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Sediment resuspension by wind, waves, and currents during meteorological frontal passages in a micro-tidal lagoon

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ABSTRACT

Meteorological frontal passages are recognized as important mechanisms for remobilizing sediment in estuaries along the northern Gulf of Mexico, but few studies have addressed factors beyond wind speed as a predictor for resuspension. To better understand resuspension mechanisms during these events, this study investigated the effects of wind, waves, and currents on suspended sediment concentration near the seabed during frontal passages in the shallow, micro-tidal West Galveston Bay located along the Texas coast. In late January and early February 2013, two multi-day deployments of instrumented pods (an acoustic Doppler velocimeter, and an acoustic wave and current profiler) were conducted to capture two separate frontal passages. The results indicate that the bed shear stress under the combined effect of waves and currents showed a much stronger relationship to sediment resuspension ($R^2 = 0.90$) than wind stress alone ($R^2 = 0.55$), or currents alone ($R^2 = 0.72$). Increases in the bed shear stress due to the combined effects of waves and currents resulted from increased wave height, which is strongly related to fetch within the bay. Therefore, understanding fetch-limited wave heights as a function of wind speed and direction, in conjunction with basin geometry, may be a better way to predict sediment resuspension during meteorological frontal passages in the shallow bays of the northern Gulf of Mexico.

1. Introduction

Sediment remobilization in shallow estuaries can have ecosystem-wide implications by redistributing sediment-associated biogeochemical constituents throughout the system (Bianchi, 2007). Typically, this may require high-energy events such as increased fluvial discharge, or spring tides (Baumann et al., 1984; Castaing and Allen, 1981; Geyer et al., 2001; Hensel et al., 1998; Nichols, 1993). In northern Gulf of Mexico (GOM) estuaries specifically, meteorological events such as hurricanes and tropical storms can also be effective drivers in sediment remobilization (Childers and Day, 1990; Conner et al., 1989; Day et al., 2000; Hayes, 1967; Perez et al., 2000; Turner et al., 2006; Walker, 2001). Hurricanes and tropical storms however, generally affect a relatively small spatial area, and are infrequent at a specific site, thus their impact may not be as significant in estuaries compared to more regular meteorological forcings. In contrast, literature has shown that seasonal meteorological frontal events (winter cold fronts), because of their frequent occurrence, and larger spatial extent, may have greater impact compared to hurricanes on estuarine and coastal environments in the northern GOM (Moeller et al., 1993; Pepper et al., 1999; Roberts et al., 1987).

These cold fronts can influence sediment resuspension, and overall sediment transport within the estuary. As an example, the Atchafalaya-Vermillion Bay region receives sediment and water input from the Atchafalaya River. Annual sediment transport from cold fronts for Atchafalaya-Vermillion Bay was estimated to be about 12% of the yearly average sediment discharge from the river (Walker and Hammack, 2000). Additionally, most of the sediment transport along Louisiana's Chenier-plain coast is thought to be driven by cold fronts, resulting in regional–scale accretion for this area, located along a largely eroding section of the GOM coast (Kineke et al., 2006).

The sediment transport during these events may also have critical impacts on ecosystem functioning by modifying sediment

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delivery to nearby marshes (Baumann et al., 1984; Childers and Day, 1990; Draut et al., 2005; Perez et al., 2000; Reed, 1989), nutrient transport, and other biogeochemical fluxes both within, and out of the system (Booth et al., 2000; Day et al., 2000; Perez et al., 2003). In a study investigating natural and anthropogenic mechanisms for sediment resuspension in Galveston Bay, Dellapenna et al. (2006) estimated that sediment resuspension from cold fronts annually was equivalent to ~40% of the suspended sediment load from the bay's fluvial source. While they found that shrimp trawling can resuspend the equivalent of >250% of the fluvial supply to the bay, because cold fronts occur during winter months concurrent with peaks in primary productivity, versus shrimp trawling that dominantly occurs in summer months, resuspension during cold fronts likely has a greater impact on ecosystem health. Throughout the northern GOM, cold fronts are an important meteorological event with high sediment transport potential (Armbruster et al., 1995; Chaney and Stone, 1996; Crout and Hamiter, 1981; Dingler et al., 1993; Roberts et al., 1987; Stone and Wang, 1999), but they may also be an important forcing mechanism in other mid-latitude, low-energy coastal environments (Pepper and Stone, 2004).

Northern GOM cold fronts are typically associated with large increases in wind speed, and rapid shifts in wind direction. The rapid shifts in wind speed and direction often result in dramatic changes in water level. Sometimes referred to as “wind-tides,” the changes in water level height, and the water volume flux can exceed what would be predicted from astronomical tides (Perez et al., 2000; Smith, 1977). As a result, wind stress associated with these events has often been the focus mechanism driving sediment resuspension from the shallow coastal waters in studies from the region (Huh et al., 1991, 2001; Roberts et al., 1987; Walker, 1996; Walker and Hammack, 2000). For example, research in Mobile Bay established a critical wind stress for erosion, where suspended sediment concentrations increased rapidly above background levels in the bay with increased wind stress (Ha and Park, 2012).

