ADCIRC Based Storm Surge Analysis of Sea Level Rise in the Galveston Bay and Jefferson County Area in Texas

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Table of Contents

1. Introduction 1

2. ADCIRC Model Overview 3

3. Data Sources 8

4. ADCIRC Model Setup 10
   4.1 ADCIRC Mesh 10
   4.2 Application of Land Cover 10
   4.3 Eustatic Sea Level Rise 11

5. Results 12
   5.1 Maximum Storm Surge Elevation 12
   5.2 Analysis of Nonlinear SLR Effects 13
   5.3 Inundation Limits 15
   5.4 Marsh Loss and Subsidence Sensitivity Test 16
   5.5 Water Surface Elevation Time Series 17

6. Limitations 19

7. Conclusions 20

8. Recommendations 22

9. References 23

Tables

Table 1  Manning’s n and $Z_0$ Values for SLAMM Land Cover Classes
Table 2  Manning’s n and $Z_0$ Values for C-CAP Land Cover Classes
Table 3  SLAMM Sea Level Rise Scenarios (mm)
Table 4  Increase in Inundated Area for Future Scenarios Under Hurricane Ike Conditions
Table 5  Storm Surge Time Series Output of Twelve Selected Locations
Table of Contents

Figures

Figure 1: Location Map of the Combined Galveston Bay and Jefferson County Study Area

Figure 2: ADCIRC Model Schematic

Figure 3: ADCIRC Mesh Domain and Topographic Contours (feet NAVD88)

Figure 4: ADCIRC Mesh Topographic Contours (feet NAVD88)

Figure 5: ADCIRC Mesh with 2004 Topographic Contours (feet NAVD88) for the Study Domain

Figure 6: ADCIRC Mesh Resolution for the Study Domain

Figure 7: 2004 Initial Land Cover Data Used By SLAMM (based on NWI) for the Galveston Bay Area, Including Jefferson County, TX

Figure 8: SLAMM 2050 Scenario for the Galveston Bay Area, Including Jefferson County, TX

Figure 9: SLAMM 2100 Scenario for the Galveston Bay Area, Including Jefferson County, TX

Figure 10: C-CAP Land Cover Data

Figure 11: ADCIRC Mesh with 2050 Topographic Contours (feet NAVD88) for the Study Domain

Figure 12: Differences due to local subsidence in ADCIRC Mesh Topography for 2050 and 2004 Conditions

Figure 13: ADCIRC Mesh with 2100 Topographic Contours (feet NAVD88) for the Study Domain

Figure 14: Differences due to local subsidence in ADCIRC Mesh Topography for 2100 and 2004 Conditions

Figure 15: 2004 Conditions ADCIRC Nodal Manning’s $n$ Values for the Study Domain

Figure 16: 2004 Conditions ADCIRC Nodal $Z_0$ Values in the Study Domain for Southerly Winds

Figure 17: 2004 Conditions ADCIRC Nodal $Z_0$ Values in the Study Domain for Northerly Winds

Figure 18: 2050 Conditions ADCIRC Nodal Manning’s $n$ Values for the Study Domain
Figure 19: 2050 Conditions ADCIRC Nodal $Z_0$ Values in the Study Domain for Southerly Winds

Figure 20: 2050 Conditions ADCIRC Nodal $Z_0$ Values in the Study Domain for Northerly Winds

Figure 21: Difference between 2004 and 2050 Conditions ADCIRC Nodal Manning's $n$ Values for the Study Domain

Figure 22: Difference between 2004 and 2050 Conditions ADCIRC Nodal $Z_0$ Values in the Study Domain for Southerly Winds

Figure 23: Difference between 2004 and 2050 Conditions ADCIRC Nodal $Z_0$ Values in the Study Domain for Northerly Winds

Figure 24: 2100 Conditions ADCIRC Nodal Manning's $n$ Values for the Study Domain

Figure 25: 2100 Conditions ADCIRC Nodal $Z_0$ Values in the Study Domain for Southerly Winds

Figure 26: 2100 Conditions ADCIRC Nodal $Z_0$ Values in the Study Domain for Northerly Winds

Figure 27: Difference between 2004 and 2100 Conditions ADCIRC Nodal Manning's $n$ Values for the Study Domain

Figure 28: Difference between 2004 and 2100 Conditions ADCIRC Nodal $Z_0$ Values in the Study Domain for Southerly Winds

Figure 29: Difference between 2004 and 2100 Conditions ADCIRC Nodal $Z_0$ Values in the Study Domain for Northerly Winds

Figure 30: Summary of SLR Scenarios Utilized by the SLAMM Model

Figure 31: Maximum Storm Surge Elevation Contours (feet NAVD88) for Hurricane Ike for 2004 Model Conditions

Figure 32: Location of Measured High Water Marks in the Study Area for Hurricane Ike

Figure 33: Comparison of Computed ADCIRC Maximum to Measured High Water Marks for Hurricane Ike, Initial Conditions

Figure 34: Comparison of Hurricane Ike Storm Surge Simulation Results from the New Nature Conservancy ADCIRC Model and the Original FEMA ADCIRC Model

Figure 35: Maximum Storm Surge Elevation Contours (feet NAVD88) for Hurricane Ike for 2050 Model Scenario

Figure 36: The Difference Between 2050 Maximum Storm Surge Elevation and 2004 Maximum Storm Surge Elevation for Hurricane Ike
Table of Contents

Figure 37: Maximum Storm Surge Elevation Contours (feet NAVD88) for Hurricane Ike for 2100 Model Conditions

Figure 38: The Difference Between 2100 Maximum Storm Surge Elevation and 2004 Maximum Storm Surge Elevation for Hurricane Ike

Figure 39: Relative Surge Amplification for the 2050 Scenario

Figure 40: Relative Surge Amplification for the 2100 Scenario

Figure 41: Plot of the Inundation Extents for the Three Scenarios

Figure 42: Maximum Storm Surge Elevation Contours (feet NAVD88) for Hurricane Ike for a Sensitivity Test using the Subsided Topography and Frictional Characteristics of the 2100 Scenario and a 2004 Sea Level Value

Figure 43: Increase in Peak Surge for the Sensitivity Test

Figure 44: Map Outlining Twelve Locations where Water Surface Elevation Time Series are Analyzed for the Various SLR Scenarios

Figure 45: Map Outlining Two Hundred Locations where Water Surface Elevation Time Series are Analyzed for the Various SLR Scenarios

Figure 46: Water Surface Elevation Time Series for Six Locations

Figure 47: Water Surface Elevation Time Series for Six Locations
## ACRONYMS AND ABBREVIATIONS

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
</tr>
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<tbody>
<tr>
<td>ADCIRC</td>
<td>ADvanced CIRCulation</td>
</tr>
<tr>
<td>C-CAP</td>
<td>Coastal Change Analysis Program</td>
</tr>
<tr>
<td>FEMA</td>
<td>Federal Emergency Management Agency</td>
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<tr>
<td>FIS</td>
<td>flood insurance study</td>
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<tr>
<td>HRD</td>
<td>Hurricane Research Division</td>
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<tr>
<td>HWM</td>
<td>high water marks</td>
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<tr>
<td>lidar</td>
<td>light detection and ranging</td>
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<tr>
<td>LMSL</td>
<td>local mean sea level</td>
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<tr>
<td>MEOW</td>
<td>maximum envelope of water</td>
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<tr>
<td>m</td>
<td>meter</td>
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<tr>
<td>mph</td>
<td>miles per hour</td>
</tr>
<tr>
<td>NLCD</td>
<td>National Land Cover Dataset</td>
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<tr>
<td>NOAA</td>
<td>National Oceanic and Atmospheric Administration</td>
</tr>
<tr>
<td>OWI</td>
<td>Oceanweather, Inc.</td>
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<tr>
<td>SLAMM</td>
<td>Sea-Level Affecting Marshes Model</td>
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<tr>
<td>SLR</td>
<td>sea level rise</td>
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<tr>
<td>STWAVE</td>
<td>STeady State Spectral WAVE</td>
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<tr>
<td>TNC</td>
<td>The Nature Conservancy</td>
</tr>
<tr>
<td>UnSWAN</td>
<td>unstructured Simulating WAves Near-shore</td>
</tr>
<tr>
<td>USACE</td>
<td>U.S. Army Corps of Engineers</td>
</tr>
<tr>
<td>UTC</td>
<td>Coordinated Universal Time</td>
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<tr>
<td>WSE</td>
<td>water surface elevation</td>
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1. Introduction

This modeling effort was motivated by the need to provide a series of technical tools to the members of the Governor’s Gulf of Mexico Alliance to better understand the effects of sea level rise (SLR) and storm surge in key coastal areas. The implementation of the ADvanced CIRCulation (ADCIRC) model for SLR analysis complements the information produced by previous studies conducted by The Nature Conservancy (TNC). The products provided as part of this effort will help coastal managers, scientists and the conservation community in identifying the additional threat posed by storm surge given one meter of SLR by 2100 in the study area. This project has been funded through grants from the Gulf of Mexico Foundation and the Mississippi Department of Marine Resources who have been supported by the Gulf of Mexico Alliance.

