area, lee slopes of sandwaves of two profiles commonly cross at a point approximately half way downslope. Therefore, migration rates were measured separately for the upper and lower lee slopes. Migration rates of megaripples were not established, since individual megaripples that were identified in one season could not be identified on the images and profiles of the following season. Grain size analyses were dry sieving for grains > 2 mm and Malvern for grains < 2 mm.

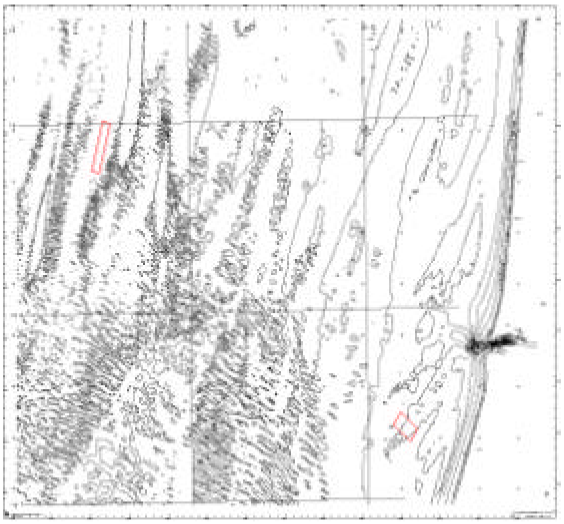

Figure 1: Bathymetry map of the North Sea near Ijmuiden, Netherlands, indicating the location of the coastal site in the shoreface-connected ridge area and the offshore site in a sandwave field.

Results

All morphologic descriptions are observations made in March 2001, after a 3 month period of fair weather conditions (*www.weeronline.nl*) and one month into a 2.5 months period during which the sites were closed to beam-trawl fishing. The megaripples were by far the best developed in March 2001, which corresponds to the most natural circumstances and non-extreme conditions for sea bed morphology. The morphodynamic descriptions are based upon 4 journeys in March, July and September 2001 and April 2002.

1. Coastal shoreface-connected-ridge site

Multibeam images and profiles of the seabed in the coastal area reveal a shoreface-connected ridge with superimposed sandwaves and, in their turn, superimposed megaripples (Figure 2). These compound sandwaves are three-dimensional in form and strongly asymmetric in cross section (Table 1) with their lee sides facing north-northeast. The wavelength of the northern sandwave is 760 m and the height difference between the flat-topped crest plateau and the troughs is 1.5 m. The orientation of the axis of the ridge is 36° from UTM north; the orientations of the sandwave crests are 101° and 108°. The respective orientations of megaripples near the sandwave crests are 101 and 107°, and thus perfectly parallel to the sandwave crests, and 103° on the stoss side of both sandwaves. Megaripples have sinuous out-of-phase, two-dimensional crests and are asymmetric in cross section. Their average length is 6.6 m. Although the megaripples are approximately uniform, their appearance on the sonograms changes over the length of a sandwave. Megaripples in the sandwave troughs are coarse-pixeled and are characterised by both high- (dark) and low-backscatter (light) intensities, whereas megaripples on the stoss slopes and lower crest plateaus are smooth and merely highlighted with low-backscatter intensities (light-coloured acoustical shadows) (Figure 2).

