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Near bed suspended sediment flux by single turbulent events

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ABSTRACT

The role of small scale single turbulent events in the vertical mixing of near bed suspended sediments was explored in a shallow shelf sea environment. High frequency velocity and suspended sediment concentration (SSC; calibrated from the backscatter intensity) were collected using an Acoustic Doppler Velocimeter (ADV). Using quadrant analysis, the despiked velocity time series was divided into turbulent events and small background fluctuations. Reynolds stress and Turbulent Kinetic Energy (TKE) calculated from all velocity samples, were compared to the same turbulent statistics calculated only from velocity samples classified as turbulent events (Re_{events} and TKE_{events}). The comparison showed that Re_{events} and TKE_{events} was increased 3 and 1.6 times, respectively, when small background fluctuations were removed and that the correlation with SSC for TKE could be improved through removal of the latter. The correlation between instantaneous vertical turbulent flux (w') and SSC fluctuations (SSC') exhibits a tidal pattern with the maximum correlation at peak ebb and flood currents, when strong turbulent events appear. Individual turbulent events were characterized by type, strength, duration and length. Cumulative vertical turbulent sediment fluxes and average SSC associated with individual turbulent events were calculated. Over the tidal cycle, ejections and sweeps were the most dominant events, transporting 50% and 36% of the cumulative vertical turbulent event sediment flux, respectively. Although the contribution of outward interactions to the vertical turbulent event sediment flux was low (11%), single outward interaction events were capable of inducing similar SSC' as sweep events. The results suggest that on time scales of tens of minutes to hours, TKE may be appropriate to quantify turbulence in sediment transport studies, but that event characteristics, particular the upward turbulent flux need to be accounted for when considering sediment transport on process time scales.

1. Introduction

Near bed turbulence in coastal environments plays an essential role in the entrainment and horizontal and vertical mixing of suspended sediment. Near bed turbulence may arise through boundary layer bursting or interaction of flow with obstacles such as bedforms, vegetation or structures and can grow to water depth-scale.

Turbulent statistics are commonly used to quantify these semi random velocity fluctuations. In tidal environments, cyclic changes of turbulent statistics such as Reynolds stress, turbulent kinetic energy (TKE), TKE production and TKE dissipation have been described for different tidal stages (Korotenko et al., 2013; Rippeth et al., 2002; Souza and Howarth, 2005) with higher turbulence occurring during maximum ebb and flood currents and weaker turbulence during slack water. These studies also have described a tidal asymmetry with one tidal phase exhibiting higher turbulence than the other. High suspended sediment concentrations (SSC) were observed during peak current velocities and high turbulence levels while SSC decreased around slack water (e.g. Yuan et al., 2008). Large and small velocity fluctuations make up the velocity signal and are averaged in the calculation of statistical parameters. This is valid to study average turbulent quantities and momentum exchange over the averaging time period, but cannot be utilized to study instantaneous, temporally energetic velocity fluctuations known as turbulent events (Trevethan and Chanson, 2009). Turbulent events however, play a dominant role in sediment transport (Naqshband et al., 2014; Paiement-Paradis et al., 2011) and it has become increasingly apparent that studies on sediment transport on short time scales have to consider the interaction of SSC and instantaneous turbulent events:

Commonly the turbulent events of the boundary layer burst cycle are described by quadrant analysis of velocity fluctuations (Lu and Willmarth, 1973). In this method, turbulent events are separated into four different groups by the simultaneous sign of velocity fluctuations, namely “outward interaction”, “ejection”, “inward interaction” and

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"sweep" (Lu and Willmarth, 1973). In earlier studies on turbulent events (e.g. Soulsby, 1983; Heathershaw and Thorne, 1985) attention was devoted to ejection and sweep events as these occurred most frequent in a velocity time series. These events were shown to contribute about 65 to 80 percent to the total Reynolds stress (Hansen and Reidenbach, 2012; Le Couturier et al., 2000; Soulsby et al., 1994). Ejections, moving a parcel of water up, and sweeps, transporting high momentum fluid towards the bed, are the main events mobilizing and transporting sediments (Fernandez et al., 2006; Gyr and Schmid, 1997; Kostaschuk and Villard, 1999; Le Couturier et al., 2000; Nelson et al., 1995; Shugar et al., 2010; Wren et al., 2007). It shall be noted that ejections ($u'<0, w'>0$) and sweeps ($u'>0, w'<0$) extract energy from the mean flow and both positively contribute to Reynolds stress (Bennett and Best, 1995; Hardy et al., 2009). However, the two types of events opposingly affect the concentration of suspended sediments at the measuring level. An in phase correlation between ejections and SSC and an out of phase correlation between sweeps and SSC was reported in several studies (Kostaschuk and Villard, 1999; Le Couturier et al., 2000; Shugar et al., 2010; Soulsby et al., 1994). This behavior probably explains the poor correlation between local Reynolds stress and sediment movement addressed by Wren et al. (2007) and Paiement-Paradis et al. (2011). In addition, small scale turbulent event measurement of Wren et al. (2007) showed a low correlation between the type of turbulent event and local SSC. Although these studies highlighted the importance of ejection and sweep events, their individual role in sediment transport is disputable. Understanding the interaction of turbulent events and local sediment concentration thus may allow to interpret the sudden changes of SSC observed by previous researchers (Ha et al., 2009; Kostaschuk and Villard, 1999; Kwoll et al., 2014; Lapointe, 1996; Le Couturier et al., 2000; Palanques et al., 2002; Soulsby et al., 1994).

