

## Characterizing hurricane storm surge behavior in Galveston Bay using the SWAN + ADCIRC model



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### ABSTRACT

The SWAN + ADCIRC shallow-water circulation model, validated for Hurricane Ike (2008), was used to develop five synthetic storm surge scenarios for the upper Texas coast in which wind speed was increased and landfall location was shifted 40 km westward. The Hurricane Ike simulation and the synthetic storms were used to study the maximum water elevations in Galveston Bay, as well as the timing and behavior of surge relative to the hurricane track. Sixteen locations indicative of surge behavior in and around Galveston Bay were chosen to for analysis in this paper. Results show that water surface elevations present in Galveston Bay are dominated by the counterclockwise hurricane winds and that increasing wind speeds by 15% results in approximately 23% (+/− 3%) higher surge. Furthermore, shifting the storm westward causes higher levels of surge in the more populated areas due to more intense, higher shore-normal winds. This research helps to highlight the vulnerability of the upper Texas Gulf Coast to hurricane storm surge and lends insight to storm surge and flood mitigation studies in the Houston–Galveston region.

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### 1. Introduction

In the past decade, numerous major hurricanes have significantly impacted the states bordering the Gulf of Mexico. This activity was marked by the 2004, 2005 and 2008 seasons, which produced some of the costliest hurricanes on record, including Hurricanes Ivan, Charley, Frances and Jeanne (2004), Katrina, Wilma and Rita (2005), and Ike, Gustav and Dolly (2008) (Blake and Gibney, 2011). Of these, Hurricanes Ike (Category 2) and Katrina (Category 3) produced two of the highest recorded storm surges in recent history, 5.33 m and 8.47 m, respectively (Berg, 2009). The enormity of the impact that a major hurricane can have on an unprepared population was clearly demonstrated during Hurricane Katrina when widespread inundation killed 1833 people (Knabb et al., 2005). Such an event indicates the need for highly accurate storm surge prediction to further hurricane preparedness, which can only be obtained through a clear understanding of the factors that contribute to storm surge and its behavior in specific coastal settings.

Hurricanes act over a wide range of spatial scales as they develop in deep water, propagate over the continental shelf, and interact with coastlines. Waves generated in the deeper waters of the Gulf are transformed into storm surge in the near shore environment due to rapid

changes in both bottom friction and bathymetry. Several recent studies have attempted to quantify the factors that effect storm surge behavior via computational modeling. Irish et al. (2008) used the Advanced Circulation (ADCIRC) model to evaluate the relationship between storm size (radius of winds) and peak surge for different bottom slopes. Their results showed that as storm size increased, so did peak surge and that this relationship became increasingly pronounced for milder sloping coastal bathymetry. Furthermore, a sensitivity analysis was conducted to evaluate the impact of hurricane track (angle of approach) and forward speed on peak surge. The results of this analysis concluded that for mildly sloping topographic bottoms, the more negative, or easterly, angle of approach produced surges that were larger than the due north track. In addition, the analysis showed that increased forward speed led to greater surges for steep to moderate slopes, but produced little effect over mild slopes.

More recently, Rego and Li (2009) used the Finite-Volume Coastal Ocean Model (FVCOM) to show that faster hurricanes produced higher surges, but smaller total flooded volumes, concluding that slower storms with velocities of 3.5 to 5 m/s produce more total flooding along the Louisiana–Texas (LATEX) Shelf. Other studies have focused on storm surge behavior in smaller bodies of water such as closed or semi-enclosed bays. In a study of Tampa Bay, Florida, Weisberg and Zheng (2006) found that a slow approach resulted in larger storm surge in the bay because of the time it takes to redistribute the mass of water. After conducting a landfall sensitivity analysis, they found

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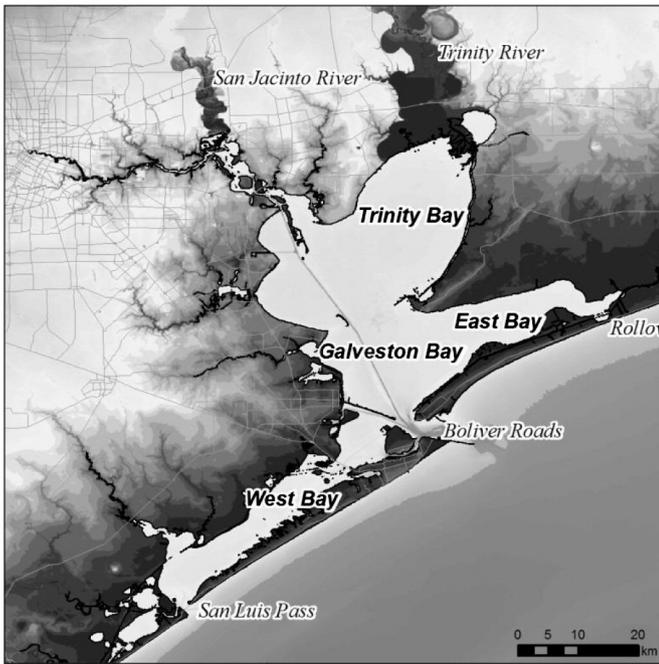


Fig. 1. Map of the Galveston Bay system and surrounding areas showing the four sub-bays, two contributing rivers, and three major tidal outlets. Significant roads are shown in gray.

that the worst case scenario for storm surge occurs when the hurricane makes landfall north of the bay resulting in maximum winds at the mouth of the bay. Such results support Rego and Li (2010) concluded that wind field asymmetry has a significant impact both on the height of peak surge and on the total flooded volumes.

Rego and Li (2010) used FVCOM to observe storm surge propagation through Galveston Bay and examine the influence of the barrier island system on water elevations. They conclude that the relationship between the height of the barrier islands and storm surge is non-linear and that reducing the height of the barrier produces significantly higher surge in Galveston Bay. The authors also found that the

counterclockwise winds produced by Ike caused a westward gradient of approximately  $-0.09$  m/km ahead of the passing of the eye of the storm and an eastward gradient of approximately  $0.08$  m/km after the passing of the eye. It is important to note, however, that the hurricane track shown in the paper does not reflect the track published by the National Hurricane Center for Ike (Berg, 2009). The authors conclude that the surge oscillation is a phenomenon caused by Ike's intensity, the bay's geometry, and Ike's track, but they stop short of examining whether the oscillations are consistent under varying landfall locations.

Hurricane storm surge simulation is a powerful tool for analyzing the physics of storms, designing protection systems, evaluating risk, and planning emergency evacuation. Therefore, hurricane models must be reliable for a wide range of storm characteristics in large computational domains if they are to robustly capture complex storm surge interactions on coastal topography. In this paper, we employ the newly developed SWAN + ADCIRC wave and circulation model on an unstructured, high-resolution mesh incorporating the Western Atlantic, Gulf of Mexico and Texas coastlines. This coupled model is highly efficient, operates on a single computational mesh, and seamlessly integrates both the pertinent physics and numerics of such a complicated physical system (Dietrich et al., 2011a). It has been successfully applied to study the effects of Hurricanes Katrina, Rita, Gustav, and Ike on the Southern Louisiana coastline (Dietrich et al., 2011a, 2011b, 2012; Kennedy et al., 2011). While previous studies have examined the influence of factors such as forward speed, angle of approach, storm size, and barrier islands on peak surge, we use the SWAN + ADCIRC model to assess how varying the wind speed and landfall location of Hurricane Ike influences the behavior of storm surge at locations in and around Galveston Bay.