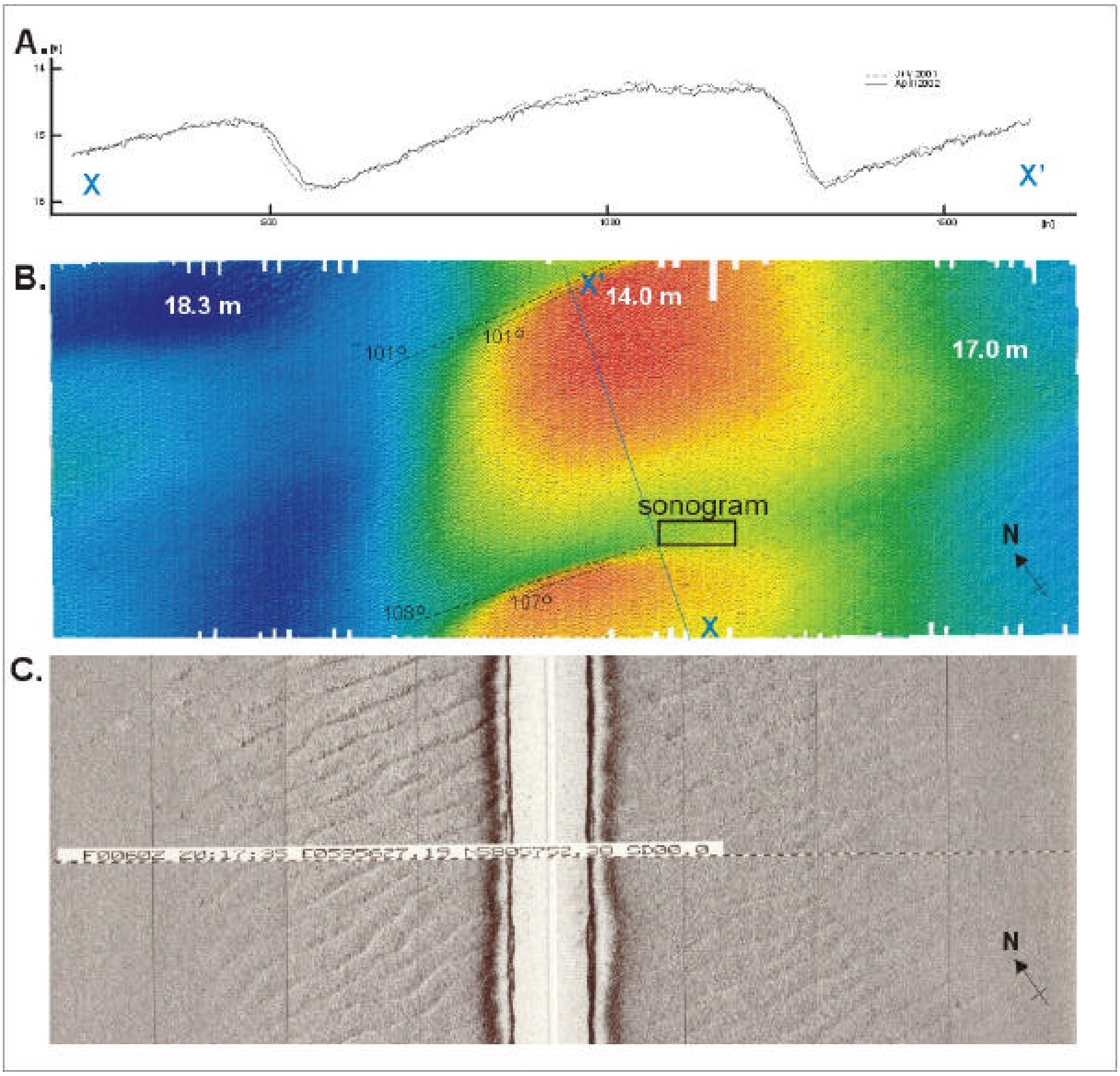

Figure 2: morphology of the coastal site. A. bathymetry of July 2001 and April 2002, B. multibeam image with crest orientations of sandwaves and megaripples, waterdepths and locations of bathymetry profiles and sonogram, and C. uncorrected sidescan sonar image of the box in B. The slant range is 100 m and the sailing course was 36° (from bottom to top).

Morphodynamics of bedforms have been investigated both in plan view and in cross-sectional profile. Multibeam images of the coastal area in July and September 2001 and April 2002 show little difference in the morphology of the sandwaves on the shoreface connected ridge. The distinct megaripples that are visible on the March 2001 image, however, had faded in June/July either completely (merely grainy structure on the sonograms) or to a barely recognisable lineation, apart from a zone of distinct ripples limited to the seaward flank of the shoreface-connected ridge. In October all bedforms had been obliterated into a flat bed, and a low-relief terrace morphology had been generated. Multibeam images of both July and September 2001 show 25 m diameter hummocks in the landward part of the coastal site, which are related to a near gale (see Passchier and Kleinhans, this volume).

