Storm surge propagation in Galveston Bay during Hurricane Ike

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A B S T R A C T

We studied Hurricane Ike’s storm surge along the Texas–Louisiana coast using the fully nonlinear Finite-Volume Coastal Ocean Model (FVCOM, by Chen et al., 2003) with a high-resolution unstructured mesh. The model was validated with USGS surge data collected during Hurricane Ike. This study focused on 1) how the surge wave propagates into and within Galveston Bay and 2) the importance of the bay’s barrier system. Ike’s coastal surge propagated alongshore due east towards Louisiana, partly because of Bolivar Peninsula, which, together with Galveston Island, provided a barrier protecting the bay. In the upper bay, a west–east oscillation of water surface gradient of about 0.08 m/km was found and studied. We then varied Bolivar Peninsula’s topography for different simulations, examining the role of barrier islands on surge propagation into the bay. Results suggest that when the Peninsula’s height (or volume) was reduced to about 45% of the original, with two breaches, the bay was exposed to dangerously high water levels almost as much as those if the Peninsula was leveled to just 0.05 m above the Mean Sea Level, underlining the nonlinear nature of this bay-barrier system.

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1. Introduction

Storm surge is a long-period wave caused by extreme wind and atmospheric pressure gradient. Numerical modeling of coastal surge has played an important role in engineering design, disaster planning and coastal management since the 1970s, and the rate of new publications indicates a renewed interest in surge modeling around the world. Tropical cyclones, with lower interior pressures and higher wind speeds, typically produce significantly higher surges than extratropical cyclones (Resio and Westerink, 2008). The impact of a hurricane’s surge on the coastal region depends not only on the characteristics of the forcing (a storm’s intensity, size and speed) but also on the path of the storm and on the geometric properties of the waterbody.

We used the fully nonlinear Finite-Volume Coastal Ocean Model (FVCOM; Chen et al., 2003) with a high-resolution unstructured mesh to study Hurricane Ike’s storm tide of September 2008 along the Texas–Louisiana coast. The United States Geological Survey (USGS) surge dataset of East et al. (2008) allowed for validation of the model and in-depth discussion of this rare and powerful hurricane-induced storm surge in the semi-enclosed Galveston Bay. We examined how the surge wave propagated into Galveston Bay and the importance of its barrier system, with a new set of simulations using different coastal geometries to represent increasing degrees of coastal erosion.

Most storm surge studies focus on the coastal distribution of peak surges (e.g. Xie et al., 2006; Westerink et al., 2008) and only a few investigate surge dynamics within bays. Valle-Levinson et al. (2002) described the response of the lower Chesapeake Bay to Hurricane Floyd (September 1999). Using observed data, they focused on water exchange processes through the estuary’s wide entrance. They reported a westward pileup of water within the lower bay when winds were northeasterly, and a seaward barotropic pressure gradient force caused by the change of winds to northwesterly that resulted in a net outflow. Xie et al. (2004) discussed inundation algorithms and flooding velocities using the Princeton Ocean Model. They simulated a Category-3 hurricane (on the Saffir–Simpson scale) moving northward 50 km off the eastern border of a synthetic bowl-shaped waterbody with a 60 km diameter. They compared inundation patterns with and without enforcing mass conservation, with threshold depths of 0.5–0.8 m, and with inundation speeds given by surface vs. vertically-averaged currents. They indicated a SW–NE surface elevation difference of about 5 m, when the hurricane was due east of the model domain.

Weisberg and Zheng (2006a) used FVCOM to investigate the impact of hurricane storm surges in the vicinity of Tampa Bay (Florida) and the sensitivity to points of landfall and direction of approach of the hurricane. They concluded that a hurricane traveling up the axis of the bay was the best of the worst cases with regard to storm surge, while acknowledging that it was difficult to define an overall worst case direction. Their results, however, were not compared against observed...
surges. They also did not quantify the 8-hour east-west oscillation of the sea level slope. Weisberg and Zheng (2006b) studied surge induced by Hurricane Charley (August 2004) and found that its translation up Charlotte Harbor’s (Florida) bay axis explained the relatively small storm surge inside the bay, despite its Category-4 status. The opening of a new inlet in North Captiva Island, 450 m wide, was explained based on a strong horizontal pressure gradient force across a narrow low-lying strip of the island (a 1.25 m surge on the gulf side and 0.9 m depression on the sound side). Data from 4 stations was used in validation.

Shen et al. (2006) simulated Hurricane Floyd’s storm tide of September 1999 in Chesapeake Bay, with a substantial dataset for validation. They concluded that water levels inside the bay can be explained by the superposition of two distinct mechanisms: offshore surge propagation into the bay and local wind forcing. Their results indicated that water levels in the lower bay were more influenced by the incoming surge wave caused by remote effects, while at the upper bay they were mainly caused by local wind. Given the geometry of the region, they focused on variations along the bay, but showed southwestward followed by southeastward surface gradients (elevation differences of about 0.8 m, from coast to coast) separated by about 6 h.

With the exception of Cañizares and Irish (2008), the estuaries previously studied have wide openings, without barrier islands protecting them from storm surges. Cañizares and Irish (2008) simulated the impact of barrier island overwash and breaching on bay water levels along the south shore of Long Island, New York. Their nearshore and bay hydrodynamic model was dynamically coupled with the wave and morphological models in the Delft3D system (Deltares, 2009). Comparing the results with those without sediment transport and morphological change, barrier island overflow contributed 1 m to the total water level in Moriches Bay for the September 1938 Hurricane, for the December 1992 Nor’easter. Although limited in wind fields and bathymetric accuracy, their results indicated the magnitude and variability of barrier island overflow.

Using FVCOM, we examined Hurricane Ike’s flooding along the Texas–Louisiana coast, the surge dynamics within the bay and the impact of barrier systems to surge propagation into Galveston Bay.

