Suspended sediment dynamics above submerged compound sand waves observed during a tidal cycle

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ABSTRACT: Detailed Acoustic Doppler Current Profiler (ADCP) data of the three-dimensional current-field, echo intensity, modulation of suspended sediment concentration (SSC), and related water level and wind velocity have been analyzed as a function of water depth over asymmetric submerged compound sand waves during a tidal cycle in the Lister Tief of the German Bight in the North Sea. Signatures of vertical current component, echo intensity and calculated SSC modulation in the water column depend strongly on wind and horizontal current speed as well as on wind and horizontal current direction, respectively. Bursts of vertical current component and echo intensity are triggered by the sand waves itself and also by superimposed megaripples due to current/wave interaction.

1. INTRODUCTION

Ocean color 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 color. However, this implies that measurements of water quality parameters are needed to understand and analyze climate change. Measurement of the wavelength variation of the beam attenuation coefficient *c* provides information on the major constituents of the water which influenced its color. Ocean color is also important for technical applications and operations, because the usage of new remote sensing technologies for hydrographic purposes such as airborne light detection and ranging (LIDAR) bathymetry (ALB) systems for shallow coastal surveys depends strongly on turbidity of the water column.

Substantial phenomena of suspended matter concentration during two tidal cycles at two anchor stations in the southern North Sea were described by Joseph (1954). It was shown by Hennings & Herbers (2014) that strong currents flowing over steep bottom topography are able to stir up the sediments to form both a general continuum of suspended sediment concentration (SSC) and localized pulses of higher SSC in the vicinity of the causative bed feature itself. These observations were in agreement with the basics on dynamics of the circular vortex with applications to oceanic vortex and wave motions (Bjerknes, 1921; Defant, 1961). A decrease in water clarity of the southern and central North Sea was reported by Capuzzo et al. (2015). The authors concluded that changes in water clarity were more likely driven by an increase in SSC.

Our study area was the Lister Tief, 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, respectively, as shown in Figure 1. The tidal gauge station List is located 4.8 km southerly of transects AB shown in Fig. 1. Present seabed morphology created in the Lister Tief is a complex configuration of different bed forms. The submerged compound sand waves (Van Dijk & Kleinhans, 2005) investigating in this study are four-dimensional in space and time. Small-scale as well as megaripples are superimposed on sand waves as presented and discussed in Hennings & Herbers (2006). The analyzed flood dominated sand waves have gentle slopes of the order of 1^{o} and steep slopes up to 31^{o}.

Our primary intention is to investigate how wind speed and direction and speed over ground of the measuring platform will affect signatures of vertical current component *w*, echo intensity E_3, and SSC modulation $log((\delta c/c_0)_3$ over submerged compound sand waves during a tidal cycle. Another central question is whether localized pulses of higher SSC in the vicinity of the causative sea bed features depending on wind velocity and spatial resolution rise high enough in the water column and become resolvable to the extent that they create distinct signatures in space-borne optical imagery.

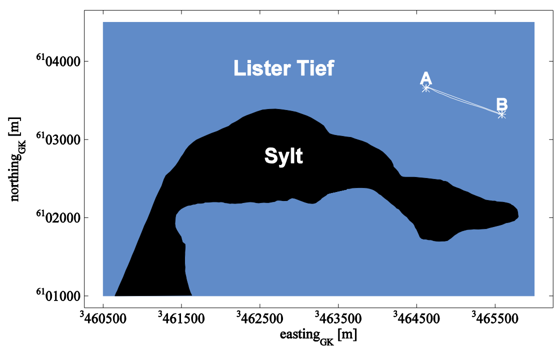

Figure 1. Study area of the tidal inlet of the Lister Tief located northerly of the island of Sylt in the German Bight of the North Sea. Transects of the analyzed ADCP measurements are indicated by capital letters AB.

2. MEASUREMENTS

The water level measured at the tidal gauge station List, the wind and current velocity *w*, E_3 of beam No. 3 (fore beam) measured by the Acoustic Doppler Current Meter (ADCP) and the SSC modulation expressed as $log((\delta c/c_0)_3$ of beam No. 3 as a function of water depth over asymmetric submerged compound sand waves on the sea bottom of transect AB (for location see Fig. 1) are shown in Figures 2a-e for ebb tidal current phase. The duration of the measurement time during the tidal phase is indicated by a vertical black beam in Fig. 2a. Each transect has been rotated by an angle of 19° that the current component *u* is directed perpendicular to the sand wave crest. By using this procedure the *v*-component of the current field is minimized and can be neglected as a first approximation. The rotation point is marked at the highest sand wave crest (reference crest) shown in Fig. 2c-e. The current velocities shown in Figs. 2b are water depth averaged current velocity values. The time resolution of the wind and current velocity arrows shown in Figs. 2b is 30 s.