The comparison of the July 2001 and April 2002 profiles of the coastal area reveals a northward migration of the sandwaves (Figure 2). The horizontal displacement of the lee side of the southern sandwave was 7.5-12.5 m, that of the trough between the dunes 15.0 m, that of the lee side of the northern sandwave 5.0-7.5 m and of the trough on the north side 5.0 m, which are significant with a horizontal error of 1 - 3 m. These values correspond to a migration rate of 6.5 to 20 m a^{-1}. The vertical displacement was zero in the trough between the sandwaves and negative in all other measured locations, though less than the vertical error of 0.15 m. Apart from the general shape, individual megaripples were not comparable between the profiles.

	Coastal site		**Offshore site (averages)**	
	Sandwaves	Megaripples	Sandwaves	Megaripples
Wavelength L [m]	760	6.6	203	10.14
Waveheight H [m]	1.5	0.05-0.10	1.79	< 0.40
Dune index, *L/H*	507	132-66	126	>25
Crest orientation [from UTM north]	101° and 108°	101° and 107° (103° on stoss)	91°	121° (136° in troughs; 110° near crests)
Symmetry index, L_{stoss}/L_{lee}	10.7	-	4.23	-
Gradient stoss side	0.20°	-	0.66°	-
Gradient lee side	1.11°	-	2.34°	-
Migration rate [m a^{-1}]	6.5 – 20	-	-3.4 – 10.2	-
Waterdepth [m]	14-18.3		26-30	
Median range [μm]	280-366		254-304	

Table 1: statistics of the bedform morphology, dynamics and grain size at two sites in the North Sea

Seabed sediments in the coastal area are moderately-sorted fine to coarse sands with grain sizes ranging between 150 and 900 μm and sample medians ranging between 280-366 μm. Grainsize distributions are near-normal, but slightly skewed, and vary slightly between samples. A fining trend in sample medians is apparent perpendicular away from the shore, which seems to overrule the grain size differences between sandwave crests and troughs and the shoreface-connected ridge top and swales. Seasonal variations of the median are about 20 μm.

2. Offshore sandwave field

The seabed morphology in the offshore area comprises nearly two-dimensional compound sandwaves (Figure 3). In cross-sectional profile, the sandwaves are asymmetric, though less asymmetric than those in the coastal area (Table 1), with their lee slopes facing north. Most sandwaves are sharp-crested, but few are rounded (Figure 3). The average wavelength of the sandwaves is 203 m and the average waveheight is 1.79 m. The sandwaves have continuous, straight to sinuous crests, although some display open or buttress junctions. The average orientation of the crests is 91° from UTM north.