In 2011, TNC and Warren Pinnacle Consulting, Inc. applied the Sea-Level Affecting Marshes Model (SLAMM) to analyze the potential effects of SLR on Galveston Bay and the Jefferson County area in Texas (Warren Pinnacle Consulting 2011a, 2011b). The SLAMM analyses provided forecasts of future Galveston Bay area and Southern Jefferson County marsh landscapes under various potential SLR scenarios through the year 2100.

The intent of this project is to utilize the SLAMM data to analyze the effects of future landscapes and SLR on storm surge. Future landscapes include changes in land cover type and coastal subsidence. The land cover changes are implemented by utilizing the available SLAMM output information. Subsidence is accounted for by applying a region wide value assumed in the SLAMM analyses (Warren Pinnacle Consulting 2011a, 2011b). A SLR rate of one meter by 2100 is analyzed for this study for 2050 and 2100 conditions.

Three scenarios of SLR were analyzed using the ADCIRC hydrodynamic model; the model evaluated the initial conditions in 2004 and future 2050 and 2100 scenarios. ADCIRC is a physics based, unstructured mesh finite element model, solving the shallow water equations for time dependent, free surface circulation problems (Luettich et al. 2004). ADCIRC is commonly applied for tidal studies, including hurricane storm surge and flooding applications by state and federal agencies throughout the United States.

Hurricane Ike is the storm selected for analysis in this study area due to its relatively recent landfall in the study area. Because of the recent nature of the storm,
Hurricane Ike is well documented and critical data necessary to hindcast a hurricane, such as highly accurate wind and pressures fields, are readily available. Hurricane Ike made landfall as a strong Category 2 hurricane at Galveston, Texas on September 13, 2008 at approximately 8:00 AM UTC. Winds reached over 145 miles per hour (mph) in the Gulf of Mexico, while the Texas coast incurred sustained winds of over 110 mph rendering storm surge of over 20 feet in some locations. Hurricane Ike greatly impacted Texas communities, causing widespread flooding, immense economic damage and considerable loss of life. A location map of the combined Galveston Bay and Jefferson County study area is shown if Figure 1. The path of Hurricane Ike and the extents of the SLAMM models are also included. All maps and coordinates in this report are referenced to the NAD83 horizontal datum and NAVD88 vertical datum.
2. ADCIRC Model Overview

ADCIRC was selected for this storm surge analysis, as it is a highly vetted and commonly utilized storm surge analysis model. ADCIRC is the standard coastal storm surge model used by the U.S. Army Corps of Engineers (USACE) and was the model applied in recent coastal Texas flood insurance study (FIS) conducted by USACE and the Federal Emergency Management Agency (FEMA) (USACE 2011). The FIS model mesh was constructed utilizing the most recent and accurate elevation data available in Texas and Louisiana to determine flood risk under current conditions. The ADCIRC modeling system was validated during the FEMA FIS using Hurricanes Allen, Bret, Carla, Rita and Ike. Hurricane Ike was hindcasted with a high level of skill in the FIS.

This study is able to build from the FIS by extending the analysis of Hurricane Ike to include consideration of future scenarios. The ADCIRC model constructed in the FIS is a highly accurate and robust system that has been thoroughly validated and reviewed by some of the leading experts in the field of coastal engineering. The Nature Conservancy is able to leverage this model to accurately simulate storm surge for current and proposed future conditions, with minor variations to the model setup, aside from model adjustments necessary to define future conditions. All model parameters utilized for the FIS were applied to this study unless otherwise noted. The most recent version of ADCIRC, version 49, was applied for this study as well as the FIS.

The ADCIRC hydrodynamic model solves the shallow water equations on unstructured, linear triangular elements. ADCIRC is a physics based model, using the depth-integrated barotropic equations of mass and momentum conservation subject to the incompressibility, Boussinesq (elimination of the vertical coordinate), and hydrostatic pressure approximations. The depth-integrated implementation is used, where the water level and depth-averaged velocity are solved for at each triangle vertex, referred to as nodes.

The ADCIRC model is a computational code that is compiled to simulate flow processes. Input files are required to describe the region of interest and its characteristics, boundary conditions and forcing mechanisms (e.g., wind fields). Though the inputs vary, the computational code version remains the same throughout the study. The critical inputs for this study are the computational mesh, surface characteristics file, and meteorological forcing files, such as wind and pressure fields. A modeling schematic for ADCIRC is shown in Figure 2.
The computational mesh consists of nodes, which are the locations where the ADCIRC model solves the shallow water equations. Nodes communicate with each other via linear triangular finite elements. The computational modeling process requires that the physical system is accurately described and characterized at the nodal locations. This means that topographic and bathymetric elevations must be accurately represented by the nodes. In addition, all vertical geometric features such as levees, river banks, and roads must be incorporated into the mesh by strategic placement of nodes. These small-scale features require careful consideration because they can impede the flow and focus the storm surge. Topographical mappings and surveys, including high-resolution light detection and ranging (lidar)-based surveys, can easily neglect these features due to their relatively small horizontal scale. Such small horizontal scales require special handling in order to concisely represent each feature in the mesh.

Unstructured finite element meshes permit shallow water equation solutions that can localize resolution. In this case, resolution is focused in the study area as a whole and more specifically in critical areas such as dredged channels and levees. The elements vary in size from multiple kilometers in the open ocean to resolutions as fine as 15 meters in the study area. Varying resolution throughout the mesh domain leads to globally and locally more accurate solutions, while saving on computational expense.

The computational mesh developed for the FIS, referred to as TX2008, was the basis for this study as well. All mesh elevations are referenced to a vertical datum: NAVD88. The TX2008 mesh between approximately Freeport, TX and Calcasieu Lake, LA was applied for this study. South of Freeport, the TX2008 mesh was reduced in order to save on the computational cost. However, the mesh is identical in the study area and produces the same results as the full mesh when simulating Hurricane Ike. The resulting ADCIRC mesh is referred to as TX2004_TNC.

Figure 3 displays the mesh domain of the TX2004_TNC mesh. Note that the mesh domain includes the western North Atlantic, Caribbean Sea and Gulf of Mexico. The large domain allows the mesh to accurately propagate storm surge through the Caribbean and Gulf of Mexico, onto the continental shelf and onland. This is particularly critical for a storm such as Hurricane Ike, which produced an early rise of water or a so called hurricane forerunner. The unstructured nature of the ADCIRC mesh allows for courser element sizes in the open waters and higher resolution near and onshore. Over ninety percent of the computational nodes for the TX2008 mesh reside in coastal Texas.
Figure 4 shows a mesh domain and elevation contours in the Gulf of Mexico. The study area is shown in the northwest corner of the domain. Details of the study area elevations can be seen in Figure 5. Mesh resolution is depicted in Figure 6. Note that some critical conveyance areas, such as the Houston Ship Canal are highly resolved, while other areas such as the deep waters of the Gulf of Mexico are more coarsely resolved.

Elevations are applied to the mesh using grid scale averaging techniques. For each mesh node, the maximum extents of the adjacent elemental centroids are determined to establish the area limits used for averaging elevation data. All topographic survey data, within the area limits are averaged and applied to the given node. Thus, the size of the area used for mesh scale averaging varies as elemental resolution varies. Specific details can be found in the documentation for the recent FEMA study (USACE 2011).

