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ORIGINAL RESEARCH ARTICLE

Galveston Bay dynamics under different wind conditions

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Summary The Regional Ocean Model System (ROMS) was used to simulate flow and hydrographic (temperature, salinity) patterns in a shallow, relatively flat-bottomed estuary with two subestuaries, one with an elongated shape and the other with a roughly circular shape. Simulations were used to elucidate the wind stress effect on a tidally formed cyclonic gyre in Galveston Bay, Texas (USA). The form factor suggests that Galveston Bay is a mixed, mainly diurnal system with tides that propagate out of phase by less than 1 h from side to side of the estuary. Temperature and salinity patterns suggest that the influence of the estuary extends oceanward, up to a distance commensurate with the 14 m depth isobath (~10 km offshore), during a diurnal tidal cycle. A tidally generated cyclonic gyre was observed to form in the circular subestuary, suggesting that this region may be more productive than others. This tidally formed gyre appeared to weaken and even disappear under certain wind stress conditions. Simulations suggest that the entire bay was able to flush only under northeasterly wind conditions, while for all other wind directions (northwesterly, southeasterly and southwesterly), the water appeared to pile up in the circular subestuary. Furthermore, most of the ocean-bay exchange was found to occur through the north entrance to the bay where the effects of the gyre were observed. Thus, it is expected that much of the exchange of water-borne substances, pollutants and plankton between the bay and the ocean occurs through this entrance.
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1. Introduction

Coastal marine ecosystems areas have been studied to understand sediment transport (Agardy, 2000; Salas-Monreal et al., 2009), zooplankton dispersion (Becerro et al., 2006; Chacon-Gomez et al., 2013; Holliday and Pieper, 1980) and the spatial and temporal variability of hydrodynamics and currents (Avendaño-Alvarez et al., 2017; Goreau and Hayes, 1994; Salas-de-Leon et al., 2004a; Wilkinson and Souter, 2008). In estuaries, gyres are commonly generated by current rectification (Storlazzi et al., 2006) due to the coastal boundaries. These gyres are one of the most important factors affecting the distribution of productive areas, sedimentation, vertical water movements, pollutants, and suspended matter concentrations (Salas-Monreal et al., 2009). Cyclonic gyres have been shown to generate highly productive areas by pumping deeper, high-nutrient, cold waters to the surface in the open ocean (Salas-de-León et al., 2008); however, in shallow waters the effects of gyres have not yet been fully described (Aretxabaleta et al., 2008; Wang et al., 1994). Cyclonic gyres in shallow waters are expected to disperse the water, pollutants, and suspended matter, since anticyclonic gyres have been found to concentrate such substances (Salas-de-Leon et al., 2004a). Thus, it is important from an ecosystem standpoint to understand the physical mechanisms associated with such gyres in shallow systems and their relation to residence time of the water-borne substances, as well as their trajectories.

The description of gyres in estuaries has been based both on *in situ* data (Cloern et al., 1983; Geyer et al., 2000; Officer, 1981; Salas-Monreal and Valle-Levinson, 2009) and model outputs (Dalrymple et al., 1990; Spiteri et al., 2008). The Regional Oceanic Modeling System (ROMS), which is a free-surface, hydrostatic, primitive equation model has been successfully used to describe currents and channel dynamics in estuaries. Xinyu and Valle-Levinson (2007) performed numerical experiments to simulate river discharge, with and without the influence of tides, in a shallow estuary and to describe the buoyancy effects on the circulation. Using the ROMS, Scully et al. (2009) found that the dominant along-channel momentum balance in estuaries is not always between the pressure gradient and the bottom stress. The nonlinear advective acceleration term can be on the same order of magnitude. The ROMS has also been used to study lateral circulation and to estimate sediment transport in estuaries (Chen and Sanford, 2009). The suspension (or resuspension) and deposition of matter are processes of particular importance in estuarine systems and arise mainly due to the presence of cyclonic and anticyclonic gyres, respectively.

The goal of this study is to advance the understanding of flow patterns and gyres generated in shallow flat estuaries under the influence of winds, tides, and river discharges. A recent oil spill in Galveston Bay, Texas (USA) (>635 m^3 on March 23, 2014), resulting from a barge and cargo ship collision in the Houston Ship Channel, provided the impetus for the present study (Houston Chronicle, April 6, 2014). Model simulations and comparison to *in situ* data were carried out for the month of April 2014 in Galveston Bay to elucidate the relative importance of the terms in the momentum equation and to describe the variability of tidally generated gyres under different wind forcing conditions. The Galveston Bay estuary represents an ideal set up for the present study since it includes two differently shaped sub-estuaries (Fig. 1) directly influenced by two rivers.

Galveston Bay, the second largest estuary in the Gulf of Mexico (Fig. 1), has a surface area of 1600 km^2, is 50 km long, and is 27 km wide. The bathymetry is relatively flat with a mean depth of 3 m, except in the northern entrance (Houston Ship Channel), where a 12 m deep channel is located (Dupuis and Anis, 2013). The bay has an intertidal range of 0.5 m. The bay is connected to the Gulf of Mexico *via* two inlets (southern entrance and northern entrance) and has two major freshwater sources, the San Jacinto and Trinity Rivers (Fig. 1). The estuary is one of the most important shipping hubs in the USA and home to the Port of Houston, the largest port in the USA, and based on foreign tonnage, this estuary is the sixth largest in the world. More than one-third of the USA chemical production facilities and oil refineries are located around the bay, and one-third of commercial fishing income and one-half of sport fishing expenditures in Texas come from the estuary. Previous studies have already described the general dynamics of the bay using model simulations to reproduce the general circulation (Rayson et al., 2015), the effect of hurricanes within the bay (Rego and Li, 2010), and the effect of varying fresh water inputs on the oyster population within Galveston Bay (Klinck et al., 2002).

This manuscript reports the results of a study that explores the dynamics of tidally formed cyclonic gyres in a shallow estuary. This manuscript incorporates field observations and model simulation results and addresses the following three main objectives: (1) the variability of tidally generated gyres under different wind forcing conditions, (2) the distance of the river influence on the estuary and (3) the relative importance of the terms in the momentum equation.

2. Material and methods

The ROMS has been used to model internal tides and to estimate tidal fields, mixing and current patterns (Robertson, 2006; Salas-de-Leon et al., 2004a; Scully et al., 2009; Sutherland et al., 2011; Xinyu and Valle-Levinson, 2007). According to Robertson (2006), the semidiurnal baroclinic tides are well simulated with ROMS. The free-surface, hydrostatic, primitive equation ocean model uses sigma coordinates in the vertical (Haidvogel et al., 2000) to increase the accuracy of the simulations. In this study, the ROMS was setup following the basic configuration described in Salas-Monreal et al. (2012) to elucidate the effect of the wind stress in a shallow estuary and the influence of fresh water inputs on flow dynamics. The model was configured for the domain shown in Fig. 1. At the locations of freshwater inflow into the estuary (San Jacinto and Trinity Rivers), salinity was assumed to be zero and temperature equal to 15°C. River velocity discharges were set to 0.40 $m\,s^{-1}$ for both rivers (~100 $m^3\,s^{-1}$), which are representative values for this time of the year according to O'Donnell (2005). Tidal sea surface elevations, used to force the model at the external boundary, were obtained from the North Jetty station located at the entrance of the Galveston Bay (Fig. 1; http://tidesandcurrents.noaa.gov/harcon.html?id=8771341). Initial ocean salinity and temperature (inside and outside of the

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