ADCIRC Based Storm Surge Analysis of Sea Level Rise in Grand Bay

December 20, 2011
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**ACRONYMS AND ABBREVIATIONS**

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<tr>
<td>ADCIRC</td>
<td>ADvanced CIRCulation</td>
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<tr>
<td>C-CAP</td>
<td>Coastal Change Analysis Program</td>
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<td>FEMA</td>
<td>Federal Emergency Management Agency</td>
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<td>FIS</td>
<td>flood insurance study</td>
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<td>HRD</td>
<td>Hurricane Research Division</td>
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<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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<td>km</td>
<td>kilometer</td>
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<tr>
<td>LMSL</td>
<td>local mean sea level</td>
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<td>MEOW</td>
<td>maximum envelope of water</td>
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<td>m</td>
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<td>mi</td>
<td>mile</td>
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<td>mm</td>
<td>millimeter</td>
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<td>mph</td>
<td>miles per hour</td>
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<td>NERR</td>
<td>National Estuarine Research Reserve</td>
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<td>NLCD</td>
<td>National Land Cover Dataset</td>
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<td>NOAA</td>
<td>National Oceanic and Atmospheric Administration</td>
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<td>NWFWMD</td>
<td>Northwest Florida Water Management District</td>
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<td>NWI</td>
<td>National Wetland Inventory</td>
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<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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<td>SLR</td>
<td>sea level rise</td>
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<tr>
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<tr>
<td>TNC</td>
<td>The Nature Conservancy</td>
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<tr>
<td>SWAN</td>
<td>Simulating WAVes Near-shore</td>
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<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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<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, scientist 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 Grand Bay National Estuarine Research Reserve (NERR) and National Wildlife Refuge in Mississippi and Alabama (Warren Pinnacle Consulting 2011). The SLAMM analyses provided forecasts of future Grand Bay area marsh landscapes under various potential SLR scenarios through the year 2100.

The intent of this project is to utilize the SLAMM model output to analyze the effects of future landscapes and SLR on storm surge. Future scenarios include changes in land cover type and coastal subsidence in the area. 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 2011). 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 2009 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 Katrina 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 Katrina is well documented and critical data necessary to hindcast a hurricane, such as highly accurate wind and pressures fields, are readily available. Hurricane Katrina made its first landfall as a Category 3 hurricane near Buras, Louisiana at approximately 11:00 AM UTC. Katrina made a second landfall near the Mississippi and Louisiana border at approximately 3:00 PM UTC on August 29, 2005. Winds reached over 170 miles per hour (mph) in the Gulf of Mexico, while the Louisiana and Mississippi coast incurred sustained winds of over 120 mph rendering storm surge of over 30 feet in some locations in Mississippi. Hurricane Katrina greatly impacted Gulf Coast communities from Louisiana to Florida, causing widespread flooding, immense economic damage and loss of life. Hurricane Katrina is one of the most devastating natural disasters in United States history. A location map of the study area is shown if Figure 1. The path of Hurricane Katrina and the extents of the SLAMM models are also included. Hurricane Katrina center track is approximately 74 mi (118 km) from Grand Bay NERR. 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 Florida flood insurance study (FIS) conducted by the Northwest Florida Water Management District (NWFWMD) and the Federal Emergency Management Agency (FEMA) in the Big Bend region of Florida (Atkinson et al. 2011, Salisbury et al. 2011, Coggin et al. 2011, Gangai et al. 2011, Toro et al. 2011). A FIS is currently ongoing in the Panhandle of Florida and Alabama, including the Grand Bay area, applying a similar approach as the Big Bend FIS study. As part of the Panhandle FIS, a system of coupled models, ADCIRC and Simulating WAVes Nears Nearshore (SWAN), were used to simulate storm surge flooding for a large number of hurricane scenarios. The results of the computer models will be used to derive the statistical frequency of inundation for the coastal counties of the Florida Panhandle and Alabama. The skill of the model was established through the simulation of the waves and surge for Hurricanes Katrina (2005), Ivan (2004), Dennis (2005), Georges (1998), and Opal (1995). Hurricane Katrina was hindcasted with a high level of skill in the Panhandle FIS.

