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AN ERROR QUANTIFICATION METHODOLOGY FOR HURRICANE STORM SURGE SIMULATIONS

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AN ERROR QUANTIFICATION METHODOLOGY
FOR HURRICANE STORM SURGE SIMULATIONS

A Thesis
Presented to
the Graduate School of
Clemson University

In Partial Fulfillment
of the Requirements for the Degree
Master of Science
Civil Engineering

by
Bin Pei
December 2012

Accepted by:
Dr. Weichiang Pang, Committee Chair
Dr. Firat Y. Testik
Dr. Nadarajah Ravichandran
ABSTRACT

This thesis describes the development of a procedure to quantify errors in hurricane storm surge simulations using a decoupled wind-surge model. The state-of-the-art storm surge simulation program, ADCIRC (Advanced Circulation), and the Georgiou’s wind field model were used to simulate the storm surge heights associated with 169 historical hurricanes from 1922 to 2011 along the coast of North Carolina, South Carolina and Georgia. The storm surge modeling errors were quantified by comparing the measured to the simulated annual maximum surge heights at nine water level observation stations maintained by the Center for Operational Oceanographic Products and Services (CO-OPS). The simulated surge heights consisted of both systematic errors and random errors. A power equation was used to adjust the systematic errors in the simulated storm surge heights. The random errors, which are defined as the ratio of the measured to the systematic-error-adjusted simulated annual maximum surge heights, were found to follow a lognormal distribution. To confirm the validity of the error quantification methodology, the simulated annual, 5-year and 10-year maximum surge heights were adjusted using the modeling errors quantified for each of the nine CO-OPS water stations and compared to the actual storm surge observations. Good agreements were observed between the actual measurements and the error-adjusted surge elevations. The proposed methodology for quantifying modeling errors can be applied to adjust for storm surge predictions of longer return periods and used to develop design surge hazard maps.
DEDICATION

This thesis is dedicated to my beloved parents and family.
ACKNOWLEDGMENTS

First, I would like to express my sincere gratitude to my major advisor, Dr. Weichiang Pang, and co-advisors, Dr. Firat Y. Testik and Dr. Nadarajah Ravichandran, for their invaluable advices, encouragements, and inspirations. Without their elaborate guidance and persistent help, this thesis would not have been possible.

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CHAPTER ONE
INTRODUCTION

Motivation

Hurricane storm surge is an abnormal rise of water induced by the low pressure and strong wind of hurricane over shallow coastal waters. During a hurricane event, storm surges are often the greatest threats to the coastal communities, even greater than the powerful gusts and floods caused by torrential rainfall (Islam et al. 2010; Li et al. 2012). Hurricane storm surge heights may be on the order of several meters and may devastate the coastal areas, causing loss of lives, property damage, and inundation with significant ecological impacts. According to the tropical cyclone reports (http://www.nhc.noaa.gov/pdf/) from the National Hurricane Center (NHC), some of the notable hurricane storm surge events (with high water levels) are selected and listed in Table 1.1. As can be seen, the Saffir-Simpson hurricane category at landfall is not necessarily a good predictor for surge height range. For instance, Hurricane Katrina (2005) made landfall as a category 3 hurricane; however, the surge heights caused by Hurricane Katrina were significantly higher than those of Hurricanes Ivan (2004) and Opal (1995) which were both category 3 hurricanes at landfall.
Table 1.1: Notable hurricane storm surge events

<table>
<thead>
<tr>
<th>Hurricane Name</th>
<th>Ike</th>
<th>Katrina</th>
<th>Ivan</th>
<th>Opal</th>
<th>Andrew</th>
<th>Hugo</th>
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<tr>
<td>Category* at Landfall</td>
<td>2</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Highest Category</td>
<td>4</td>
<td>5</td>
<td>5</td>
<td>4</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Surge Height (m)</td>
<td>4.6-6.1</td>
<td>7.6-8.5</td>
<td>3.0-4.6</td>
<td>3.0-7.3</td>
<td>2.4-7.0</td>
<td>6.0 (max)</td>
</tr>
<tr>
<td>Property Damage (billion in current year)</td>
<td>24.9</td>
<td>75</td>
<td>14.2</td>
<td>3</td>
<td>26.5</td>
<td>8</td>
</tr>
</tbody>
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* Categories correspond with the Saffir-Simpson hurricane wind scale (Simpson, 1974)

With the gradual increase of global sea surface temperature and the increase of annual hurricane frequency, more intense hurricanes with higher storm surge elevations may be expected (Rego 2009). Hence, accurate predictions of storm surge elevations are becoming more and more important for a variety of reasons including public safety, hazard mitigation, post-hurricane emergency response, and resilient coastal structure design (Chen et al. 2009). Due to the inherent randomness associated with the meteorological events, the complex nature of coastal environments, and the simplified assumptions made in storm surge modeling, errors do exist in storm surge simulations. Recent storm surge studies in the U.S. either did not consider modeling errors associated with the numerical models (e.g. Phan et al. 2007; Lin et al. 2010) or only quantified the modeling errors for a few selected major hurricane events (e.g. Demirbilek et al. 2008; Ebersole et al. 2009; Dietrich et al. 2011). Flather et al. (1998) conducted an extensive storm surge study for the northwest Europe. It is obvious that the outcomes of the study
for the northwest Europe region cannot be applied to the U.S. due to the differences in meteorological and geological conditions. Therefore, to reliably predict the storm surge heights along the U.S. coastline, it is of paramount importance that the errors associated with the specific numerical models employed for the storm surge predictions or simulations are quantified using actual surge observations.

**Objectives**

The main objective of this study was to develop a methodology to quantify the modeling errors associated with the system of models used for storm surge simulation which includes the ADCIRC (Advanced Circulation) storm surge model (Luettich et al. 1992), the Georgiou (1985) wind field model, the HURDAT hurricane database (Jarvinen et al. 1984) and the ADCIRC tide database (Westerink et al. 1993). As an illustrative example, the proposed methodology was utilized to quantify the modeling errors at nine locations corresponding to real water level observation stations along the coast of North Carolina, South Carolina and Georgia by comparing the ADCIRC model simulated and station measured annual maximum surge heights. It was found that the model simulations suffer both systematic and random errors. The model tends to slightly underestimate and overestimate the actual annual maximum surge heights for low- and high-surge elevation events, respectively. To account for the modeling errors, a power equation was utilized to quantify the systematic errors and a lognormal distribution was used to quantify the random errors. To confirm the validity of the proposed error quantification methodology,
the error-adjusted annual, 5-year and 10-year maximum surge height simulations were compared to the actual storm surge observations at the nine water stations. Good agreements were observed between the actual recorded and the error-adjusted cumulative maximum surge height distributions.
The storm surge simulation procedure used in this study consists of two components: storm surge modeling and hurricane wind field modeling (Figure 2.1).

Figure 2.1: Hurricane storm surge simulation procedure
Storm Surge Models

In recent years, significant advancements have been made in the procedures for hurricane storm surge simulations (Kolar and Westerink 2000; Resio and Westerink 2008; Dawson et al. 2008). There are a number of computer models with varying complexities that are currently being used by researchers and risk analysts to simulate storm surges. Among these models, the ADCIRC (Advanced Circulation) model and the SLOSH (Sea, Lake, and Overland Surges from Hurricanes) model (Jelesnianski et al. 1992) have been widely used and shown to provide surge simulations with reasonable accuracy (Aggarwal 2004).

SLOSH Model

The SLOSH model is a two-dimensional finite difference hydrodynamic model developed by the National Weather Service (NWS) for real time forecasting of hurricane storm surges (Jelesnianski et al. 1992). It also plays an important role in providing storm surge guidance for hazard analysis to the Federal Emergency Management Agency (FEMA), the U.S. Army Corps of Engineers (USACE) and local emergency managers (Glahn et al. 2009).

In the SLOSH model, the governing equations of motion for the Cartesian coordinate was first developed by Platzman (1963) and later modified by Jelesnianski (1967) with a bottom slip coefficient:
\[
\frac{\partial u}{\partial t} = -g(D + h) \left[ B_r \frac{\partial (h - h_0)}{\partial x} - B_i \frac{\partial (h - h_0)}{\partial y} \right] + f(A_r v + A_i u) + C_r x_r - C_y y_r \tag{2.1}
\]

\[
\frac{\partial v}{\partial t} = -g(D + h) \left[ B_r \frac{\partial (h - h_0)}{\partial y} - B_i \frac{\partial (h - h_0)}{\partial x} \right] - f(A_r u - A_i v) + C_y y_r + C_x x_r \tag{2.2}
\]

\[
\frac{\partial h}{\partial t} = - \frac{\partial u}{\partial x} - \frac{\partial v}{\partial y} \tag{2.3}
\]

where, \( u \) and \( v \) are the components of transport; \( g \) is the acceleration due to gravity; \( D \) is the depth of still water relative to a common datum; \( h \) is the water height above the datum; \( h_0 \) is the hydrostatic water level; \( f \) is the Coriolis parameter; \( x_r \) and \( y_r \) are the components of surface stresses; and \( A_r, A_i, B_r, B_i, C_r, C_i \) are the bottom stress terms.

In SLOSH, the U.S. Eastern Coast and Gulf of Mexico are divided into different regions, named the SLOSH basins, in which grids are created for surge calculations (Figure 2.2). Although refined cells or meshes can be constructed near-shore, the modeling domain and grid resolution are still limited, especially for simulating complex shorelines. Because of its relatively coarse resolution and small analysis domains, the SLOSH model may produce 20% or more errors in surge height simulations for certain areas (Jelesnianski et al. 1992; Blain 1997; Aggarwal 2004).

The ADCIRC model was used in this study to simulate hurricane storm surge elevations. The ADCIRC model not only enables one to construct fine grids around the studied shoreline for improved accuracy, it also allows one to specify temporal and spatial varying wind field information for different historical hurricanes. Advective terms, horizontal viscosity and astronomical tides, which are not considered in the
The SLOSH model [see Eqns. (2.1) to (2.3)], can also be taken into account in the ADCIRC program. Therefore, the ADCIRC model may produce better results than SLOSH, however with a higher computational overhead, if a highly refined mesh is used and the hurricane wind fields are adequately described. The use of the ADCIRC model for storm surge modeling is well documented (Dietsche et al. 2007; Blain et al. 2010; Forbes et al. 2010), and it is actively employed by a number of research institutes and federal agencies for storm surge forecasting.

