On waterspouts related to marine sandwaves

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Abstract

During the first experiment of the “Operational radar and optical mapping in monitoring hydrodynamic, morphodynamic and environmental parameters for coastal management (OROMA)” project within the Fifth Framework Programme of the European Commission (EC) unique hydrodynamic mechanisms related to marine sandwaves have been observed. The sea bed morphology of the Lister Tief, a tidal inlet of the German Bight in the North Sea, reveals a complex configuration of different bedforms being four-dimensional in space and time. A significant upward orientated component u_{vert} of the three-dimensional current velocity field has been measured by the Acoustic Doppler Current Profiler (ADCP) as straight lines at tidal current speeds > 0.4 m s^{-1}. These marked vertically so called waterspouts are located above the crests of marine sandwaves. They cause upwelled water with turbulence patterns at the water surface and are predominantly visible at low wind speeds of 2 m s^{-1} to 4 m s^{-1}. Often megaripple fans have been developed at the troughs of such marine sandwaves. These megaripple fans are associated with marine sandwaves that have large angles of lee flanks > 10^0 with arcuate crests.

1. Introduction

Already Stewart and Jordan (1964) observed suspended sediment in the water column just over the crests of submerged sand ridges on Georges Shoal of Georges Bank, Gulf of Maine, USA. The current direction was normal to the ridge during these observations. Nearly 20 years later Harden Jones and Mitson (1982) showed that large marine sandwaves between the Sandettie and Outer Ruytingen Banks in the Southern Bight of the North Sea are associated with enhanced noise levels at their crests. They called these features “plume-like traces” which have been recorded by 30 kHz and 100 kHz echo sounders as well as by 300 kHz sector-scanning sonar. Some hypothesises have been discussed by these authors that underwater sound sources might be used by fish shoals as indicators of tidal flow or as acoustic beacons by migrants on passage. It was concluded that the noise was generated by the movement of bottom sediments which might be detected by marine species such as herring and plaice shoals. Furthermore, Harden Jones and Mitson (1982) showed also the relation between the intensity of measured 300 kHz bottom noise and water current velocity associated with a group of small sandwaves lying 150 m to 160 m to the southwest of the Outer Ruytingen anchor station (position: 51^0 06.2’ N, 1^0 53.1’ E). Noise from sandwaves increased with current velocity and bottom noise was not detected at current velocities below 0.4 m s^{-1}. This was an important result because it has to be noticed here that the lower limit of the current velocity of 0.4 m s^{-1} coincides with the lower limit of current velocity when observing significant Normalized Radar Cross Section (NRCS) modulations due to marine sandwaves (Alpers and Hennings, 1984). Stolte (1994) showed distinct links between NRCS and sea surface sonar conditions. Smith (1986) observed on aerial photos a pair of light streaks associated with the crests of submerged ridges in the sea area of Nantucket Shoals, Massachusetts, USA. It is assumed that these streaks are caused by suspended sediment at large tidal current velocities. The streaks often coincided with a boundary between rough and smooth water at the sea surface. Soulsby et al. (1991) showed that the near bed region above the trough of an asymmetric sandwave in the tidal estuary of the river Taw, southeast England, has the largest values of turbulent kinetic energy, Reynolds stress and sediment concentration. The sandwave trough acts as a source of these quantities. At peak flow no flow separation was observed, but during the decelerating phase flow reversed up to 40 % of the time. Until now it has been noticed that strong acoustic scatter is often observed within the water column expected to be turbulent, but it has never been clear if this is because of higher plankton or suspended matter concentration in turbulent regions. Recently, Ross and Lueck (2003) showed that turbulent microstructure strongly scatters sound at 307 kHz.

The investigations carried out during the “Operational radar and optical mapping in monitoring hydrodynamic, morphodynamic and environmental parameters for coastal management (OROMA)” project have the objective to improve the effectiveness of new monitoring technologies such as shipborne imaging radars in coastal waters. In this context some first results of an experiment in the Lister Tief, a tidal inlet of the German Bight in the North Sea, will be presented here. The sea bed morphology of the Lister Tief is shown in section 2. In section 3 selected Acoustic Doppler Current Profiler (ADCP) measurements have been analysed. Some first theoretical considerations are presented in section 4. Finally, section 5 contains the discussion and conclusions.