Mesh scale averaging is applied for two reasons. The first reason is that each ADCIRC node must represent an approximation to the terrain in a region surrounding it. In order to appropriately describe the area, each nodal elevation must incorporate data from the surrounding area rather than from a single data point. The exception to this rule is when vertically pronounced features (such as levees and channels) are assigned specific elevations to correctly capture small scale hydraulic conveyances and impedances. The second reason is for model stability purposes. Mesh scale averaging creates a more smooth elevation surface than direct sampling, which in general leads to better model stability.

In addition, ADCIRC requires a description of the terrain roughness over which the wind blows and waves and surge propagate. This roughness accounts for the resistance due to vegetation and resistance due to constructed urban, suburban, and industrial areas. Surface roughness significantly influences the flow of a fluid over a surface, whether the fluid is water or air. In the case of water flowing over a surface, the bottom friction force that is developed is an important resistance mechanism that must be accurately quantified. The Manning’s $n$ bottom friction resistance formulation is applied in this study. This formulation is widely used and is a standard formulation in hydraulic computations. In the case of air flowing over a rough surface, the wind boundary layer is modified and the resulting ten-meter above ground level wind speed is modified prior to computing the surface drag. The wind boundary layer does not adjust instantaneously to the local roughness but adjusts slowly based on the roughness in the upwind direction over which the wind has already passed. In order
ADCIRC Based Storm Surge Analysis of Sea Level Rise in the Galveston Bay and Jefferson County Area in Texas

te evaluate the physical effect of bottom resistance and the wind boundary layer, the roughness of the land surface needs to be described.

Land roughness in overland regions is characterized by land cover conditions such as urban, forested, agricultural, or marsh. The Manning’s $n$ associated with these land classifications was selected or interpolated/extrapolated from standard hydraulic literature (Chow 1959, Henderson 1966, Barnes 1967, Arcement and Schneider 1989). The roughness lengths or more specifically “nominal” roughness lengths $Z_0$ used to adjust the wind boundary layer are defined by the FEMA HAZUS program (FEMA 2005). The wind values are used as adjusted by the $Z_0$ wind roughness parameter.

Using land cover information, each ADCIRC node is assigned a Manning’s $n$ and $Z_0$ value by the same grid scale averaging technique used to assign elevation information. The ADCIRC and UnSWAN models then use the nodal attribute information to resist flow, attenuate waves, and dynamically adjust wind speeds during a storm surge event. The FIS applied Manning’s and $Z_0$ derived from the Coastal Change Analysis Program (C-CAP; http://www.csc.noaa.gov/digitalcoast/data/ccapregional/) and the National Land Cover Dataset (NLCD http://www.epa.gov/mrlc/nlcd-2006.html). For this study, SLAMM output data was applied where available and supplemented by C-CAP data outside of the SLAMM domain.

Assimilated Hurricane Ike wind fields were coupled with the ADCIRC hydrodynamic model for this study. Ike winds were assimilated using National Oceanic and Atmospheric Administration’s (NOAA) Hurricane Research Division (HRD) H*WIND system (Powell and Houston 1996, Powell et al. 1996, Powell et al. 1998) and were then blended with Gulf-scale winds using an IOKA System (Cox et al. 1995, Cox and Cardone 2000) developed by Oceanweather, Inc. (OWI). The Hurricane Ike assimilated winds include 8.75 days of wind data starting at 12:00 p.m. (UTC) on September 5, 2008. A data-assimilated hurricane wind field provides the capability to accurately represent the state of the hurricane at each moment the analysis is performed. The H*WIND assimilation procedure assimilates all available observations (from aircraft, ships, buoys and stations) of wind speed and direction during the storm. H*WIND composites all of the observations relative to the storm’s center and transforms them to a common reference condition of a ten-meter height, one-minute averaged wind speed, and marine exposure.
ADCIRC was coupled with the STeady State Spectral WAVE (STWAVE) nearshore wave model in the FIS. However, for this study, ADCIRC has been coupled with the unstructured Simulating WAves Near-shore (UnSWAN) wave model. The UnSWAN model was selected for two reasons. First, STWAVE wave radiation stresses produced for the Hurricane Ike hindcast in the FIS were produced specifically for the TX2008 ADCIRC mesh. Since the mesh was edited for this study to speed up computational time, the wave radiation stress files that exist from the FIS do not directly map to the TNC ADCIRC mesh. Secondly, UnSWAN and STWAVE wave radiation stresses have been found to have similar effects on storm surge when hindcasting Hurricanes Ike, Gustav, Rita and Katrina. Dietrich et al. describe this in detail in a recent publication centered around the hindcast of Hurricane Gustav, which like Hurricane Ike made landfall in 2008 (Dietrich et al. 2011). UnSWAN and ADCIRC are coupled on a ten minute interval for this analysis.

Hurricane Ike simulations do not include tidal forcing at the mesh boundary. Accurate tidal forcing is computationally demanding and adds limited benefit to understanding the relative effects of SLR under various storm surge conditions. Rather than incorporating tidal forcing, each simulation assumes a constant water surface elevation as an initial condition, based on the appropriate SLR for each scenario, as was done for hypothetical storm simulations during the FIS study. Note that though including tides has limited benefit to an extreme event analysis such as this study, analysis of daily tides is beneficial to examining SLR impacts aside from extreme events. A dynamic sea level rise tidal analysis would better inform marsh tidal prism and hydroperiod, which are ultimately critical to analyzing potential changes to the marsh environment along the coast in models such as SLAMM.

The hardware platform used to simulate the ADCIRC model is a high-performance computing cluster. Parallel computing is commonly used for ADCIRC applications, as it’s highly scalable. For this project, the computational resource was the IBM High Performance Computing cluster, named "Stokes", located at the University of Central Florida. Stokes is a cluster of 83 Blades with Dual Xeon Quad-Core processors for a total of 664 cores (256 cores were utilized for each simulation) operating 3.0 GHz. Total memory is 1.6 TB RAM and communication is by 20Gbps Infiniband. The machine OS is Linux and the scripting language perl, the shell language bash, the Intel Fortran compiler, and the graphic package GMT all exist on the computer system. The software package GMT has been used to facilitate post-simulation graphical analysis of the solutions, including many of the graphics in this document.
3. Data Sources

The primary data sources for this study are topographic, bathymetric and land cover data that are applied to the ADCIRC mesh and surface characteristics files. All other ADCIRC inputs necessary for simulation, such as the Hurricane Ike assimilated winds, are setup identical to the FIS. The FEMA FIS study additionally supplied the TX2008 ADCIRC mesh. The TX2008 ADCIRC mesh was assembled by applying the most recent topographic and bathymetric surveys available, including statewide lidar, natural and USACE dredged channel surveys, and independent levee surveys conducted by county and city personnel. Lidar data was gathered and processed for Harris County in 2002 and in 2006 for Orange, Jefferson, Chambers, Galveston, Brazoria and Matagorda Counties. Bathymetric data was supplied by USACE Galveston and incorporated the most recent statewide surveys available from USACE, NOAA and other agencies. Further details are available in the 2011 FEMA FIS documentation. Elevation surveys were mapped to the ADCIRC mesh using grid scale averaging techniques.

SLAMM datasets for the initial conditions in 2004, and 2050 and 2100 scenarios were supplied by The Nature Conservancy (Warren Pinnacle Consulting 2011a, 2011b). SLAMM datasets used the land covers from the National Wetland Inventory (NWI; http://www.fws.gov/wetlands/). The SLAMM datasets assume a eustatic SLR of one meter by 2100. SLAMM data was utilized for this study in areas where the data are available. ADCIRC mesh areas outside of the SLAMM model domains applied C-CAP 2005 land cover data. The C-CAP data were downloaded from NOAA’s website.