Galveston Bay covers an area of approximately  $1554$  km<sup>2</sup> and is a shallow, wind-driven system that is, on average, 2 to 4 m deep. Galveston Bay, as defined in this paper, is made up of four sub-bays: Trinity, Galveston, West and East, which receive freshwater inflow from the San Jacinto and Trinity Rivers (Fig. 1). There are three tidal outlets to the system: San Luis Pass, Boliver Roads, and Rollover Pass. San Luis Pass and Boliver Roads account for approximately 20% and 80% of the system's tidal exchange, respectively, while Rollover Pass contributes to less than 1% of tidal exchange (GBNEP (Galveston Bay National Estuary Program), 1994).

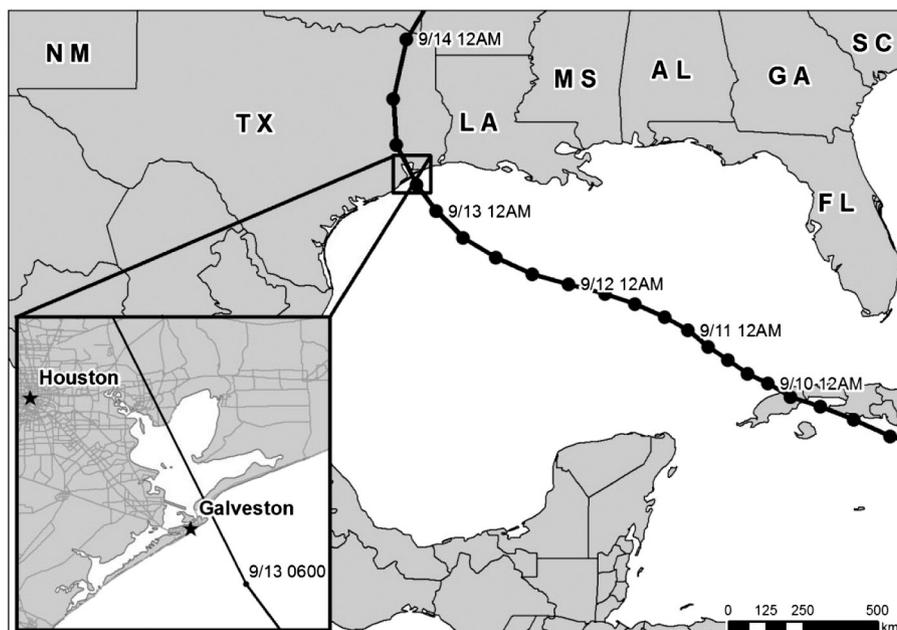


Fig. 2. The National Hurricane Center track for Hurricane Ike as it approaches the Houston–Galveston region is shown in black. The distance between each point represents a six hour time interval (UTC).

Since 1850, sixteen hurricanes with surge heights greater than 5 m have struck Galveston Bay, the most notable of which occurred in 1900 and remains the deadliest natural disaster in U.S. history, killing an estimated 8000 people. Between 1902 and 1904, a 17-foot seawall was built at the east end of Galveston Island and the island was backfilled to lift buildings above sea level. Today the seawall is approximately 16 km long. In response to Hurricane Carla in 1961, a levee system was built to protect Texas City, one of the most vulnerable industrial areas in the Galveston Bay system. The levee was completed in 1987, is 6 m high, and protects a 93 km<sup>2</sup> area. A larger comprehensive levee system was once proposed to protect Galveston Bay, but was never built.

On September 13, 2008 at 0600 GMT, Hurricane Ike made landfall just north of Galveston Island as a strong Category 2 (176 km/h, 950 mb) before traveling through Galveston Bay and making landfall again just east of Houston near Baytown (Berg, 2009) (see Fig. 2). For

a Category 2 hurricane, Ike had an uncharacteristically large wind field with a radius to maximum winds of approximately 74 km and hurricane force winds reaching as far as 200 km from the eye. The large wind field and relatively slow forward speed (approximately 5 m/s in the 12 h before landfall) resulted in large volumes of water that inundated east Texas and large portions of Louisiana. Storm surge in excess of 3 m was seen in and around Galveston Bay and the highest measured storm surge occurred in Chambers County, where FEMA collected a high water mark of 5.3 m 19 km inland (Berg, 2009). The City of Galveston flooded from the back-side due to rising waters in Galveston Bay, but both the seawall at Galveston and the Texas City Levee protected these communities from the storm surge. However, along the rest of the upper Texas coast, damages from Hurricane Ike amounted to \$29.5 billion, making it the third costliest storm in history, exceeded only by Hurricanes Katrina and Sandy (Blake and Gibney, 2011; Blake et al., 2013).

