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Sandbank occurrence on the Dutch continental shelf in the North Sea

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Abstract Sandbanks, the largest of bed patterns in shallow sandy seas, pose a potential risk to shipping. They are also valuable elements of natural coastal protection, dissipating the energy of waves. In the Southern Bight of the North Sea, several sandbank areas have been reported in the literature. However, based on an objective crest–trough analysis of the bathymetry of the Dutch continental shelf, the present study shows that sandbanks are more widespread than commonly considered. These banks are relatively low, presumably explaining why they have not been documented before. This widespread occurrence of sandbanks in the North Sea is in agreement with theoretical predictions based on stability analysis techniques. The possible interference between large-scale human activity and low-amplitude open-shelf ridges implies that one should be careful not to overlook these patterns if none should appear in a preliminary (visual) assessment. The only part of the Southern Bight in which no ridges can be seen is a circular area with a diameter of about 50 km near the mouth of the river Rhine. Here, freshwater outflow affects the direction of tidal ellipses and residual flow, and suppresses the formation of open ridges.

Introduction

Sandy beds of shallow seas are covered by a wide range of bed patterns. The largest of these, sandbanks, are well known for the risk they pose to shipping. Even in modern times of high-performance navigation equipment, occasionally a ship becomes stranded on a sandbank during a storm. Nearer to the coast, their impact can be more positive. The limited depth above sandbanks dissipates much energy from waves and storm surges, reducing erosion forces on the coast. Dyer and Huntley (1999) distinguish four types of sandbanks: moribund ridges, headland banks related to coastal headlands, estuarine banks situated in the mouth of estuaries, and open-shelf ridges. The latter, which can be tens of metres high with a spacing of 5–10 km, form the focus of this paper.

Open-shelf ridges have been observed in sandy shallow shelf seas all over the world (Off 1963), including the Korea Straight (Park et al. 2003), the east coast of Australia (Harris et al. 1992) and along the east coast of North America (Swift et al. 1978; Dalrymple and Hoogendoorn 1997; Goff et al. 1999). The Southern Bight of the North Sea displays several ridge areas, as has been reported by van Alphen and Damoiseaux (1989) and Dyer and Huntley (1999): the *Norfolk Banks*, the *Flemish Banks*, the *Dutch Banks*, the shoreface-connected ridges of the Dutch shoreface, and the *Zeeland Ridges* (see Fig. 1).

Open-shelf ridges can be subdivided into tidal sandbanks and shoreface-connected ridges. Offshore, the crests of tidal sandbanks are at small angles counter-clockwise to the direction of the tide (Dyer and Huntley 1999) in the Northern Hemisphere, and clockwise in the Southern Hemisphere. Tidal sandbanks can be kilometres long and tens of metres high with a spacing of 5–10 km. Closer to the coast, the orientation of the ridge crests is influenced by the coast and the shoreface (Trowbridge 1995). On the landward side the ridges are connected to the shoreface, with the seaward side facing into the yearly averaged residual current, explaining why they are called shoreface-connected ridges. Their spacing and height are slightly smaller than those of tidal sandbanks, i.e. roughly 3–5 km and 5–7 m respectively.