Figures 7 through 9 exhibit land cover for the initial conditions in 2004 and the SLAMM scenarios for 2050 and 2100, respectively. Note that the SLAMM data are not available for the entire ADCIRC mesh domain. In areas that SLAMM data are not available, C-CAP data is applied to the surface characteristics file. C-CAP 2005 land cover data for Texas and Louisiana are displayed in Figure 10. C-CAP data is a static dataset and thus is identical for 2004, 2050 and 2100 scenarios. A combined SLAMM and C-CAP land cover dataset is created for each scenario. Table 1 outlines the Manning’s $n$ and $Z_0$ values assigned to each SLAMM land cover class. Similarly Table 2 outlines the Manning’s $n$ and $Z_0$ values for each C-CAP land cover class. Higher Manning’s $n$ and $Z_0$ values equate to increased bottom friction and wind reduction. These values were determined from values identified in literature and those outlined in the Texas FEMA FIS (USACE 2011, Chow 1959, Henderson 1966, Barnes 1967, Arcement and Schneider 1989, FEMA 2005). The exceptions
are SLAMM classes for developed dry land and undeveloped dry land. Due to the
spatial extent of these land classes, numerous C-CAP land cover types align with
these classes. To assign reasonable frictional parameters to these SLAMM classes,
C-CAP values shown in Table 2 were spatially averaged across the domain for both
developed dry land and undeveloped dry land. Spatial averaging and inspection of
the dominant C-CAP land cover classes for both SLAMM classes were used to
define the values shown in Table 1.
4. ADCIRC Model Setup

4.1 ADCIRC Mesh

The TX2004_TNC was constructed by maintaining the TX2008 mesh from approximately Freeport, TX to Lake Calcasieu, LA and reducing mesh resolution south of Freeport.

The 2050 and 2100 ADCIRC meshes were constructed by applying subsidence to the TX2004_TNC mesh. The Galveston Bay area SLAMM study applied a constant subsidence rate of 3.05 mm/yr throughout the entire Galveston Bay domain (Warren Pinnacle Consulting 2011b). For the Southern Jefferson County SLAMM analysis, a region wide constant subsidence of 4.25 mm/yr was applied (Warren Pinnacle Consulting 2011a). These subsidence rates were applied by lowering the ADCIRC mesh elevations by the appropriate subsidence amount in the area defined by each SLAMM model. For instance, the Galveston Bay area subsided 140.3 mm between 2004 and 2050. The resulting 2050 model elevations are shown in Figure 11. Figure 12 displays the areas and amount of subsidence between 2004 and 2050. Figure 13 and Figure 14 show similar mesh elevations and differences for the 2100 scenario.

4.2 Application of Land Cover

A combined land cover dataset for each scenario is created using the SLAMM and C-CAP data. The domain wide dataset is applied onto the ADCIRC nodes using a distance weighted mesh scale averaging function to define Manning’s $n$ and $Z_0$ values. Manning’s $n$ values are averaged based on immediately surrounding roughness values. Wind boundary layer re-adjustments, $Z_0$, depend upon roughness conditions upwind of the location because the wind boundary layer does not adjust to a new roughness instantaneously. Therefore, upwind wind reduction factors are computed for 12 compass directions by examining all roughness coefficients up to 6 miles away. Then the directional roughness used at each computational point within the mesh is based upon the existing wind direction, which is important for highly varying wind fields such as hurricanes.

The resulting Manning’s $n$ and $Z_0$ values for 2004, 2050 and 2100 conditions are shown in Figure 15 through Figure 29. The figures include absolute values and differences between 2004 and future conditions. Two of the 12 directional $Z_0$ parameters are shown for northerly and southerly winds. Note that the area of
change between 2004 $Z_0$ values and future values is highly dependent on the wind direction. Additionally, the figures reveal that the changes in land cover and the related changes in roughness values for 2100 are notably more substantial than those in 2050.

### 4.3 Eustatic Sea Level Rise

The computations are vertically referenced to NAVD88, which is a geodetic equipotential surface and therefore provides a sound reference for our computations when adjusted for the offset to local mean sea level (LMSL). The average offset between LMSL and NAVD88 for the study areas is 0.38 foot (USACE 2011). Annual sea surface variability in the Gulf of Mexico is significantly influenced by the thermal expansion of surface ocean waters and by other factors including coastal currents, riverine runoff, variability in salinity, seasonal prevailing winds, and atmospheric pressure. Long-term sea level variability has been quantified at various stations throughout the Gulf of Mexico by NOAA (2001, 2007). The increase in surface elevations is bi-modal with a rise in water levels in spring, a mid-summer decrease, a rise in later summer and fall, and finally a decrease in late fall and winter. The maximum mid-September to mid-October water level increase above the annual average is 0.50 foot at Galveston Pier 21 (94.7933W, 29.3100N). The combined adjustment from LMSL to NAVD88 and the annual sea surface variability in the study area during landfall of Hurricane Ike was approximately 0.906 feet (0.276 meters). Thus the initial water surface elevation (WSE) for the ADCIRC model is set to 0.276 meters NAVD88 for the 2004 scenario.

Eustatic SLR is accounted for in the 2050 and 2100 scenarios in the same manner that the SLAMM models account for SLR. **Figure 30** and **Table 3** summarize the SLR scenarios modeled by the TNC SLAMM Project. The middle curve, representing 1 meter of SLR by 2100 is the selected curve for this analysis. For this SLR scenario, the global SLR is 184.4 mm between 1990 and 2025. Similarly, the SLR for 2050 is estimated at 409.2 mm and 1000.0 mm for 2100. A linear interpolation between 1990 and 2025, assumes the SLR to be 73.8 mm in 2004. Therefore, the eustatic SLR for 2050 is 409.2 mm less 73.8 or 335.4 mm. The eustatic SLR for 2100 is 1000.0 mm less 73.8 mm or 926.2 mm.

The initial WSE in the ADCIRC model for the 2050 and 2100 scenarios is set to the initial WSE of 0.276 meters together with the eustatic SLR. The 2050 initial WSE is 0.612 meters and the 2100 initial WSE is set to 1.202 meters.
5. Results

5.1 Maximum Storm Surge Elevation

The simulation of Hurricane Ike for the base condition produced a peak surge of approximately 19 feet. Figure 31 shows the maximum surge pattern as derived as a maximum envelope of water (MEOW). A MEOW is the maximum storm surge elevation computed at any point during the hurricane and is used to understand maximum inundation patterns. The MEOW shows higher surge values east of the eye of the storm. This is expected due to stronger winds occurring east of the eye of the storm and the counterclockwise direction of the circulating winds during the hurricane.

ADCIRC and UnSWAN computations of Hurricane Ike have been thoroughly reviewed and published previously (USACE 2011). The FIS review included comparisons of ADCIRC simulation results to measured high water marks (HWM), wave measurements, and water surface gauge measurements. Because the model developed and used in this study has been derived from the previously validated FIS model, only two comparisons were performed to confirm the accuracy of the TX2004_TNC model. To make a direct comparison of the simulated maximum surge to the available HWM data, the value from the MEOW is extracted at each of the HWM locations (longitude, latitude). Figure 32 shows the locations of the HWMs distributed across the study region. In Figure 32, the markers are colored by the quality of match between the simulation and the HWMs. Note that the majority of markers are in the +/- one-foot range. The shaded white area represents the coverage of the SLAMM data. Figure 33 displays the same data as in Figure 32, but displays the data as a scatter plot. In Figure 33, a perfect match between simulation and data would lie along the solid black line. The solid red line is the trend line of the result and the dashed lines bracket the +/- two-foot difference range. The scatter in the data is largely between +/- two-foot range. Additionally, the general trend is quite good with a correlation coefficient of 0.86 and a slope of 0.98. Figure 34 provides an indication of how the model created in this study for The Nature Conservancy performs in comparison to the original FEMA-approved model. It can be seen that points inland from the coast have a very good match between the two models. However, there is a slight over-prediction in the five to eight foot surge range. This is due to differing model setups. The primary difference between the two setups are the wave models used, the lack of tides in The Nature Conservancy model and the land cover data source used to derive the friction coefficients. Regardless of the differing model setups, The Nature Conservancy model produces
accurate results that compare well to the measured data and is able to simulate Hurricane Ike much more efficiently than the FIS model.

The same Hurricane Ike meteorological forcing was applied to the future scenario models and the maximum surge was computed. The maximum surge for the 2050 result is shown in Figure 35 and the difference between the 2050 condition and the 2004 base condition is shown in Figure 36. Recall that for the 2050 scenario, the analyzed SLR value is 1.343 feet (0.402 m). Note that the increase in surge throughout the region varies from a minimum of approximately 1.3 feet offshore to a maximum of approximately 6 feet north of Interstate 10 above Trinity Bay and Lake Anahuac areas. The dark red regions around the inundation limits in Figure 36 show areas that are flooded in the future condition but were originally not flooded for the base condition. Areas that show an increase in maximum surge of more than 1.3 feet are typically bays and low lying topography inland from the coast or adjacent to marsh areas that degraded between 2004 and 2050. The exception is the region of peak surge north of High Island near the town of Winnie (see Figure 1 for location reference). This area near Winnie results in flooding depth increases of more than 1.3 feet because the strongest winds impact this area. More specifically, the area near Winnie is additionally impacted by the storm track itself.

