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Acoustic turbulence measurements of near-bed suspended sediment dynamics in highly turbid waters of a macrotidal estuary

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A B S T R A C T

Sediment–turbulence interactions near the bed are still poorly understood in highly turbid estuaries, especially in the presence of fluid mud layers. This results primarily from the difficulty in measuring co-located velocity and suspended sediment concentration (SSC) at sufficiently high rate to resolve small turbulent flow scales. In this paper, we show how a set of commercial acoustic and optical backscattering systems known as ADCPs, ADVs and OBSs, can be deployed and used in a complementary way to perform large-scale profilings of tidal current and SSC combined with high-resolution velocity and SSC measurements in the highly turbid near-bed zone. The experiment was done in the Gironde estuary (France) which is well known for its turbidity maximum zone characterized by high SSC values, above 1 g l^{-1} near the surface.

A first simple inversion method is proposed to convert the backscattered acoustic intensity measured with ADV into SSC data in the highly turbid near-bed zone. Near-bed SSC data from the OBS are used to compensate for the important acoustic sediment attenuation effect at an acoustic frequency of 6 MHz. No a priori knowledge of acoustic backscattering properties of mud suspensions is required with this calibration procedure. We obtain an attenuation coefficient for mud suspensions of 0.28 m^2/kg at 6 MHz leading to a good agreement between the SSC timeseries from the three ADV receivers and the OBS over the entire tidal cycle.

The obtained SSC data are then analyzed with respect to the near-bed velocity, Reynolds shear stress and turbulent kinetic energy (TKE) timeseries in order to identify the relevant sediment transport processes during the tidal cycle. Significant differences in bed shear stress and TKE levels are found between ebb and flood stages with effects on near-bed sediment dynamics. During the ebb, maximum levels of tidal current, bed shear stress and TKE are associated with a reduction of near-bed sediment concentration (from 400 kg m^{-3} down to 100 kg m^{-3}). Bed liquefaction process is assumed to occur at this moment with the presence of highly concentrated mud layer and a possible lutocline at a distance of less than 20 cm above the bed. During the first 1.5 h of flood, turbulent activity remains moderate. The near-bed flood current is then inhibited very abruptly while a sudden increase in SSC occurred above the bed.

Assuming that the ADV is able to estimate relevant turbulent erosion fluxes, the co-located velocity and SSC are multiplied and compared with settling flux measurements made onboard under quiescent water conditions. The mean sediment settling fluxes (averaged over 3 min) increase with SSC and are in relative good coherence with fluxes in quiescent water below the hindered regime, for SSC below 15 g l^{-1}. Reducing averaging time from 3 min to 30 s allows to increase the range of turbulent fluxes and SSC values, up to 99 g l^{-1}. At this scale, fluxes keep increasing quasi-linearly at higher SSC, suggesting the inhibition (delay or reduction) of the hindered settling regime as previously shown by Gratiot et al. (2005) from laboratory experiments. However, the 3-min averaged concentration field remained too low to conclude definitively on the effectiveness of such a process. Further analysis conducted at higher SSC regimes and under fully verified equilibrium are necessary.

1. Introduction

Acoustic backscattering systems (ABS) have been developed and used intensively over the past twenty years in field and laboratory studies of flow and sediment transport processes occurring in coastal, estuarine and inland flows (Thorne and Hanes, 2002). If velocity measurements can be considered as robust and reliable to date, the SSC measurements are still subject to open questions particularly when the suspended sediments differ in terms of size, shape and density from non-cohesive fine sand. Fine sand mixtures have been studied thoroughly in the

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literature providing the acoustic properties have been determined accurately (Thorne and Buckingham, 2004). The implementation of ABS such as ADCPs and ADVs in very turbid environments is not well documented. Some examples of relevant use of acoustic instruments are given by Fugate and Friedrichs (2002), Simpson et al. (2005) and Verney et al. (2007), working at suspended sediment concentrations (SSC) below 1 g l^{-1}. The main problems in turbid environments are related to unknown scattering and attenuation characteristics of the suspended sediments which are affected by flocculation processes (Gratiot et al., 2000). Whether flocculation affects or not the acoustic back- and total scattering cross section of very fine suspended sediments is still unknown at present. For this reason, the interpretation of near-bed, highly concentrated velocity and SSC measurements is usually subject to strong assumptions on the quality of the acquired data. Improvements in sediment concentration profiling based on ultrasonic inversions have recently been achieved when proper calibration can be performed. Examples are Merckelbach (2006), Tessier et al. (2008) and Thorne and Hurther (2009). For the ADVs, some recent work has been achieved to reveal relationships between acoustic backscattering strength (measured by acoustic Doppler velocimeters) and SSC in a wide concentration range, between 0.02 and more than 10 g l^{-1} (Ha et al., 2009). This consisted of experiments in the laboratory, with calibrated suspended sediment. Even if acoustic inversion appears to be a powerful tool to investigate sediment dynamics, the performance in natural conditions for very fine suspended material at high concentrations (above 1 g l^{-1}) is still poorly assessed.