2. Hurricane Ike

Hurricane Ike caused extensive damage and over 100 deaths across Hispaniola, Cuba, and the coasts of Texas and Louisiana. It reached peak intensity with 230 km/h winds and minimum central pressure (MCP) of 935 mbar over the central Atlantic Ocean before hitting the island of Cuba. Ike was the most intense storm in the 2008 Atlantic hurricane season (Berg, 2009) and had the highest Integrated Kinetic Energy of any Atlantic storm in the past 40 years (Powell and Reinhold, 2007). Hurricane Ike re-intensified after battering Cuba and reached its maximum strength over the Gulf of Mexico (GoM) at 00h00 UTC September 11 (winds of 215 km/h, MCP of 944 mbar), Ike made landfall as a strong Category-2 hurricane along the eastern part of Galveston Island, Texas at 07h30 UTC, 09/13/2008 (Fig. 1). The hurricane’s center continued northwestward bordering Galveston Bay, then northward across eastern Texas and Arkansas, where it weakened to an extratropical storm (Berg, 2009).

Maximum storm surge heights of 1.5–3 m were observed along the coast of central Louisiana, increasing to 3–4 m along the southwestern Louisiana and extreme upper Texas coast near Sabine Pass (Berg, 2009). Even as far east as the Rigolets in southeast Louisiana (the channel leading to Lake Pontchartrain) storm surge reached almost 2 m (Li et al., 2010). Ike’s powerful surge caused widespread overland inundation even around Lake Pontchartrain (Li et al., 2009). USGS sensors indicate that areas in Jefferson County, Texas, and Cameron Parish, Louisiana, had surge heights up to 5.2 m above NAVD88 (East et al., 2008). The highest overall surges occurred on the Bolivar Peninsula and in parts of Chambers County, in Texas. The highest watermark recorded by the Federal Emergency Management Agency was 5.4 m

Fig. 1. (a) Regional map of northern Gulf of Mexico, (b) study area with features mentioned in the text. The dashed line marks Hurricane Ike’s track.
above NAVD88, about 18.5 km inland in Chambers County. Storm surge levels on Galveston Island and on the west side of Galveston Bay were about 3–4 m, and farther south along the Texas coast surges of 1.5–3 m were recorded down to Freeport, TX (Berg, 2009).

3. The numerical model

We simulated tide and storm surge using the time-dependent FVCOM of Chen et al. (2003), which has been tested against other well-established models and is being widely used in ocean circulation studies (e.g. Chen et al., 2007; Huang et al., 2008), in surge applications (Weisberg and Zheng, 2006a,b; 2008; Aoki and Isobe, 2007; Rego and Li, 2009a,b; Rego and Li, 2010), and others (e.g. Li et al., 2008; Meselhe et al., 2010). FVCOM uses a terrain-following sigma coordinate transformation in the vertical and a non-overlapping unstructured triangular grid in the horizontal to resolve dynamics in regions with complex shorelines. This model uses the modified Mellor and Yamada (1982) “level 2.5” turbulent closure scheme for vertical mixing and Smagorinsky (1963) eddy parameterization for horizontal dissipation and diffusion. FVCOM solves the primitive equations by using a flux calculation integrated over each model grid control volume, ensuring mass, momentum, energy, salt, and heat conservations in individual control volumes and over the entire computational domain.

The flooding/drying process in FVCOM is simulated using an unstructured wet/dry point treatment technique. A viscous boundary layer \(D_{\text{max}}\) is added at the bottom to avoid singularities when the local water depth approaches zero and wet/dry points redefined using a sum of \(D\) (the total depth) and \(D_{\text{min}}\). Each grid node is treated as a wet point for \(D>D_{\text{max}}\) otherwise it is a dry point. When a triangular cell is treated as dry, the velocity at the centroid of this triangle is set to zero and no flux is allowed through the three side boundaries. This cell is removed from the flux calculation in the tracer control elements (Chen et al., 2003, 2008). Typically, this layer is set to \(0.02<D_{\text{max}}<0.20\) m (e.g., Weisberg and Zheng, 2008). Sensitivity analyses (Rego, 2009) showed that the surge propagation was not sensitive to values within this range, and \(D_{\text{max}} = 0.05\) m was used.

The surface wind stress is computed from \(\tau_{w} = C_{d} \rho_{a} \frac{V_{W}}{r} \vec{V}_{W}\), where \(\rho_{a}\) is the air density, \(V_{W}\) is the wind speed at 10 m height, and \(C_{d}\) is a drag coefficient dependent on wind speed, originally assumed constant when \(V_{W} > 25\) m/s, following Large and Pond (1981). A correction for strong winds was used, as suggested by Powell et al. (2003) and Jarosz et al. (2007): \(C_{d}\) was decreased from \(2.11 \times 10^{-3}\) to \(1.80 \times 10^{-3}\), for \(V_{W} > 40\) m/s. Sensitivity analyses using this correction showed a small improvement for surges near Hurricane Ike’s track (Rego, 2009).

The model domain extended from the Mexico–U.S.A. border to the Mississippi River Delta in Louisiana, with an 850 km long open boundary arching in between, covering water depths of 1000–3000 m in the most part (Fig. 2a). A total of 206,711 triangular cells comprised the horizontal. The mesh resolution increased from 9 km on the open boundary towards Hurricane Ike’s landfall. Mesh resolution on the upper continental shelf between Freeport, TX and Calcasieu Pass, LA was about 500 m. The finest mesh resolution (180 m) was around Galveston Bay entrance (Fig. 2b). Sensitivity studies showed that grid resolutions of 250 m or greater caused unrealistic high coastal surges and retarded surge inundation in important coastal passes (both sides of Galveston Island in Texas, and Sabine and Calcasieu Passes in Louisiana).

The bottom stress in the 2-D case is based on the depth-averaged velocity, whereas in the 3-D case it is based on the near-bottom velocity (in both cases, following a quadratic relation). In hindcasts the effective bottom drag coefficient can be calibrated, but drag coefficients are not physically the same and important physics may not be resolved due to compensation of errors (Weisberg and Zheng, 2008; Rego and Li, 2010). Our model application accounts for this by using two (equally-spaced) sigma layers in the vertical, whereas most storm surge applications are run in 2-D.

In southwest Louisiana and around Galveston Bay the model domain extended beyond the land–sea interface to the 6 m elevation contour. Land cells had a coarser 500–1000 m resolution (deemed sufficient by e.g. Dietsche et al. (2007)). Bathymetry data was a combination of the US Coastal Relief Model (NOAA, 2009), of LiDAR data from the Louisiana Statewide Atlas (LSU, 2009), and of elevation data from the National Elevation Dataset (USGS, 2009).

