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Investigation of the variability of floc sizes on the Louisiana Shelf using acoustic estimates of cohesive sediment properties

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ABSTRACT

Vertical profiles of suspended sediment concentration and floc size estimated from acoustic backscatter are used together with turbulent shear estimates to investigate cohesive sediment flocculation under different flow conditions. Concentration measurements by optical backscatter sensors at two levels are used to calibrate the acoustic backscatter intensity. A strong correlation is observed between suspended sediment concentration and turbulence intensity. Mean size of flocs increases toward the bottom except within the bottom few centimeters, where floc breakage is observed due to strong turbulence. Simultaneous shear rate and floc size profiles show that low shear promotes flocculation at low concentrations. Increasing turbulence intensity increases the amount of sediment in the water column, but decreases the floc size, indicating floc breakage. Thus, these effects are seen at cm-scale vertical resolution in the field for the first time. The results support previously published numerical, experimental and lower resolution field studies.

1. Introduction

Estimating concentrations of suspended cohesive sediments and their transport in estuaries and coastal waters is of great importance to shoreline morphology, underwater detection, navigation, water quality, and fate of pollutants and bio-matter. Highly variable properties of mud flocs (e.g., size, density and strength) is the main cause for cohesive sediment transport processes to be more complicated than noncohesive sediments. Floc hydrodynamic properties (e.g., settling velocity) differ significantly from those of the primary particles and are difficult to understand due to the complex structure of the floc and its high sensitivity to hydrodynamic forcing. Many types of flocculation models have been developed for quantitative prediction of floc size, floc density and settling velocity in the bottom boundary layer (e.g., Winterwerp, 2002; Son and Hsu, 2011) in order to provide reliable sediment input to numerical cohesive sediment transport models. Accurate floc sizes at high temporal and spatial resolution are still difficult to measure.

In shear flows, aggregation of flocs is dominantly controlled by flow turbulence and sediment availability (Berhane et al., 1997; Dyer and Manning, 1999; Winterwerp et al., 2007; Safak et al., 2013b). According to the schematic representation of Dyer (1989) (see his Fig. 3), the floc grows with increasing sediment concentration at low levels of turbulence due to increasing probability of particle collision. However, aggregation transitions to fragmentation if the intensity of collisions or turbulent shear exceeds a certain threshold. In this case, a limiting maximum size might occur. In other words, flow turbulence controls both floc growth and breakage depending on its level (e.g., Hill et al., 2001; Fugate and Friedrichs, 2002; Safak et al., 2013b). This evidence is mostly based on laboratory settling column experiments in which a homogeneous turbulence field, produced by an oscillating grid, induces aggregation (e.g., Mietta et al., 2009; Kumar et al., 2010). A few attempts (e.g., Lee et al., 2012; Safak et al., 2013b) investigating floc size variability at high turbidity have been made in the field based on only a small number of measurements of size distribution and sediment concentration high in the water column (1–2 m above the sea-floor). In addition, the intensity of turbulence was defined solely with bottom shear stress. Because the amount of sediment and the turbulence level vary vertically, floc properties are likely to change in the bottom boundary layer. Therefore, the suitability of existing relationships for cohesive fine sediments in wave-energetic environments is yet to be established.

A comprehensive investigation of the relation between suspended sediment concentration (SSC), turbulence, and floc size requires information on sediment and flow characteristics near the bed at multiple elevations. While direct measurement of high-resolution SSC profile is difficult (e.g., using optical sensors), recent studies (Hamilton et al.,

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1998; Gartner, 2004; Hoitink and Hoekstra, 2005; Ha et al., 2011; Sahin et al., 2013) reveal that it can be estimated indirectly at cm-scale vertical resolution in muddy environments using acoustic techniques (Sheng and Hay, 1988; Libicki et al., 1989; Lynch et al., 1991; Thorne et al., 1993; Holdaway et al., 1999). Measuring the vertical profile of suspended particle size in the bottom boundary layer is also difficult, measurements in wave-dominated environments are very few, and spatial resolution is low (e.g., Dyer and Manning, 1999; Uncles et al., 2010). Attempts in sandy environments indicate that if multiple frequencies are available, acoustic profilers are also capable of estimating the vertical distributions of sediment concentration and size (e.g., Hay and Sheng, 1992; Thosteson and Hanes, 1998; Crawford and Hay, 1993; Thorne and Hanes, 2002). However, the capability of estimating floc size has not been tested for cohesive sediments.

The objective of this study is to investigate a three-way interaction between sediment concentration, turbulence, and floc size based on data collected on the muddy Atchafalaya Shelf (Section 2) using acoustic measurement techniques that are new to cohesive sediment environments (Section 3). In Section 4, near-bed current velocity measurements are used to estimate turbulence intensity profiles. The variability of floc sizes at different turbulence intensities and sediment availability conditions and the significance of the findings on sediment dynamics at the site are discussed in Section 5, and conclusions are summarized in Section 6.