This study is able to build from the FIS by extending the analysis of Hurricane Katrina 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 same ADCIRC model version applied for the FIS was applied for this study.

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 natural ridges, 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 (Coggin et al. 2011).

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 coastal highways. 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 Panhandle FIS was applied for this study. All mesh elevations are referenced to a vertical datum: NAVD88. Figure 3 displays the mesh domain of the ADCIRC 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 overland. 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 ADCIRC computational nodes reside in coastal Florida, Alabama and Mississippi.
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. The extents of the ADCIRC domain shown in Figure 5 are intended to define only the areas that will be wetted during storm surge events. Thus the ADCIRC model domain contains areas that are hydraulically connected to the Gulf of Mexico coast and have topographic values lower than approximately twelve meters NAVD88. Study area mesh resolution is depicted in Figure 6. Note that some critical areas, such as the study area, are highly resolved, while other areas are more coarsely resolved. Focusing resolution is a means to reduce computational cost, similar to strategically defining the model domain.

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 (Coggin et al. 2011, Atkinson et al. 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 highways 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 to 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 SWAN models then use the nodal attribute information to resist flow, attenuate waves, and dynamically adjust wind speeds during a storm surge event. The Panhandle FIS applied Manning’s and $Z_0$ derived from the Coastal Change Analysis Program (C-CAP; http://www.csc.noaa.gov/digitalcoast/data/ccapregional/). For this study, SLAMM output data was applied where available and supplemented by C-CAP data outside of the SLAMM domain.

Assimilated Hurricane Katrina wind fields were coupled with the ADCIRC hydrodynamic model for this study. Katrina 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 refined by the available direct wind measurements using Interactive Objective Kinematic Analysis (IOKA)System (Cox et al. 1995, Cox and Cardone 2000) developed by Oceanweather, Inc. (OWI). 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.
For this analysis, ADCIRC was coupled with the structured SWAN wave model output applied for the Panhandle FIS study. SWAN and ADCIRC are coupled on a ten minute interval.

Hurricane Katrina 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 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 Katrina assimilated winds, are setup identical to the FIS. The FEMA FIS study additionally supplied the ADCIRC mesh. The ADCIRC mesh was assembled by applying the most recent topographic and bathymetric surveys available, including statewide lidar and natural and dredged channel surveys. Lidar data was gathered and processed for the Mississippi, Alabama and Florida Panhandle region in various years from 2002 to 2010. Bathymetric data was supplied by the NWFWMD and incorporated the most recent statewide surveys available from NWFWMD, USACE, NOAA and other agencies. Further details are available in the FEMA FIS documentation (Coggin et al. 2011).

SLAMM datasets for the initial conditions in 2009, and 2050 and 2100 scenarios were supplied by The Nature Conservancy (Warren Pinnacle Consulting 2011). 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 2009 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 the study area are displayed in Figure 10. C-CAP data is a static dataset and thus is identical for 2009, 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 Panhandle FEMA FIS (Atkinson et al. 2011, Chow 1959, Henderson 1966, Barnes 1967, Arcement and Schneider 1989). 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 more accurate frictional parameters to the ADCIRC model, C-CAP values shown in Table 2 and Figure 10 were applied rather than SLAMM data for the developed dry land and undeveloped dry land classes.
4. ADCIRC Model Setup

4.1 ADCIRC Mesh

The 2009 scenario ADCIRC mesh is identical to the Panhandle FIS ADCIRC mesh. The 2050 and 2100 ADCIRC meshes were constructed by applying subsidence to the 2009 mesh. The SLAMM study applied a constant subsidence rate of 1.23 mm/yr throughout the entire study area (Warren Pinnacle Consulting 2011). The subsidence rate was applied by lowering the ADCIRC mesh elevations by the appropriate subsidence amount in the area defined by each SLAMM model. The subsidence rate in Grand Bay area is 1.23mm/year, thus the 2050 subsidence is 50.4 mm (1.23 mm/year x 41 years) and the 2100 subsidence is 111.9mm (1.23 mm/year x 91 years).