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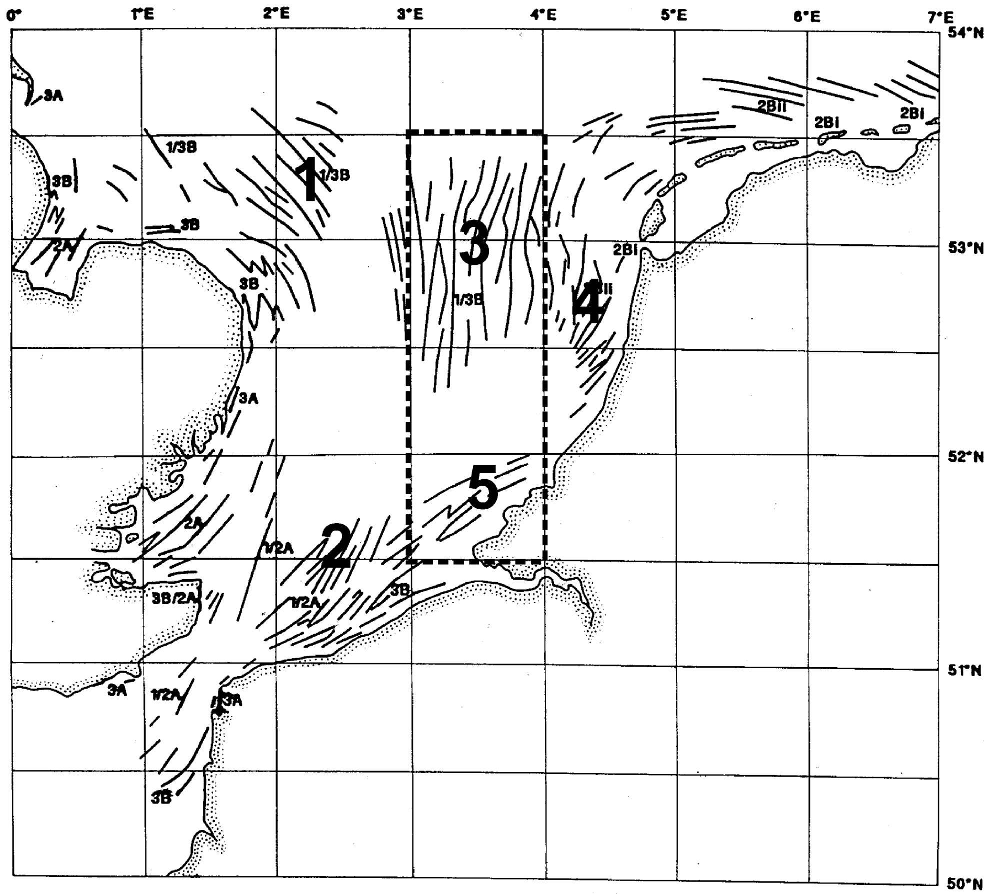

Fig. 1 Presence of tidal sandbanks on the Dutch continental shelf in the North Sea, based on literature available to date (van Alphen and Damoiseaux 1989; Dyer and Huntley 1999): *1* the Norfolk Banks, *2* the Flemish Banks, *3* the Dutch Banks, *4* the shoreface-connected ridges of the Dutch shoreface and *5* the Zeeland Ridges. The *dashed rectangle* denotes the area investigated by Roos et al. (2004)

There are varying scientific views on mechanisms explaining these ridges. Among geologists, there is consensus that many open-shelf ridges or, at least, their cores are remnants of the moraines of glaciers (Houbolt 1968; Berné et al. 1994). Pingree and Griffiths (1979) showed a positive relationship between the convergence zones of tidal shear stress around the British Isles and the distribution of ridges. Huthnance (1982) identified instability at the interface between water and sediment under tidal flow, which results in the development of tidal sandbanks. Following Dyer and Huntley (1999), open-shelf ridges may well result from combinations of these mechanisms. Moribund features are reshaped to fit present-day conditions, as described by Pingree and Griffiths (1979) or Huthnance (1982).

More recently, modellers have successfully simulated the development of tidal sandbanks (Hulscher 1996; Roos et al. 2004) and shoreface-connected ridges (Calvete et al. 2001), following the ideas of Huthnance (1982) and Trowbridge (1995) respectively. However, they have been unable to explain the patchy occurrence of sandbanks in the North Sea described in the literature, and shown in Fig. 1 (van Alphen and Damoiseaux 1989; Dyer and Huntley 1999).

For one, the flow conditions are far too regular to result in such abrupt variations in the occurrence of sandbanks. Notably, Hulscher and van den Brink (2001) and van der Veen et al. (2006) predict a more regular occurrence of sandbanks covering most of the southern North Sea. There are also no indications that variations in sediment characteristics could result in the patchy occurrence of the sandbanks (van der Veen et al. 2006).