The maximum surge for the 2100 result is shown in Figure 37 and the difference between the 2100 condition and the base condition is shown in Figure 38. Recall that for the 2100 scenario, the analyzed SLR value is 3.039 feet (0.926 m). Note that the increase in surge throughout the region varies from a minimum offshore to a maximum of approximately 8 feet north of Interstate 10 above Trinity Bay and Lake Anahuac. The dark red regions around the inundation limits show areas that are flooded in the 2100 condition but were originally not flooded for the initial condition in 2004. The nonlinear storm surge patterns seen in the 2050 comparison to 2004 are also exhibited in the 2100 scenario. Regions like Trinity Bay, near Lake Anahuac and Winnie exhibit flooding increases greater than the SLR value itself.

5.2 Analysis of Nonlinear SLR Effects

In order to further analyze patterns of nonlinear SLR impacts, relative surge amplification was plotted for both the 2050 and 2100 scenarios. Relative surge amplification for future scenarios is the factor increase in maximum surge from the base conditions, normalized by the SLR value. Amplification is the consequence of many factors, including site location, geometry, frictional characteristics, meteorological forcing, and the 2004 conditions storm surge elevations. Examining
nonlinearities in SLR related response is important in understanding the dynamic complexities of SLR in extreme events, particularly in identifying areas at the greatest risk. A static SLR analysis would be equivalent to adding a constant SLR value to the Hurricane Ike storm surge values modeled for 2004 conditions. However, the ADCIRC model dynamically calculates the many interdependent factors involved in a SLR analysis, making a fully dynamic analysis possible instead of a static SLR assumption.

**Figure 39** is a plot of relative surge amplification for the 2050 scenario and **Figure 40** is relative surge amplification for the 2100 scenario. In these images, the contour values show the factor of increase in maximum surge normalized by the SLR value analyzed in each case. For the difference in surge at geographic coordinates (x,y) defined as:

\[
 dz(x,y) = \text{surge\_future\_condition} - \text{surge\_2004},
\]

then **Figure 40** plots:

\[
 2100\_\text{relative\_surge\_amplification} = \frac{dz(x,y)}{(2100\_\text{initial\_WSE} - 2004\_\text{initial\_WSE})}
\]

or

\[
 2100\_\text{relative\_surge\_amplification} = \frac{dz(x,y)}{(1.2025 \text{ meter} - 0.2800 \text{ meters})}
\]

and similarly for the 2050 scenario. This way of looking at the data spatially demonstrates the factor in which the surge increase compares to the SLR amount. For regions far offshore, the increase in water level is exactly equal to the SLR increase, so the amplification factor is unity; a factor of unity is equivalent to a static SLR application at that specific location. Inland regions show that the increase in surge is greater than the addition of the SLR water increment by a factor of two or three. At the coast, the surge amplification factor is less than unity because relatively more water is propagating inland, thus the relative surge decreases immediately offshore. Comparison of **Figure 39** and **Figure 40** shows that the amplification factor decreases with greater SLR increment. For very large SLR increments, the amplification decreases because the additional water volume contribution from the SLR increment becomes more dominant. Conversely, for lower SLR increments, the amplification factor increases. For this region and for this storm event, the relative
amplification is greatest in the northern portions of Trinity Bay where the amplification is over two. The northern portion of Trinity Bay experiences amplification because of the storm track, the bay's proximity to the coast, and the physical parameters of the bay such as size and depth. However inland (generally north) from Trinity Bay, the amplification increases to nearly a factor of three due to the proximity to Trinity Bay, as well as the marsh degradation projected by the SLAMM model. These amplification results are consistent with previous estimates of the effect of SLR on coastal surge along the Gulf of Mexico (Smith et al. 2010, Atkinson et al. 2007) in which the peak increase is a factor of two or three times the SLR amount. Thus, simply adding the SLR amount to present day surge maxima will under-predict the future storm surge.

5.3 Inundation Limits

In addition to the increased water surface elevation that may occur in the future, these results also permit consideration of the additional surface area that may be flooded in the future. The maximum surge plots provide an indication of the extents of inundation for each of the scenarios. Likewise, the plots of difference in maximum storm surge between future and base scenarios can provide an estimate of the increase in flooded area that may be expected under the future scenarios. Note that both Figure 36 and Figure 38 reveal dark red regions around the edges of the inundation limits. As stated earlier, these are regions that are newly flooded in the future due to SLR and the associated marsh degradation. By summing the individual areas of all of the ADCIRC finite elements that are not flooded in the base simulation but flooded in either of the future simulations, an estimate is derived for the total increase in flooded area. The 2050 simulation predicts an addition of 246 square miles of inundation. The 2100 simulation predicts an increase of 689 square miles, which is nearly three times that of the 2050 scenario. Table 4 provides a summary of the increase.

The distribution of the future flooded regions tends to follow the water line of the peak surge envelope as incremental increases in surge push water slightly further onshore. Low lying regions will tend to experience more inundation than regions of steeper topography gradients. Additionally, areas that demonstrate high surge amplification factors and areas impacted by the strongest winds also reflect relatively larger changes in inundation limits. Therefore, these areas will vary with varying meteorological conditions. A better understanding of these complex relationships requires further simulations with variable SLR and meteorological scenarios.
However, the simulation of even one storm, such as Hurricane Ike, shows the importance of a dynamic SLR analysis rather than a static SLR analysis.

Another way to visualize the increased extents of inundation is to superimpose transparent polygons that cover the wetted extents of the three scenarios. In Figure 41, the blue polygon shows the 2004 inundation limits, the yellow polygon the 2050 inundation limits, and the red polygon the 2100 inundation limits. Note that the colors in the legend are slightly different to those in the map due to the transparency of overlapping colors. Regardless, it is possible to clearly see where the extent of flooding increases. Consideration of these graphics can reveal which regions are at more risk to increased flooding for the future scenario and meteorological forcing explored in this study.

5.4 Marsh Loss and Subsidence Sensitivity Test

A sensitivity test was performed to explore the relative importance of bottom friction, subsidence, and the increase in sea level in the ADCIRC model. To test this, a Hurricane Ike simulation was run with the subsided 2100 topography and the 2100 friction characteristics reflecting the 2100 SLAMM scenario marshes, but with the 2004 initial sea level. The maximum surge is shown in Figure 42 and the difference in surge from the 2004 base scenario is show in Figure 43. Note that the increase in surge for this scenario is much less than the maximum surge obtained when using the full 2100 scenario (including the 1.2025 m initial water surface) shown in Figure 37. The implication is that the combined contribution of frictional changes and subsidence can be less than the contribution to peak surge from an increase in sea level. Nevertheless, as seen in Figure 43 the changes in peak storm surge are over one foot in many areas and particularly high north of Lake Anahuac where marsh degradation was notable in the SLAMM output scenario. Similar changes in surge response can be seen adjacent to East Bay, where marsh degradation is also notable.

Thus, as expected, changes in marsh characteristics and marsh loss impact storm surge. A reduced marsh area footprint can reduce storm surge and wave attenuation. In order to better understand the surge and wave attenuation potential of marshes in this area, further studies are required to isolate critical parameters during analysis, such as only analyzing changes in marsh frictional parameters rather than the combined analyses of marsh changes and subsidence. Additionally, numerous meteorological conditions must be analyzed. Inspection of Figure 43 supports further analysis to discern the influence of each model parameter. For
instance, though areas such as Lake Anahuac and East Bay show increased storm surge for the 2100 sensitivity test, other areas that are not adjacent to notable marsh degradation show similar increases in storm surge. Examples are the area between High Island and Port Arthur and northern Galveston Bay. Both of these areas are believed to show increases in storm surge due to subsidence, high winds, local geometries and location relative to landfall of Hurricane Ike. East Bay and Lake Anahuac area are influenced by the same parameters, thus limiting the analysis to understand the attenuation effects of marshes alone.