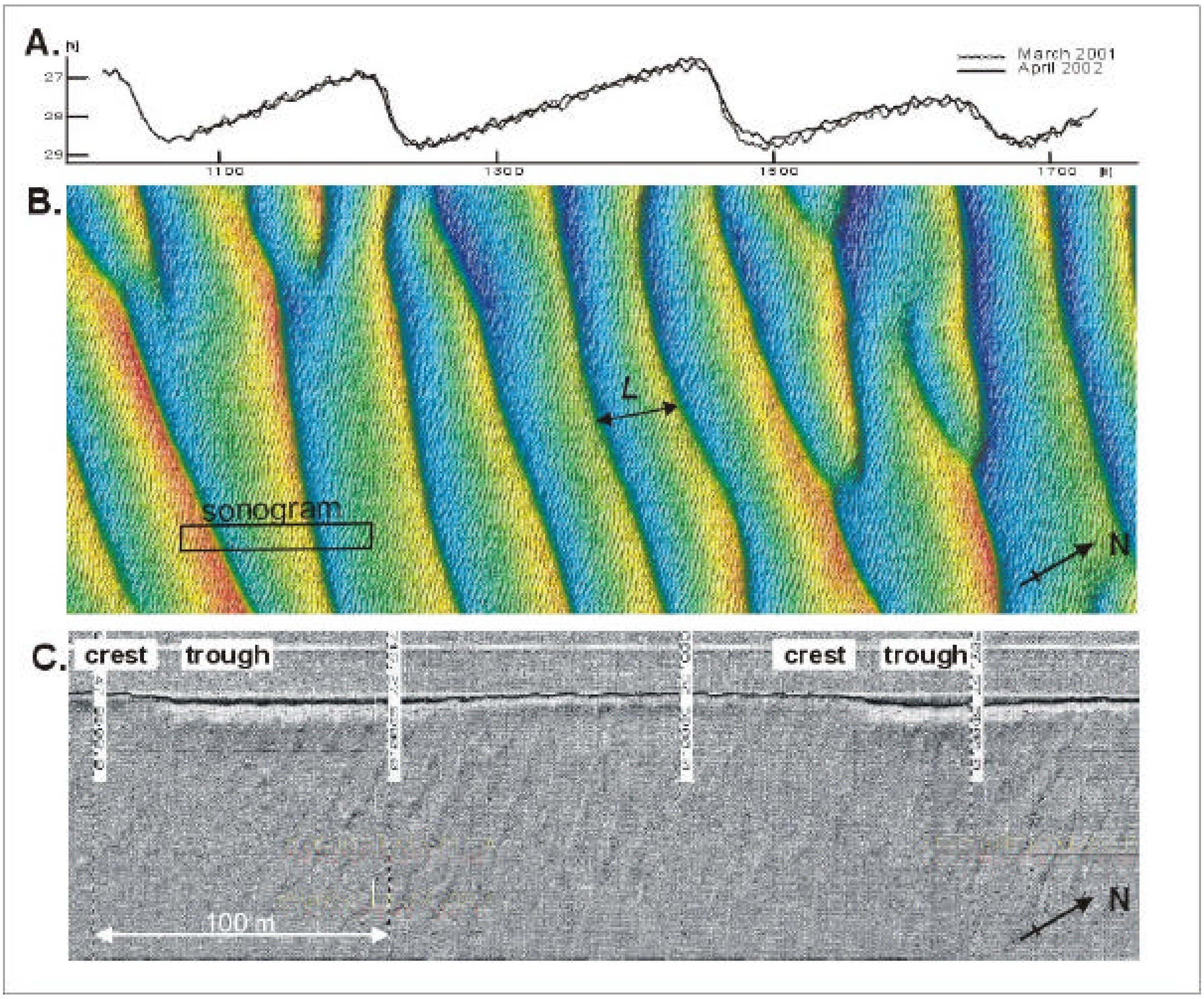

Figure 3: morphology of the offshore site. A. bathymetry (southern part of the area), B. multibeam image, C. uncorrected sidescan sonar image of the box in B. The visible slant range is 75 m, the distance between two white lines is ~100 m and the sailing course was 30º (from left to right).

The average crest orientation of the superimposed asymmetric megaripples is 121°, which thus makes an angle of 30° with the average crest orientation of the sandwaves. The orientations of megaripples systematically vary over the length of a sandwave, with orientations of 136.5° in the throughs, 116.6° on the stoss sides and 110.6° near the crests (Figure 4). Near the sandwave crests the angle between crest orientations of the sandwaves and megaripples is thus approximately 19.6º. On the sonograms, a repetitive and systematic pattern of variable forms and appearances of megaripples – similar to the variable appearance in the coastal site – corresponds to the wavelengths of sandwaves (Figure 3). In sandwave troughs, megaripples are discontinuous and sinuous, showing enhanced backscatter in their wide troughs. On stoss slopes, megaripple crests are the most continuous and straight (2D), with light acoustic shadows. Here, the megaripple length is 10.14 m and heights are up to 0.40 m. Near sandwave crests, megaripple crests are straight 2D and vague or absent. With very few exceptions, megaripples are absent on lee slopes of the sharp-crested sandwaves and are present on the rounded sandwaves.