Materials and methods

Bathymetry of the Dutch continental shelf

The research presented here is based on bathymetric surveys resulting from echo soundings by the Dutch Hydrographic Office and the Ministry of Transport, Public Works and Water Management. The bathymetry of the Dutch continental shelf was composed as a mosaic of survey data collected over about 10 years. The data were stored on a rectangular grid with a spacing of 200 m in both horizontal directions.

The accuracy in the positioning during the collection period has improved from errors in the order of tens of metres in 1994 to about 2 m now. The error margin of individual measurements in the vertical is 20–25 cm and fairly constant during the period. This mosaic incorporates some additional errors due to the datasets not being collected simultaneously. It can be assumed that these are negligible for the analyses of sandbanks, of which the dynamics take place on timescales of decades to centuries and on length scales of kilometres.

Crest and trough detection

The crest and trough detection is based on a two-dimensional version of the widely used profile analysis for rhythmic bed patterns (e.g. O'Connor 1992; Lanckneus et al. 1994).

The bathymetry is smoothed using weighted averaging in which the weight reduces linearly with distance (13-point Bartlett window) to remove the local minima and maxima related to the smaller-scale sand waves. The size of this window (2,600 m) is less than the typical wavelength of sandbanks and larger than the typical size of sand waves. The data are then analysed along lines parallel to the east–west axis. Since the offset of these lines relative to the principal axis of the tide is no more than 45° (van der Molen 2002), the crests of the sandbanks can easily be detected along the lines.

The crest and trough positions are defined as the location of the highest and lowest points in the smoothed profiles respectively. Height of the sandbanks is defined as the vertical difference between the crest and the line connecting two neighbouring troughs. Knaapen (2005) determined the height directly from the smoothed data but this leads to an underestimation. The analysis is now adapted by fitting a fourth-order polynomial through the measurement points in the unfiltered data in the vicinity of the extreme points in the smoothed profile. This is a minor variation to the technique applied successfully to analyse sand waves (Knaapen 2005) and mega-ripples (Knaapen et al. 2005). In Roos et al. (2004), this technique is used to visualise the abundance of sandbank occurrence in a part of the Dutch continental shelf (shown by the dashed rectangle in Fig. 1). Here, I extend this work to the complete Dutch shelf and compare the findings to the existing literature.

Results

Sandbank occurrence in the North Sea

Figure 2 shows the bathymetry of the Dutch continental shelf. The *Dutch Banks* as well as the *Zeeland Ridges* can be distinguished clearly in the central and southern part of the image respectively. Some shoreface-connected ridges can be seen in the east of Fig. 2, adjacent to the coast.

Figure 3 shows all the local maxima in the bathymetry along the east–west profiles. The thickness and colour of the dots is proportional to the local ridge height, thereby including the variation in height along the crest. Despite some remaining noise, the sandbanks can clearly be identified from elongated rows of dots.

Most dominant are the *Dutch Banks* (area 3, Fig. 3). The height in this area varies between about 7.5 and the 29 m of the Brown Bank. In the southern part of the research area, the *Hinder Banks* are visible (southwest of area 8). The height of these banks measures 5 to 7.5 m. The *Zeeland Ridges* (area 5, Fig. 3) reach heights of 15–20 m. The shoreface-connected ridges along the Dutch coast (area 4, Fig. 3) reach heights of about 7.5 m, whereas those along the Wadden Sea islands reach heights of only 2.5–3 m (area 6, Fig. 3). Above the Zeeland Ridges, some low (2.5–5 m) tidal sandbanks are visible, which progressively merge in the direction of area 9.

The only part of the Southern Bight in which no open-shelf ridges can be seen is a circular area with a diameter of about 50 km near the mouth of the river Rhine (area 9). In most of this area, short-crested maxima are present without a clear crest orientation. The crest height varies between 2.5 and 5 m.

North of the *Dutch Banks*, some ridges appear in a 'v-shape' configuration (area 7). In area 8 (Fig. 3), where the *Dutch Banks*, the *Hinder Banks* and the *Zeeland Ridges* meet, tidal sandbanks and shoreface-connected ridges coexist, resulting in a typical pattern resembling an egg box (see Fig. 4).