Here the model is forced by tides and wind stress. Although for extratropical systems both atmospheric pressure variations and alongshore wind stresses are generally the most important (Weisberg and Zheng, 2006b), in tropical systems it is the across-shore wind stress that accounts for most of the storm surge, and many storm surge studies do not include the atmospheric pressure term (e.g. Chu et al., 2000; Jones and Davies, 2004; Dube et al., 2005). Surface wind waves were not included, as we were only investigating the effects of the conventional long wave storm surge. Their effect was partially accounted for by using the hurricane wind correction in the wind stress scheme; with regard to coastal wave setup, this term is relatively less important in wide continental shelves (McNees et al., 2009). Terms representing baroclinicity were not included in our simulations, and the results obtained are thus for the barotropic case. Sensitivity tests for the case of Hurricane Ike showed that including observed river discharges and changes in the density field had negligible effects in the simulated surges (Rego, 2009).

4. Hurricane wind field

A common practice for creating hurricane winds in storm surge modeling (e.g. Peng et al., 2006a,b; Weisberg and Zheng, 2008) is to reconstruct the wind field by fitting the analytical cyclone model from Holland (1980). The radial distribution of wind relative to the storm center and the maximum wind speed are specified such that:

\[
V_w = \sqrt{\frac{B(P_{\text{amb}} - MCP)}{\rho_a}} \left(\frac{RMW}{r}\right)^b \exp\left(-\frac{RMW}{r}\right)^2
\]

(1)

\[
V_{\text{max}} = \sqrt{\frac{B(P_{\text{amb}} - MCP)}{\rho_a}} \left(\frac{RMW}{r}\right)^b \exp\left(-\frac{RMW}{r}\right)^2
\]

(2)

where \(r\) is the radial distance from the hurricane center, \(V_w\) is the wind speed as a function of \(r\), \(\rho_a\) is the air density (= 1.15 kg/m³), \(P_{\text{amb}}\) and MCP are the ambient and minimum central atmospheric pressures, respectively, \(e\) is the natural logarithm base (= 2.718...), \(RMW\) is the Radius of Maximum Winds, \(V_{\text{max}}\) is the maximum sustained wind speed, and \(B\) is the “peakness” storm scale parameter, 1.0–2.25.

Many past studies use a constant \(B\) without comparing against observed data (Peng et al., 2006a,b; Weisberg and Zheng, 2006a). We applied Holland (1980) with the gridded H*WIND dataset of Powell et al. (1996), in much the same way as Rego and Li (2009a,b). Terms \((P_{\text{amb}} - MCP)\) and \(B\) were determined iteratively using Eqs. (1) and (2) and the combination of these terms that produced a wind profile with the smallest Root Mean Square Error as compared to H*WIND’s profile was chosen at each snapshot.

Wind representation was further improved to account for hurricane asymmetries and land effects around landfall. Unlike Hurricane Rita, which made landfall on a relatively simple coast (Rego and Li 2009a,b), Hurricane Ike made 3 landfalls near a major bay (Fig. 1). Thus, for 6 critical hours, about half of the hurricane-strength winds were over land while the remaining half was over either the GoM or Galveston Bay. Hurricane parameters RMW, \(V_{\text{max}}\) and \(B\) were determined separately for 8 “cones” of 45°, hereby accounting for land effects in the model. Open water winds were stronger in the “relative” East, Southeast, South and Southwest cones (e.g. relative North is forward on the hurricane’s track, relative West to its left) (Fig. 3a). Between first and second landfalls (Fig. 3b) variations in
RMW and $V_{\text{max}}$ were much larger than those over the Gulf. This approach is more accurate than merely applying a decay rate factor after landfall to the whole wind field (as e.g. DeMaria et al., 2006), more straightforward than other similar methods (as e.g. Xie et al., 2006), but less comprehensive than directional land-masking procedures based on land roughness data (as e.g. Westerink et al., 2008).

The 1-minute averaged $H^*WIND$ winds were then multiplied by a factor of 0.89 to adjust to a 10-minute average period (Powell et al., 1996). Jelesnianski’s (1972) forward motion correction was also used (increasing the wind speed in the right quadrants). The inflow angle was harder to estimate. In Phadke et al. (2003) it varies linearly from 10° at the center to 20° at RMW, while Peng et al. (2006b) admit this is an “elusive” parameter for forecasters and test constant of 0–40°. Here, following Rego and Li (2009a,b) the inflow angle was set to 10° everywhere, in all simulations.

5. Model calibration for tide

The model was first run without wind forcing, for 36 days. Offshore tidal boundary conditions were specified using the ADCIRC database of Mukai et al. (2002), which covers the entire Western North Atlantic Ocean, including the Gulf of Mexico. The Eastcoast 2001 database defines the computed elevation amplitude and phase (resolved to $10^{-5}$ m and 0.001°, respectively) for the O1, K1, Q1, M2, S2, N2, and K2 astronomical tidal constituents as well as the steady (Z0), and the M4 and M6 overtones — see also Mukai et al. (2001). Another adjustment was required, as these constituents do not capture the long-term, seasonal component of astronomical tides. Using data from the National Oceanic and Atmospheric Administration / National Ocean Service (NOAA/NOS) data for stations in Table 1, the average sum of the Solar Annual and Solar Semiannual constituents was taken into account by adding 0.1 m to the open boundary levels.
Calibrating the tidal application of FVCOM consisted of varying the bottom friction coefficient (constant in the entire domain), with a coefficient of 0.005 yielding the best results. Changing Smagorinsky's coefficient (constant in the entire domain), with a

Table 1
NOAA/NOS stations used in tidal calibration. Each column shows Observed Amplitude (Ao, in m), Modeled Amplitude (Am, in m), and Phase Difference (Pd, modeled—observed, in hours), for the three major tidal constituents in the region.