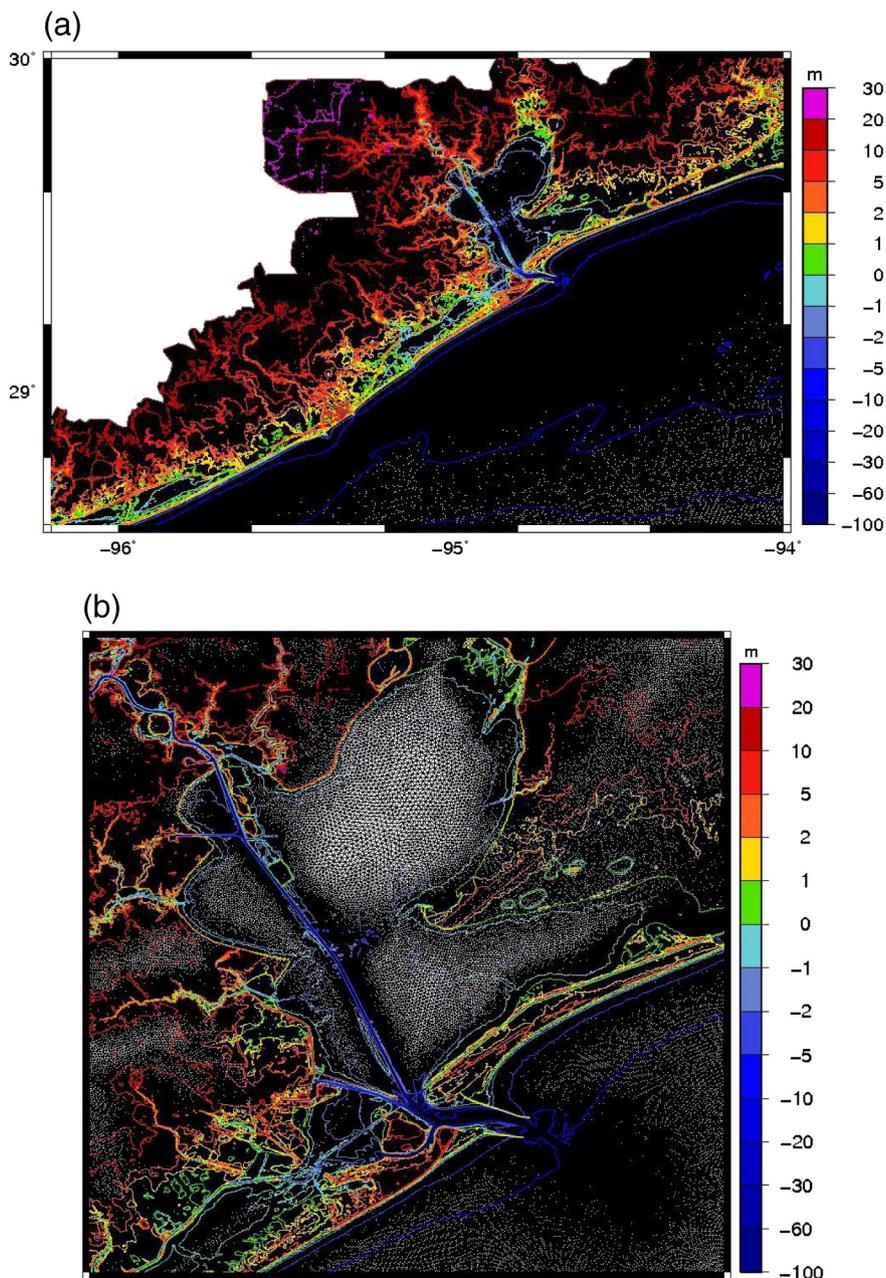


Fig. 3. (a) ADCIRC mesh for the upper Texas coast and (b) high resolution mesh for Galveston Bay.

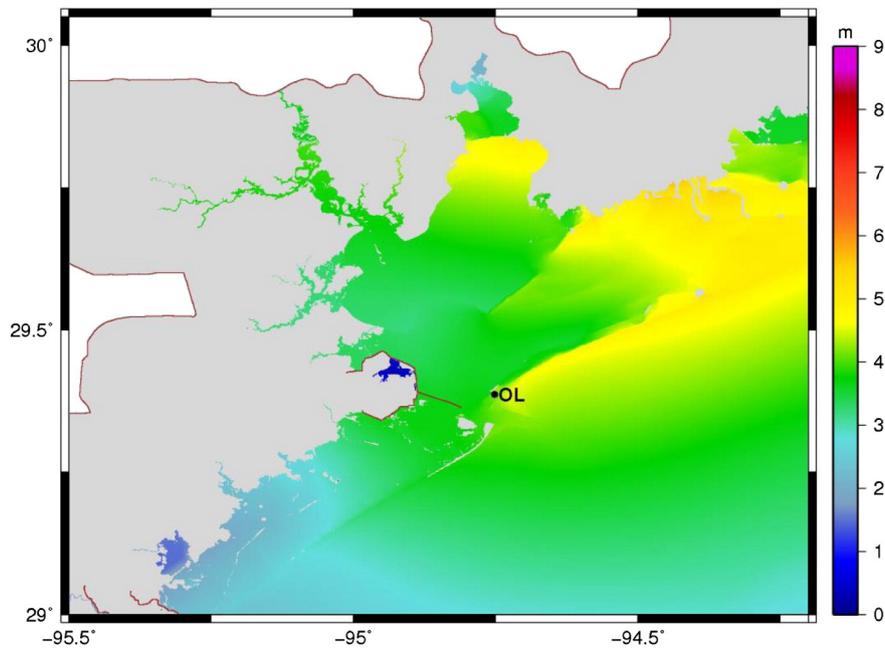


Fig. 4. Maximum elevations obtained from ADCIRC validated for Hurricane Ike at the original landfall (OL) location.

## 2. Methodology

### 2.1. SWAN + ADCIRC model

We employ the tightly coupled Simulating Waves Nearshore (SWAN) model and Advanced CIRCulation (ADCIRC) model to simulate the evolution of waves and storm surge from deep water to the coastal region. The wave model is a fully implicit finite difference method recently extended to unstructured grids that employs a sweeping Gauss–Seidel technique to compute the numerical solution (Zijlema, 2010). The procedure is stable for any time step and allows for local mesh refinement in areas of interest. Because individual wave phenomena occur on a scale too small to be resolved on large domains, the wave action density is computed by SWAN in geographic, spectral and temporal spaces.

The ADCIRC model solves the depth-averaged barotropic form of the shallow water equations for water levels and momentum (Dawson et al., 2006; Luettich and Westerink, 2004). Employing a continuous

Galerkin finite element technique, the Generalized Wave Continuity Equation (GWCE) is solved in a combined and differentiated form of the continuity and momentum equations which results in a stable and non-oscillatory solution. The depth-integrated currents are solved in the vertically-integrated momentum equations. A three- and two-level time discretization is employed for the GWCE and momentum equations, respectively.

The solution technique employs boundary conditions, input parameterizations, wetting and drying of elements, unstructured mesh refinement, and efficient parallel communication. Further implementation details are well described in related publications. ADCIRC has been validated for various hurricanes occurring in the Southern Louisiana coastline (Dietrich et al., 2010; Hope et al., 2013; Westerink et al., 2008) and has been utilized extensively by the US Army Corps of Engineers, the Federal Emergency Management Agency, and local agencies to evaluate flood risk and to explore potential flood mitigation strategies.

The use of the unstructured mesh version of SWAN resolves several issues previously associated with the coupling of wave and circulation

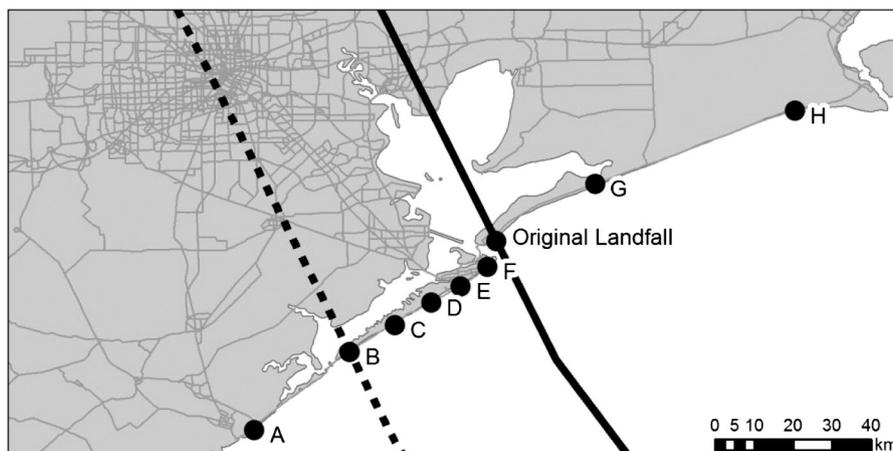


Fig. 5. Eight hypothetical landfall locations (A–H) were examined to determine a probable worst case scenario for the given angle of approach from the Hurricane Ike track. The original landfall (OL) and new landfall (NL) tracks are shown as a solid and a dotted line, respectively.

models. Previous implementations employed heterogeneous meshes, where each model would be solved on a separate submesh and solution information is interpolated and passed between models via external files or a generic framework. The tightly coupled SWAN + ADCIRC paradigm allows both wave and circulation interactions to be solved on the same unstructured mesh resulting in a more accurate and efficient solution technique. It has been widely recognized as a successful strategy for modeling storm surge applications (Dietrich et al., 2011a; Dietrich et al., 2012).