In the southwest sector of Fig. 3, a pattern is visible with a height between 5 and 7.5 m, and a much denser spacing. The orientation is completely different from that of both the sandbanks and the shoreface-connected ridges.

Discussion

All papers describing the sandbanks in the North Sea (e.g. Dyer and Huntley 1999; van de Meene and van Rijn 2000; Knaapen et al. 2001) refer to the work of van Alphen and Damoiseaux (1989). This work is based on navigational maps, showing the minimum water depth per area of 1 km^2. With this resolution, noise by sand waves, bed patterns with a wavelength of about 250 m and crests perpendicular to the tidal current which can be several metres high, will mask any sand ridge that is lower. Consequently, van Alphen and Damoiseaux (1989) present only the larger sand ridges (about 5 m and higher). The 250-m resolution of the dataset used for the present work allows for a more detailed investigation. In fact, the technique proposed by Knaapen (2005) would detect every ridge or bank, even those with very low amplitudes in the order of 1 m. It also determines their length and spacing, including their along-crest variability. Such a detailed analysis of bathymetric data has not been reported in the literature yet.

Existing literature on sandbanks has focused on the higher sandbanks and shoreface-connected ridges. Off (1963) gives an overview of sandbank occurrence worldwide and their heights. The lowest offshore features mentioned are about 4 m (12 ft) high in the Persian Gulf (tidal sandbanks) and the

