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STORM SURGE HAZARD DATABASE FOR THE UNITED STATES USING STOCHASTIC HURRICANE MODEL: DEVELOPMENT, BIAS CORRECTION AND APPLICATIONS

A Thesis
Presented to
the Graduate School of
Clemson University

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

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by
Samiuddin Fazil Mohammed
May 2019

Accepted by:
Dr. Weichiang Pang, Committee Chair
Dr. Thomas E. Cousins
Dr. Brandon Ross

ABSTRACT

This thesis describes the development of a high-resolution storm-surge hazard database, which can be used for estimating the long-term storm surge hazard at any given site along the eastern coast of the United States (US). A stochastic hurricane track model is used to generate a set of one hundred thousand years of synthetic hurricane tracks. The SLOSH (Sea, Lake and Overland Surges from Hurricanes) model is used to simulate the storm surge in the Atlantic basin caused by selected synthetic hurricane tracks. The study domain covers a region of about 20 miles from the coastline containing more than 220,000 grid points (or observation points) for recording the peak storm surges of each synthetic hurricane track. A uniform grid of resolution of 1.1 km is proposed for this study.

Hind cast simulation of a set of 16 hurricanes was performed to quantify the modeling error of SLOSH model in terms of its ability to predict the surge height that occurred along the US coastline. The SLOSH predicted surges for the 16 historical hurricanes were validated against historical storm surge data obtained from various tide stations and post-hurricane high watermarks along the eastern coast of the US. These modeling errors were then quantified for each SLOSH study region (basin). The simulated surge heights for each basin were then adjusted for systematic error (bias) to assist in the development of more robust, reliable and accurate hazard maps. The biased adjusted surge heights were used to generate (1) storm surge hazard curves (surge height versus return period) for the 220,000 grid points, and (2) storm surge hazard maps for different return periods.

A hazard visualization tool was developed to view the surge hazard footprint. The availability of this information of long-term hazard for more than 220,000 locations along the US coast can be a useful tool for coastal city developers and planners, decision makers, risk analysts and engineering firms responsible for designing structures for hurricane induced storm surge hazards. Also, such a database and the visualization tools (maps, hazard curves) can improve the risk communication in the community and help in mitigating the losses (monetary and life) due to the storm surge by creating storm surge risk awareness in the society.

DEDICATION

In loving memory of my dad.

ACKNOWLEDGEMENTS

I would like to thank my advisor and committee chair, Dr. Weichiang Pang, for his guidance, help and continued encouragement throughout the course of this research. I would like to express my gratitude to committee members, Dr. Thomas E. Cousins and Dr. Brandon Ross for their guidance and help. I am grateful to AIG for supporting this research project and their constructive and thoughtful input.

Thanks are due to Blake Lytle, GIS specialist at Clemson for always guiding me through the difficulties I faced in operating GIS during my research. I would take this opportunity to thank Jeff Denton, CITI deputy director of Data Science for helping me learn new concepts in big data analysis, and always helping me fix my problems with big data. I would also like to thank Sereen, who constantly supported me and helped me solving my problems with statistics.

I would also like to give my appreciation to my friends and research group members who helped me overcome my research difficulties and kept me progressing.

Thanks are due to my parents and family for their unconditional love, patience, and unwavering support.

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CHAPTER ONE

INTRODUCTION

Motivation

The total loss caused by tropical storms contributes about 55% of losses due to all disasters (NCEI, 2018). On average since 1971, damages due to hurricanes and cyclones cost $700 billion per year globally. This is equivalent to wiping out the GDP of Argentina every single year, which is the eighth largest country in the world. For communities in the United States, recent storms like Hurricane Michael (2018), Florence (2018) and Harvey (2017) are reminders of how vulnerable the eastern and gulf coasts are to storms. Storms are uncertain in their path and can shift at a moment's notice. Consider Hurricane Florence, which was expected to make landfall as a category 4 storm in North Carolina but instead slowed down and made landfall as a category 2 storm. Hurricane Michael, which was expected to make landfall as a category 2 storm, suddenly strengthened within 24 hours giving little or no time for evacuation planning and made landfall as a category 4 storm with wind speeds of 155 miles/hour. Hurricane Harvey hit Texas as a category 4 storm in the last week of August 2017 causing a damage of more than $125 billion, making it the second costliest storm in the US history. The 2017 Hurricane Harvey was followed by another hurricane Irma that brought waves of about 20 feet higher than normal tides whereas Harvey was a rain-dominated storm with more than 50 inches of rain. Three of the costliest tropical storms, namely Katrina 2005, Harvey 2017, Sandy 2012, resulted in a total of $360 (USD) billion loss (NCEI, 2018).

Much of the United States' densely populated Atlantic and Gulf Coast coastlines lie less than 15 feet above the mean sea level (National Hurricane Center). The historical storm surge data alone is not enough to assess the risk from catastrophic events since a weak storm has diverse stochastic aspects as compared to a strong storm, which has a lower frequency and longer return period. As a result of increase in sea surface temperature, an increase in the frequency of such events is expected (Rego and Li, 2009). A storm surge hazard database needs to be developed to capture probable potential losses due to such events along with the randomness associated with such meteorological events and better map out locations of critical infrastructure such as hospitals, airports, etc.

This storm surge geo-spatial database will help improve understanding the risk of property damage due to flood at any location in the United States. With more accurate data, stakeholders including developers, city planners, and insurance providers can modify their planning to reflect more accurate property damage risk.

Background

During a hurricane event, when the water is pushed towards the shore by the wind forces it causes storm surge and the water level rises above the normal tide resulting in a storm tide. The total storm tide depends on the interaction of tidal stage, inverted barometer effects, wind stress, coastal topography, bathymetry and geology. The height of storm surge is a function of maximum winds' radius, intensity, translational speed, and direction. Being one of the major forces in a hurricane, storm surge can pose a potential hazard in the form of severe coastal flooding and devastation inland. Coastal geomorphology, vegetation (or lack of it), levees and sea-walls also affect storm surge. Within an embayment, surge may be further concentrated, whereas at a cape, it is spilled away. Steep slope results in breaking waves whereas gentle slopes can result in long wave run-ups, waves can cause significant damage to lower elevation buildings near the coast and in open bays, even without flooding.

The first component is the tidal stage; this can profoundly affect the storm tide during the time of hurricane landfall. However, ignoring the tidal stage does not bias storm surge results positively or negatively as tidal variation occurs with the same frequency and magnitude. Instead, they merely present an envelope of best and worst case scenarios (Phan *et al.*, Slinn *et al.*, 2010). In the United States, the Gulf Coast sees mixed or semidiurnal micro tidal (< 2 m magnitude) events, while the Atlantic coast has diurnal mesotidal (2–4 m magnitude) events (Pinet, 1998). The storm tides are highly correlated with the tidal effect during a hurricane's landfall. A hurricane making a landfall at the time of high tides will cause more flooding and damage as compared to a hurricane making a landfall at the time of low tides.

The second component is the response of sea surface to the pressure drop near the eye of the storm creating a vacuum, pushing the water into the hurricane’s eye, which results in the rise of the sea surface. It is one of the least contributing component to storm surge when compared to the other components. Ambient atmospheric pressure fluctuates around 1012 millibars. Every millibar drop in pressure causes a centimeter rise in the local sea level in deep water (Anthes, 1982). It contributes about 5% of the total storm surge.

Another component is the wind stress tide, caused by wind forces acting on the water surface. The high-speed winds from the hurricane push the water to the shore as it makes landfall (Ingargiola *et al.*, 2013), Interaction between the sea and atmosphere boundary causes energy to be transferred from a hurricane's winds to the water column, causing a build-up near the shoreline. SLOSH (Sea Lake and Overland Surges from Hurricanes) uses an empirically derived constant drag coefficient. Approximate wind stress per unit mass is given by equation *1.1*

$$\tau = c_d \frac{\rho_{air}}{\rho_{sw}} \, |W|W \qquad (1.1)$$

Where:

τ = Surface wind stress per unit mass

c_d = Dimensionless drag coefficient

ρ_{air} = Density of air

ρ_{sw} = Density of sea water

W = Wind velocity vector at 10 meters above sea surface

The variation in local bathymetry near the coast is one of the major factors affecting the storm surge. The US coast has a varying bathymetry with as low as 25 meters in Gulf of Mexico making it prone to storm surge. Figure 1 and 2 shows the variation in the bathymetry along the US coastline. The resulting storm surge varies by ±10% for amplitude with variations less than ±40% of the initial bathymetry. Fluctuations up to ±60% in bathymetry would generate a difference at the coast of at most ±20% (Weaver and Slinn, 2010).

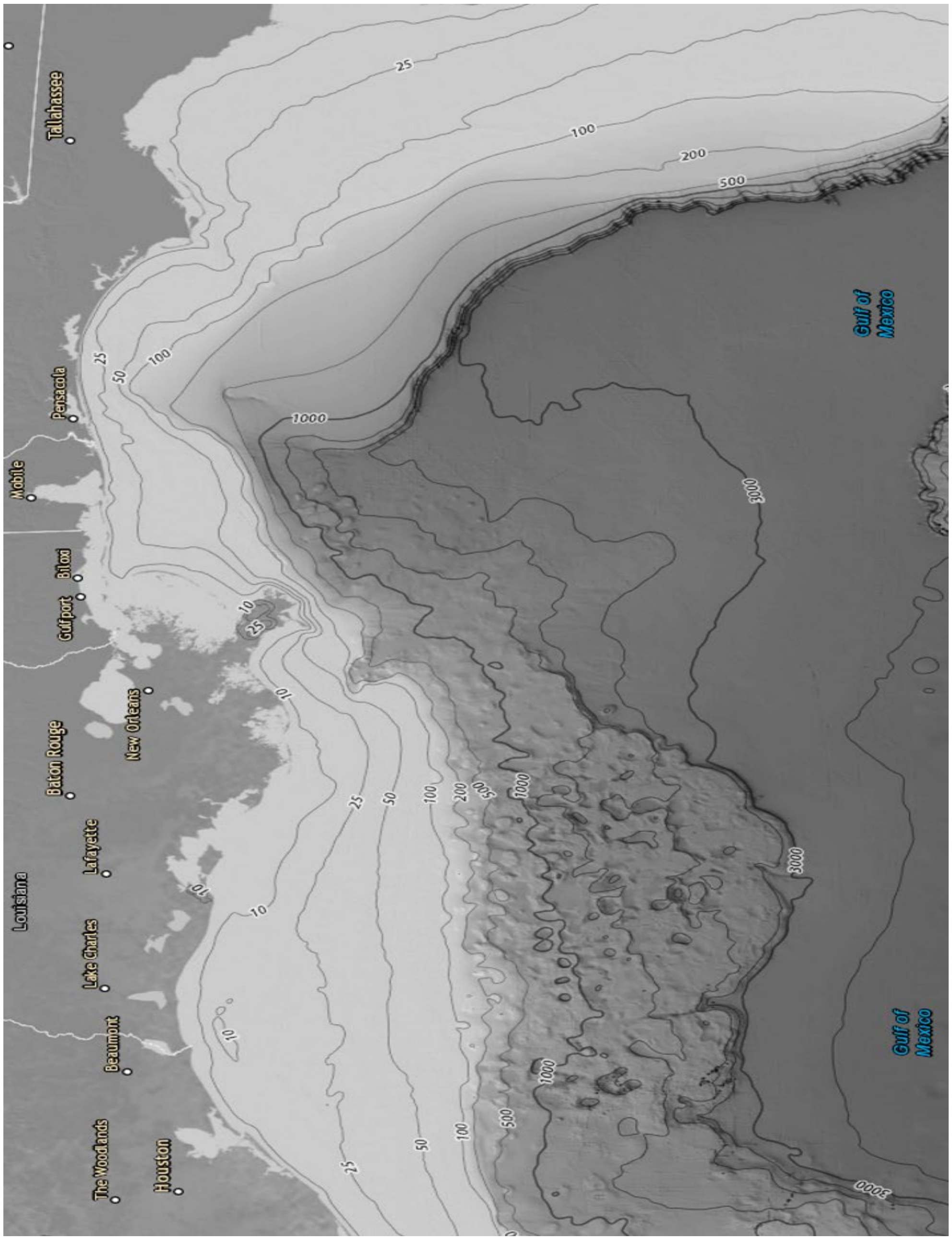


Figure 1: Gulf coast bathymetry in meters (adopted from ArcGIS online)

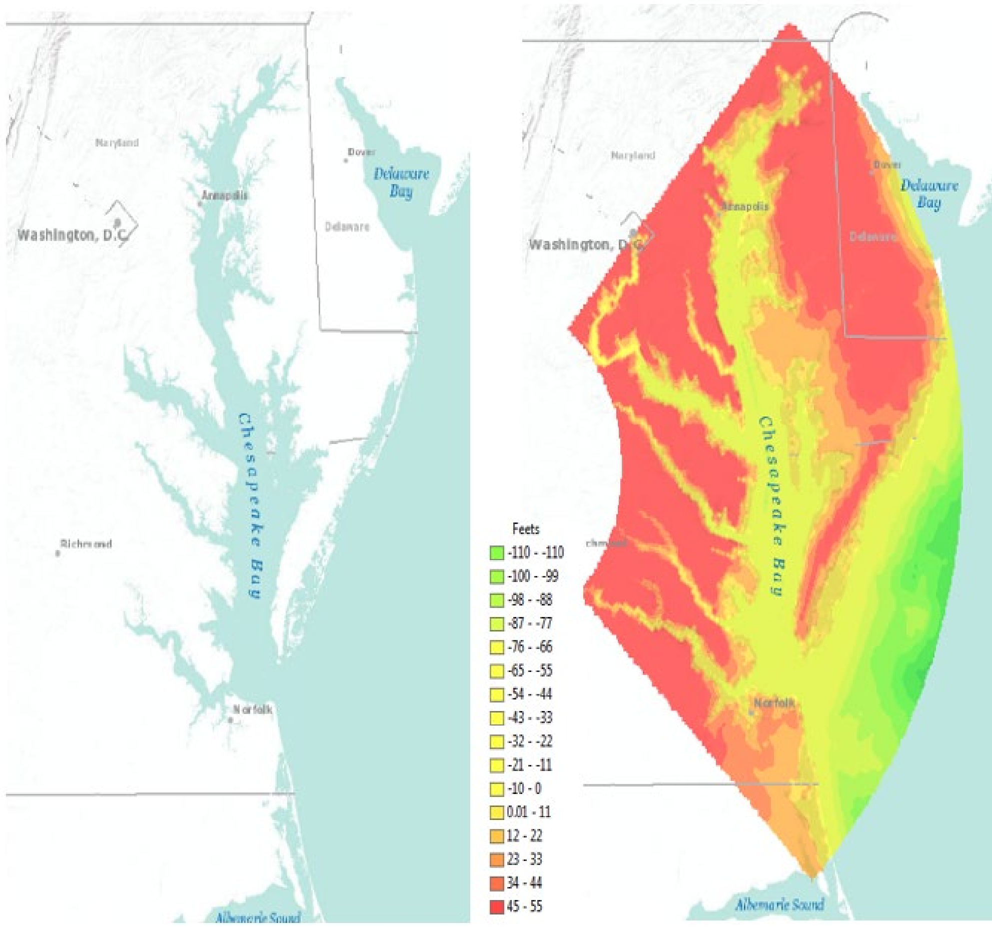


Figure 2: Chesapeake basin bathymetry

Objectives

The present study has three primary objectives: (i) Develop a uniform and fine resolution storm surge hazard database by coupling a synthetic hurricane model with a hydrodynamic model (SLOSH) to capture the randomness of such future events and estimate the long term storm surge hazard for the eastern coast of the US. (ii) Validate the model by simulating surges from historical storms and compare the results of the simulated storm surges with that of the observed water levels at different locations along the coastline to quantify modeling errors. These errors were then used to adjust the Mean Return Interval

(MRI) curves for systematic modeling errors and quantify the uncertainty in return periods and respective surge heights. (iii) Create a tool to visualize the surge footprints and prepare risk maps for an example coastal location (Miami, FL). This storm surge geo-spatial database will help improve understanding of the risk of property damage due to flood at any location along the United States coast. The visualization tool can be a valuable asset to improve the risk awareness in the community.

Overview of Analysis Approach

A stochastic hurricane track model (Liu, 2014) was used to generate synthetic storms which varied in their intensity and direction. The simulated hurricane database by Liu (2014) contains 100,000 years of simulated hurricanes with more than 1 million tracks. Since storm surge simulation using a finite element or finite difference model is computationally intensive and not all hurricanes cause significant surges to the coastal regions, a methodology to select candidate hurricanes that may yield appreciable storm surge was utilized. Any simulated hurricane with its closest distance between the hurricane eye and the coastline d_j less than $2R_{max}$ ($d_j < 2R_{max}$) where R_{max} is the radius of the maximum wind of the hurricane, was considered as a candidate hurricane based on a prior sensitivity study by Pei (2015). Figure 6 presents the criteria of selection of candidate hurricane tracks. Numerical model SLOSH was used to calculate the storm surge for the Atlantic and Gulf of Mexico coasts of the United States using selected candidate hurricane tracks. The model divides the US coast into a set of 33 domains called as basins. For each candidate hurricane, the storm surge from SLOSH was interpolated in the study area using the uniform and high-resolution 0.01°x0.01° grid representing the study region. The grid extends up to 20 miles inland to capture surge inundation as well as inland flooding due to storms. A high-resolution storm surge database was developed for the entire eastern coastline of the United State coast.

Study Area

SLOSH has been applied to the entire Atlantic and Gulf of Mexico coasts of the United States. The model subdivides the US coast into different regions referred as basins as shown in Figure 3. This subdivision of the coastal areas into different basins has been performed based on the population density at the coast and topography of these coastal areas. These basins are continuously expanding polar grids in the areas of interest along the coastline and implement simple boundary conditions (Jelesnianski *et. al.*1992) with coarse mesh in deep waters. These grids were later refined to a uniform size with a high resolution of 0.01°x0.01.

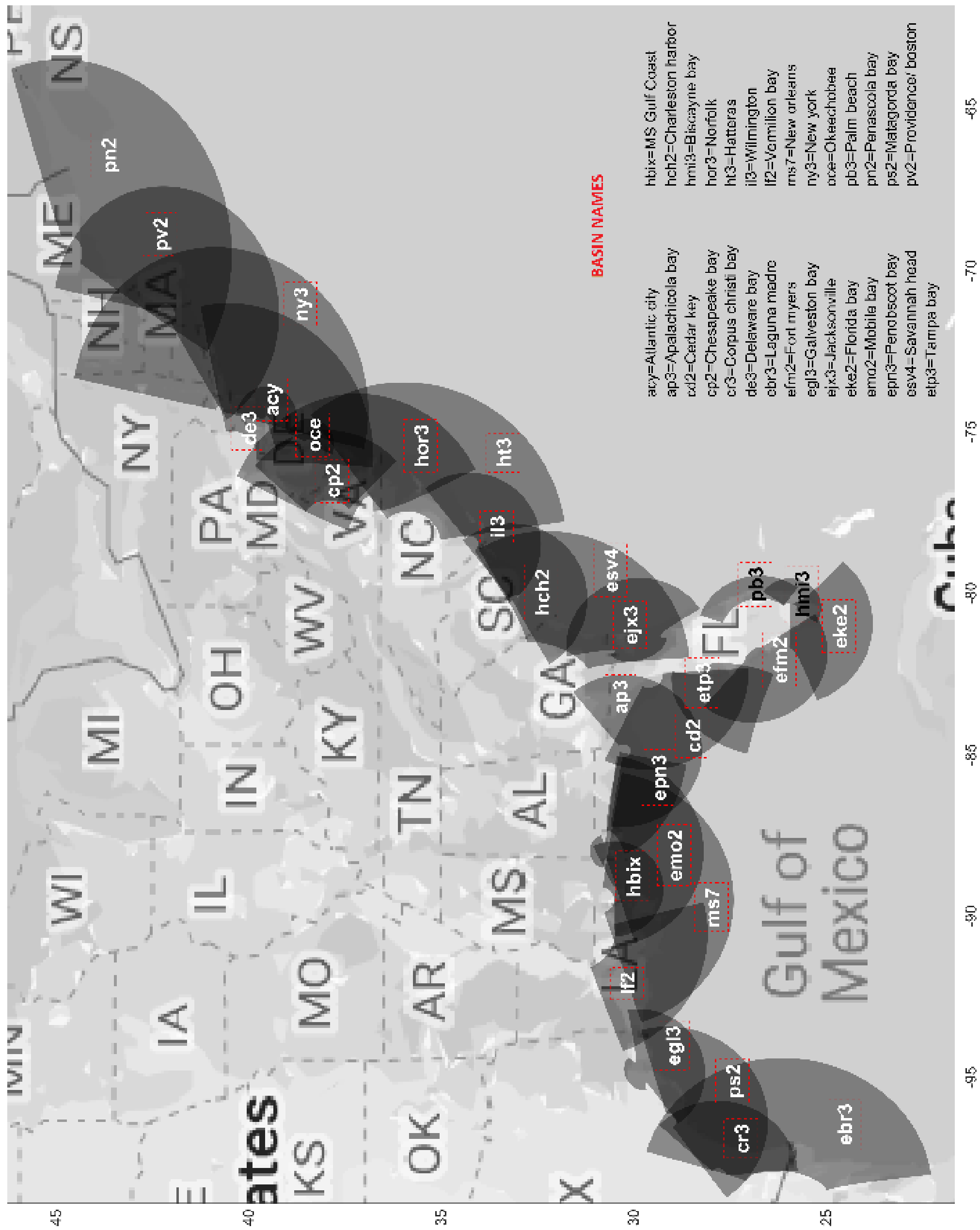


Figure 3: SLOSH basins for the U.S. coasts

CHAPTER TWO

HURRICANE AND STORM SURGE SIMULATIONS

Stochastic Hurricane Simulation Methodology

A statistical (stochastic) hurricane model was used in this study to generate synthetic tropical cyclones under given large-scale atmospheric and ocean environments, which may be estimated from observations or climate modelling. This method overcomes the limitation of having limited historical track database by generating synthetic storms using Monte Carlo simulation method such that they are in statistical agreement with observations, and it agrees well with various other methods used to simulate hurricanes (Vickery *et al.*,2000; Huang *et al.*,2001; Emanuel *et al.*, 2006; Vickery *et al.*, 2009).

In this study, the stochastic simulation program by Liu (2014) was used. An overview of the simulation methodology is provided in Figure 5. The simulation process begins with the genesis model where the number of events per simulation year are determined and hurricane parameters are randomly selected for the first time step using the historical database (HURDAT). After generating the initial location of the hurricane, the tracking model generates the position of the storm based on the heading direction and the forward speed in the next time step. This is followed by calculation of the storm intensity based on the location of the hurricane track and other environmental parameters such as the sea surface temperature. If the hurricane made landfall, a decay model is used to simulate the hurricane intensity for the next time step. However, if the hurricane is still on the ocean, the hurricane intensity is calculated using a relative intensity model. Once the location of the storm and the value of the storm intensity based on the location of the track is determined, the radius to maximum winds (R_{max}) and the Holland B parameter are determined at every 6-hour time step as a function of the latitude and central pressure and are then interpolated linearly to 1-hour increment. If the value of the central pressure exceeds the atmospheric pressure the track simulation is terminated. This process is repeated for every event in the total number of simulation years. The Figure 4 below shows a hurricane track with various parameters.

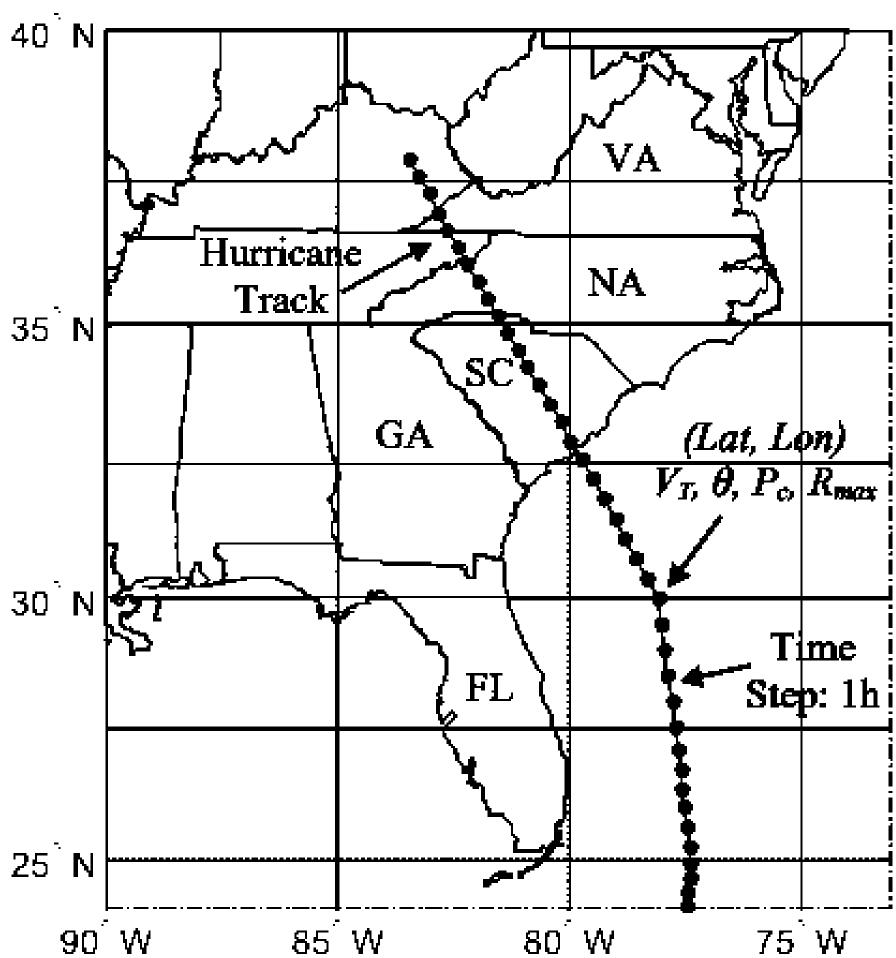


Figure 4: Sample synthetic hurricane track (Pei 2015)

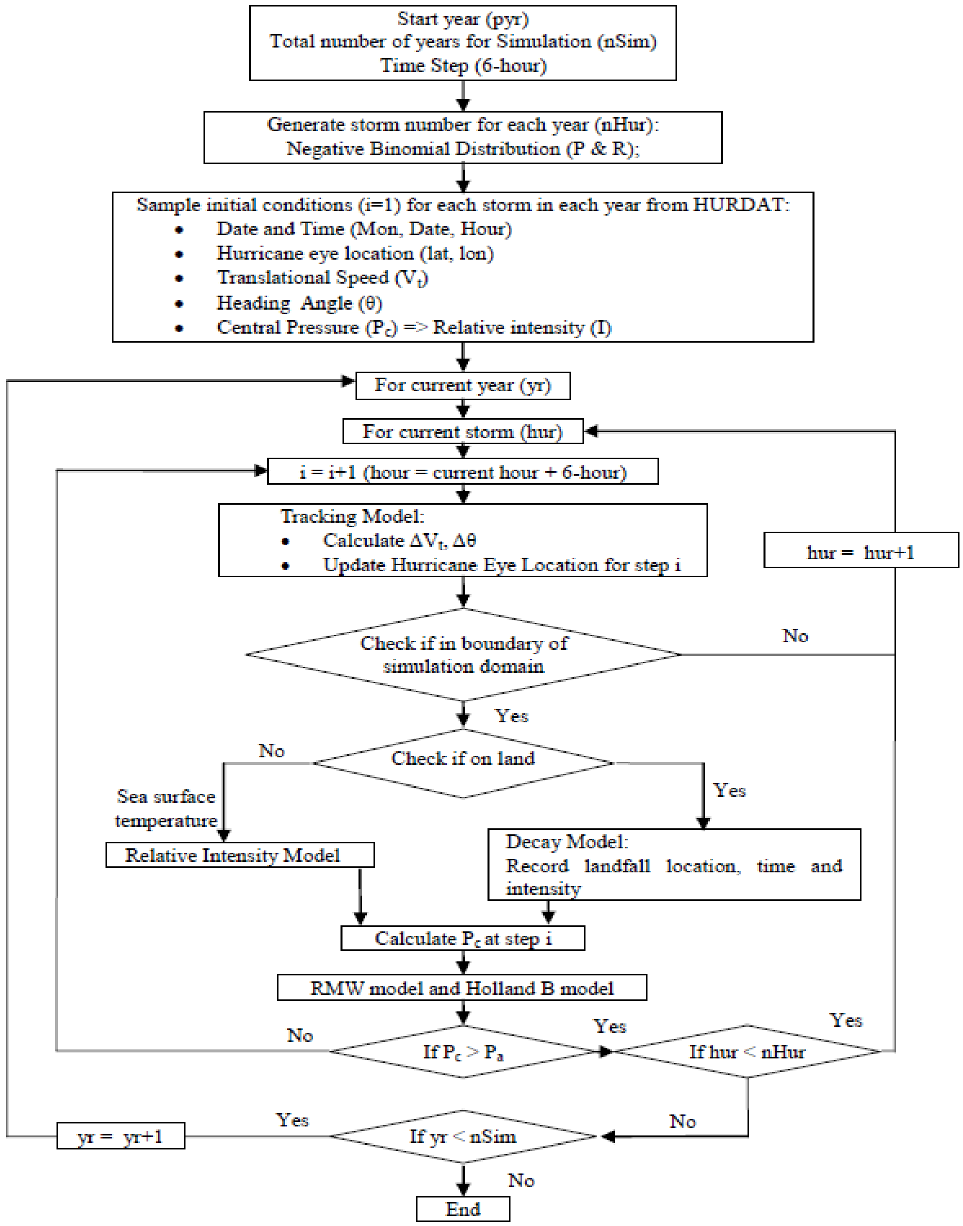


Figure 5: Flowchart illustrating the stochastic simulation procedure to generate synthetic hurricane catalog (Liu, 2014)

Storm Surge Simulation Methodology

Storm surge was simulated using the SLOSH (Sea Lake and Overland Surges from Hurricanes) model. Model validation was performed for 16 historical hurricanes. The results of validation can be found in chapter 4. The basic process for simulation of storm surge during a synthetic hurricane is as described below:

First for each simulated hurricane, the Radius of maximum wind (Rmax) was calculated and closest distance (D_j) from the eye of the hurricane to the coastline. For any synthetic hurricane track to be a candidate of a given domain, a threshold was set to be as twice of the radius to maximum winds ($2R_{max,j}$) at every time step j (1-h interval). Any simulated hurricane at time step j with $D_j < 2R_{max}$ is considered as a candidate hurricane and is selected for storm surge calculation. This approach was adopted based on a sensitivity study, which verified that $2R_{max}$ threshold is adequate to capture the hurricanes that can produce significant surge(Pei *et al.*, 2014). The 100,000-year hurricane simulations resulted in 1,038,322 simulated hurricanes originated from the North Atlantic Ocean out of which 504,826 events were considered to be as candidate hurricanes. For these selected candidate hurricanes, track parameters like the position of hurricane eye, translational speed, heading angle, central pressure deficit, and radius to maximum wind were calculated with a 1-h time interval. These parameters are used as an input for the SLOSH model to calculate maximum surge levels. For the SLOSH simulations, the wind and pressure are calculated using a semi parametric wind field model within the SLOSH model. The differences between the wind field computed by SLOSH's parametric wind field model and surface wind field observations were within a range of 6% or less (Lin *et al.*, 2010). The Surge heights predicted by the model has a reported accuracy of ±20% (Jelesnianski *et al.*, 1992).

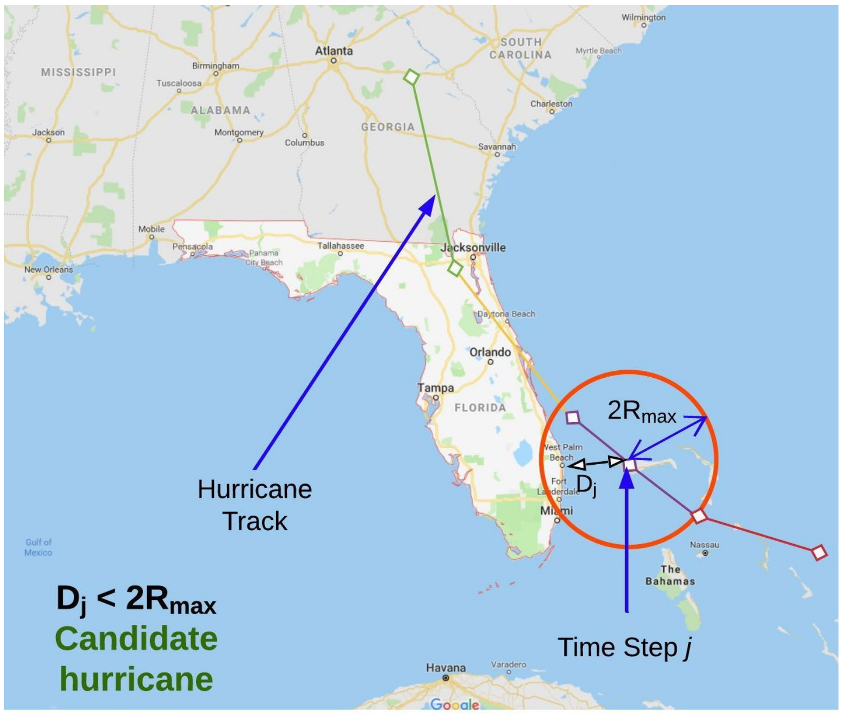


Figure 6: Selection of candidate hurricane events

<u>Storm Surge Models: A Review</u>

In addition to the two leading storm surge models in the US (SLOSH and ADCIRC), there are many other models that have been developed and applied all around the world by government agencies as well as the academic world. A brief overview of the predominant models is described in order to show improvements in storm surge modeling and illustrate how various problems in storm surge modeling are being addressed.