The resulting 2050 model elevations are shown in Figure 11. Figure 12 displays the areas and amount of subsidence between 2009 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 2009, 2050 and 2100 conditions are shown in Figure 15 through Figure 29. The figures include absolute values and differences between 2009 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 2009 $Z_0$ 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 are similar for 2050 and 2100.
4.3 Eustatic Sea Level Rise

The computations are 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 accounted for in the model initial conditions. 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 combined adjustment from LMSL to NAVD88 and the annual sea surface variability in the study area during landfall of Hurricane Katrina was approximately 0.836 feet (0.255 meters). Thus the initial water surface elevation (WSE) for the ADCIRC model is set to 0.255 meters NAVD88 for the 2009 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 SLAMM. 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 100.1 mm in 2009. Therefore, the eustatic SLR for 2050 is 409.2 mm less 100.1 or 309.1 mm. The eustatic SLR for 2100 is 1000.0 mm less 100.1 mm or 899.9 mm.

The initial WSE in the ADCIRC model for the 2050 and 2100 scenarios is set to the initial WSE of 0.255 meters together with the eustatic SLR. The 2050 initial WSE is 0.564 meters and the 2100 initial WSE is set to 1.155 meters.
5. Results

5.1 Maximum Storm Surge Elevation

The simulation of Hurricane Katrina for the base condition produced a peak surge of over fifteen feet in the study area. 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.

ADCIRC and SWAN computations of Hurricane Katrina have been thoroughly reviewed and published previously (Atkinson et al. 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 applied in this study has been derived from the previously validated FIS model, only two comparisons were performed to confirm the accuracy of the model. To make a direct comparison of the simulated maximum surge to the available gauge peak (high water mark of a gauge measurement during the storm) information, the value from the MEOW is extracted at each of the gauge locations (longitude, latitude). Figure 32 shows the locations of the gauges 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 with a very good match in the study area. 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 0.84 and a slope of 0.92. 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 the models compare very well at all locations. The TNC model performs as well as the state of the art FEMA storm surge model in the study area. The differences between the TNC and FEMA model setups are 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 Katrina much more efficiently than the FIS model by not including tides in the simulation.
The same Hurricane Katrina 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 2009 base condition is shown in Figure 36. Recall that for the 2050 scenario, the analyzed SLR value is 1.014 feet (0.309 m). Note that the increase in surge throughout the region is largely similar to the SLR value of 1 foot, except for areas north of Highway 90 where SLR values are generally higher. 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.

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 2.952 feet (0.900 m). Again, note that the increase in surge throughout the region is largely similar to the SLR value (2.952 feet), except for areas north of Highway 90 where SLR values are generally higher. 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 2009.

### 5.2 Analysis of Nonlinear SLR Effects

In order to 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 2009 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 Katrina storm surge values modeled for 2009 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:

\[ dz(x,y) = \text{surge\_future\_condition} - \text{surge\_2009}, \]

then Figure 40 plots:

\[ \text{2100\_relative\_surge\_amplification} = \frac{dz(x,y)}{(2100\_initial\_WSE - 2009\_initial\_WSE)} \]

or

\[ \text{2100\_relative\_surge\_amplification} = \frac{dz(x,y)}{(1.155 \text{ meters} - 0.255 \text{ meters})} \]

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 offshore and near the coast, 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, specifically northwest of Highway 90, show that the increase in surge is greater than the addition of the SLR water increment by a factor of 1.2 to 1.5. 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 high as a factor of two or three times the SLR amount. The SLR amplification occurs north of Highway 90 because the higher storm surge levels nonlinearily increase overtopping of the highway. Thus, simply adding the SLR amount to present day surge maxima will under-predict the future storm surge and under predict the risk of flooding in this area.