2. Sea bed morphology

One of the major challenges of morphodynamic modelling is the consideration of different scale interactions of tidal current ridges, marine sandwaves, and (mega) ripples (De Vriend, 1997). A hierarchy of superimposed bedforms on a sand ridge ranging from linguoid ripples, small sandwaves, and up to large marine sandwaves was published by Field et al. (1981). The analysis made by Knaapen et al. (2001) in the southern North Sea has revealed a new regular pattern labelled as long bed waves, in addition to the well-known sandwaves and tidal current ridges. These long bed waves have also been observed already on SEASAT Synthetic Aperture Radar (SAR) imagery in 1978 (Alpers and Hennings, 1984) but little attention was paid to it at that time.

In this section especially the interaction between large asymmetrical marine sandwaves (spacing: 200-500 m) with large lee slopes and associated mega ripples (spacing: > 1 m) located in the troughs of sandwaves will be outlined. A preprocessed map of the sea bottom topography of the whole study area in the Lister Tief as recorded during the OROMA experiment in August 2002 is shown in Figure 1a. The location of the study area is presented in Figure 1b. Sounding tracks at 50 m distances have been gathered by the NAVISOUND 2000 echo sounder in combination with a Differential Global Positioning System (DGPS). The transducer system of the NAVISOUND 2000 echo sounder system was installed at the port side of R.V. *Ludwig Prandtl* at a distance of 20 m from the bow of the ship. The data triplets (x, y, z), with x and y the two horizontal coordinates and z the vertical coordinate, respectively, have been interpolated onto a grid of 20 m by 20 m and is visualized in a map based on Gauss-Krüger-Coordinates as presented in Fig. 1a. The coverage of the rectangular study area is 3850 m by 1350 m. A noisy interrupted signature of a water depth change of a submarine terrain edge ranging from 34 m to 14 m is visible in the northeastern part of the study area resulting due to the applied interpolation technique. The profile of the analysed ADCP measurements (see section 3) is also included in Fig. 1a by the straight line.

The sea bed morphology of the Lister Tief tidal channel is a complex configuration of different bedforms. The sandwaves investigated in this study are four-dimensional in space and time. Small scale as well as megaripples are superimposed on sandwaves. The sandwaves have heights ≤ 11 m and often crest to crest distances (spacings) > 300 m. In the past, systematic morphological investigations have been carried out to study the migration of sandwaves (Ulrich and Pasenau, 1973). In the northern section of the test area most of the sandwaves have ebb tide oriented forms; in the southern part most of them are flood tide oriented. In the southeastern part the stoss slopes of sandwaves are of the order of ?z/?x ≤ 0.017. The lee slopes have maximum values of ?z/?x = 0.591. Sandwaves with a mean height larger than 3 m migrate 60 m - 80 m per year east- or westward depending on the strength of the local flood and ebb tidal current velocity. During every tide a water volume of about $5.25 \cdot 10^8$ m^3 passes the tidal channel, which is bounded by the islands of Sylt to the south and Rømø to the north. These islands are connected by dams to the mainland and therefore the Lister Tief is the entrance of an artifical tidal bight.

Observations made by Aliotta and Perillo (1987) in the mouth of the Bahia Blanca Estuary, Argentina, showed that the orientation of the crestlines and the separation between crests of sandwaves varied according to their position in the field. They reported that the two sectors in which the sandwave field has been divided were almost perfectly separated by bifurcations of the crestlines. The observation of megaripple fans are associated with an angle > 10^0 of the lee flank and an arcuate orientation of the sandwaves, respectively (Aliotta and Perillo, 1987; Hennings et al., 1993). It is considered that the formation of megaripple fans is due to flow separation at the crests of sandwaves. This mechanism is visible at the water surface by the existence of turbulence patterns. The position of such patterns was observed near the crests of sandwaves (Hennings et al., in press). Similar observations have been made in the Brahmaputra river by Coleman (1969).