ADCIRC

ADCIRC – 2DDI (2-Dimensional, Depth Integrated) is a shallow water, hydrodynamic, finite element model with variable unstructured grids capable of simulating the hurricane wind field and calculating the storm surge. ADCIRC is useful for simulating the hydrodynamics in the deep ocean, continental shelves, coastal seas, and estuarine systems(Turan *et al.*, 2018). In 1991, Luettich and Westerink developed the ADCIRC model. ADCIRC can be used to model tides and wind driven circulation; analyse the hurricane storm surge and inland flooding; dredging and material disposal feasibility; larval transport analysis and nearshore marine works(Adcirc Guide; Luettich et. al.. ADCIRC's Finite Element based solution strategy helps in creating a very large, variable resolution, unstructured, flexible model domain as big as the entire ocean basin or more localized, such as estuaries or bays. ADCIRC requires boundary conditions, including forcing boundaries and land boundaries. We can also specify the tidal constituents, normal flow, wind and/or wave radiation stresses, atmospheric pressure and outward radiation of waves (meteorological forcing). It is capable of full wetting/drying elements (Luettich, 2004). Nodes of the elements are designated as "dry nodes", "interface nodes", and "wet nodes". A node which is connected to dry elements which have barriers in place making sure that the flow through the element to be zero is called as "dry node". A node which is connected to all wet elements is a wet node and is included in the full flow domain. Interface nodes connect the wet and dry element. Boundaries connecting interface nodes are considered as standard land boundaries. ADCIRC uses the Holland model to calculate the hurricane wind field. When combined with wave models like SWAN (Simulating WAves Nearshore), ADCIRC can provide hurricane storm surge elevations including wind-wave impacts.

ADCIRC solves shallow water circulation assuming that horizontal scales of motion are greater than the vertical scales(Blain, no date). 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 (Scheffner *et al.*, 1994).

SURGE

SURGE is a 3-D hydrodynamic model of ocean circulation for coastal areas based on the Princeton Ocean Model (POM) developed in 1987. SURGE helps in simulating storm surges and flooding as well as horizontal currents. It uses NOAA/NOS bathymetry data and high-resolution LIDAR survey data. The advantage of using SURGE model is it has a fine resolution with three-dimensionality. The absence of radiation stress, wave-enhanced surface stress and wave-induced bottom friction makes it inaccurate.

POM

One of the widely used Finite Difference coastal ocean models is the Princeton Ocean Model (POM; (Blumberg and Mellor, 1987)). POM is a 3-D and fully nonlinear hydrodynamic model that has been in development and used by a wide range of users over the past three decades. It has been applied for use in tropical storm surge modeling in North Carolina (Xie *et al.*,2003; Peng *et al.*, 2004; Pietrafesa *et al.*, 2007). In this application storm surge has been coupled various models such as meteorological (wind, pressure, and precipitation), wave, and river discharge models to estimate the impact and damage due to storm surge more accurately and more close to reality.

CH3D

Another well-developed Finite Difference model that has been applied to predict the storm surge is the "Curvilinear grid Hydrolidynamics model in 3D". CH3D is capable of handling large-scale simulations as it can run on MPI and high performance computers (Sheng and Alymov, 2002). CH3D uses a structured curvilinear grid and has been applied on domains with the resolution reaching less than 20 meters. It is a fully nonlinear model that has been coupled with wave models and with larger scale circulation models. Various wind models have been used to provide input.

FVCOM

The fully nonlinear 3-D model FVCOM has been applied to storm surge simulations in Florida (Weisberg and Zheng, 2006). This modeling application demonstrates a mass-conserving 3-D simulation on an unstructured grid extending past the continental shelf (Dube *et al.*, 2010). Several projects have focused on approaches that leverage models available in the community. Finally, commercial hydrodynamic modeling systems by the Danish Hydraulic Institute (DHI) and Deltares (Delft Hydraulics) are widely used in storm surge risk assessment.

MIKE

The hydrodynamic model MIKE calculates the storm surge elevations based on the set of differential equations called the Navier Stokes equations (DHI, 2017b). MIKE uses finite volume method (FVM) to solve the Navier Stokes equations. MIKE 21 FM has two types of numerical schemes for the solution: the Low Order (LO) and the Higher Order (HO) schemes (DHI, 2017b).

The selection of the numerical scheme depends upon the number of cores available to perform the task as the later can be computationally demanding. The LO scheme takes less simulation time with a limitation of giving a lower quality result as compared to the later one(DHI, 2017a). The MIKE 21 FM model demonstrated a good capacity to simulate the astronomical tide. The results obtained with only the astronomical forcing applied showed a close correlation with the data from the tidal gauges. However, it has been reported that during the storm surge simulations the model tend to underestimate the surge elevation values (Rita B Fonseca).

SLOSH

SLOSH model is an efficient two-dimensional finite difference hydrodynamic model formulated by the National Weather Service [NWS] used for numerical simulations of the storm surge prediction. It plays a significant 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 were first developed by (Platzman, 1963) and later modified by (Jelesnianski, 1967) with a bottom slip coefficient.

SLOSH uses a curvilinear grid system to allow higher resolutions inland and a coarser resolution in deep waters. It computes surges over bays and estuaries and includes sub-grid features such as channels and barriers. For storm surge heights of individual hurricanes, SLOSH has been reported with an accuracy of +-20% (NWS, 2011). Figure 7 shows the SLOSH basins coverage for east and gulf coastlines of the US.

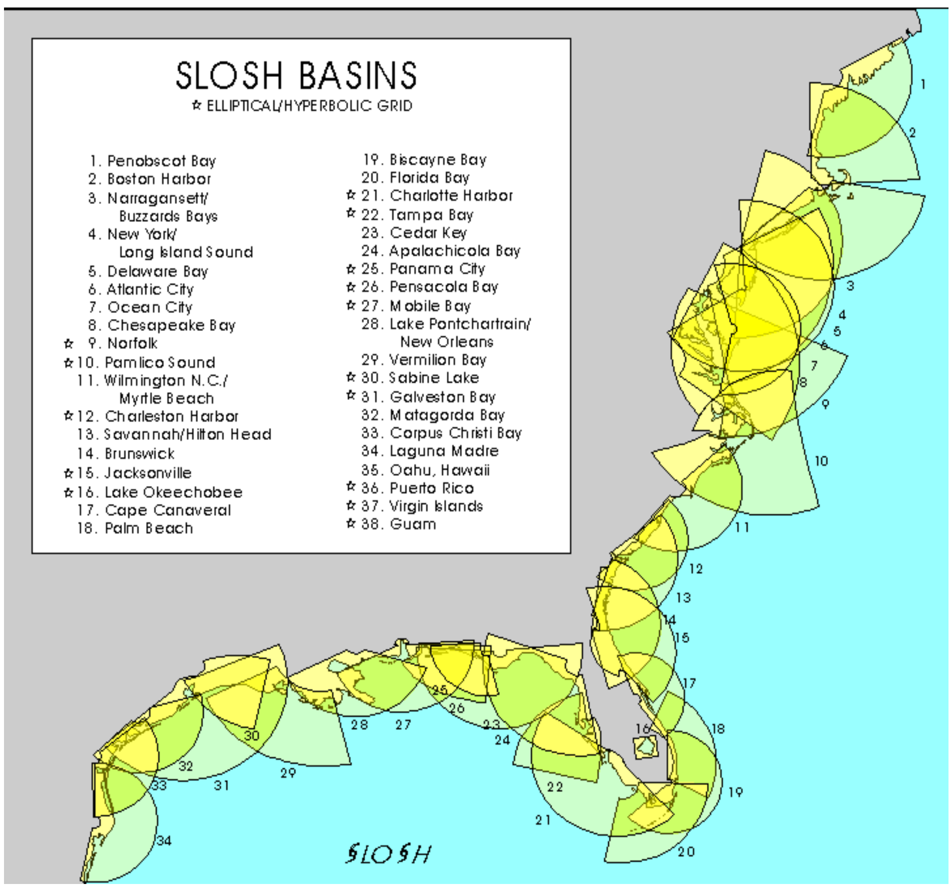


Figure 7: SLOSH model basins for East and Gulf coastlines of the U.S. (Glahn *et al.*, 2009)

SLOSH Methodology

The transport equations of motion are given as

$$\frac{\partial u}{\partial t} = -g(D+h)\left[B_r \frac{\partial(h-h_o)}{\partial y} - B_i \frac{\partial(h-h_o)}{\partial y}\right] + f(A_r v + A_i u) + C_r x_\tau - C_i y_\tau \tag{1.2}$$

$$\frac{\partial v}{\partial t} = -g(D+h)\left[B_r \frac{\partial(h-h_o)}{\partial y} - B_i \frac{\partial(h-h_o)}{\partial y}\right] + f(A_r v + A_i u) + C_r y_\tau - C_i x_\tau \tag{1.3}$$

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_τ and y_τ are the components of surface stresses; and

A_r, A_i, B_r, B_i, C_r, C_i are the bottom stress terms.

The model applies the law of conservation for mass relating the horizontal transports (u, v) to the sea level rise. eq. 1.4 shows the continuity equation with Boussinesq's approximation for incompressible flow. Vertical velocity is assumed to be negligible and SLOSH's form of the continuity eq. 1.5 is obtained, note that x and y in this equation are the real and imaginary components of the complex plane, respectively.

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0 \tag{1.4}$$

$$\frac{\partial h}{\partial t} = -\frac{\partial u}{\partial x} - \frac{\partial v}{\partial y} \tag{1.5}$$

For each time step, u and v are solved, leading to a new surge level, h, at every grid location predefined in SLOSH. The model uses a simplified wind model based on pressure and radius of the maximum winds to calculate the storm surge for each grid point.

complete derivation of the SLOSH equations of motion can be found in (Jelesnianski, 1967) and Appendix A of the SLOSH Technical Report (Jelesnianski, Chen and Shaffer, 1992).

SLOSH Computational Grid

SLOSH has been applied to the entire U.S. Atlantic and Gulf of Mexico coasts of the U.S. The model is subdivided into different regions referred as basins. This subdivision of the coastal areas into different basins us done depending upon population density at the coast, topography of the areas. These basins have a finer resolution particularly near susceptible features such as inlets and channels. The polar grid helps in implementation of simple boundary conditions. These basins are a continuously expanding polar grids to allow for both finer resolution in the areas of interest along the coastline, and implementation of simple boundary conditions (Jelesnianski *et al.*,1992) and stretching to coarse mesh in deep waters or areas of lesser interest. The shape of the grids helps the SLOSH model to be computationally efficient. A typical simulation of a storm using

SLOSH takes about 3 minutes which is about 50 times faster when compared with other storm surge models when ran on a typical desktop. This made SLOSH an ideal choice for simulation of a 100000-year event catalog.

An example of a SLOSH basin is the New York (NY3) Basin. It consists of 188 arcs and 164 radials with a resolution of about 500 m around New York. Another example of SLOSH basin is the Hyperbolic Miami (HMI3) Basin, it consists of a hyperbolic grid of 23,750 points and covers the area between Lake Okeechobee and the Bahamas. This basin has a fine resolution mesh of around 2 km near the coast and much coarser resolution mesh of about 4 km in deeper waters of the Atlantic. Figure 8shows the variation in the grid resolution for the two basins.

It should be noted that all of the inputs and output values of SLOSH are based on real space (longitudinal and latitudinal coordinates for the polar grid points). A grid interpolation was performed for all computations to transform the storm surge data from polar grid to rectangular grid of a uniform and finer resolution about 1 km near the coastline and about 5 km coarser resolution after 20 miles inland, to keep the model computationally efficient. Figure 9 represents the coverage of uniform surge grid for the US.

SLOSH implements four boundary conditions for this computational grid (Phan *et al*; Slinn *et al.*,2010)

- Surface gradients are replaced by the nearest interior, contiguous point in shallow water.
- Surface gradients are replaced by the storm's hydrostatic gradient in intermediate depths.

- Hydrostatic height of the storm is set at height points of boundary squares in deep water.
- Zero transport over dry land.

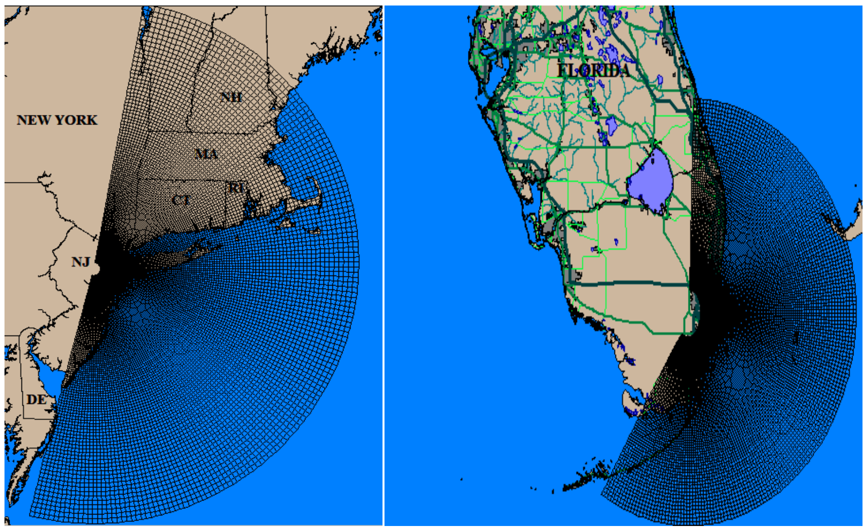


Figure 8: SLOSH computational grids: Figure on the left represents the New York Basin (NY3) and Figure on the right is the Hyperbolic Miami Basin (HMI3) (Taken from **SLOSH Display Program)**

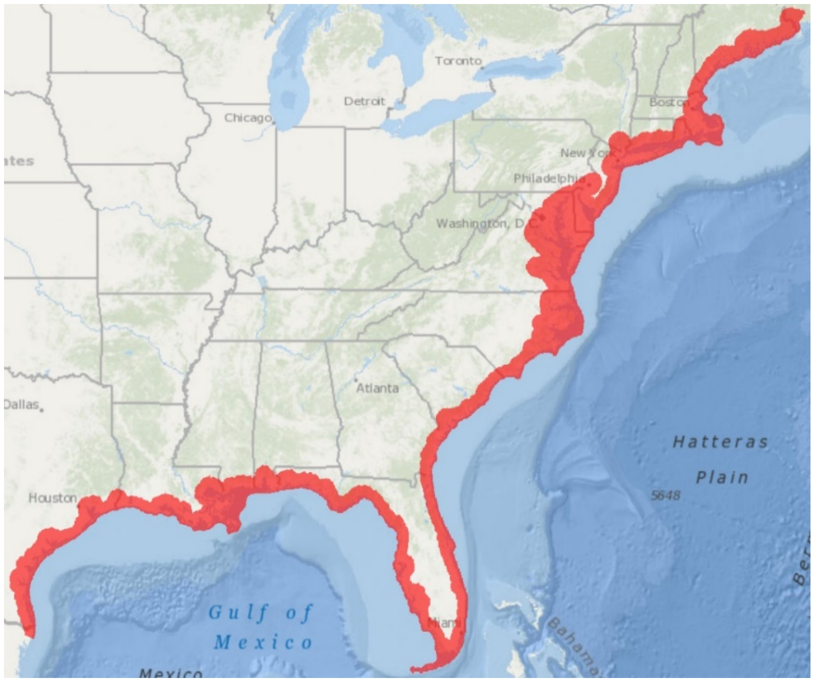


Figure 9: Surge Grid for the US coast

SLOSH Input Parameters

SLOSH requires the position of the storm, radius of maximum wind and intensity as input for generating a track file. These values are saved in a SLOSH TRK file, which contains up to 100 track points of data. The location of the storm's center, central pressure, radius of maximum wind and direction was calculated at every point. Each point is an hourly progression of the hurricane. An example of a TRK file used in our study can be found in Appendix A**.** At the storm's center and far away from the hurricane, wind speed tapers off to zero. A vector correction for the storm's motion is added to the stationary wind speed to arrive at the wind vector used in surface shear stress computations (Jelesnianski, 1967)

SLOSH Output

SLOSH gives the output in the form of a REX file which is SLOSH specific animation file containing the storm surge results for each time step respectively. These files contains information about the surge elevation, wind speed and wind direction at every 10 minutes of simulation.

SLOSH refers the results of storm surge heights relative to the vertical datum, NAVD88. For estimating the losses, one might want to determine the flood depth of surge flooding at a location, this can be done by subtracting the ground elevation (relative to NAVD88) at that location from the potential surge height. Within the SLOSH model, an average elevation is assumed within each grid square.

As mentioned before, all of the inputs and output values of SLOSH are based on real space (longitudinal and latitudinal coordinates for the polar grid points). Interpolation was performed for the SLOSH output to transform the Surge depth corresponding to a polar grid into rectangular grid of a uniform and finer resolution about 1 km near the coastline and about 5 km coarser resolution after 20 miles inland from the coastline to keep the model computationally efficient.

SLOSH Model was not used to calculate the flood depth as it uses an average grid elevation. Whereas, a true terrain height may vary significantly within a SLOSH grid square. The depth of surge flooding above terrain at a specific site in the grid square can be calculated more precisely by subtracting the DEM data from the model-generated storm surge height at that site. Figure 10 shows the schematic workflow of SLOSH model with required inputs and the resulting outputs.

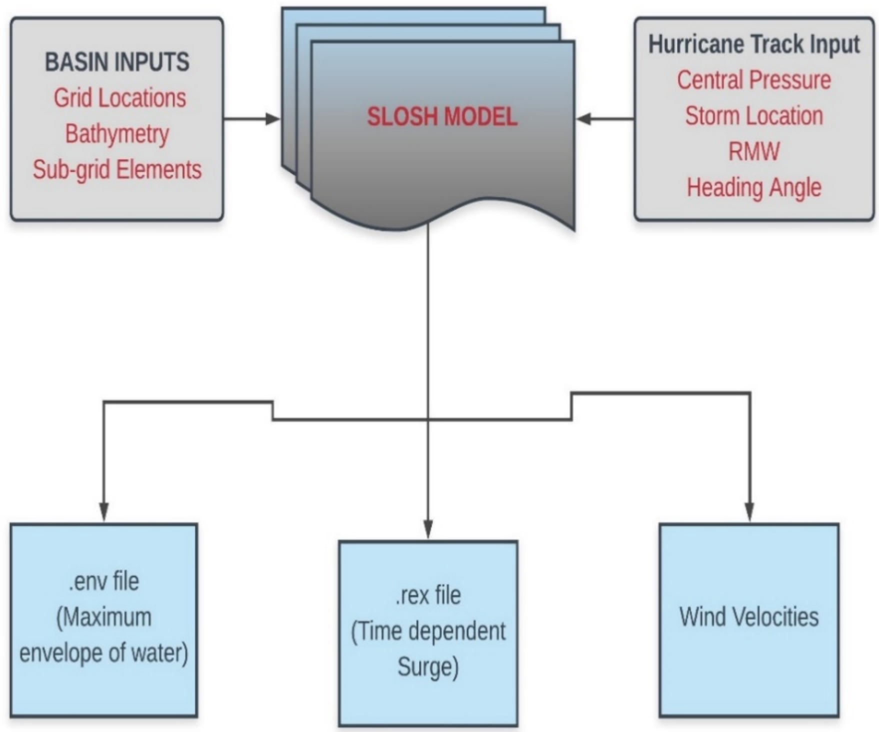


Figure 10: SLOSH schematic flowchart

CHAPTER THREE

DEVELOPMENT OF STORM SURGE HAZARD DATABASE

Significance of the Hazard Database

The major advantage of creating the hazard database is that it can help in reducing the uncertainties in the storm surge levels by simulating a large number of synthetic storms. The variations in the storm track parameters can significantly affect the surge levels. For instance, the storm size can have a major contribution in the rise of water levels above predicted levels of normal tide than intensity of the storm(Irish *et al.*, 2008) and storms moving faster will produce high surges as compared with storms moving slowly(Irish *et al.*, 2008; Rego and Li, 2009). These uncertainties are taken into account by the large number of simulations of the synthetic storms and developing a more robust hazard database.

Methodology

For the current study, Figure 11 outlines the framework of the approach applied for the development of Storm Surge Hazard Database.

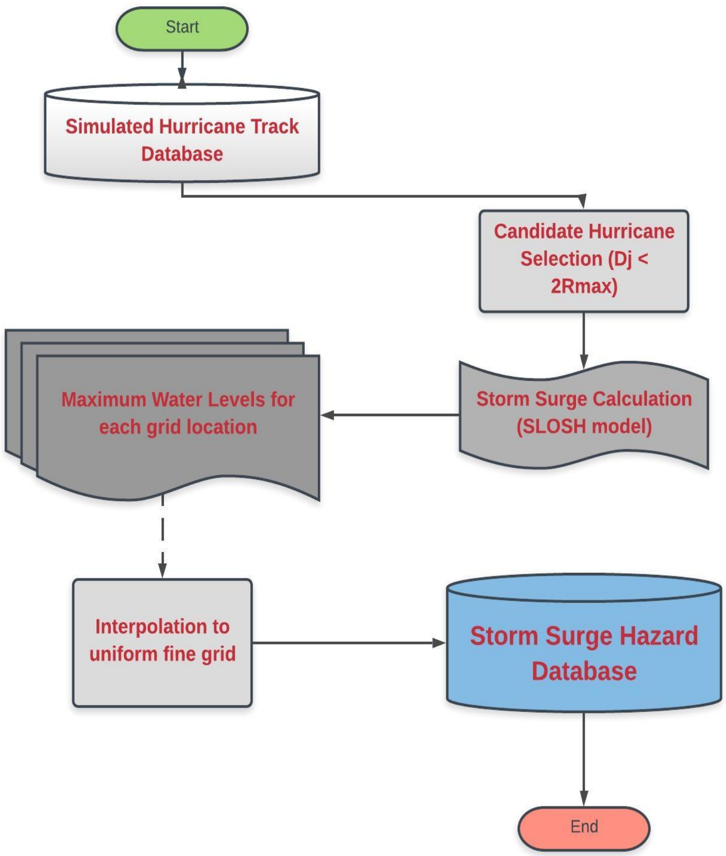


Figure 11: Framework for creating hazard database

Synthetic Storm Simulation

A limitation of using historical data is that the number of events in the historical database is scarce and a very low number of hurricanes make landfall in a selected study region making it unsuitable for long-term probable hazard estimation. In addition, it is difficult to make meaningful extrapolation for such spatially variable and large size of the domain from a small set of historical data. A statistical hurricane model was used in this study to generate synthetic tropical cyclones under given large-scale atmospheric and ocean environments. The stochastic simulation comprised of 4 modules, namely (i) Genesis module (ii) Tracking module (iii) Central pressure module and lastly (iv) decay module. The full database contains a set of 100,000 years of simulated tracks which were created using empirical track method with 7 key variable parameters. The tracks varied in the Location of the eye (latitude and longitude) of hurricane, radius of maximum winds, forward speed of the storm, central pressure, heading angle and Holland B parameter which were calculated on 6-hour basis These parameters were linearly interpolated to an hourly increment.

Candidate Hurricanes

Any simulated hurricane which is physically realistic and that came within a distance D_j less than $2R_{max}$ from the coastline ($D_j < 2R_{max}$) where R_{max} is the radius of the maximum wind of the hurricane, was considered as a candidate hurricane. A sensitivity study conducted by Pei(2015) showed that the $2R_{max}$ was an adequate threshold for the purpose of selecting the candidate hurricanes. The 100,000-year hurricane simulations resulted in 1,038,322 simulated hurricanes originated from the North Atlantic Ocean out of which 504,826 events were considered to be as candidate hurricanes. Figure 12 shows a set of 500 such candidate hurricanes in the Atlantic basin.

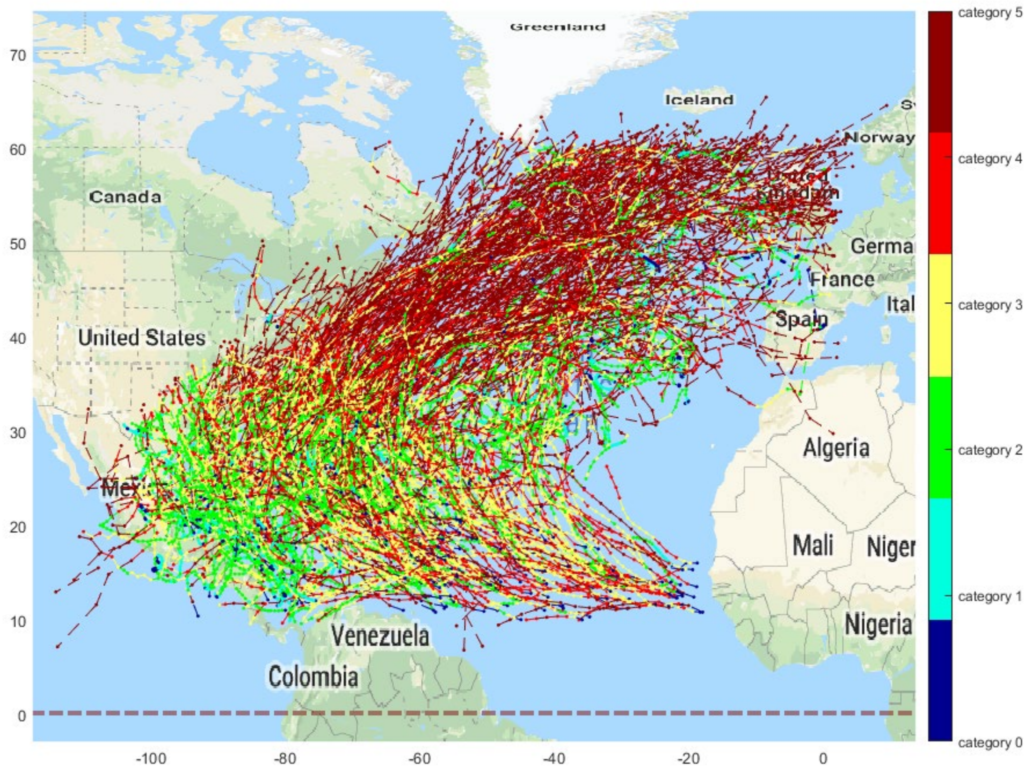


Figure 12: Set of 500 synthetic hurricane tracks

Storm Surge Modeling

SLOSH (Sea, Lake and Overland Surges from Hurricanes) model developed by Jelesnianski(Jelesnianski *et al.*, 1992) was used to simulate the surge heights associated with each candidate hurricane event respectively. First, the surface wind stresses are computed. Second, these wind stresses are used as an input to the SLOSH model for computing the time histories of storm surge heights. However, some modeling limitations do exist. Out of three main contributors to overall storm surge namely pressure setup, wind setup and wave setup (Zachry *et al.*, 2015). The storm surge has been modeled considering first two. The wave effect was not included in the study. However, it has been reported that waves can significantly result in a water level rise in the range of 10 - 50%(Dean and Walton, 2009). Dynamic variations in tide are ignored in the model. The initial water level was set to zero in this analysis and the surge heights were calculated with respect to NAVD88. With these known limitations, the data can still be used appropriately for various applications. Figure 10 shows the schematic workflow of the SLOSH model with required inputs and the resulting outputs.

Fine Resolution Hazard Database Development

Lin et al. studied the long term storm surge risk in NYC using synthetic hurricanes and compared the surge spatial pattern of ADCIRC and SLOSH. Their study showed that the surge spatial pattern agrees well between the two models in most simulations. However, it was concluded that SLOSH was unable to capture some local features due to its coarser resolution and ADCIRC simulations were inefficient in terms of computation time (Lin *et al.*, 2012). Therefore, surge was calculated using SLOSH to make the simulations efficient and opted for a uniform fine resolution grid to overcome these drawbacks. SLOSH has predefined structured grids (polar, elliptical or hyperbolic) with variable resolution having fine resolution close to shoreline and coarser offshore resolution. There exist a considerable overlap between the SLOSH basins to cover the complete coast for storm surge calculations. For each candidate hurricane, the surge depth was computed in the given study area. If a hurricane was passing through the overlapping region of two basins and produces significant surge then the larger value of the two simulated basins was selected as the water depth resulted from the storm for that region. The results from the SLOSH model were interpolated to obtain a uniform and high-resolution database for a 0.01°x0.01° grid representing the study region, which extends 20 miles inland to capture inland flooding, and surge inundation.

The details of the hazard database size for each SLOSH basin are summarized in the table below. Simulation of tens of thousands of storms over the study domain is computationally intensive. A high performance computer was used to simulate the storm surge, which supported in parallel run of multiple storms at the same instance. Making it possible to run 100,000 simulations and handle a big database efficiently.

Table 1: An outlook of the surge database size and time requirements for storm surge simulation

SLOSH Basin	Number of Candidate Storms	Selecting Candidate Storms	Simulating Storm Surge	Extracting and Interpolating Surge	Total Simulation time (hours)	File Size (gb)
		Time Required for Simulation (hours)				
acy	47,952	3	36	36	75	45
ap3	112,581	5	48	48	100	21
cd2	115,165	5	48	48	100	23
co2	78,952	4	36	36	78	4.1
cp2	105,895	5	48	48	100	29
cr3	55,390	3	36	36	78	9.8
de3	117,385	5	48	48	100	33
ebr3	76,120	4	36	36	78	14
efm2	78,021	4	36	36	78	18
egl3	34,986	4	36	36	78	9.2
ejx3	100,596	5	48	48	100	12
eke2	69,054	5	36	36	78	18
emo2	127,741	5	48	48	100	53
epn3	72,584	4	48	48	100	7.8
esv4	129,590	8	72	72	154	42
etp3	63,900	4	36	36	76	4.8

hbix	84,376	4	36	36	80	24
hch2	102,155	5	48	48	100	18
hmi3	59,365	5	48	48	100	4.1
hor3	137,160	8	72	72	148	63
hpa2	56,173	3	24	24	52	4.9
ht3	120,156	8	72	72	156	39
il3	98,554	4	72	72	148	14
lf2	88,358	4	72	72	148	19
ms7	142,726	8	72	72	148	36
ny3	104,386	5	48	48	100	35
oce	43,860	4	24	24	52	1.6
pb3	81,148	5	48	48	100	4.1
pn2	105,565	5	48	48	100	45
ps2	39,400	4	24	24	52	7
pv2	79,852	4	72	72	148	60
					Total Database Size	**718.4**

CHAPTER FOUR

STORM SURGE MODEL VALIDATION

Methodology

Validation of SLOSH model has been carried out by different researchers to evaluate the performance of the model (Jelesnianski *et al.*,1992; Jarvinen, 1999; Glahn *et al.*, 2009; Forbes and Rhome, 2012; Kerr *et al.*, 2013; Forbes *et al.*, 2014). For an individual hurricane simulation, SLOSH has been reported to be within +/-20% range (NWS, 2011). 79% of the time, for best track data the storm surge model errors can be less than 2 feet(Jarvinen, 1999). High errors were found for low surge levels and can show significant dispersion (Glahn *et al.*, 2009). Modeled surge tends to scatter significantly at low levels of increase in water heights. Jelesnianski studied a total of 16 historical storms and simulated storm surge using best track data at 9 locations and reported that SLOSH model can have +/-20% error range (Jelesnianski *et al.*, 1992). A validation study was performed using best track data for hurricane Sandy for New York basin and it was reported that root mean squares of errors of storm surge was less than 1.4 feet at 13 water stations and the correlation between modeled and observations was more than 0.8. (Forbes *et al.*, 2014).

In this chapter, a brief discussion on the validation and performance of the storm surge modeling system is presented. The main criterion for validation of the storm surge model was to find the error between the measured and modeled data by comparing the simulated surge with measured water levels for different SLOSH basins at NOAA tide gauge stations, USGS storm surge sensors and high water marks. To test the accuracy of the modeled surge heights, a set of 16 historical storms were considered and the track details for each storm were obtained using the HURDAT and IBTrACK database and each historical hurricane track was then converted into a format required by SLOSH. The numerically simulated storm surge using SLOSH basins was obtained. Water levels from these historical hurricane simulations were then compared to a set of NOAA water stations, high water marks, and storm surge sensors. A database with 508 observations was developed.

The aim of these simulations was to analyze the performance of the model and quantify the error in the model for each basin. It was observed that simulated surge matches well with the measured data. However, there are some modeling errors in storm surge, which needs to be adjusted. Modeling errors need to be quantified, as it is important for an accurate estimation of long-term storm surge probability using stochastic simulation. Figure 13 shows a comparison of modeled and observed data for each individual hurricane.

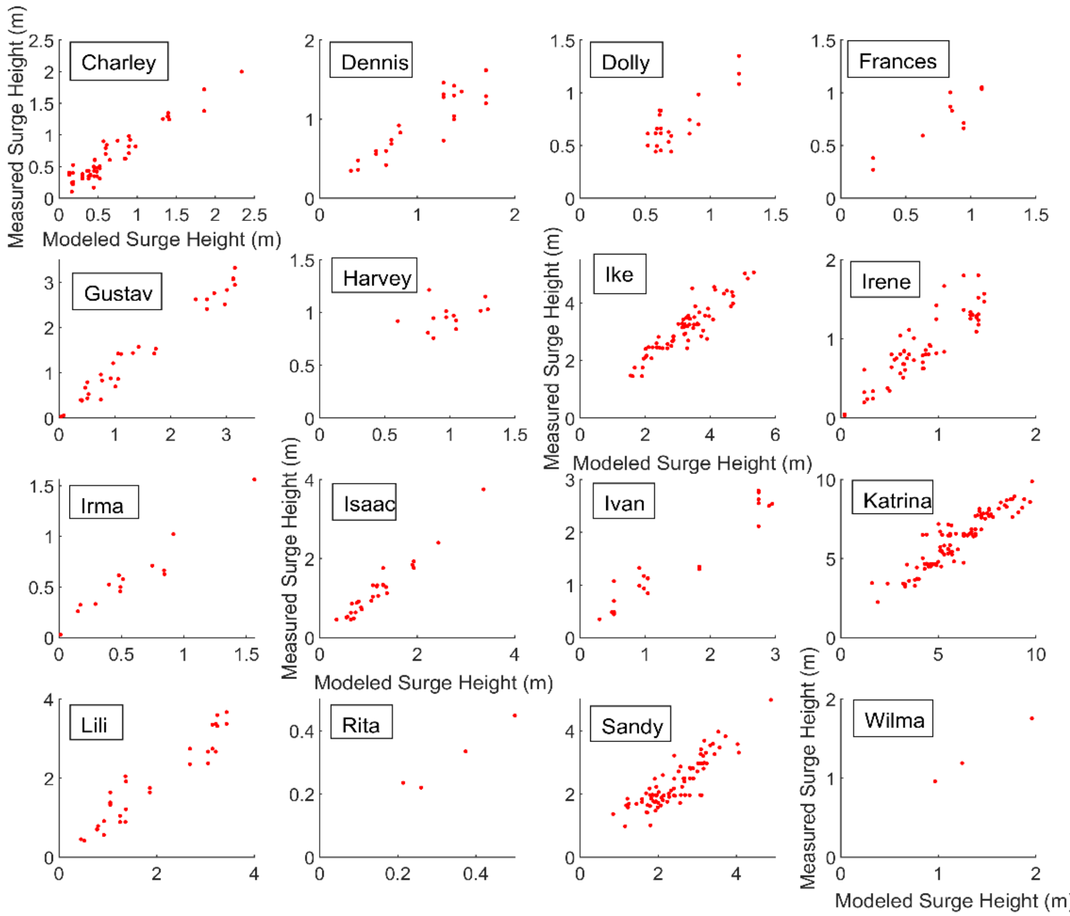


Figure 13: SLOSH model-simulated surge height *vs.* Observed data.