Some regions show an amplification factor of less than one. These areas are low elevation regions near the coast and the areas immediately inland from these regions. Subsidence and decreased frictional resolution are the cause of amplification factor of less than one. Decreased friction on the water column due to changes in marsh characteristics and increased storm surge depths (due to SLR) result in a combined decrease in local bottom friction resistance on the water column. Reduced frictional resistance allows storm surge to locally convey more easily in future scenarios, thus reducing the peak storm surge values locally. Reduced
bottom friction resistance due to increased storm surge depths is also the explanation for a difference in the amplification factor for the 2050 and 2100 scenarios. Comparison of Figure 39 and Figure 40 shows that the amplification factor decreases with greater SLR increment, thus the amplification factor is greater for the 2050 scenario than the 2100 scenario.

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 222 square miles of inundation throughout the model domain comprising of a portion of the Mississippi, Alabama and Florida Panhandle coastlines. The 2100 simulation predicts an increase of 382 square miles, which is nearly two 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 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.

Another way to visualize the increased extents of inundation is to superimpose transparent datasets that cover the wetted extents of the three scenarios. In Figure 41, the blue polygon shows the 2009 inundation limits, the yellow polygon the 2050 inundation limits, and the red polygon the 2100 inundation limits. Output locations align with ADCIRC nodal locations. 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 Sensitivity Test

A sensitivity test was performed to explore the relative importance of bottom friction and the increase in sea level in the ADCIRC model. To test this, a Hurricane Katrina simulation was run with the 2100 subsided topography and friction characteristics reflecting the 2100 SLAMM scenario marshes, but with the 2009 initial sea level. The maximum surge is shown in Figure 42 and the difference in surge from the 2009 base scenario is show in Figure 43.

For Hurricane Katrina in the study area, changes in marsh characteristics and marsh loss impact storm surge in areas north of Highway 90. As shown in Figure 43, maximum water surface elevations for the 2009 conditions and the sensitivity test are within 0.25 foot for most of the study area. However, north of Highway 90, the sensitivity test renders maximum storm surge values of approximately 0.5 foot higher. The sensitivity study shows that the 2009 scenario attenuates surge more south of Highway 90, thus overtopping the highway at a slower rate than the sensitivity study simulation.

This hindcast simulation shows that a reduced marsh area footprint can reduce storm surge and wave attenuation in the Grand Bay area. 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 focused analysis of marsh frictional parameters rather than the combined analyses of marsh changes and subsidence. Additionally, numerous meteorological conditions must be analyzed.

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, eighteen of which are included in this analysis. Table 5 lists the four station locations which are shown in Figure 44. Figure 45 shows the two hundred locations inspected during the project. Figure 46 depicts the storm surge hydrographs for the four 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 77, 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.

All four stations show similar trends, with the difference in water surface elevation being generally the SLR value applied. The peak surge for the 2100 scenario is approximately three feet higher than 2009 simulation, while the peak surge for the 2050 scenario is approximately one foot higher. The sensitivity study output is nearly identical to the 2009 simulation output. This is expected because of the trends shown in Figure 43.

One of the most important trends to note in this area is the duration of peak surge for future scenarios, particularly 2100. The duration of high surge is as much as 1.25 times longer for 2100 than other scenarios. The longer duration of high storm surge values for the 2100 scenario is common amongst all of the 200 locations investigated. 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 such as Highway 90, 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. In 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.
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 Katrina scenario applied in this study generates a relatively high surge throughout much of the study area. Additionally, different meteorological forcing, such as a higher frequency event, could result in larger impacts on surge caused by changes in coastal marshes. Since different storm events will produce different surge responses, the contribution of friction to the force balance will also vary. 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 Katrina conditions has produced data insightful to qualitatively understanding the impacts on storm surge due to sea level rise 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 Katrina more efficiently than the FIS model due to conducting the 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 similar for 2050 and 2100.

- The difference between 2009 and future conditions storm surge response varies nonlinearly due to sea level rise and marsh degradation. The largest differences occur north of Highway 90 due to increases in overtopping rates along the highway in future scenarios.

- The marsh degradation and subsidence sensitivity study qualitatively demonstrated that changes in marsh conditions and subsidence in the study area have limited impact on storm surge attenuation in most areas for these storm conditions. Areas north of Highway 90 are most heavily impacted by the changes in marsh conditions and subsidence.