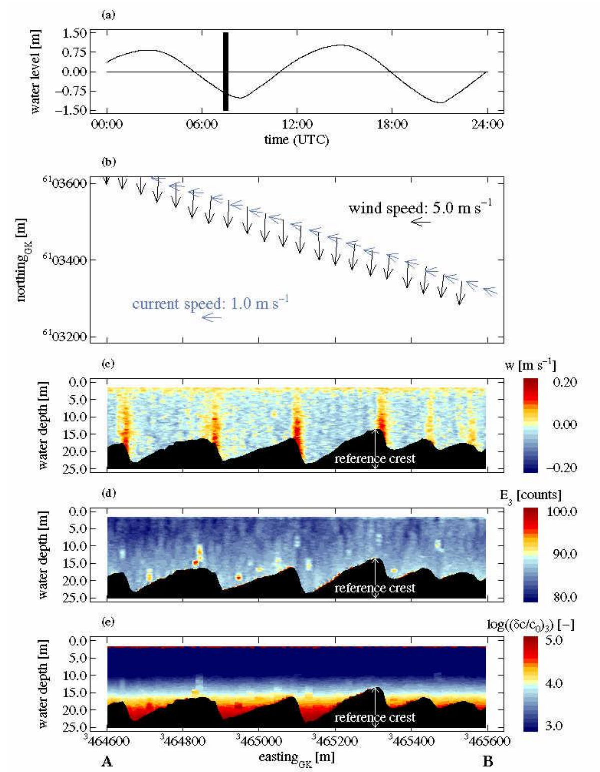

Figure 2. Analyzed data of ADCP beam No. 3 as a function of position and water depth over asymmetric sand waves of transect AB indicated in Fig. 1 in the study area of the Lister Tief during ebb tidal phase at 0721-0740 UTC on 10 August 2002; a) water level measured at the tidal gauge station List, b) wind and current velocity (the two horizontal arrow-scales indicate a wind speed of 5.0 m s^{-1} and a current speed of 1.0 m s^{-1}, respectively), c) vertical current component *w* of the three-dimensional current field, d) echo intensity E_3, and e) calculated SSC modulation of $log((\delta c/c_0)_3$. The duration of the measurement time is marked by a vertical black beam in a). The position of the reference crest is indicated at the highest sand wave crest in c)-e) of transect AB..

The acquisition time of the measurements shown in Figs. 2a-e was during ebb tidal phase at 0721-0740 UTC on 10 August 2002, after previous high water at station List at 0226 UTC on 10 August 2002. A measured wind speed between 6.7 m s^{-1} and 7.5 m s^{-1} from northerly direction has been observed (Fig. 2b). The mean current speed u_0 was 0.7 m s^{-1} with a mean current direction of 281°. It is shown in Fig. 2b that the angle between the current and wind direction is 90°. The up- and downward components *w* of the current velocity (Fig. 2c) are regularly distributed above the stoss and lee slopes of sand waves. Echo intensity counts E_3 are reduced in the water column and near the sea bottom of sand waves because the observation time of transect finished 45 minutes before low tide at station List. The modulations in $log((\delta c/c_0)_3$ (Fig. 2e) show enhanced values only near the sea bottom of sand waves.

2.1. Time dependent measurements

The water level measured at the tidal gauge station List with the acquisition times of analyzed transects while the research vessel is sailing against the current direction during ebb tidal current phase, the wind velocities, the current component *u* (east direction), the echo intensity E_3 of beam No. 3 (fore beam) measured by the ADCP, the vertical current component *w*, the calculated suspended sediment concentration SSC modulation expressed as $log((\delta c/c_0)_3$ of beam No. 3 as a function of time over asymmetric submerged sand waves on the sea bottom of transects AB (for location see Fig. 1) are shown in Figures 3a-h. The parameters *u*, E_3, *w*, and $log((\delta c/c_0)_3$ are a function of time and space observed before low water at 0829 UTC on 10 August 2002 at tidal gauge station List. All parameters are vertically water depth averaged values of five single transects during ebb tidal current phase between 0516 UTC and 0740 UTC on 10 August 2002 while the research vessel is sailing against the current direction (acquisition times see Fig. 3a). Measured wind speeds between 5.8 m s^{-1} and 7.5 m s^{-1} from northerly directions have been observed (Fig. 3b). Negative, enhanced and positive values of *u*, E_3, and *w*, respectively, show definite phase relationships with the 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. All signatures of *u*, E_3, *w*, and $log((\delta c/c_0)_3$, respectively, show spatially dependent variations. During the pronounced ebb tidal current phase the intensities of *u*, *w*, and $log((\delta c/c_0)_3$ are not time dependent. Only E_3 shows a time dependent behavior (see Fig. 3d).