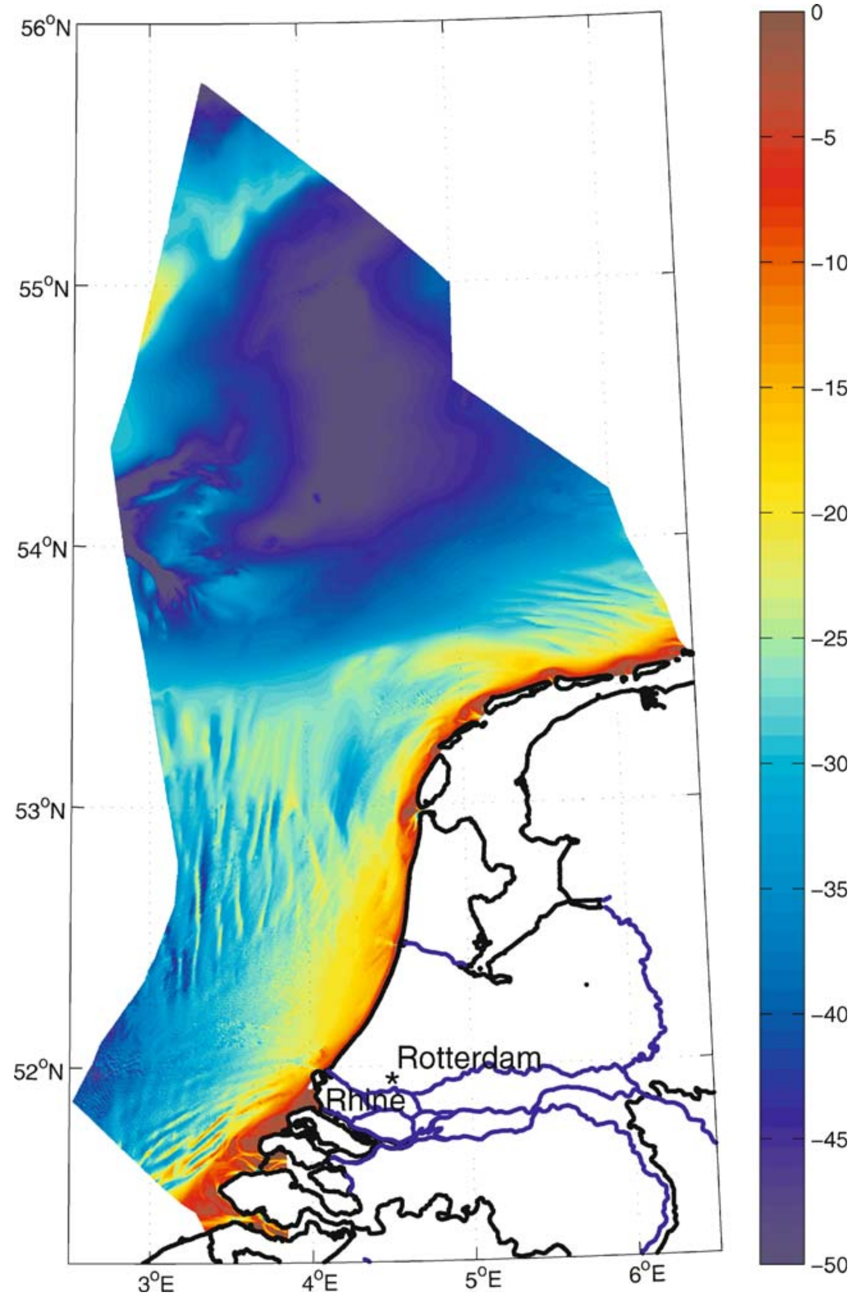

Fig. 2 Detailed bathymetry of the Dutch continental shelf, used in the present study. The bathymetry (*colour scale*) is given in metres relative to mean sea level

Coast of Borneo (shoreface-connected ridges). The majority consist of banks in the range of 10 to 30 m. In the North Sea, neither van Alphen and Damoiseaux (1989) nor Dyer and Huntley (1999) give any bank heights. van de Meene and van Rijn (2000) describe the Dutch shoreface-connected ridges as being 2–6 m high. Roos et al. (2004) give profiles showing 8–12 m banks for the Dutch sandbanks and 20–28 m features for the Flemish Banks. Other work focuses on individual banks: the Middelkerke bank is about 20 m high (Trentesaux et al. 1999).

The results presented above show that the open-shelf ridges are spread over a larger area than has been reported by van Alphen and Damoiseaux (1989) or Dyer and Huntley (1999). According to Fig. 1 (based on Dyer and Huntley 1999), the ridges occur in patches with links between the *Dutch Banks* (area 3) and the *Dutch shoreface-connected ridges* (area 4), and a narrow corridor along the Wadden Sea islands to the shoreface-connected ridges in the German Bight (unspecified in Fig. 1 but shown as area 6 in Fig. 2). In reality, however, there is hardly any patchiness in occurrence. The *Dutch shoreface-connected ridges* merge completely with the *Dutch Banks*, and the narrow corridor above the Wadden Sea islands is an integral part of the *Dutch Banks*. The latter extend south to the *Hinder Banks* which, in turn, are linked to the *Flemish Banks* immediately south of the study area (see Fig. 1). These Hinder Banks are part of a