<table>
<thead>
<tr>
<th>Station name; ID #</th>
<th>K1</th>
<th>O1</th>
<th>M2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Ao, Am, Pd</td>
<td>Ao, Am, Pd</td>
<td>Ao, Am, Pd</td>
</tr>
<tr>
<td>NOS Usgc Freeport, TX; 8772447</td>
<td>0.153, 0.166, −0.03</td>
<td>0.145, 0.159, +0.70</td>
<td>0.095, 0.078, +0.03</td>
</tr>
<tr>
<td>Galveston Pleasure Pier, TX; 8771510</td>
<td>0.171, 0.173, +0.05</td>
<td>0.161, 0.163, +0.74</td>
<td>0.139, 0.108, +0.08</td>
</tr>
<tr>
<td>Galveston Bay Entrance, TX; 8771341</td>
<td>0.144, 0.165, −0.35</td>
<td>0.135, 0.156, +0.22</td>
<td>0.113, 0.108, +0.05</td>
</tr>
<tr>
<td>Eagle Point, TX; 8771013</td>
<td>0.117, 0.067, +0.66</td>
<td>0.114, 0.065, +1.33</td>
<td>0.034, 0.019, −0.17</td>
</tr>
<tr>
<td>Clear Lake, TX; 8770931</td>
<td>0.105, 0.073, −0.21</td>
<td>0.105, 0.070, −0.60</td>
<td>0.037, 0.024, −0.88</td>
</tr>
<tr>
<td>Round Point, TX; 8770559</td>
<td>0.108, 0.076, +0.94</td>
<td>0.103, 0.073, +1.81</td>
<td>0.051, 0.029, +0.34</td>
</tr>
<tr>
<td>Sabine Pass North, TX; 8770570</td>
<td>0.132, 0.181, −0.80</td>
<td>0.123, 0.167, −0.28</td>
<td>0.123, 0.150, −0.13</td>
</tr>
<tr>
<td>Calcasieu Pass, LA; 8768094</td>
<td>0.144, 0.188, −0.10</td>
<td>0.136, 0.173, +0.60</td>
<td>0.146, 0.151, +0.46</td>
</tr>
</tbody>
</table>

Table 2
Stations used for Hurricane Ike’s storm tide validation. Negative timing differences indicate modeled surge ahead of time. Positive peak differences indicate modeled elevation value greater than observation (both in m above MSL).

<table>
<thead>
<tr>
<th>Station name</th>
<th>Obs. peak (m)</th>
<th>Peak diff., m (rel.)</th>
<th>Peak diff. (h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NOS Usgc Freeport, TX</td>
<td>1.98</td>
<td>−0.24 (−12%)</td>
<td>+4.0</td>
</tr>
<tr>
<td>NOS Eagle Point, TX (Fig. 5d)</td>
<td>3.46</td>
<td>0.13 (4%)</td>
<td>+0.1</td>
</tr>
<tr>
<td>NOS Sabine Pass North, TX</td>
<td>4.13</td>
<td>0.02 (0%)</td>
<td>0</td>
</tr>
<tr>
<td>NOS Calcasieu Pass, LA</td>
<td>3.27</td>
<td>−0.04 (−1%)</td>
<td>−1.5</td>
</tr>
<tr>
<td>USGS TX-MAT-009</td>
<td>1.66</td>
<td>−0.14 (−8%)</td>
<td>+2.5</td>
</tr>
<tr>
<td>USGS TX-BRA-004</td>
<td>1.60</td>
<td>−0.05 (−3%)</td>
<td>+3.0</td>
</tr>
<tr>
<td>USGS TX-BRA-009 (Fig. 5a)</td>
<td>1.91</td>
<td>+0.01 (1%)</td>
<td>+4.0</td>
</tr>
<tr>
<td>USGS TX-BRA-008</td>
<td>2.01</td>
<td>−0.15 (−7%)</td>
<td>+2.5</td>
</tr>
<tr>
<td>USGS TX-BRA-002</td>
<td>2.00</td>
<td>+0.24 (12%)</td>
<td>+1.2</td>
</tr>
<tr>
<td>USGS TX-BRA-001</td>
<td>2.14</td>
<td>+0.22 (10%)</td>
<td>+5.0</td>
</tr>
<tr>
<td>USGS TX-GAL-015 (Fig. 5b)</td>
<td>2.45</td>
<td>−0.30 (−12%)</td>
<td>−2.0</td>
</tr>
<tr>
<td>USGS TX-GAL-011</td>
<td>3.38</td>
<td>−0.09 (−3%)</td>
<td>−2.0</td>
</tr>
<tr>
<td>USGS TX-GAL-010</td>
<td>3.62</td>
<td>−0.73 (−20%)</td>
<td>−1.0</td>
</tr>
<tr>
<td>USGS TX-GAL-016 (Fig. 5c)</td>
<td>3.55</td>
<td>−0.64 (−18%)</td>
<td>−2.0</td>
</tr>
<tr>
<td>USGS TX-GAL-008 (Fig. 5g)</td>
<td>3.81</td>
<td>−0.08 (−2%)</td>
<td>+1.0</td>
</tr>
<tr>
<td>USGS TX-GAL-019</td>
<td>2.85</td>
<td>+0.80 (28%)</td>
<td>+0.15</td>
</tr>
<tr>
<td>USGS TX-GAL-022</td>
<td>3.52</td>
<td>+0.62 (23%)</td>
<td>−0.25</td>
</tr>
<tr>
<td>USGS TX-HAR-002 (Fig. 5e)</td>
<td>3.63</td>
<td>+0.31 (9%)</td>
<td>−0.15</td>
</tr>
<tr>
<td>USGS TX-HAR-004</td>
<td>3.64</td>
<td>+0.24 (7%)</td>
<td>−4.5</td>
</tr>
<tr>
<td>USGS TX-CHA-004</td>
<td>4.58</td>
<td>−0.25 (−5%)</td>
<td>−1.0</td>
</tr>
<tr>
<td>USGS TX-CHA-003 (Fig. 5f)</td>
<td>3.64</td>
<td>−0.09 (−2%)</td>
<td>−1.0</td>
</tr>
<tr>
<td>USGS TX-GAL-002</td>
<td>3.92</td>
<td>−0.53 (−14%)</td>
<td>+1.0</td>
</tr>
<tr>
<td>USGS TX-GAL-001 (Fig. 5h)</td>
<td>4.84</td>
<td>−0.03 (−1%)</td>
<td>−0.5</td>
</tr>
<tr>
<td>USGS TX-GAL-005 (Fig. 5i)</td>
<td>4.65</td>
<td>−0.26 (−6%)</td>
<td>−0.5</td>
</tr>
<tr>
<td>USGS TX-JEF-001</td>
<td>4.82</td>
<td>−0.18 (−4%)</td>
<td>0</td>
</tr>
<tr>
<td>USGS TX-JEF-002 (Fig. 5j)</td>
<td>5.00</td>
<td>0.01 (0%)</td>
<td>+0.25</td>
</tr>
<tr>
<td>USGS TX-JEF-004</td>
<td>4.68</td>
<td>−0.12 (−3%)</td>
<td>+0.15</td>
</tr>
<tr>
<td>USGS TX-JEF-005</td>
<td>4.75</td>
<td>−0.09 (−2%)</td>
<td>0</td>
</tr>
<tr>
<td>USGS TX-JEF-006</td>
<td>4.30</td>
<td>−0.04 (−1%)</td>
<td>−0.5</td>
</tr>
<tr>
<td>USGS TX-JEF-007 (Fig. 5k)</td>
<td>3.83</td>
<td>−0.39 (−10%)</td>
<td>−0.5</td>
</tr>
<tr>
<td>USGS TX-JEF-008</td>
<td>3.17</td>
<td>+0.06 (2%)</td>
<td>0</td>
</tr>
<tr>
<td>USGS TX-JEF-009</td>
<td>4.01</td>
<td>+0.97 (24%)</td>
<td>−0.5</td>
</tr>
<tr>
<td>USGS LA-CAM-001</td>
<td>4.54</td>
<td>−0.48 (−11%)</td>
<td>+0.15</td>
</tr>
<tr>
<td>USGS LA-CAM-002</td>
<td>4.30</td>
<td>−0.57 (−13%)</td>
<td>−0.5</td>
</tr>
<tr>
<td>USGS LA-CAM-003 (Fig. 5l)</td>
<td>3.02</td>
<td>+0.01 (0%)</td>
<td>−1.25</td>
</tr>
<tr>
<td>USGS LA-CAM-010</td>
<td>3.04</td>
<td>−0.20 (−7%)</td>
<td>0</td>
</tr>
<tr>
<td>USGS LA-CAM-012</td>
<td>3.06</td>
<td>−0.22 (−7%)</td>
<td>−0.5</td>
</tr>
</tbody>
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6. Storm surge validation