3. CONCLUSIONS

It can be summarized here that our investigations are a further step forward to understand the complex links between wave current interaction,

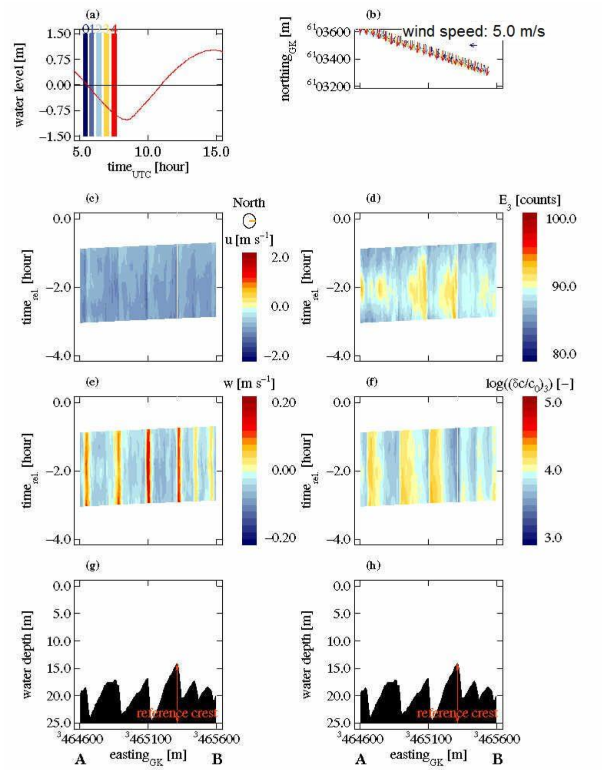

Figure 3. a) Water level measured at the tidal gauge station List with the acquisition times (marked by Nos. 1-5) of analyzed 5 single transects during ebb tidal current phase (current direction from B to A) while the research vessel is sailing against the current direction on 10 August 2002, b) wind velocities (the horizontal arrow-scale indicates a wind speed of 5.0 m s^{-1}), c) current component u (east direction), d) echo intensity E_3 of beam No. 3 (fore beam) measured by the ADCP, e) vertical current component *w*, f) calculated suspended sediment concentration SSC modulation expressed as $log((\delta c/c_0)_3$ of beam No. 3, and g)-h) water depth profiles of asymmetric submerged sand waves on the sea bed of transects AB (for location see Fig. 1).

turbulence, bed morphology and sediment transport above compound sand waves in a tidal inlet.

We would like to add here that our phase shift measurements of *u*, E_3, *w*, and $log((\delta c/c_0)_3$ are consistent with the experimental data published by Joseph (1954) of time dependent measurements over almost four tidal cycles at an anchor station in the North Sea where turbidity maxima had been first observed near the sea bed before tidal current speeds maximized.

Based on in situ measurements of several oceanographic and meteorological parameters regarding the hydrodynamics above submerged compound sand waves the following conclusions are drawn:

1. The magnitudes of echo intensity E_3 and calculated suspended sediment concentration SSC modulation expressed as $log((\delta c/c_0)_3$ depend on wind and current speed as well as on wind and current direction.
2. Sand suspensions are strongly dependent on the impact of wave activity to maintain high concentrations in the water column. Wave orbital motion at the sea bed is sufficient at measured wind speeds between 11.7 m s^{-1} and 13.3 m s^{-1} from southeasterly direction to stir up sand particles.
3. Bursts of w and E_3 may be also triggered at the disturbances due to 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.
4. All averaged signatures of u, E_3, w, and $log((\delta c/c_0)_3$ show spatially variations during ebb and flood tidal current phases.
5. Negative, enhanced and positive values of u, E_3, and w, respectively, show a definite phase relation with the sand wave crest and upper gentle slope regions of the sand waves during ebb tidal current phase while the research vessel is sailing with or against the current direction. In contrast, enhanced $log((\delta c/c_0)_3$ shows a phase relationship with the trough regions of sand waves during ebb tidal current phase. Moderate wind speeds between 5.8 m s^{-1} and 7.5 m s^{-1} from northerly directions were observed.
6. Positive, enhanced and positive values of u, E_3, and w, respectively, show a phase relationship with the sand wave crest and upper gentle slope regions of sand waves during flood tidal current phase while the research vessel is sailing with and against the current direction. In contrast, enhanced $log((\delta c/c_0)_3$ shows a phase relationship with the trough regions of sand waves during flood tidal current phase. All averaged signatures of u, E_3, w, and $log((\delta c/c_0)_3$ show spatially variations due to enhanced wind speeds. High wind speeds between 9.2 m s^{-1} and 13.3 m s^{-1} from southeasterly directions were observed.
7. During pronounced ebb and flood tidal current phases the intensities of u, w, and $log((\delta c/c_0)_3$ are not time dependent, whereas the local magnitudes of these parameters are variable in space above the sand waves.
8. Intense ejections caused by tidal current velocity can transport higher SSC near the bottom boundary at the causative sea bed features towards the free water surface. Such hydrodynamic mechanism creates distinct SSC signatures visible in air- and space-borne optical imagery.

4. ACKNOWLEDGMENT

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