Figure 2.2: SLOSH basins for U.S. Eastern Coast and Gulf of Mexico
The ADCIRC model is a well developed hydrodynamic finite element model. It has highly flexible and unstructured grids which can be used to solve the governing equations for coastal and ocean circulations (Luettich et al. 1992). In this study, two-dimensional ADCIRC model ADCIRC-2DDI (2-Dimensional Depth Integrated) was utilized. As a finite element program, ADCIRC requires a minimum of three sets of inputs for hurricane storm surge calculations (Figure 2.1). These inputs are (1) finite element mesh with bathymetric information; (2) boundary conditions, including forcing boundaries and land boundaries; and (3) meteorological forcing (wind stresses or wind velocities, and atmospheric pressures). Different outputs, such as water elevations, water velocities and flow directions, can be provided from the results of the ADCIRC model.

In ADCIRC-2DDI, water velocities are obtained from the solutions of the momentum balance equations, and water elevations are obtained by solving the depth-integrated continuity equation in Generalized Wave Continuity Equation (GWCE) form (Westerink et al. 1994). In spherical coordinates, the primitive continuity equation [Eqn. (2.4)] and the primitive momentum balance equations [Eqns. (2.5) and (2.6)] are expressed as follows:

\[
\frac{\partial \zeta}{\partial t} + \frac{1}{R \cos \phi} \left[ \frac{\partial (UH)}{\partial \lambda} + \frac{\partial (VH \cos \phi)}{\partial \phi} \right] = 0
\]  

(2.4)
\[
\frac{\partial(UH)}{\partial t} + \frac{1}{R \cos \phi} \left[ \frac{\partial(UUH)}{\partial \lambda} + \frac{\partial(UVH \cos \phi)}{\partial \phi} \right] - \left( \frac{\tan \phi}{R} U + f \right) VH = \tag{2.5}
\]
\[
\frac{\partial(VH)}{\partial t} + \frac{1}{R \cos \phi} \left[ \frac{\partial(VUH)}{\partial \lambda} + \frac{\partial(VVH \cos \phi)}{\partial \phi} \right] + \left( \frac{\tan \phi}{R} U + f \right) UH = \tag{2.6}
\]

where, \( \zeta \) is the free surface elevation relative to mean sea level; \( U \) and \( V \) are the depth-averaged horizontal velocities; \( t \) is the time; \( R \) is the radius of the Earth; \( \phi \) and \( \lambda \) are the degrees latitude and longitude, respectively; \( H \) is the total height of the water column; \( p_s \) is the atmospheric pressure at the free water surface; \( \rho_0 \) is the reference density of water; \( \alpha \) is the effective Earth elasticity factor; \( \eta \) is the Newtonian equilibrium tide potential; \( \tau_s \) is the bottom stress; and \( M_\lambda \) and \( M_\phi \) are the depth-integrated horizontal diffusions:

\[
M_\lambda = \frac{E_{h_\lambda}}{R^2} \left[ \frac{1}{\cos^2 \phi} \frac{\partial^2(UH)}{\partial \lambda^2} + \frac{\partial^2(UH)}{\partial \phi^2} \right] \tag{2.7}
\]
\[
M_\phi = \frac{E_{h_\phi}}{R^2} \left[ \frac{1}{\cos^2 \phi} \frac{\partial^2(VH)}{\partial \lambda^2} + \frac{\partial^2(VH)}{\partial \phi^2} \right] \tag{2.8}
\]

where, \( E_{h_\lambda} \) is the horizontal eddy diffusion coefficient.

In Eqns. (2.5) and (2.6), \( \tau_{s\phi} \) and \( \tau_{s\lambda} \) are the applied free surface stresses along the latitudinal and longitudinal directions, respectively, which are functions of hurricane wind velocities:
\[ C_d = 0.001(0.75 + 0.067W) \leq 0.003 \]  
(2.9)

\[ \tau_{x\phi} = 0.001293 C_d V_\phi W \]  
(2.10)

\[ \tau_{x\lambda} = 0.001293 C_d V_\lambda W \]  
(2.11)

where, \( C_d \) is the drag coefficient; \( V_\phi \) and \( V_\lambda \) are the surface wind velocities; and \( W \) is the wind speed magnitude given by:

\[ W = \sqrt{V_\phi^2 + V_\lambda^2} \]  
(2.12)

The GWCE for spherical coordinates (Kolar et al. 1994) is derived by combining a time-differentiated form of Eqn. (2.4) and a spatially differentiated form of Eqns. (2.5) and (2.6), along with Eqn. (2.4) multiplied by a constant \( \tau_0 \) (Luettich et al. 1992), which is also known as the wave continuity weighting factor:

\[
\frac{\partial^2 \zeta}{\partial t^2} + \tau_0 \frac{\partial \zeta}{\partial t} - \frac{1}{R \cos \phi} \frac{\partial}{\partial \lambda} \left[ \frac{1}{R} \cos \phi \left[ \frac{\partial(UUH)}{\partial \lambda} + \frac{\partial(UVH \cos \phi)}{\partial \phi} \right] - \left( \frac{\tan \phi}{R} U + f \right) VH \right] \\
+ \frac{1}{R \cos \phi} H \frac{\partial}{\partial \lambda} \left[ p_x + g(\zeta - \alpha \eta) \right] + \frac{E_b_0}{R \cos \phi} \frac{\partial^2 \zeta}{\partial \lambda \partial t} - \frac{\tau_{\lambda \phi}}{\rho_0} \left( \tau_{\phi \phi} - \tau_{\lambda \phi} \right) VH \\
- \frac{1}{R} \frac{\partial}{\partial \phi} \left[ \frac{1}{R \cos \phi} \left[ \frac{\partial(VUH)}{\partial \lambda} + \frac{\partial(VVH \cos \phi)}{\partial \phi} \right] + \left( \frac{\tan \phi}{R} U + f \right) UH \right] \\
- \frac{1}{R} \left[ \frac{\partial(VH)}{\partial t} + \tau_0 VH \right] = 0
\]  
(2.13)

In ADCIRC, this partial differential equation is discretized in space after time discretization of the derived Galerkin’s weighted residual statements (Luettich et al. 1992). The ADCIRC inputs include the Newtonian equilibrium tide potential \( \eta \) (described in the next section) and the applied free surface stresses \( \tau_{\lambda \phi} \) and \( \tau_{x \phi} \) [Eqns.
As the only output needed in this study, water elevation $\zeta$ was calculated in each time step and recorded at every observation station.

**Astronomical Tides**

In this study, the total water elevations including the tidal heights were calculated and compared with the real water level measurements. The tidal potential function described by Reid (1990) was utilized in this study:

$$
\eta(\lambda, \phi, t) = \sum_{n,j} \alpha_{jn} C_{jn} f_{jn}(t_0) L_j(\phi) \cos \left[ 2\pi(t - t_0)/T_{jn} + j\lambda + \nu_{jn}(t_0) \right] 
$$

where, $\alpha_{jn}$ is the effective earth elasticity factor for tidal constituent $n$ of species $j$, $C_{jn}$ is the constant characterizing the amplitude of tidal constituent $n$ of species $j$, $f_{jn}$ is the time-dependent nodal factor, $\nu_{jn}$ is the time-dependent astronomical argument, $T_{jn}$ is the period of constituent $n$ of species $j$, $j$ represents the tidal species ($j=0$, declinational, $L_0 = 3\sin^2\phi - 1$; 1, diurnal, $L_1 = \sin2\phi$; and 2, semi-diurnal, $L_2 = \cos^2\phi$), and $t_0$ is the reference time.

The tidal periodic forcing imposed along the ADCIRC grid open boundaries is a function of multiple tidal constituents. Seven major constituents, denoted as $K_1$, $K_2$, $M_2$, $N_2$, $O_1$, $Q_1$, $S_2$ in the ADCIRC tide database (Westerink et al. 1993), were considered in this study. It has been shown that the summation of these seven major constituents surpasses 95% in amplitude of the total tidal signal (Murray 2003). The latest version of the ADCIRC tide database has been verified using real elevations from over 100
observation stations. The ADCIRC tide database was shown to be more accurate than the Le Provost tide database (Le Provost et al. 1995) at the area of focus in both amplitudes and phases. Note that the Le Provost tide database utilizes a coarse mesh which covers the entire world. The larger errors of the Le Provost tide database may be attributed to the coarse resolution grids with sizes ranging from 30km at the land boundaries to 400km in the deep ocean (Le Provost et al. 1995). The relatively coarse grid resolutions of the Le Provost database may produce large errors close to the shallow coastal waters. As can be clearly seen from Figures 2.3 to 2.5, the simulated tide elevation time histories from the ADCIRC tide database generally agree well with the measured tide elevations at three water level observation stations within the area of interest. However, large errors are produced for tide simulations using the Le Provost tide database.

![Figure 2.3: Comparisons between measured and simulated tide elevations at Station 8665530 using both ADCIRC and Le Provost tide database](image-url)
Figure 2.4: Comparisons between measured and simulated tide elevations at Station 8656483 using both ADCIRC and Le Provost tide database.