5.5 Water Surface Elevation Time Series

Storm surge time series data for all four simulations was analyzed. Over two hundred locations were plotted and inspected, twelve of which are included in this analysis. Table 5 lists the twelve station locations which are shown in Figure 44. The twelve points were selected due to their location near population centers or marsh areas that changed between SLAMM base and future conditions. Figure 45 shows the two hundred locations inspected. Figure 46 and Figure 47 depict the storm surge hydrographs for the twelve locations. Hydrographs represent water surface elevations at locations only during model computation, which occurs when the water surface elevation is higher than the nodal elevation. For locations such as station 93 near Port Arthur, the hydrograph output duration for all scenarios is shorter than other locations due to the higher elevation represented in the ADCIRC model at that location. Therefore the duration of inundation at that location is less than other locations. Additionally, it should be noted that due to subsidence, nodal elevations vary between scenarios which results in longer hydrograph model output for future scenarios compared to the base scenario.

Station 34 near Freeport and station 200 near the city of Galveston show a difference in response that is dominated by the SLR component itself, rather than marsh loss and subsidence. This is because both locations are west of the eye of Hurricane Ike and adjacent to areas of limited change in frictional parameters (i.e. limited marsh change). Areas west of the eye of the hurricane have lower surge elevations that those east of the eye, due to the counterclockwise wind direction. Additionally, locations west of the eye typically experience the strongest winds in the offshore or shore parallel directions. Thus, future 2050 and 2100 conditions exhibit higher surge values than 2004 by approximately the respective SLR values. The 2100 sensitivity study without SLR renders storm surge values slightly higher to those of the 2004 base case.
Note that at both station 34 and station 200, the duration of high surge is as much as 1.5 to 2 times longer for 2100 than other scenarios. The longer duration of high storm surge values for the 2100 scenario is common amongst nearly all of the 200 locations investigated. The change in inundation duration varies spatially based on station location, model elevations, base case storm surge response and the SLR value analyzed. Changes in inundation duration are important to understand since the resulting damage of a given storm surge event can be due to the duration of inundation in some cases. For instance, where storm surge overtops roads, barrier islands and levees, the economic impacts of the storm surge on the protected side are commonly directly related to the volumes of water overtopping. Overtopping volumes are a function of overtopping duration. It should be noted that a damage assessment taking into account overtopping duration is not possible without taking a dynamic approach to assessing SLR, such as the approach outlined in this study.

Stations 93, 95 and 97 exhibit relative storm surge changes similar to stations 34 and 200. These three stations are close to the coast, near Port Arthur, on Bolivar Peninsula and east of High Island respectively. Based on the amplification factor in Figure 39 and Figure 40, this is to be expected. Note that the 2100 sensitivity test with 2004 water levels renders the most similar time series as the 2004 base scenario near High Island. This is due to the locations proximity to the coast and the limited frictional parameter changes implemented nearby.

Inspection of locations as groups is also very informative. For instance, variance in amplification factors (shown in Figure 39 and Figure 40) along the west coast of Galveston Bay can be further examined by inspecting locations at Clear Lake and the Houston Ship Canal (Note that the increased WSE for future scenarios at location 156, Houston Ship Canal, at approximately 9:00 PM UTC on 9/13 is a numerical oscillation rather than a real world response and should be ignored for this analysis). A similar amplification factor relationship can be better understood by studying locations on either side of Bolivar Peninsula. Hydrograph plots for stations 72, 95, 40 and 80 show trends in amplification factor and sensitivity to friction and subsidence from the Gulf of Mexico side of Bolivar Peninsula to a location north of East Bay. One noteworthy detail is the change in the 2100 sensitivity study hydrograph between East Bay at station 40 and location 80 north of East Bay. Due to the notable change in marsh characteristics north of East Bay, storm surge increases in the 2100 sensitivity study at a higher rate than the 2050 SLR analysis. In this case, the combined impact of marsh degradation and subsidence has nearly as significant of an effect on storm surge on SLR alone. A similar relationship occurs at the locations near Lake Anahuac at the northern end of Trinity Bay.
6. Limitations

The results must be qualified by noting the following two limitations of this study. First, only one meteorological forcing and one SLR increment has been considered in this sensitivity test. The Hurricane Ike scenario applied in this study is a very large storm which generates a large surge and thus deep water throughout much of the region. As the water column gets deeper, the relative importance of bottom friction decreases. Since different storm events will produce different surge responses, the contribution of friction to the force balance will also vary. Thus, while friction does not appear to be a dominant contribution for this large slow storm, a smaller, fast moving storm may be more influenced by frictional variations. A comprehensive study of storm surge flooding for future scenarios would require simulations of a larger number of storms which cover a spectrum of storm characteristics.

Second, the frictional characteristics for the future scenarios have been derived from the SLAMM land cover classes. While SLAMM captures many of the details of marsh vegetation types at the coast, there are very few land classes in the inland region. As a consequence, future friction scenarios for inland areas are nearly identical with the exception of marsh changes in the regions near the coast. SLAMM does not account for tree and vegetation mortality due to increased salinity of groundwater and other climatic effects. The inland penetration of surge can be quite extensive, thus may be affected by vegetation changes inland from the coast. Thus, without characterizing changes away from the coast and without exploring the influence of inland land cover changes, the SLAMM forecast may under-predict the effect of vegetation changes on peak surge.
7. Conclusions

The simulation of the four current and future landscape scenarios under Hurricane Ike conditions has produced data insightful to qualitatively understanding the impacts on storm surge due to sea level rise, subsidence and marsh degradation. The resulting 2050 and 2100 storm surge scenarios are insightful both in terms of understanding the change in storm surge conditions due to various ADCIRC model input modifications and understanding regions that will be most greatly impacted by storm surge for future SLR scenarios under the given meteorological conditions.

Some key findings from this study are:

- The Nature Conservancy ADCIRC model produces accurate results that compare well to the measured data and the FIS mode.

- The Nature Conservancy ADCIRC model is able to simulate Hurricane Ike more efficiently than the FIS model due to the reduced domain and analysis without tides.

- The SLAMM model output can be accurately mapped to the ADCIRC model. Changes in land cover represented in the SLAMM model output and the related changes in roughness values in the ADCIRC model are more substantial in 2050 than 2100.

- The difference between 2004 and future conditions storm surge response varies nonlinearly due to sea level rise, subsidence and marsh degradation.

- Relative surge amplification for future scenarios can be as high as three for Hurricane Ike conditions in the study area.

- Some areas, such as north of Trinity Bay near Lake Anahuac, demonstrate notable changes in the water surface elevation due to the combined contribution of frictional changes and subsidence. Other areas, such as west of the eye of the storm, show that the changes in water surface elevation are similar to the increase in sea level, reflecting a limited change in surge due to subsidence and marsh loss.
• The marsh degradation sensitivity study qualitatively demonstrated that changes in marsh conditions and subsidence along the coast do impact storm surge attenuation in some areas for this scenario.

• The simulation of even one storm, such as Hurricane Ike, shows the importance of a dynamic SLR analysis rather than a static SLR analysis. Simply adding the SLR amount to present day surge maxima will underpredict the future storm surge in many areas.

This study is a worthwhile first step towards understanding the potential impacts of sea level rise, subsidence and marsh degradation along the Galveston Bay area and Jefferson County coast in Texas. Though the analysis was limited to a four simulations, the dynamic nature of sea level rise in extreme events is clearly demonstrated in the model results. Given the dynamic and complicated nature of sea level rise during extreme events, as well as the associated adverse environmental and economic impacts, further analysis is recommended in this study area.
8. Recommendations

Further simulations are recommended to quantitatively analyze the impacts of the model variables analyzed as part of this study. A detailed examination incorporating numerous meteorological conditions is necessary to better understand the spatially varying impacts of sea level rise, subsidence, and marsh change during extreme events. Each model consideration, such as the influence of marshes on storm surge, must be systematically studied by varying parameters in the ADCIRC model.

The recommended study would require isolating model changes in order to understand the impact of changing an individual model variable. This would require analysis that diverges from the methodology of this study, which largely incorporated all SLAMM output to best represent a possible future scenario. Rather than incorporating sea level rise, subsidence and marsh changes directly from SLAMM output, it is recommended that SLAMM output or similar studies, be used as a guide to establishing realistic testing guidelines. Using these guidelines, each variable would be individually analyzed with all other variables held constant.

