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Implications of intermittent turbulent bursts for sediment resuspension in a coastal bottom boundary layer: A field study in the western Yellow Sea, China

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ABSTRACT

Previous experiments carried out in the laboratory flumes and open channels have shown that close to the wall sediment resuspension is largely dominated by a sequence of intermittent, powerful and large-scale motions called coherent structures (or burst cycle) which mainly account for Reynolds stress generation. However, the difficulties in simultaneously measuring the fluctuations of velocities and sediment concentration close to the seabed during the field observations inhibit the further understanding of this laboratory discovery in the marine regime. In the present paper, field data sets collected within a coastal bottom boundary layer (BBL) in the western Yellow Sea are examined comprehensively to reveal the relationships between coherent structures and sediment resuspension. The following results are obtained: (1) the bulk of turbulent sediment flux ($\overline{c'w'}$) is accomplished by 'ejection' (56%) and 'sweep' (42%) events, while contributions coming from outward and inward interactions are negligible; (2) wall turbulence containing coherent structures vertically transport momentum more efficiently than suspended sediments; (3) spectral scaling of sediment concentration reveals that two types of suspended sediment clouds with different sizes were existent during the peak flood. The large-size particle clouds contain coarse sediments locally resuspended from seabed, whereas the smaller particle clouds consist of silts and clays, and act as "washload" advected from Jiaozhou Bay and Yellow Sea by tidal flows; (4) wavelet transform can provide a more intuitive way to study and visualize the relationship between the burst cycle and sediment suspension, and the results clearly show that the intermittent Reynolds stress generation is accompanied by intense sediment resuspension.

1. Introduction

Sediment resuspension is one of the main processes that control the suspended sediment transport in coastal seas. It is commonly regarded that sediment resuspension is related to the time-averaged bed shear stress in many engineering and sedimentological applications. Once the shear stress exceeds a critical value, sediments are eroded and resuspended into the water column. The bed shear stress explains sediment dynamics in a time-averaged manner; however, from a "microscale" perspective, the instantaneous suspension of sediment is largely controlled by small-scale turbulent processes close to the seabed. How sediment particles respond to the wall turbulence is critical to the understanding of sediment resuspension.

Studies on the wall turbulence dynamics have been conducted by several authors for long. Laboratory experiments by Grass (1971), Wallace et al. (1972), Willmarth and Lu (1972) have shown that turbulence is generated intermittently by burst cycles near the boundary, which is also called coherent structures. In more detail, a burst consists of a powerful and well-organized sequence of events occurred near the wall, among which ejections and sweeps are two primary phases, while outward and inward interactions are two much weaker phases. In ejection phase low-speed fluid is ejected away from the wall, and in sweep phase high-speed fluid penetrates towards the wall (Sumer and Oguz, 1978; Sumer and Deigaard, 1981). Willmarth and Lu (1972) found that the largest contribution to the Reynolds stress occurs during the phases of ejections and sweeps. Field observations in the tidal estuaries, conducted by Gordon (1974) and Heathershaw (1974) respectively, revealed that the bursting cycles do occurs in geophysical boundary layers, and its intermittent nature plays a dominating role in momentum transport and mass mixing.

Progress in the understanding of the physics underlying sediment resuspension is in parallel with the studies on the wall turbulence. Jackson (1976) related the burst cycle to the sediment-laden kolks and boils observed in natural waters, and indicated that upward momentum flux in the bursts provides the vertical anisotropy in the turbulence which is needed to suspend sediment. Laboratory experiments using photographic technique (Sumer and Deigaard, 1978) have

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shown that the bed particles are pushed into the low-speed wall streaks by the sweep-type fluid motions intermittently and subjected to the upward ejection-type fluid motions. Thereafter, more experiments using flow visualization technique, LDA and fast video-system (Kaftori et al., 1995; Nino and Garcia, 1996) also supported Summer's findings. After examination of the field data collected in the south coast of England, Heathershaw and Thorne (1985) speculated that bedload transport of coarse sediments was driven by sweep-type events, while suspended load transport of finer sediments would be dominated by the ejection of low-momentum fluid away from the boundary. By examining the experimental data collected in an open channel, Cellino and Lemmin (2004) confirmed the sediment entrainment patterns proposed by Heathershaw and Thorpe.

Even though a number of laboratory experiments have been reported, application of theories to highly-variable marine environment still needs further facts. The main obstacle that relates coherent structure to sediment resuspension in the field observations is a lack of robust and easy-to-handle field equipment to measure turbulent velocity and suspended sediment concentration (SSC) simultaneously close to seabed. Recently, commercially-available acoustic instruments such as the acoustic Doppler velocimeter (ADV) have been developed. By collecting three-dimensional velocities and SSC in the same sampling volume, ADV can delineate turbulence and sediment dynamics processes at a much finer resolution than have been used previously. In 14–15 Dec 2005, a quadrapod equipped with ADV, optical backscatter sensor (OBS) was bottom-mounted in the western coast of Yellow Sea. In this paper, different tools (i.e., spectral analysis, quadrant classification, etc.) are utilized to study the turbulent characteristics of sediment concentration fluctuations and their relationship with turbulent velocities, and more importantly, to clarify the mechanisms underlying the sediment resuspension.