Figure 2.5: Comparisons between measured and simulated tide elevations at Station 8651370 using both ADCIRC and Le Provost tide database.
The ADCIRC surge modeling parameters were set as constant values throughout the study using a control file named fort.15. Most of the parameters were attained as the default values recommended by the ADCIRC model developers (Westerink et al. 1994) or from other studies (Murray 2003; Dietsche et al. 2007); while the rests, such as time step and bottom friction, were determined using Eqns. (2.15) to (2.17) and a parameter sensitivity analysis for the area of focus. Some of the key modeling parameters used in this study, along with their brief descriptions, are listed in Table 2.1. A sample ADCIRC control file (fort.15) with key parameters highlighted is presented in Appendix A.
Table 2.1: Values of ADCIRC surge modeling parameters

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
<th>Descriptions</th>
</tr>
</thead>
<tbody>
<tr>
<td>NOLIBF</td>
<td>2</td>
<td>parameter controlling the type of bottom stress parameterization (hybrid nonlinear bottom friction law is used)</td>
</tr>
<tr>
<td>NOLIFA</td>
<td>2</td>
<td>finite amplitude terms are included in the model run and wetting and drying function is enabled</td>
</tr>
<tr>
<td>NCOR</td>
<td>1</td>
<td>a spatially varying Coriolis parameter is calculated</td>
</tr>
<tr>
<td>NTIP</td>
<td>1</td>
<td>tidal potential forcing is used</td>
</tr>
<tr>
<td>NWS</td>
<td>4</td>
<td>wind velocity and atmospheric pressure are read in a PBL/JAG format at selected ADCIRC grid nodes</td>
</tr>
<tr>
<td>NRAMP</td>
<td>1</td>
<td>a hyperbolic tangent ramp function is applied</td>
</tr>
<tr>
<td>G</td>
<td>9.81</td>
<td>gravitational constant (m/s²)</td>
</tr>
<tr>
<td>TAU0</td>
<td>-1</td>
<td>weighting factor that weights the relative contribution of the primitive and wave portions of the GWCE (if the depth is ≥ 10 TAU0 is set to 0.005; if the depth is &lt; 10, TAU0 is set to 0.020)</td>
</tr>
<tr>
<td>DTDP</td>
<td>6</td>
<td>ADCIRC time step (in seconds)</td>
</tr>
<tr>
<td>WTIMINC</td>
<td>900</td>
<td>meteorological wind time interval (in seconds)</td>
</tr>
<tr>
<td>DRAMP</td>
<td>10.00</td>
<td>value (in decimal days) used to compute the ramp function that ramps up ADCIRC forcing from zero</td>
</tr>
<tr>
<td>H0</td>
<td>0.05</td>
<td>minimum water depth (units of length)</td>
</tr>
<tr>
<td>ESLM</td>
<td>5</td>
<td>spatially constant horizontal eddy viscosity for the momentum equations (units of length²/time)</td>
</tr>
</tbody>
</table>
ADCIRC Time Step

In ADCIRC, computational time step was recommended to meet the Courant number requirement for numerical stability (Westerink et al. 1994). The Courant number was suggested to remain less than 1.0 for the whole study domain. The Courant number, \( C_g \), can be calculated as:

\[
C_g = \frac{(gh_n)^{1/2} \Delta t}{\Delta x}
\]

where, \( h_n \) is the node depth, \( \Delta t \) is the time step, and \( \Delta x \) is the spacing between adjacent nodes. In this study, a time step of 6s was used (Table 2.1, DTDP = 6) to maintain the numerical stability.

Bottom Friction

The quadratic bottom friction equation with a hybrid nonlinear bottom friction law (Table 2.1, NOLIBF = 2) is defined as (Westerink et al. 1994):

\[
\tau_* = \frac{C_f (U^2 + V^2)^{1/2}}{H}
\]

where, \( C_f \) is the bottom friction coefficient expressed as:

\[
C_f = C_{f_{\text{min}}} \left[ 1 + \left( \frac{H_{\text{break}}}{H} \right)^{\gamma/\delta} \right]^\delta
\]
where, $C_{f_{\text{min}}}$ is the minimum bottom friction coefficient; $H_{\text{break}}$ is the break depth acts as a threshold in the hybrid bottom friction relationship (as illustrated in Figure 2.6, if water depth is greater than $H_{\text{break}}$, $C_f$ approaches $C_{f_{\text{min}}}$; if water depth is less than $H_{\text{break}}$, $C_f$ increases as the water depth decreases); $\theta$ is the parameter that determines how rapidly the hybrid bottom friction approaches its limits; and $\gamma$ is the parameter that tells how the friction coefficient increases as the water depth decreases.

Figure 2.6: Relationship between water depth and bottom friction coefficient
In this study, $H_{break}$, $\theta$ and $\gamma$ are taken as recommended values from the ADCIRC model as 1m, 10 and 1/3, respectively. The value of $C_{f_{\text{min}}}$ is determined using sensitivity analysis of tide elevations at a few water level observation stations within the study domain. The outcomes at three observation stations are presented in Figures 2.7 to 2.9 with varying $C_{f_{\text{min}}}$ values ranging from 0.0001 to 0.025. As can be clearly seen, since the ADCIRC simulations with a $C_{f_{\text{min}}}$ value of 0.0025 matched the observed data, 0.0025 was taken as the $C_{f_{\text{min}}}$ value for subsequent storm surge simulations.

![Figure 2.7: Sensitivity analysis of bottom friction coefficient at Station 8665530](image-url)
Figure 2.8: Sensitivity analysis of bottom friction coefficient at Station 8656483

Figure 2.9: Sensitivity analysis of bottom friction coefficient at Station 8651370
A variable-size finite element mesh (Figure 2.10) with 200,500 nodes and 398,819 elements was created for storm surge modeling using the NGDC (National Geophysical Data Center) GSHHS (Global Self-consistent, Hierarchical, and High-resolution Shoreline) full resolution coastline database and the 6-arc second NGDC U.S. Coastal Relief Model (CRM) seamless bathymetric and topographic data (http://www.ngdc.noaa.gov/mgg/coastal/crm.html). This variable-size mesh was created for the coast of North Carolina, South Carolina and Georgia in which the highest resolution was given to the shallow water regions along the coastline with a minimum mesh size or distance between two nodes of less than 200 meters (Figure 2.10). Since the maximum recorded surge heights at the CO-OPS stations in the study domain was about 2.5 meters, in order to account for the largest surge event, the mesh was extended from the sea into the land until the land boundaries reached about 3 meters above the mean sea level.

The finite element mesh was generated using a commercial program named SMS (Surface-water Modeling System), version 10.1.10. SMS is a state-of-the-art mesh generation tool with the capabilities of reading background images, editing coastline files, importing bathymetric and topographic data, and automatically generating unstructured grids. A screenshot of the SMS interface is given in Figure 2.11. The following steps were followed to generate the finite element mesh:

1. Locate the area of interest and import a background image
(2) Download the coastline file accordingly from the GSHHS database, read and edit the coastline per the background image

(3) Download and read the corresponding CRM bathymetric and topographic data

(4) Define a study domain and create polygons

(5) Create a mesh size function and smooth the function

(6) Generate a desirable finite element mesh

Figure 2.10: Finite element mesh for the Coast of North Carolina, South Carolina and Georgia
Hurricane Wind Field Model

Model Description

In the ADCIRC model, meteorological forcing or hurricane driven forces are applied to the finite element grids in terms of wind stresses (or wind speeds) and air pressures. In this study, the wind field model proposed by Georgiou (1985) was employed to characterize the hurricane wind velocities and atmospheric pressures at a discrete time interval.
The National Hurricane Center (NHC) maintains a database of all historical tropical storms and hurricanes that occurred in the Atlantic Ocean, Gulf of Mexico and Caribbean Sea (Jarvinen et al. 1984) called HURDAT. For each historical hurricane, parameters such as the hurricane track (latitude and longitude of hurricane eye), translational speed ($V_T$), heading angle ($\theta$), and central pressure ($P_c$) were recorded at a 6-hour time interval (Figure 2.12). These parameters are the basic parameters required to compute the hurricane wind field (Georgiou 1985):

$$V_g^2 = \frac{r}{\rho_a} \frac{dP_e}{dr} + V_g (V_T \sin \beta - fr)$$  \hspace{1cm} (2.18)

where, $V_g$ and $V_T$ are the gradient and translational wind speeds, respectively; $r$ is the radial distance from the hurricane center (eye); $\rho_a$ is the air density; $\beta$ is the angle measures from the hurricane translational direction to where the wind speed is being considered (counter-clockwise is positive); and $f$ is the previously defined Coriolis parameter:

$$f = 2\Omega \sin \phi$$  \hspace{1cm} (2.19)

where, $\Omega$ is the angular rotation rate of the earth ($7.272 \times 10^{-5}$ rad/s).

In Eqn. (2.18), $P_e$ is the air pressure at distance $r$ from the hurricane eye. The air pressure field is described using the following equation:

$$P_r = P_c + (P_a - P_c) e^{-\left(\frac{r_{min}}{r}\right)^B}$$  \hspace{1cm} (2.20)

where, $P_c$ is the hurricane central pressure; $P_a$ is the ambient air pressure (1013 mbar); $B$ is the pressure profile parameter, also known as the *Holland B* parameter (Vickery and
and $R_{\text{max}}$ is the radial distance measured from the hurricane eye to the location where the wind speed is maximum, termed radius-to-maximum wind. Note that the $R_{\text{max}}$ is not provided in the HURDAT. The following equation proposed by Vickery et al. (2000) was used to compute the $R_{\text{max}}$ of each storm:

$$\ln(R_{\text{max}}) = 2.636 - 0.0005086(P_a - P_c)^2 + 0.0394899\phi$$  \hspace{1cm} (2.21)

Where, $\phi$ is defined previously as the latitude of the hurricane eye.