Additionally, beyond analyzing extreme events such as Hurricane Ike, it is recommended that daily tides are analyzed independent of storm conditions. SLAMM incorporates a static sea level rise assumption. However, as shown in this study, hydrodynamics in the area are quite dynamic and spatially varying. Thus a tidal analysis applying ADCIRC is expected to be notably different than a static sea level rise tidal assumption would render. Though this study was focused on Hurricane Ike, the same hydrodynamic principles are applicable in the analysis of daily tides. A dynamic sea level rise tidal analysis would better inform marsh hydroperiod, which are ultimately critical to analyzing potential changes to the marsh environment along the coast in models such as SLAMM.
9. References


ADCIRC Based Storm Surge Analysis of Sea Level Rise in the Galveston Bay and Jefferson County Area in Texas

Tables
Table 1  Manning’s $n$ and $Z_0$ Values for SLAMM Land Cover Classes

<table>
<thead>
<tr>
<th>Class</th>
<th>Class Name</th>
<th>Manning’s $n$</th>
<th>$Z_0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Developed Dry Land</td>
<td>0.120</td>
<td>0.500</td>
</tr>
<tr>
<td>2</td>
<td>Undeveloped Dry Land</td>
<td>0.070</td>
<td>0.400</td>
</tr>
<tr>
<td>3</td>
<td>Swamp</td>
<td>0.100</td>
<td>0.250</td>
</tr>
<tr>
<td>4</td>
<td>Cypress Swamp</td>
<td>0.100</td>
<td>0.550</td>
</tr>
<tr>
<td>5</td>
<td>Inland Fresh Marsh</td>
<td>0.070</td>
<td>0.110</td>
</tr>
<tr>
<td>6</td>
<td>Tidal Fresh Marsh</td>
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<td>0.450</td>
</tr>
<tr>
<td>7</td>
<td>Transitional Salt Marsh</td>
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<td>0.090</td>
</tr>
<tr>
<td>8</td>
<td>Mangrove</td>
<td>0.060</td>
<td>0.200</td>
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<tr>
<td>10</td>
<td>Estuarine Beach</td>
<td>0.035</td>
<td>0.090</td>
</tr>
<tr>
<td>11</td>
<td>Tidal Flat</td>
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<td>0.110</td>
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<tr>
<td>12</td>
<td>Ocean Beach</td>
<td>0.030</td>
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<tr>
<td>15</td>
<td>Inland Open Water</td>
<td>0.025</td>
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<tr>
<td>16</td>
<td>Riverine Open Water</td>
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<td>0.001</td>
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<tr>
<td>17</td>
<td>Estuarine Water</td>
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<td>0.001</td>
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<td>Open Ocean</td>
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<td>0.001</td>
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<td>20</td>
<td>Irregularly Flooded Marsh</td>
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<td>0.110</td>
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<td>22</td>
<td>Inland Shore</td>
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<tr>
<td>23</td>
<td>Tidal Swamp</td>
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<td>0.250</td>
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Table 2  Manning’s $n$ and $Z_0$ Values for C-CAP Land Cover Classes

<table>
<thead>
<tr>
<th>Class</th>
<th>Class Name</th>
<th>Manning’s $n$</th>
<th>$Z_0$</th>
</tr>
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<tbody>
<tr>
<td>2</td>
<td>High Intensity Developed</td>
<td>0.120</td>
<td>0.500</td>
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<td>3</td>
<td>Medium Intensity Developed</td>
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<td>Cultivated Land</td>
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<td>Pasture/Hay</td>
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<td>0.060</td>
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<td>8</td>
<td>Grassland</td>
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<td>Deciduous Forest</td>
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<td>Evergreen Forest</td>
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<td>Mixed Forest</td>
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<td>Scrub/Shrub</td>
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<td>Palustrine Emergent Wetland</td>
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<td>Estuarine Forested Wetland</td>
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<td>17</td>
<td>Estuarine Scrub/Shrub Wetland</td>
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<td>Unconsolidated Shore</td>
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Table 3  SLAMM Sea Level Rise Scenarios (mm)

<table>
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<tr>
<th></th>
<th>A1B- Max</th>
<th>A1B- Mean</th>
<th>1 meter</th>
<th>1.5 meters</th>
<th>2 meters</th>
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<tbody>
<tr>
<td>1990</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
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<tr>
<td>2025</td>
<td>128</td>
<td>76</td>
<td>184.4</td>
<td>276.7</td>
<td>368.9</td>
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<tr>
<td>2050</td>
<td>284</td>
<td>167</td>
<td>409.2</td>
<td>613.8</td>
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<tr>
<td>2075</td>
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<td>278.5</td>
<td>698.1</td>
<td>1047.2</td>
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<tr>
<td>2100</td>
<td>694</td>
<td>387</td>
<td>1000.0</td>
<td>1500.0</td>
<td>2000.0</td>
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</table>

Note: The A1B-Max and A1B-Mean are Intergovernmental Panel on Climate Change scenarios applied by the SLAMM model (Warren Pinnacle Consulting 2011a, 2011b).

Table 4  Increase in Inundated Area for Future Scenarios Under Hurricane Ike Conditions

<table>
<thead>
<tr>
<th>SLR Scenario</th>
<th>Increase in Flooded Area</th>
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<tr>
<td></td>
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<td>2050</td>
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<td>2100</td>
<td>689</td>
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Table 5  Storm Surge Time Series Output of Twelve Selected Locations

<table>
<thead>
<tr>
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ADCIRC Based Storm Surge Analysis of Sea Level Rise in the Galveston Bay and Jefferson County Area in Texas

Figures
Figure 1: Location Map of the Combined Galveston Bay and Jefferson County Study Area

Note: The SLAMM boundaries are shaded blue. The Hurricane Ike track is shown as a red line.
Figure 2: ADCIRC Model Schematic

Note: Water current and wave condition output data are not part of the scope of work of this study.
Figure 3: ADCIRC Mesh Domain and Topographic Contours (feet NAVD88)

Note: The mesh domain includes the western North Atlantic, Caribbean Sea and Gulf of Mexico.
Figure 4: ADCIRC Mesh Topographic Contours (feet NAVD88)

Note: The image domain outlines the Gulf of Mexico, with the study area in the upper left corner.
Figure 5: ADCIRC Mesh with 2004 Topographic Contours (feet NAVD88) for the Study Domain

Note: Brown lines denote internal boundaries to represent features such as the Port Arthur levee, Freeport levee, and the Texas City levee.
Figure 6: ADCIRC Mesh Resolution for the Study Domain

Note: Cool colors are high resolution and warmer colors denote coarser resolution. Contours represent spatial resolution in feet. Brown lines denote internal boundaries to represent features such as the Port Arthur levee, Freeport levee, and the Texas City levee.
Figure 7: 2004 Initial Land Cover Data Used By SLAMM (based on NWI) for the Galveston Bay Area, Including Jefferson County, TX

Note: The black line denotes the ADCIRC model boundary.
Figure 8: SLAMM 2050 Scenario for the Galveston Bay Area, Including Jefferson County, TX

Note: The black line denotes the ADCIRC model boundary
Figure 9: SLAMM 2100 Scenario for the Galveston Bay Area, Including Jefferson County, TX

Note: The black line denotes the ADCIRC model boundary.
Figure 10: C-CAP Land Cover Data

Note: The black line denotes the ADCIRC model boundary.
ADCIRC Mesh with 2050 Topographic Contours (feet NAVD88) for the Study Domain

Note: Mesh topography incorporates constant subsidence. Brown lines denote internal boundaries to represent features such as the Port Arthur levee, Freeport levee, and the Texas City levee.
Figure 12: Differences due to local subsidence in ADCIRC Mesh Topography for 2050 and 2004 Conditions

Note: Brown lines denote internal boundaries to represent features such as the Port Arthur levee, Freeport levee, and the Texas City levee. Black lines depict the coastline.
Figure 13: ADCIRC Mesh with 2100 Topographic Contours (feet NAVD88) for the Study Domain

Note: Mesh topography incorporates constant subsidence. Brown lines denote internal boundaries to represent features such as the Port Arthur levee, Freeport levee, and the Texas City levee.
Figure 14: Differences due to local subsidence in ADCIRC Mesh Topography for 2100 and 2004 Conditions

