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# Modeling the tidal and sub-tidal hydrodynamics in a shallow, micro-tidal estuary

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ABSTRACT

The three-dimensional hydrodynamics of Galveston Bay were simulated in two periods of several month duration. The physical setting of Galveston Bay is described by synthesis of long-term observations. Several processes in addition to tidal hydrodynamics and baroclinic circulation processes contribute substantially to the observed variability of currents, water level and salinity. The model was therefore forced with realistic water levels, river discharges, winds, coastal buoyancy currents (due to the Mississippi River plume) and surface heat fluxes. Quantitative metrics were used to evaluate model performance against observations and both spatial and temporal variability in tidal and sub-tidal hydrodynamics were generally well represented by the model. Three different unstructured meshes were tested, a triangular mesh that under-resolved the shipping channel, a triangular mesh that resolved it, and a mixed quadrilateral-triangular grid with approximately equivalent resolution. It is shown that salinity and sub-tidal velocity are better predicted when the important topographic features, such as the shipping channel, are resolved. It was necessary to increase the seabed drag roughness in the mixed quadrilateral-triangular grid simulation to attain similar performance to the equivalent triangular mesh.

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## 1. Introduction

Galveston Bay is one of the largest estuaries on the Gulf Coast and is the busiest petrochemical port in the United States. In addition to heavy industrial use, the estuary has a substantial ecological function including coastal habitat for migratory birds, oyster production and a recreational fishing industry (Lester and Gonzalez, 2011). Oil spills are common in the bay. Between 1998 and 2009 there were almost 4000 reported spills with a combined volume of 400,000 gallons (Lester and Gonzalez, 2011). In March 2014, 168,000 gallons of heavy bunker fuel was spilled into the bay in a single incident when a ship and a barge collided. Understanding and accurately predicting the estuarine hydrodynamics is a crucial step towards determining the fate and transport of oil in the system.

Galveston Bay covers an area of 1360 $km^2$ and has an average depth of 2–3 m (Fig. 1). The man-made Houston Shipping Channel (HSC) is the primary deep bathymetric feature with a depth of 15 m and average width of 200 m traversing from the main Gulf entrance (Bolivar Roads) to the Buffalo Bayou in the northern part of the bay. The Trinity River enters the shallow Trinity Bay perpendicular to the axis of the shipping channel. The other side embayments, East and West Bay, are topographically separated by the man-made Texas City Dike and Hanna Reef, a natural oyster reef. Most of the heavy industry is along the western shoreline close to the HSC and near Texas City while most of the oyster reefs and bayous that provide bird habitat are in the side embayments and along the eastern shore.

The geomorphological classification of the bay is a coastal lagoon with a barrier island (Schroeder and Wiseman, 1999). The physical setting (geometry, bathymetry, forcing) of the bay is similar to other estuaries along the Gulf Coast (e.g., Mobile Bay, Alabama and Barataria Bay, Louisiana) yet different from the drowned river type estuaries upon which the majority of estuarine literature is based (e.g., Hansen and Rattray, 1966; Geyer and MacCready, 2014).

The Trinity River contributes about 75% of the total flow into Galveston Bay, and the salinity distribution within the bay is primarily driven by freshwater discharge (Orlando, 1993). During a typical year the wet period is April–June and the average salinity within the bay is 5–10 psu lower than the drier months of Aug–Oct. Despite having an average depth of 3 m, Trinity Bay remains