Figure 2.12: An example of historical hurricane track and gradient wind field (Hurricane Hugo)
Substituting Eqn. (2.20) into (2.18) gives the gradient wind speed at location \((r, \beta)\):

\[
V_g = \frac{1}{2} (V_r \sin \beta - f_r) + \sqrt{\frac{1}{4} (V_r \sin \beta - f_r)^2 + B \frac{P_a - P_e}{\rho_a} \left(\frac{R_{max}}{r}\right)^b} e^{-\left(\frac{\theta_{max}}{r}\right)^b}
\]  

(2.22)

The direction \((\psi_g)\) of the gradient wind speed is:

\[
\psi_g = 90^\circ - \beta - \theta
\]  

(2.23)

where, \(\theta\) is the hurricane heading angle measured from north (counter-clockwise is positive). Thus, the wind direction \(\psi_g\) is measured from east (counter-clockwise is positive); and the gradient wind speed components along the latitudinal and longitudinal directions are:

\[
V_{g\phi} = V_g \sin(\psi_g)
\]  

(2.24)

\[
V_{g\lambda} = V_g \cos(\psi_g)
\]  

(2.25)

In ADCIRC, the surface wind speed (10-meter elevation from the ground) is required as part of the meteorological forcing for storm surge simulations. In order to convert the wind speed from gradient level to surface level, the conversion factors developed by Vickery et al. (2009) were used. Vickery et al. (2009) suggested a conversion factor over water of around 0.71 per a boundary layer model, and about 19% reduction for sea-land transitions.
Determination of Hurricane Time Interval

Hurricane information (wind velocities and atmospheric pressures) is read into the ADCIRC model with an evenly spaced time interval (between hurricane time steps, see Table 2.1, WTIMINC), which is usually larger than the time step (Table 2.1, DTDP) used for solving the governing equation of the ADCIRC model. The ADCIRC model uses linear interpolation to upsample the hurricane wind velocity and atmospheric pressure time histories to match the computational time steps. According to the ADCIRC source code, linear interpolation is performed for hurricane wind speeds \( W_T \) with a weighting factor \( \kappa \):

\[
\kappa = \frac{T - T_1}{\Delta T} \tag{2.26}
\]

\[
W_T = W_1 + \kappa(W_2 - W_1) \tag{2.27}
\]

where, \( T \) is the time in the model (corresponding to current computational time step); \( T_1 \) is the time at previous hurricane time step; \( \Delta T \) is the hurricane time interval and; \( W_1 \) and \( W_2 \), read from the input file, are wind velocities at previous and next hurricane time steps, separately.

Figures 2.13 and 2.14 show seven snapshots of sample hurricane wind fields interpolated using a time step (hurricane time interval) \( \Delta T \) of 6h and 1h, respectively. As can be clearly seen from Eqns. (2.26) and (2.27) along with Figures 2.13 and 2.14, the smaller the hurricane time interval is, the more accurate the wind speeds can be
represented; however, it takes more time to discretize the larger input file during the preprocessing phase in parallel computing.

Therefore, a methodology was proposed to determine a proper hurricane time interval to account for both accuracy and computational demand. As illustrated in Figure 2.15, the travel distance between any two hurricane time steps of each individual hurricane analyzed in this study (described in the next section) was not allowed to exceed

\[ \frac{R_{\text{max}}}{2} \] (half of the radius-to-maximum wind) at that particular step. In other words, the maximum hurricane time interval was not allowed to surpass the minimum travel time of

\[ \frac{R_{\text{max}}}{2} \] at every step of each individual hurricane. The minimum time \( T_{\text{min}} \) required to travel a distance equal to \( \frac{R_{\text{max}}}{2} \) was calculated as:

\[
T_{\text{min}} = \min\left(\frac{R_{\text{max},i}/2}{V_{T,i}}\right)
\] (2.28)

where, \( R_{\text{max},i} \) is the radius from hurricane eye to the maximum wind speed at hurricane time step \( i \); and \( V_{T,i} \) is the translational wind speed at hurricane time step \( i \).
Figure 2.13: Snapshots of sample hurricane wind fields with 6h time interval
Figure 2.14: Snapshots of sample hurricane wind fields with 1h time interval
Figure 2.15: Wind fields used for hurricane time interval determination

Figure 2.16 shows the relationship between the hurricane numbers and the rank ordered minimum travel time of each hurricane within the study domain. According to this figure, a 15-minute hurricane time interval $\Delta T$ was deemed adequate for the purpose of generating wind fields for storm surge simulations.

Therefore, the temporal variation of hurricane wind field was modeled using a series of discrete wind fields at a 15-min time increment (see Table 2.1, WTIMINC = 900). Since the hurricane parameters in HURDAT are for a 6-hour time interval, linear interpolations were performed to obtain the wind field parameters for a 15-min time increment. Eqn. (2.22) was then used along with the gradient-to-surface wind speed conversion factors to calculate the 10-m surface wind speeds for each historical hurricane.
event at a 15-min time step. The surface wind speeds and air pressures at the nodes of the finite element mesh (Figure 2.10) were inputted into the ADCIRC program as forcing functions to compute the storm surge elevations. A MATLAB code (as attached in Appendix B) was written to automatically generate these hurricane input files (fort.22) for the ADCIRC model.

![Graph showing minimum travel time of historical hurricanes within the study domain](image)

Figure 2.16: Minimum travel time of historical hurricanes within study domain

Owing to the computational demand of large number of hurricane storm surge calculations, the high performance computing (HPC) facility at Clemson University, the *Palmetto Cluster*, was utilized to conduct the storm surge simulations. The storm surge analysis for one hurricane was carried out on eight processors in parallel. The use of
parallel computing reduced the analysis time significantly compared to the analysis performed on a typical single-processor personal computer.
CHAPTER THREE

SIMULATIONS AND MODELING ERROR QUANTIFICATION

Hurricane and Storm Surge Simulations

The wind fields of 169 historical hurricanes from 1922 to 2011 were computed using the Georgiou’s wind field model and the HURDAT database. The wind field data for each hurricane were then converted into a format that is consistent with the input file format of ADCIRC to simulate the hurricane storm surges. Prior to the hurricane storm surge simulation, tidal forcing was ramped over a period of 10 days to obtain a stable tidal solution for the study domain. For each historical hurricane, the water elevations at nine locations along the coastline of the study domain were simulated and recorded using the ADCIRC program. These nine locations correspond to the locations of the Center for Operational Oceanographic Products and Services (CO-OPS) water level monitoring stations along the coast of North Carolina, South Carolina and Georgia (Figure 3.1). The CO-OPS station numbers, latitudes and longitudes are given in Table 3.1. Figures 3.2 to 3.6 show the comparisons between the measured and simulated storm surge time histories of five historical hurricanes at five observation stations. As can be seen from these figures, while the simulated storm surges generally agree well with the measured surge elevations, modeling errors between the observed and simulated surge elevations do exist.
Figure 3.1: Locations of water level observation stations along the Coast of North Carolina, South Carolina and Georgia

Figure 3.2: Comparisons between measured and simulated surge elevations for Hurricane Hanna (2008) at Station 8658120

Station 8658120
Hurricane Hanna (2008.9.1 18:00 - 9.7 18:00)

Figure 3.2: Comparisons between measured and simulated surge elevations for Hurricane Hanna (2008) at Station 8658120
Figure 3.3: Comparisons between measured and simulated surge elevations for Hurricane Ernesto (2006) at Station 8665530

Figure 3.4: Comparisons between measured and simulated surge elevations for Hurricane Gaston (2004) at Station 8670870
Figure 3.5: Comparisons between measured and simulated surge elevations for Hurricane Charley (2004) at Station 8656483

Figure 3.6: Comparisons between measured and simulated surge elevations for Hurricane Kyle (2002) at Station 8661070
Table 3.1: Modeling error parameters for water level observation stations along the Coast of North Carolina, South Carolina and Georgia

<table>
<thead>
<tr>
<th>Water Station Number</th>
<th>Latitude (deg)</th>
<th>Longitude (deg)</th>
<th>Number of Data Points</th>
<th>$\bar{S}_s$ (m)</th>
<th>$\varepsilon$</th>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>$c_0$</td>
<td>$c_1$</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>$\mu_{\ln \varepsilon}$</td>
<td>$\sigma_{\ln \varepsilon}$</td>
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</table>
Modeling Error Quantification

Modeling errors of hurricane storm surge simulations were quantified by comparing the model simulated and the actual observed annual maximum surge elevations. Note that the errors associated with the wave effects were inherently included in the modeling errors quantified in this study since observations at the CO-OPS stations included waves that could not be subtracted from the real measurements. The annual maximum surge height statistics since 1922 (90 years in total) were compiled for each of the nine water stations using the historical measurements obtained from the CO-OPS database. Data were collected for each water station starting from the following year when the particular station was established. Note that some data points were missing due to sensor failures at the water stations during a few major hurricane events. These data points were excluded from the modeling error calculations performed for the affected stations. It should be noted that only the annual maxima caused by the tropical storms were considered in this study. Surges due to other storms such as the nor’easter storms were not considered in this study.

The scatter plots between the measured ($S_m$) and simulated ($S_s$) annual maximum storm surge heights at four selected stations are presented in Figures 3.7 to 3.10 (see Appendix C for more figures at all other locations). As can be clearly seen, the measured and simulated surges do not have a 1:1 relationship (i.e. measurements equal to simulations) which indicates that modeling errors exist. The modeling errors quantified in this study consist of two components: systematic and random errors. The systematic
errors in the model lead to biases between the simulated values and the actual measurements which are caused by the model structure and parameterizations employed to describe the actual meteorological conditions such as the omission of wave effects, the selection of finite element grids, the use of wind field model to represent the actual wind vortex, and etc. The random errors are errors arise due to the inherent randomness in the meteorological events. For instance, the inherent randomness in the wind turbulence, variation in wind direction, and etc. may cause random errors between the model simulated and the observed surge heights.

Figure 3.7: Measured versus simulated storm surge heights at Station 8651370
Figure 3.8: Measured versus simulated storm surge heights at Station 8658120

Figure 3.9: Measured versus simulated storm surge heights at Station 8665530
A previous study has shown that the relationship between the measured and simulated storm surge heights can be characterized using a power equation times a random error term (Pang et al. 2009):

\[ S_m = \bar{S}_s e = c_0 (\bar{S}_s)^{c_1} e \]  

(3.1)

The power equation \((\bar{S}_s = c_0 S_s^{c_1})\) was used to account for the systematic errors of the model while the random errors were described using the error term \((e)\) computed as the measured surge height \((S_m)\) divided by the \textit{systematic-error-adjusted} annual maximum surge height \((\bar{S}_s)\). The \(c_0\) and \(c_1\) are the site-specific constants of the power equation which were determined via least-squares regression analysis of the logarithmic transformation of Eqn. (3.1):
\[
\ln(S_m) = \ln(c_0) + c_1 \ln(S_s) + \ln(\varepsilon)
\]  
(3.2)

The least-squares lines (shown as solid lines in Figures 3.7 to 3.10) pass through the center of mass of all the data points. In Figures 3.7 to 3.10, the systematic errors are depicted as the differences between the least-squares lines (solid lines) and the dash lines with a 1:1 relationship between the measurements and simulations. The random errors are represented as the dispersion of data points around the least-squares lines.