- The simulation of even one storm, such as Hurricane Katrina, 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 under-
predict the future storm surge in some areas, most notably those north of Highway 90.

This study is a worthwhile first step towards understanding the potential impacts of sea level rise and marsh degradation in and around Grand Bay. 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 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 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 Katrina, it is recommended that daily tides are analyzed independent of storm conditions. SLAMM incorporates a static sea level rise assumption. However, 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 Katrina, the same hydrodynamic principles are applicable in the analysis of daily tides. A dynamic sea level rise tidal analysis would better inform marsh hydroporiod, 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 Grand Bay

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>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>2</td>
<td>Undeveloped Dry Land</td>
<td>N/A</td>
<td>N/A</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>
<td>0.130</td>
<td>0.450</td>
</tr>
<tr>
<td>7</td>
<td>Transitional Salt Marsh</td>
<td>0.065</td>
<td>0.090</td>
</tr>
<tr>
<td>8</td>
<td>Mangrove</td>
<td>0.060</td>
<td>0.200</td>
</tr>
<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>
<td>0.040</td>
<td>0.110</td>
</tr>
<tr>
<td>12</td>
<td>Ocean Beach</td>
<td>0.030</td>
<td>0.090</td>
</tr>
<tr>
<td>15</td>
<td>Inland Open Water</td>
<td>0.025</td>
<td>0.001</td>
</tr>
<tr>
<td>16</td>
<td>Riverine Open Water</td>
<td>0.035</td>
<td>0.001</td>
</tr>
<tr>
<td>17</td>
<td>Estuarine Water</td>
<td>0.035</td>
<td>0.001</td>
</tr>
<tr>
<td>19</td>
<td>Open Ocean</td>
<td>0.025</td>
<td>0.001</td>
</tr>
<tr>
<td>20</td>
<td>Irregularly Flooded Marsh</td>
<td>0.050</td>
<td>0.110</td>
</tr>
<tr>
<td>22</td>
<td>Inland Shore</td>
<td>0.030</td>
<td>0.090</td>
</tr>
<tr>
<td>23</td>
<td>Tidal Swamp</td>
<td>0.100</td>
<td>0.250</td>
</tr>
</tbody>
</table>
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>
</thead>
<tbody>
<tr>
<td>2</td>
<td>High Intensity Developed</td>
<td>0.120</td>
<td>0.500</td>
</tr>
<tr>
<td>3</td>
<td>Medium Intensity Developed</td>
<td>0.100</td>
<td>0.390</td>
</tr>
<tr>
<td>4</td>
<td>Low Intensity Developed</td>
<td>0.070</td>
<td>0.330</td>
</tr>
<tr>
<td>5</td>
<td>Developed Open Space</td>
<td>0.035</td>
<td>0.330</td>
</tr>
<tr>
<td>6</td>
<td>Cultivated Land</td>
<td>0.100</td>
<td>0.060</td>
</tr>
<tr>
<td>7</td>
<td>Pasture/Hay</td>
<td>0.055</td>
<td>0.060</td>
</tr>
<tr>
<td>8</td>
<td>Grassland</td>
<td>0.035</td>
<td>0.040</td>
</tr>
<tr>
<td>9</td>
<td>Deciduous Forest</td>
<td>0.160</td>
<td>0.650</td>
</tr>
<tr>
<td>10</td>
<td>Evergreen Forest</td>
<td>0.180</td>
<td>0.720</td>
</tr>
<tr>
<td>11</td>
<td>Mixed Forest</td>
<td>0.170</td>
<td>0.710</td>
</tr>
<tr>
<td>12</td>
<td>Scrub/Shrub</td>
<td>0.080</td>
<td>0.120</td>
</tr>
<tr>
<td>13</td>
<td>Palustrine Forested Wetland</td>
<td>0.150</td>
<td>0.710</td>
</tr>
<tr>
<td>14</td>
<td>Palustrine Scrub/Shrub Wetland</td>
<td>0.075</td>
<td>0.110</td>
</tr>
<tr>
<td>15</td>
<td>Palustrine Emergent Wetland</td>
<td>0.070</td>
<td>0.110</td>
</tr>
<tr>
<td>16</td>
<td>Estuarine Forested Wetland</td>
<td>0.150</td>
<td>0.550</td>
</tr>
<tr>
<td>17</td>
<td>Estuarine Scrub/Shrub Wetland</td>
<td>0.070</td>
<td>0.120</td>
</tr>
<tr>
<td>18</td>
<td>Estuarine Emergent Wetland</td>
<td>0.050</td>
<td>0.110</td>
</tr>
<tr>
<td>19</td>
<td>Unconsolidated Shore</td>
<td>0.030</td>
<td>0.090</td>
</tr>
<tr>
<td>20</td>
<td>Bare Land</td>
<td>0.030</td>
<td>0.090</td>
</tr>
<tr>
<td>21</td>
<td>Open Water</td>
<td>0.025</td>
<td>0.001</td>
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<tr>
<td>22</td>
<td>Palustrine Aquatic Bed</td>
<td>0.035</td>
<td>0.040</td>
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<tr>
<td>23</td>
<td>Estuarine Aquatic Bed</td>
<td>0.030</td>
<td>0.040</td>
</tr>
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</table>