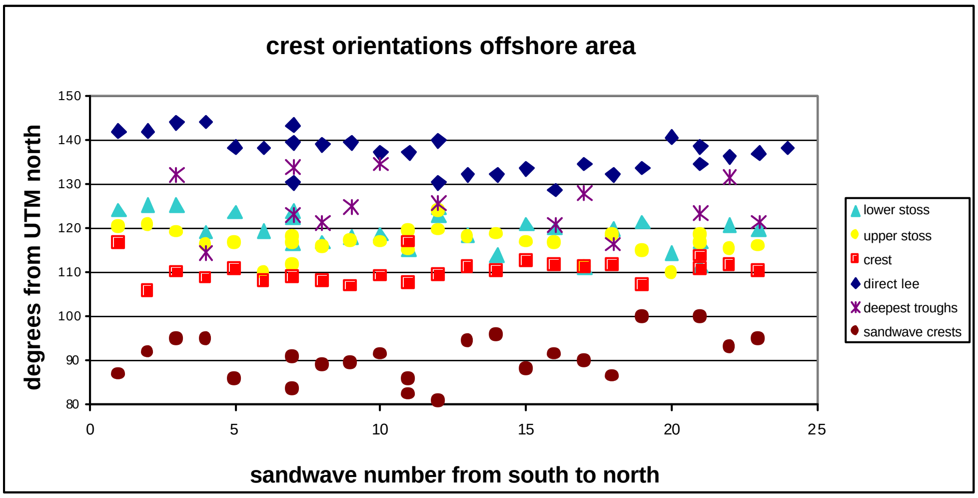

Figure 4: crest orientations of megaripples on different parts of the sandwaves in the offshore area.

Plan-view morphodynamics of sandwaves in the offshore area are low. Sandwaves are not significantly changed in pattern, size or appearance. Megaripples on the other hand, vary in form from continuous and straight with wavelengths of approximately 7 m in March 2001, via intensely bifurcated megaripples with zig-zag junctions and wavelengths of 7 to 10 m in June/July, to straight 2D megaripples with few zig-zag junctions and wavelengths of approximately 2 m in October 2001.
The comparison of the March 2001 and April 2002 profiles in the offshore area reveals that the cross-sectional shapes of individual sandwaves, too, remain similar (Figure 3). The horizontal displacement of upper lee slopes of individual sandwaves varies between 3.75 m southward, in the direction of the subordinate ebb tidal current, and 3.75 m northward, in the direction of the dominant flood current. The horizontal displacement of the lower lee slopes varies between 0 and 11.25 m northwards. These values correspond to a migration rate of sandwaves in the offshore area of -3.41 to 3.41 m a^{-1} for upper lee slopes and 0 to 10.24 m a^{-1} for lower lee slopes. The vertical displacement of stoss sides and troughs between 0.00 m and 0.25 m, which is smaller than the height difference of the megaripples.

Seabed sediments in the offshore area are better-sorted fine to coarse sands with grain sizes ranging between 150 and 700 μm and sample medians ranging between 254-304 μm. Grainsize distributions are near-normal and vary less between samples than in the coastal area. No fining or coarsening trends are apparent in the medians at this site, apart from perhaps slightly coarser sandwave crests than troughs, although this pattern is not systematic. Seasonal variations of the medians are about 10 μm.

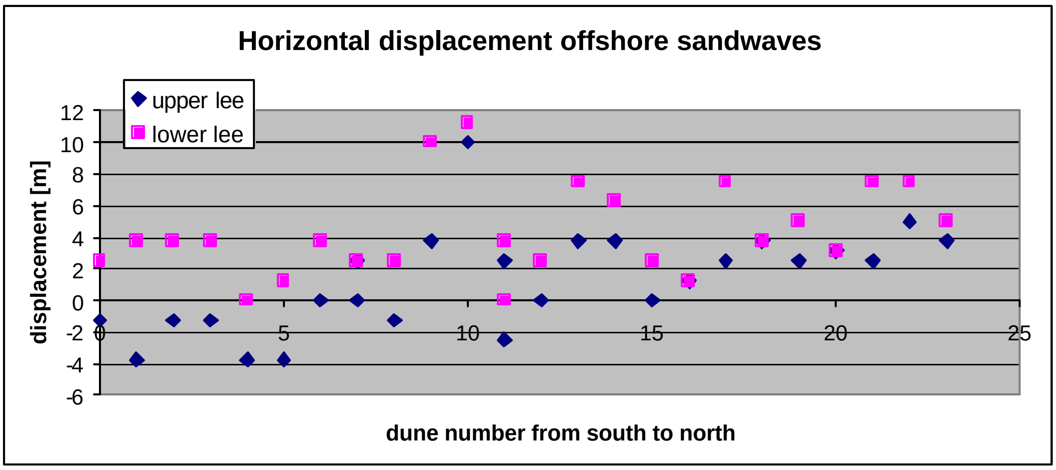

Figure 5: migration rates of upper and lower lee slope of individual sandwaves in the offshore area.