2. Field experiment

2.1. Study site and instrumentation

The field observations were made near the 5-m isobath on the inner shelf fronting the Atchafalaya Bay in the northern Gulf of Mexico over a 10-day period between March 27th and April 6th, 2008 (Fig. 1). The muddy, nearly flat (maximum slope less than 1:1000) Atchafalaya Shelf has been the focus of several sediment and wave–current interaction studies due to the presence of mud, energetic wave climate and spatial uniformity (Allison et al., 2005; Draut et al., 2005; Jaramillo et al., 2009; Safak et al., 2010, 2013a, 2013b; Sahin et al., 2012, 2013; Sheremet et al., 2011, and many others). The individual size of sediment particles is in the range of 2 and 7 μm, with 17% fine-sand (Allison et al., 2000, 2005; Sheremet et al., 2005; Safak et al., 2010; Sahin et al., 2013). Sediment loaded fresh water plume associated with the Atchafalaya River discharge brings approximately 84 metric tons per year of sediment (Mossa, 1996), affecting the shelf. In addition, between December and April, energetic wave activity associated with cold atmospheric fronts reworks the bed, mobilizing large quantities of sediment. These two competing processes cause the formation of near-bed fluid mud layers, which move onshore and offshore over the submerged river delta (Sahin et al., 2012).

The instrumentation (Fig. 2) included a downward-pointing 1500-kHz PC-ADP (Pulse-Coherent Acoustic Doppler Profiler, Sontek/YSI), a downward-pointing single frequency ABS (Acoustic Backscatter Sensor, 700-kHz, Marine Electronics, Isle of Guernsey), and two synchronized OBS-3s (Optical Backscatterance Sensor, D&A Instruments, Campbell Sci.). The PC-ADP, which uses three beams oriented 15° off the vertical axis, sampled pressure, near-bed current velocities and backscatter profiles at 2-Hz in 27 bins of 3.2 cm following a 15 cm blanking distance. The ABS, sampling once every minute for the entire experiment duration, measured the intensity of acoustic return from 137 bins of 0.57-cm covering a distance of 30 to 110 cm below the instrument head. The OBS-3s, sampling synchronously with the PC-ADP, provided direct SSC observations at 16 and 42 cmab (cm above the bed). The calibration of the OBSs was done in the laboratory using sediment and water samples collected at the site. Representative data statistics were calculated for 20-min intervals resulting in a 751-point time series of mean values.

The PC-ADP pressure time series segments of 10-min length were de-trended and de-meaned, then divided into 128 s blocks with 50% overlap, and tapered using a Hanning window. The resulting spectra had approximately 17 degrees of freedom, with a frequency resolution of 0.0078 Hz. Wave spectra were corrected to account for the mean depth of the sensors using linear wave theory, with a high-frequency cutoff defined by a depth attenuation of wave variance value larger than 95%. The significant wave-height H_s was estimated based on the first spectral moment $H_s = 4\sqrt{\int_{f_1}^{f_2} S_{\eta\eta}(f)df}$ where $S_{\eta\eta}$ is the spectral density of sea surface elevation η at frequency f. A spectral tail proportional to f^{-5} was added to cover the high frequency range.

2.2. Observations

Observations of 20-min averages of significant wave height, vertical profiles of near-bed PC-ADP current backscatter profiles, acoustic

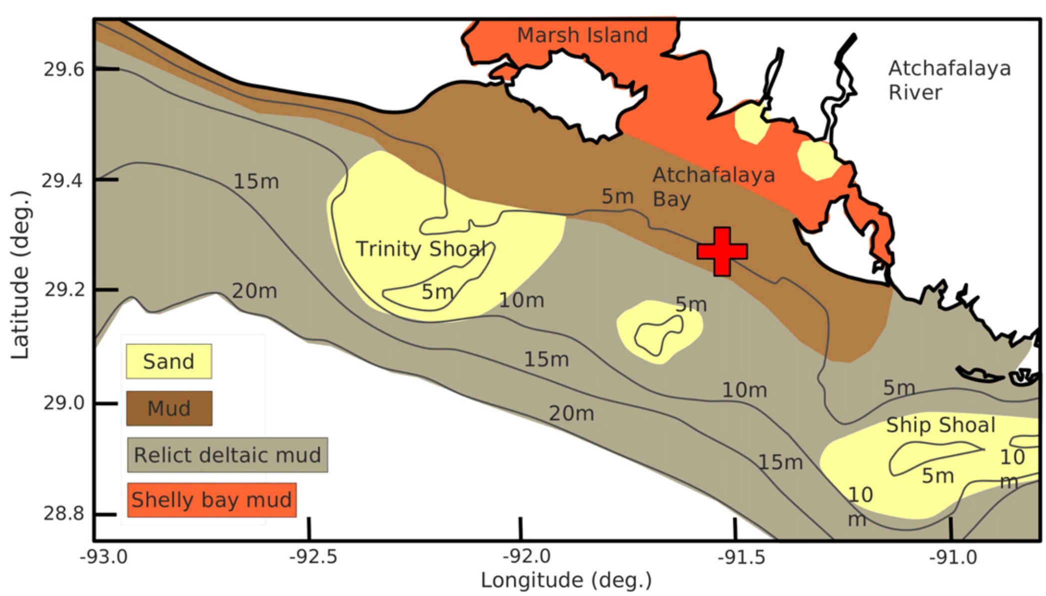

Fig. 1. Map showing the approximate distribution of the surficial sediments on the Atchafalaya Shelf (Jaramillo et al., 2009), and the location of the instrumented platform ("+", 29.26° latitude north, 91.57° longitude west).