The fidelity of a storm surge model significantly depends on the use of a suitably large physical domain. Although our region of interest focuses on Galveston Bay, the computational domain includes the western North Atlantic Ocean, eastern U.S. seaboard and entire Gulf of Mexico (Fig. 3). This technique addresses several numerical and physics related boundary condition issues to improve the physics of deep to inland water coupling along a range of scales (Blain et al., 1994, 1998; Hagen et al., 2000). Our unstructured finite element mesh consists of 3,323,388 nodes with resolution down to 30 m in the nearshore, incorporating a significant amount of detail around Galveston.

### 2.2. Hurricane Ike validation

The ten day computational simulation was cold started without tidal spin-up on September 5, 2008 at 1200 GMT. Wind forcing was derived from a large scale field reconstructed post-storm via NOAA's Hurricane Research Division Wind Analysis System (H\*WIND) (Cox et al., 1995; Hope et al., 2013; Powell et al., 1998). Calculations were performed on the Lonestar parallel computer at the Texas Advanced Computing Center at the University of Texas at Austin using 2400 cores in less than 5 h of wall-clock time. The maximum water surface elevation over the course of the ADCIRC + SWAN simulation for Hurricane Ike is displayed in Fig. 4 for the Houston/Galveston region of interest. The hurricane made landfall near Galveston Island at 0600 GMT on September 13, 2008, 6 days and 6 h after the start of the simulation. SWAN + ADCIRC was validated for Hurricane Ike in a related paper by Hope et al. (2013) in which the authors captured 599 high water marks along the Gulf Coast within an average absolute difference of 0.12 m. Comparing measured high water marks to predicted ADCIRC peak water levels resulted in an  $R^2$  value of 0.91. The research presented here utilizes the validated model to examine the behavior of storm surge within the Galveston Bay system under conditions where landfall and wind speed are varied.

### 2.3. Synthetic hurricane simulations

To examine hurricane scenarios that are closely related to the path and size of Ike, we shifted the track along the Texas coast, while maintaining the angle of approach, to explore various landfall locations both east and west of the original landfall (points A–H in Fig. 5). Physically, a track shifted somewhat to the west was expected to produce a greater impact (higher storm surge level) in the Houston region due to the counterclockwise rotation of the wind forces both shore parallel and perpendicular to the east of the eye. Using eight landfall locations, we determined that the hurricane with the highest surge impact in the most vulnerable areas of the Houston/Galveston region, including the Houston Ship Channel and populated cities of Kemah and Galveston, makes landfall at point B (shown in Fig. 5). Here forth, we refer to point B as the “New Landfall” location. Under these conditions, practically the entire bay system is encompassed within the radius of maximum winds (approximately 74 km). Additionally, we explored the impact of increasing the wind speed for Hurricane Ike along both the Original Landfall (OL) and New Landfall (NL) tracks. An increase in 15% of the overall wind speed results in a Category 3 hurricane at landfall (202 km/h) and a 30% increase yields a high Category 4 (229 km/h).

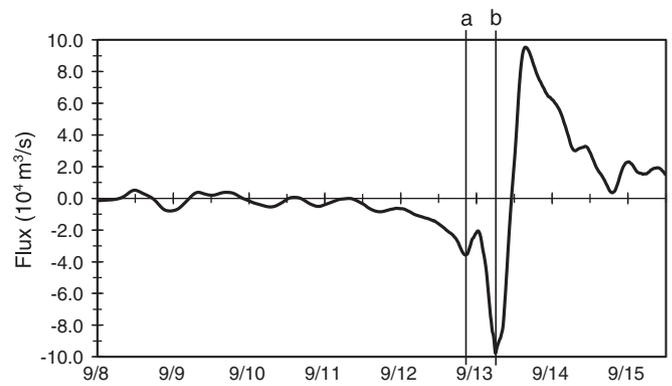


Fig. 6. Flux profile at Boliver Roads where (a) is the time at which the forerunner peaks at the coast (9/12/08 2100 GMT) and (b) is the time at which Hurricane Ike makes landfall at OL (9/13/08 0600 GMT).