<u>Case Study: Hurricane Sandy</u>

Hind cast simulation of Hurricane Sandy was done to quantify the SLOSH model in terms of its ability to predict the surge height that occurred along the US coastline. The historical data used to run the simulation was obtained from The Hurricane Database (HURDAT), managed by the National Hurricane Center, which contains information of all the hurricanes that have occurred within the Atlantic Ocean since 1851. A quantitative comparison was made between the simulated and the observed water level data obtained from NOAA reports.

Hurricane Sandy formed in the western Caribbean, south of the island of Jamaica in a region of low wind shear, warm water and a broad area of low pressure on 22 October 2012 making its first landfall near Kingston, Jamaica as a category 1 storm (Forbes *et al.*, 2014). It made second landfall in Cuba on 25 October 2012 with wind speeds ranging between 110 to 115 as a category 3 storm. 110 mph wind gusts were reported in Cuba. The storm started to weaken up and the radius of maximum wind reached larger than 185 km over Bahamas. The storm started to curve slightly towards west due to a baroclinic trough, which steered the storm northwest. It began its transition into an extra tropical storm near Atlantic City, NJ. However, 2.5 h prior to its final landfall. It approached the coast as a category 1 hurricane and made landfall at 23:30 UTC.

As Hurricane Sandy made a turn towards the mid-Atlantic coast and continued to grow in size, storm affected major parts of the US coast starting from North Carolina to New England, higher storm effects were observed across New Jersey, New York and Connecticut. The maximum observed storm surge was measured at Kings Point, NY 3.856 m above normal predicted tide levels, which was 30 minutes prior to landfall (Blake *et al.*, 2013; Fanelli, Fanelli and Wolcott, 2013). The storm resulted in a surge of 2.87 m at battery, NY and destroyed over 100,000 homes. Figure 14 represents the path of hurricane Sandy. The black line represents the SLOSH NY3 basin boundary.

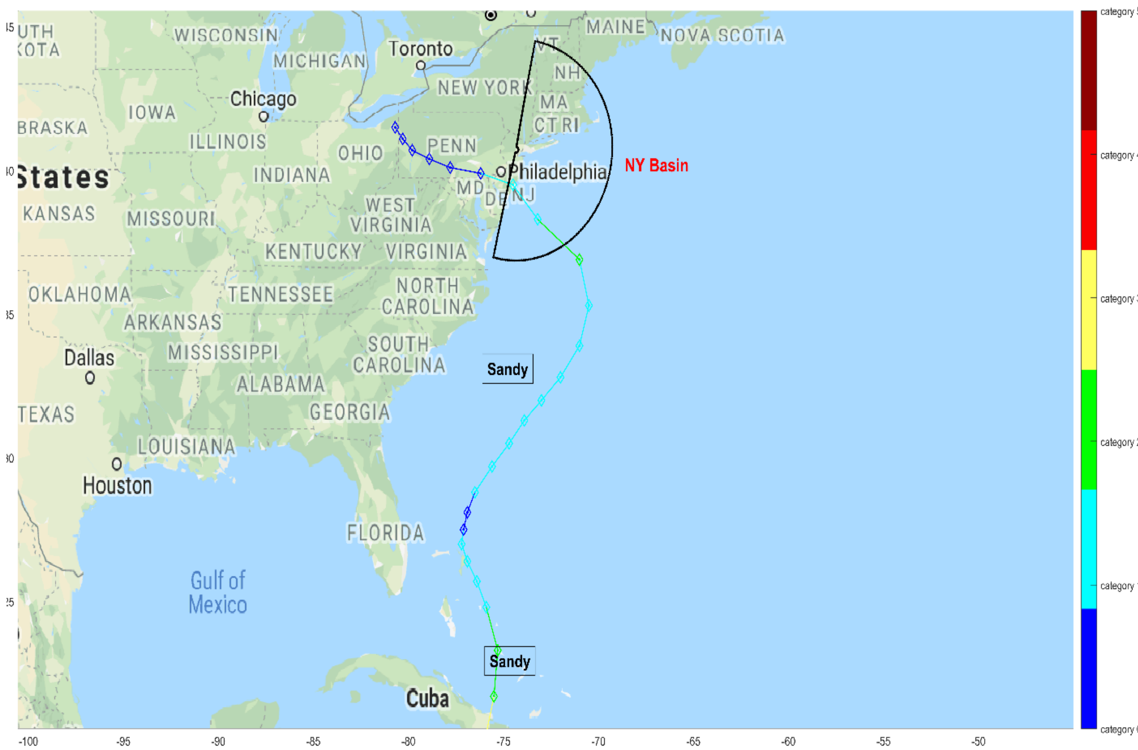


Figure 14: Hurricane Sandy track

Tidal and total water elevations were obtained from NOAA tidal gauge stations located in the SLOSH New York basin. The observed data was used to compare modeled water levels. Figure 15 shows the modeled surge height versus the observed surge height at NOAA water stations, High Water Marks and USGS temporary placed Storm Surge Sensors. A total of 99 observation points were obtained from which included 26 High water marks(HWM) and 60 Storm Surge Sensors(SSS). The model tends to underestimate the surge heights in case of the SSS data as it often includes the impact of waves, which were not considered in these hindcast simulations. The Root Mean Square Error for the highest observed and modeled surge was 0.45 m.

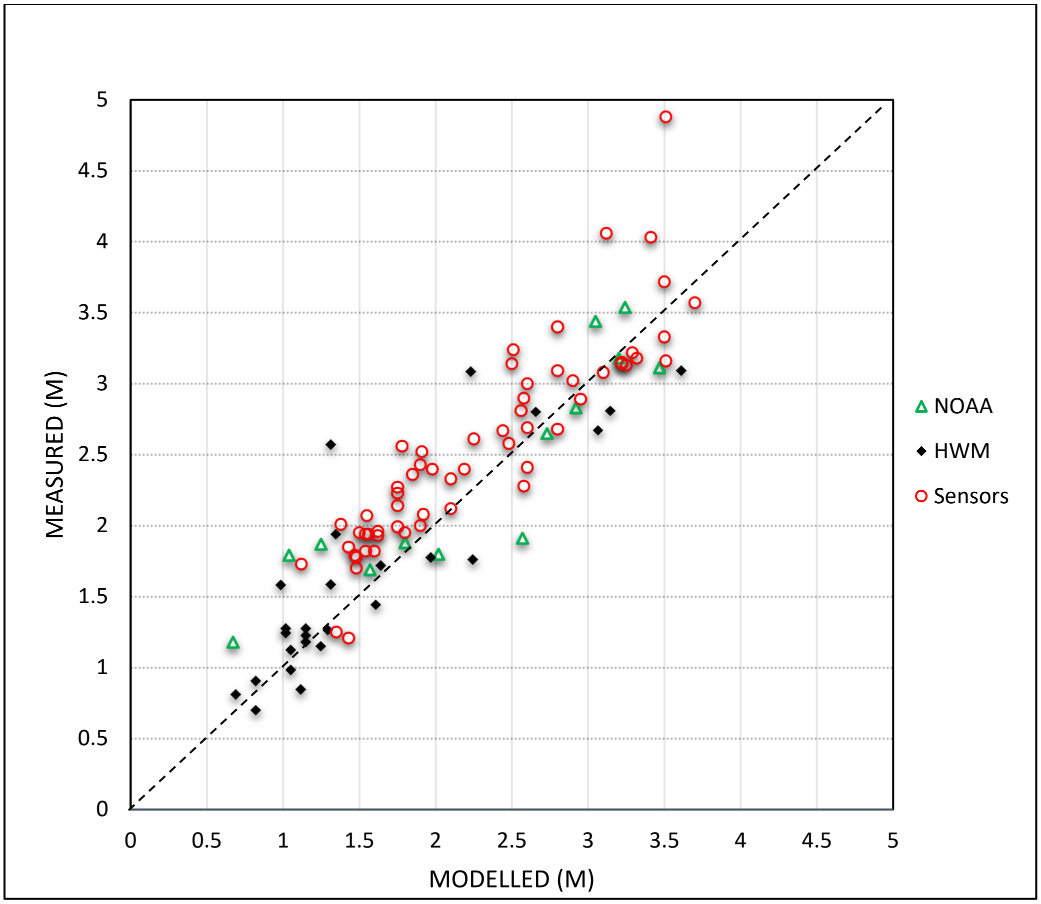


Figure 15: SLOSH modeled surge Versus Observed data

Table 2 summarizes the model performance in terms of relative error of the NOAA, HWM and SSS vs SLOSH respectively. More than 85% of the observations had errors of less than or equal to 30%. Nearly half of the time, SLOSH was able to capture the surge effectively with an error less than 10%. The mean error in modeled observations as compared to NOAA observation data was 0.1 m.

Table 2: Summary of Mean Error and Partition of relative error between observed and SLOSH simulated surge for all measurements: NOAA tide gauges, USGS SSS and HWM.

Sample Size	99
Mean Error NOAA (m)	0.10
Mean Error HWM (m)	0.18
Mean Error SSS (m)	0.26
Relative Error	Number of Observations
< 10%	40
10 to 20%	32
20 to 30%	16
>30%	11

A comparison of water levels at 13 different observation stations lying inside the SLOSH's New York basin is shown in the Figure 17.

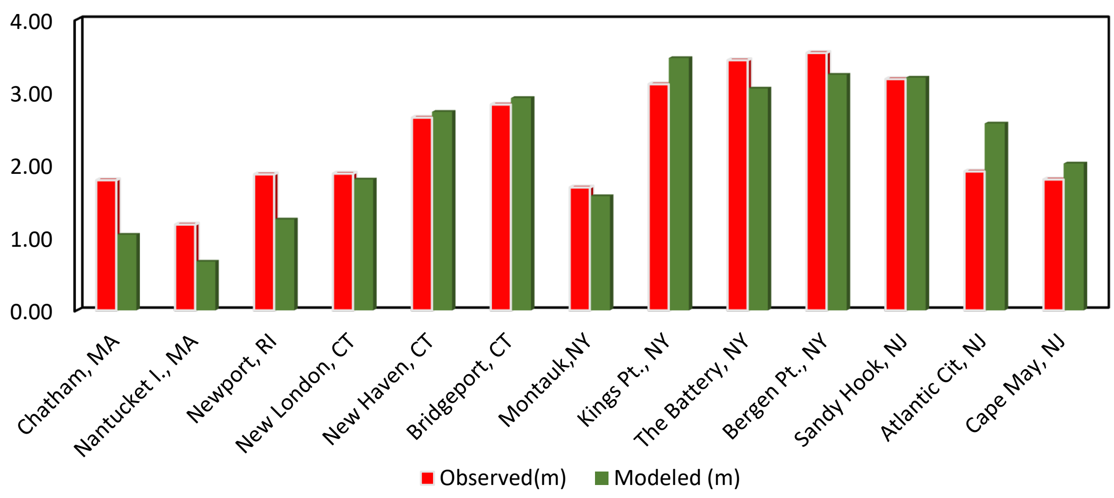


Figure 16: Hurricane Sandy modeled vs observed water levels at NOAA stations

Bias Correction Approach for SLOSH Basins

Figure 18 and Figure 22 represents the tracks of selected candidate historical hurricanes for validation study for the Mobile basin and New York basin respectively. Mapping of NOAA tide station locations has been displayed in Figure 19 and Figure 23. Hind-cast simulations were driven for the candidate hurricanes for analysis and verification. The results of the analysis were then compared to the observed values. Figure 20 and Figure 24 portrays the scatter plots and relationship between the observed and the modeled data in mobile (emo2) and New York (ny3) basin respectively. It can be noted that the simulated surge values fall within a range of 10%-30% error. It is evident that the observed surge and the modeled surge do not have a linear 1:1 relationship indicating existence of modeling errors. Also, It is apparent that SLOSH seems to exhibit under prediction of the surge in New York basin, these aleatory and random uncertainties in the SLOSH model surge depths needs to be quantified and bias corrected. The quantification of errors is addressed by adjusting the model for systematic and random errors. The systematic errors may arise due to limitations in modeling physics using model parameters and inability to replicate the actual meteorological conditions. For instance, bottom friction calculation, Coriolis effect, numerical representation, and wind speed calculations, which may indirectly/directly influence the storm surge calculations. The random errors may occur due to the randomness in the hurricane track in terms of speed, size, heading angle and severity. By accounting these errors, we can make the model more representative of the real world conditions.

In order to remedy the systematic bias in the storm surge heights least squares regression can be used (power model) (Pei *et al.*, 2013). After adjusting the model for systematic errors using $C_0(S_s)^{C_1}$, the random errors (ε) can be taken into account by dividing the measured surge height by systematic error adjusted surge height. The random errors (ε) represents the scattermess around the fitted power curve and are independent of $\overline{S_s}$. The adjustment of systematic errors using non-linear regression will result in two basin specific constants namely C_0 andC_1. The power equation is given by:

$$S_m = C_0(S_s)^{C_1} * \varepsilon \tag{4.1}$$

Taking natural log on both sides of the equation, we have the following equivalent equation. This equation has the form of linear regression model.

$$\ln(S_m) = \ln(C_0) + C_1 * ln(S_s) + \ln(\varepsilon) \tag{4.2}$$

The random errors are assumed to follow lognormal distribution and to find the parameter of the distribution; the random error is fitted to lognormal distribution. The total number of observation points for each basin, the adjusted power regression constants C_0 and C_1 along with location and scale parameters of the lognormal distribution of random errors and are listed in table 2. It can be noted from table 2 that the mean of the random error is always equal to zero, supporting the assumption that random errors follow lognormal distribution. That is, the power equation can be used to remove the modeling biases and the resulting systematic-error-adjusted surge simulations only suffer the random errors. The PDF and CDF of lognormal distribution is given in equation 4.3 and 4.4. Table

3 lists details of estimated parameters for both systematic and random errors for each SLOSH basin.

Probability density function (PDF):

$$f(x) = \frac{1}{\sqrt{2\pi}\,\sigma(x-\lambda)} \exp\left\{-\frac{[\ln(x-\lambda)-\mu]^2}{2\sigma^2}\right\},\ x > \lambda,\ \sigma > 0 \tag{4.3}$$

Cumulative distribution function (CDF):

$$F(x) = \int_{\lambda}^{x} \frac{1}{\sqrt{2\pi}\,\sigma(t-\lambda)} \exp\left[-\frac{[\ln(t-\lambda)-\mu]^2}{2\sigma^2}\right] dt,\ x > \lambda,\ \sigma > 0 \tag{4.4}$$

Where μ is the location parameter, σ is the scale parameter and λ is the threshold parameter.

Figure 21 and Figure 25 shows the lognormal distribution fit of random errors for two different basins.

Table 3: Systematic Adjusted Surge Height coefficients and Lognormal distributed Error Parameters

Basin Names		**# Points**	**Adjusted Surge Coefficients**		**Random Error Parameters (Lognormal)**			
			C0	**C1**	**μ**	**σ**	**ε_{05}**	**ε_{95}**
emo2	Mobile bay	144	0.97	1.001	0.00001	0.182	0.78	1.24
ny3	New York	79	1.14	0.891	-0.028	0.223	0.751	1.17
egl3	Galveston bay	92	1.114	0.937	-0.009	0.129	0.83	1.21
ms7	New Orleans	49	1.019	0.99	-0.008	0.245	0.736	1.513
lf2	Vermilion bay	36	1.075	0.934	-0.004	0.264	0.621	1.55
de3	Delaware bay	24	1.005	1.015	-0.017	0.35	0.61	1.7
cp2	Chesapeake bay	19	0.889	0..94	-0.013	0.395	0.648	1.72
hmi3	Biscayne Bay	17	0.93	1.0872	-0.006	0.313	0.65	1.27
ht3	Hatteras	16	0.91	1.023	-0.006	0.523	0.507	1.61

pv2	Providence/ Boston	13	1.024	0.891	-0.007	0.307	0.65	1.284
etp3	Tampa bay	12	0.971	0.835	-0.028	0.411	0.514	1.3
ap3	Apalachicola bay	12	1.047	1.136	-0.105	0.416	0.652	1.68
ebr3	Laguna Madre	12	0.974	0.614	-0.012	0.28	0.754	1.251

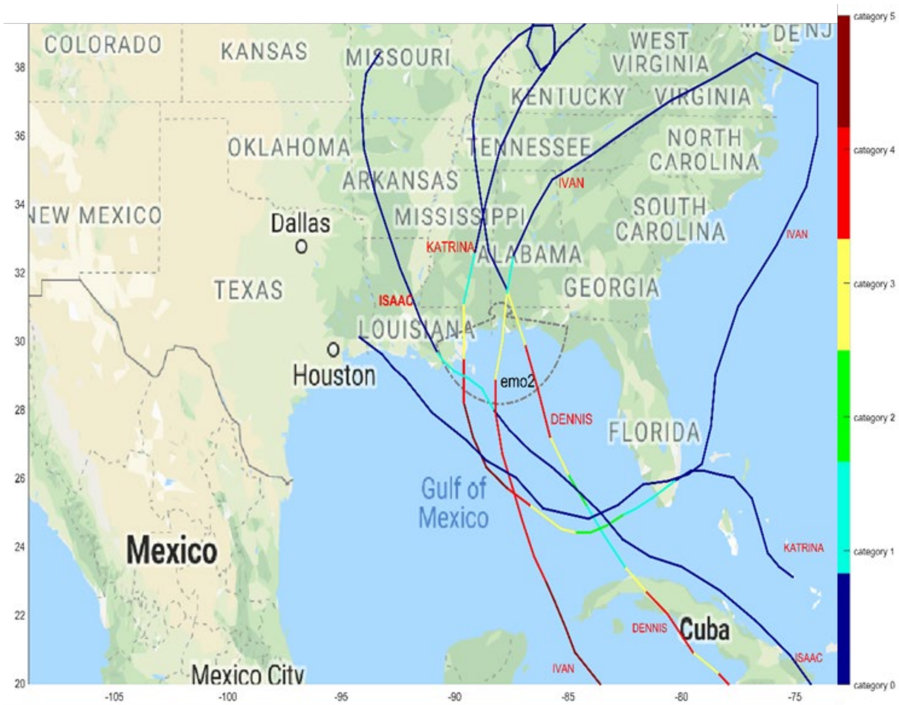


Figure 17: Selected historical hurricanes for ‘emo2’ basin

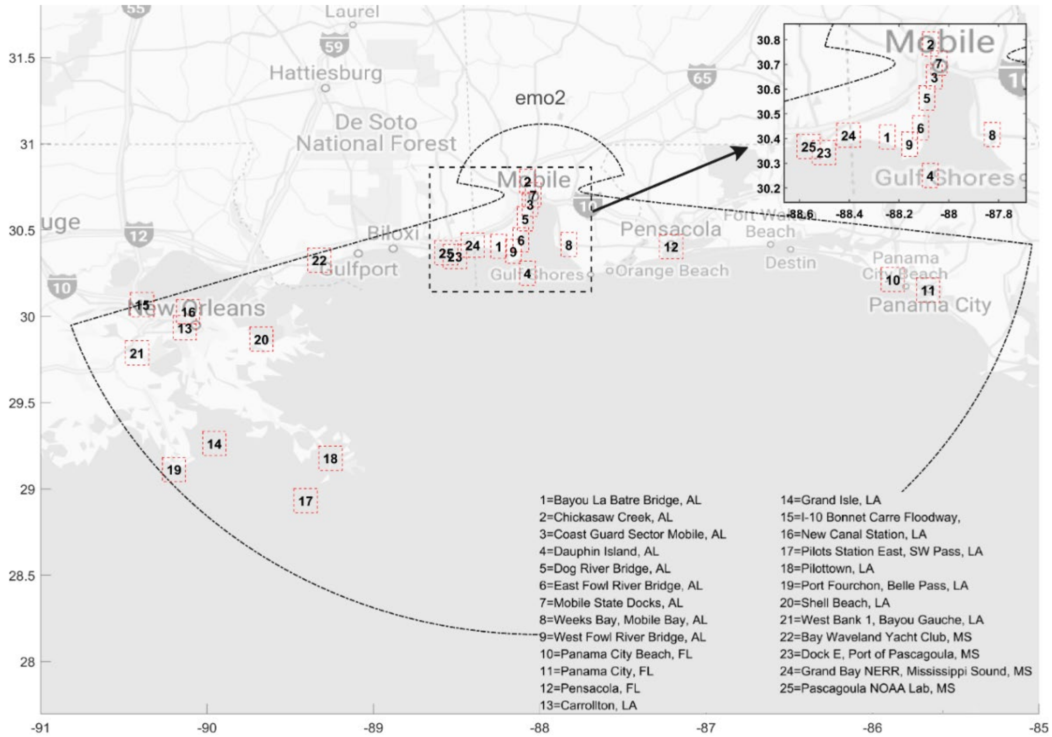


Figure 18 : Location of water stations for ‘emo2’ basin

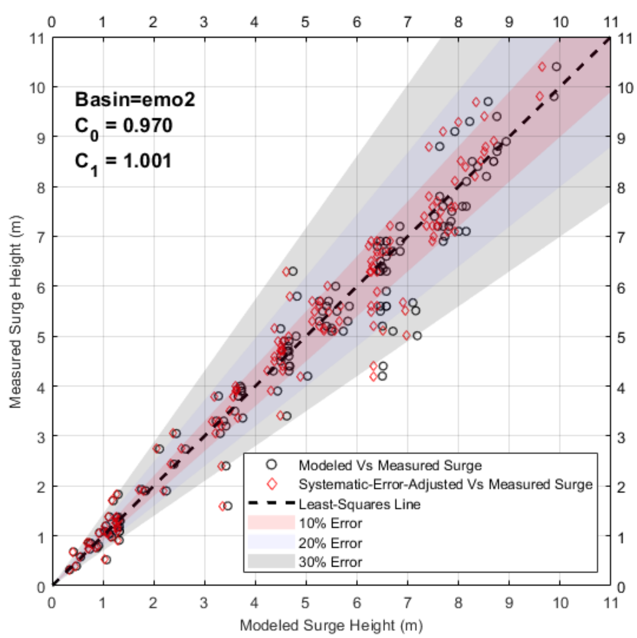


Figure 19 : Measured versus Simulated storm surge heights for ‘emo2’ Basin

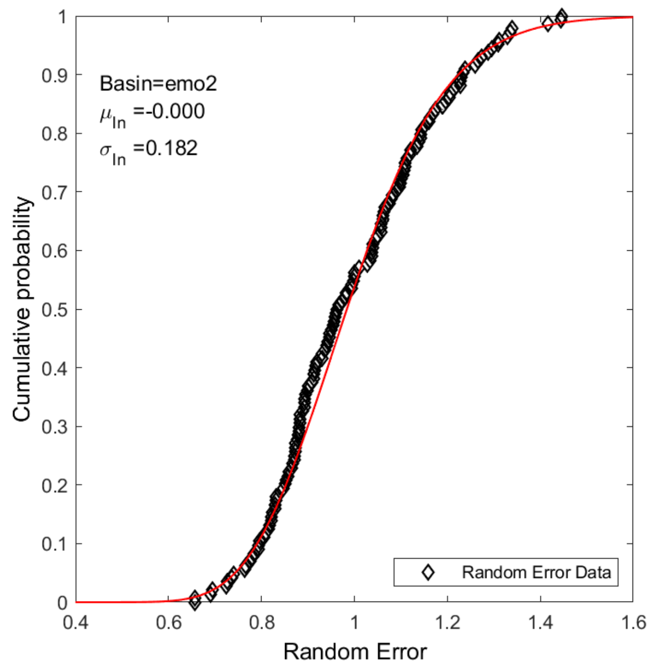


Figure 20: Lognormal distribution fit of random errors for ‘emo2’ basin

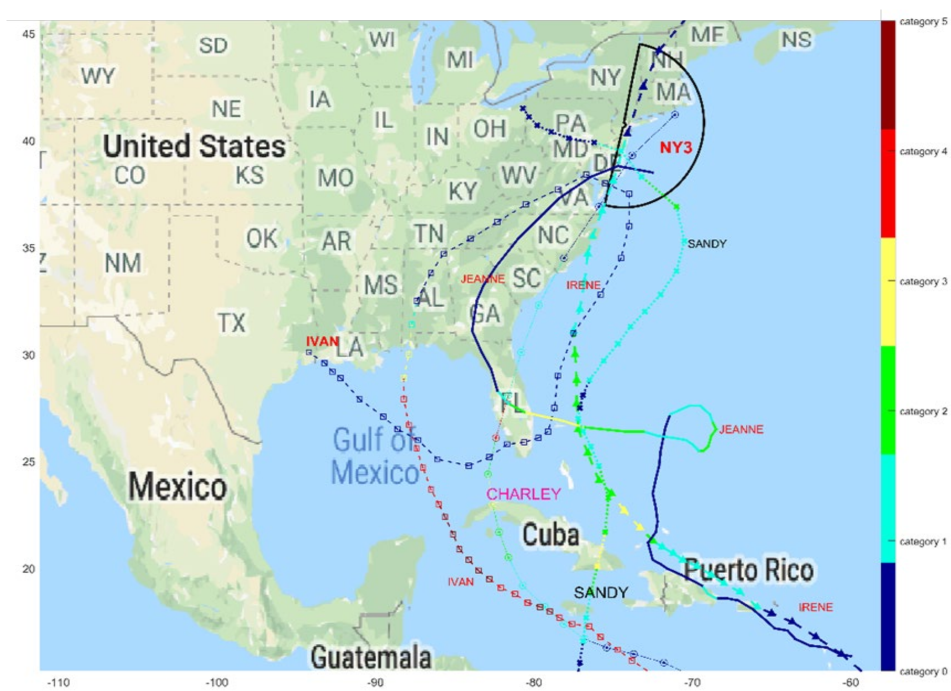


Figure 21: Selected historical hurricanes for ‘ny3’ basin

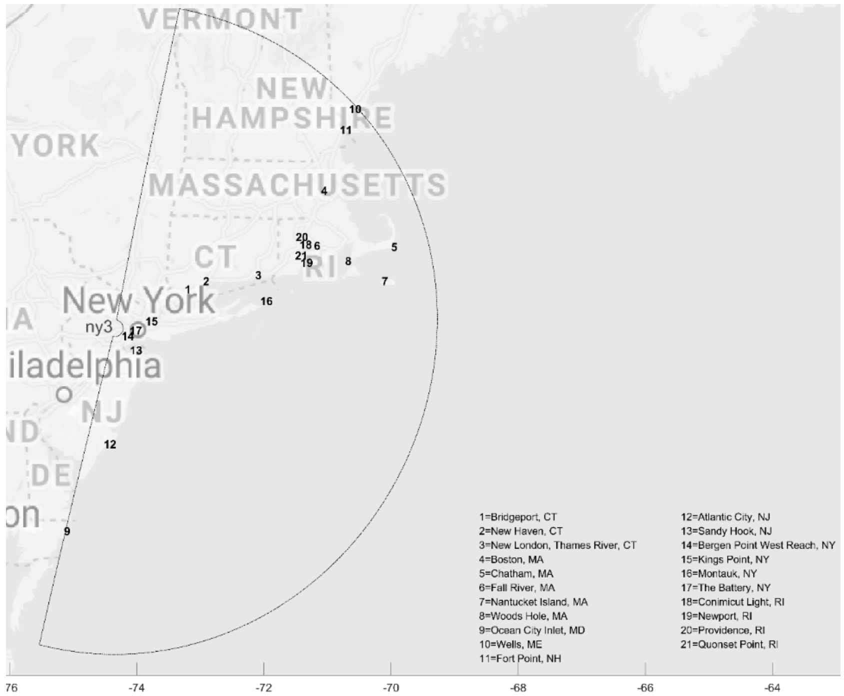


Figure 22 : Location of water stations for ‘ny3’ basin

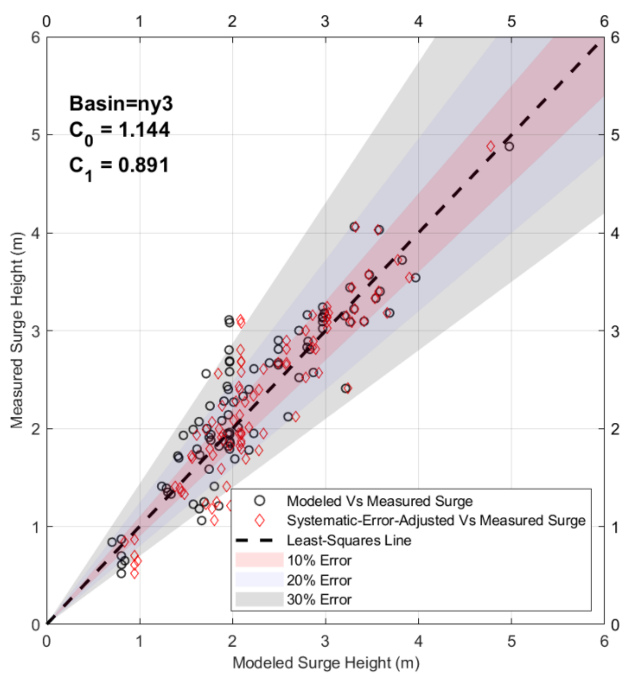


Figure 23 : Measured versus simulated storm surge heights for ‘ny3’ Basin

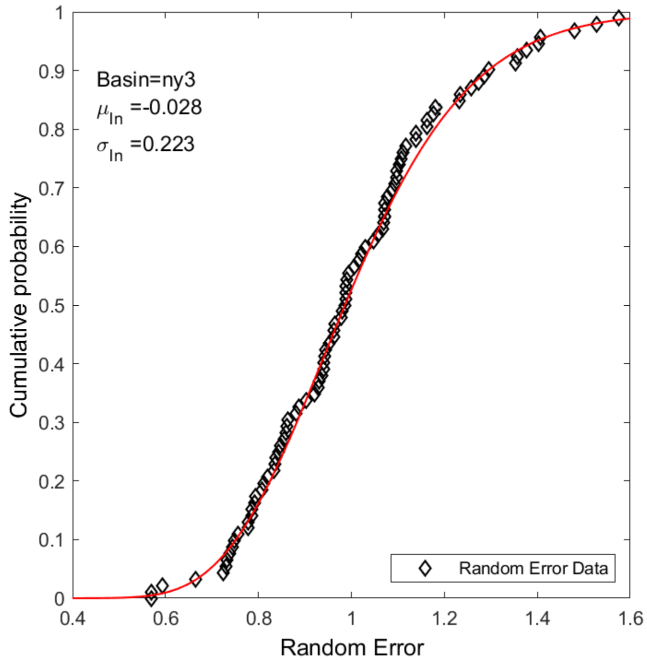


Figure 24: Lognormal distribution fit of random errors for ‘ny3’ basin

CHAPTER FIVE

ESTIMATION OF LONG-TERM PROBABILISTIC STORM SURGE AND ASSOCIATED UNCERTAINTY

Several studies have been performed in the last decade to estimate the long-term surge probabilities and return intervals. (Walton, 2000; Keim, Muller and Stone, 2007; Legg *et al.*, 2010; Lin *et al.*, 2010, 2012, 2014; Apivatanagul *et al.*, 2011; Needham and Keim, 2012; Shrestha *et al.*, 2014; Sota and Mori, 2014). A comprehensive historical storm surge database was developed consisting of 195 surges along US coast since 1880 (Needham and Keim, 2012). This database was limited as it represented surge return periods based on a particular location rather than the extent of storm surge inundation. This limited observation data can be fitted using extremal fitted probability distributions. However, it may result in under prediction in case of large extremes of the data (Walton, 2000). This makes it difficult to accurately assess the risk from extreme events with long return periods and may lead to incorrect portrayal of the variability in surge hazard for a large spatially variable extent. Also, the historical data is unreliable due to its limited size and can be bias in predicting the risk of extremes for any coastal areas (Lin *et al.*, 2014). Another approach to estimate the long-term surge probability is empirical simulation technique (EST) using a non-parametric analysis of historical data (Borgman, 1992). However, it was reported that EST overestimates the expected values (Agbley and Basco, 2008). In the current study, synthetic hurricanes are generated where the genesis point of the storm is sampled from the known spawn locations of historical hurricanes recorded in HURDAT(Liu, 2014; Pei *et al.*, 2014). The main goal is to derive a hazard curve that may assist in best estimate the frequency and captures uncertainty of certain storm surge. A two-step approach is proposed to better capture the extreme event frequency. Firstly, derive the surge hazard curve by using stochastic hurricane simulation and SLOSH model that represents a good understanding of the risk. Secondly, consider the effect of modeling errors during the storm surge simulation and adjust the hazard curve for these errors. As previous studies suggest that SLOSH might under predict or over predict surge (Lin *et al.*, 2012; Kerr *et al.*, 2013; Forbes *et al.*, 2014).

Methodology

The return period / recurrence interval of storm surge is defined as the estimated likelihood of having that surge again over a given time period. Return period estimates of a hazard at a given site can be a useful tool during the development, planning and mapping phases of critical infrastructures to ensure their safety and resistance to such extreme events.