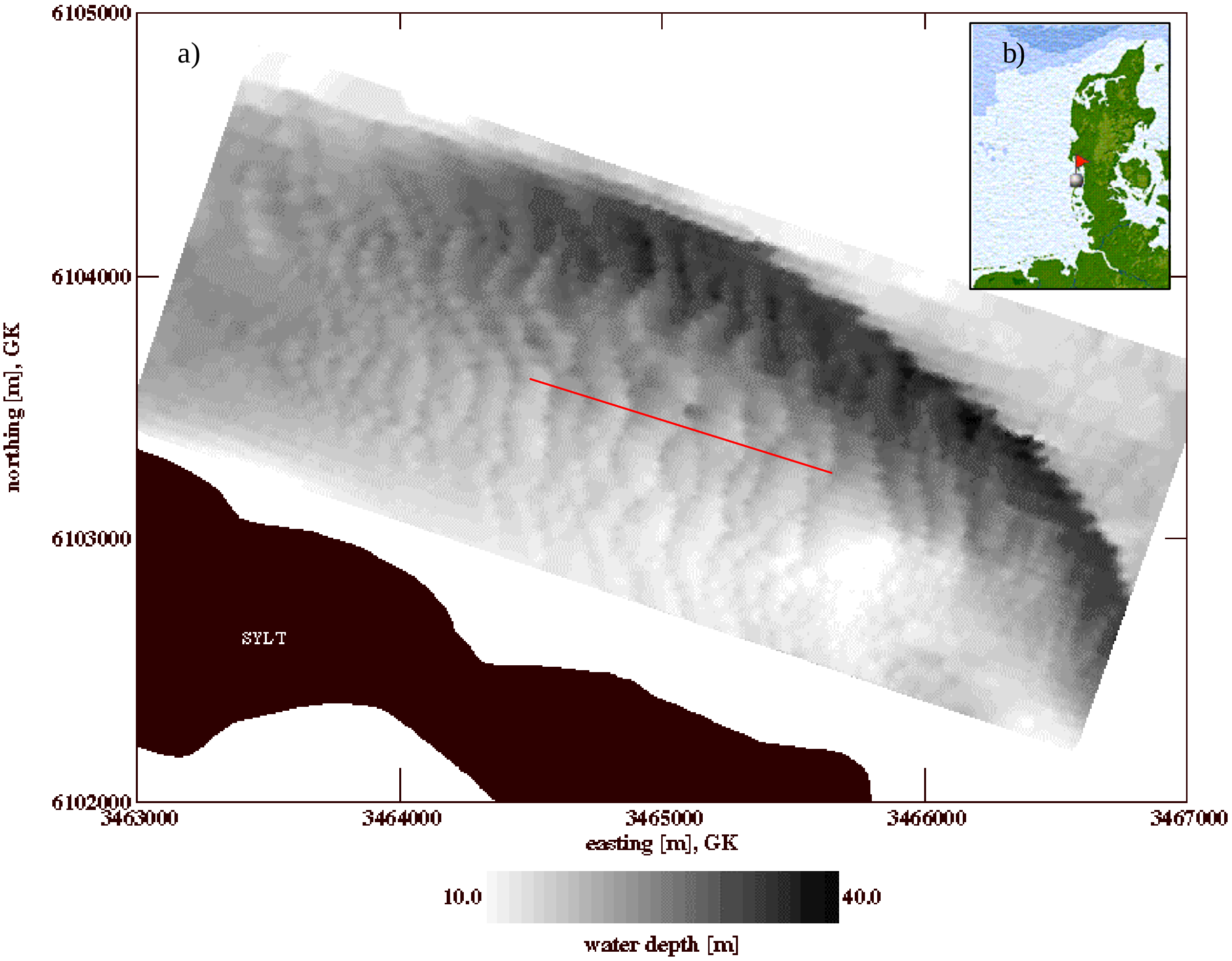

Fig. 1 - a) Preprocessed map of the sea bottom topography of the whole study area in the Lister Tief as recorded by the NAVISOUND 2000 echo sounder in combination with a DGPS system during the first OROMA experiment in August 2002. The data have been interpolated onto a grid of 20 m by 20 m and are

visualized in a map based on Gauss-Krüger-Coordinates. The profile of the analysed ADCP measurements shown in Figs. 2a-b is also included as a straight line. b) Location of the study area in the German Bight of the North Sea.