Interpretation and discussion

1. effects on morphology

Based upon the classic literature of marine bedforms, long and low sandwaves with dune indices larger than 15, and asymmetric sandwaves with symmetry indices larger than 3 are interpreted to be current-generated (Allen, 1968; Collinson and Thompson, 1989). Lee sides facing north-northeast and north-northeastly-migrating sandwaves agree with the flood-dominated tidal currents. The continuous, two dimensional, straight- and sharp-crested sandwaves in the offshore area, however, would classically suggest a wave-generated origin (e.g. Reineck, 1961 in:Allen, 1968; Collinson and Thompson, 1989), although Allen (1968) argues that many trains of straight-crested, two-dimensional ripples were observed on beds of gently flowing streams which are unaffected by surface waves.
The occurrence of the 3D sandwaves seems to be limited to the shoreface-connected ridge. 2D Sandwaves in offshore area are not restricted in their lateral continuation.

The flattening of sandwaves in the coastal area may be due to vertical confinement. However, waterdepths of 14 to 17 m would allow bedform heights of 2.3 to 2.8 m, which is 1/6 of these waterdepths (Yalin, 1972). Moreover, Flemming (2001) concluded that waterdepth is not the primary control on bedform height. Instead, the flattening may be caused by the truncation of sandwaves due to wave action during gales or storms in such a magnitude or frequency that the sandwaves cannot be built up again before another truncation. Wave theory calculates that during fair weather conditions, such as in January to March 2001 with surface wave heights between 0.3 and 2.5 m, Shields mobility parameters at these waterdepths are mostly below the critical value of 0.03 to 0.06 (for equations see Kleinhans et al., this volume). Figure 6A shows that only waves with significant waveheights of >2m and periods of >5s exceed the threshold for motion at the bed at 14-17 m waterdepth. These and larger waves, such as occurred in July and September 2001, are able to truncate the sandwaves or remold the smaller bedforms into wave-generated bedforms. At the offshore site, waterdepths are sufficiently large to reduce the frequency or magnitude of surface wave impact on the sandwaves. For currents, the critical Shields parameter is only exceeded at current velocities larger than 0.4 m s^{-1} (Figure 6B). Hence, only during the largest flow velocities of spring floods are sediment mobility is suficient to change the seabed in the North Sea.

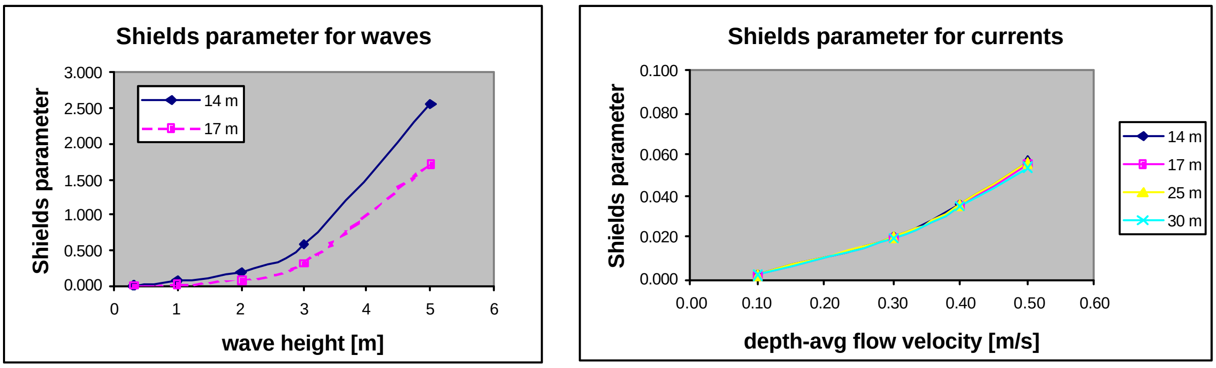

Figure 6: Shield parameter plots for A. surface wave height and
B. depth-averaged current velocity at different waterdepths.

The absence of megaripples on lee slopes of sharp-crested sandwaves *versus* the presence of megaripples on the on lee sides of rounded sandwaves was previously attributed to the uni-directional current with flow separation in the former situation and a bi-directional current with unseparated flow in the latter situation (Figure 9.35 in: Reading, 1986). In this paper, the absence of megaripples on the lee slopes of sandwaves in the offshore area suggests that flow separation occurred, despite the low gradients. These contrasting processes were previously explained by a different asymmetry in tidal curves (Reading, 1986). However, both types of sandwaves occur within the same site in which tidal curves are expected to be similar. Also, the morphology of sandwaves in coastal and offshore areas are very different, whereas the surface tidal curve asymmetry in both areas are very similar (*www.waterbase.nl*). It is therefore suggested that the asymmetry of the tidal curve does not control the morphology of the sandwaves and that the threshold gradient for flow separation to occur is 2º.