Error Adjustment and Application of Hazard Curve in Historical Storm-surge Return Interval Estimation

Error Adjustment of Hazard Curve

1. Parametric Approach:

The following steps were used to estimate the long-term probability of surge at a specific site. First, for a given study domain, a set of candidate hurricanes were selected based on the criteria ($D_j < 2R_{max}$) from the stochastic hurricane track database containing one hundred thousand year of simulated tracks. Second, the SLOSH model was used to run storm surge simulations for the selected set of selected candidate hurricanes and a hazard database was developed at every 0.01-degree uniform distance in the study domain extending from Texas to Maine. Third, at any given location of interest, the maximum storm surge for each candidate track was recorded. Fourth, the recorded maximum surge from each candidate hurricane was sorted and ranked in the order of lowest to highest. Fifth, a histogram of peak surge at any given site of interest was created. Sixth, the probability of exceedance and the mean recurrence interval were calculated using equations 5.3 and 5.4. Finally, hazard curve was adjusted for systematic modeling errors using the coefficients provided in table 3 and generate the confidence bounds for return periods.

The probability of surge height (s_i) greater than certain surge threshold value(S) can be described as:

$$P_t(s_i > S) = 1 - \sum_{x=0}^{\infty} P(s_i \leq S \,|x)\, p_t(x) \tag{5.1}$$

Where $P(s_i \leq S \,|x)$ is the occurrence probability for surge $(s_i \leq S)$ for given number of candidate events(x) and $p_t(x)$ is the probability of x events that occur over a period of time (t).

Assuming $p_t(x)$ follows a Poisson distribution the P_t can be expressed as:

$$P_t(s_i > S) = H_t(S) = 1 - \exp\left(-\frac{n}{Y}t\right) \tag{5.2}$$

where, H_t is the hazard value from the distribution for t-year probability of exceedance, where n is the total number of hurricanes meeting the condition $(s_i > S)$ and Y is the total number of years. If $\frac{n}{Y}$ is very small then the occurrence probability is given by:

$P(s_i > S) = \frac{n}{Y}$ (5.3)

The site-specific long-term probabilistic surge heights and respective return periods can be calculated using the following equation

$MRI\ (s_i > S) = \frac{1}{\lambda P(s_i > S)} = \frac{Y}{n}$ (5.4)

where λ is the mean annual occurrence rate

The hazard curve was then adjusted for the systematic modeling errors. The adjusted surge for a given return period can be determined using the following equation:

$\overline{S_s} = C_0 (S_s)^{C_1}$ (5.5)

where $\overline{S_s}$ is the systematic adjusted surge height

C_0, C_1 are the power regression constants listed in table 3 for each basin.

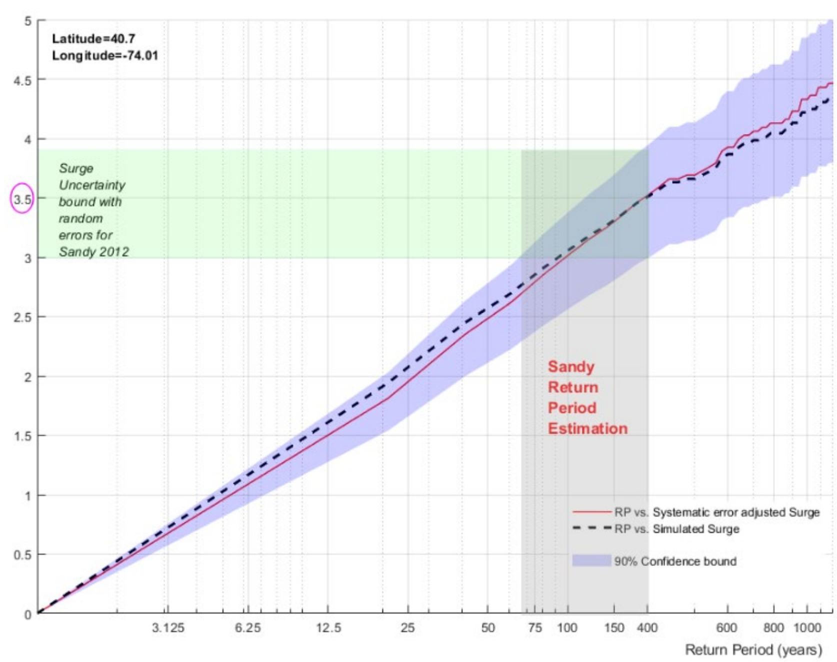


Figure 25: Return level plot for storm surge in Battery Park, NY (Non-Parametric)

2. Non-Parametric Approach:

As a case study for non-parametric approach, I considered long-term risk assessment of storm surge at the Battery Park, NY.

Hurricane simulation model was made to run and storm surge was simulated for resulted candidate hurricanes. A total of 9880 simulated storms caused a significant amount of surge. Only 99 simulated storms had surge height higher than 3 meter, with a scarce dataset of 19 storms causing an extreme surge of greater than 4 meter. The largest simulated surge caused by a hurricane was observed to be 5.77 meter. Figure 26 (a) shows the distribution of storm surge into different bins. As it can be seen that this site has low number of recurrences of high intensity surge showing that the data is heavily tailed. For the heavy tailed extreme surge heights, probability of exceedance and return intervals were calculated using 5.6, 5.7 and 5.8. The hazard curve can then be adjusted for systematic modeling errors using the coefficients provided in table 3 and generate the confidence bounds for return periods.

The quantile-quantile (Q-Q) shows that surge distribution has a heaver tail than exponential as expected in case of extreme surges. However, this tail is important to determine the risk of extreme storm surges in any storm surge prone areas. Figure 26 (b) shows the exponential Q-Q plot for simulated storm surge. This should be a 1:1 line if the data follows an exponential distribution. A best fit was found to estimate this heavy upper tail of the simulated storm surge. Generalized Pareto distribution with peaks over threshold (POT) was used to estimate this upper tail.

The Peaks over threshold (POT) approach generates a subset of data points from a simulated surge data by only considering those events above a defined threshold in this case we set 95th percentile of the surge data as the threshold (1.77 m). Simulated surge is more likely to be from a same distribution when we consider set of the data above a certain threshold. In addition to this, data peaks can also be considered statistically independent, the distribution of the peak events is indeed following a Generalized Pareto distribution. Figure 26 (c) shows the Q-Q plot for the GPD quantiles showing that the data shows good agreement with the GPD model and strengthens the evidence that belongs to GPD.

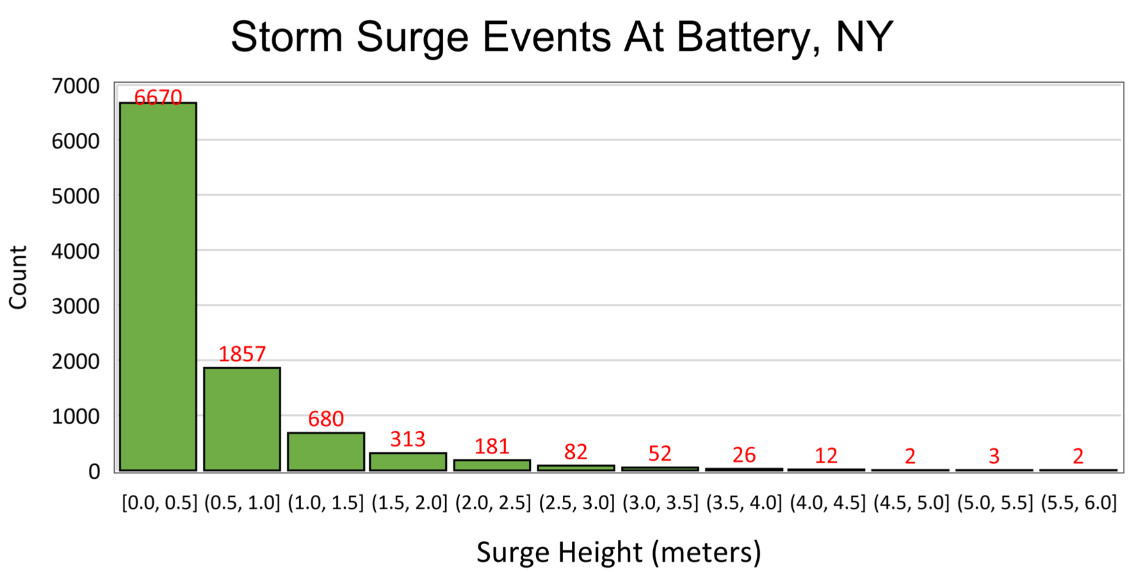
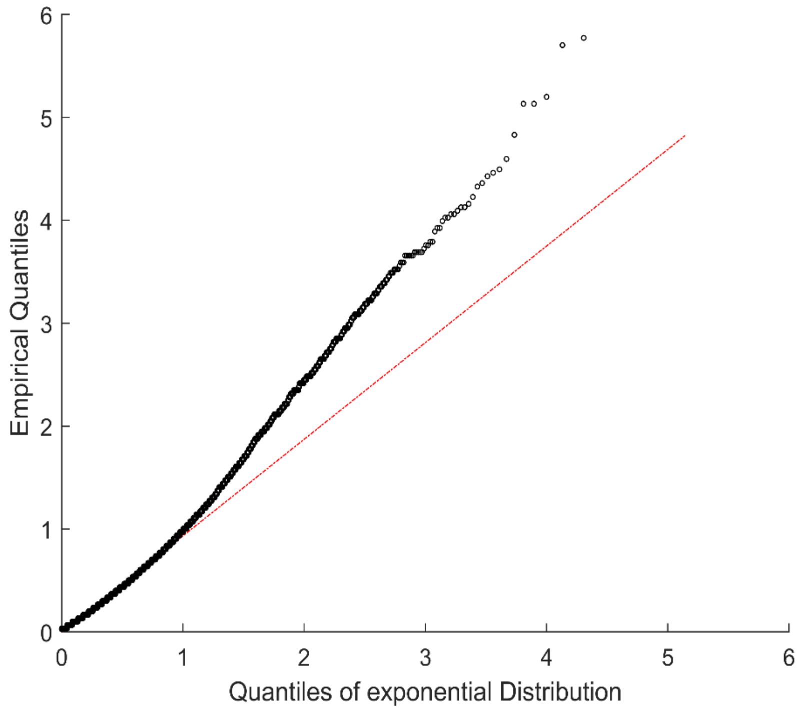
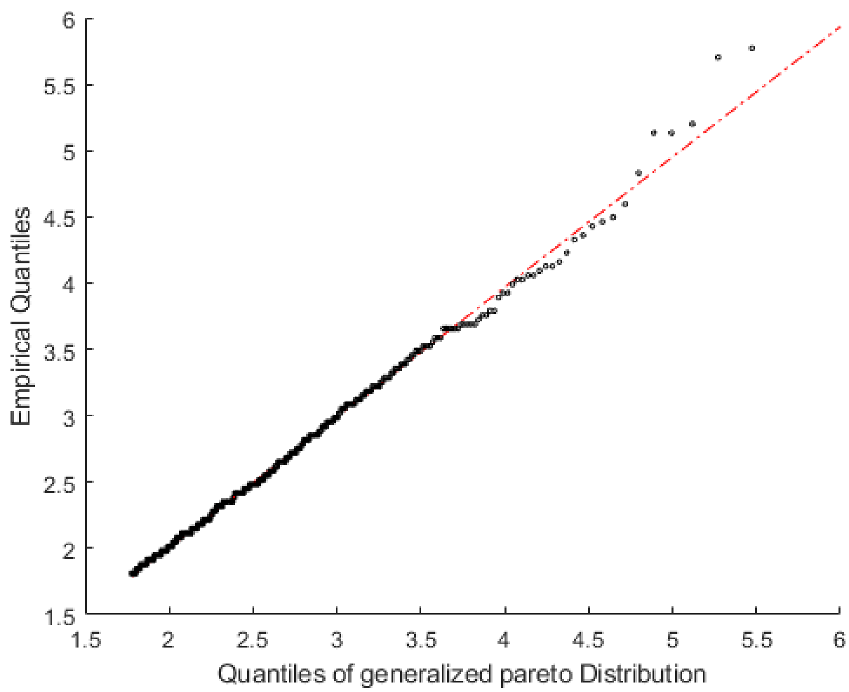


Figure 26: (a) Histogram of SLOSH simulated storm surge at Battery Park, NY



26(b) QQ plot of simulated storm surge at Battery Park, NY



26(c) QQ plot of simulated storm surge at Battery Park, NY above a threshold of 1.77 m

The probability of storm surge exceeding a threshold is given as:

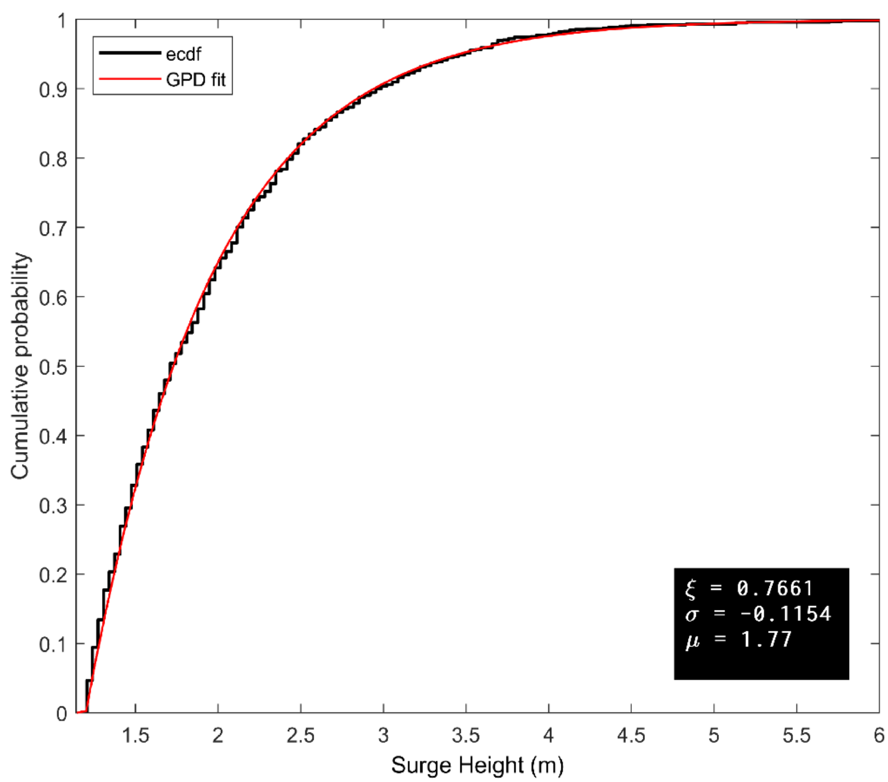
$$F_u(s) = P(X - u \ \leq s \mid X > u) \quad (5.6)$$

For large u, GPD is given as

$$F_u(s) = 1 - (1 + \xi \ \frac{s}{\sigma})^{\frac{-1}{\xi}}; s \geq 0 \quad (5.7)$$

where ξ is the shape parameter and σ is the scale parameter.

The threshold is selected based on 90th percentile of the simulated surge dataset. The scale, shape and location parameters were estimated using maximum likelihood estimation (MLE) method and the cumulative probability distribution of surge data is shown in figure 26 (d).



26(d) Cumulative Distribution and estimated parameters of the GPD fit

The Annual exceedance frequency of a given storm surge is calculated using the method described by Lin (Lin *et al.*, 2010). And is given as the product of the surge height exceedance probability and the annual frequency of the storm and can be written as:

$$P\{X > l\} = [1 - F_u(l - u)] * P\{X > u\};\ l > u \qquad (5.8)$$

where $P\{X > u\}$ is the chance that the storm surge will exceed the threshold (1.77 m) and is calculated to be 0.0328 for the present scenario. Annual storm frequency is given as ratio of total storms occurring at the site to the total length of simulation years. Annual frequency of the storm is calculated to be 0.9882.

The mean return period of the storm surge is estimated using equation (5.4) which is the reciprocal of the annual exceedance frequency. The obtained hazard curve was then adjusted for the systematic modeling errors due in the storm surge using equation (5.5) and a new adjusted hazard curve was estimated. From Figure 27, it can be noted that the adjustment in the storm surge hazard for modeling errors has increased the surge estimates for longer return intervals. It can be interpreted that developing the surge hazard using the raw data from SLOSH can under predict the long-term risk at Battery Park, NY. Also, for a given return period, the storm surge estimates can still be improved and made more accurate by adding wave run up and consider climate change. Figure 27 shows the storm surge return level plot at Battery Park, NY.

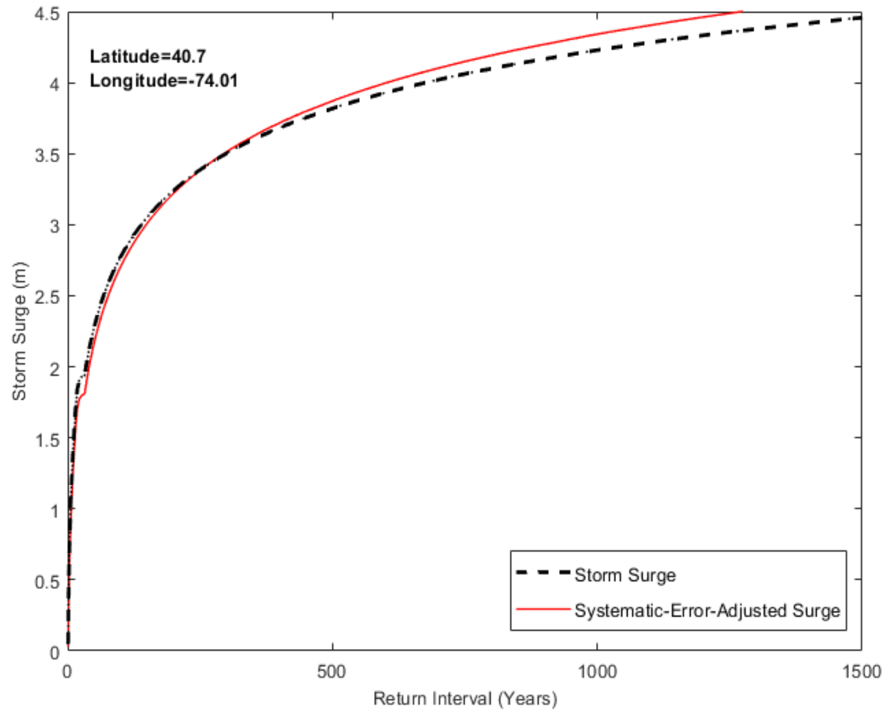


Figure 27: Return level plot for storm surge in Battery Park, NY

The dashed black line is the storm surge without adjustments and the red line is the surge after adjustment. This strengthens the hypothesis that the modeling errors does have an impact on long term estimates of storm surge and must be considered in estimation of long term return periods of extreme events. The 90% confidence bounds were estimated by using 5^{th} and 95^{th} percentile of the shape and scale parameter estimates of the GPD fit shown in Figure 28.

Historical Storm Surge Return Period Estimation

After generating a hazard database, one of its important application can be prediction of surge return periods for historical storms. We considered Battery Park, NY as our candidate site to estimate the return period of hurricane Sandy. Sandy produced a

Surge of 3.5 meters (circled in Figure 28) causing a catastrophic flooding. The total damage from Hurricane Sandy was over $70 billion USD (NCEI, 2018).

We tried to estimate the frequency of Hurricane Sandy storm-surge using our hazard curve to assess the risk of such storm hitting the NY coast and the return period of a particular storm surge intensity at Battery Park, NY.

A number of studies exist discussing about the assignment of a return period to hurricane Sandy (Lin *et al.*, 2010, 2012; Jay and Talke, 2013; Sweet *et al.*, 2013; Forbes *et al.*, 2014; Shrestha *et al.*, 2014). Lin used numerical simulation technique and fitted the extreme event surge using Generalized Pareto Distribution to assess the risk of storm surge at Battery Park, NY. The hazard curve developed by Lin indicates that the Hurricane Sandy was having a return period of about 650 years. Soon after, Lin performed another study to predict the surge using a high resolution storm-surge model and developed a current scenario and future sea level rise scenarios showing that Sandy have a return period of about 550 years and an event of that intensity can happen more frequently in future. A study performed based on the annual extremes indicated the storm tide of Sandy to be 1570 years (Sweet *et al.*, 2013). A study was performed GPD analysis using bootstrapping technique to infill unknown data between 1821 and 1843 and considering 53 events with storm tide greater than 1.25 m(Jay and Talke, 2013). They reported the Hurricane Sandy return level to be approximately 300 Years (in a range of 200-400 years).

We estimated the return period of sandy and found it to be in strong agreement with the study done by Jay and Talke indicating surge return interval of Sandy to be in a range of 240 to 360 years.

To assess the risk of long term surge, we estimated a range for a 100 year storm surge and 500 year storm surge. The 100 year storm surge can possible be anywhere between 2.65 m to 2.9 m. A once in 500 year storm surge can be in between 3.74 to 4 m. These estimates appear to closely match the values of long term hazard reported as 2.62 m for 100-year return interval and slightly on a higher side as compared with 3.26 m for 500 year return interval (Rosenzweig and Solecki, 2010).

This risk assessment methodology can be adopted for all other historical storms and all other coastal regions as well.

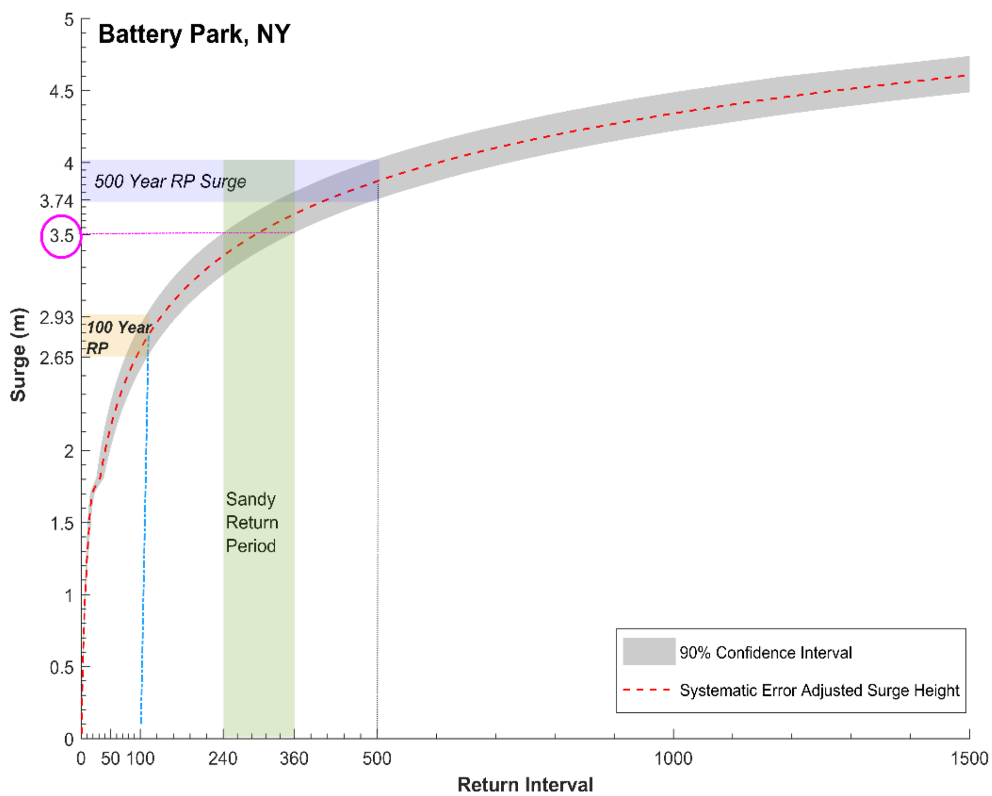
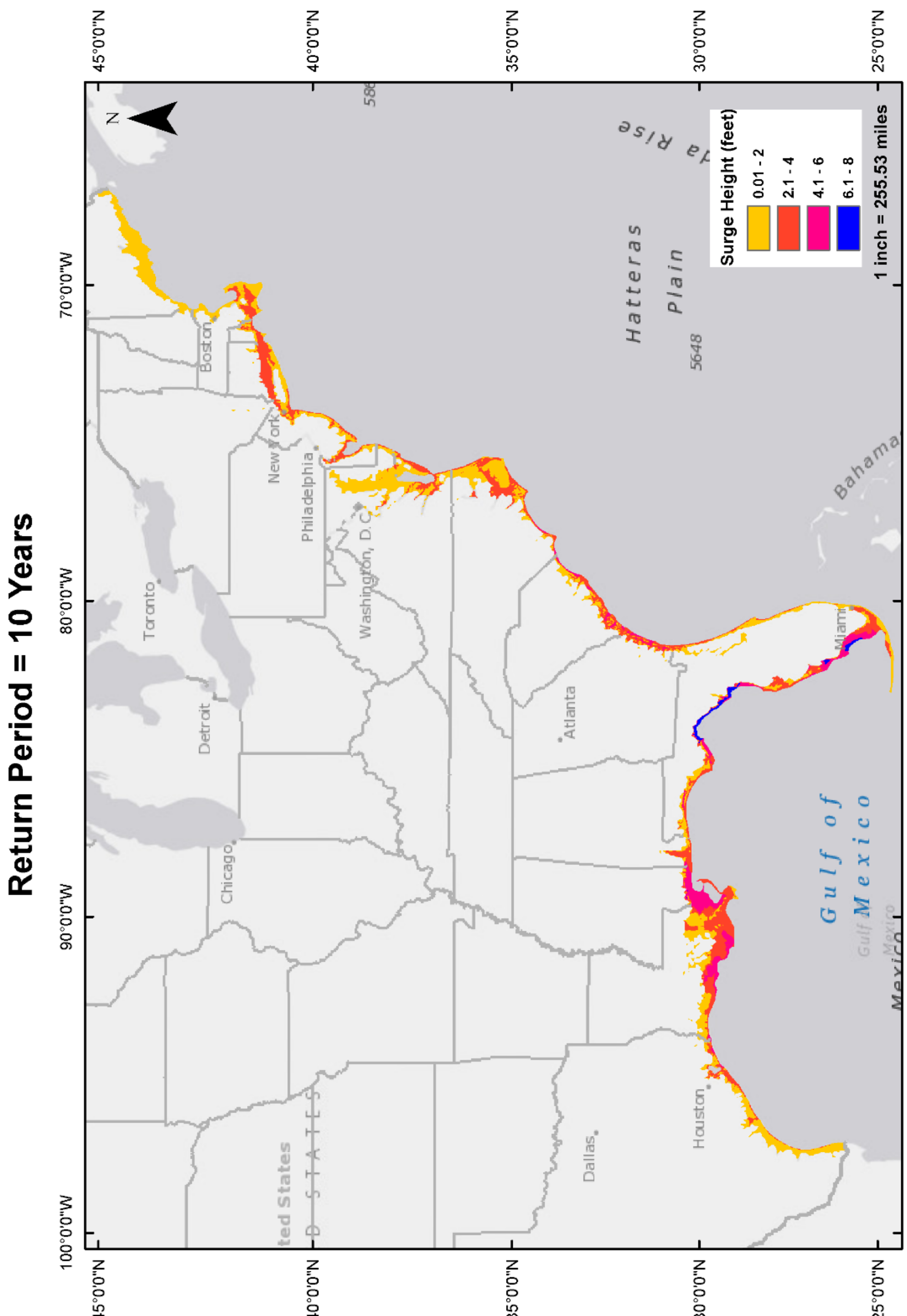


Figure 29: Estimating return period for storm surge of hurricane Sandy in Battery Park

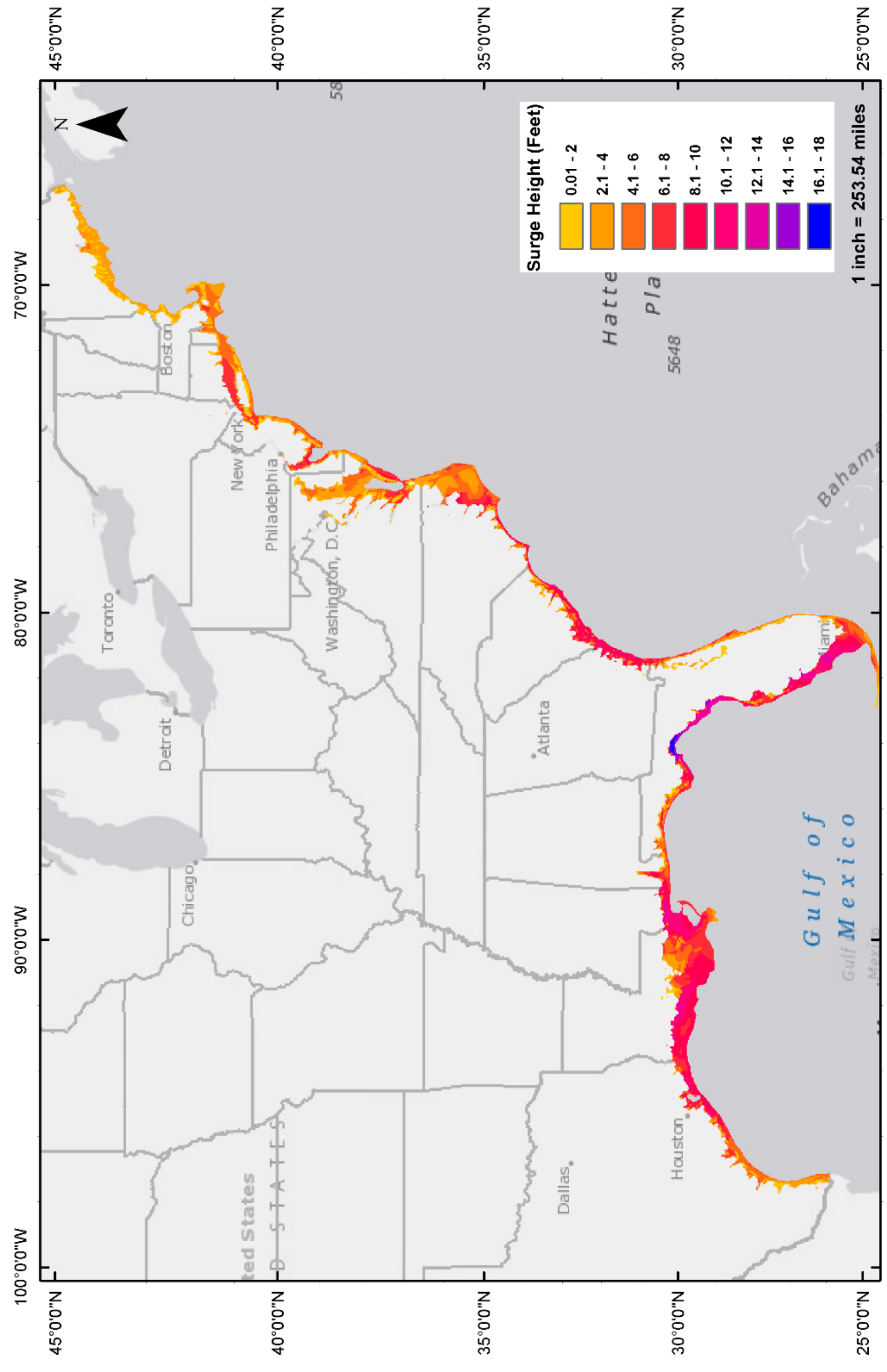
Development of high-resolution hazard risk maps

It is important to be able to translate the accurate hazard risk information to nonprofessionals and to common people effectively and with least effort. Hazard maps can be a useful tool for interpretation of the hazard information (Kockelman, 1980) and helps understand how vulnerable an area is to a particular hazard. When used correctly, hazard maps can contribute to improving the risk communication in the community and help in mitigating the losses (monetary and life) due to storm surge and also help in focusing on the hazard prone areas during the early planning stages for appropriate mapping locations for critical infrastructures.

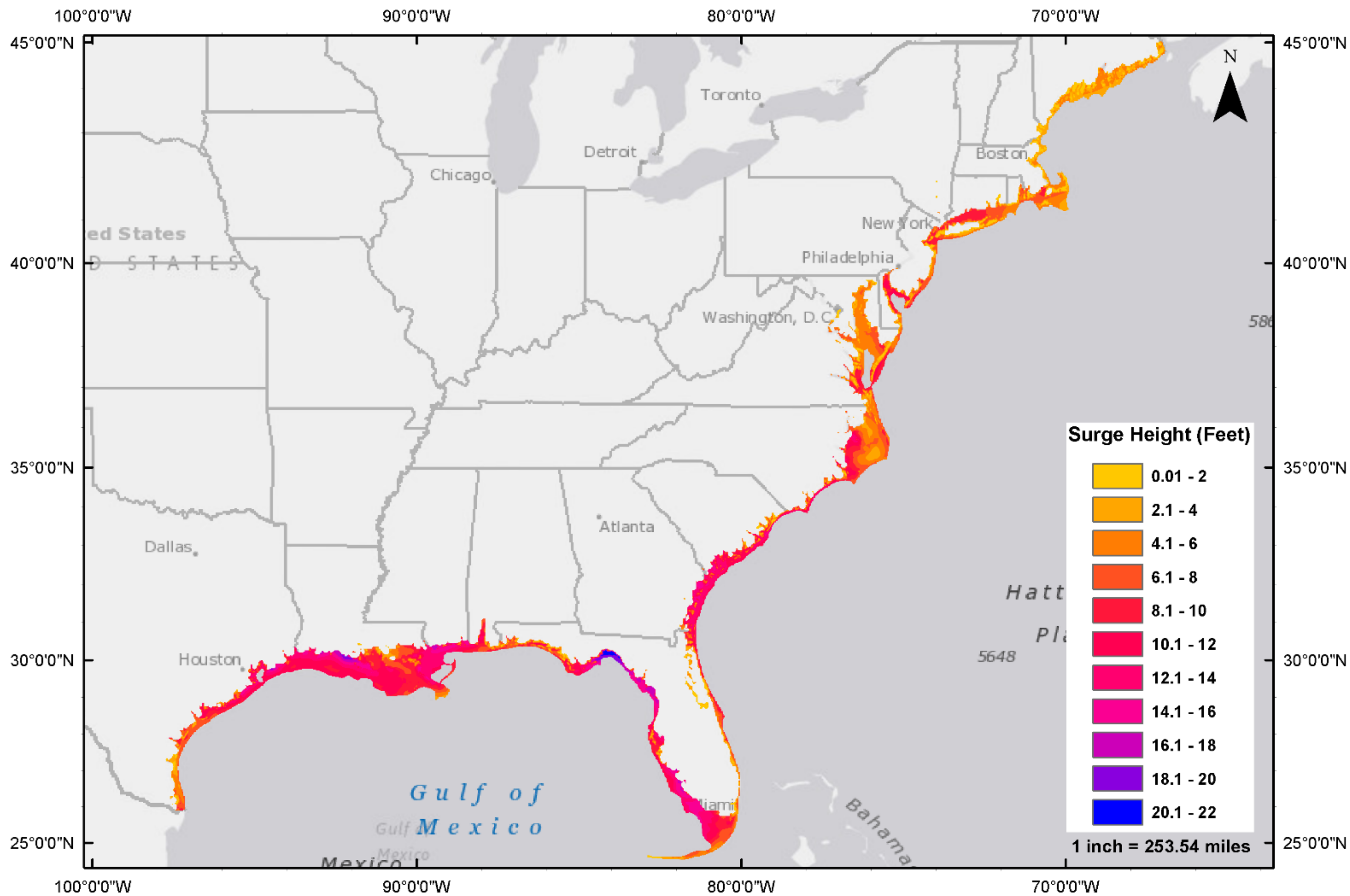
To develop these maps, we calculate the surge height exceedance at each grid point. At each grid point, we derive an empirical CDF representing the probability of surge exceeding a certain threshold in any given year. The CDF can then be inverted in order to get the 10-year, 100-year, 300-year, 1000-year surge exceedances which are the surge with a probability of occurring once in 10-year, 100-year, 300-year, 1000-year or in other words the surge with probability of occurrence in a given year exceeding 0.1, 0.01, 0.003, 0.001 respectively. Next, we integrate this information to create a seamless raster layer for each return period using ArcGIS. Each of the resulting raster represents the different hazard layer for the United States. The following figure 29(a-d) shows the extent and variation in the surge inundation areas for different return periods. These maps can play an important role in identification of the areas for safe placement of critical infrastructure such as nuclear power plants, oil refineries, and electricity generating facilities. These maps can also help in assessing the exposure of population along the coast to storm surge inundation at different probable surge return intervals and can be a useful tool for decision making and future planning.