3. ADCP measurements

Detailed water depth dependent ADCP measurements above asymmetrical flood tide oriented large marine sandwaves have been carried out on 10 August 2002 between 05:00-05:15 UTC on board R.V. *Ludwig Prandtl* during ebb tidal current phase. The analysed section of the profile had a length of 1290 m. Selected ADCP data are shown in Figures 2a-b as a function of the horizontal space component perpendicular to the sandwave crest x_{perp}. All depth cells (bins) with a vertical spatial resolution of 0.25 m have been considered for the calculation of the current velocity covering the water depths between 2.32 m and about 1m above the sea bottom. At the interface between the water and the sea bed the ADCP data have to be considered with caution due to acoustic interference from the sea bottom. The water depth measured by the ADCP is coloured in black in Figs. 2a-b. Water depth measurements derived by the NAVISOUND 2000 echo sounder are indicated by the bright line. The slightly different water depth data are due to the different positions of the transducer systems on board R.V. *Ludwig Prandtl* and the different footprints. All measured ADCP data shown in Figs. 2a-b indicate distinct changes across the track ranging from the near water surface to the sea bed. The most significant variations of all parameters are related to the crests of the sandwaves. The vertical component u_{vert} of the current velocity as a function of x_{perp} and the water depth is presented in Fig. 2a varying between $-10 \text{ cm s}^{-1} \leq u_{vert} \leq 6 \text{ cm s}^{-1}$. Marked waterspouts of the direct upward orientated vertical component u_{vert} of the current velocity have been developed at the crests of sandwaves and are simultaneously superimposed on the divergent zones of the perpendicular component relative to the sandwave crest of the current velocity $?u_{perp} /?x_{perp}$ (Hennings et al., in press). The downward orientated vertical component is located at the troughs and gentle slopes of the sandwaves. The shear of u_{vert} is presented in Fig. 2b as $?u_{vert}/?x_{perp}$ and varying between $-0.002 \text{ s}^{-1} \leq ?u_{vert}/?x_{perp} \leq 0.002 \text{ s}^{-1}$; $(?u_{vert}/?x_{perp})_{max}$ is positioned above the troughs and $(?u_{vert}/?x_{perp})_{min}$ above the crests of sandwaves, respectively.

4. Theory

According to observations made by Stewart and Jordan (1964) and due to the results of the ADCP measurements derived during the first OROMA experiment the assumption of the theory concerning the strain rate published by Alpers and Hennings (1984) has to be reflected again. There was a significant disagreement between theoretically results of the strain rate generated by the surface current published by Alpers and Hennings (1984) and observations obtained by Smith (1986) at the crests of submarine ridges in the sea area of Nantucket Shoals, Massachusetts, USA. This leads to the speculation that the current velocity may not be barotropic near the crests of submarine ridges or marine sandwaves of distinct shapes and that mass conservation may not only be maintained through an acceleration or deceleration of the flow. Assuming an incompressible fluid, the equation of continuity is expressed as

$$\frac{\partial w}{\partial z} = -(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y})$$

(1)

where u, v, and w are the velocity components in x, y, and z directions, respectively.
Solving the vertical component equation of motion for $?w/?z$ equals

$$\frac{\partial w}{\partial z} = -\frac{1}{w}\left(\frac{\partial w}{\partial t} + u\frac{\partial w}{\partial x} + v\frac{\partial w}{\partial y}\right) - \alpha\frac{\partial p}{\partial z} + 2\omega\cos\phi\, u - g + A_x\frac{\partial^2 w}{\partial x^2} + A_y\frac{\partial^2 w}{\partial y^2} + A_z\frac{\partial^2 w}{\partial z^2}$$

(2)

where t is the time, α is the specific volume of water, p is the pressure, ω is the angular speed of rotation of the earth about its axis, ϕ is the geographic latitude, g is the acceleration due to gravity, and A_x, A_y, and A_z, respectively, are the kinematic eddy viscosity components.