Table 3  SLAMM Sea Level Rise Scenarios (mm)

<table>
<thead>
<tr>
<th></th>
<th>A1B- Max</th>
<th>A1B- Mean</th>
<th>1 meter</th>
<th>1.5 meters</th>
<th>2 meters</th>
</tr>
</thead>
<tbody>
<tr>
<td>1990</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2025</td>
<td>128</td>
<td>76</td>
<td>184.4</td>
<td>276.7</td>
<td>368.9</td>
</tr>
<tr>
<td>2050</td>
<td>284</td>
<td>167</td>
<td>409.2</td>
<td>613.8</td>
<td>818.4</td>
</tr>
<tr>
<td>2075</td>
<td>484.5</td>
<td>278.5</td>
<td>698.1</td>
<td>1047.2</td>
<td>1396.3</td>
</tr>
<tr>
<td>2100</td>
<td>694</td>
<td>387</td>
<td>1000.0</td>
<td>1500.0</td>
<td>2000.0</td>
</tr>
</tbody>
</table>

Note: The A1B-Max and A1B-Mean are Intergovernmental Panel on Climate Change scenarios applied by the SLAMM model (Warren Pinnacle Consulting 2011).
### Table 4  Increase in Inundated Area for Future Scenarios Under Hurricane Katrina Conditions

<table>
<thead>
<tr>
<th>SLR Scenario</th>
<th>Increase in Flooded Area</th>
<th></th>
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</thead>
<tbody>
<tr>
<td></td>
<td>sq mile</td>
<td>acre</td>
<td></td>
</tr>
<tr>
<td>2050</td>
<td>222</td>
<td>142,258</td>
<td></td>
</tr>
<tr>
<td>2100</td>
<td>382</td>
<td>244,460</td>
<td></td>
</tr>
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</table>

### Table 5  Storm Surge Time Series Output of Four Selected Locations

<table>
<thead>
<tr>
<th>Station Number</th>
<th>Location Description</th>
<th>Longitude</th>
<th>Latitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>Mississippi Sound</td>
<td>-88.40122</td>
<td>30.328262</td>
</tr>
<tr>
<td>46</td>
<td>North Bayou</td>
<td>-88.46073</td>
<td>30.374461</td>
</tr>
<tr>
<td>77</td>
<td>Orange Grove</td>
<td>-88.44699</td>
<td>30.422956</td>
</tr>
<tr>
<td>109</td>
<td>University Road</td>
<td>-88.30407</td>
<td>30.395814</td>
</tr>
</tbody>
</table>
Figure 1: Location Map of the Grand Bay

Note: The SLAMM boundaries are in orange. The Hurricane Katrina 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 North Atlantic, Caribbean 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 north.
Figure 5: ADCIRC Mesh with 2009 Topographic Contours (feet NAVD88) for the Study Domain
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. Black lines denote coast lines.
Figure 7: 2009 Initial Land Cover Data Used By SLAMM (based on NWI) for the Grand Bay Area