The relationships between \(S_m\) (actual measurements) and \(\overline{S}_s\) (systematic-error-adjusted surge elevations) at four selected stations are plotted in Figures 3.11 to 3.14 (the rests are given in Appendix D). It can be seen that the \(S_m\) and \(\overline{S}_s\) data pairs are scattered along the 1:1 line (measurements equal to simulations), which indicates that the systematic errors have been corrected. Meanwhile, the relationships between \(\overline{S}_s\) and \(\varepsilon\) (random errors) are shown in Figures 3.15 to 3.18 along with the correlation coefficients (\(\rho\)) calculated at the selected stations (figures for all other locations are presented in Appendix E). As can be clearly seen, the systematic-error-adjusted surge heights and the random error terms are essentially uncorrelated (|\(\rho\)| less than 0.05). This confirms that the random errors (\(\varepsilon\)) are independent of \(\overline{S}_s\).
Figure 3.11: Measured versus systematic-error-adjusted surge heights at Station 8651370

Figure 3.12: Measured versus systematic-error-adjusted surge heights at Station 8658120
Figure 3.13: Measured versus systematic-error-adjusted surge heights at Station 8665530

Figure 3.14: Measured versus systematic-error-adjusted surge heights at Station 8670870
Figure 3.15: Correlation analysis between systematic-error-adjusted surge heights and random errors at Station 8651370

Figure 3.16: Correlation analysis between systematic-error-adjusted surge heights and random errors at Station 8658120
Figure 3.17: Correlation analysis between systematic-error-adjusted surge heights and random errors at Station 8665530

Figure 3.18: Correlation analysis between systematic-error-adjusted surge heights and random errors at Station 8670870
Figures 3.19 and 3.20 show the cumulative diminutions of the systematic-error-adjusted surge heights ($\bar{S}_s$) and the random errors ($\varepsilon$) fitted to the lognormal cumulative distribution functions (CDFs) at two selected stations (figures for other locations can be found in Appendix F):

$$F_x = \Phi\left(\frac{\ln(x) - \mu_{\ln x}}{\sigma_{\ln x}}\right) \quad (3.3)$$

where, $F_x$ is the lognormal cumulative distribution function; $\Phi(.)$ is the standard normal CDF; $\mu_{\ln x}$ is the logarithmic mean, also known as the location parameter; $\sigma_{\ln x}$ is the logarithmic standard deviation, also known as the scale parameter; and $x$ is the random variable (i.e. either $\bar{S}_s$ or $\varepsilon$). The logarithmic means ($\mu_{\ln x}$) and standard deviations ($\sigma_{\ln x}$) of the random errors and the regression constants ($c_0$ and $c_1$) of the power equation [Eqn. (3.1)], as well as the number of data points used to fit the lognormal distribution parameters, are listed in Table 3.1 (columns 4 to 8). Note that the logarithmic means of the random errors ($\mu_{\ln x}$) for all the stations are essentially equal to zero, which indicates that the random errors are unbiased. In other words, the power equation can be used to remove the modeling biases and the resulting systematic-error-adjusted surge simulations ($\bar{S}_s$) only suffer the random errors.
Figure 3.19: Lognormal distribution fits of systematic-error-adjusted surge heights and random errors at Station 8665530
Figure 3.20: Lognormal distribution fits of systematic-error-adjusted surge heights and random errors at Station 8670870
The Kolmogorov-Smirnov (K-S) test statistics for the lognormal distribution fits of the systematic-error-adjusted surge heights ($\bar{S}_s$) and the random errors ($\varepsilon$) are listed in Table 3.2 (columns 2 and 3) along with the corresponding critical values of the K-S test at a significance level of $\alpha = 0.05$ (column 5). In Table 3.2, the bracketed values are the numbers of data points used to fit the lognormal distribution parameters. It can be seen that the K-S test statistics are all smaller than the critical values, which means the lognormal distribution can be used to describe the distribution of $\bar{S}_s$ and $\varepsilon$. 
Table 3.2: Kolmogorov-Smirnov test statistics and critical values for lognormal distribution fits of the systematic-error-adjusted surge heights, random errors, and annual, 5-year and 10-year maximum surge heights ($\alpha = 0.05$)

<table>
<thead>
<tr>
<th>Water Station Number</th>
<th>$\bar{S}_e$</th>
<th>$\varepsilon$</th>
<th>Annual Max.</th>
<th>Critical Values (for cols. 2 to 4)</th>
<th>5-yr Max.</th>
<th>Critical Values (for col. 6)</th>
<th>10-yr Max.</th>
<th>Critical Values (for col. 8)</th>
</tr>
</thead>
<tbody>
<tr>
<td>8651370</td>
<td>0.107</td>
<td>0.082</td>
<td>0.153</td>
<td>0.242 (30)</td>
<td>0.158</td>
<td>0.519 (6)</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>8652587</td>
<td>0.205</td>
<td>0.083</td>
<td>0.164</td>
<td>0.338 (15)</td>
<td>*</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>8654400</td>
<td>0.117</td>
<td>0.083</td>
<td>0.150</td>
<td>0.281 (22)</td>
<td>0.223</td>
<td>0.563 (5)</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>8656483</td>
<td>0.190</td>
<td>0.158</td>
<td>0.132</td>
<td>0.281 (22)</td>
<td>0.194</td>
<td>0.563 (5)</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>8658120</td>
<td>0.157</td>
<td>0.105</td>
<td>0.065</td>
<td>0.160 (70)</td>
<td>0.131</td>
<td>0.349 (14)</td>
<td>0.160</td>
<td>0.483 (7)</td>
</tr>
<tr>
<td>8661070</td>
<td>0.075</td>
<td>0.099</td>
<td>0.103</td>
<td>0.242 (30)</td>
<td>0.279</td>
<td>0.519 (6)</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>8665530</td>
<td>0.092</td>
<td>0.104</td>
<td>0.069</td>
<td>0.148 (82)</td>
<td>0.116</td>
<td>0.318 (17)</td>
<td>0.146</td>
<td>0.430 (9)</td>
</tr>
<tr>
<td>8670870</td>
<td>0.077</td>
<td>0.090</td>
<td>0.099</td>
<td>0.160 (70)</td>
<td>0.131</td>
<td>0.349 (14)</td>
<td>0.116</td>
<td>0.483 (7)</td>
</tr>
<tr>
<td>8677344</td>
<td>0.148</td>
<td>0.136</td>
<td>0.184</td>
<td>0.391 (11)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

* Kolmogorov-Smirnov (K-S) tests were not performed when there were less than 5 data points. Numbers in brackets mean the numbers of data points used to determine the critical K-S values.
CHAPTER FOUR
RESULT VALIDATION

Validation of Error-Adjusted Storm Surge Distributions

To verify the validity of the modeling error correction terms developed in this study, the recorded annual, 5-year and 10-year maximum storm surge distributions were compiled for each water level observation station and compared to the model simulated and adjusted maximum surge heights. Using the modeling error adjustment parameters quantified for the nine water stations (Table 3.1 columns 5 to 8), the following steps were performed to adjust the simulated surge heights:

1) For each station, determine the annual maximum surge heights based on the surge elevations simulated using the ADCIRC program ($S_s$).

2) Adjust the model simulated annual maximum surge heights ($S_s$) for systematic errors using the power equation [Eqn. (3.1), $\tilde{S}_s = c_0 (S_s)^{c_1}$] and the site-specific coefficients $c_0$ and $c_1$ provided in Table 3.1 (columns 5 and 6).

3) Fit the systematic-error-adjusted surge simulations ($\tilde{S}_s$) to a lognormal distribution and estimate the logarithmic mean and standard deviation parameters ($\mu_{\ln\tilde{S}_s}$ and $\sigma_{\ln\tilde{S}_s}$).

4) Correct the systematic-error-adjusted annual maximum surge distribution for random errors by multiplying the random error term ($\varepsilon$) to $\tilde{S}_s$. Note that lognormal distributions are self-replicating under multiplications or divisions; thus the product of
lognormally distributed $\bar{S}$, and $\varepsilon$ also follows a lognormal distribution. The lognormal distribution parameters, logarithmic mean ($\ln \mu$) and logarithmic standard deviation ($\ln \sigma$), of the final error-adjusted surge heights ($\bar{S}, \varepsilon$) are given in Eqns. (4.1) and (4.2), respectively:

$$\ln \mu = \ln \mu_{inS} + \ln \mu_{in\varepsilon}$$  

$$\ln \sigma = \sqrt{\ln \sigma_{inS}^2 + \ln \sigma_{in\varepsilon}^2}$$

where, the lognormal distribution parameters for $\bar{S}$ ($\ln \mu_{inS}$ and $\ln \sigma_{inS}$) are determined in step 3 and the lognormal distribution parameters for $\varepsilon$ ($\ln \mu_{in\varepsilon}$ and $\ln \sigma_{in\varepsilon}$) are given in Table 3.1 (columns 7 and 8).

5) Substitute the logarithmic mean ($\ln \mu$) and standard deviation ($\ln \sigma$) determined in step 4 into Eqn. (3.3) to compute the CDF values ($F_x$) of the error-adjusted annual maximum surge heights.

6) Assuming the annual maximum surge heights are independent from year to year, calculate the 5-year and 10-year maximum surge CDF values by raising the annual $F_x$ values to the 5-th and 10-th power, accordingly ($F_x^5$ and $F_x^{10}$).

The annual, 5-year and 10-year maximum surge height distributions and the lognormal fits for three selected stations are shown in Figures 4.1 to 4.3 [the annual data are presented in subplot (a); the 5-year and 10-year data are shown in subplot (b)]. Figures for all other locations are presented in Appendix G. Circles, triangles and diamonds represent the annual, 5-year and 10-year maximum surge heights, respectively.
The K-S tests were performed to determine the goodness-of-fits of the lognormal distributions for the annual, 5-year and 10-year maximum surge data (Table 3.2). As shown in Table 3.2 (columns 4, 6 and 8), the K-S values are all below the critical K-S values, which mean the annual, 5-year and 10-year maximum distributions can be reasonably approximated using the lognormal distributions.

