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Surge dynamics across a complex bay coastline, Galveston Bay, TX

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ABSTRACT

While tidal exchange across bay coastlines has been well studied, research to date has not provided a comprehensive analysis of the volume of surge that can flow across bay coastlines during tropical cyclone events. Such insight can particularly be useful for understanding coastal storm surge dynamics that influence regional inundation and can help guide surge mitigation strategies for semi-enclosed bay systems. In this study, a suite of 80 synthetic tropical cyclones were simulated to characterize the volume of surge that flows across Galveston Bay's complex 98 km coastline, which is made up of tidal inlets, intermittent barrier islands, and existing surge defenses along the Upper Texas Gulf Coast. Tropical cyclone characteristics analyzed in this study include the wide variety of tropical cyclone intensity (V_{max}) and size (R_{max}) combinations possible for the region, with the storm surge response of each tropical cyclone simulated using the ADCIRC + SWAN model. In-depth analysis of coastal and in-bay storm surge responses was performed for baseline or existing conditions as well as scenarios representing severe barrier island erosion and future conditions based on intermediate sea level projections for the year 2050 and 2 100. Findings demonstrate that while the majority of surge may flow across tidal inlets for smaller, weaker storms, a storm intensity and size threshold exists that results in greater flow across barrier islands, having important implications for surge mitigation strategies. Analysis demonstrates that while this threshold may occur for extreme tropical cyclones under baseline conditions, this transition can occur for relatively, significantly weaker and smaller storms under the erosion and sea level rise scenarios evaluated.

1. Introduction

The U.S. Gulf and North Atlantic Coasts are incised by numerous bay environments that commonly serve as metropolitan areas and industrial ports. While such geographic locations may provide exceptional social and economic opportunities, they are also vulnerable to tropical cyclone storm surge. Storm surge-driven disasters can dramatically impact the short and long-term well-being of the local inhabitants and infrastructure of these regions, and can potentially have larger, regional or national effects because of the economic importance of these communities. In recent years, a number of inhabited bays have experienced severe storm surge impacts, including Chesapeake Bay (Hurricane Isabel – 2003; Sheng et al., 2010), Galveston Bay (Hurricane Ike – 2008; Hope et al., 2013; Sebastian et al., 2014), and New York Harbor (Hurricane Sandy – 2012; Brandon et al., 2014).

During tropical cyclones, barrier islands provide a natural form of protection that can help prevent coastal surge from entering a bay, whereas tidal inlets serve as a direct connection through which coastal surge can enter a bay. Although tidal exchange that occurs across tidal inlets is generally well-characterized, exchange that takes place across bay coastlines during tropical cyclone events is less predictable. This is due to non-linear surge interactions across coastline-bay environments that depend on various factors, including the bathymetry of tidal inlets and topography of barrier islands, tropical cyclone characteristics and their respective influence on storm surge, and erosion and breaches that can alter barrier islands during tropical cyclone strikes. In addition, while

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it is known that sea level rise will exacerbate coastal flooding, exactly how it will impact the exchange of storm surge across bay coastlines during TC events is not known. Such analysis is important to understand coastal storm surge dynamics that can help guide surge mitigation strategies for present-as well as future-conditions.

Past studies have evaluated TC storm surge flows across different coastal sections (e.g. tidal inlets and barrier islands) of the coastlines of Louisiana (Grzegorzewski et al., 2011), Long Island, New York (Cañizares and Irish, 2008), and Galveston Bay (Rego and Li, 2010; Sebastian et al., 2014). However, these studies only considered the impacts of a few historical or synthetic tropical cyclone events with randomly varying characteristics or only portions of a bay's coastline. While single event analyses can be useful for understanding what may have happened during a historical event, in order to comprehensively understand and characterize the non-linear variations and relative changes in flow that can occur across tidal inlets and barrier islands of a bay's coastline, a range of storms with standardized characteristics must be evaluated using physics-based numerical models.

The objective of this paper is to characterize general trends in flow across Galveston Bay's complex coastline using the tightly coupled ADvanced CIRCulation (ADCIRC) and Simulating WAves Nearshore (SWAN) model (referred to as ADCIRC + SWAN). This study uses the term "coastal surge" to refer to surge that flows across a bay's coastline and "local surge" to refer to surge solely generated within a bay. Coastal surge was quantified by determining the volume of surge or net flow entering Galveston Bay due to inundation overwash across the bay's coastline for a suite of 80 synthetic tropical cyclones and Hurricane Ike (2008) for reference. Galveston Bay is located along the Upper Texas (TX) Coast of the Gulf of Mexico, and was chosen as the study location because of vulnerability, societal importance and its complex coastline, which is made up of various tidal inlets, barrier islands, and an existing seawall. By using tropical cyclones with a wide variety of possible storm size (represented by radius to maximum winds or R_{max}) and intensity (represented by maximum 1-min sustained wind speed or V_{max}) combinations that could impact the study area, non-linear trends in the volume of surge that flows across Galveston Bay's coastline and its different tidal inlet and barrier island sections was evaluated. In addition to understanding general trends in coastal surge dynamics due to variations in the R_{max} and V_{max} of storms, sensitivity analysis was performed with respect to TC forward speed (V_f). Finally, variations in coastal surge dynamics relative to baseline or existing conditions were evaluated for projected sea level increases in the year 2050 and 2 100 and severe erosion scenarios for the bay's barrier islands based on conditions observed post-Ike (2008).