Observations by East et al. (2008) provided data for surge validation. The USGS deployed a temporary network of pressure sensors at 65 sites to record the timing and magnitude of inland flooding and coastal surge generated by Hurricane Ike, and 59 sensors were recovered. Water levels, referenced to NAVD88, were converted into MSL using National Geodetic Survey (2009). Only 33 of these stations were used here; the remainders were located either too far horizontally or too close to the coast and were therefore discarded.

Fig. 3. Wind profiles fitted to H’WIND dataset: (a) 16h30 UTC 09/12 and (b) 07h30 UTC 09/13/2008. Parameters RMW, Vmax, and B determined separately for eight 45° cones.

from landfall or on areas not resolved in our model. Data from four NOAA/NOS stations was also used (Table 2).

The inverse pressure adjusting method was used at the open boundary to partially account for meteorological forcing (Jones and Davies, 2004; Shen et al., 2006). Lastly, noticing that observed water levels in this region were consistently 0.20–0.30 m higher than predicted levels for the ∼10 days before and after landfall, an extra 0.25 m was added to account for what appears to be a low-frequency weather effect. Stations used to demonstrate model validation are shown in Fig. 4. Curves for these 12 stations are shown in Fig. 5 (a 5-minute filter was applied to USGS time-series for clarity). Results for all 37 stations are shown in Table 2.

FVCOM results matched well against observed water levels in most stations. Peak amplitude differences were typically below 15%, in records where peak storm tide was 2–5 m (Table 2). Exceptions were stations TX-GAL-010, TX-GAL-011 and TX-GAL-016 (Fig. 5c), where modeled peak levels were 0.7–0.9 m below observations. These three stations were on or “behind” Galveston Island, very close to Hurricane Ike’s path and to its left. Two factors can explain this difference: the exclusion of air pressure effects (relatively important directly on the storm’s path), and our admittedly overestimated winds blowing from land “against” the surge (land effects were not included explicitly). Other exceptions were stations TX-GAL-019 and TX-GAL-022 (see Fig. 5e for a similar case) where the model overestimates peak levels by about 0.80 m; here observed surge showed a triple peak not fully captured by the model. For station TX-JEF-009, peak surge levels were apparently overestimated in the model by almost 1 m. However, observed levels should be seen with caution, as this station is very near TX-JEF-002 (farther from landfall; Fig. 5j), which recorded peak surges 1 m higher than TX-JEF-009.

With respect to the timing of storm tide, modeling results typically had only a ±0.5 h shift (or smaller). Exceptions were some stations farther southwest where modeled curves lagged observations by 2.5–5.0 h (with peak differences of up to ±0.20 m). It can be shown that because surge curves were not as sharp here, a very close match can still yield a time-of-peak difference (Fig. 5a). The only other exception was for station USGS TX-HAR-004, where modeled water levels were 4.5 h early. In this area (see Fig. 5e for a similar case) there were multiple short-scale peaks and the model only captured the enveloping curve.

Even when the model slightly over- or underestimated peak surges (Fig. 5i,j,k), it did accurately capture the local surge’s curve. As far away from landfall as station LA-CAM-003, the model represented the surge well (Fig. 5l). The stations where the highest surges were recorded, east of Galveston Bay entrance, showed a good match with observations (Fig. 5g,h,i,j). There was, nevertheless, a pre-peak prominence not fully captured by the model; also, the modeled surges receded slightly earlier than observations. These issues had been noticed in studies with higher resolution meshes (e.g. Westerink et al., 2008). These might be due to Kelvin wave setup ahead of the storm as it transited onto the shelf (not entirely represented in the model because of the restricted domain used). However, hurricane shelf waves are typically important only when hurricanes travel fast and parallel to the coast — i.e. on the US Atlantic coast rather than on the GoM (Mercer et al., 2002; Morey et al., 2006). In the present study, poor bathymetry data in the Galveston Bay Entrance region was the most likely culprit.