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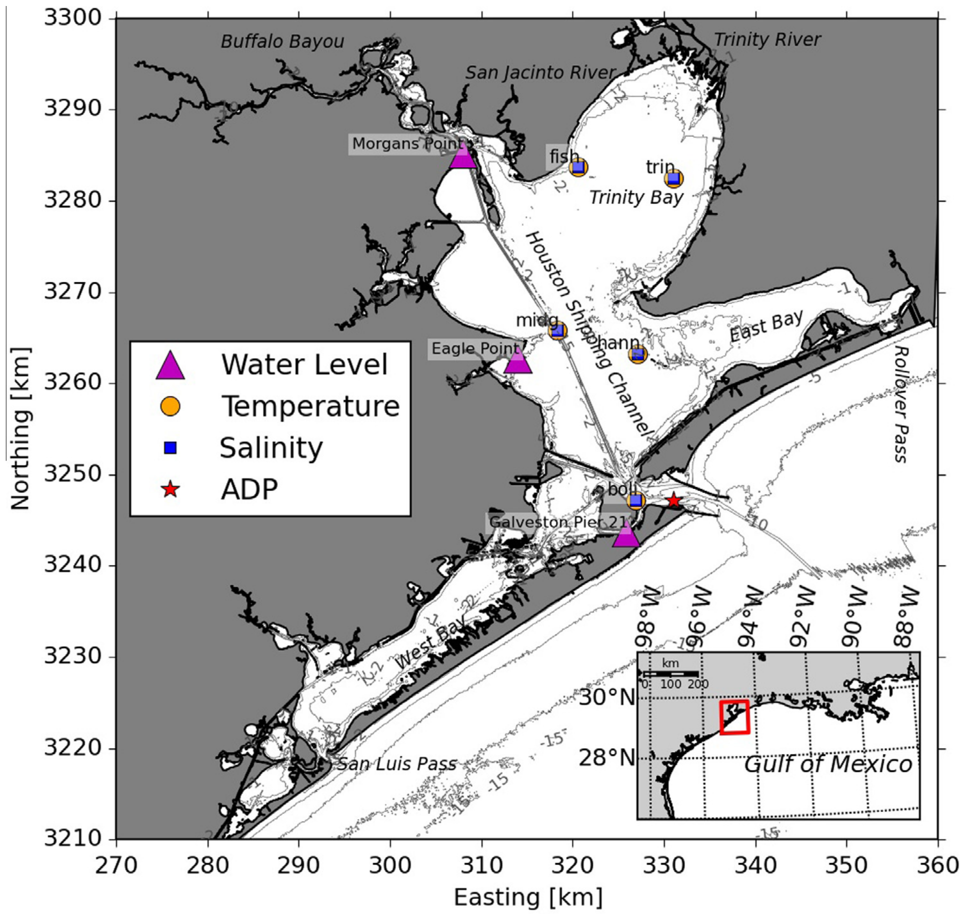


**Fig. 1.** Bathymetry of Galveston Bay showing the locations of observation sites.

stratified throughout the year. Other than the deeper HSC, this was the only part of the bay that was found to be stratified in the hydrographic observations examined by Orlando (1993). The understanding of salt transport within the bay is that seawater intrudes into the upper reaches of the bay via the HSC and freshwater leaves along the eastern margins (Powell et al., 2003). This general understanding of the bay circulation is based upon limited field observations and coarse resolution hydrodynamic modeling.

The tides in the Gulf of Mexico are classified as micro-tidal and are primarily diurnal. Despite the small amplitude of the tides, topographic features, such as constrictions at the entrances to bays and estuaries, can lead to locally strong tidal currents in excess of $1\ \mathrm{m\,s^{-1}}$ (Schroeder and Wiseman, 1999). Tidal forcing only accounts for a fraction of the total water level variability along the Gulf Coast; Ekman setup due to the east–west component of wind stress as well as seasonal variations in the circulation in the Gulf of Mexico also drive substantial water level fluctuations (Schroeder and Wiseman, 1999; Cox et al., 2002). Cox et al. (2002) improved their water level predictions by including the tidal variability plus a linear regression model relating wind stress to water level.

Previous Galveston Bay hydrodynamic model applications have addressed several issues but little of this work is available in peer-reviewed journals. Berger et al. (1995) developed a 3D finite-element model that was used to evaluate the effect of modifications to the shipping channel on salinity distribution. The 3D model had three vertical layers. Klinck and Hofmann (2002) coupled the model of Berger et al. (1995) to an oyster population model to show that widening the HSC would increase the habitable region within the bay. Matsumoto et al. (2005) developed a depth-averaged model of the bay to understand the influence of structures such as the Texas City Dike on the residual circulation patterns in the bay. An operational nowcast/forecast model has been developed to provide water level and currents for navigation and also for oil spill response (Schmalz, 2000; Schmalz and Grant, 2000). In this model, the bay and shipping channel were discretized using separate grids to resolve the length scale differences between the shipping channel and the rest of the bay. While the model of Schmalz and Grant (2000) was able to resolve the velocity and water level throughout the bay fairly accurately, it under-represented the salinity stratification observed within the shipping channel. A common weakness in all of these models was that three-dimensional processes, such as vertical shear and baroclinic flow, were either ignored or under-resolved.

The purpose of this paper is to describe Galveston Bay's circulation characteristics and present a new hydrodynamic model capable of resolving the important processes. Modeling oil transport in the embayments bordering the Gulf of Mexico is the motivation for developing this model. Accurately simulating the hydrodynamics that drive oil transport is a multi-scale physics problem in which the full space–time spectrum of variability must be captured. Aspects of Galveston Bay hydrodynamics considered include salinity variability and its relationship to freshwater discharge, tidal dynamics including tidal frequency and the sub-tidal frequency water level and current variability and water temperature variability. Water temperature is often neglected in estuarine models due to the dominance of salinity on the baroclinic pressure gradient, however we include it because it influences the evaporation rate and is important for biological processes such as oyster larval recruitment (e.g., Klinck and Hofmann, 2002). Adequate

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