The focus on wind speed as the primary mechanism driving resuspension during these events is likely due in part because it is easy and routinely measured, but as noted by Ha and Park (2012) the wind stress threshold for erosion observed in Mobile Bay neglected any contribution from wave-induced bed shear stress. While wind in these environments drives wave formation and sometimes current generation, for estuaries in general, both waves and currents contribute significantly to sediment resuspension and transport (see review by Green and Coco, 2014). Booth et al. (2000) noted that in shallow, micro-tidal environments, wind-driven surface waves are one of the primary mechanisms for resuspension, but they only used linear wave theory to model resuspension based on wind speeds. Understanding what is happening near the bed as a result of the wind, waves, and currents during these events may add insight to the resulting sediment dynamics, and improve our predictive capabilities for resuspension and transport during winter cold fronts. To our knowledge however, no study to date has made direct measurements in an estuary of waves and currents during a cold front event, to investigate sediment resuspension from the seabed.

The purpose of this study, therefore, is to directly investigate the impacts of a cold front passage on sediment suspension in a shallow, micro-tidal estuary within the northern GOM. Two separate instrumented pod deployments were conducted in West Galveston Bay (WGB) to capture two different frontal passages in late January and early February 2013. The data presented here will correlate observations of wind stress, bed shear velocity from currents only, and bed shear velocity from the combined effect of waves and currents to sediment resuspension. Through this, we aim to better understand the predictor for sediment resuspension from cold fronts in northern GOM estuaries beyond wind speed alone, by incorporating the combined effect of waves and currents near the bed during the event.

2. Study area

Galveston Bay, located in the northern GOM, is the second largest estuary in Texas with a surface area of ~1400 km^2 (Fig. 1). Similar to other GOM bays, Galveston Bay is shallow (average depth 2.1 m), micro-tidal (0.5–0.7 m range), and has a deep shipping channel oriented along its main axis (Armstrong, 1982; Solis and Powell, 1999). The bay is considered to be meteorologically dominated, given its small tides, shallow depths, and high susceptibility to wind forces (Solis and Powell, 1999; Ward Jr, 1980). The prevailing south-southeast winds can generate waves across the open bay resulting in water-column mixing and erosion (Ward Jr, 1980). Stratification in the open bay is rare, only occurring during freshets. The freshets are derived primarily from the Trinity and, to a lesser extent, the San Jacinto Rivers that flow into the northeastern and northwestern shores of Galveston Bay proper, respectively. These two rivers have a combined net inflow of ~390 m^3/s (Armstrong, 1982; Ward Jr, 1980).

WGB is a ~200 km^2 back barrier lagoon sub-estuary within the Galveston Bay System (Fig. 1). Separated from the open GOM by Galveston Island, WGB is tidally serviced by the San Luis Pass (SLP) tidal inlet to the west, connected to Galveston Bay proper to the east, and is generally around 2 m in depth or less. Freshwater inflow into WGB from the Trinity and San Jacinto rivers through Galveston Bay proper is limited due to the Houston Ship Channel (HSC), Texas City Dike, and Pelican Island (Powell et al., 2003). The primary source of freshwater to WGB is from Chocolate Bayou. Chocolate Bayou has a drainage basin of ~1000 km^2, and an average inflow of ~3 m^3/s, with a maximum flow of ~10 m^3/s and a minimum flow of ~0.5 m^3/s (USGS Gage Statin 08078000 near Alvin, TX from the years 1960–2013). In open areas of WGB, wave heights are typically less than 0.2 m (Ravens et al., 2009), average current velocities are less than 0.05 m/s (Dekshenieks et al., 2000), and fair-weather suspended sediment concentrations (SSC) in the bay are typically ~20 mg/l (Ward and Armstrong, 1992).

Although the astronomical tides are small, the meteorologically-

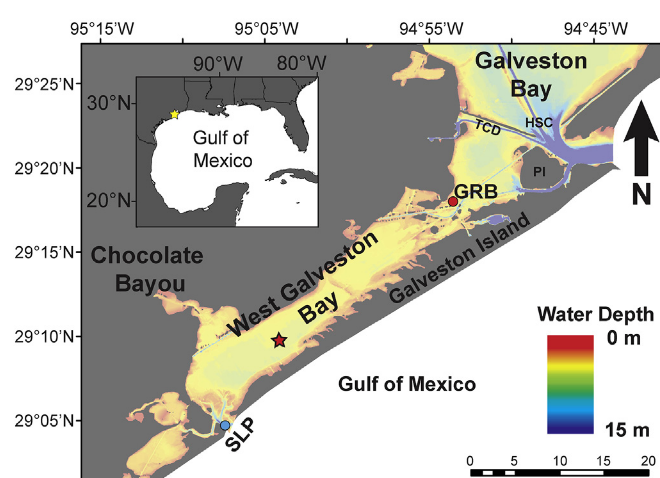

Fig. 1. Map of the West Galveston Bay study area, where the red star indicates the location of the instrument deployment site. Wind data were collected at the station at San Luis Pass (SLP, blue dot), and water level data were from the station at the Galveston Railroad Bridge (GRB, red dot). Other geographic locations mentioned in the text are also labeled on the map including: the Texas City Dike (TCD), Houston Ship Channel (HSC), and Pelican Island (PI). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)