Our results also showed satisfactory qualitative agreement with inundation maps (only provided as images) from the National Weather Service (2009) for coastal Texas and Louisiana, which should be compared to our Fig. 6. The highest inundations (3–5 m) were measured on the coastal strip between Galveston Bay and Sabine Lake, and small patches in lower areas reached 5 m inundation heights. Overall, we conclude that FVCOM gave reliable coastal storm tide.

Current velocity data from the Texas Automated Buoy System (tabs.ger.galveston.edu) was also used in validation. Three TABS stations existed in the model domain at the time of the storm, and all records had data gaps. Station R was very far from the region of interest (near Calcasieu Pass) and station F was located in deeper waters and very close to the hurricane’s path (making it difficult for our 2-layer model to capture the strong variability). Fig. 7 shows a modeled-to-observed vector plot for TABS station B, located at a depth of 19 m (see also Fig. 4). Although there is a 16 h gap in the measurements, it is shown that modeled currents are within reasonable agreement with
observations: the switch from SW to NE currents occurs at about 12–14 h on September 13; strongest currents reach up to 2.2 m/s (consistent with stations F and R; not shown) whereas for the 24 h before peak, current magnitudes are 0.4–0.8 m/s.

7. Scenarios tested

Insight into how surge propagation is affected by the geometry of Bolivar Peninsula was gained by running different scenarios in which

Fig. 5. Validation time-series plots: observed (solid light line) vs. modeled (dark dashed line) storm tide curves. Stations (a) through (l) defined in Fig. 4.
only this factor was varied. The same winds and tides of Hurricane Ike were used in all simulations summarized in Table 3, where the single parameter varied was the bathymetry (representing different degrees of erosion). A limitation in our methodology was that the wind field was not affected by topography. Because storm surge and coastal inundation are very sensitive to the winds, future studies should account for this effect.

Here, to study the effects of barrier islands on coastal inundation we assumed constant bathymetries for each scenario while focusing on the varying hydrodynamics. Roelvink et al. (2009) took the opposite approach and modeled dune erosion, overwash and breaching, but with simplified hydrodynamics: their approach assumed that two 72 hour storms with varying surge and wave conditions could be approximated by two 10 hour simulations with constant maximum surge and wave conditions.

Fig. 8a shows original elevations: most of the peninsula was at least 1 m above MSL, with a strip about 300 m wide of higher ground, 1.5–3 m above MSL, stretching alongshore for 28 km. Scenario B (not shown) represents a typical post-hurricane situation: elevations on the peninsula were reduced to 2/3 of their original heights except on a 500 m wide strip behind the dune, where elevations were increased by 0.3 m. For a quantitative estimate of the specific value to be deposited landward of the foredune, we used USGS Hurricanes and Extreme Storms Group (2009), who compared airborne LIDAR surveys of pre- and post-storm topography on the Texas coast. In Bolivar Peninsula erosion along the shoreline reached 1 m, while landward there were areas of ~0.3 m deposition, indicating landward...

![Validation map of maximum overland inundation (determined as the highest simulated water level above ground).](image_url)

**Fig. 6.**

**Table 3**

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Bathymetry simulated</th>
<th>Peninsula: volume above MSL ($10^6$ m$^3$)</th>
<th>Galveston Bay: total flooded volume ($10^6$ m$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Existing</td>
<td>162.0</td>
<td>3583 (100%)</td>
</tr>
<tr>
<td>B</td>
<td>Eroded dune</td>
<td>118.9</td>
<td>4276 (119%)</td>
</tr>
<tr>
<td>C</td>
<td>Further erosion and 2 breaches</td>
<td>73.5</td>
<td>4625 (129%)</td>
</tr>
<tr>
<td>D</td>
<td>Plateau 0.05 m above MSL</td>
<td>5.6</td>
<td>5249 (147%)</td>
</tr>
<tr>
<td>E</td>
<td>Plateau 0.30 m below MSL</td>
<td>−40.6</td>
<td>5780 (161%)</td>
</tr>
</tbody>
</table>
movement of at least some of the eroded sediment. This pattern follows Santa Rosa Island’s (Florida) pre- and post-storm profiles for Hurricane Opal (October 1995), given by Stone et al. (2004), and is also consistent with Otvos and Carter’s (2008) description of erosion caused by Hurricane Rita (August 2005) in Mississippi–Alabama barrier islands. This demonstrates how tropical storms can be both “constructive” and “destructive” on barrier environments with respect to their sediment budget (Stone et al., 2004).

Scenario C (Fig. 8b) represents a situation of severe coastal erosion: peninsula elevations from Scenario B were reduced by a further 2/3 and two breaches opened up, 0.60 m deeper but still 0.1–0.5 m above MSL. These 600 m wide breaches are similar to that studied in Weisberg and Zheng (2006b). Scenario C could happen if another similar hurricane passed on the same track shortly after Ike, before the barrier system had time to replenish itself. Although an unlikely scenario, Allison et al. (2005) presented a study of two powerful storms affecting the same region of central Louisiana, separated by only 7 days in 2002. Scenarios D and E (not shown) are extreme cases for which the peninsula was reduced to a leveled plateau 0.05 m above and 0.30 m below MSL, respectively.

8. Hurricane Ike’s surge and inundation in Galveston Bay

Hurricane Ike made landfall on the eastern part of Galveston Island, along a NNW track that followed the western side of Galveston Bay, with its center alternating between land and water for about 60 km (Fig. 9). Here inundations refer to the elevation above the still water levels (i.e. above MSL for bay points and above topography for land points), a simple way to illustrate surge over both water and land.