## 3. Results

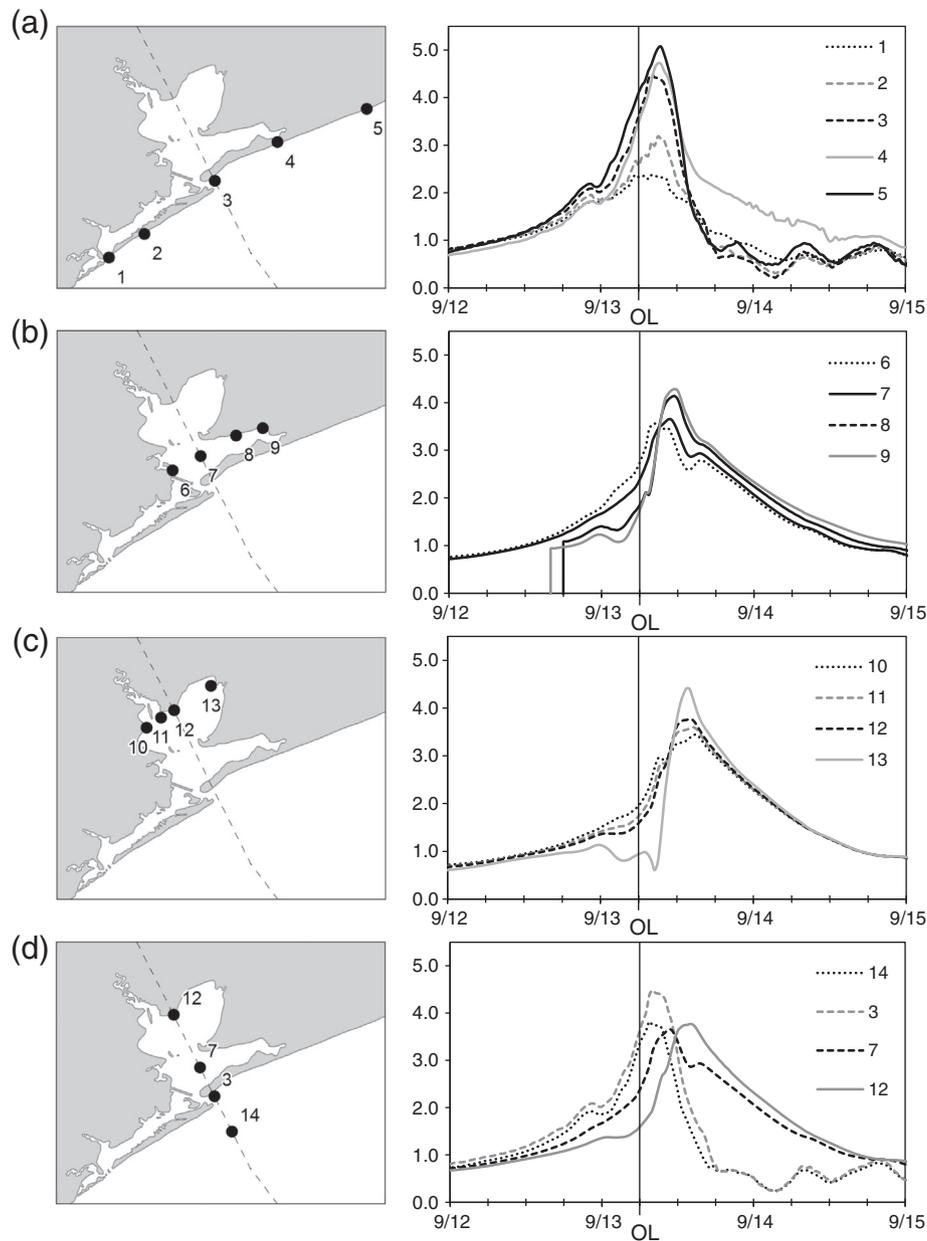
### 3.1. Hurricane Ike analysis

ADCIRC + SWAN was used to measure the flux across Boliver Roads every 900 s over 10 days beginning on 9/5/08 at 1200 GMT. The resulting flux profile is shown in Fig. 6, where negative flux corresponds to water entering Galveston Bay and positive flux is water exiting the Bay. Water levels in Galveston Bay began deviating from tidal fluctuations at around 0000 GMT on 9/12/08 and an initial peak flux occurs on 9/12/08 at 2100 GMT (a) corresponding to the peak forerunner at the coastline. A second higher peak flux occurs on 9/13/08 at 0600 GMT (b) corresponding to the time the hurricane makes landfall at Galveston Island. From this, we estimate that approximately  $4.6 \times 10^9 \text{ m}^3$  of water entered the Galveston Bay system via Boliver Roads due to the combined effect of the forerunner and storm surge, doubling the total volume of water in the Bay. The flux reversed abruptly between 1045 and 1100 GMT on 9/13/08 as the water began to flow back into the Gulf of Mexico reflective of a dominant change in wind direction as Hurricane Ike crossed Galveston Bay.

Wave heights in the Gulf of Mexico reached as high as 7.5 m, but diminished closer to shore. Inside Galveston Bay maximum wave heights were limited to 2–2.5 m. Wave heights were roughly constant in surge heights seen at points along the shore, and in Galveston Bay. Maximum water surface elevations (waves + surge) were mapped for the Hurricane Ike simulation (Fig. 4) and 41 stage hydrographs in 0.5 hour time steps were extracted from the results. The locations of the stage hydrographs were chosen based on their proximity to heavily populated areas, land features of interest, the hurricane track, and each other. Of these, fourteen points, shown to be indicative of storm surge behavior in Galveston Bay, were chosen to be discussed in detail in this paper. The

Table 1  
Peak (m) and time of peak (GMT) at points 1–14 during Hurricane Ike on 9/13/08.

Point	Peak	Time of peak
1	2.38	06:30
2	3.18	07:30
3	4.48	06:30
4	4.72	07:30
5	5.07	08:00
6	3.56	07:00
7	3.65	09:00
8	4.14	10:00
9	4.28	10:00
10	3.44	13:30
11	3.60	13:00
12	3.77	12:30
13	4.41	12:00
14	3.81	06:00



**Fig. 7.** Hurricane Ike storm surge (m) at 14 points indicative of surge behavior. Time is in GMT and landfall on 9/13/08 at 0600 GMT is marked as “OL.” a. Location of points and hydrograph output for the coast. b. Location of points and hydrograph output for the lower bay. c. Location of points and hydrograph output for the upper bay. d. Location of points and hydrograph output for the track.

peak surge and time to peak for each of these points are shown in Table 1 and the resulting stage hydrographs are provided in Fig. 7a–d and are divided amongst points along the barrier islands, points on the hurricane track, and points perpendicular to the hurricane track in West Bay and Trinity Bay. The timing and magnitude of key hydrograph components (rising limb, peak, and receding limb) were analyzed and the results are discussed in the following sections.

### 3.1.1. Forerunner surge

Although the center of the storm was more than 400 km offshore, a substantial water level increase occurred along the western Louisiana and northern Texas coast a full day before landfall. This unanticipated forerunner surge was driven by strong shore-parallel currents and winds (Hope et al., 2013; Kennedy et al., 2011). The forerunner surge, otherwise known as the Ekman setup, is specific to wide, shallow coastal shelves subject to large wind fields.

The forerunner caused water levels to begin rising at the coast at approximately 2100 GMT on September 12th, 9 h in advance of hurricane landfall (0600 GMT) (see Fig. 7a). Despite no variation in timing along this portion of the coast, the magnitude of the forerunner was generally higher extending to the east of the landfall location, reaching a maximum height greater than 2 m near point 5, which is within the radius of maximum winds (approximately 74 km). As seen in Fig. 8a, the back side of Galveston Island and parts of West Bay were impacted by the forerunner traveling along Boliver Peninsula and entering Galveston Bay via Boliver Roads (Fig. 6); however, the peaking effect of the forerunner was negligible at points deeper inside the bay system, indicating that the presence of the barrier islands reduced the conveyance of the forerunner into the greater Galveston Bay. The gradual rise in water within the bay system seen at points 6, 7, 10, 11, and 12, but not at points 8, 9, or 13 (Fig. 7b and c), coupled with the time-lapse figures shown in Fig. 8a–c, indicates that rising water levels in the western part of the bay were driven by the combined effect of counterclockwise,