From Figures 4.1 to 4.3, it can be seen that the dispersions of the unadjusted model simulated annual maximum surge heights (solid dots) are generally less than that of the observed surge heights (hollow circles). In other words, the slopes of the unadjusted model simulated cumulative maximum surge distributions, which do not include the random errors, are steeper than that of the corresponding observed cumulative surge distributions which inherently include the random errors. For engineering application, the upper percentile values, for instance the 90 or 95 percentile, are typically taken as the design values to ensure that the actual surge heights will be less than the design values 90% or 95% of the times. The surge data estimated without correcting for the modeling errors (both the systematic and random errors) are potentially un-conservative and may underestimate the actual surge elevations particularly for the extreme high surge events. As can be clearly seen in Figures 4.1 to 4.3, the final error-adjusted annual, 5-year and 10-year maximum surge distribution curves generally match the actual observed surge data (circles, triangles and diamonds) well.
Figure 4.1: Comparisons between measured and simulated annual, 5-year and 10-year maximum surge heights adjusted for modeling errors at Station 8658120
Figure 4.2: Comparisons between measured and simulated annual, 5-year and 10-year maximum surge heights adjusted for modeling errors at Station 8665530
Figure 4.3: Comparisons between measured and simulated annual, 5-year and 10-year maximum surge heights adjusted for modeling errors at Station 8670870
Validation for Individual Hurricane Events

To verify if the proposed methodology can correct the surge height modeling errors for individual hurricane events, simulated annual maximum surge height data points were adjusted one by one at four selected water stations using the aforementioned method and plotted to Figures 4.4 to 4.7 with the corresponding measured surge heights (similar figures for all other stations can be found in Appendix H). As can be clearly seen in these figures, the proposed methodology that worked for corrections of surge height distributions for a group of hurricane events over a long period does not work well for individual hurricanes. The RMS (root-mean-square) errors between the simulated and measured annual maximum surge heights before and after the adjustments were also calculated at all nine water level observation stations and listed in Table 4.1. In Table 4.1, “distribution” means the RMS errors were computed per rank-ordered simulated and measured surge data, while “individual” means the simulated surge heights were adjusted individually and paired with the correspondingly measured data. The same conclusion can be made based upon this table. The methodology works for surge height distributions for a group of hurricanes but not for individual events. Therefore, the methodology presented in this study should only be used to adjust the surge height distributions for long-term hurricane events and should not be used to adjust the simulated surge heights of individual hurricanes.
Figure 4.4: Measured verse simulated surge heights adjusted for individual hurricane events at Station 8651370

Figure 4.5: Measured verse simulated surge heights adjusted for individual hurricane events at Station 8658120
Figure 4.6: Measured verse simulated surge heights adjusted for individual hurricane events at Station 8665530

Figure 4.7: Measured verse simulated surge heights adjusted for individual hurricane events at Station 8670870
Table 4.1: RMS errors between simulated and measured annual maximum surge heights before and after adjustments

<table>
<thead>
<tr>
<th>Water Station Number</th>
<th>RMS Errors before Adjustments (m)</th>
<th>RMS Errors after Adjustments (m) (for Distributions)</th>
<th>RMS Errors after Adjustments (m) (for Individual Events)</th>
</tr>
</thead>
<tbody>
<tr>
<td>8651370</td>
<td>0.21</td>
<td>0.08</td>
<td>0.23</td>
</tr>
<tr>
<td>8652587</td>
<td>0.35</td>
<td>0.19</td>
<td>0.34</td>
</tr>
<tr>
<td>8654400</td>
<td>0.14</td>
<td>0.07</td>
<td>0.15</td>
</tr>
<tr>
<td>8656483</td>
<td>0.19</td>
<td>0.07</td>
<td>0.19</td>
</tr>
<tr>
<td>8658120</td>
<td>0.16</td>
<td>0.04</td>
<td>0.19</td>
</tr>
<tr>
<td>8661070</td>
<td>0.16</td>
<td>0.09</td>
<td>0.19</td>
</tr>
<tr>
<td>8665530</td>
<td>0.18</td>
<td>0.07</td>
<td>0.21</td>
</tr>
<tr>
<td>8670870</td>
<td>0.17</td>
<td>0.03</td>
<td>0.17</td>
</tr>
<tr>
<td>8677344</td>
<td>0.21</td>
<td>0.09</td>
<td>0.20</td>
</tr>
</tbody>
</table>
CHAPTER FIVE

SUMMARY AND CONCLUSIONS

A total of 90 years (1922-2011) of historical hurricane storm surges from 169 individual hurricane events were simulated using the ADCIRC program with a high performance computing facility. The wind velocities and air pressures computed using the Georgiou’s wind field model and the information from the HURDAT served as the inputs for the ADCIRC program. The model simulated water elevations were recorded at nine locations which corresponded to the locations of nine real observation stations maintained by the Center for Operational Oceanographic Products and Services (CO-OPS) along the coastline of North Carolina, South Carolina and Georgia.

Using the measured hurricane storm surge heights at the CO-OPS water stations, the annual maximum surge height statistics were computed at the nine water level observation stations. The modeling errors (systematic and random errors) were estimated for each water stations by comparing the simulated to measured annual maximum surge heights. A power equation was utilized to quantify the systematic errors in the surge simulations and a lognormal distribution was used to characterize the random errors in the surge heights. The error-adjusted simulated surge heights have been shown to match well with the real storm surge measurements. Even though the determined modeling errors are only applicable to the specific combination of storm surge model (i.e. ADCIRC) and hurricane wind field model used in this study, the methodology employed to quantify the modeling errors can be easily applied to other models (e.g. SLOSH model combined with the Vickery et al. (2000) wind field model).
Error quantification plays an important role in long-term storm surge simulations. Most of the CO-OPS stations have less than 90 years of recorded surge data. Hence, to determine the storm surge heights for return periods greater than 90 years, one will need to rely on stochastic models and long-term hurricane storm surge simulations to predict the surge heights with long mean return intervals. Modeling errors presented in this study can be used to correct for the errors introduced in long-term storm surge simulations and to generate reliable storm surge hazard maps.
CHAPTER SIX

FUTURE WORK

This study can be further improved by addressing the possible shortcomings in storm surge simulations. The simulated surge heights will be more accurate if wave set-up is taken into account. The wave components, which are important in storm surge simulations, can be considered by running the coupled ADCIRC+SWAN (Simulating Waves Nearshore) model. By doing more, instead of a few parameter sensitivity studies, more reliable surge modeling parameters (such as break depth and horizontal eddy diffusion coefficient) can be obtained rather than only taking the recommended values. It should be noted that the standard deviation of the errors determined using the methodology presented herein is likely tied to the resolution of the finite element mesh. To reduce the error range, one may improve the quality and resolution of the finite element mesh (i.e. decrease the minimum distance between two nodes), using more detailed coastline database, and/or more accurate bathymetric and topographic data.

For possible applications of this proposed methodology, other than generating reliable storm surge maps as mentioned in previous sections, it can be used for any other studies relevant to storm surge simulations to adjust for simulated surge heights, as long as the site-specific measured data are available. For instance, the study of climate change on hurricane storm surges, the development of site-specific joint distributions of hurricane wind and storm surge, the long-term loss estimation subject to combined hurricane wind and storm surge, and so forth.
APPENDICES
Appendix A

A Sample ADCIRC Control File (fort.15)

Error_Quantification    ! RUNDES - UPTO 32 CHARACTER ALPHANUMERIC RUN
DESCRIPTION
Hurricane_N                 ! RUNID - UPTO 24 CHARACTER ALPHANUMERIC RUN
IDENTIFICATION
1        ! NFOVER - NONFATAL ERROR OVERRIDE OPTION
2        ! NABOUT - ABBREVIATED OUTPUT OPTION PARAMETER
-1       ! NSCREEN - OUTPUT TO UNIT 6 PARAMETER
0        ! I HOT - HOT START OPTION PARAMETER
2        ! ICS - COORDINATE SYSTEM OPTION PARAMETER
0        ! IM - MODEL RUN TYPE: 0,10,20,30 = 2DDI, 1,11,21,31 = 3D(VS), 2 = 3D(DSS)
2        ! NOLIBF - NONLINEAR BOTTOM FRICTION OPTION
2        ! NOLIFA - OPTION TO INCLUDE FINITE AMPLITUDE TERMS
1        ! NOLICA - OPTION TO INCLUDE CONVETIVE ACCELERATION TERMS
1        ! NOLICAT - OPTION TO CONSIDER TIME DERIVATIVE OF CONV ACC TERMS
0        ! NWP - NUMBER OF NODAL ATTRIBUTES
1        ! NCOR - VARIABLE CORIOLIS IN SPACE OPTION PARAMETER
1        ! NTIP - TIDAL POTENTIAL OPTION PARAMETER
4        ! NWS - WIND STRESS AND BAROMETRIC PRESSURE OPTION PARAMETER
1        ! NRAMP - RAMP FUNCTION OPTION
9.81     ! G - ACCELERATION DUE TO GRAVITY - DETERMINES UNITS
-1       ! TAU0 - WEIGHTING FACTOR IN GWCE
6.00     ! DTDP - TIME STEP (IN SECONDS)
0.00     ! STATIM - STARTING SIMULATION TIME IN DAYS
0.00     ! REFTIME - REFERENCE TIME (IN DAYS) FOR NODAL FACTORS AND EQUILIBRIUM ARGS
900      ! WTIMINC - METEOROLOGICAL WIND TIME INTERVAL
11.75    ! RNDAY - TOTAL LENGTH OF SIMULATION (IN DAYS)
10.00    ! DRAMP - DURATION OF RAMP FUNCTION (IN DAYS)
0.35 0.30 0.35  ! A00, B00, C00 - TIME WEIGHTING FACTORS FOR THE GWCE EQUATION
0.05 1 1 0.05  ! H0, INTEGER, INTEGER, VELMIN - MINIMUM WATER DEPTH, ANY INTEGER, ANY INTEGER, MINIMUM VELOCITY OF WETTING
-77.28 32.63  ! SLAM0, SFEA0 - LONGITUDE AND LATITUDE ON WHICH THE CPP COORDINATE PROJECTION IS CENTERED
5.00  ! ESLM - SPATIALLY CONSTANT HORIZONTAL EDDY VISCOSITY FOR
THE MOMENTUM EQUATIONS