The angle between the crest orientations of sandwaves and superimposed megaripples in the offshore area has previously been interpreted as caused by the variation of the tidal current direction over sandwaves (Hennings *et al.*, 2000). Indeed, this may explain the deflection of megaripple orientations, however, not the angle between crests of superimposed bedforms. The reported deflection of the tidal current is confirmed by the systematic change of megaripple crest orientations over the length of a sandwave, as observed in the offshore area (Figure 4). Here, megaripples near the sandwave crests are oriented approximately normal to the overall tidal current direction (measured 19º on surface current charts). The megaripple orientation on the lower stoss and in troughs are rotated by the deflected flow, but why the sandwave crests are orientated 91° remains unexplained. The hypothesis that sandwaves are relict forms from former conditions (e.g. Hennings *et al.*, 2000) has been refuted by *(i)* their "non-degraded" (i.e. sharp-crested) cross sectional profiles, *(ii)* the positive relation between upper/lower lee migration, and, *(iii)* albeit slowly, they migrate (rates > 0 m a^{-1}) and aggrade vertically and are thus contemporarily being developed.

In the coastal area, both sandwave and megaripple crests are oriented approximately normal to the surface tidal current of 19°, parallel to the coastline. The current deflection at this site seems minor with megaripple crest orientations on the stoss slopes of 103° and showing adjustment to the orientation of the sandwave crests when approaching these crests. Although less than in the offshore area, the large-scale morphology controls the orientation of the megaripples by deflecting the local flow.

The different appearance and form (offshore area) of megaripples over the length of a sandwave suggests that not only flow direction is different but that the flow type or velocity also differ over the length of a sandwave. Different appearances of megaripples over the length of a sandwave cannot be due to different ensonification angles of the sidescan sonar, since the sidescan sonar tracks were sailed in the migration direction of the sandwaves.

2. effects on morphodynamics

The always northward directed migration, the high migration rate and the vertical displacement of zero to negative, suggesting erosion, of sandwaves in the coastal area *versus* the lower migration rates and horizontal displacement varying between southward, northward and zero and the always positive vertical displacement, suggesting deposition, in the offshore area reveal that the dynamic behaviour of sandwaves in the North Sea is highly variable. Both the sandwave asymmetry and their migration rates indicate that the mobility of sandwaves due to tidal currents is larger in the coastal area than in the offshore area. The different migration behaviour of sandwaves in the coastal and offshore areas is explained by the higher current velocities in the coastal site.

The calculations of Shield parameters (Figure 6) show that during fair weather conditions in March, when wave action is subordinate near the bed, the megaripples are well developed, whilst in all other seasons, when wave action is more effective near the bed, megaripples are poorly developed or absent. At the offshore site, megaripples are also developed best under fair weather conditions in March, and the remolding of the bedforms is less than in the coastal area. Both the contrast over time and between the two sites of different waterdepth support the hypothesis that wave action controls the small-scaled morphology (megaripples) of the seabed.

Conclusions

1. The flattened sandwaves in the coastal area result from the truncation of sandwaves caused by wave action during gales and storms. Waterdepths in the offshore area are sufficient to reduce the frequency or magnitude of surface wave impact on the sandwaves.
2. Megaripples are formed by maximum tidal currents under fair weather conditions and remolded or obliterated by wave action during near gales, gales and storms.
3. The threshold of lee slope gradients for flow separation to occur is 2^o and determines the occurrence of megaripples on the lee slopes of sandwaves.
4. The mobility of the sandwaves in the coastal area due to tidal currents is larger in the coastal area than in the offshore area.
5. The offshore sandwaves are not relict forms but active sandwaves.
6. The variable orientations and appearances of megaripples over the length of a sandwave are explained by the deflection of the local flow by the large-scale morphology of sandwaves. This effect is largest in the offshore area and smaller in the coastal area. However, the angle between the sandwave and megaripple crests in the offshore area versus the parallelism of them in the coastal area remain unexplained.

Acknowledgements

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