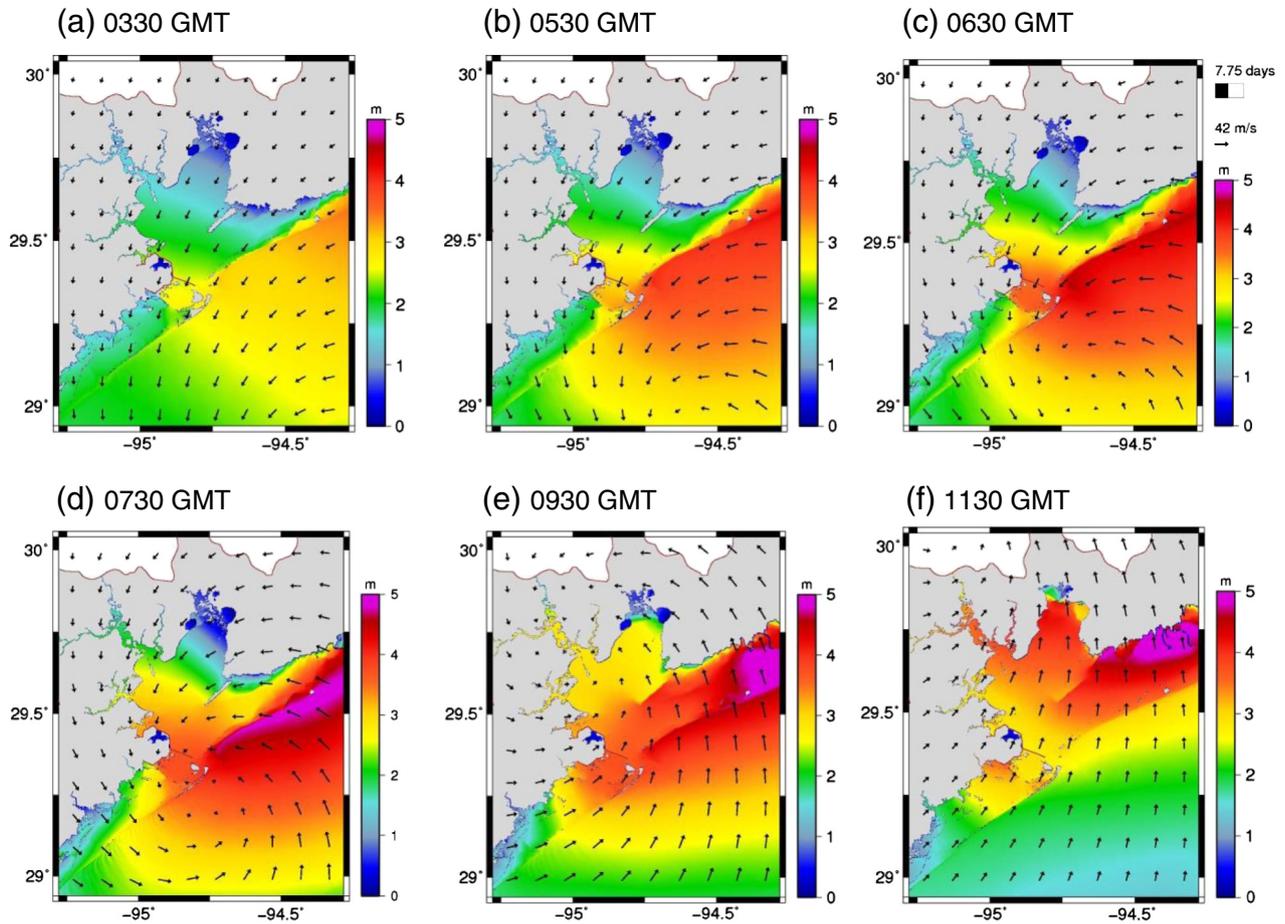


Fig. 8. Wind-setup over the period of landfall of Hurricane Ike on September 13, 2008 showing the impact of counterclockwise winds in Galveston Bay.

western shore-normal winds in the bay and shore-parallel winds along the LATEX shelf, while the counterclockwise winds dominated the surface elevations in the eastern part of the bay, negating the impact of the forerunner in East Bay and Trinity Bay.

### 3.1.2. Peak surge

At the coast, the surge peaked just after Hurricane Ike made landfall at 0600 GMT on September 13th (Fig. 7a). Maximum wind speeds in the northeastern quadrant of the storm, coupled with forward movement caused the surge to reach its highest levels to the east of the landfall location. The peak surge at coastal points reached a maximum of approximately 5.07 m near point 5 (Fig. 7a). The radius to maximum winds (approximately 74 km) roughly corresponds to the distance between the eye of the storm and point 5 at the time of the peak. This location experienced high, shore-normal winds at the time of landfall and briefly thereafter, which explains why it corresponds to the highest peak surge. To the west of the landfall location, surge decreases with distance from the landfall location, caused by the competition between winds blowing counter clockwise (coast toward Gulf) and the forward motion of the storm.

Along the path of the storm (Fig. 7d), peak surge reached a maximum height (4.48 m) at Boliver Peninsula (point 3). While there is little difference in timing between points 3 and 14 (+0.5 h), the height and volume of surge are much greater at point 3 than at point 14 (+0.67 m), indicating that the barrier islands cause the surge to “pile up” in front of the islands. The height of surge drops significantly (−0.83 m) between points 3 and 7 and increases slightly between points 7 and 12 (+0.05 m). Between points 3 and 7 and 7 and 12, the peak occurs later in time

(+2.5 h and +2.0 h, respectively). Because there is little shift in timing at points outside of the bay system, the difference in time to peak inside the system indicates that the surge dynamics within the shallow bay are dominated by wind. Given this explanation, the peak surge at point 12 occurs latest in time because it is subjected to counterclockwise winds pushing water away from the location, or westward, lasting much longer than at point 3 or 7, thus inhibiting peak surge from occurring earlier (see Fig. 8). The rising limb of the hydrograph for point 12 is also indicative of this phenomenon as the entire rising limb of the hydrograph is shifted by approximately 2.5 h from point 7.

There is a significant water surface gradient that appears perpendicular to the hurricane track as the hurricane approaches landfall and crosses Galveston Bay. It is caused primarily by wind setup and can be further illustrated using Fig. 7b–c and supported by Fig. 8. The combinations of hydrographs have three notable characteristics. Points 6, 7, 10 and 11 rise gradually before 0600 GMT on September 13, corresponding to a drop in water levels at the opposing points 8, 9 and 13. This shows the impact of counterclockwise winds pushing water levels westward before landfall (Fig. 8d). The peak at point 6 (~0900 GMT) and points 10 and 11 (~1230 GMT), roughly corresponds to the passing of the hurricane through Galveston Bay (Fig. 8d–e). The opposing points, 8, 9, and 13, peak at elevations exceeding 4 m, due to the combined effect of winds pushing water eastward following the passing of the hurricane eye and the forward motion of the hurricane.

The intersection of the hydrographs at 0730 GMT in Fig. 7b and at 0930 GMT in Fig. 7c indicates the time at which the winds shift directions, or when the eye passes points 7 and 12, respectively. The shift in timing between the two hydrographs puts the forward motion of

