Comparison and characteristics of oceanographic in situ measurements and simulations above submerged sand waves in a tidal inlet

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Ocean colour and its transparency are related to turbidity caused by substances in water like organic and inorganic material. One of the essential climate variables (ECV) is ocean colour. However, this implies the correct interpretation of observed water quality parameters. Acoustic Doppler Current Profiler (ADCP) data of the three-dimensional current-field, echo intensity, modulation of suspended sediment concentration (SSC), and related water levels and wind velocities have been analysed as a function of water depth above submerged asymmetric compound sand waves during a tidal cycle in the Lister Tief of the German Bight in the North Sea.

1 Introduction

It is well known that a strong coherence exists between fluctuations of turbidity, phytoplankton, and suspended sediment concentration (SSC) induced by disturbances of tidal current velocities. Substantial phenomena of SSC during two tidal cycles at two anchor stations in the southern North Sea were described by Joseph (1954). There he showed that a phase shift of 30 to 45 minutes happened between turbidity and current velocity maximum.

In situ observations in the past showed that submerged sand waves and internal waves associated with vertical current components can be sources of enhanced SSC in the water column above sea bottom topography. Often, such SSC features can come up to the water surface in shallow tidal seas of the ocean. The study presented by Hennings et al. (2002) showed that in a stratified two water layer system, simultaneous reductions in the near-surface water temperature and beam transmittance have been recorded, whereas fluorescence data are increased above sand waves. A good linear relationship between water depth and total suspended sediment (TSM) data derived from Moderate Resolution Imaging Spectroradiometer (MODIS) measurements above sand ridges in the southern Yellow Sea was found by Tao et al. (2011). The TSM concentration was proportional to the inverse water depth; high TSM concentrations were located above shallow parts of sand ridges. It was shown by Hennings and Herbers (2014) that strong currents flowing over steep bottom topography are able to stir up the sediments to form both a general continuum of SSC and localised pulses of higher SSC in the vicinity of the causative bed feature itself. Tide-dependent variations in the formation and dynamics of suspended sediment patterns coupled to mean flow and turbulence above asymmetric bed forms were examined by Kwoll et al. (2014).

2 Measurements conducted during a tidal cycle

The study area of the Lister Tief is a tidal inlet of the German Bight in the North Sea bounded by the islands of Sylt to the south and Rømø to the north. The positions of analysed runs along transect AB in the Lister Tief are presented in Fig. 1. Tide gauge station List is located 4.8 km southerly of transect AB. The seabed morphology in the Lister Tief is a complex configuration of continuously changing different bed forms. The submerged compound sand waves investigated in this study are four-dimensional in space and time. Small-scale as well as megaripples are superimposed on sand waves as...
presented here and already discussed in Van Dijk and Kleinhans (2005) as well as in Hennings and Herbers (2006). Analysed flood dominated sand waves have stoss slopes of the order of 2° and lee slopes up to 31°.

Water levels measured at tide gauge station List, wind and current velocities, vertical current components $w$, echo intensities $E_3$ of fore beam No. 3 measured by ADCP and calculated SSC modulations expressed as $\log((\delta c / c_0)_3)$ of beam No. 3 as a function of water depth are presented. The constant SSC equilibrium term is defined by $c_0$ and $\delta c$ is the time-dependent perturbation term of the local SSC $c$. All parameters are measured and calculated over submerged asymmetric compound sand waves on the sea bottom during several runs along transect AB.

As an example, measurements during run 51 are shown in Fig. 2 for ebb tidal current phase. The duration of the measurement time is indicated by a vertical black line in Fig. 2a. Each run has been rotated by an angle of 19° in order to direct the current component $u$ perpendicular to the sand wave crest. Hence, the $v$-component of the current field is minimised and can be neglected as a first approximation. The rotation point is marked at the highest sand wave crest along the profile named as reference crest, shown in Fig. 2c to 2e. The current vectors shown in Fig. 2b are water depth averaged velocity values. Time interval of both, wind and current velocity arrows, is 30 s. Especially Fig. 2d illustrates the resuspension expressed by $E_3$ in progress at ebb tides.