In very turbid macrotidal estuaries, fluid mud layers are common features. They can form on the bottom because of a high settling rate of suspended particles, which is generally associated with the maximum turbidity zone. Density stratifications induced by these highly concentrated suspensions can cause damping of turbulence generated in the bottom boundary layer (Le Hir et al., 2001; Winterwerp et al., 2001; Winterwerp, 2002). Thus, sediment–fluid interactions determine conditions of deposition or re-entrainment of sediment in the water column. In October 2004, a scientific survey was performed in the Gironde estuary with the objective of performing near-bed turbulence measurements with a consistent set of instruments. Turbulent fields of velocity and SSC were measured near bottom and throughout the water column during a complete tidal cycle with two optical backscatter sensors (OBS), two acoustic Doppler velocimeters (ADV), CTD with OBS sensor and an acoustic Doppler current profiler (ADCP).

In this paper, our purpose is to show how a set of complementary instruments can be deployed and used in highly turbid waters to identify the flow and sediment transport processes during an entire semi-diurnal neap tidal cycle, across the water column and within the near-bed zone. For this purpose, we will first present the inversion methods used to extract SSC from an ADV in the highly turbid near-bed region. The obtained results will be compared to SSC timeseries from calibrated OBS measurements to validate the methodology. Then, timeseries over the tidal cycle of tidal current profiles, near-bed velocities, turbulent Reynolds shear stress, TKE, SSC profiles and near-bed SSC, are analyzed and discussed in terms of sediment transport processes. Finally, *in situ* turbulent erosion fluxes are compared with settling flux under quiescent water conditions. It opens a discussion on the experimental work of Gratiot et al. (2005) concerning the possible effect of turbulence on hindered settling process.

2. Field experiments and data processing

2.1. Background on the dynamics of the study site

The Gironde estuary is a macrotidal estuary (6 m range at spring tide) situated in the SW of France. It is the largest estuary of Western Europe (Fig. 1a). The tide propagates 160 km upstream of the mouth located at the Atlantic Ocean. Mean river discharge is approximately 1000 $m^3 s^{-1}$, adding both freshwater inflows from the Garonne and the Dordogne rivers. The estuary is well known for its developed turbidity maximum, formed by the combined processes of tidal pumping and residual gravitational circulation. While tidal pumping is dominant under low river flow conditions, residual circulation acts especially during river flood events (Allen et al., 1980, Sottolichio et al., 2001). In the core of the turbidity maximum, typical SSCs are easily over 1 g l^{-1} near the surface and several g l^{-1} near the bottom. During neap tides, SSC tends to decay and high settling rates of suspended sediment lead to the formation of fluid mud layers on the bottom over a maximal thickness of about 2 m above the bed

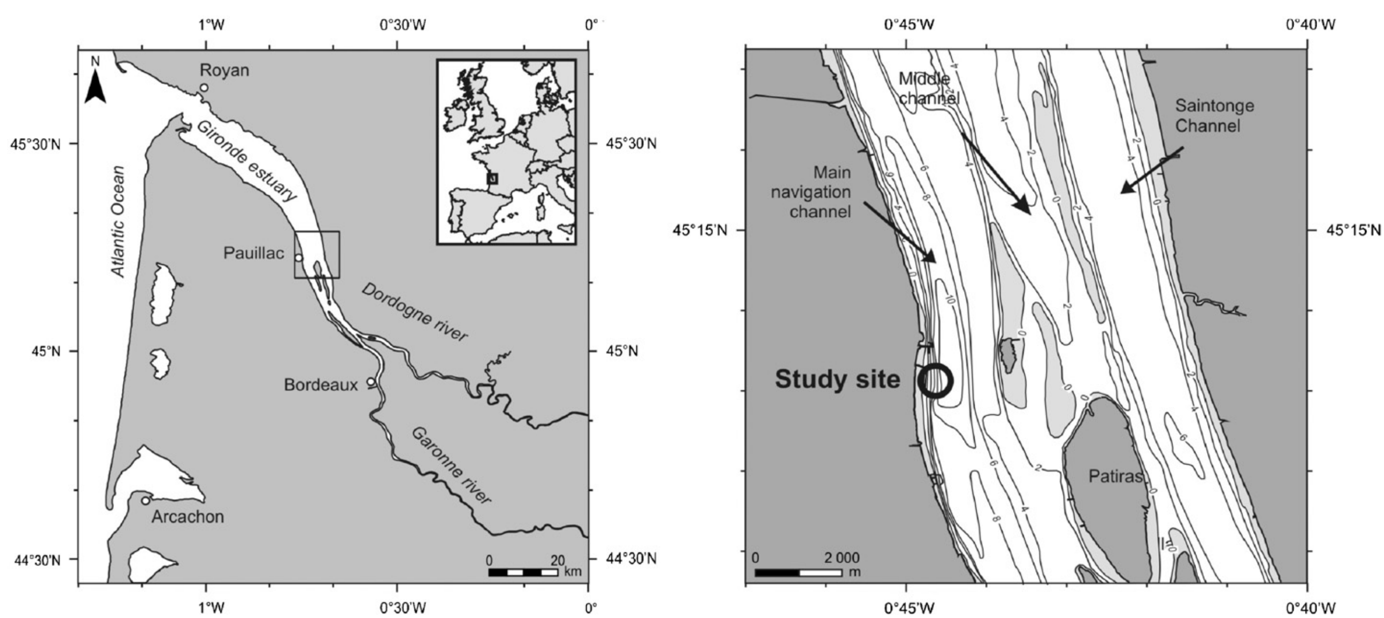

Fig. 1. Study site. Left: location of the Gironde estuary. Right: geomorphological description of the study site.