2. Study site and methods

2.1. Site description

The study site was adjacent to the coastline of Shandong Peninsula (~1.2 km from the shore) and 2 km away from the Jiaozhou Bay (JB) mouth (Fig. 1). JB is a semi-enclosed bay with an area of about 340 km^2 and an averaged water depth of about 7 m. Tides in the bay are semidiurnal with a mesotidal tidal range of 2.73 m. Although more than ten rivers flow into the bay, the total input of freshwater and sediment is limited. Suspended sediment concentration (SSC) is quite low, with the maximum value less than a few tens of mg/L. The majority of the bed sediment in the bay are silt and clay; however, sediment types around the narrow JB mouth mainly consist of coarse particles ranging from very fine sand to medium sand (i.e., 63–500 µm) (Li et al., 2002). In this study, the in-situ bottom grab samples analyzed in the laboratory reveal a significant portion of very fine and fine sand (i.e., 63–250 µm) (Yuan et al., 2008).

The field experiment started at 15:00 Dec 14 2005 and lasted for two semidiurnal tidal cycles. During the 25-hour period, the mean water depth of the study site was 18 m, and the tidal range exceeded 3.1 m. Currents profiles measured by ADCP showed pronounced tidal asymmetry. The peak flood current was approximately 0.5 m/s, more than twice that of the ebb current. The northwesterly winds were prevailing, with the mean and maximum speeds of 9.3 ± 1.7 and 13 m/s. However, no apparent wind wave was generated due to short fetch. Shipboard CTD profiling revealed the water column was well-mixed due to persistent wind energy input from the sea surface and strong tidal mixing near the bottom. The sediment concentration above the seabed (0.45 mab) varied between 7 and 15 mg/L and corresponded to tidal currents generally. Furthermore, median particle size d_{50} measured by LISST-100 also exhibited tidal variations, varying between 15 and 100 µm. The instantaneous response of sediment concentration and d_{50} to tidal flows suggests that tidally-induced bed shear stress is the main mechanism that acts on the seabed to stir up the sediments (Yuan et al., 2008).

The field observations included a bottom-mounted quadrapod located at 36.04°N, 120.32°E, and profiling measurements from the R/V Dongfanghong-2 moored immediately adjacent to the quadrapod. The quadrapod was equipped with RDI WorkHorse 600 kHz ADCP, Nortek 6 MHz ADV and Alec OBS fitted with CTD sensors. The ADV was mounted 0.45 m above the bottom (mab) to record turbulent velocities and echo intensity simultaneously with the sampling frequency of 16 Hz. The OBS was also mounted at the same height to record turbidity. For OBS, the sampling frequency was 2 Hz with burst interval of 5 min. In this paper, we mainly focus on the data recovered from ADV and OBS, a complete description of the whole instrumentation can be found in Yuan et al. (2008).

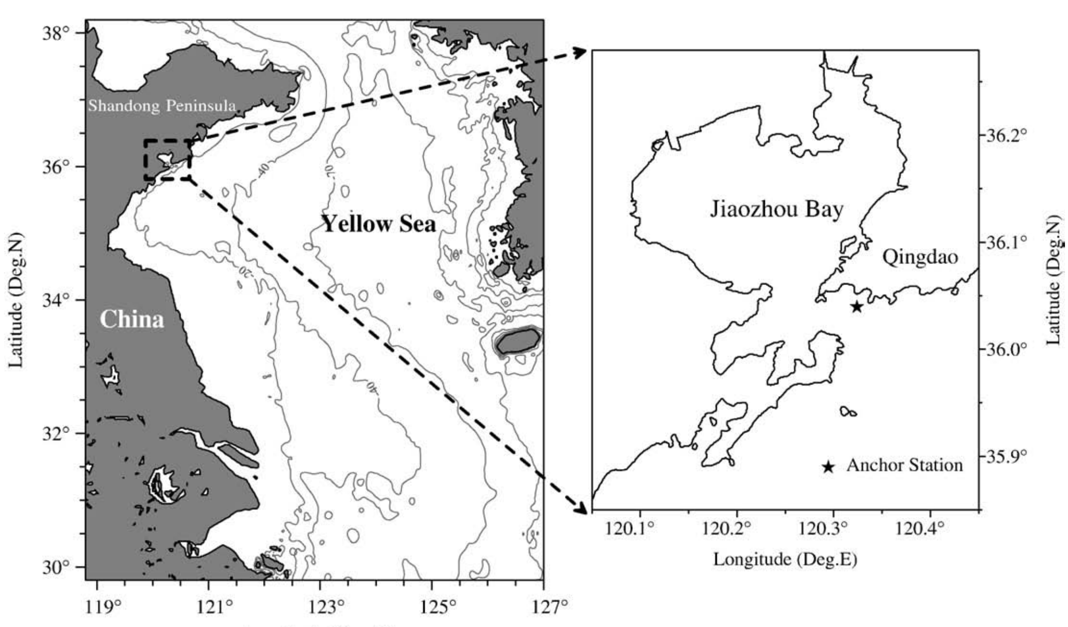

Fig. 1. Maps of study site. The mooring station, marked by solid star, was located about 2 km to the east of the Jiaozhou Bay mouth and 1.2 km to the south of the coastline.