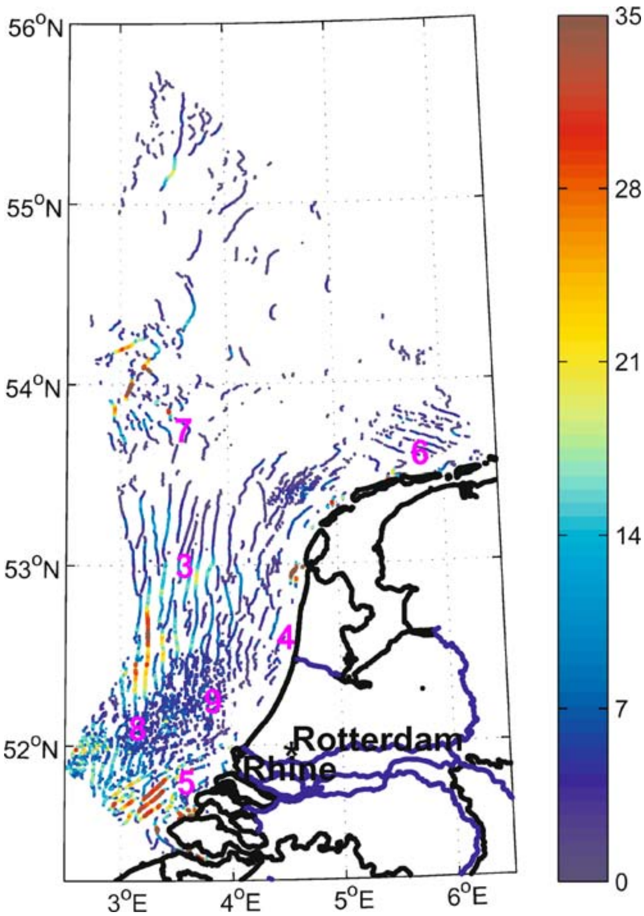

Fig. 3 Crests of sandbanks on the Dutch continental shelf, based on an objective crest–trough analysis. The *colours* are proportional to the height of the sandbank on a particular profile

group which stretches much further east than has been known so far. A narrow band is still visible between the areas 5 and 9 in Fig. 3.

The absence of sandbanks near the mouth of the river Rhine can be explained by the outflow of the Rhine. According to de Boer et al. (2006), this freshwater flux affects the flow in the wide vicinity of the mouth. The salinity gradient has a direct effect on the tidal flow in a plume extending about 25 km offshore and about 50 km alongshore. This area corresponds well with the area devoid of bed forms in Fig. 3, between the Rhine mouth and area 9 that shows no crests at all. However, the influence of freshwater on the direction of the tidal ellipses reaches much further west. de Boer et al. (2006) show that the tidal ellipses are affected by freshwater flow up to at least 40 km offshore, this being the boundary of their study area.

In the area around the freshwater inflow, the tidal ellipses are cyclonic during neap tide and anti-cyclonic during spring tide, an effect related to the ratio between the tidal current velocity and the freshwater outflow. According to Besio et al. (2006), the orientation of tidal sandbanks is related to the direction of the tidal ellipse. With a cyclonic tidal ellipse, the sandbank crests are offset clockwise whereas, with an anti-cyclonic ellipse, the offset is counter-clockwise (in the Northern Hemisphere). If the direction of the tidal ellipses changes as a result of a changing ratio between freshwater flow and tidal flow, any ridge pattern will readjust to the new situation. With a rapidly changing orientation, it seems likely that this will restrict the growth of a directional ridge. As a result, the dominating patterns would be directionally neutral, e.g. round, with a wavelength similar to that of tidal sandbanks and with minimal height. This would explain the unstructured and localised maxima recorded in area 9.

The classification of the *Zeeland Ridges* is still being discussed. Their orientation fits well with the definition of shoreface-connected ridges (Trowbridge 1995) but a proper shoreface is missing, due to the delta formed by the rivers Scheldt and Meuse. Besio et al. (2006) classify the *Zeeland Ridges* as tidal sandbanks of which the orientation is affected by the anti-cyclonic direction of the tidal ellipse. In area 8, however, the anticlockwise- and clockwise-oriented ridges coexist. It is impossible to explain this coexistence with the theory of Besio et al. (2006). This coexistence suggests that the *Zeeland Ridges* are indeed shoreface-connected ridges.

The v-shape pattern in the patch of ridges immediately north of the Southern Bight (area 7) suggests that these are remnants of the Holocene Rhine delta. However, as argued by Fitch et al. (2005), the present-day morphology may not match the Holocene topography. Since then, some sediment transport will have taken place, and it is unclear how this has affected the morphology.

The pattern with the shorter spacing in the southwest of the Dutch continental shelf is the long bed-wave described by Knaapen et al. (2001), which is found superimposed on the Hinder Banks (left of area 8).

Open-shelf ridges: scientific implications

Although the newly identified open-shelf ridges are relatively low, the fact that the ridges are so widespread has both scientific and practical implications.

The model of Hulscher (1996) is based on a linear stability analysis. Hulscher and van den Brink (2001) showed that this model predicts more tidal sandbanks in the Southern Bight of the North Sea than the number reported by Dyer and Huntley (1999). According to van der Veen et al. (2006), incorporating a grain size-dependent critical shear stress gave little improvement in the comparison between the model prediction and earlier observations. It has to be noted that van der Veen et al. (2006) use the critical shear stress only as a threshold for sediment movement, not as a process causing a reduction in sediment transport.