0.00010  ! CORI - CORIOLIS PARAMETER - IGNORED IF NCOR = 1
7      ! NTIF - TOTAL NUMBER OF TIDAL POTENTIAL CONSTITUENTS
K1    ! TIPOTAG - NAME OF TIDAL POTENTIAL CONSTITUENT
0.141565 0.000072921158358 0.736000 1.109950 252.220000  ! TPK, AMIGT, ETRF,
FFT, FACET - CONSTITUENT PROPERTIES
K2    ! TIPOTAG - NAME OF TIDAL POTENTIAL CONSTITUENT
0.030704 0.000145842317201 0.693000 1.306850 324.200000  ! TPK, AMIGT, ETRF,
FFT, FACET - CONSTITUENT PROPERTIES
M2    ! TIPOTAG - NAME OF TIDAL POTENTIAL CONSTITUENT
0.242334 0.000140518902509 0.693000 0.964400 328.680000  ! TPK, AMIGT, ETRF,
FFT, FACET - CONSTITUENT PROPERTIES
N2    ! TIPOTAG - NAME OF TIDAL POTENTIAL CONSTITUENT
0.046398 0.00013789699487 0.693000 0.964400 103.440000  ! TPK, AMIGT, ETRF,
FFT, FACET - CONSTITUENT PROPERTIES
O1    ! TIPOTAG - NAME OF TIDAL POTENTIAL CONSTITUENT
0.100514 0.000067597744151 0.695000 1.178440 77.250000  ! TPK, AMIGT, ETRF,
FFT, FACET - CONSTITUENT PROPERTIES
Q1    ! TIPOTAG - NAME OF TIDAL POTENTIAL CONSTITUENT
0.019256 0.000064958541129 0.695000 1.178440 212.020000  ! TPK, AMIGT, ETRF,
FFT, FACET - CONSTITUENT PROPERTIES
S2    ! TIPOTAG - NAME OF TIDAL POTENTIAL CONSTITUENT
0.112841 0.0001454444104333 0.693000 1.000000 0.000000  ! TPK, AMIGT, ETRF,
FFT, FACET - CONSTITUENT PROPERTIES
7      ! NBFR - NUMBER OF PERIODIC FORCING FREQUENCIES ON
ELEVATION SPECIFIED BOUNDARIES
K1    ! BOUNTAG - ALPHA DESCRIPTOR OF FORCING FREQUENCY ON NEXT
LINE
0.000072921158358 1.109950 252.220000  ! AMIG, FF, FACE - FORCING
FREQUENCY, NODAL FACTOR, AND EQUILIBRIUM ARGUMENT IN DEGREES
K2    ! BOUNTAG - FORCING CONSTITUENT NAME
0.000145842317201 1.306850 324.200000  ! AMIG, FF, FACE - FORCING
FREQUENCY, NODAL FACTOR, AND EQUILIBRIUM ARGUMENT IN DEGREES
M2    ! BOUNTAG - FORCING CONSTITUENT NAME
0.000140518902509 0.964400 328.680000  ! AMIG, FF, FACE - FORCING
FREQUENCY, NODAL FACTOR, AND EQUILIBRIUM ARGUMENT IN DEGREES
N2    ! BOUNTAG - FORCING CONSTITUENT NAME
0.00013789699487 0.964400 103.440000  ! AMIG, FF, FACE - FORCING
FREQUENCY, NODAL FACTOR, AND EQUILIBRIUM ARGUMENT IN DEGREES
O1    ! BOUNTAG - FORCING CONSTITUENT NAME
0.000067597744151 1.178440 77.250000  ! AMIG, FF, FACE - FORCING FREQUENCY, NODAL FACTOR, AND EQUILIBRIUM ARGUMENT IN DEGREES Q1  ! BOUNTAG - FORCING CONSTITUENT NAME
0.000064958541129 1.178440 212.020000  ! AMIG, FF, FACE - FORCING FREQUENCY, NODAL FACTOR, AND EQUILIBRIUM ARGUMENT IN DEGREES S2  ! BOUNTAG - FORCING CONSTITUENT NAME
0.000145444104333 1.000000 0.000000  ! AMIG, FF, FACE - FORCING FREQUENCY, NODAL FACTOR, AND EQUILIBRIUM ARGUMENT IN DEGREES K1  ! ALPHA - FORCING CONSTITUENT NAME AGAIN
0.089851  176.716  ! EMO, EFA - AMPLITUDE AND PHASE IN DEGREES
0.089860  176.722
0.089869  176.728
0.089878  176.734
0.089885  176.735

Eliminated

0.110100  194.395
0.110110  194.397
0.110110  194.398
0.110120  194.398
0.110130  194.397
K2  ! ALPHA - FORCING CONSTITUENT NAME AGAIN
0.020517  30.843  ! EMO, EFA - AMPLITUDE AND PHASE IN DEGREES
0.020520  30.815
0.020522  30.786
0.020525  30.757
0.020526  30.724

Eliminated

0.032125  36.150
0.032123  36.157
0.032121  36.164
0.032120  36.171
0.032135  36.170
M2  ! ALPHA - FORCING CONSTITUENT NAME AGAIN
0.491160  356.691  ! EMO, EFA - AMPLITUDE AND PHASE IN DEGREES
0.491180  356.685
0.491200  356.680
0.491220  356.674
0.491200  356.667

Eliminated
N2  ! ALPHA - FORCING CONSTITUENT NAME AGAIN
0.850290  9.329
0.850260  9.337
0.850250  9.344
0.850260  9.350
0.850620  9.347

Eliminated

O1  ! ALPHA - FORCING CONSTITUENT NAME AGAIN
0.114620  342.325  ! EMO, EFA - AMPLITUDE AND PHASE IN DEGREES
0.114630  342.319
0.114640  342.313
0.114640  342.306
0.114640  342.299

Eliminated

Q1  ! ALPHA - FORCING CONSTITUENT NAME AGAIN
0.012577  178.255  ! EMO, EFA - AMPLITUDE AND PHASE IN DEGREES
0.012579  178.253
0.012580  178.252
0.012580  178.250
0.012580  178.251

Eliminated

0.014797  194.755
S2  ! ALPHA - FORCING CONSTITUENT NAME AGAIN

0.014797  194.755
0.014798  194.755
0.014799  194.753
0.014800  194.752

Eliminated

0.145680  28.713
0.145670  28.720
0.145670  28.726
0.145670  28.730
0.145730  28.729

90  ! ANGINN - MINIMUM ANGLE FOR TANGENTIAL FLOW
0 0.00 0.00 0.00  ! NOUTE, TOUTSE, TOUTFE, NSPOOLE - FORT 61 OPTIONS
0  ! NSTAE - NUMBER OF ELEVATION RECORDING STATIONS, FOLLOWED
      BY LOCATIONS ON PROCEEDING LINES
0 0.00 0.00 0.00  ! NOUTV, TOUTSV, TOUTFV, NSPOOLV - FORT 62 OPTIONS
0  ! NSTAV - NUMBER OF VELOCITY RECORDING STATIONS, FOLLOWED
      BY LOCATIONS ON PROCEEDING LINES
0 0.00 0.00 0.00  ! NOUTM, TOUTSM, TOUTFM, NSPOOLM - METEOROLOGICAL
      OUTPUT INFO
0  ! NSTAM - NUMBER OF METEOROLOGICAL RECORDING STATIONS,
      FOLLOWED BY LOCATIONS ON PROCEEDING LINES
0 0.00 0.00 0.00  ! NOUTGE, TOUTSGE, TOUTFGE, NSPOOLGE - GLOBAL
      ELEVATION OUTPUT INFO (UNIT 63)
0 0.00 0.00 0.00  ! NOUTGV, TOUTSGV, TOUTFGV, NSPOOLGV - GLOBAL
      VELOCITY OUTPUT INFO (UNIT 64)
0 0.00 0.00 0.00  ! NOUTGW, TOUTSGW, TOUTFGW, NSPOOLGW - GLOBAL
      METEOROLOGICAL OUTPUT INFO (UNIT 73/74)
0  ! NFREQ - NUMBER OF FREQUENCIES IN HARMONIC ANALYSIS
0.00 0.00 0.00  ! THAS, THAF, NHAINC, FMV - HARMONIC ANALYSIS
      PARAMETERS
0 0 0 0  ! NHASE, NHASV, NHAGE, NHAGV - CONTROL HARMONIC
      ANALYSIS AND OUTPUT TO UNITS 51, 52, 53, 54
0 0  ! NHSTAR, NHSINC - HOT START FILE GENERATION PARAMETERS
1 0 1.0E-10 25  ! ITITER, ISLDIA, CONVCR, ITMAX - ALGEBRAIC SOLUTION
      PARAMETERS
Appendix B

A Sample MATLAB Code Used to Generate Hurricane Input Files (fort.22) for ADCIRC

Model

% ADCIRC input file - fort.22 generation
% NWS = 4 - wind velocity and atmospheric pressure are read at selected
%        ADCIRC grid nodes
clc;
clear;

node_filename='node_file.txt'; % input node file name
interval=15; % input hurricane step time interval (min)
g2s=0.71; % gradient to surface conversion factor

node_file=load(node_filename); % load node file
nLat=node_file(:,3); % latitude of nodes, vector
nLon=node_file(:,2); % longitude of nodes, vector

load('polygon.txt'); % load domain polygon
load('Eff_Hur.mat'); % load a list of effective hurricanes
load('HURDAT2011.mat'); % load HURDAT hurricane database

cd('input'); % change directory
for i=1:length(Eff_Hur) % loop through effective hurricanes
    Hur=HURDAT(1,Eff_Hur(i,1)); % find hurricane in HURDAT
    mkdir(num2str(Eff_Hur(i,1))); % create an input file folder
    cd(num2str(Eff_Hur(i,1)));

    filename='fort.22'; % create an empty input file
    fid=fopen(filename,'w'); % open the file

    % select hurricane time steps within the domain
    in=inpolygon(Hur.Lat,Hur.Lon,polygon(:,2),polygon(:,1));
    idx=find(in==1); % find time steps within the domain