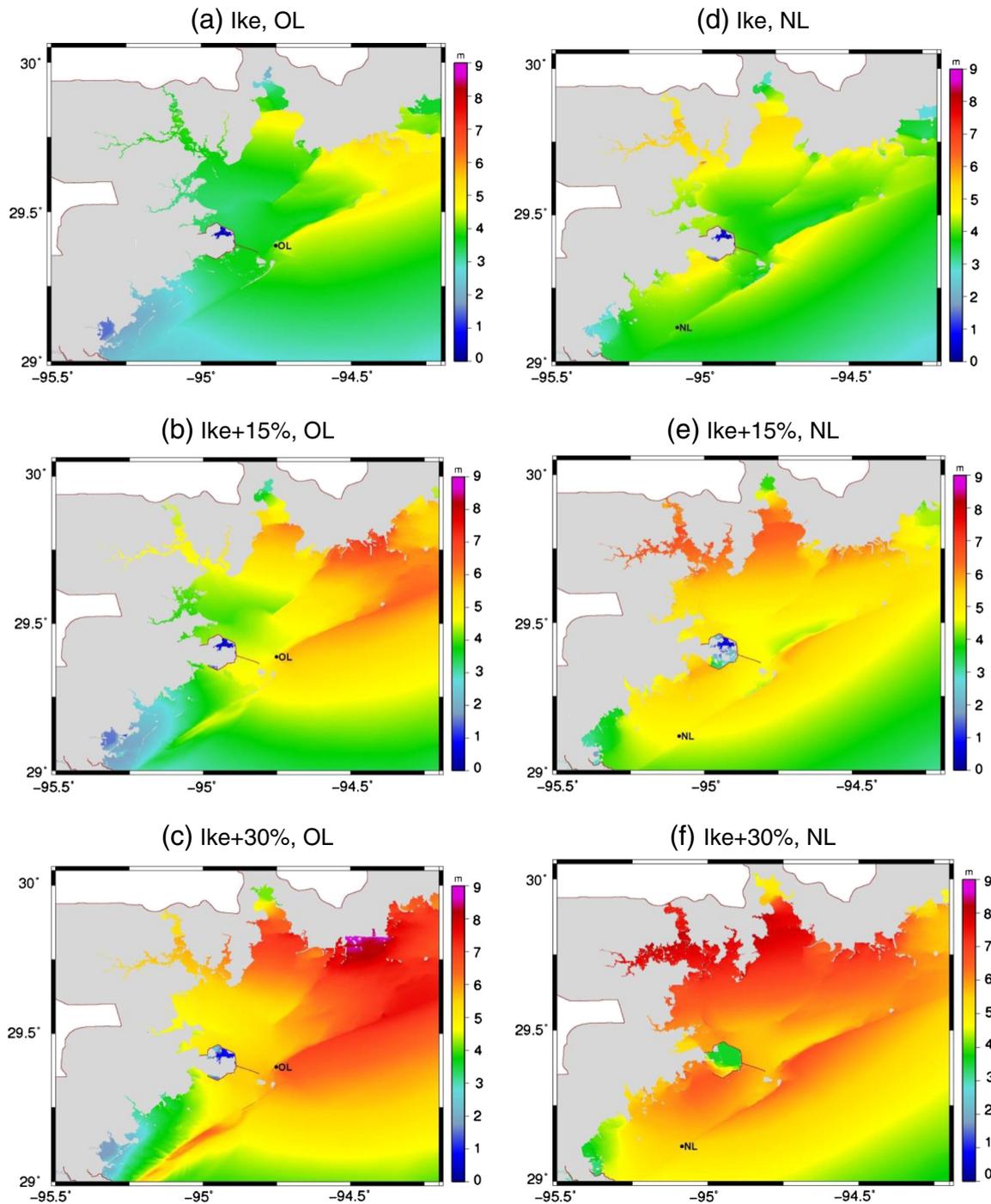


Fig. 9. Maximum water surface elevations from ADCIRC + SWAN for the Hurricane Ike original, +15%, and +30% wind scenarios at the original landfall (OL) and new landfall (NL) locations. a. Ike, OL. b. Ike + 15%, OL. c. Ike + 30%, OL. d. Ike, NL. e. Ike + 15% NL. f. Ike + 30%, NL.

the hurricane-driven surge in the bay at approximately 3.4 m/s. Finally, the maximum surge height in Galveston Bay is approximately 4.41 m and occurs at 1200 GMT near point 13. This significant surge height is caused by the volume of open water east of this location available to be pushed by high shore-ward winds after the hurricane eye has passed. The peak timing corresponds roughly to the time at which the flux through Boliver Roads reverses direction and the bay has reached its maximum volume (Fig. 6). The maximum east–west elevation gradient in the bay was calculated to be approximately  $-0.06$  m/km between points 10 and 13 at 1130 GMT on September 13.

### 3.1.3. Receding limb

The behavior associated with the recession of the surge differs significantly between points outside (1–5, 14) and those inside (6–13) the bay system. At points outside the bay system, the surge drops rapidly over approximately 11 h and returns to normal tide fluctuations, while inside the bay system, the height of the water remains elevated for over 24 h. Because the model does not consider rainfall-runoff, it is apparent that this difference in recession behavior is caused by the presence of the barrier islands which create significant impedance to the outward flow of surge.

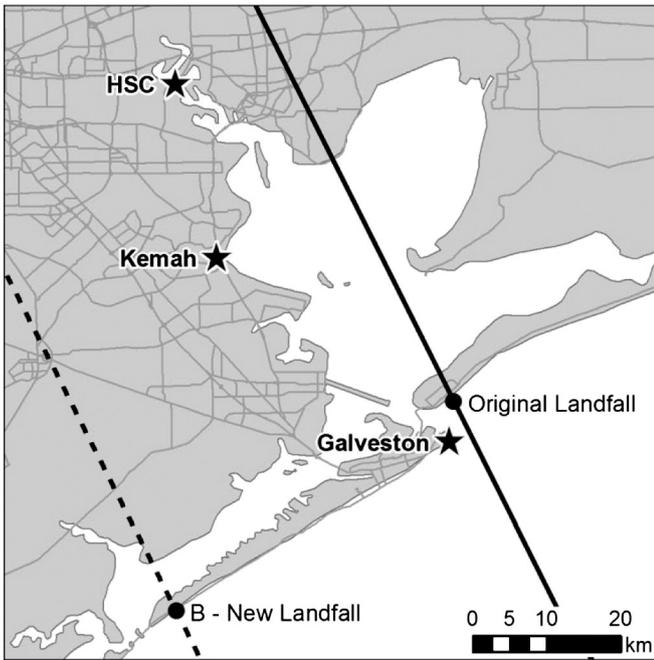


Fig. 10. Location of Galveston, Kemah, and the Houston Ship Channel (HSC).

Although the ADCIRC + SWAN model is limited by its inability to model the morphological processes that impact barrier islands during hurricane events, some discussion of the topic is merited here. In the model, the barrier islands present a source of significant overland roughness causing the falling limb of hydrographs representative of points located behind the islands to recede more slowly than those progressing through open channels as seen by higher elevations in the receding limb of the surge hydrograph at Rollover Pass (point 4 in Fig. 7a). In actuality, surge that enters Galveston Bay via overtopping the barrier islands is likely to cause significant erosion and even breach of the barrier island creating new tidal outlets. Such erosion was widely recorded along the Boliver Peninsula post-Ike (Goff et al., 2010; Wallace and Anderson, 2009).

3.2. Synthetic storms analysis

The behavior discussed in the previous sections was not unique to Hurricane Ike, but a function of the bay system as shown by modeling the storm with higher wind speeds and at other landfall locations. Fig. 9 shows the ADCIRC output for the Hurricane Ike simulation and five synthetic storms (Ike + 15%, OL; Ike + 30%, OL; Ike, NL; Ike + 15%, NL; Ike + 30%, NL). The results indicate that water surface

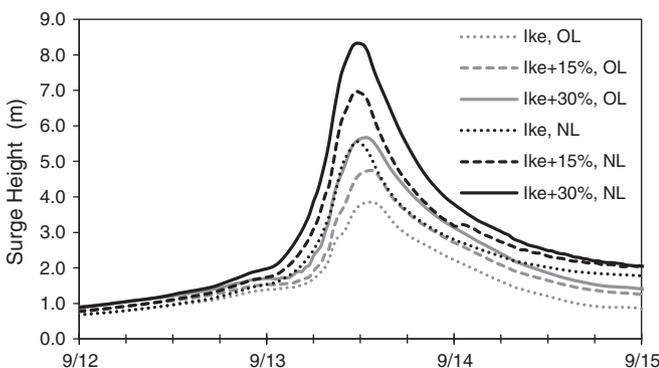


Fig. 11. Output hydrographs at the Houston Ship Channel generated in ADCIRC + SWAN for Hurricane Ike and the five synthetic storms.

Table 2 Description of synthetic storms at original landfall (OL) and new landfall (NL) locations.

Name	Description
Ike, OL	Validated Hurricane Ike (Category 2) making landfall with maximum winds of approximately 176 km/h.
Ike + 15%, OL	Category 3 storm making landfall near Galveston (OL) with maximum winds of approximately 202 km/h.
Ike + 30%, OL	Category 4 storm making landfall near Galveston (OL) with maximum winds of approximately 229 km/h.
Ike, NL	Category 2 storm making landfall near San Luis Pass (NL) with maximum winds of approximately 176 km/h.
Ike + 15%, NL	Category 3 storm making landfall near San Luis Pass (NL) with maximum winds of approximately 202 km/h.
Ike + 30%, NL	Category 4 storm making landfall near San Luis Pass (NL) with maximum winds of approximately 229 km/h.

elevations within Galveston Bay increase with increasing wind speed and shifting landfall location further westward along the coast. At the forty-one points examined in and around Galveston Bay, increasing hurricane wind speed by 15% caused water surface elevations to increase by 23% (+/- 5%). At points inside Galveston Bay, water surface elevations increased by 23% (+/- 3%) for every 15% increase in wind speed. Note that all points were located in or near the radius of maximum winds.