At 07h00 UTC, 09/13/2008 (half an hour before landfall), the highest nearshore water levels of about 5.2 m were offshore Bolivar Peninsula, which was completely flooded (Fig. 9a). A strip of 4.5–5 m inundations stretched due east along the shore from this location. Inundation levels in East Bay, behind the peninsula, were just 2.5–3.2 m at this time. On the left-hand side of Ike’s track, nearshore inundation levels of 0.7–2.7 m increased eastward, and in West Bay behind Galveston Island they were 1.8–3.1 m. The 3–3.5 m inundation band reached from offshore up to the north coast of the bay, uninterrupted. Given the specific relationship between bay geometry and hurricane track, a clear gradient of water elevations occurred inside the bay, 0.5–4.0 m increasing westward, along a distance of about 38 km (Fig. 9a). One and a half hours later (Fig. 9b), nearshore water levels dropped to 2.6–3.4 m along Bolivar Peninsula, increasing eastward. The highest levels of 4–4.5 m propagated east, deflected by the Peninsula and forced by the ENE alongshore winds. Inundation in East Bay increased to 3–3.6 m. On the left-hand side of Ike’s track, nearshore inundation levels decreased to 0.2–1.2 m, and in West Bay increased slightly to 1.7–2.7 m. Over most of Galveston Bay winds blew northwestward at this time, and the across-bay gradient disappeared.
Another 1.5 h later (Fig. 9c), nearshore water levels decreased further to 1.4–1.8 m along Bolivar Peninsula and to 0.4–0.5 m along Galveston Island; some patches started to dry over both barrier systems. The highest levels of 2.5–3 m propagated alongshore due east and reached Sabine Pass. Inundation levels in East Bay were 2.5–3.5 m, and in West Bay 1.2–2.5 m. At this time, water levels in the bay were higher than on the continental shelf. Over most of Galveston Bay, hurricane winds blew northeastward and a weak (reverse) eastward gradient formed. At 11h30 UTC (Fig. 9d), nearshore water levels were 0.4–0.5 m along Galveston Island and about 0.8 m from the bay entrance to Sabine Pass. Over Bolivar Peninsula and Galveston Island, greater portions were dry. Inundation levels continued to decrease in East Bay (1.8–3.6 m) and in West Bay (0.9–1.8 m). Hurricane Ike’s center was about 30 km off the map and its weakening winds blew ENE over Galveston Bay; in the upper bay, the eastward gradient strengthened to 1.3–4.2 m across the bay.

This surge propagation could have been inferred merely from NOAA and USGS data, although with a narrower perspective. For coastal surge magnitude and timing, compare data from Fig. 5 g,h,j. Peak surge increases west to east, from 3.7 to 4.8 and 5 m, whereas time-of-peak increases from 6h20 to 6h50 and 7h30 UTC, respectively, indicating an eastward coastal surge propagation. Although closer to the hurricane’s track, peak surge behind Galveston Island was lower, increasing eastward from 2 to 3.5 m (stations TX-GAL-016 and TX-GAL-016, Fig. 5b,c). On the right-hand side of Ike’s path, even stations much farther away had higher or comparable peak surges, e.g. TX-JEF-007 with 3.8 m and LA-CAM-003 with 3 m (Fig. 5k,l). Cross-bay elevation gradients could be implied from data in stations NOS Eagle Point, TX (Fig. 5d) and TX-HAR-002 (Fig. 5e), compared to stations TX-CHA-3 (Fig. 5f) and TX-CHA-004 (not shown). Modeled water levels in west Galveston Bay show an exaggerated decrease after peak surge, by about 0.4–0.8 m (Fig. 5d,e), most likely a result of incorrect bathymetry and the uncertainty in the inflow angle which make negative surges inherently more difficult to model than positive ones (Peng et al. 2006b). On the east, the model anticipates the arrival of the peak by half an hour (Fig. 5f), a minor flaw.
These westward and eastward elevation gradients that occurred between west Galveston bay and east Trinity bay (and East bay) are remarkable oscillations that had rarely been described. Other studies have mentioned similar phenomena, but for larger basins with rather wide openings. Here we used FVCOM on a high-resolution mesh, aided by widespread and good quality observations, to go a step further and analyze the "sloshing" created by a hurricane bordering on a semi-enclosed bay. This effect is shown in Fig. 10, where elevations above MSL (and not inundations; this is only different over land points) are shown over time along the 52 km line defined in Fig. 4. Fig. 10a shows the more intuitive, 3-D surface, while Fig. 10b presents its 2-D version. As the hurricane approached (hours 45–50 after 00h UTC, 09/11), the wind pushed water inside the bay westward, creating a sharp peak and a sharp westward elevation difference, from 0.5 to 4.5 m, at about 55 h. As the hurricane advanced, water was quickly pushed eastward, and a reversed gradient peaked just 5 h after the first peak. It is also shown (Fig. 10b) that the build-up inside the bay was much faster than the set-down. The 1 to 4 m build-up between 45 and 55 h was much more intense than the 2.5 to 2 m set-down between hours 63 and 70.

The initial westward gradient (of about $-0.09$ m/km) was slightly stronger than the subsequent eastward gradient (of about $+0.08$ m/km), as storm winds decayed with time after landfall. Given the hurricane's track relative to the bay and its counterclockwise winds, this phenomenon was not entirely unexpected. While other studies had indicated similar oscillations, we have further quantified the process, both in space (from $-0.09$ to $+0.08$ m/km) and in time (a 5 hour interval), and these values were validated by a good match against USGS data from the many recording sensors around Galveston Bay. The magnitude of these gradients was a function of the storm's intensity and proximity to the bay, but also of the bay's geometry; their separation in time is a direct result of the hurricane's traveling speed. This single oscillation and quick damping (Figs. 10 and 11) indicate this is not a response related to the natural seiching period of the Bay, but rather to the imposed path of the storm.

9. Quantifying the effect of barrier systems

Nearshore surge propagated alongshore due east, towards Louisiana, and Bolivar Peninsula contributed to this "deflection" of the surge energy, protecting the bay (although landfall was on Galveston Island). Having shown this in the previous section, an evaluation of how the system’s major barrier impacts surge propagation into

![Fig. 10. Modeled storm surge development along the line defined in Fig. 4, under Scenario A: (a) intuitive 3-D form and (b) flattened down form.](image)

![Fig. 11. Comparison of Galveston Bay region-wide (a) total flooded volumes, in km³ and (b) maximum elevations, in m, under Scenarios A through E.](image)
Galveston Bay is discussed next. Evolution of total inundation volumes (computed as totals for Galveston Bay and its surrounding inundation areas) for the 5 tested scenarios are shown in Fig. 11a. The 4 vertical dashed lines indicate the instants when Fig. 9’s snapshots were taken. Instant (a) is half-hour before landfall on Galveston Island; instant (d) is approximately the time when Bay–Gulf outflow begins and flooded volumes decrease for Scenario A. Inundation areas varied from an average of 200 km² under normal circumstances, up to a peak of 1700–1900 km² (depending on the scenario) during peak storm surge. Results are summarized in Table 3.