Often in the quadrant analysis, only the type of event is considered by defining a threshold such as a hole size. Particularly, no further identification of turbulent event characteristics or temporal variation thereof are taken into account. Recognizing this, Gordon and Witting (1977) expanded the definition of a turbulent event from a single $u'w'$ sample to all consecutive velocity fluctuations of the same quadrant (u', w') that pass the defined threshold criterion. As a result, in addition to the type of events, other characteristics such as duration and average strength could be attributed to turbulent events. Using this approach, Soulsby (1983) observed a larger number of sweep and ejection events compared to outward and inward interaction events. He showed that an increase in Reynolds stress is mainly caused by an increase in the strength of events. In addition, ejection and sweep events had longer durations than outward and inward interactions. Le Couturier et al. (2000) showed that the duration of ejections and sweeps varied with the tidal cycle with lower durations occurring under low mean velocity. Trevethan and Chanson (2009) confirmed the variation of duration and strength over the tidal cycle. However, they found that duration and strength are independent variables. In addition to the number, strength and duration, Amirshahi et al. (2016) reported on the length of turbulent events and showed how the strength of individual events related to average Reynolds stresses. In addition, they showed that positive backscatter fluctuations, as a proxy for higher SSC, were mainly related to ejection events. However, a detailed study into what characteristics of individual event types drive suspended sediment transport has not been conducted. In fact, to the best knowledge of authors, the relevant contributory factors of turbulent events determining the associated sediment has not been identified yet.

Previous researchers documented the occurrence of intermittent sediment suspension events (Bagherimiyab and Lemmin, 2012; Bradley et al., 2013) in which strong turbulent events are believed to be the main reason behind sediment suspension (Hofland, 2005; Kwoll et al., 2014; Naqshband et al., 2014; Shugar et al., 2010). Using two Acoustic Doppler Current Profilers (ADCPs; 1 Hz up-looking bottom mounted and 0.42 Hz down-looking ship mounted), Kwoll et al. (2014), showed a tidal variation in the scale of large scale turbulence above bedforms. SSC was higher during the ebb, when depth-scale, strong flow structures with the frequency between 0.01 and 0.167 Hz were observed. This scale of flow structures disappeared during the flood and lower SSC was detected. Bradley et al. (2013) quantified the sediment volume (suspension events) associated with such large scale turbulent events by an ADCP (ensembles of 0.45 s). Their result showed that about 60% of the total sediment transport was associated with suspension events, indicated as higher than median of the deviation from SSC. In both studies, the number of flow structure/suspension events increased with the flow velocity. Albeit of a different scale, these studies document the importance of finding a quantitative description of the interaction of turbulent events and suspended sediments.

On smaller scale, we therefore investigate co-located velocity and suspended sediment fluctuations of single turbulent events using high frequency ADV time series. The velocity time series is separated into turbulent events and small background fluctuations using the detection scheme and quadrant analysis of Amirshahi et al. (2016). We compare results of the common approach to calculate turbulent statistics (hereinafter called "total turbulent statistics") with turbulent statistics calculated only from the velocity samples related to turbulent events (hereinafter called "turbulent event statistics"). Moreover, we determine the vertical turbulent sediment flux for each type of turbulent event to compare the ability of different turbulent events to mix sediments into the water column. Finally, the cumulative average SSC for each type of turbulent event is examined to discuss the effect of the four type of turbulent events on sediment transport.

2. Study area and data collection

The study field site is located at station D of the NOAH project (North Sea Observation and Assessment of Habitats) in the German Bight, North Sea, about 35 km west of Helgoland Island (54°5.47'N, 7°21.52'E) in water depths of approximately 34 to 37 m (3 m tidal range) subjected to semi-diurnal tides. The tidal ellipse was aligned mainly to WNW and ESE during the ebb and flood, respectively (Fig. 1). Measurements were carried out during the research cruise HE441 of research vessel RV Heincke. During the cruise, the MARUM/COSYNA bottom lander SedObs was deployed on March 21, 2015 (Baschek et al., 2017). This study shows the results of one tidal cycle when the weather was calm and surface waves were negligible.

At the top of the lander and with a distance of about 2 m to the bed, a 1 MHz 3D Acoustic Ripple Profiler (3D-ARP) (Bell and Thorne, 2007) was installed to measure the seabed bathymetry. Small asymmetrical ripples of about 1.3 cm height and 21.5 cm length were observed by frequent scanning of the 3D-ARP (Krämer and Winter, 2016). The bedforms were directed toward the WNW-ESE direction. During the respective tidal cycle, no bedform migration was observed.

Closer to the bed and attached to the leg of the lander, a Nortek Vector Acoustic Doppler Velocimeter (ADV) was mounted a distance away from the SedObs legs to ensure no disturbance of the measuring volume of the ADV through wakes created by the lander. The ADV measuring volume was placed at a height of around 12 cm above the bed. High frequency (32 Hz) three dimensional flow velocities were measured. In addition, the ADV was also used to estimate SSC through calibration of backscatter intensity (BSI) data (Ha et al., 2009; Lohrmann and Calibration, 2001; Salehi and Strom, 2011). Calibration of the BSI data to SSC was achieved by seafloor sediments sampled using a Shipek grab. Grain size analysis of the bed sample showed a unimodal distribution of very fine sand with a median grain size (d_{50}) of 105 μm. The ninetieth percentile of bed material size (d_{90}) was smaller than 152 μm. Last, the pressure sensor of the ADV measured with the same frequency as the velocity time series. The results of this sensor were used to determine surface wave parameters. The aforementioned setup allowed calculation of simultaneous near bed velocity and SSC to study the role of individual turbulent events in mixing of suspended sediments.

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