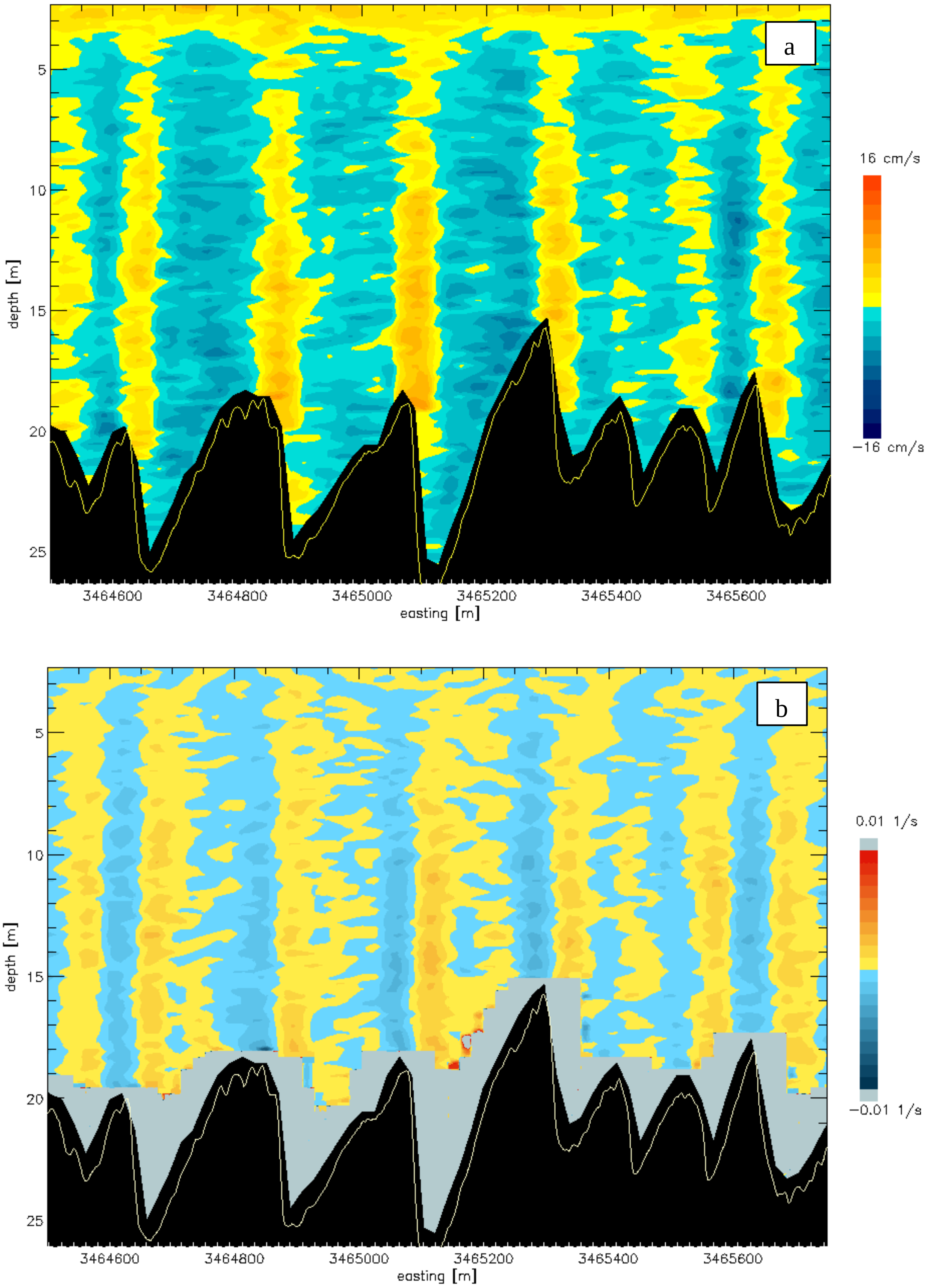

Fig. 2 - a) Vertical component u_{vert} and b) gradient of the vertical component $?u_{vert}/?x_{perp}$ of the current velocity, respectively, as a function of the horizontal space component perpendicular to the sandwave crest x_{perp}. The ADCP data from the near water surface to the sea bed have been obtained on board R.V. *Ludwig Prandtl* during ebb tidal phase on 10 August 2002 during 05:00-05.15 UTC.