Since, as discussed later, the volume of surge across the bay's coastline and hence its different coastline sections can serve as an indicator of the extent of inland inundation behind the bay's coastline, information from this study can be useful for understanding how regional surge impacts to the bay may vary for different TC characteristics. Furthermore, the location and height of surge mitigation designs for the region can be designed more effectively by understanding where and how much surge flows across Galveston Bay's tidal inlets and barrier islands for different tropical cyclone characteristics under current and future sea level conditions.

Since analysis of coastal surge dynamics provides useful insight for surge mitigation strategies in the study region, proof-of-concept simulations involving the introduction of surge mitigation features (i.e. levees) were additionally performed to inform coastal engineers of some of the practical findings from this study. This analysis involved optimizing levee placement based on further understanding baseline coastal storm surge dynamics. In addition, local surge was evaluated to understand the residual surge that can still develop within Galveston Bay when fully protected by a coastal barrier that prevents coastal storm surge from flowing into the bay. This analysis highlights the levels of local surge that can develop due to wind-fetch that acts across the bay, which depends on various factors, including the volume of water in the bay, the local bathymetric and topographic features of the bay, and tropical cyclone intensity and other meteorological characteristics.

While results apply to Galveston Bay, the methods used to advance the understanding of surge dynamics and guide general surge mitigation concepts can be applied to other bay environments. Section 2 outlines the study area of interest and Section 3 the methodology used to evaluate the coastal and local surge response in the study area. In Section 4 results are provided, followed by a discussion of the study's findings and its implications in Section 5. Finally, a brief conclusion is provided in Section 6.

2. Study area

Galveston Bay is a semi-enclosed, tidally influenced bay located on the Upper Texas Gulf Coast with a surface area of approximately 1 554 km^2 and an average depth of roughly 3 m (Fig. 1a). As the seventh largest estuary in the United States, the bay serves as the primary connection between the Gulf of Mexico and inland communities of the greater Houston-Galveston region. Primary freshwater tributary dischargers to the bay include the Lower San Jacinto River (LSJR) and the Trinity River, while minor tributaries include smaller bayous such as Clear Creek (Fig. 1a). Along the perimeter of Galveston Bay, more than half a million (545,346) people live less than 7.6 m above mean sea level (U.S. Census Bureau, 2010). The bay is also home to critical facilities, including the second largest petrochemical complex in the world, and the number one port in the U.S. in terms of export tonnage (Port of Houston Authority, 2015).

The Houston-Galveston region's historical vulnerability to extreme tropical cyclone events has demonstrated the need to protect it from storm surge. Since 1900, the bay has experienced 21 TC strikes within a 100 km radius from the center of the bay, 8 of which were Category 3 (49.39 m/s or 110 mph) or greater (NOAA, 2016a). While the 5.2 m Galveston Seawall and the 4.6–7.6 m Texas City Levee help protect localized areas (Fig. 1a), a significant number of people and infrastructure are still vulnerable to storm surge in the Houston-Galveston region.

Storm surge can flow across various sections of Galveston Bay's coastline, including its tidal inlets, barrier islands, and the Galveston Seawall. To help understand, predict, and protect against surge impacts to the entire Houston-Galveston region, this study evaluates the volume of storm surge that can flow across the bay's coastline and its different sections. As discussed in the results section, the volume of surge that flows across the bay's coastline can provide a direct indication of regional impacts as compared to peak surge which can vary significantly throughout the bay. Fig. 1a and b outline Galveston bay's different coastline sections, which are referred to throughout the paper, from west to east, as Tidal Inlet 1 (T1) for San Luis Pass, Barrier Island 1 (B1) for west Galveston Island, Barrier 2 (B2) for the Galveston Seawall, Tidal Inlet 2 (T2) for Bolivar Roads, and Barrier Island 3 (B3) for Bolivar Peninsula.

B1 and B3 partially protect the region against storm surge as natural sand barrier islands. While the topography along these barrier islands varies significantly in their respective alongshore and cross-sectional dimensions (Fig. 1b), B1 and B3 stand from 0.75 to 2 m above MSL. Peak dune elevations along the seaward facing side of these barrier islands range from 1.5 to 3 m above MSL for B1 and B3. The main tidal inlets along the bay's coastline include T1 and T2, which, respectively, contribute roughly 20% and 80% of the diurnal tidal exchange that occurs between the bay and the Gulf of Mexico (Lester and Gonzalez, 2011). T2 makes up the majority of tidal exchange because of its extensive width (3.75 km) and maximum depth of roughly 15 m, as compared to T1, which has a width of 1.1 km and a maximum depth of 4.25 m (Fig. 1b).

Various local and regional surge mitigation strategies have been proposed for the Houston-Galveston region since Hurricane Ike (2008) made landfall directly at Bolivar Roads (T2) (Merrell et al., 2011; GCCPRD, 2015; SSPEED Center, 2015; Torres et al., 2017). Many of the strategies include coastal barriers or levees along Galveston Bay's barrier islands and/or flood gates across the bay's tidal inlets; however the extent

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