Scenarios B and C produced total peak flooded volumes greater than Scenario A’s by 19% and 29%, respectively. Scenarios D and E yielded total peak flooded volumes 47% and 61% greater than that caused under Scenario A (Table 3). Also, scenarios having smaller barrier system led to earlier and more severe flooding, but also to faster flushing-out of flooded waters. Curves for Scenarios D and E rise earlier and higher than all other curves, but also drop faster and lower than the others (Fig. 11a), which is consistent with Rego et al. (in press).

Consistent with the “sloshing” effect described in the previous section, there were two peaks for the highest inundation levels, separated by about 5 h (Fig. 11b). Under Scenarios A–D the first peak of highest levels represents inundations in western Galveston Bay and onshore Bolivar Peninsula (e.g. Fig. 9a). For Scenario E (with no barrier), this first peak of highest levels represents inundations in western Galveston Bay and on the northern East Bay. The second peak’s inundations were located up in Trinity Bay for all scenarios (e.g. Fig. 9d). The highest inundation level curves (also decreasing in the expected fashion from E to A), were not as separated as total flooded volume curves, indicating how these peak water levels were relatively localized.

Original results (Fig. 9) were compared with those of Scenarios C (Fig. 12) and D (Fig. 13), for another perspective on the varying dynamics within the bay. The severely eroded dune with breaches was

Fig. 12. Same as Fig. 7, but under Scenario C.
(expectedly) a less effective barrier than the original peninsula, and East
Bay water levels were about 1 m higher than Scenario A’s before landfall
(Figs. 9a and 12a). The low peninsula in Scenario D offered little
resistance to the passage of the surge, but East Bay water levels were
only 0.5 m higher than those in Scenario C, before landfall (Figs. 12a and
13a). For instant (b), the time-of-peak flooded volumes, inundation
levels were 3.0, 3.6 and 3.8 m in Galveston Bay and 3.7, 4.4 and 4.6 m in
the Houston Ship Channel for Scenarios A, C, and D, respectively.

We conclude that in this respect the major change was from Scenarios
A to C, and that the change to Scenario D had relatively less impact. Thus a
Peninsula with a height (or volume) reduced to about 45% and two
breaches exposed the interior bay to higher water levels almost as much
as a Peninsula leveled to just 0.05 m above MSL. Results also indicate that
the same kind of eastwest oscillations of surface gradients existed for
Scenarios C and D, only about 0.5 m higher than for Scenario A.

Fig. 14 shows inundation levels along the line defined in Fig. 4, for
the same four snapshots (covering a 4h30 period), for all scenarios; it
shows how varying barrier geometries affected the sloshing of Fig. 10. At
each instant, the upper-bay gradients were similar for varying scenarios
(exceptions were land points in the east). Scenario A’s gradients
(westward of −0.09 m/km, eastward of +0.08 m/km) are slightly
stronger than those from Scenarios B–E (westward of −0.08 to −0.07,
eastward of +0.07 to +0.06, respectively), because as water depth
increased inside the bay the wind became less effective at raising water
levels. Finally, we point out how in Fig. 14a,b the curves for various
scenarios are the farthest apart, while in Fig. 14c,d they are the closest
together: this is consistent with the evolution of total inundation
volumes, which peaked for instant (b) and are converging for (d)
(Fig. 11a). These results suggest that changes in the barrier system
geometry did not change the basic dynamics of the upper-bay sloshing
(similar gradients), but did cause considerable 1–2 m variations in the
background level, with potentially destructive consequences.

10. Conclusions

We used FVCOM with a high-resolution mesh to study Hurricane
Ike’s storm tide along the Texas–Louisiana coast, where coastal surge
heights up to 5.2 m above NAVD88 were measured. A hurricane’s
coastal surge depends to a large extent on the path of the storm and on the geometric properties of a waterbody. We focused on how the surge propagated into Galveston Bay and on the importance of its barrier system. The surge data collected by the USGS during Ike allowed for the validated modeling of this rare situation during which a powerful hurricane traveled over a medium-sized, semi-enclosed bay. FVCOM results matched well against observed water levels at most USGS and NOAA stations, with peak amplitude differences mostly below 15% and timing errors typically under ±0.5 h. Even when slightly over- or underestimating peak surges, the model adequately captured the main features of the storm surge.

We showed that coastal surge propagated alongshore towards Louisiana, and that Bolivar Peninsula contributed to this deflection and had a significant role in protecting the bay (although landfall was on Galveston Island). We identified a fast-reversing cross-bay elevation gradient in upper Galveston Bay, and analyzed the “sloshing” that formed as the hurricane traveled northward bordering the western side of this semi-enclosed bay. The westward followed by eastward elevation gradients between west Galveston bay and east Trinity bay (and East bay) represent remarkable oscillations that had not been fully described. These sharp, opposing surface gradients (of about 0.08 m/km) occurred in just 5 h. The effect of the “sloshing” should be considered in future studies as an additional source of coastal flooding.

Different scenarios were simulated in which only Bolivar Peninsula’s bathymetry was varied (representing increasing degrees of coastal erosion), to study how this system’s major barrier impacts surge propagation into Galveston Bay. Compared to the original bathymetry, Scenarios B–E yielded 19%, 29%, 47% and 61% greater total peak flooded volumes, respectively. For the time-of-peak flooded volumes, we showed that the major change was from Scenarios A to C, and that the change to Scenario D had relatively little extra impact. This suggests that a realistic erosion scenario to this peninsula exposes the interior bay to dangerously high water levels almost as much as a peninsula that is leveled to just 0.05 m above MSL.

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