Return Period = 100 Years



Return Period = 300 Years



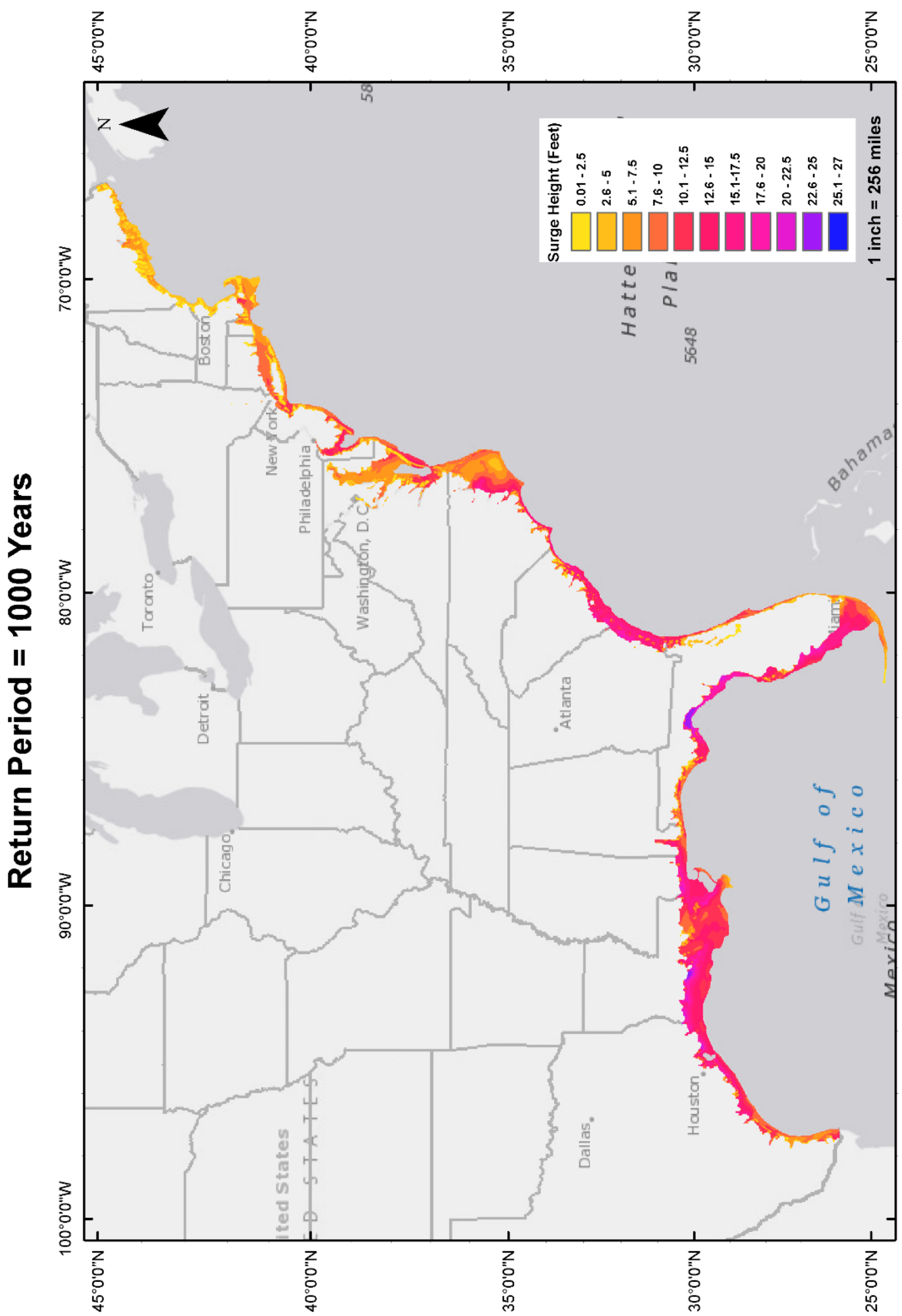


Figure 30 (a - d): Storm Surge map layers for different return periods

Another application of the hazard database can be visualizing the risk of certain surge height at a location. Figure 30 shows a map with varying return periods of 5 feet surge for Miami, FL. It can be noticed that as we get away from the coast the return period of 5 feet surge keeps getting lower as the locations away from the coast has a lower risk of storm surge as compared to the locations right on the coast. From the map, it can be read that the Miami beach can see a surge of 5 feet once in every 500 years. Also, it can be noted that Carol City which is 8 miles from the coast has a higher return interval of 2000 years for the surge of 5 feet which means that it has a lower risk of having a high surge. In other words, the probability of having a surge of 5 feet in carol city is as low as 0.0002 whereas the Miami beach has a probability of 0.002 for the same surge height. Miami beach has ten times higher chance of having surge exceeding 5 feet as compared with Carol city. This information is useful for identification of surge hazard vulnerable areas and also guide in selection of appropriate locations for critical infrastructures, future siting, and improve future investment decisions.

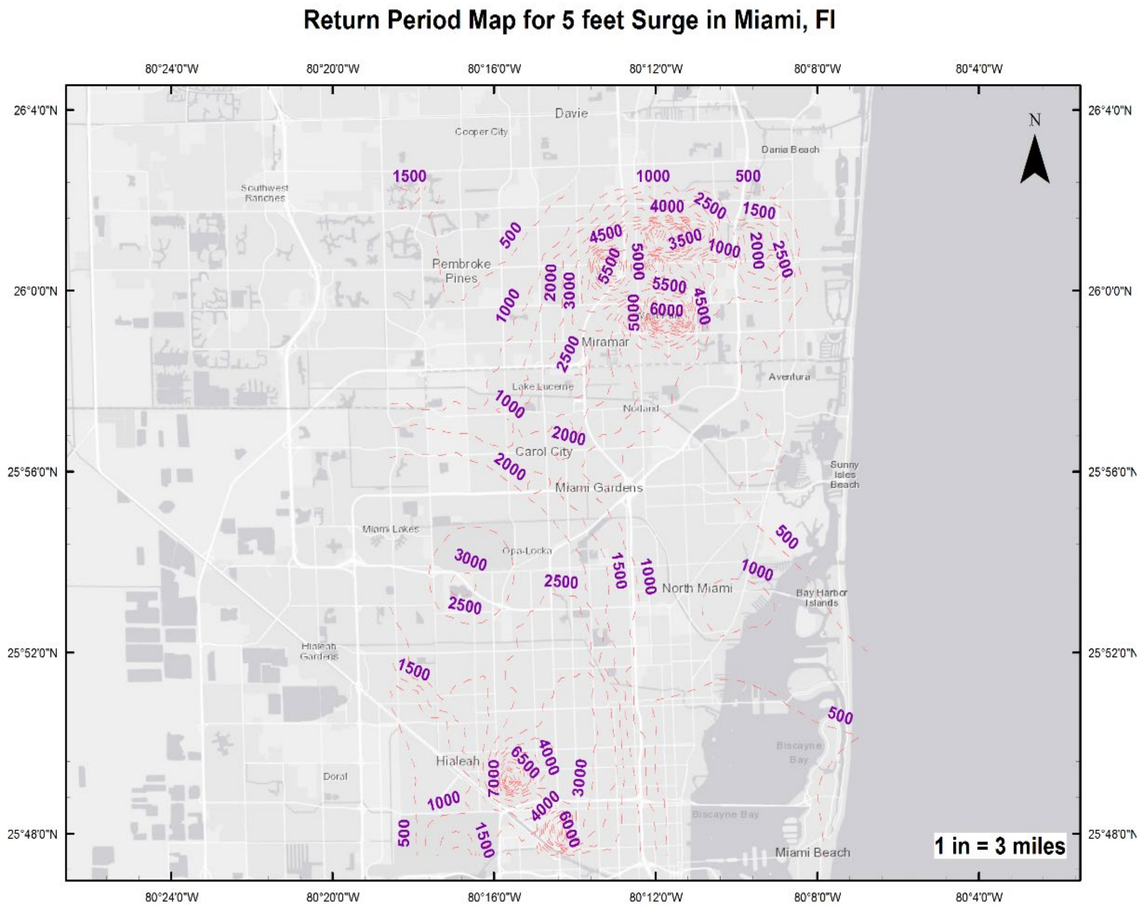


Figure 31: Return period map for 5 feet storm surge at Miami, FL

Error Adjustment

To illustrate the potential effect of the error quantification on the surge inundation area. A case study is explored in Miami region which focus on assessing the change in the surge inundation area for a 1000-year return period surge hazard before and after quantifying the model for systematic errors. Figure 31 shows the region in Miami, FL selected for this case study. A selected region has a coverage area of 316.25 square kilometers.

Figure 32 shows a hazard risk map for 1000-year mean recurrence interval before adjusting model error for Miami, FL. From Figure 33 it can be concluded that the error adjustment does have an impact on the flooding area. The total inundation area increases by 0.07%. Figure 30 shows the variation in surge heights for a return period of 1000 years in Miami, FL. It can be noticed that, after error adjustment the surge height between 10 to 12 feet can increase by more than 500 percent while the areas with lower surge heights seem to be in decreasing order. Again, emphasizing on the importance of including the model errors in long term estimation of the storm surge hazard.

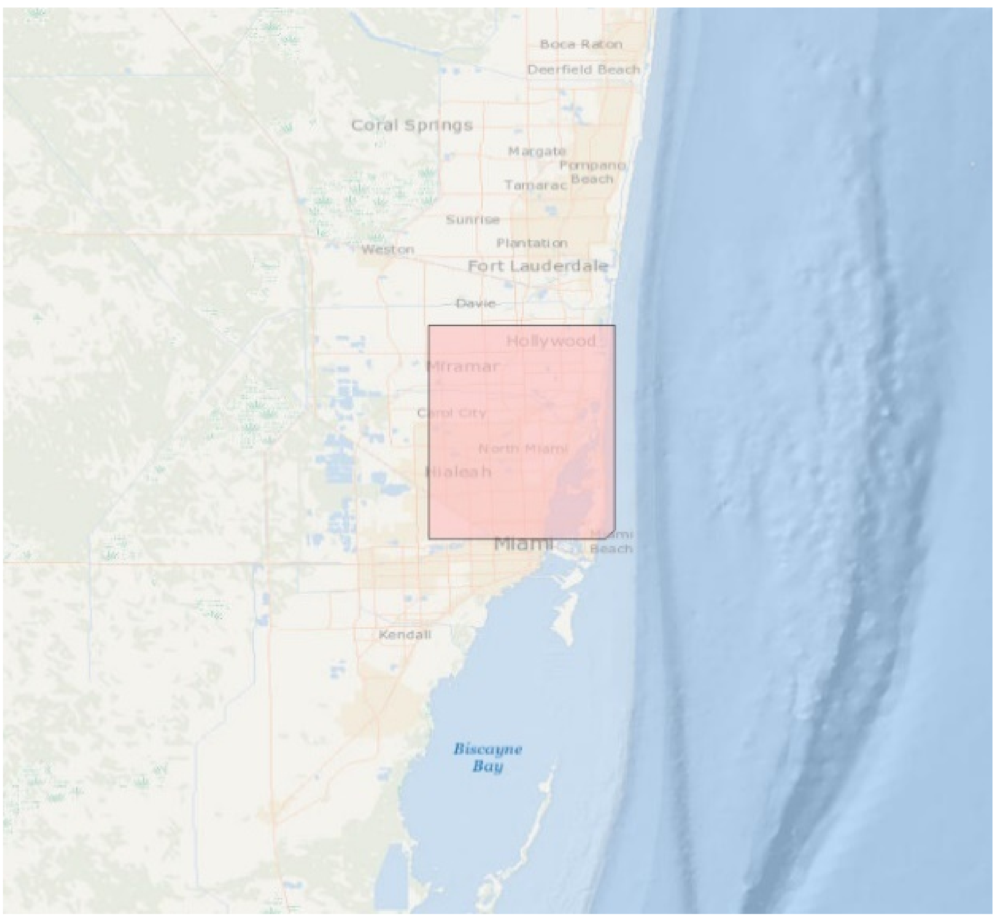


Figure 32: The study region selected in Miami

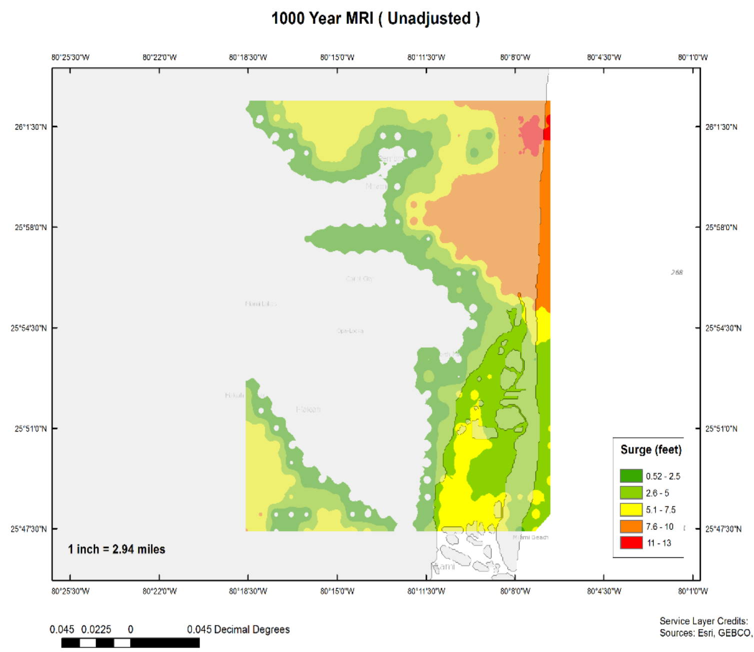


Figure 33 : Hazard map for 1000-year mean recurrence interval before adjusting model error for Miami, FL

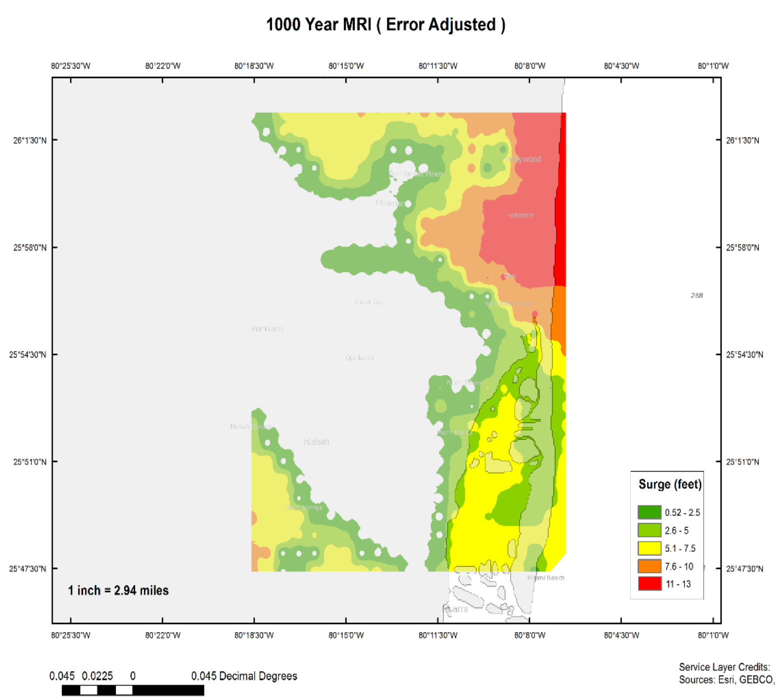


Figure 34 : Hazard map for 1000-year mean recurrence interval after adjusting model error for Miami, FL

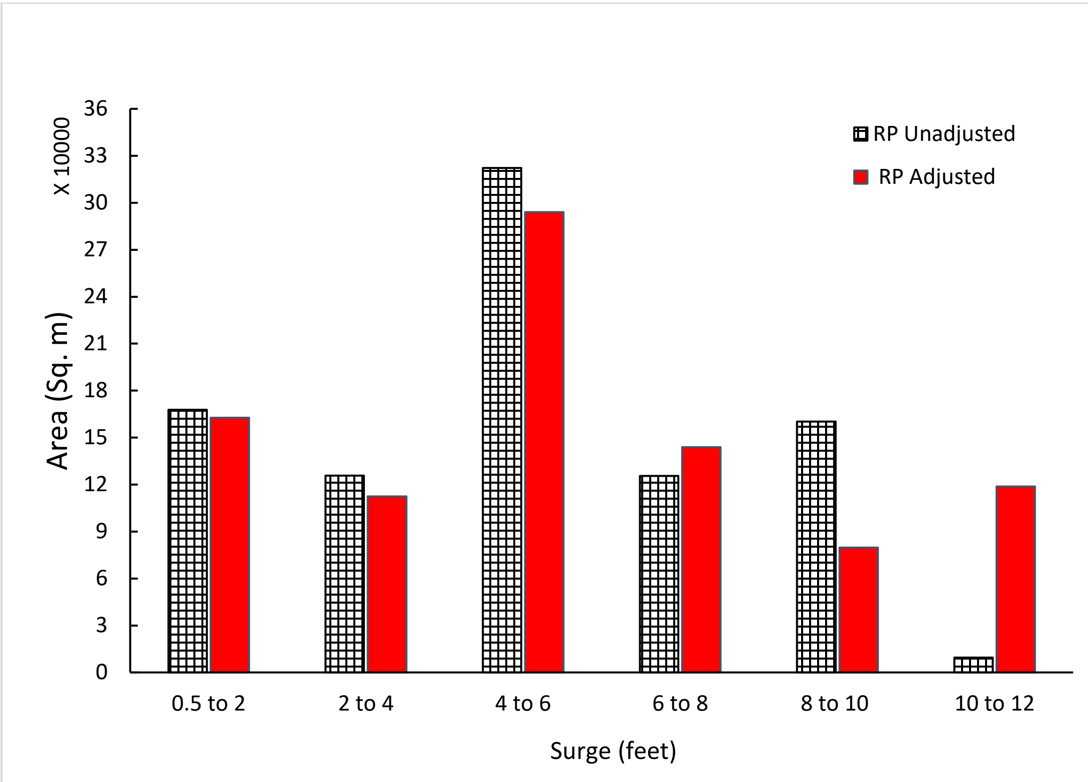


Figure 35: Comparison between inundation areas before and after error adjustments

CHAPTER SIX

SUMMARY AND CONCLUSIONS

A high-resolution storm-surge hazard database was developed which can be useful for estimating the long-term storm surge hazard at any given site in the Atlantic basin region. An empirical track model was used to generate a set of one hundred thousand synthetic hurricane tracks. SLOSH (Sea, Lake and Overland Surges from Hurricanes) model was used to simulate the storm surge. A methodology of hazard database development is presented. Hind cast simulation of a set of 16 hurricanes was performed to quantify the SLOSH model in terms of its ability to predict the surge height that occurred along the US coastline. The resulting surge was recorded and validated against historical storm surge data obtained from various tide stations across the US coast. These errors were then quantified for each SLOSH study region (basin). A case study of error quantification of hurricane Sandy is presented. Site specific hazard curves were developed and were then adjusted for errors to assist in the development of more robust, reliable and accurate hazard maps.

The bias in SLOSH model is undermining our ability to capture the long-term variability in the return periods and accurately estimate the storm surge risk. This new approach, based upon quantification of model errors can possibly be a more accurate way to assess the uncertainty in long-term risk and generate more robust risk maps. Assignment of a region based error coefficient makes it possible to correct the bias in the SLOSH model over a spatially variable large extent. This method being flexible can easily be modified and applied to any region given it has enough historical data to quantify the model errors.

CHAPTER SEVEN

FUTUTRE WORK

It is to be noted that no dynamic tide signals were used, also wave-induced setup was not included into the present study. Further work can be carried out to account for the climate change and combine the present study with sea level rise, tide and wave effects. SLOSH model can be downscaled to capture the surge variation to a higher accuracy. A high-resolution dynamic storm surge model can be used to simulate the surge. Currently used hurricane simulation model generates storms randomly but spawns from known historical locations, which limits its robustness when the historical data is insufficient. New methods for storm population generation such as Joint probability method (optimal sampling) can be investigated. A detailed data analysis on category wise inundation and find the maximum envelopes of water for each category can be performed. This work can be extended to calculate the losses due to hazard consistent hurricanes using the surge hazard for a specific return period and calculate the losses using HAZUS. Effect of the hurricane parameters on losses for a set of hazard consistent hurricanes can be studied and a sensitivity analysis of losses to these parameters can be performed.

APPENDICES

Appendix A

Saffir Simpson Scale

Saffir-Simpson scale was developed in 1971 by Herbert Saffir and Bob Simpson, who classified hurricanes into 5 different categories based on the wind intensity. It was later adopted by National Hurricane Center in 1973. The main objective of the scale was to estimate the probable damage and potential flooding when a hurricane makes landfall. Previously, the scale considered the effect of flooding and wind intensity of a hurricane. Beginning the 2010 hurricane season, the National Hurricane Center categorized storms using an updated version of the Saffir-Simpson scale. The updated Saffir-Simpson Hurricane Wind Scale kept the same wind speed ranges as the original Saffir-Simpson Scale for each of the five hurricane categories, but removed the relationship between category and specific storm surge and flooding effects to each category. This modification to the previous scale comes as realizations were made that storm surge values and associated flooding are difficult to be taken into account and tied in with a category as the flooding and surge are dependent on a combination of the storm's intensity, radius, direction and barometric pressure, as well as the bathymetric and topographical features. Minor modification was made to the Saffir-Simpson Hurricane Wind Scale during 2012 hurricane season. The upper limit of wind speed of category IV was increased by 1 mph while broadening the range of category IV wind speeds by 2 mph. The main aim of this modification was to solve the rounding issues of the wind speed so that the wind intensity can be converted correctly from one unit to another and keep storms in the correct category regardless of the units used.

Table A- 1: Categories of hurricane and respective expected damage and wind speed range

Category of Hurricane	Wind speed (mph)	Damage	Examples
I	74 – 95	Minimal	Sandy 2012
II	96 -110	Moderate	Dolly 2008
III	111-130	Extreme	Katrina 2005
IV	131-155	Extensive	Irma 2017
V	> 155	Catastrophic	Andrew 1992

Table A- 2: Revised Saffir-Simpson Hurricane Wind Scale

Category of Hurricane	Previous Wind Speed range (mph)	Updated Wind Speed range (mph)
I	74 – 95	74 – 95
II	96 -110	96 -110
III	111-130	111-129
IV	131-155	130-156
V	> 155	> 157

Appendix B

Matlab Codes

1. Create SLOSH Historical Tracks Input Data

```
function[Storm] = SLOSH_track_hist(storm_data,basin,root)

%This Function reads an excel file with all hurricane parameters and
%outputs the MAT file which is in readable format for SLOSH track file

%********** INPUT **********
%File = Name of the excel file with all the historical data
%Storm_data = Name of the storm file
%basin = Nameof the basin in which you to create the SLOSH Track for
%Root = Directory where all basin are available
%********** EXAMPLE **********
%%Read_Historical_Track_data_from_excel('Historical_Tracks','Charley_04',2004,3)

%********** OUTPUT **********
% A .MAT file with all attributes of a single storm
```

```
if nargin < 3 || isempty(root)
root
='C:\Users\samiudm.CAMPUS\Desktop\Historical_storms_SLOSH_EBTRACKS\Basins
';
if nargin < 2 || isempty(basin)
basin ='emo2';
if nargin < 1 || isempty(storm_data)
storm_data = 'Michael.mat';
end
end
end

% This will take the storm.mat file data and use it to generate the trk file

% SCRIPT USED TO CREATE TRACK FILES FOR SLOSH MODEL
% HISTORICAL HURRICANES

load(storm_data); % load EBTRACKS database
load(fullfile(root,basin,basin,'coastline.mat')); % load coastline file (Long Lat)
load(fullfile(root,basin,basin,'boundary.mat')); % load boundry file (Long Lat)

%% This calculated the parameters for the central pressure if the field is not existant
for j=1:length(Hur.Pc)
if isnan(Hur.Pc(j)) % if Pc is NaN
% use empirical equation to estimate Pc
%Vt=0.868976242*Hur.Vt_mps(j)*2.23694; % m/s -> mph
Vt=Hur.Vt_mph(j); %mph
Vm=Hur.Vmax_mph(j); %mph
Vg=Vm-1.5*Vt^0.63;
Hur.Pc(j)=1013-((Vg-5.843+0.558*Hur.Lat(j))/14.118)^2;
end
end
% it is possible that Pc(1) is still NaN because Vt(1) can be NaN
if isnan(Hur.Pc(1))
st=3;
else
st=2;
end
% interpolate from 6h interval to 1h increment
LAT=Hur.Lat(st); LON=Hur.Lon(st); VT_MPH=Hur.Vt_mph(st);
HEADDIR=Hur.HeadDir(st); PC=Hur.Pc(st); RMAX = Hur.Rmax(st);
t=3;
for j=st:length(Hur.Lat) % loop through selected hurricane track
Lat=linspace(Hur.Lat(j-1),Hur.Lat(j),t+1);
```

```
LAT=[LAT,Lat(2:t+1)];
Lon=linspace(Hur.Lon(j-1),Hur.Lon(j),t+1);
LON=[LON,Lon(2:t+1)];
Vt_mph=ones(1,t+1)*Hur.Vt_mph(j);
VT_MPH=[VT_MPH,Vt_mph(2:t+1)];
HeadDir=ones(1,t+1)*Hur.HeadDir(j);
HEADDIR=[HEADDIR,HeadDir(2:t+1)];
Pc=linspace(Hur.Pc(j-1),Hur.Pc(j),t+1);
PC=[PC,Pc(2:t+1)];
Rmax=linspace(Hur.Rmax(j-1),Hur.Rmax(j),t+1);
RMAX=[RMAX,Rmax(2:t+1)];
end
VT_MPS = VT_MPH * 0.44704;
HUR=[LAT',LON',VT_MPS',HEADDIR',PC',RMAX'];
% polyxpoly
% find the closest point from hurricane track to coastline
% intersection
PP =InterX([LON';LAT'],[coastline(:,1);coastline(:,2)]);
loni = PP(1,:);lati = PP(2,:);
if ~isempty(loni) % having intersection with coastline
for j=1:length(LAT)-1 % find first intersection
[lonj,latj]=InterX(LON(j:j+1),LAT(j:j+1),coastline(:,1),coastline(:,2));
if ~isempty(lonj) % find closest point
dist1=distance2(LAT(j),LON(j),latj,lonj);
dist2=distance2(LAT(j+1),LON(j+1),latj,lonj);
if dist1>dist2
idx=j+1;
else
idx=j;
end
break
end
end
else % no intersection with coastline
distmin=[];
for j=1:length(LAT) % find minimum distance2
disti=distance2(LAT(j),LON(j),coastline(:,2),coastline(:,1));
distmin(j)=min(disti);
end
idx=find(distmin==min(distmin));
end
% data modification
hur=ones(100,6);
if length(LAT)<100 % modify short tracks
```

```
gap=100-length(LAT);
bgn=round(gap/2);
nd=gap-bgn;
for k=1:bgn
hur(k,:)=HUR(1,:);
end
for k=101-nd:100
hur(k,:)=HUR(end,:);
end
hur(bgn+1:100-nd,:)=HUR;
lf_step=idx+bgn;
elseif idx<70 % control landfall step to the nearest 70th
hur=HUR(1:100,:);
lf_step=idx;
elseif length(LAT)-idx<30
hur=HUR(length(LAT)-99:length(LAT),:);
lf_step=idx-length(LAT)+100;
else
hur=HUR(idx-69:idx+30,:);
lf_step=70;
end
% find steps within slosh domain boundary
idxin=find(inpolygon(hur(:,1),hur(:,2),boundary(:,1),boundary(:,2)));
% calculate Longitude(+), Vt, Delta_P and Rmax
hur(:,2)=-hur(:,2);
hur(:,3)=hur(:,3)/0.44704; % Vt_mps -> mph
hur(:,5)=1013-hur(:,5); % dp
hur(:,6)=hur(:,6); %  mi
% create track file
mkdir([num2str(Hur.Year),'_',num2str(Hur.StormNoOfYear)]);
cd([num2str(Hur.Year),'_',num2str(Hur.StormNoOfYear)]);
fid=fopen(string(basin)+'_'+string(storm_data(1:end-7))+'.trk','w');
fprintf(fid,'\n'); fprintf(fid,'\n');
for j=1:100
if j==lf_step
fprintf(fid,'%17s%3d%8.4f%8.3f%8.2f%8.2f%8.2f%8.2f%5d %s\n',...
'NAP-----  ',j,hur(j,:),j,'---NAP');
else
fprintf(fid,'%17s%3d%8.4f%8.3f%8.2f%8.2f%8.2f%8.2f%5d\n',...
' ',j,hur(j,:),j);
end
end
% determine start and end step
if ~isempty(idxin)
```

```
stp=min(idxin)-6;
enp=max(idxin)+6;
else
stp=lf_step-12;
enp=lf_step+6;
end
if stp<1
stp=1;
end
if enp>100
enp=100;
end
fprintf(fid,'%3d%3d%3d%16sIBGNT ITEND JHR\n',stp,enp,lf_step,' ');
% not used
fprintf(fid,'HR0000 12 SEP 2018       NEAREST APPROACH, OR LANDFALL,
TIME\n');
% no initial water height
fprintf(fid,'  0.0  0.0              SEA AND LAKE DATUM');
disp(num2str(lf_step));
fclose(fid);
Year = Hur.Year;
StormNoOfYear = Hur.StormNoOfYear;
cd ..
end

%LATLON=[LAT',LON'];
%save('LATLON.mat','LATLON')
%
%geoshow(hur(:,1),hur(:,2), 'DisplayType', 'point', 'Color', 'b', 'MarkerEdgeColor', 'auto')
%plot_google_map('maptype','roadmap')
```

2. Pick Maximum Wind and Surge

```
function [] = lpalmettomaxsurge(text_file,storm_year,basin_name,opfolder)

% Written by Sami Mohammed

% This is a .m file that reads in data from a txt in the form of a rex file
% The Max Wind and Surge data is slected and saved to a mat file which can
% further be interpolated and plotted


if nargin < 4 || isempty(opfolder)
   opfolder ='surgemax';
```

```
    if nargin < 3 || isempty(basin_name)
        basin_name ='acy';
        if nargin < 2 || isempty(storm_year)
            storm_year ='2004_3';
            if nargin < 1 || isempty(text_file)
                text_file = 'acy_Charley.txt';
            end
        end
    end
end
tic
cd(string(storm_year)+'/'+string(basin_name)+'/'+string(basin_name))
load('latlondpth.mat')
Y=max(latlondpth(:,2));
X=length(latlondpth)/Y;


vcells = zeros(Y,1);
wind = zeros(Y,1);
%    for I = 0 : X-1
%        for J = 1 : Y
%
%       vcells(J+(I*313),1)=I+1;
%       vcells(J+(I*313),2)=J;
%
%        end
%    end

%%
% calls the function that reads the data data lines
cd ..
cd ..
cd ..
fid1 = fopen(string(pwd)+'\'+string(storm_year)+'\'+string(text_file), 'r');            % Opens
file and defines as fid
fopen(fid1);                          % Opens file fid

z= fgetl(fid1);                       % skips the first 4 values because they will all be 0 for the
null set
fgetl(fid1);
fgetl(fid1);
fgetl(fid1);
it=0;
L=1;                                  % L is preallocated
```

```
while  L ~= 0

    a = fscanf( fid1, '%f');
    fgetl(fid1);
    L = logical(a);
    it = it + 1;

end
dataPts = it;
fclose(fid1);            %closes the file
% latd=zeros(dataPts);
% lond=zeros(dataPts);
if exist('vcells.mat', 'file')
    load('vcells.mat')
    load('stormnum.mat')

    [size1,size2]=size(vcells);
else
    size2 = 0;
end

%% reading the file ----------------------------------------------------
fid=fopen(string(pwd)+'\'+string(storm_year)+'\'+string(text_file), 'r');
% open the file
fopen(fid);
a = zeros(70000,1);
b = zeros(70000,1);
it = 1;

%make sure the file is not empty
finfo = dir(string(storm_year)+'/'+string(text_file));
fsize = finfo.bytes;
if fsize < 20
    Max(1) = (-55);
else
    tic
    z=fgetl(fid);                              % opens and skips first line
    while ~feof(fid)                            % runs while the file is open
        fseek(fid, 1, 'cof');
        grid = fscanf( fid, '%d');

        a(it) = grid(1,1);    %I
        b(it) = grid (2,1);   %J
```

```
        fseek(fid, 7, 'cof');
        latd(it)=fscanf( fid, '%f');

        fseek(fid, 6, 'cof');
        lond(it)=fscanf( fid, '%f');

        fgetl(fid);
        fgetl(fid);
        FormatString=repmat('%f',1,5);
        Data = textscan(fid,FormatString,'delimiter',','); % Read data block
        Data=cell2mat(Data);

        for remove = 1:length (Data(:,4))
          if (Data(remove,4)) > 50
            Data(remove,4)=0;
          else
            ;
          end
        end
        vcells(b(it)+(a(it)*Y) ,1+size2 ) = max(Data(:,4));
        it = it + 1;
    end

    %% select only the cells we want to validate for our experiment
    stormnum{size2+1}=z;
    latlon(:,1)=latd;
    latlon(:,2)=lond;

save(string(storm_year)+'/'+string(basin_name)+'/'+string(basin_name)+'/'+string(opfolde
r)+'/'+string(text_file(5:end-4))+'vcells.mat','vcells')

save(string(storm_year)+'/'+string(basin_name)+'/'+string(basin_name)+'/'+string(opfolde
r)+'/'+string(text_file(5:end-4))+'stormnum.mat','stormnum')
    %  save('latlon.mat','latlon')
end
toc
fclose('all');          %closes the file
```

Appendix C

Best Tracks data for Selected Storms

The following tables show the best tracks for selected hurricanes. The track details were obtained from HURDAT 2 (HURricane DATabase) and IBTrACS (International Best Track Archive for Climate Stewardship). The Track data has information about location of the hurricane, translation speed, size, central pressure, time and heading angle of the hurricane.