### 2.1 Time dependent measurements of vertical water depth averaged data

The base of Fig. 3 is a data set measured on 10 August 2002 between 0516 UTC and 0740 UTC while the research vessel was sailing against the ebb tidal current direction over asymmetric flood orientated submerged sand waves along transect AB. Fig. 3a shows the water level recorded at the tide gauge station List as a function of time. Herein, the acquisition times of five analysed single runs are marked. In Fig. 3b wind speeds are represented by arrows in a geocoded coordinate system. All other data are shown as a function of time and position in east-west direction. Fig. 3c to 3f illustrate time series of vertically averaged values for current component $u$ (east direction, indicated by a compass symbol with a red stick in Fig. 3c), echo intensity $E_3$ of fore beam No. 3 measured by ADCP, vertical current component $w$, and calculated SSC modulations expressed as $\log((\delta c / c_0)_3)$ of beam No. 3. The water depth profiles of the asymmetric sand waves are shown in Fig. 3g to 3h.

Wind speeds between 5.8 m s$^{-1}$ and 7.5 m s$^{-1}$ from northerly directions were measured (Fig. 3b). Negative, enhanced and positive values of $u$, $E_3$, and $w$, respectively, show phase relationships with sand wave crests of the sea bed. In contrast, enhanced $\log((\delta c / c_0)_3)$ shows a phase relationship with the sand wave troughs of the sea bed. The parameters $u$, $w$, and $\log((\delta c / c_0)_3)$ are only weakly time dependent. All signatures of $u$, $E_3$, $w$, and $\log((\delta c / c_0)_3)$, respectively, show spatially dependent variations in $x$-direction above the sand waves.

### 3 Theory of hydrodynamics above submerged sand waves

The focus of this section is the understanding and mathematical description of dynamic buoyancy density, total energy density, and action density above submerged asymmetric sand waves due to semi-diurnal lunar $M_2$ tidal motion. The dynamic buoyancy density $\bar{A}_d$ is defined by

$$\bar{A}_d = \frac{\bar{A}_d}{T - 2\omega} = \frac{1}{2} \rho \cdot (c_0 - 1) \cdot \mathbf{u}^2$$  \hspace{1cm} (1)

where $\bar{A}_d$ is the dynamic buoyancy in the water column of volume $V(x,y,z)$ with the horizontal and
vertical space coordinates \( x, y, \) and \( z, z_b \) is the local water depth, \( F \) is the infinitely thin horizontal plane element, \( \rho \) is the water density, \( c_a \) is the dimensionless lift coefficient, and \( \bar{u} \) is the vertical average current velocity perpendicular to the sand wave crest. The dimensionless lift coefficient \( c_a \) is defined by Dätwyler (1934) for a flat plate as
\[
c_a = \frac{\pi}{\sin(\pi \cdot \beta)} \cdot \left[ \frac{1}{1 - \beta^2} \right]^{\frac{1}{2}}
\]
and
\[
\beta = \frac{\alpha}{\pi}
\]
with \( \alpha \) the slope angle of the stoss or lee plane of the sand wave. Both, stoss as well as lee sides of the sand wave were approximated by a flat plate. However, here \( c_a \) was subtracted by 1 in equation (1), whereas Dätwyler (1934) normalised \( c_a \) by 1.

The reason is here that both upwelling (positive) as well as downwelling (negative) values of \( c_a \) can arise above sand waves. As a first approximation, for the downforce at the lee side of the sand wave, the negative value (downforce coefficient) of the lift coefficient \( c_a \) is used here. Kinematic molecular viscosity and roughness effects at the sea bed are neglected.

The gradient of the dynamic buoyancy density perpendicular to the sand wave crest is derived as
\[
\frac{\partial \rho g D_d}{\partial x} \approx \left( c_a - 1 \right) \rho \bar{u} - \frac{\partial \bar{u}}{\partial x} - \frac{\partial u}{\partial x}
\]
where \( g \) is the acceleration due to gravity and \( z_R \) is the reference water depth at the trough of sand wave.

The action density \( N \) is defined by
\[
N = \frac{E}{\omega'}
\]
where \( \omega' \) is the radial frequency of the semi-diurnal lunar M2 tidal wave with
\[
\omega' = \frac{2 \pi}{T}
\]
where \( T \) is the period of the semi-diurnal lunar M2 tidal wave.