    % hurricane parameter calculations
    % calculate Pc using an empirical equation for hurricanes
    % with Pc missing
    for j=1:length(Hur.Pc)
        if isnan(Hur.Pc(j))
            Vt=0.868976242*Hur.Vt_mph(j);
        else
            pcemp=Vt^2/12.7;
            pcemp=pcemp/2.5

            % calculate omega
            g2s=0.71;
            omega=g2s*sqrt(pcemp);

            % calculate g0
            g0=2*omega/2.5

            % calculate g1
            g1=pcemp/2.5

            % calculate nu
            nu=g1/omega

            % calculate f0
            f0=omega/2.5

            % calculate f1
            f1=pcemp/omega

            % calculate f2
            f2=pcemp/2.5

            % calculate f3
            f3=pcemp/pcemp

            % calculate f4
            f4=pcemp/pcemp

            % calculate f5
            f5=pcemp/pcemp

        end
    end

\[ Vm = 0.868976242 \times \text{Hur.Vmax}_\text{mph}(j); \]
\[ Vg = Vm - 1.5 \times Vt^{0.63}; \]
\[ \text{Hur.Pc}(j) = 1013 - ((Vg - 5.843 + 0.558 \times \text{Hur.Lat}(j))/14.118)^2; \]
\[ \text{dp} = 1013 - \text{Hur.Pc}; \quad \% \text{central pressure deficit} \]
\[ \text{Hur.Rmax} = \exp(2.636 - 0.00005086 \times \text{dp}^2 + 0.0394899 \times \text{Hur.Lat}); \quad \% \text{Rmax, km} \]
\[ \text{Hur.B} = 1.38 + 0.00184 \times \text{dp} - 0.00309 \times \text{Hur.Rmax}; \quad \% \text{B parameter} \]

\% create empty hurricane time steps for tidal ramping
\% j = 1:960 \% ramp 10 days
\% loop through hurricane time steps
\begin{verbatim}
for j = 1:960
    fprintf(fid, '#
');
    fprintf(fid, '%05i %+8.4E %+8.4E %+8.4E
', 1, 0, 0, 1013);
end
\end{verbatim}

\% part = 360/interval; \% interpolation times
\% loop through hurricane time steps
\begin{verbatim}
for j = n:m-1
    \% linear interpolations
    Lat = linspace(Hur.Lat(j), Hur.Lat(j+1), part+1);
    Lat = Lat(1:part);
    Lon = linspace(Hur.Lon(j), Hur.Lon(j+1), part+1);
    Lon = Lon(1:part);
    Rmax = linspace(Hur.Rmax(j), Hur.Rmax(j+1), part+1);
    Rmax = Rmax(1:part);
    Pc = linspace(Hur.Pc(j), Hur.Pc(j+1), part+1);
    Pc = Pc(1:part);
    B = linspace(Hur.B(j), Hur.B(j+1), part+1);
    B = B(1:part);
    HeadDir = ones(1, part+1) * Hur.HeadDir(j);
    HeadDir = HeadDir(1:part);
    Vt_kph = ones(1, part+1) * Hur.Vt_kph(j);
    Vt_kph = Vt_kph(1:part);
end
\end{verbatim}

\% d = distance(Lat(k), Lon(k), nLat, nLon); \% "d" is in deg.
\% d = distdim(d, 'deg', 'km'); \% convert to kilometers
\% compute gradient wind speeds
\% gradWspeed is a MATLAB function written based upon
\% Eqn. 2.22
\[ [W, Wx, Wy, xi] = \text{gradWspeed}(\text{Lat}(k), \text{Lon}(k), \text{Rmax}(k) \times 1000, \ldots
\]  \[ \text{HeadDir}(k), \text{Vt}_\text{kph}(k)/3.6, 101300, \text{Pc}(k) \times 100, \text{B}(k), 1.2, \ldots
\]  \[ \text{nLat}, \text{nLon}); \]
\% find the node numbers located within 10*Rmax
ind = find(d<10*Rmax(k));
ind = ind(:); % convert to column vector
% if the "ind" is not empty
% (i.e. nodes < 10*Rmax are located)
if ~isempty(ind)
    % create pressure field
    r=distance(nLat(ind),nLon(ind),Lat(k),Lon(k));
    r=distdim(r,'deg','km'); % convert degrees to meters
    % compute node pressures
    p=Pc(k)+(1013-Pc(k))*exp(-(Rmax(k)./r).^B(k));
    data=[ind';(Wx(ind).*g2s*1.944)';(Wy(ind).*g2s*1.944)';p'];
    fprintf(fid,' #
');
    fprintf(fid,' %05i %+8.4E %+8.4E %+8.4E 
',data);
else % empty means the wind field is out of the domain
    fprintf(fid,' 
');
    fprintf(fid,'%05i %+8.4E %+8.4E %+8.4E
',1,0,0,1013);
end
end
end

fprintf(fid,'#'); % end of file
fclose(fid); % close the file

cd .
end
Appendix C

Measured versus Simulated Storm Surge Heights at All Other Observation Stations

Figure C-1: Measured versus simulated storm surge heights at Station 8652587
Figure C-2: Measured versus simulated storm surge heights at Station 8654400

Station 8654400
($c_0=1.015$, $c_1=0.909$)

Least-squares Line

Measurements = Simulations

Figure C-3: Measured versus simulated storm surge heights at Station 8656483

Station 8656483
($c_0=1.000$, $c_1=0.868$)

Least-squares Line

Measurements = Simulations

76
Figure C-4: Measured versus simulated storm surge heights at Station 8661070

Station 8661070
\(c_0=0.999, c_1=0.895\)

Figure C-5: Measured versus simulated storm surge heights at Station 8677344

Station 8677344
\(c_0=1.151, c_1=0.767\)
Appendix D

Measured versus Systematic-Error-Adjusted Surge Heights at All Other Observation Stations

Figure D-1: Measured versus systematic-error-adjusted surge heights at Station 8652587
Figure D-2: Measured versus systematic-error-adjusted surge heights at Station 8654400

Figure D-3: Measured versus systematic-error-adjusted surge heights at Station 8656483
Figure D-4: Measured versus systematic-error-adjusted surge heights at Station 8661070

Figure D-5: Measured versus systematic-error-adjusted surge heights at Station 8677344
Appendix E

Correlation Analysis between Systematic-Error-Adjusted Surge Heights and Random Errors at All Other Observation Stations

Figure E-1: Correlation analysis between systematic-error-adjusted surge heights and random errors at Station 8652587
Figure E-2: Correlation analysis between systematic-error-adjusted surge heights and random errors at Station 8654400

Figure E-3: Correlation analysis between systematic-error-adjusted surge heights and random errors at Station 8656483
Figure E-4: Correlation analysis between systematic-error-adjusted surge heights and random errors at Station 8661070

Figure E-5: Correlation analysis between systematic-error-adjusted surge heights and random errors at Station 8677344
Appendix F

Lognormal Distribution Fits of Systematic-Error-Adjusted Surge Heights and Random Errors at All Other Observation Stations

Figure F-1: Lognormal distribution fits of systematic-error-adjusted surge heights and random errors at Station 8651370
Figure F-2: Lognormal distribution fits of systematic-error-adjusted surge heights and random errors at Station 8652587
Figure F-3: Lognormal distribution fits of systematic-error-adjusted surge heights and random errors at Station 8654400

Station 8654400
($\mu_{ln}=-0.160, \sigma_{ln}=0.204$)

Station 8654400
($\mu_{ln}=-9.8e-6, \sigma_{ln}=0.157$)
Figure F-4: Lognormal distribution fits of systematic-error-adjusted surge heights and random errors at Station 8658683
Figure F-5: Lognormal distribution fits of systematic-error-adjusted surge heights and random errors at Station 8658120
Figure F-6: Lognormal distribution fits of systematic-error-adjusted surge heights and random errors at Station 8661070

Station 8661070
($\mu_{ln}=0.174$, $\sigma_{ln}=0.196$)

Station 8661070
($\mu_{ln}=-1.0e-5$, $\sigma_{ln}=0.136$)
Figure F-7: Lognormal distribution fits of systematic-error-adjusted surge heights and random errors at Station 8677344

Station 8677344
($\mu_{ln}=0.377$, $\sigma_{ln}=0.117$)

Station 8677344
($\mu_{ln}=-6.7e-6$, $\sigma_{ln}=0.123$)
Appendix G

Comparisons between Measured and Simulated Annual, 5-year and 10-year Maximum Surge Heights Adjusted for Modeling Errors at All Other Observation Stations

Figure G-1: Comparisons between measured and simulated annual, 5-year and 10-year maximum surge heights adjusted for modeling errors at Station 8651370
Figure G-2: Comparisons between measured and simulated annual, 5-year and 10-year maximum surge heights adjusted for modeling errors at Station 8652587
Figure G-3: Comparisons between measured and simulated annual, 5-year and 10-year maximum surge heights adjusted for modeling errors at Station 8654400
Figure G-4: Comparisons between measured and simulated annual, 5-year and 10-year maximum surge heights adjusted for modeling errors at Station 8656483
Figure G-5: Comparisons between measured and simulated annual, 5-year and 10-year maximum surge heights adjusted for modeling errors at Station 8661070
Figure G-6: Comparisons between measured and simulated annual, 5-year and 10-year maximum surge heights adjusted for modeling errors at Station 8677344
Appendix H

Measured verse Simulated Surge Heights Adjusted for Individual Hurricane Events at All Other Observation Stations

Figure H-1: Measured verse simulated surge heights adjusted for individual hurricane events at Station 8652587

Measurements = Simulations

(RMS=0.34m)
Figure H-2: Measured verse simulated surge heights adjusted for individual hurricane events at Station 8654400

Figure H-3: Measured verse simulated surge heights adjusted for individual hurricane events at Station 8656483
Figure H-4: Measured verse simulated surge heights adjusted for individual hurricane events at Station 8661070

Figure H-5: Measured verse simulated surge heights adjusted for individual hurricane events at Station 8677344
REFERENCES


Coastline revised from Global Self-consistent, Hierarchical, and High-resolution Shoreline data set available through the U.S. National Geophysical Data Center, NESDIS, NOAA, NGDC GEODAS Coastline Extractor, 2012.