Table C- 1: Best Track for Hurricane Frances 2004

Latitude (Degrees)	Longitude (Degrees)	Translation Speed (mph)	Heading Angle	Radius to Max Winds (miles)	Wind Speed (mph @ 10m)	Central Pressure (mBar)
25.7	-77.2	9.56	85	32.67	103.5	961
25.9	-77.5	3.87	90	33.48	103.5	959
25.9	-77.5	3.87	95	35.07	94.18	960
26.1	-77.8	7.88	95	46.66	93.15	960
26.4	-78	6.53	95	49.01	94.18	961
26.6	-78.1	5.82	105	45.1	93.15	960
26.7	-78.4	8.02	105	42.56	94.18	960
26.9	-78.8	6.78	115	43.8	93.15	961
26.9	-79	5.16	115	46.2	94.18	962
26.9	-79.3	4.63	130	29.89	93.15	962
27	-79.4	4.84	130	24.99	94.18	951
27.1	-79.7	10.28	150	33.82	93.15	960
27.2	-80.2	10.99	150	33.82	93.15	960
27.2	-80.4	4.63	155	35.3	93.15	960
27.2	-80.5	5.07	155	36.98	93.15	963
27.3	-80.7	8.14	155	35.21	93.15	963
27.7	-81.2	11.33	195	31.42	92.84	975
27.9	-81.7	10.85	195	30.01	77.37	980
28	-82.2	6.77	250	6.21	71.42	975
28.1	-82.3	6.21	250	7.79	66.65	975
28.3	-82.7	11.69	240	35.81	65.46	976
28.6	-83.3	9.34	240	89.66	57.96	981
28.7	-83.5	7.01	55	63.97	56.92	981

29.1	-83.6	10.78	55	89.75	57.96	980
29.5	-84	13.01	55	14.4	56.92	980
30.1	-84.1	12.95	55	12.14	57.96	980
30.6	-84.3	12.06	55	39.75	47.61	982

Table C- 2: Best Track for Hurricane Lili 2002

Latitude (Degrees)	Longitude (Degrees)	Translation Speed (mph)	Heading Angle	Radius to Max Winds (miles)	Wind Speed (mph @ 10m)	Central Pressure (mBar)
24	-87.9	15.68	104	10.11	98.32	955
24.4	-88.4	13.95	104	11.81	98.32	955
24.8	-88.9	14.73	105	12.06	108.67	953
25.3	-89.4	17.05	105	8.38	119.02	941
25.9	-90	17.89	99	8.46	124.2	938
26.6	-90.3	16.13	99	8.46	124.2	938
27.2	-90.6	19.32	99	11.44	129.38	942
27.8	-91.1	24.12	99	9.63	129.38	942
28.4	-91.4	18.15	99	11.44	129.38	942
28.7	-91.7	12.86	99	17.04	108.67	957
29	-91.9	14.2	99	17.04	108.67	957
29.4	-92.2	15.06	99	17.04	108.67	957
29.8	-92.2	13.84	99	25.62	95.22	965
30.2	-92.3	15.66	99	24.17	95.22	965
30.7	-92.4	19.32	99	38.94	71.42	965

Table C- 3: Best Track for Hurricane Isabel 2003

Latitude (Degrees)	Longitude (Degrees)	Translation Speed (mph)	Heading Angle	Radius to Max Winds (miles)	Wind Speed (mph @ 10m)	Central Pressure (mBar)
27.8	-71.4	8.27	330	79.57	93.15	959
28.2	-71.5	8.67	330	75.72	94.18	956
28.5	-71.7	10.46	330	62.89	98.32	957
29	-72	11.47	330	59.09	99.36	957
29.4	-72.2	8.97	330	63.78	98.32	958
29.7	-72.4	7.94	330	62.55	99.36	957
30	-72.6	11.89	330	43.77	98.32	957
30.6	-73	14.35	330	45.23	94.18	956
31.1	-73.3	11.87	330	45.32	93.15	955
31.5	-73.6	11	330	45.92	94.18	955
31.9	-73.9	13.29	330	45.91	93.15	956
32.5	-74.3	15.71	320	44.23	94.18	957
33.1	-74.7	16.2	320	45.13	93.15	957
33.7	-75.2	17.63	320	48	90.04	957
34.4	-75.7	19.31	320	50.29	87.97	956
34.9	-76.1	21.35	320	46.31	90.04	957
35.4	-76.6	26.33	320	46.80	90.04	959
36.2	-77.1	24.05	320	37.24	90.04	960
36.6	-77.5	17.61	320	28.96	83.32	965
37	-77.9	20.53	330	38.48	72.61	968
37.7	-78	18.55	330	79.18	65.46	972
38.3	-78.4	17.94	330	89.92	61.89	978
39.2	-78.7	24.46	330	88.49	53.56	987
40.3	-79.5	28.32	330	89.45	40	996

Table C- 4: Best Track for Hurricane Charley 2004

Latitude (Degrees)	Longitude (Degrees)	Translation Speed (mph)	Heading Angle	Radius to Max Winds (miles)	Wind Speed (mph @ 10m)	Central Pressure (mBar)
13.7	-68.3	28.21	280	26.82	41.4	1005
14.5	-69.7	32.95	280	19.27	40.36	1005
15.2	-70.8	27.27	35	19.89	46.57	999
15.7	-71.8	24.25	35	29.44	46.57	999
16	-72.8	23.73	55	29.16	56.92	999
16.4	-73.8	23.55	55	9.14	57.96	999
16.9	-74.7	19.28	105	39.03	56.92	999
16.9	-75.4	16.78	105	11.1	57.96	999

16.5	-76.1	16.88	280	22.11	62.1	996
16.6	-76.8	16.88	280	17.05	67.28	993
17	-77.5	17.09	115	17.05	67.28	993
17.2	-78.2	16.88	115	17.05	67.28	993
17.8	-78.7	14.76	115	19.06	67.28	993
18	-79.2	16.26	115	17.77	76.59	989
18.6	-79.9	19.8	135	12.37	77.63	986
19.2	-80.5	19.03	135	12.96	76.59	986
19.7	-81.2	18.18	125	10.39	82.8	983
20.4	-81.5	18.78	125	8.59	94.18	980
21.2	-81.9	17.29	130	11.11	93.15	980
21.7	-82.3	12.99	130	11.01	94.18	976
22.2	-82.4	15.25	115	10.88	93.15	975
23	-82.6	20.22	115	7.31	94.18	973
23.9	-82.9	18.46	170	8.72	98.32	970
24.3	-82.9	13.76	170	9.07	99.36	969
24.7	-82.9	15.62	180	9.21	99.36	970
25.2	-82.8	18.53	180	7.19	98.32	965
25.7	-82.5	20.24	180	7.08	112.81	964
26	-82.4	21.16	30	6.26	129.38	954
26.9	-82.2	24.66	10	6.21	129.38	941
27.7	-81.8	28.53	10	6.21	119.03	950
28.4	-81.4	26.31	20	6.21	92.84	965
29.1	-81.1	24.42	20	6.21	89.27	975
30.1	-80.8	24.66	20	13.31	76.59	993
31.2	-80.5	27.66	20	40.19	77.63	994
32.3	-79.7	27.09	20	41.33	76.59	993
33.2	-79	33.27	20	36.39	67.28	990
34.8	-77.9	36.97	20	34.51	67.28	995
36	-77	30.54	30	23.23	67.28	1000
36.9	-75.9	29.15	30	13.81	44.51	1008
37.9	-74.9	32.28	40	13.1	40	1012
39.2	-73.8	36.68	40	6.92	40	1013
40.8	-73	41.53	40	9.3	40	1012
42	-71	45.05	0	6.21	40	1013

Table C- 5: Best Track for Hurricane Ivan 2004

Latitude (Degrees)	Longitude (Degrees)	Translation Speed (mph)	Heading Angle	Radius to Max Winds (miles)	Wind Speed (mph @ 10m)	Central Pressure (mBar)
22.6	-86	10.67	60	23.84	144.9	924
23.1	-86.1	9.43	60	23.97	139.72	925
23.4	-86.2	8.28	55	24.54	124.2	932
23.7	-86.5	10.51	60	24.55	126.27	931
24.2	-86.6	12.94	60	23.37	124.2	929
24.7	-87	12.15	60	23.65	126.27	929
25.1	-87.2	11.14	60	26.66	124.2	932
25.6	-87.4	13.18	60	25.47	126.27	934
26.1	-87.8	14.03	70	26.99	124.2	938
26.7	-87.9	13.89	70	27.74	126.27	939
27.3	-88	13.02	55	26.63	119.02	939
27.8	-88.2	13.01	55	26.95	121.1	939
28.4	-88.3	13.94	55	24.19	119.02	933
28.8	-88.2	10.44	55	25.95	121.1	931
29	-88.2	8.78	40	25.95	121.1	931
29.3	-88.1	12.84	20	24.19	119.02	933
29.7	-87.9	16.16	20	23.08	121.1	936
30.2	-87.8	20.72	20	22.37	116.95	943
30.9	-87.7	19.17	20	27.76	116.95	947
31.6	-87.7	12.9	20	33.43	83.32	965
32	-87.5	12.81	10	40.68	77.37	970
32.6	-87.1	13.6	10	49.7	72.61	975
33.1	-87	3.03	15	21.52	59.51	980
33	-86.99	3.02	10	21.5	59.5	984

Table C- 6: Best Track for Hurricane Jeanne 2004

Latitude (Degrees)	Longitude (Degrees)	Translation Speed (mph)	Heading Angle	Radius to Max Winds (miles)	Wind Speed (mph @ 10m)	Central Pressure (mBar)
26.1	-71.2	8.3	50	18.71	90.04	969
26.1	-71.6	8.3	60	19.19	87.97	969
26.1	-72	8.45	60	18.71	90.04	969
26.2	-72.4	9.61	70	19.19	87.97	969
26.3	-72.9	11.62	70	17.47	90.04	969
26.4	-73.5	14.67	75	16.62	87.97	965
26.5	-74.3	14.56	75	15.53	90.04	964
26.5	-74.9	13.45	80	28.02	87.97	964

26.5	-75.6	13.45	95	24.5	94.18	962
26.5	-76.2	14.48	95	23.18	93.15	958
26.5	-77	14.58	95	22.45	94.18	957
26.6	-77.6	12.19	105	20.8	103.5	955
26.8	-77.9	14.24	105	20.8	103.5	955
27	-78.4	14.88	105	20.01	103.5	953
27.1	-78.8	11.05	125	20.37	103.5	950
27.1	-79.1	11.04	125	20.37	103.5	950
27.2	-79.5	14.13	140	19.19	103.5	951
27.2	-80	13.89	140	19.19	103.5	951
27.2	-80.4	11.93	205	20.01	103.5	953
27.7	-81.4	13.07	205	22.82	103.5	960
27.9	-82	9.69	240	32.3	77.37	970
28.3	-82.2	12.02	240	33.79	72.61	972
28.8	-82.6	13.94	250	23.94	65.46	973
29.4	-82.7	12.71	250	48.81	57.13	978
29.9	-82.8	11.31	175	59.23	53.56	978
30.1	-83.3	10.99	175	70.33	51.18	981
30.5	-83.6	11.49	135	85.28	51.18	982
31	-83.8	12.91	135	85.52	46.42	985
31.6	-83.9	13.77	135	87.3	40	988

Table C- 7: Best Track for Hurricane Dennis 2005

Latitude (Degrees)	Longitude (Degrees)	Translation Speed (mph)	Heading Angle	Radius to Max Winds (miles)	Wind Speed (mph @ 10m)	Central Pressure (mBar)
12.5	-64.2	19.95	286.97	46.03	34.52	1008
13	-65.9	17.16	293.93	34.52	40.27	1007
13.6	-67.3	15.66	301.15	34.52	46.03	1005
14.3	-68.5	14.16	289.15	23.02	51.78	1000
14.7	-69.7	14.14	289.18	23.02	57.53	995
15.1	-70.9	12.50	297.54	23.02	63.29	991
15.6	-71.9	14.00	299.71	23.02	69.04	989
16.2	-73	13.44	295.51	23.02	80.55	982
16.7	-74.1	13.60	319.77	23.02	92.06	972
17.6	-74.9	16.73	308.45	17.26	103.5	967
18.5	-76.1	15.03	313.74	17.26	115.07	957
19.4	-77.1	17.49	306.57	11.51	138.09	951
20.3	-78.4	13.73	300.42	11.51	126.58	953
20.9	-79.5	17.31	317.25	11.51	149.6	938
22	-80.6	13.35	307.31	11.51	138.09	941
22.7	-81.6	12.48	310.38	11.51	115.0	960
23.4	-82.5	14.05	317.73	11.51	86.30	973
24.3	-83.4	13.33	321.25	11.51	92.06	967
25.2	-84.2	13.29	321.47	11.51	103.57	962
26.1	-85	15.12	327.15	5.75	126.58	942
27.2	-85.8	15.82	341.33	5.75	143.84	935
28.5	-86.3	17.22	339.63	11.51	138.09	930
29.9	-86.9	20.07	336.94	11.51	126.58	942
31.5	-87.7	14.90	328.56	23.02	51.78	970
32.6	-88.5	15.26	349.16	28.77	34.52	991

Table C- 8: Best Track for Hurricane Rita 2005

Latitude (Degrees)	Longitude (Degrees)	Translation Speed (mph)	Heading Angle	Radius to Max Winds (miles)	Wind Speed (mph @ 10m)	Central Pressure (mBar)
21.9	-71.5	9.22	292.18	51.79	34.52	1007
22.2	-72.3	7.81	287.29	51.79	40.28	1005
22.4	-73	8.81	285.29	34.52	51.79	1002
22.6	-73.8	9.84	283.72	34.52	57.54	999
22.8	-74.7	13.20	285.42	34.52	63.29	997
23.1	-75.9	13.96	279.76	28.77	69.05	994
23.3	-77.2	17.07	278.07	28.77	69.05	992

23.5	-78.8	15.99	278.58	40.28	69.05	990
23.7	-80.3	13.89	279.81	40.28	80.55	985
23.9	-81.6	11.81	281.48	40.28	97.82	975
24.1	-82.7	13.71	275.08	23.02	109.32	967
24.2	-84	12.62	270.25	17.26	126.59	955
24.2	-85.2	10.56	276.46	17.26	138.09	941
24.3	-86.2	7.70	287.56	23.02	166.86	920
24.5	-86.9	8.10	295.39	28.77	172.62	897
24.8	-87.6	8.63	302.38	11.51	178.37	897
25.2	-88.3	9.51	299.14	11.51	161.11	908
25.6	-89.1	9.48	299.22	11.51	143.85	913
26	-89.9	10.07	305.05	17.26	138.09	915
26.5	-90.7	10.74	310.22	23.02	132.34	924
27.1	-91.5	11.48	314.78	23.02	132.34	927
27.8	-92.3	11.63	322.53	23.02	126.59	930
28.6	-93	11.03	326.88	23.02	120.83	931
29.4	-93.6	13.62	338.63	23.02	115.08	935
30.5	-94.1	12.68	0	23.02	74.80	949
31.6	-94.1	12.71	4.37	23.02	51.79	974
32.7	-94	12.15	18.4	34.52	40.28	982

Table C- 9: Best Track for Hurricane Katrina 2005

Latitude (Degrees)	Longitude (Degrees)	Translation Speed (mph)	Heading Angle	Radius to Max Winds (miles)	Wind Speed (mph @ 10m)	Central Pressure (mBar)
24.6	-85.6	6.28	270	12.11	103.5	945
24.8	-85.9	7.78	270	10.76	103.5	944
25	-86.2	10.27	290	16.73	103.5	939
25.1	-86.8	13.52	290	16.23	129.38	935
25.4	-87.4	11.79	290	21.21	129.38	935
25.7	-87.7	10.04	300	17.64	144.9	908
26	-88.1	13.12	300	21	155.25	907
26.5	-88.6	13.89	300	20.99	157.32	906
26.9	-89	9.75	310	21.07	150.07	902
27.2	-89.1	9.1	310	20.91	143.87	904
27.6	-89.4	10.92	330	21.1	144.9	904
27.9	-89.5	10.74	330	21.79	143.87	908
28.8	-89.6	15.42	360	20.27	134.55	915
29.1	-89.6	15.4	360	20.61	130.41	918
29.7	-89.6	18.81	360	19.56	130.41	923
30.2	-89.6	18.78	360	27.96	130.41	927

30.8	-89.6	20.46	360	29.4	108.31	940
31.4	-89.6	18.73	360	45.57	98.79	955
31.9	-89.6	22.73	360	18.65	77.37	960

Table C- 10: Best Track for Hurricane Wilma 2005

Latitude (Degrees)	Longitude (Degrees)	Translation Speed (mph)	Heading Angle	Radius to Max Winds (miles)	Wind Speed (mph @ 10m)	Central Pressure (mBar)
23.9	-84.4	16.33	40	27.58	99.36	958
24.4	-83.7	17.72	50	26.78	103.5	958
24.7	-83.3	18.58	50	24.47	103.5	954
25.1	-82.8	19.74	50	24.33	107.64	954
25.5	-82.4	28	50	18.14	113.85	950
26.1	-81.4	30.11	50	14.22	113.85	950
26.3	-80.7	26.38	50	19.19	113.85	952
26.9	-80	29.1	40	27.51	93.15	956
27.3	-79.2	38.9	40	33.02	94.18	956
28.1	-78.8	41.4	40	20.79	103.5	955
29	-77.4	37.25	40	16.53	108.67	954
30.2	-76	42.96	40	11.37	112.81	955
31.6	-74.3	52.58	40	14.33	113.85	959
34.8	-70	55.89	50	27.2	103.5	965

Table C- 11: Best Track for Hurricane Dolly 2008

Latitude (Degrees)	Longitude (Degrees)	Translation Speed (mph)	Heading Angle	Radius to Max Winds (miles)	Wind Speed (mph @ 10m)	Central Pressure (mBar)
19.8	-85.8	19.73	310.21	86.31	51.79	1007
20.9	-87.2	20.07	301.42	86.31	51.79	1007
21.8	-88.8	20.58	304.34	86.31	51.79	1005
22.8	-90.4	17.13	278.04	51.79	51.79	1005
23	-92	13.96	279.75	51.79	51.79	1000
23.2	-93.3	10.22	304.42	51.79	51.79	999
23.7	-94.1	10.89	309.55	51.79	63.29	993
24.3	-94.9	10.87	309.68	17.26	69.05	990
24.9	-95.7	7.76	317.95	23.02	74.80	982
25.4	-96.2	7.76	318.07	23.02	80.55	982
25.9	-96.7	7.74	318.2	23.02	97.82	967
26.4	-97.2	6.29	280.68	23.02	86.31	967
26.5	-97.8	5.64	294.21	17.26	74.80	976

26.7	-98.3	8.43	313.21	17.26	63.29	986
27.2	-98.9	13.82	305.92	17.26	51.79	992
27.9	-100	14.97	288.28	17.26	40.28	995

Table C- 122: Best Track for Hurricane Ike 2008

Latitude (Degrees)	Longitude (Degrees)	Translation Speed (mph)	Heading Angle	Radius to Max Winds (miles)	Wind Speed (mph @ 10m)	Central Pressure (mBar)
25.5	-88.4	10.16	290	45.71	87.97	945
25.8	-88.8	12.04	290	45.91	90.04	952
26	-89.4	12.31	290	47.6	87.97	950
26.2	-89.9	10.98	290	47.85	90.04	954
26.3	-90.4	12.65	290	50.48	87.97	956
26.4	-91.1	13.55	290	48.49	90.04	957
26.7	-91.6	12.81	290	46.9	93.15	953
26.9	-92.2	11.97	290	47.98	94.18	956
27.2	-92.6	10.99	300	48.55	93.15	954
27.4	-93.1	10.98	300	50.19	94.18	957
27.7	-93.5	14.21	300	48.07	93.15	955
28.2	-93.8	18.12	300	41.64	99.36	954
28.6	-94.4	9.11	310	48.57	98.32	952
28.9	-94.5	11.33	310	45.6	99.36	952
29.7	-95	16.69	320	44.58	99.36	954
30.1	-95.1	14.47	320	48.24	99.36	956
30.5	-95.3	15.99	360	54.78	92.84	962
31	-95.3	15.08	360	17.62	83.32	964

Table C- 13: Best Track for Hurricane Gustav 2008

Latitude (Degrees)	Longitude (Degrees)	Translation Speed (mph)	Heading Angle	Radius to Max Winds (miles)	Wind Speed (mph @ 10m)	Central Pressure (mBar)
16.4	-71.2	7.99	316.3	17.26	69.05	991
16.9	-71.7	8.19	327.57	11.51	86.31	986
17.5	-72.1	10.33	312.1	11.51	92.06	981
18.1	-72.8	4.76	316.52	11.51	80.55	992
18.4	-73.1	4.00	305.15	11.51	57.54	995
18.6	-73.4	3.47	289.43	23.02	51.79	999
18.7	-73.7	4.00	305.2	11.51	51.79	998
18.9	-74	12.06	264.69	11.51	51.79	999
18.8	-75.1	8.70	202.17	11.51	46.03	999

18.1	-75.4	4.00	235.02	34.52	51.79	995
17.9	-75.7	5.59	281.95	28.77	69.05	984
18	-76.2	9.06	255.4	17.26	69.05	984
17.8	-77	8.01	286.82	11.51	69.05	987
18	-77.7	8.41	294.38	23.02	63.29	990
18.3	-78.4	10.47	303.52	28.77	57.54	989
18.8	-79.2	9.86	298	28.77	74.80	984
19.2	-80	10.42	303.67	23.02	86.31	975
19.7	-80.8	14.41	323.24	23.02	97.82	968
20.7	-81.6	14.18	317.16	23.02	126.59	955
21.6	-82.5	16.58	320.09	17.26	143.85	943
22.7	-83.5	14.09	317.58	17.26	138.09	950
23.6	-84.4	18.03	320.32	17.26	120.83	960
24.8	-85.5	17.81	315.66	17.26	115.08	961
25.9	-86.7	15.46	318.37	17.26	109.32	960
26.9	-87.7	17.60	311.2	23.02	109.32	953
27.9	-89	16.78	308.5	28.77	109.32	954
28.8	-90.3	15.97	316.46	28.77	109.32	955
29.8	-91.4	13.71	319.4	28.77	97.82	958
30.7	-92.3	11.30	315.81	23.02	69.05	971

Table C- 13: Best Track for Hurricane Irene 2011

Latitude (Degrees)	Longitude (Degrees)	Translation Speed (mph)	Heading Angle	Radius to Max Winds (miles)	Wind Speed (mph @ 10m)	Central Pressure (mBar)
17.5	-63.7	14.99	288.1	57.54	57.54	999
17.9	-65	10.45	289.46	34.52	69.05	993
18.2	-65.9	14.47	304.04	17.26	74.80	990
18.9	-67	11.81	293.11	17.26	80.55	989
19.3	-68	9.84	298.08	17.26	86.31	988
19.7	-68.8	10.78	295.45	17.26	92.06	981
20.1	-69.7	10.33	289.72	17.26	92.06	978
20.4	-70.6	7.34	298.21	17.26	92.06	978
20.7	-71.2	8.30	294.76	23.02	92.06	977
21	-71.9	7.31	298.3	23.02	92.06	969
21.3	-72.5	11.01	309.04	23.02	109.32	965
21.9	-73.3	14.09	311.04	17.26	120.83	957
22.7	-74.3	12.53	317.55	17.26	115.08	954
23.5	-75.1	10.89	309.5	34.52	109.32	952
24.1	-75.9	16.67	334.09	34.52	109.32	950
25.4	-76.6	14.12	334	34.52	103.57	950

26.5	-77.2	13.87	355.78	34.52	103.57	950
27.7	-77.3	12.68	0	34.52	103.57	946
28.8	-77.3	13.87	355.87	11.51	103.57	942
30	-77.4	12.71	355.55	46.03	97.82	947
31.1	-77.5	12.17	18.71	46.03	92.06	950
32.1	-77.1	15.26	10.9	69.05	86.31	952
33.4	-76.8	15.10	7.21	69.05	86.31	952
34.7	-76.6	9.64	16.97	51.79	86.31	952
35.5	-76.3	14.92	21.82	51.79	74.80	950
36.7	-75.7	17.36	21.45	51.79	74.80	951
38.1	-75	26.60	17.31	115.08	74.80	958
40.3	-74.1	26.78	18.5	115.08	63.29	963
42.5	-73.1	21.30	22.82	115.08	57.54	970

Table C- 14: Best Track for Hurricane Isaac 2012

Latitude (Degrees)	Longitude (Degrees)	Translation Speed (mph)	Heading Angle	Radius to Max Winds (miles)	Wind Speed (mph @ 10m)	Central Pressure (mBar)
15.20	-53.10	19.04	277.18	28.77	40.28	1005.00
15.40	-54.80	20.27	280.06	28.77	46.03	1004.00
15.70	-56.60	22.28	276.20	28.77	51.79	1003.00
15.90	-58.60	20.07	276.84	34.52	51.79	1004.00
16.10	-60.40	18.32	255.65	80.55	51.79	1004.00
15.70	-62.00	17.52	242.78	80.55	51.79	1004.00
15.00	-63.40	17.83	273.91	80.55	51.79	1004.00
15.10	-65.00	16.58	290.51	80.55	51.79	1003.00
15.60	-66.40	15.57	274.43	80.55	51.79	1003.00
15.70	-67.80	14.83	256.70	80.55	51.79	1002.00
15.40	-69.10	14.83	283.64	80.55	51.79	998.00
15.70	-70.40	13.62	319.62	69.05	57.54	995.00
16.60	-71.20	10.42	320.74	69.05	63.29	993.00
17.30	-71.80	15.17	319.54	63.29	63.29	992.00
18.30	-72.70	19.89	319.07	51.79	63.29	991.00
19.60	-73.90	19.71	314.75	69.05	57.54	997.00
20.80	-75.20	19.80	305.86	69.05	57.54	997.00
21.80	-76.70	19.95	301.59	69.05	57.54	997.00
22.70	-78.30	19.75	294.44	69.05	63.29	995.00
23.40	-80.00	15.19	283.44	69.05	63.29	995.00
23.70	-81.40	13.89	294.75	57.54	57.54	992.00
24.20	-82.60	13.96	311.55	57.54	57.54	990.00

25.00	-83.60	14.00	305.39	46.03	57.54	989.00
25.70	-84.70	12.46	303.94	46.03	63.29	987.00
26.30	-85.70	11.81	299.43	34.52	69.05	982.00
26.80	-86.70	11.54	307.03	34.52	69.05	979.00
27.40	-87.60	9.93	314.23	34.52	69.05	978.00
28.00	-88.30	8.57	323.85	34.52	74.80	975.00
28.60	-88.80	6.98	299.84	57.54	80.55	972.00
28.90	-89.40	6.46	291.01	46.03	80.55	967.00
29.10	-90.00	6.11	304.64	46.03	80.55	966.00
29.40	-90.50	4.59	319.05	40.28	74.80	968.00
29.70	-90.80	5.50	327.04	51.79	69.05	973.00
30.10	-91.10	7.00	325.48	46.03	63.29	977.00
30.60	-91.50	8.97	333.99	46.03	63.29	982.00

Table C- 15: Best Track for Hurricane Sandy 2012

Latitude (Degrees)	Longitude (Degrees)	Translation Speed (mph)	Heading Angle	Radius to Max Winds (miles)	Wind Speed (mph @ 10m)	Central Pressure (mBar)
31.9	-73.3	9.04	40	70.73	67.28	960
32.1	-73.1	9.72	40	67.1	67.28	951
32.5	-72.6	14.4	40	88.31	67.28	951
32.8	-71.9	16.68	40	87.04	67.28	951
33.4	-71.3	16.8	50	87.52	67.28	952
34	-70.9	14.66	50	88.03	67.28	950
34.5	-70.5	14.7	30	88.03	67.28	950
35.2	-70.5	15.69	30	87.77	67.28	950
35.9	-70.5	19.4	360	90.55	77.63	946
36.8	-71.1	20.22	360	80.81	76.59	946
37.5	-71.5	26.2	330	85.64	82.8	943
38.3	-73.1	30.96	330	92.84	80.73	940
38.8	-74.4	18.56	330	83.57	82.8	940
39.8	-75.4	15.57	300	38.13	77.37	952
40.5	-77	15.06	0	6.21	66.65	960
40.2	-78.4	11.64	0	15.46	46.42	983
40.8	-79.2	7.81	0	16.84	46.42	988
41.3	-79.4	6.62	0	27.81	40	992

Table C- 16: Best Track for Hurricane Harvey 2017

Latitude (Degrees)	Longitude (Degrees)	Translation Speed (mph)	Heading Angle	Radius to Max Winds (miles)	Wind Speed (mph @ 10m)	Central Pressure (mBar)
25	-94.3	9.3	320	11.99	76.59	974
25.2	-94.6	10.83	320	11.26	77.63	973
25.6	-95.1	11.59	320	7.16	94.18	967
25.9	-95.4	10.83	320	7.9	93.15	967
26.3	-95.8	11.21	320	6.21	99.36	950
26.7	-96	10.55	320	7.99	98.32	947
27.1	-96.3	10.54	320	7.65	99.36	945
27.5	-96.5	9.63	320	7.74	113.85	941
27.8	-96.8	7.68	320	7.87	116.95	941
28	-97	5.35	320	9.8	119.02	938
28.2	-97	6.27	320	10.34	119.02	942
28.5	-97.2	6.27	320	11.34	101.17	963
28.7	-97.2	4.78	340	15.73	83.32	975
28.9	-97.3	6.3	350	19.77	77.37	984
29.1	-97.6	3.81	340	21.8	72.61	987
29.1	-97.6	2.33	360	35.87	65.46	990
29.2	-97.4	3.85	60	38.93	61.89	992
29.3	-97.3	2.54	60	44.8	53.56	994
29.3	-97.4	4.26	0	58.61	46.42	998
29.2	-97.7	5.74	200	25.87	46.42	998
29	-97.6	4.53	160	25.87	46.42	998
29	-97.4	4.06	160	75.14	40	1000
29	-97.2	4.06	140	75.14	40	1000
29	-97	4.36	140	92.62	40	1000
28.9	-96.8	4.66	130	92.62	40	1000
28.8	-96.6	4.66	120	92.62	40	1000
28.7	-96.4	3.86	120	92.62	40	999
28.6	-96.3	3.57	130	72.91	40	998
28.6	-96.1	3.57	130	71.82	40	997
28.5	-96	3.87	120	71.82	40	997
28.6	-95.8	3.87	120	72.91	40	998
28.5	-95.7	5.52	110	93.19	41.4	997
28.2	-95.5	6.03	120	93.07	40.36	997
28.2	-95.3	5.87	120	93.19	41.4	997
28	-95	6.17	100	93.07	40.36	997
28.1	-94.8	4.68	90	93.19	41.4	997

28.2	-94.6	6.16	60	93.07	40.36	997
28.4	-94.3	8.39	20	90.22	41.4	997
28.8	-94.3	9.13	20	92.2	40.36	997
29.2	-94.3	11.57	30	83.18	46.57	994
28.7	-93.9	11.59	90	89.21	44.51	994
29	-93.6	7.08	40	84.87	46.57	994
29.2	-93.5	9.41	40	91.09	40.36	995
29.8	-93.4	11.9	30	39.69	40.36	990
30.2	-93.6	9.54	360	51.92	40.36	992

Table C- 17: Best Track for Hurricane Irma 2017

Latitude (Degrees)	Longitude (Degrees)	Translation Speed (mph)	Heading Angle	Radius to Max Winds (miles)	Wind Speed (mph @ 10m)	Central Pressure (mBar)
22.1	-76.5	13.03	280	14.77	139.72	925
22.2	-77.2	13.03	280	14.62	139.72	924
22.1	-77.7	11.27	280	14.82	144.9	924
22.3	-78.2	12.61	280	15.98	143.87	930
22.5	-78.8	15.4	280	15.59	139.72	930
22.6	-79.6	11.73	280	14.98	116.95	937
22.8	-79.8	8.6	280	17.88	113.85	941
23.1	-80.2	10.15	280	17.82	112.81	941
23.4	-80.5	8.06	300	15.7	113.85	933
23.3	-80.8	6.5	300	16.68	107.64	932
23.5	-81	7.04	300	15.27	108.67	933
23.7	-81.3	8.96	310	15.32	116.95	931
24.1	-81.5	9.64	320	17.88	119.02	928
24.5	-81.5	10.32	330	18.03	116.95	929
25	-81.5	13.29	350	17.33	119.02	933
25.6	-81.8	14.43	350	17.3	107.64	936
26.2	-81.8	12.69	350	18.02	107.64	938
26.7	-81.7	15.2	360	19.53	107.64	942
27.5	-81.9	17.96	350	21.36	101.17	952
28.2	-82.2	17.55	350	30.51	88.08	960
28.9	-82.6	16.46	340	39.67	77.37	965
29.5	-82.9	16.82	340	52.54	72.61	970
30.3	-83.1	16.92	340	90.35	65.46	975
30.8	-83.6	16.48	340	91.93	61.89	980