Using equations (4) to (6), the gradient of the action density \( N \) perpendicular to the sand wave crest is derived as
\[
\frac{\partial N}{\partial x} = \rho \frac{g}{2} \frac{\partial z_b}{\partial x} \left( \frac{\partial \bar{u}}{\partial x} + \bar{u} \right)
\]
Equation (8) shows that the gradient of the action density caused by the semi-diurnal M2 tidal wave is anti-proportional to the slope of the sea bed \( \partial z_b / \partial x \) and proportional to the product of the vertical averaged current speed and its gradient \( \bar{u} \cdot (\partial \bar{u} / \partial x) \), respectively.

Assuming that the vertical averaged current speed \( \bar{u} \) perpendicular to the sand wave crest obeys the continuity equation
\[
\bar{u} \cdot z_b = \text{const} = c
\]
and inserting equation (9) into equation (8) for \( \partial \bar{u} / \partial x \), the following expression is derived
\[
\frac{\partial N}{\partial x} = -\rho \frac{g}{\omega} \frac{\partial \bar{z}_b}{\partial x} \left( \frac{\partial \bar{u}}{\partial x} + \bar{u}^2 \right)
\]
where \( \partial N / \partial x \) is proportional to \( \bar{u}^2 \) and \( (z_b)^{-1} \).
For all simulations a sand wave length \( L = 220 \text{ m} \) and a sand wave height \( h_c = 6 \text{ m} \) are selected. These parameters are typical values measured in the southern part of Lister Tief (see section 2). Simulations of the sand wave profile with water depth \( z_b \), slope of the sea bed \( \partial z_b / \partial x \), vertical averaged tidal current speed \( \bar{u} \) and its gradient \( \partial \bar{u} / \partial x \), respectively, dynamic buoyancy density \( A_d \), gradient of the dynamic buoyancy density \( \partial A_d / \partial x \), kinetic energy density \( e_k \), potential energy density \( e_p \), action density \( N \), and gradient of the action density \( \partial N / \partial x \) as a function of space variable \( x \) are shown in Fig. 4a to 4e for ebb tidal current phase of asymmetric flood orientated sand waves. Typical values for the spatial resolutions \( \Delta x = 10 \text{ m} \) and \( \Delta y = 1 \text{ m} \), \( z_R = 25 \text{ m} \), gentle slope of sand wave \( \alpha_g = 2^\circ \), steep slope of sand wave \( \alpha_s = 9^\circ \), \( \rho = 1020 \text{ kg m}^{-3} \), \( \bar{u} = 0.7 \text{ m s}^{-1} \) at \( x \) with \( z_0 = z_R \), \( \bar{u} = 0.95 \text{ m s}^{-1} \) at \( x = 0 \text{ m} \) (sand wave crest), \( g = 9.82 \text{ m s}^{-2} \), and \( T = 12.42 \text{ hours} \) are calculated or inserted by using equations (1) to (10).

The tidal current velocity \( u = \bar{u} \) is presented in black in Fig. 4b during ebb tidal current phase. Due to the continuity equation (9) \( \bar{u} \) acquires its maximum absolute value at the sand wave crest. The gradient of the tidal current speed \( \partial \bar{u} / \partial x = \partial \bar{u} / \partial x \) is shown in red in Fig. 4b. A relative strong divergence flow \( \partial \bar{u} / \partial x = 0.007 \text{ s}^{-1} \) is calculated at the steep slope of the sea bed.

The dynamic buoyancy density \( A_d \), shown in black in Fig. 4c, strongly depends on the slope of the sea bed; a maximum negative value \( A_d = -50 \text{ N (downwelling)} \) is calculated at the gentle slope of the sea bed and a maximum positive value \( A_d = 160 \text{ N (upwelling)} \) is calculated at the steep slope of the sea bed during ebb tidal current phase. A reversal of \( A_d \) is obtained during flood tidal current phase. These simulations agree with ADCP measurements of vertical positive and negative components \( w \) of the tidal current velocity shown in Fig. 2c.

The gradient of the dynamic buoyancy density \( \partial A_d / \partial x \) presented in Fig. 4c in red show low and high negative values at both the gentle as well as the steep slope of the sea bed during ebb tidal current phase. Again, a reversal of \( \partial A_d / \partial x \) took place during flood tidal current phase. Maximum values of \( \partial A_d / \partial x = -2.6 \text{ N m}^{-1} \) are associated with maxi-
maximum values of $\partial u / \partial x = \partial u / \partial x$ as it is also expressed by equation (4).