The present findings, however, show that the predictions by Hulscher and van den Brink (2001) and van der Veen et al. (2006) are correct for the Dutch shelf. This strengthens the

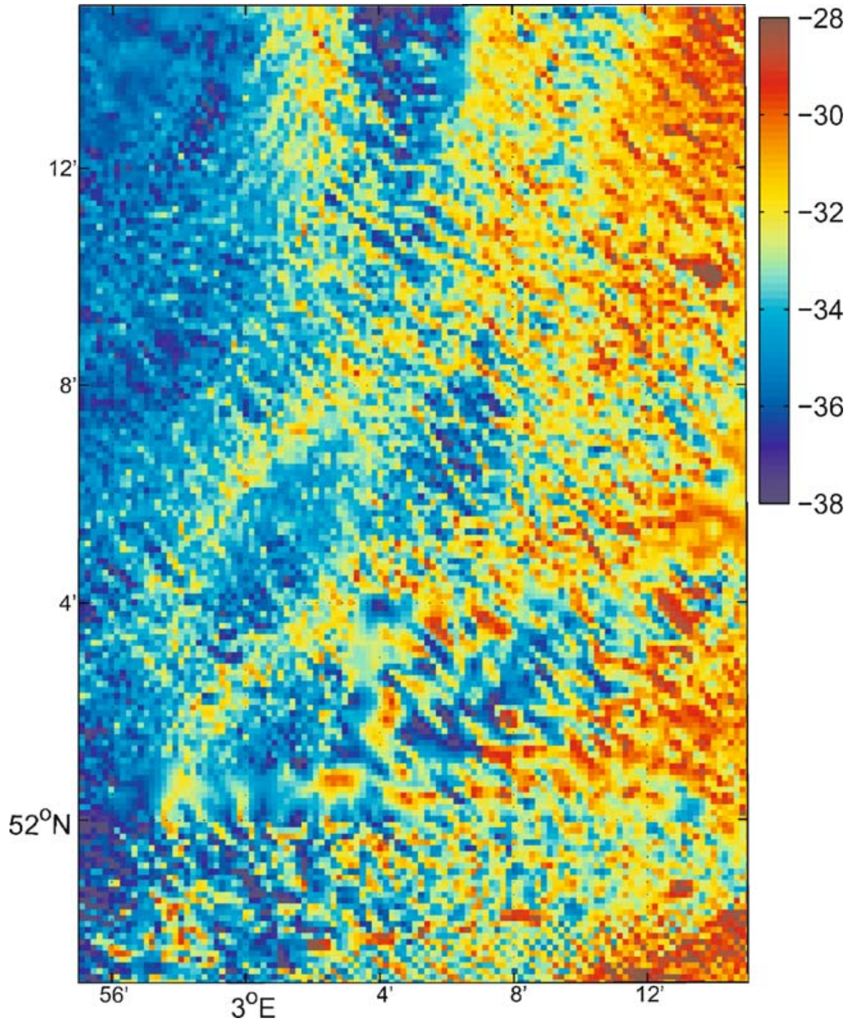

Fig. 4 Tidal sandbanks (*crests roughly north to south*) and shoreface-connected ridges (*crest southeast to northwest*), coexisting and creating a pattern resembling an egg box. The bathymetry (*colour scale*) is given in metres. The plot covers an area of 25 by 35 km

idea that the ridges in the Southern Bight of the North Sea indeed result from instabilities at the interface between the persistent tidal flow and the sandy bed.

Since the process-based model of Hulscher (1996) depends only on processes inherent to all sandy shallow seas, i.e. the tide (M_2), a bed resistance parameter and the turbulent viscosity, it is very unlikely that the model predictions would be accurate only within the North Sea. According to Hulscher's model, tidal sandbanks develop in areas with fine to medium sand and with sufficiently large tidal velocities (0.6–1 m s^{-1}). In combination with the observation made here that such an area is completely covered by ridges, this implies a similar pattern would exist in comparable areas elsewhere. If these ridges have not yet been observed in parts of such areas, then detailed analyses of bathymetric surveys should reveal low-amplitude ridges in these parts.