Appendix D

Measured Versus Modeled Storm Surge Heights for All Other Basins

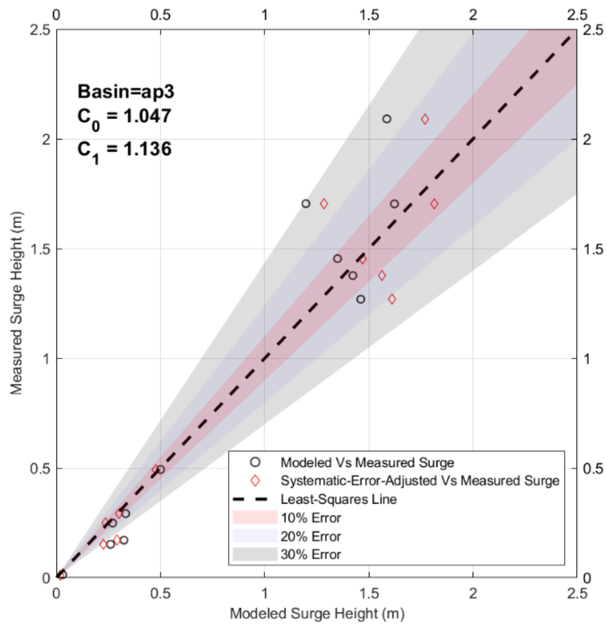


Figure D- 1: Measured versus Simulated storm surge heights for ‘ap3’ Basin

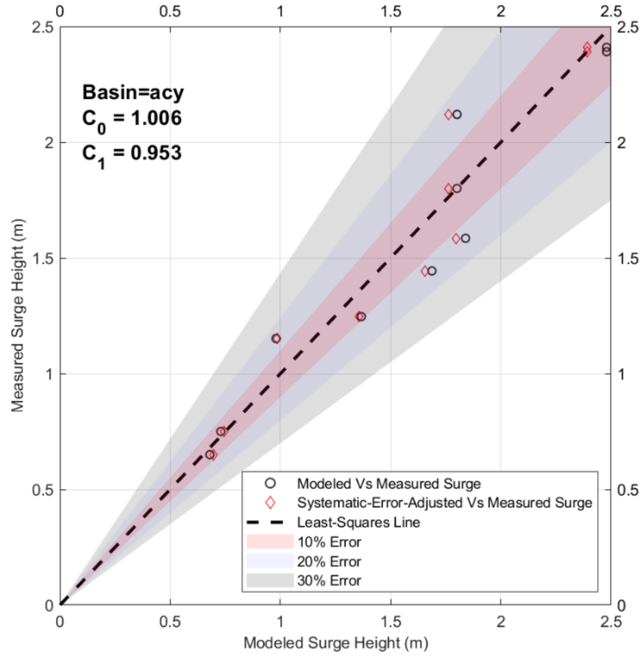


Figure D- 2: Measured versus Simulated storm surge heights for ‘acy’ Basin

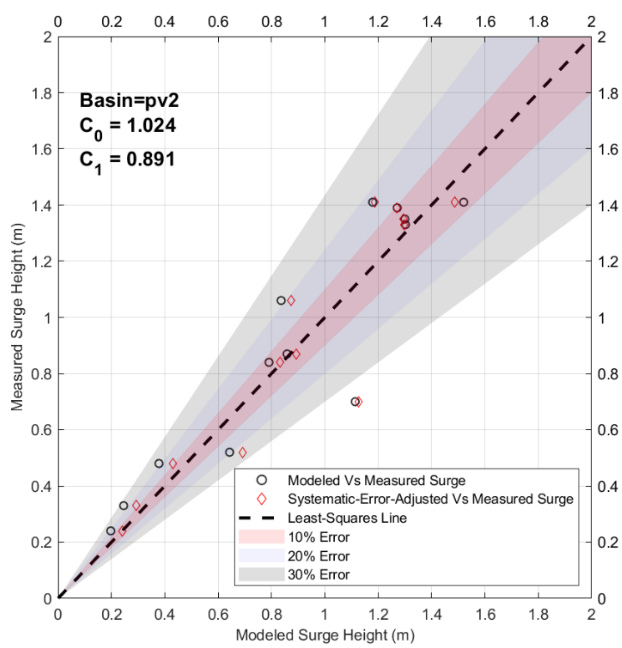


Figure D- 3: Measured versus Simulated storm surge heights for ‘pv2’ Basin

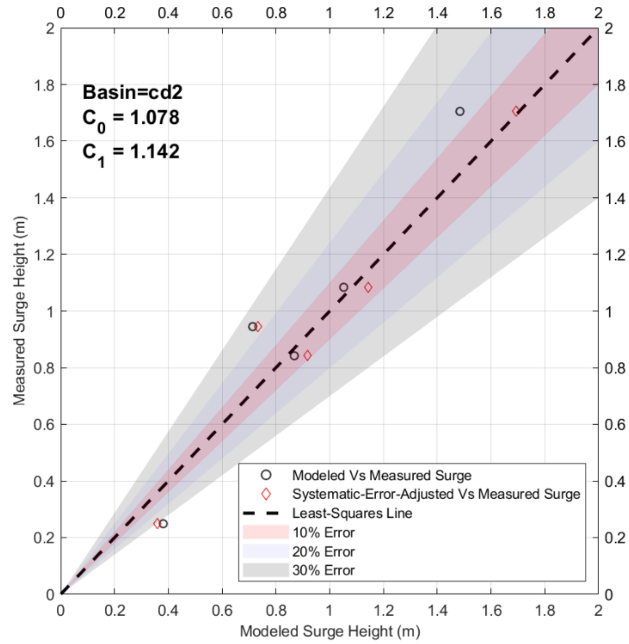


Figure D- 4: Measured versus Simulated storm surge heights for ‘cd2’ Basin

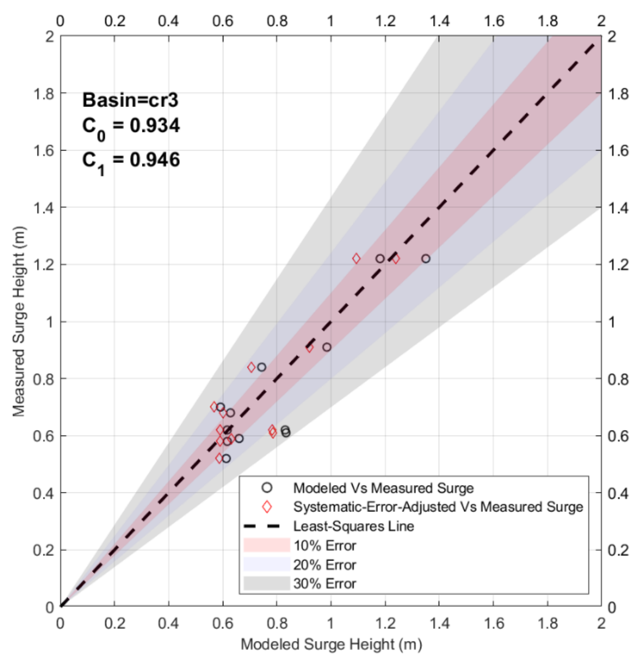


Figure D- 5: Measured versus Simulated storm surge heights for ‘cr3’ Basin

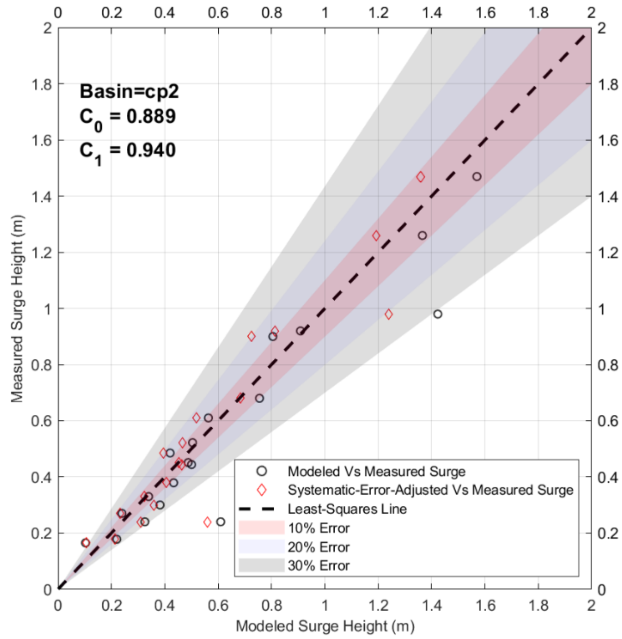


Figure D- 6: Measured versus Simulated storm surge heights for ‘cp2’ Basin

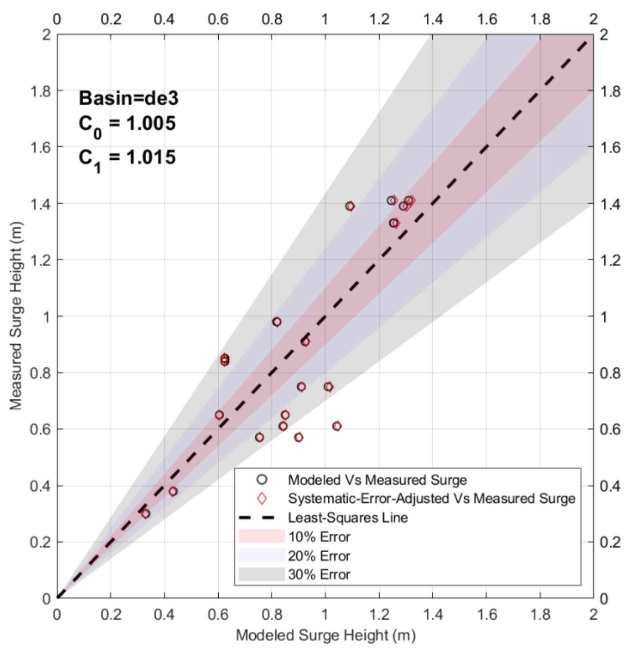


Figure D- 7: Measured versus Simulated storm surge heights for ‘de3’ Basin

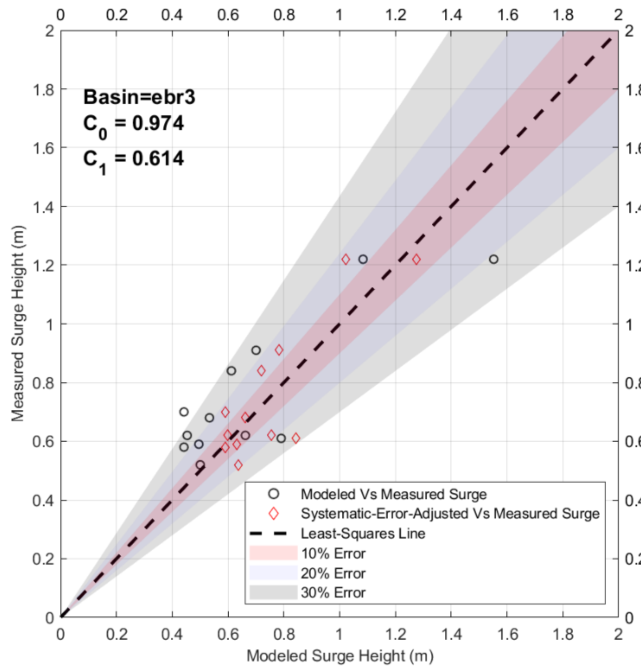


Figure D- 8: Measured versus Simulated storm surge heights for ‘ebr3’ Basin

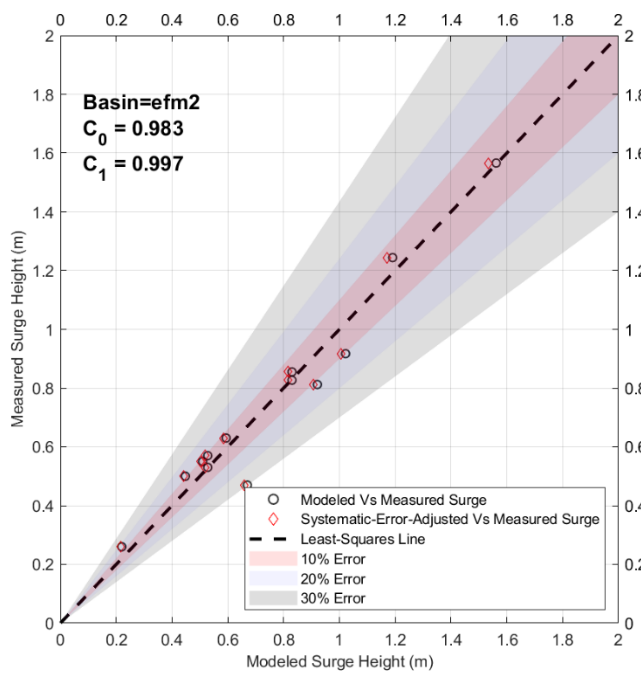


Figure D- 9: Measured versus Simulated storm surge heights for ‘efm2’ Basin

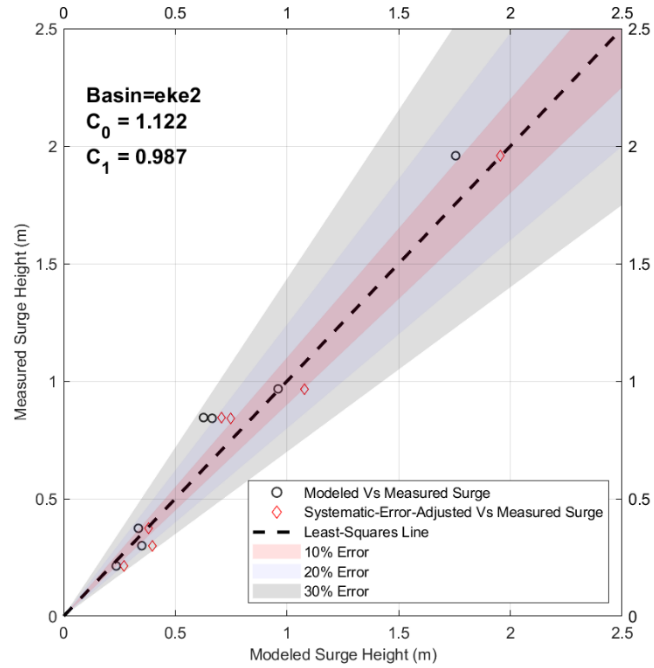


Figure D- 10: Measured versus Simulated storm surge heights for ‘eke2’ Basin

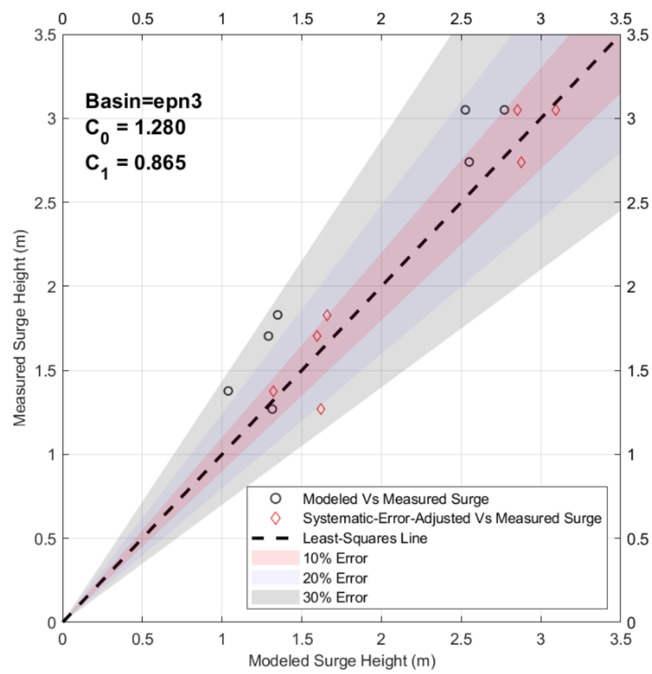


Figure D- 11: Measured versus Simulated storm surge heights for ‘epn3’ Basin

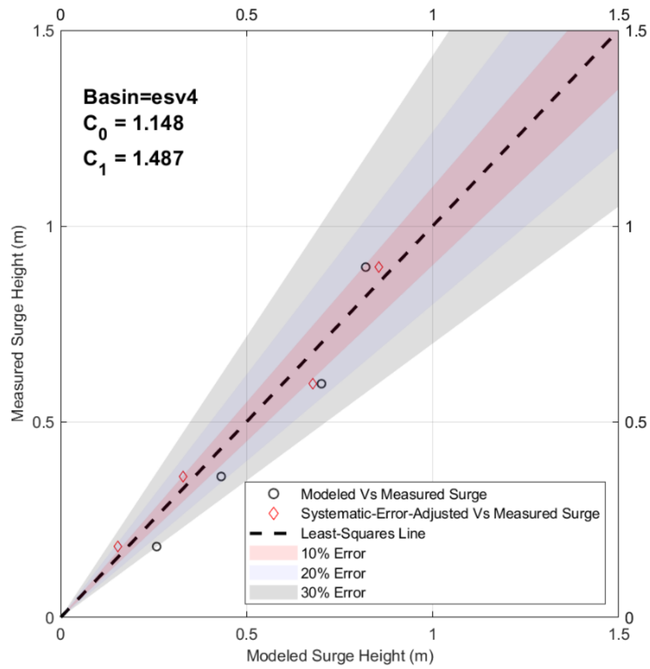


Figure D- 12: Measured versus Simulated storm surge heights for ‘esv4’ Basin

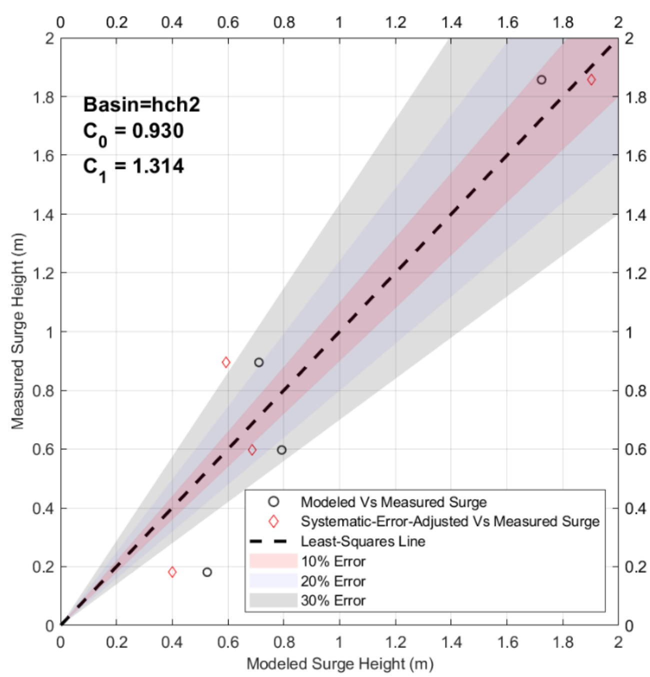


Figure D- 13: Measured versus Simulated storm surge heights for ‘hch2’ Basin

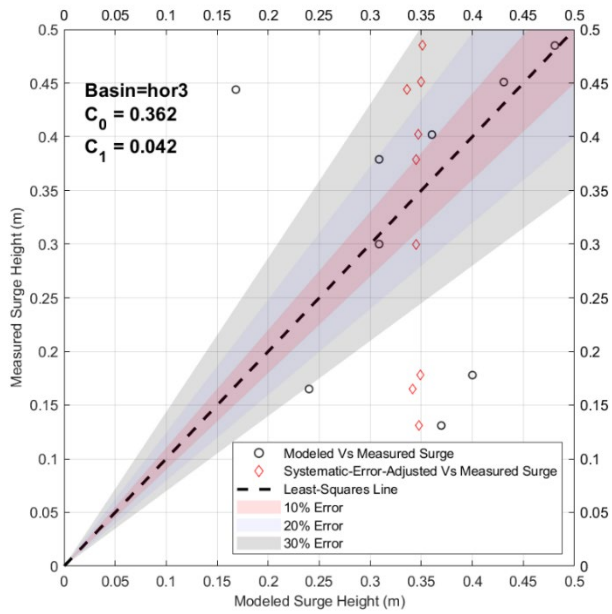


Figure D- 14: Measured versus Simulated storm surge heights for ‘hor3’ Basin

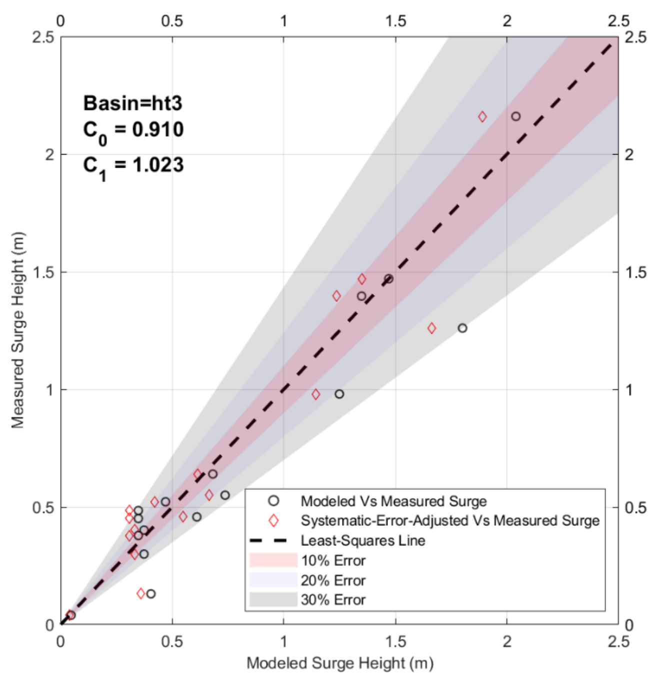


Figure D- 15: Measured versus Simulated storm surge heights for ‘ht3’ Basin

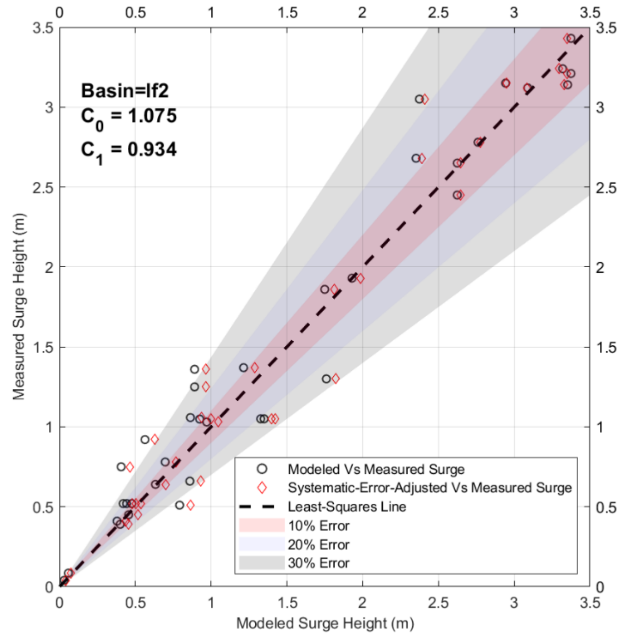


Figure D- 16: Measured versus Simulated storm surge heights for ‘lf2’ Basin

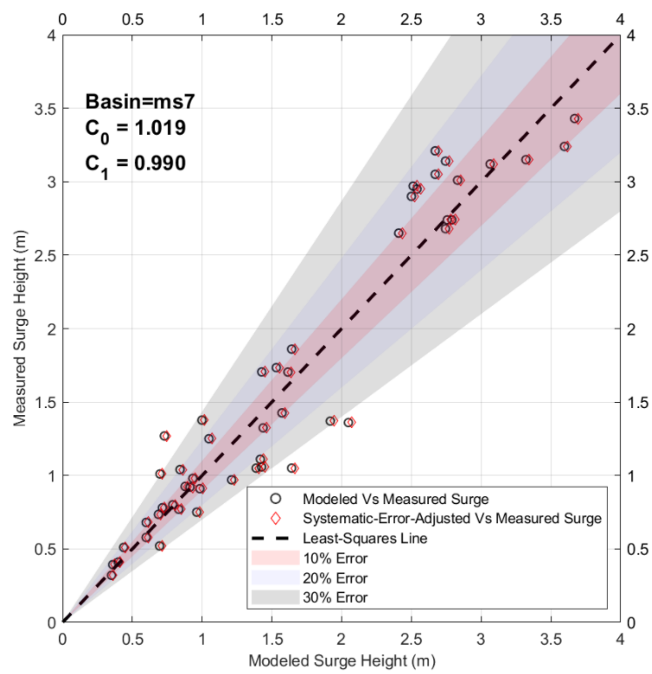


Figure D- 17: Measured versus Simulated storm surge heights for ‘ms7’ Basin

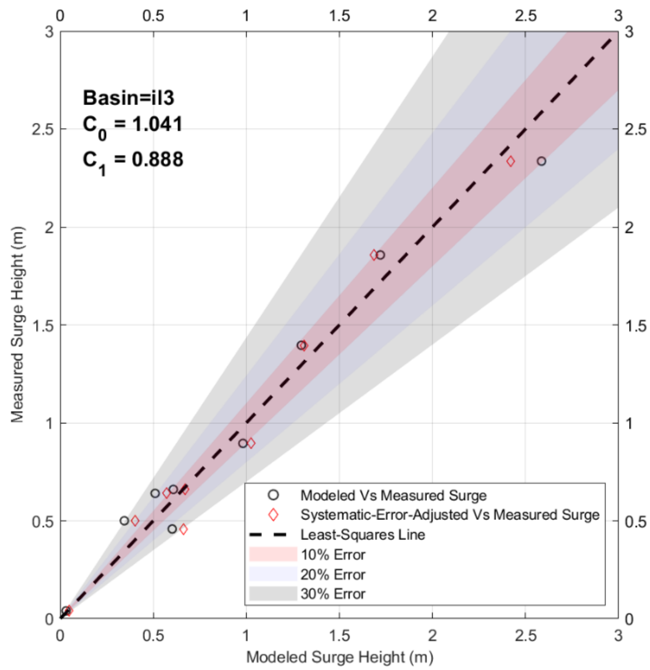


Figure D- 18: Measured versus Simulated storm surge heights for 'il3' Basin

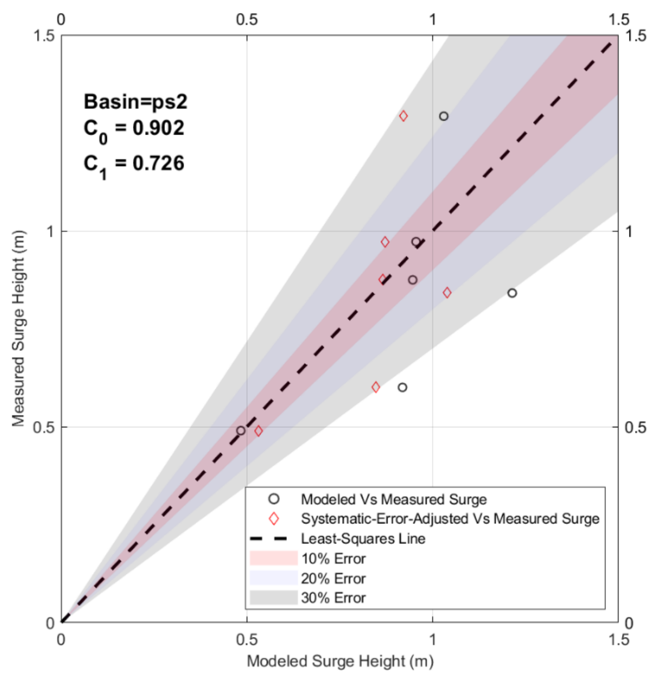


Figure D- 19: Measured versus Simulated storm surge heights for 'ps2' Basin

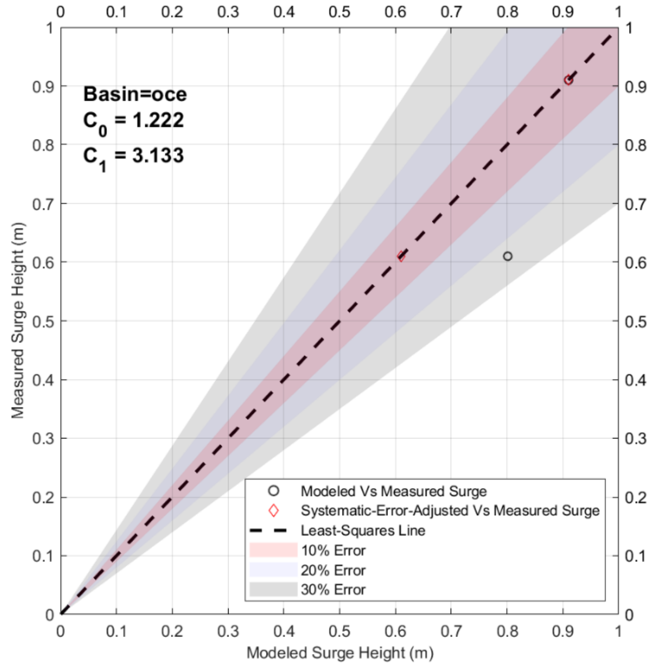


Figure D- 20: Measured versus Simulated storm surge heights for ‘oce’ Basin

Appendix E

Comparisons between Measured, Simulated and Adjusted Surge Heights for All Other Basins

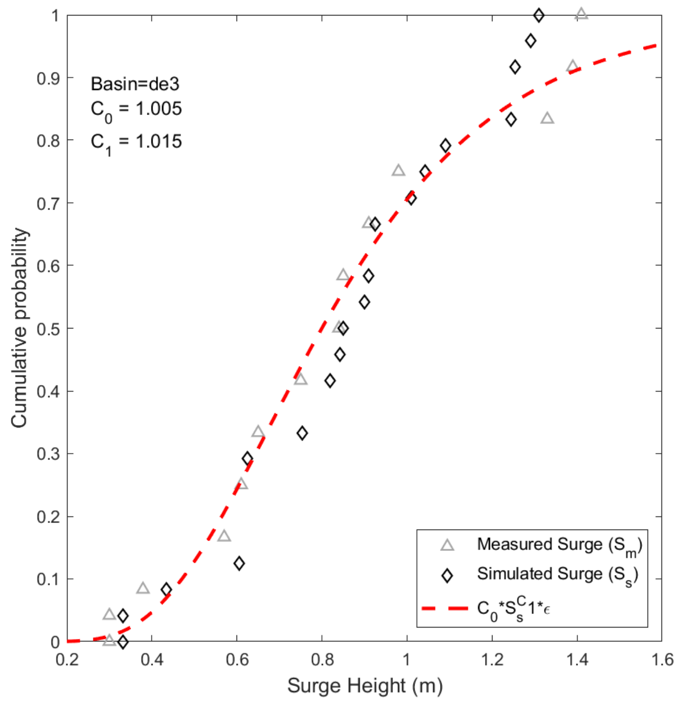


Figure E- 1: Comparison between measured, simulated and adjusted surge height for 'de3' basin

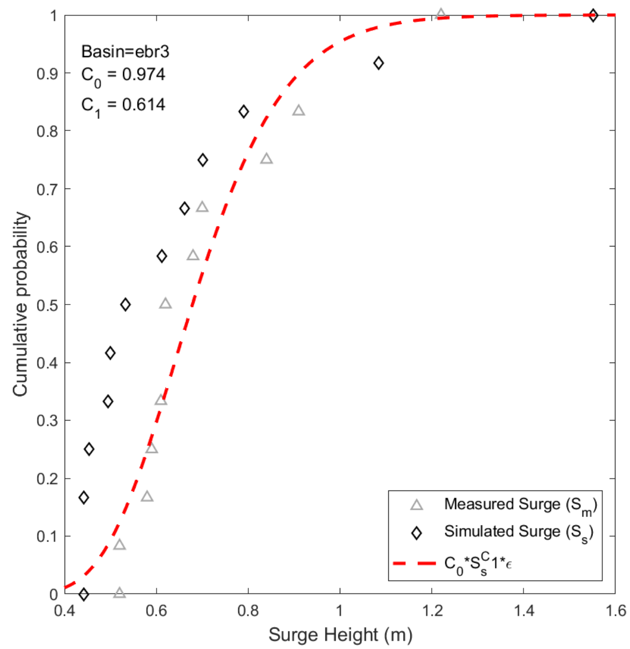


Figure E- 2: Comparison between measured, simulated and adjusted surge height for ebr3 basin

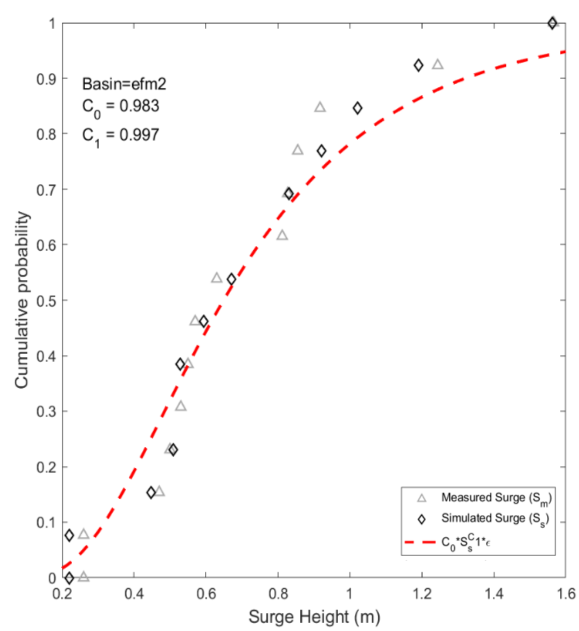


Figure E- 3**:** Comparison between measured, simulated and adjusted surge height for efm2 basin