The potential energy density $E_p$ shown in red and the kinetic energy density $E_k$ presented in black in Fig. 4d, respectively, are always positive and have the same magnitudes during ebb as well as flood tidal current phases. However, the potential energy density $E_p$ is a factor of about 349 to 500 J m$^{-3}$ stronger than the kinetic energy density $E_k$. Maximum values of $E_p$ and $E_k$ are corresponding with the sand wave crest where the current speed maximises.

The action density $N$ shown in Fig. 4e as a black curve, is always positive and has the same magnitudes during ebb as well as flood tidal current phases with maximum $N = 1.13 \times 10^7$ J s m$^{-3}$ at the sand wave crest. The total action density $N$ in the water column presented in Fig. 4e is higher at the spatial longer gentle slope region than at the shorter steep slope region of sand waves. Therefore, more suspended sediment particles are moving upwards which is also shown by the measurements of $E_3$ shown in Fig. 2d. The gradient of the action density $\partial N / \partial x$ coloured in red in Fig. 4e is positive at the gentle slope and negative at the steep slope of the sand wave during ebb as well as flood tidal current phases. Maximum values of $\partial N / \partial x = -6.0 \times 10^6$ N s m$^{-3}$ are related to maximum and high values of $\partial A_d / \partial x$, $\partial u / \partial x = \partial u / \partial x$, and $\partial A_d / \partial x$, respectively.

5 Conclusions

Based on in situ measurements of several oceanographic and meteorological parameters acquired in the Lister Tief, theory and simulations regarding the hydrodynamics above submerged asymmetric sand waves the following conclusions are drawn:

- Sand suspensions strongly depend on wave activity for high concentrations in the water column. Wave orbital motions close to the sea bed are induced by measured wind speeds between 11.7 m s$^{-1}$ and 13.3 m s$^{-1}$ from southeasterly direction to stir up sand particles.
- Bursts of $w$ and $E_3$ may be triggered at disturbances like megaripples superimposed on sand waves by current wave interaction at high current and wind speeds observed of opposite directions and measured at high spatial resolution.
- During moderate wind speeds between 5.8 m s$^{-1}$ and 7.5 m s$^{-1}$ from northerly directions, negative, enhanced and positive values of $u$, $E_3$, and $w$, respectively, show a definite phase relationship with the crest and upper gentle slope regions of sand waves during ebb tidal current phase while the research vessel is sailing with or against the current direction. In contrast, enhanced log((δ$c$ / $c_0$)$^3$) shows a phase relationship with trough regions of sand waves during ebb tidal current phase.
- Intense ejections caused by tidal current velocity transport higher SSC near the bottom boundary layer at the sand waves superimposed by megaripples towards the free water surface. Such hydrodynamic upwelling mechanism above sand waves creates distinct SSC signatures in remote sensing data visible in air- and space-borne optical imagery.
- During well developing flood and ebb tidal currents the intensities of $u$, $w$, and log((δ$c$ / $c_0$)$^3$) are only weakly time dependent. In contrast, $E_3$ shows time dependence.
- The ADCP in situ measurements are to be consistent with simulations based on the applied theory.
- The action density $N$ and its gradient $\partial N / \partial x$ due to semi-diurnal tide motion are the most important hydrodynamic parameters, which characterise comprehensively the dynamics of suspended sediment concentration (SSC) above submerged asymmetric sand waves.

Fig. 4: Simulations of oceanographic parameters applying equations (i) to (io) for ebb tidal current phase (current is directed from right to left) as a function of space variable $x$; a) sand wave profile with water depth $z_w$ in black and slope of the sea bed $\partial z_w / \partial x$ in red, b) tidal current velocity $u = \vec{u}$ in black and gradient of the tidal current velocity $\partial u / \partial x = \partial \vec{u} / \partial x$ in red, c) dynamic buoyancy density $\partial A_d$ in black and gradient of the dynamic buoyancy density $\partial A_d / \partial x$ in red, d) kinetic energy density $E_k$ in black and potential energy density $E_p$ in red, and e) action density $N$ in black and gradient of the action density $\partial N / \partial x$ in red.