Inserting equation (2) into equation (1) yields

$$-\frac{\P u}{\P x} = -\frac{u}{w}\frac{\P w}{\P x}$$
(3)

In this approximation the term -?v/?y has been neglected against the first term on the right hand side of equation (1) because it is always small. Assuming w = constant during the considered time interval then the first term on the right hand side of equation (2) is zero. The third term on the right hand side of (2) and the Coriolis term, as well as the friction terms can be neglected against the remaining terms as a first approximation because they are also small. The pressure term and g cancel each other if the hydrostatic equation

$$a\frac{\P p}{\P z} = -g$$
(4)

is used. Considering only the current velocity component perpendicular to the sandwave crest u_{perp} equation (3) reads

$$-\frac{\P u}{\P x} = -\cos^2 f_t \frac{\P u_{perp}}{\P x_{perp}} = -\cos^2 f_t \frac{u_{perp}}{w}\frac{\P w}{\P x_{perp}}$$
(5)

where ϕ_t denotes the angle between the x and x_{perp} (normal to the sandwave crest) direction.
The result of equation (5) shows that the flow is not of barotropic character near the crests and troughs of marine sandwaves which was also observed in the Lister Tief. This implies that mass is not only be conserved by an acceleration or deceleration of the flow but that up- and downwelling of the three dimensional current field can also play a significant role which is defined as a part of an advective term of the vertical component equation of motion on the right hand side of equation (3).
Inserting the following values derived from the ADCP measurements of $u_{perp} = 1$ m s^{-1}, w = 0.06 m s^{-1}, $\phi_t = 0$, and ?w/?x_{perp} = 0.002 s^{-1} into equation (5) results in -?u_{perp}/?x_{perp} = -0.03 s^{-1} for the strain rate at the crest of a marine sandwave in the Lister Tief. This result overestimates the measured strain rate of (-?u_{perp}/?x_{perp})$_{min}$ = -0.006 s^{-1} derived by the ADCP (Hennings et al., in press). However, the result derived from our theory is comparable with the measured strain rate of ?u_{perp}/?x_{perp} = 0.05 s^{-1} obtained by Smith (1986) at the crest of a submarine ridge in the sea area of the Nantucket Shoals.

5. Discussion and conclusions

During the OROMA experiment in the Lister Tief unique hydrodynamic effects associated with marine sandwaves have been observed. The existence of a significant upward orientated vertical component u_{vert} of the three-dimensional current velocity field measured by the ADCP has been shown for the first time. Marked waterspouts of u_{vert} have been measured in a more or less straight line at the crests of asymmetric flood orientated sandwaves with lee slopes larger than 10^0 at tidal current speeds larger than 0.4 m s^{-1}. These waterspouts created by u_{vert} produce upwelled water and create turbulence patterns at the water surface which are visible at low wind speeds of 2 m s^{-1} to 4 m s^{-1}. The upward orientated patterns of u_{vert} are superimposed on the divergent zones of the perpendicular component relative to the sandwave crest of the current velocity ?u_{perp} /?x_{perp} (Hennings et al., in press). The downward orientated vertical component of u_{vert} is located at the troughs and gentle slopes of the sandwaves. A regular structure of circulation cells of u_{vert} within the water column has been developed during that time of the tidal phase caused by the undulations of the sea bed. The formation of megaripple fans at the troughs of sandwaves is created by strong horizontal and vertical current shear as well as developing flow separation at the crests of sandwaves. It is also concluded that the existence of turbulence patterns at the water surface are hints of megaripple fans at the sea bed due to both large slopes as well as arcuate orientations of submarine sandwaves. Similar signatures described here as waterspouts have been presented by Harden Jones and Mitson (1982) which have been defined there as “plume-like traces”. It is concluded that the assumed sediment movement in their data is triggered by tidally induced waterspouts depending on the shape of marine sandwaves.

The theoretical assumptions showed that the flow cannot be only of barotropic character near the crests and troughs of distinct marine sandwaves. This implies that mass conservation is not only be maintained by an acceleration or deceleration of the flow. Moreover up- and downwelling of the three dimensional current field contribute too to the interaction between the flow and sea bed undulations. The calculated strain rate ?u/?x above the crests of marine sandwaves applying our theory is confirmed by Smith (1986) deriving the same order of magnitude at the crest of a submarine ridge in the sea area of the Nantucket Shoals.

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