The pattern with the characteristics of shoreface-connected ridges implies that these ridges extend further offshore than expected. It is likely that the crests of these patterns are 'infinitely' long with a gradually decreasing height offshore. This would be in agreement with Calvete et al. (2001) who, based on the assumption of an unlimited sloping shoreface, indeed predict such shoreface-connected ridges. Furthermore, tidal sandbanks and shoreface-connected ridges can occur simultaneously. This implies that they are related to different elements of a given flow condition. Thus, the present observations confirm the hypotheses in the literature that tidal sandbanks are related to tidal currents (Huthnance 1982; Hulscher 1996) and that shoreface-connected ridges are related to storm conditions (Trowbridge 1995; Calvete et al. 2001).

Open-shelf ridges: economic implications

The intensity of human activity on the Dutch shelf is increasing rapidly. So far, the effects of pipelines, platforms and dredging on the seabed itself have been limited. Marine constructions do cause local scour but, since the impact on the hydrodynamics and sediment transport is limited, the spatial extent of scour pits is limited to tens of metres (Whitehouse 1998). This scour has its effect on the stability of the constructions but does not affect the surrounding bathymetry. The spatial impact of relatively small-scale sandpits (6×

10^6 m^3) on the seabed is also limited to the direct surroundings of the pits (van Rijn et al. 2005), at least on timescales investigated so far (a few years).

However, if these activities affect the flow and sediment transport on a larger scale, such as in offshore gas mining (Fluit and Hulscher 2002) and large-scale sand mining (>50× 10^6 m^3; Roos and Hulscher 2003), then they might interact with the tidal sandbanks. Through interference, this interaction can lead to significant amplification of the sandbank pattern (Roos and Hulscher 2003). This amplification is not likely to affect large-amplitude banks, where wave action is limiting the height (Roos et al. 2004). An amplification of low-amplitude sandbanks and ridges, however, can lead to significantly higher patterns, reducing a navigation depth already critical in the Southern Bight of the North Sea, and to changes in the tidal flow conditions (Huthnance 1982).

In theory, this can be avoided by planning the large-scale activities away from areas in which sandbanks or shoreface-connected ridges occur. The present observations show, however, that it would be impossible to find areas without ridges, except close to the main navigation channel to Rotterdam Harbour. Consequently, it will be necessary to account for interactions between large-scale activities and the ridges on the complete Dutch continental shelf.

As the magnitude of the strength of the interference depends on the shape and orientation of disturbance due to human activity (Roos and Hulscher 2003), it would be wise to use this information in the planning of large-scale activities and design these such that the risk of interference with the sandbanks and ridges is minimal.

Conclusions

From the present bathymetric data, it is evident that the Dutch part of the Southern Bight of the North Sea is almost completely covered by sandbanks. It displays two different large-scale rhythmic patterns: tidal sandbanks, with the crests at a small anticlockwise angle relative to the principal tidal current, and shoreface-connected ridges with a small clockwise angle between the crests and the tide.

Many more sandbanks were observed in the present analysis than has been reported in the literature. The widespread occurrence of these tidal sandbanks agrees with model predictions based on a stability analysis (Hulscher and van den Brink 2001; van der Veen et al. 2006). Many of these features are relatively low, which would explain why they have not been observed before.

The only sector of shallow water without sandbanks on the Dutch continental shelf is affected by Rhine freshwater outflow. Changes in the direction of the tidal ellipses resulting from this freshwater suppress the growth of sandbanks of defined orientation.

In some parts, low-amplitude tidal sandbanks and shoreface-connected ridges occur together. Therefore, these patterns need to be related to different hydrodynamic processes at that location.

The possible interference between large-scale human activity and low-amplitude open-shelf ridges implies that caution is needed when neglecting this aspect in coastal management, even if the presence of these ridges were not to be identified in the course of routine mapping.

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