Note: Brown lines denote internal boundaries to represent features such as the Port Arthur levee, Freeport levee, and the Texas City levee. Black lines depict the coastline.
Figure 15: 2004 Conditions ADCIRC Nodal Manning’s $n$ Values for the Study Domain

Note: Brown lines denote internal boundaries to represent features such as the Port Arthur levee, Freeport levee, and the Texas City levee.
Figure 16: 2004 Conditions ADCIRC Nodal $Z_0$ Values in the Study Domain for Southerly Winds

Note: Brown lines denote internal boundaries to represent features such as the Port Arthur levee, Freeport levee, and the Texas City levee. The coastline is shown in white.
Figure 17: 2004 Conditions ADCIRC Nodal $Z_0$ Values in the Study Domain for Northerly Winds

Note: Brown lines denote internal boundaries to represent features such as the Port Arthur levee, Freeport levee, and the Texas City levee. The coastline is shown in white.
Figure 18: 2050 Conditions ADCIRC Nodal Manning’s n Values for the Study Domain

Note: Brown lines denote internal boundaries to represent features such as the Port Arthur levee, Freeport levee, and the Texas City levee.
Figure 19: 2050 Conditions ADCIRC Nodal $Z_0$ Values in the Study Domain for Southerly Winds

Note: Brown lines denote internal boundaries to represent features such as the Port Arthur levee, Freeport levee, and Texas City levee. The coastline is shown in white.
Figure 20: 2050 Conditions ADCIRC Nodal $Z_0$ Values in the Study Domain for Northerly Winds

Note: Brown lines denote internal boundaries to represent features such as the Port Arthur levee, Freeport levee, and Texas City levee. The coastline is shown in white.
Figure 21: Difference between 2004 and 2050 Conditions ADCIRC Nodal Manning’s $n$ Values for the Study Domain

Note: Cool colors denote a reduction in friction and warm colors an increase in friction. Brown lines denote internal boundaries to represent features such as the Port Arthur levee, Freeport levee, and Texas City levee. The coastline is shown in black.
Figure 22: Difference between 2004 and 2050 Conditions ADCIRC Nodal $Z_0$
Values in the Study Domain for Southerly Winds

Note: Cool colors denote a reduction in friction and warm colors an increase in roughness length. Brown lines denote internal boundaries to represent features such as the Port Arthur levee, Freeport levee, and Texas City levee. The coastline is shown in black.
Figure 23: Difference between 2004 and 2050 Conditions ADCIRC Nodal $Z_0$

Values in the Study Domain for Northerly Winds

Note: Cool colors denote a reduction in friction and warm colors an increase in roughness length. Brown lines denote internal boundaries to represent features such as the Port Arthur levee, Freeport levee, and Texas City levee. The coastline is shown in black.
Figure 24: 2100 Conditions ADCIRC Nodal Manning’s n Values for the Study Domain

Note: Brown lines denote internal boundaries to represent features such as the Port Arthur levee, Freeport levee, and Texas City levee.
Figure 25: 2100 Conditions ADCIRC Nodal $Z_0$ Values in the Study Domain for Southerly Winds

Note: Brown lines denote internal boundaries to represent features such as the Port Arthur levee, Freeport levee, and Texas City levee. The coastline is shown in white.
Figure 26: 2100 Conditions ADCIRC Nodal Z₀ Values in the Study Domain for Northerly Winds

Note: Brown lines denote internal boundaries to represent features such as the Port Arthur levee, Freeport levee, and Texas City levee. The coastline is shown in white.
Figure 27: Difference between 2004 and 2100 Conditions ADCIRC Nodal Manning’s $n$ Values for the Study Domain

Note: Cool colors denote a reduction in friction and warm colors an increase in friction. Brown lines denote internal boundaries to represent features such as the Port Arthur levee, Freeport levee, and Texas City levee. The coastline is shown in black.
Figure 28: Difference between 2004 and 2100 Conditions ADCIRC Nodal $Z_0$ Values in the Study Domain for Southerly Winds

Note: Cool colors denote a reduction in friction and warm colors an increase in roughness length. Brown lines denote internal boundaries to represent features such as the Port Arthur levee, Freeport levee, and Texas City levee. The coastline is shown in black.
Figure 29: Difference between 2004 and 2100 Conditions ADCIRC Nodal $z_0$ Values in the Study Domain for Northerly Winds

Note:  Cool colors denote a reduction in friction and warm colors an increase in roughness length. Brown lines denote internal boundaries to represent features such as the Port Arthur levee, Freeport levee, and Texas City levee. The coastline is shown in black.
Figure 30: Summary of SLR Scenarios Utilized by the SLAMM Model
Figure 31: Maximum Storm Surge Elevation Contours (feet NAVD88) for Hurricane Ike for 2004 Model Conditions

Note: Brown lines denote internal boundaries to represent features such as the Port Arthur levee, Freeport levee, Texas City levee and the Texas City dike. The coastline is shown in white. Hurricane Ike track in black.
Figure 32: Location of Measured High Water Marks in the Study Area for Hurricane Ike

Note: The markers are colored according to the difference between measured and computed value. Positive implies over-prediction, negative is under-prediction.
Figure 33: Comparison of Computed ADCIRC Maximum to Measured High Water Marks for Hurricane Ike, Initial Conditions
Figure 34: Comparison of Hurricane Ike Storm Surge Simulation Results from the New Nature Conservancy ADCIRC Model and the Original FEMA ADCIRC Model
Figure 35: Maximum Storm Surge Elevation Contours (feet NAVD88) for Hurricane Ike for 2050 Model Scenario

Note: Brown lines denote internal boundaries to represent features such as the Port Arthur levee, Freeport levee, Texas City levee and the Texas City dike. The coastline is shown in white. Hurricane Ike track in black.
Figure 36: The Difference Between 2050 Maximum Storm Surge Elevation and 2004 Maximum Storm Surge Elevation for Hurricane Ike

Note: Brown lines denote internal boundaries to represent features such as the Port Arthur levee, Freeport levee, and Texas City levee. The coastline is shown in black. Hurricane Ike track in black.
Figure 37: Maximum Storm Surge Elevation Contours (feet NAVD88) for Hurricane Ike for 2100 Model Conditions

Note: Brown lines denote internal boundaries to represent features such as the Port Arthur levee, Freeport levee, Texas City levee and the Texas City dike. The coastline is shown in white. Hurricane Ike track in black.
Figure 38: The Difference Between 2100 Maximum Storm Surge Elevation and 2004 Maximum Storm Surge Elevation for Hurricane Ike

Note: Brown lines denote internal boundaries to represent features such as the Port Arthur levee, Freeport levee, and Texas City levee. The coastline is shown in black. Hurricane Ike track in black.
Figure 39: Relative Surge Amplification for the 2050 Scenario

Note: The coastline is shown in black. The surge increase is normalized by the SLR increment. The scale is unitless. Hurricane Ike track in red.
Figure 40: Relative Surge Amplification for the 2100 Scenario

Note: The coastline is shown in black. The surge increase is normalized by the SLR increment. The scale is unitless. Hurricane Ike track in red.
Figure 41: Plot of the Inundation Extents for the Three Scenarios
Figure 42: Maximum Storm Surge Elevation Contours (feet NAVD88) for Hurricane Ike for a Sensitivity Test using the Subsided Topography and Frictional Characteristics of the 2100 Scenario and a 2004 Sea Level Value

Note: Brown lines denote internal boundaries to represent features such as the Port Arthur levee, Freeport levee, Texas City levee and the Texas City dike. The coastline is shown in white. Hurricane Ike track in black.
Figure 43: Increase in Peak Surge for the Sensitivity Test

Note: Brown lines denote internal boundaries to represent features such as the Port Arthur levee, Freeport levee, and Texas City levee. The coastline is shown in black. Hurricane Ike track in red.
Figure 44: Map Outlining Twelve Locations where Water Surface Elevation Time Series are Analyzed for the Various SLR Scenarios
Figure 45: Map Outlining Two Hundred Locations where Water Surface Elevation Time Series are Analyzed for the Various SLR Scenarios
Figure 46: Water Surface Elevation Time Series for Six Locations
Figure 47: Water Surface Elevation Time Series for Six Locations