Note: The black dot line denotes the ADCIRC model boundary.
Figure 8:  SLAMM 2050 Scenario for the Grand Bay Area

Note:  The black dot line denotes the ADCIRC model boundary
Figure 9:  SLAMM 2100 Scenario for the Grand Bay Area

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

**Note:** The black line denotes the ADCIRC model boundary.
Figure 11: ADCIRC Mesh with 2050 Topographic Contours (feet NAVD88) for the Study Domain

Note: Mesh topography incorporates constant subsidence.
Figure 12: Differences in ADCIRC Mesh Topography for 2050 and 2009 Conditions

Note: 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.
Figure 14: Differences in ADCIRC Mesh Topography for 2100 and 2009 Conditions

Note: Black lines depict the coastline.
Figure 15: 2009 Conditions ADCIRC Nodal Manning’s n Values for the Study Domain
Figure 16: 2009 Conditions ADCIRC Nodal $Z_0$ Values in the Study Domain for Southerly Winds

Note: The coastline is shown in black.
Figure 17: 2009 Conditions ADCIRC Nodal $Z_0$ Values in the Study Domain for Northerly Winds

Note: The coastline is shown in black.
Figure 18: 2050 Conditions ADCIRC Nodal Manning’s $n$ Values for the Study Domain
Figure 19: 2050 Conditions ADCIRC Nodal $Z_o$ Values in the Study Domain for Southerly Winds

Note: The coastline is shown in black.
Figure 20: 2050 Conditions ADCIRC Nodal $Z_0$ Values in the Study Domain for Northerly Winds

Note: The coastline is shown in black.
Figure 21: Difference between 2009 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. The mesh boundary is shown in brown. The coastline is shown in black.
Figure 22: Difference between 2009 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. The mesh boundary is shown in brown. The coastline is shown in black.
Figure 23: Difference between 2009 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. The mesh boundary is shown in brown. The coastline is shown in black.
Figure 24: 2100 Conditions ADCIRC Nodal Manning’s $n$ Values for the Study Domain
Figure 25: 2100 Conditions ADCIRC Nodal Z₀ Values in the Study Domain for Southerly Winds

Note: The coastline is shown in black.
Figure 26: 2100 Conditions ADCIRC Nodal $Z_0$ Values in the Study Domain for Northerly Winds

Note: The coastline is shown in black.
Figure 27: Difference between 2009 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.
The mesh boundary is shown in brown. The coastline is shown in black.
Figure 28: Difference between 2009 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. The mesh boundary is shown in brown. The coastline is shown in black.
Figure 29: Difference between 2009 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. The mesh boundary is shown in brown. The coastline is shown in black.
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Note: The mesh boundary is shown in brown. The coastline is shown in black.
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Note: Values are in feet. The markers are colored according to the difference between measured and computed value. Positive implies over-prediction, negative is under-prediction.
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Note: The mesh boundary is shown in brown. The coastline is shown in black.
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Note: The mesh boundary is shown in brown. The coastline is shown in black.
Figure 37: Maximum Storm Surge Elevation Contours (feet NAVD88) for Hurricane Katrina for 2100 Model Conditions

Note: The mesh boundary is shown in brown. The coastline is shown in black.
Figure 38: The Difference Between 2100 Maximum Storm Surge Elevation and 2009 Maximum Storm Surge Elevation for Hurricane Katrina

Note: The mesh boundary is shown in brown. The coastline is shown in black.
Figure 39: Relative Surge Amplification for the 2050 Scenario

Note: The mesh boundary is shown in brown. The coastline is shown in black. The surge increase is normalized by the SLR increment. The scale is unitless.
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Note: The mesh boundary is shown in brown. The coastline is shown in black. The surge increase is normalized by the SLR increment. The scale is unitless.
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Note: The mesh boundary is shown in brown. The coastline is shown in black.
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Note: The mesh boundary is shown in brown. The coastline is shown in black.
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