Stage hydrographs at the Houston Ship Channel for Hurricane Ike and the five synthetic storms are shown in Fig. 11. Increasing wind speed causes an increase in peak surge, but little variation in shape or timing of the hydrograph. Furthermore shifting the landfall location caused an increase in peak surge and a shift in timing, but little variation in hydrograph shape. This indicates that the arrival and recession of surge is fairly constant in the bay system and is primarily driven by wind direction and the geometry of Galveston Bay, while the volume and height of surge are driven by wind speed and landfall location.

4. Discussion

More than 1.6 million people live in the Hurricane Evacuation Zones bordering Galveston Bay and it is projected that this number is expected to approach 2.4 million by 2035 (H-GAC (Houston-Galveston Area Council), 2011). Storm surge impacting Galveston Bay could not only destroy millions of homes and cause loss of life, but also have the potential to cause unprecedented national economic and environmental damage. In Table 2 the peak height and timing for each of the modeled scenarios is reported at three locations: Galveston Island, Kemah, and the Houston Ship Channel. (See Table 3.)

The Houston Ship Channel and the Port of Houston, the largest U.S. petrochemical complex and the second largest port by total tonnage, respectively, are located in Galveston Bay (Port of Houston Authority, 2012). The Federal Emergency Management Agency requires structural protection to the 100-year flood level for industrial complexes, which corresponds to a Base Flood Elevation approximately 4 m above sea level near the Houston Ship Channel (City of Houston Geographic Information & Management System). The results from hurricane scenarios modeled in this study indicate that surge could greatly exceed existing protection and reach as high as 8.32 m, given higher wind speeds and shifted landfall location. Major damage to the shipping facilities and waterways in Galveston Bay could cause economic losses in excess of \$489 million per day of closure (Port of Houston Authority, 2012).

Shortly after Hurricane Ike, Dr. William Merrell at Texas A&M Galveston proposed a 100 km extension of the Galveston seawall coined the "Ike Dike" (Berger, 2009; Merrell et al., 2010). The idea was derived from the Netherlands system built after the 1953 storm after which they shortened the coastline to reduce storm surge flooding. The proposed Ike Dike would form a Coastal Spine along the barrier islands with a gate or partial closure at Boliver Roads (Jonkman et al., 2013). Similar

**Table 3**  
Peak surge (m) and time of peak (GMT) on 9/13/08 of Hurricane Ike and synthetic storms at original landfall (OL) and new landfall (NL).

	Galveston		Kemah		Houston Ship Channel	
	Peak	Time of peak	Peak	Time of peak	Peak	Time of peak
Ike, OL	4.25	06:30	3.26	13:30	3.85	13:30
Ike + 15%, OL	5.16	06:30	3.99	13:00	4.74	13:30
Ike + 30%, OL	6.11	06:30	4.75	12:30	5.67	12:30
Ike, NL	4.80	07:30	4.48	09:00	5.55	11:30
Ike + 15%, NL	5.87	07:30	5.71	09:00	6.97	11:30
Ike + 30%, NL	6.93	07:30	7.10	08:30	8.32	11:30

to Rego and Li (2010), proponents of the Ike Dike have argued that reinforcing and raising the dunes on the barrier islands will reduce surge heights in Galveston Bay. However, as shown in this paper, varying landfall location will change wind direction and cause significant setup across the bay irrelevant of the presence of a barrier at the coastline. Shore-normal winds on the west side of Galveston Bay will cause elevated water levels resulting in significant damage to coastal communities. Thus, the Ike Dike by itself cannot protect the entire Galveston Bay region under every storm scenario.

Another research organization in the region, the Severe Storm Prediction, Education and Evacuation from Disasters (SSPEED) Center at Rice University, developed a proposal for a Galveston Bay Coastal Protection Network that would encompass a variety of structural and non-structural solutions. One non-structural proposal is the development of a National Recreation Area along the Texas Coast to conserve the ecological services provided by existing local land use and develop a coastal economy centered around tourism and recreation, while discouraging further urban development in vulnerable coastal areas. The National Recreation Area, coupled with local levees and gates to protect the western shore of Galveston Bay and the larger “Centennial Gate” to protect the Houston Ship Channel, could prevent severe environmental and economic damage to the region.

Any system-wide, comprehensive approach that combines structural and non-structural solutions would significantly advance the regions' protection against storm surge. Those discussed here require further cost-benefit and engineering analysis and it will be important to consider the impact of any structural system on the Bay's ecology, as Galveston Bay is the second most productive estuary in the nation.

## 5. Conclusions

This paper used the SWAN + ADCIRC hurricane model to analyze storm surge behavior in and around Galveston Bay during Hurricane Ike (2008). The results show that the hurricane's large wind field produced a pronounced forerunner (>2 m) which impacted the coast and barrier islands along the upper Texas coast, causing water levels in Galveston Bay to begin rising almost a full day before hurricane landfall. The volume of water in the Galveston Bay system nearly doubled as a result of Hurricane Ike, highlighting the vulnerability of the system. By taking a unique approach to storm surge modeling and examining surge hydrographs, we were able to conclude that surge behavior in Galveston Bay is dominated by local wind direction and accordingly by landfall location.

The highest modeled surge during Hurricane Ike occurred to the east of landfall location where maximum hurricane winds were perpendicular to the coast. This observation prompted an analysis of shifting landfall location and increasing wind speeds to evaluate surge behavior within the bay system during more severe hurricane events with western shore-normal winds. The results indicate that shifting the storms further west and increasing wind speeds cause higher water levels in Galveston Bay and significantly higher water levels in the heavily populated coastal evacuation zones. Although the shape and timing of the surge hydrograph are relatively unaffected at increased wind speeds, the time to peak occurs earlier at the new landfall location

indicating that surge behavior in Galveston Bay is independent of wind speed, but not of landfall location.

This research does not evaluate the impact of changing forward motion of the storm or the angle of approach and these two factors could significantly impact the surge behavior within the bay. In the case of angle of approach, a more westerly heading, or more oblique angle to the coast, would result in a change in wind direction that would be more shore-normal. This could greatly affect the height of surge and the shape and timing of the stage hydrographs. Further study of these impacts on flux through Boliver Roads is also merited as such information would greatly benefit the Houston-Galveston area and other delta regions recently impacted by storm surge (i.e. Hurricane Sandy (2012)).

The results provided in this paper greatly improve our understanding of how hurricane storm surge behaves in shallow-water, semi-enclosed bay systems and gives perspective to surge height and behavior that could be seen in Galveston Bay. The results have prompted a discussion of several coastal flood mitigation strategies for the Houston-Galveston region, which are currently under evaluation. In future studies it would be beneficial to take a probabilistic approach toward determining storm surge return periods as such information would further the application of these results and help to determine whether there are structural or non-structural solutions that can adequately protect the social and industrial centers of the upper Texas Gulf Coast from storm surge.

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