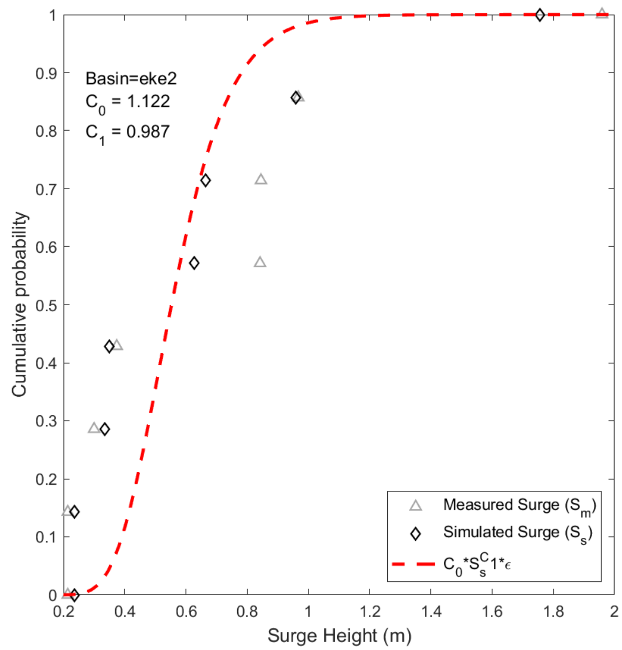


Figure E- 4: Comparison between measured, simulated and adjusted surge height for eke2 basin

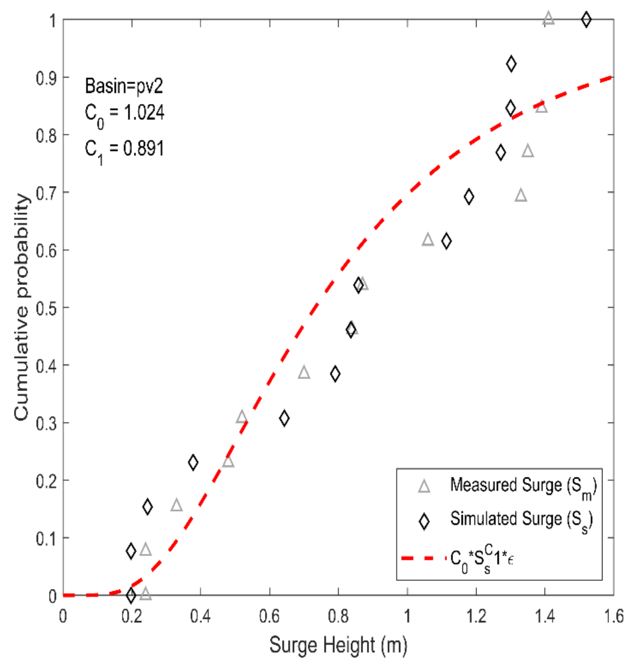


Figure E- 5: Comparison between measured, simulated and adjusted surge height for pv2 basin

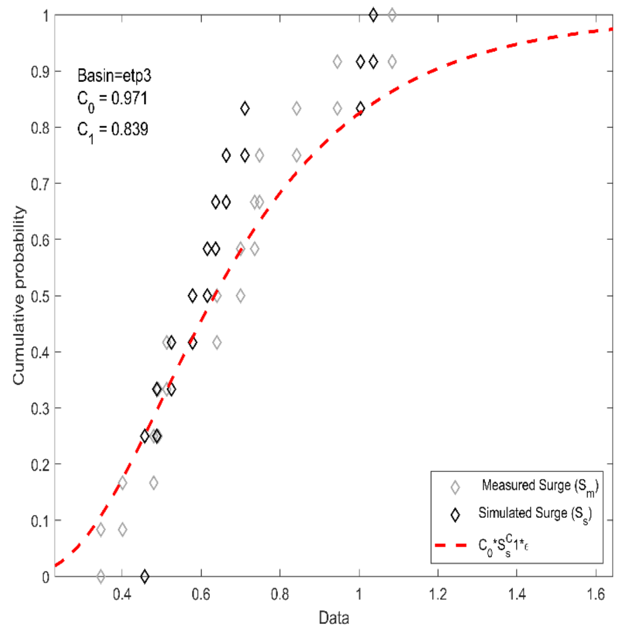


Figure E- 6: Comparison between measured, simulated and adjusted surge height for etp3 basin

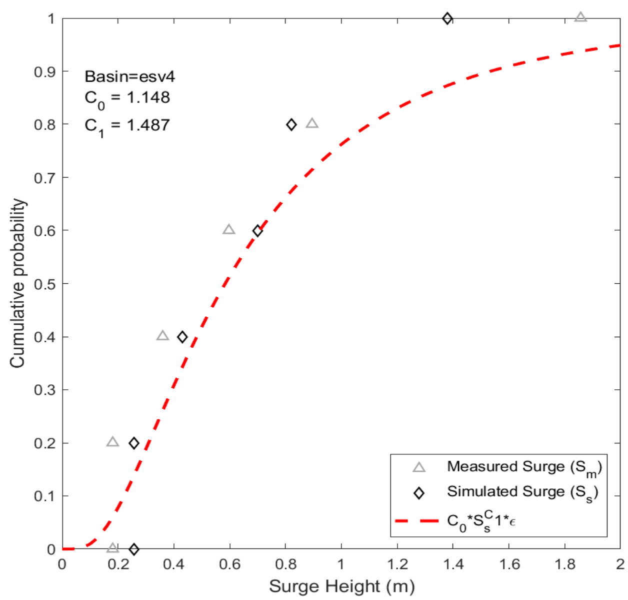


Figure E- 7: Comparison between measured, simulated and adjusted surge height for esv4 basin

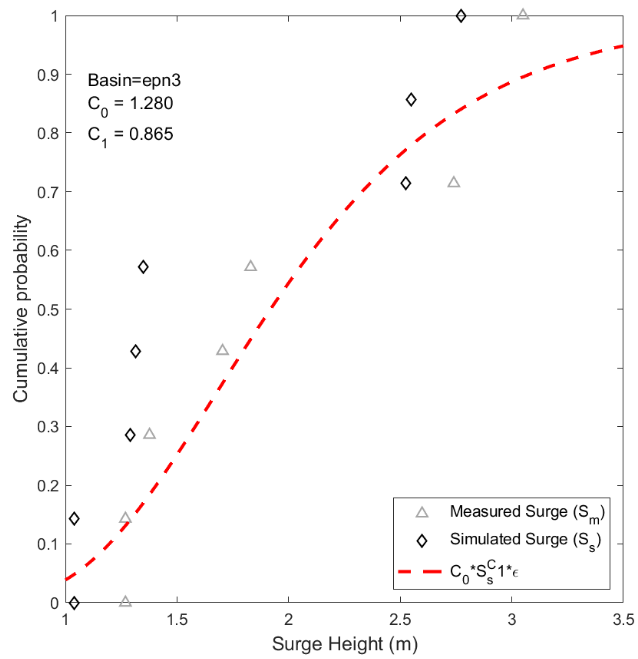


Figure E- 8: Comparison between measured, simulated and adjusted surge height for epn3 basin

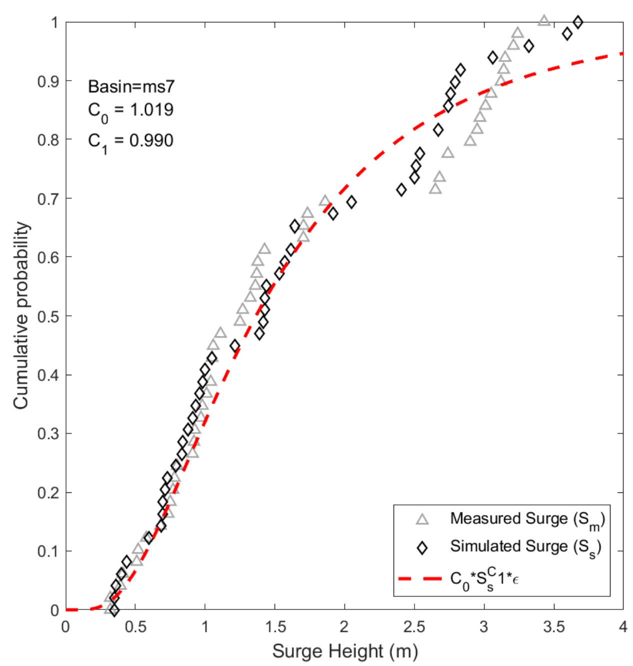


Figure E- 9: Comparison between measured, simulated and adjusted surge height for ms7 basin

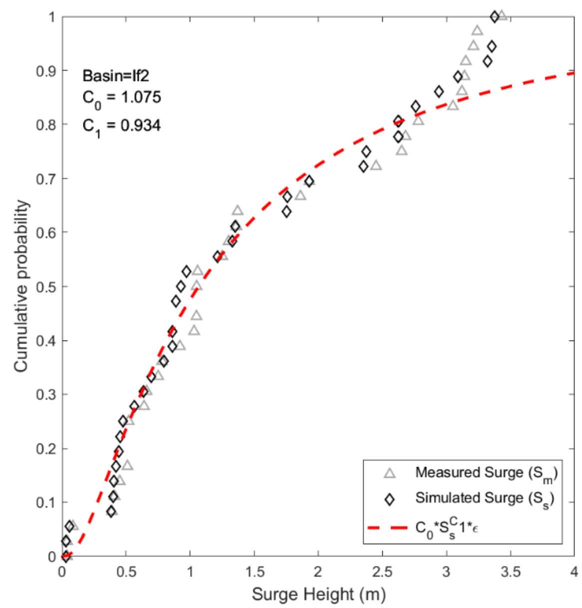


Figure E- 10: Comparison between measured, simulated and adjusted surge height for lf2 basin

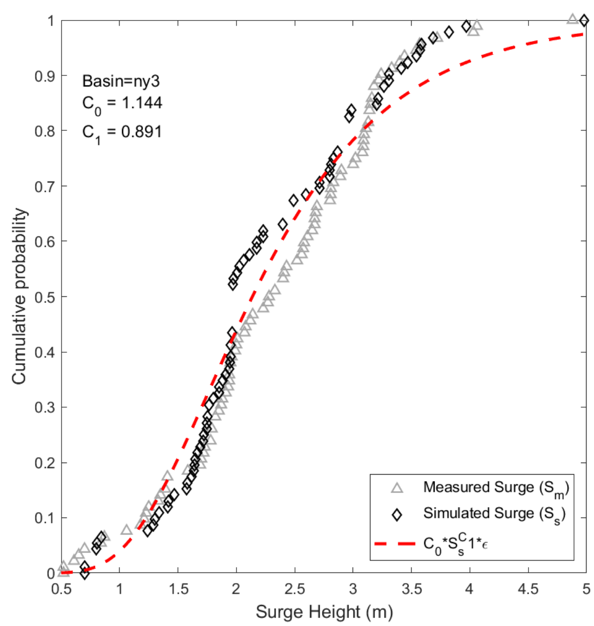


Figure E- 11: Comparison between measured, simulated and adjusted surge height for ny3 basin

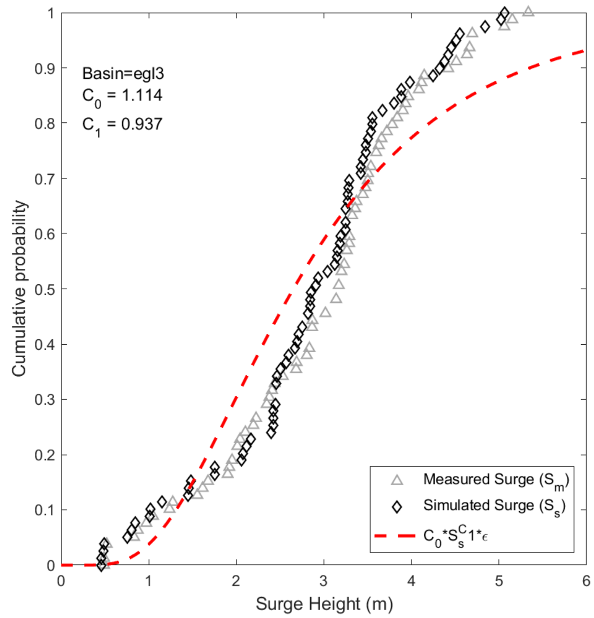


Figure E- 12: Comparison between measured, simulated and adjusted surge height for egl3 basin

Appendix F

Lognormal Distribution Fits of Random Errors for All Other Basins

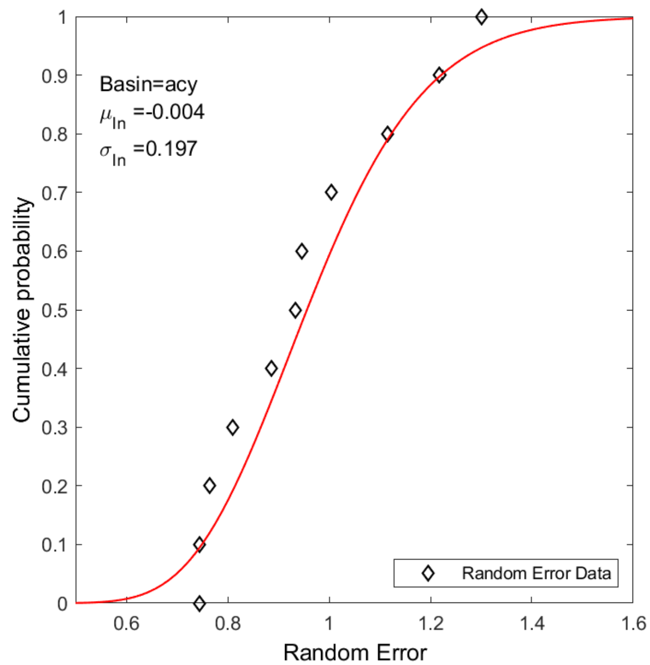


Figure F- 1: Lognormal distribution fit of random errors for ‘acy’ basin

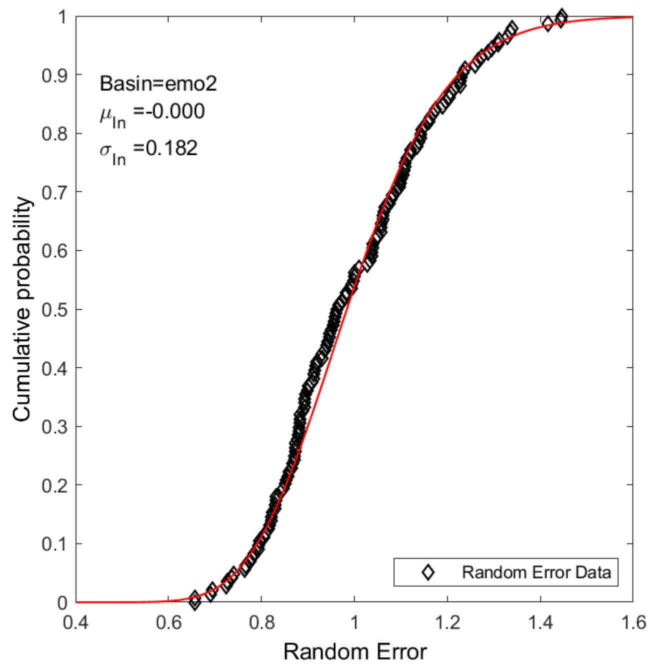


Figure F- 2: Lognormal distribution fit of random errors for ‘emo2’ basin

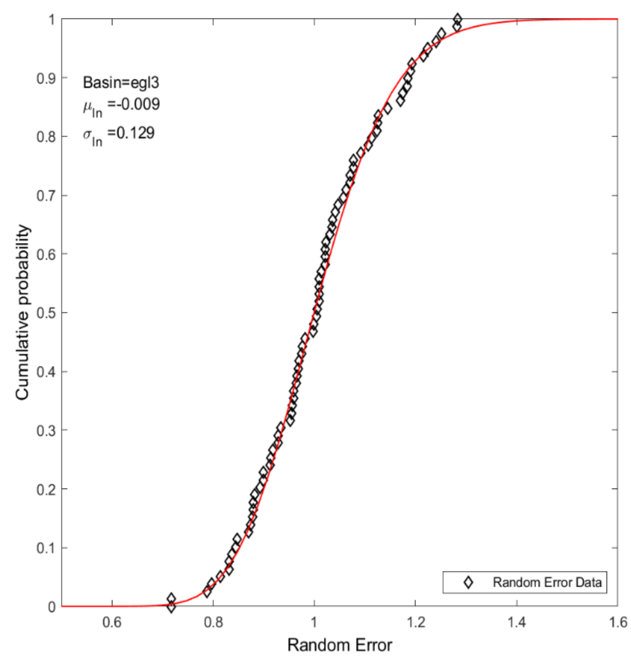


Figure F- 3: Lognormal distribution fit of random errors for ‘egl3’ basin

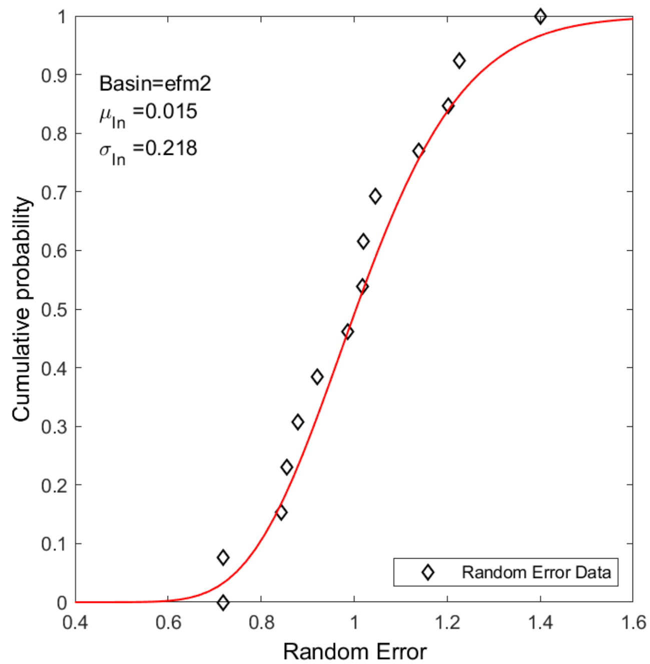


Figure F- 4: Lognormal distribution fit of random errors for ‘efm2’ basin

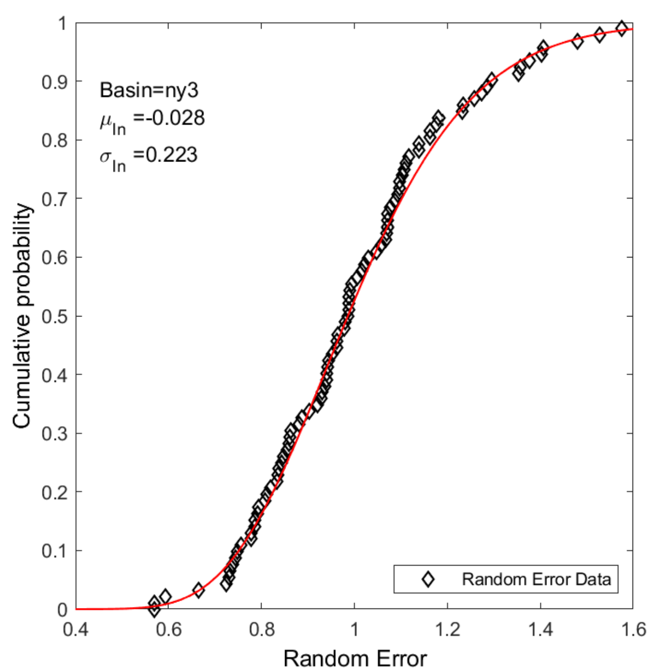


Figure F- 5: Lognormal distribution fit of random errors for ‘ny3’ basin

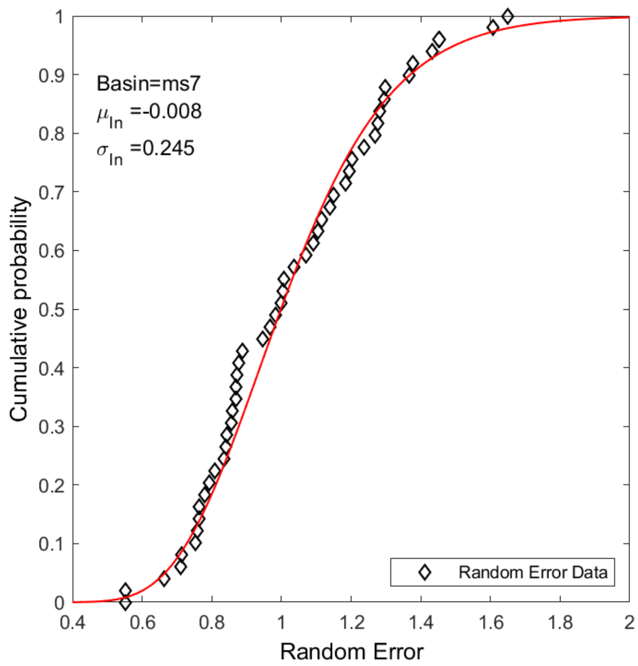


Figure F- 6: Lognormal distribution fit of random errors for ‘ms7’ basin

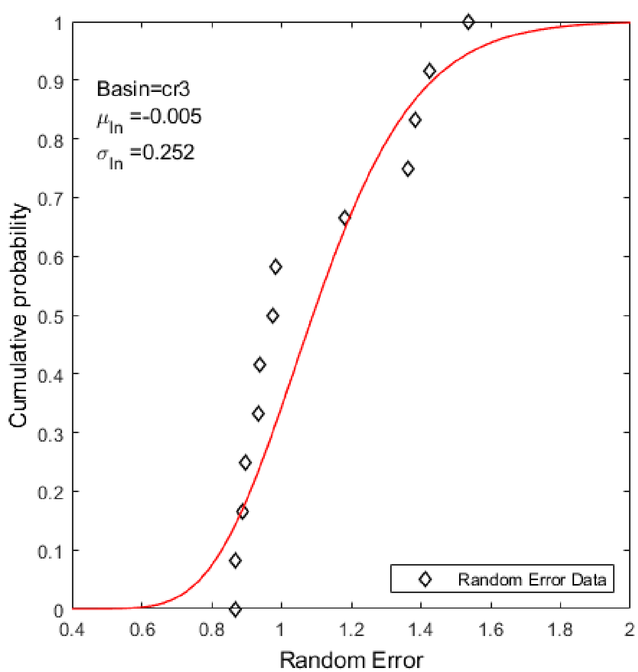


Figure F- 7: Lognormal distribution fit of random errors for ‘cr3’ basin

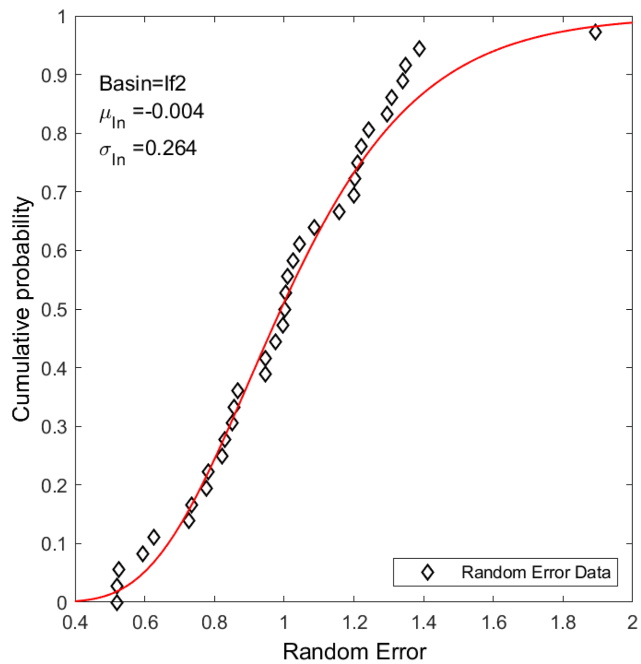


Figure F- 8: Lognormal distribution fit of random errors for ‘lf2’ basin

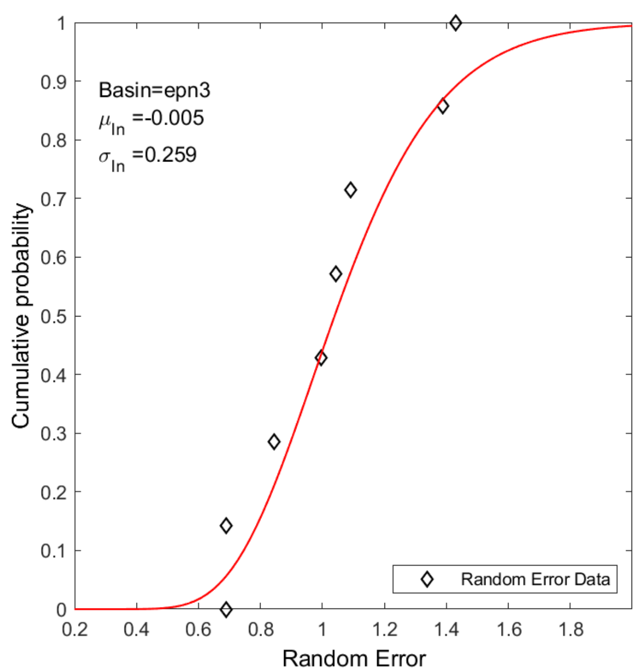


Figure F- 9: Lognormal distribution fit of random errors for ‘epn3’ basin

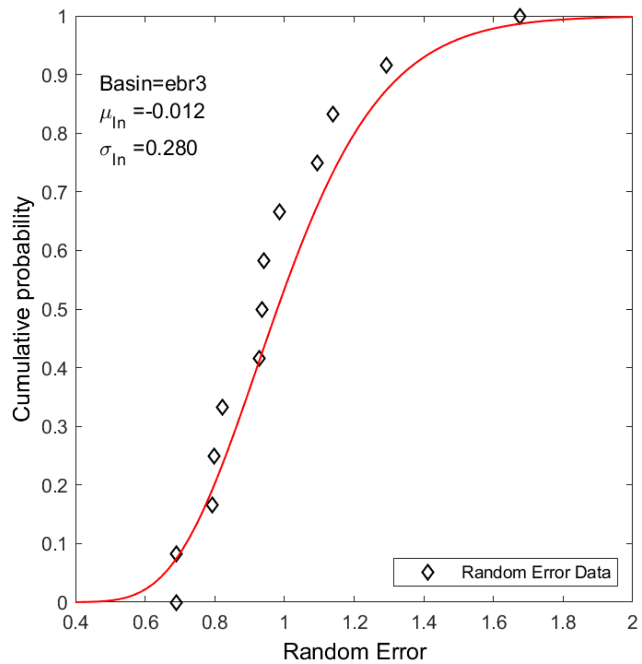


Figure F- 10: Lognormal distribution fit of random errors for ‘ebr3’ basin

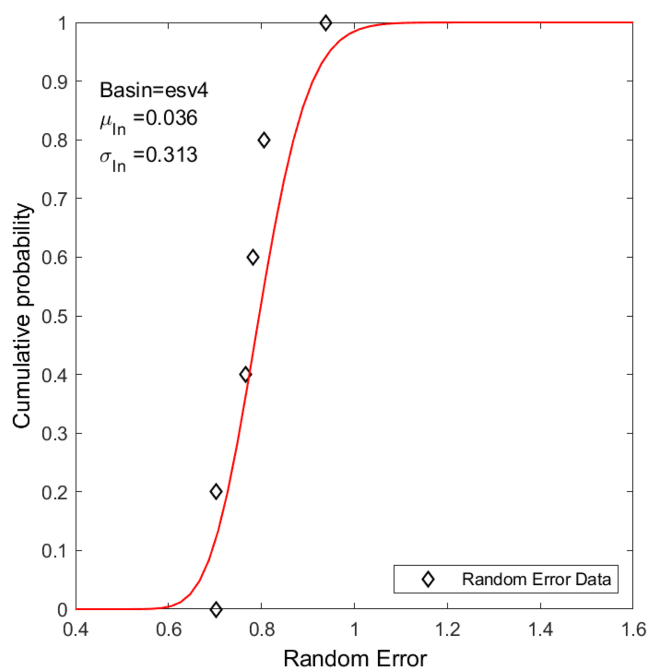


Figure F- 11: Lognormal distribution fit of random errors for ‘esv4’ basin

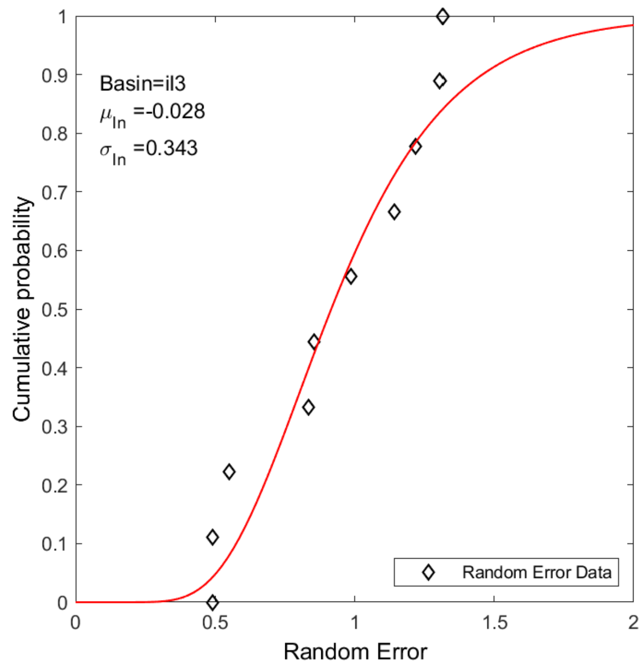


Figure F- 12: Lognormal distribution fit of random errors for ‘il3’ basin

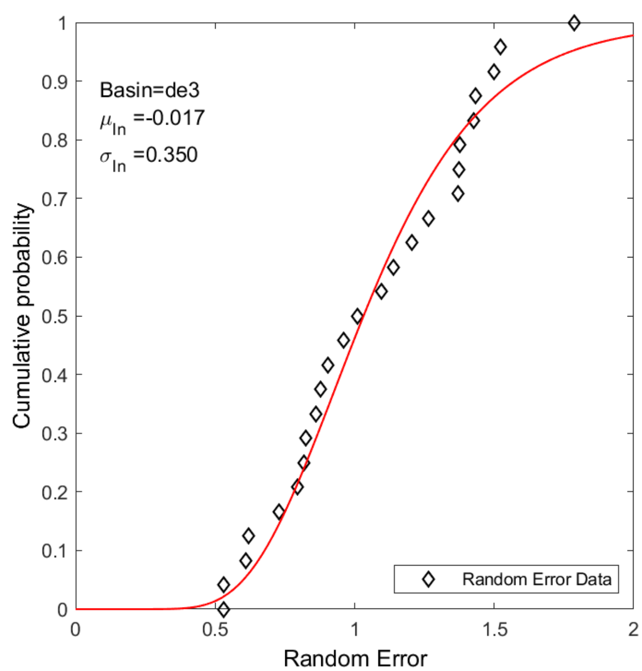


Figure F- 13: Lognormal distribution fit of random errors for ‘de3’ basin

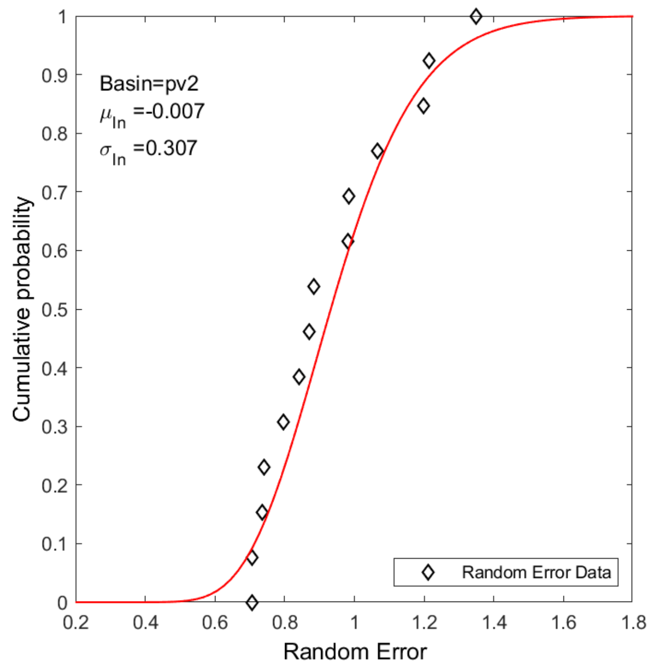


Figure F- 14: Lognormal distribution fit of random errors for ‘pv2’ basin

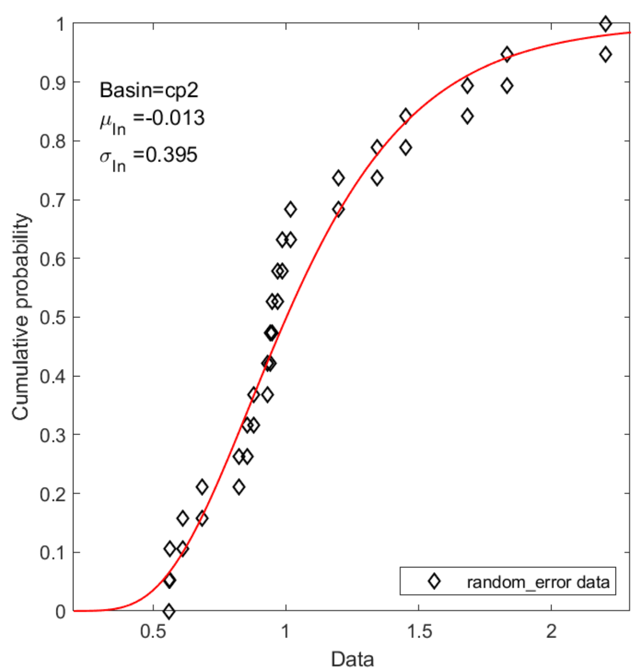


Figure F- 15: Lognormal distribution fit of random errors for ‘cp2’ basin

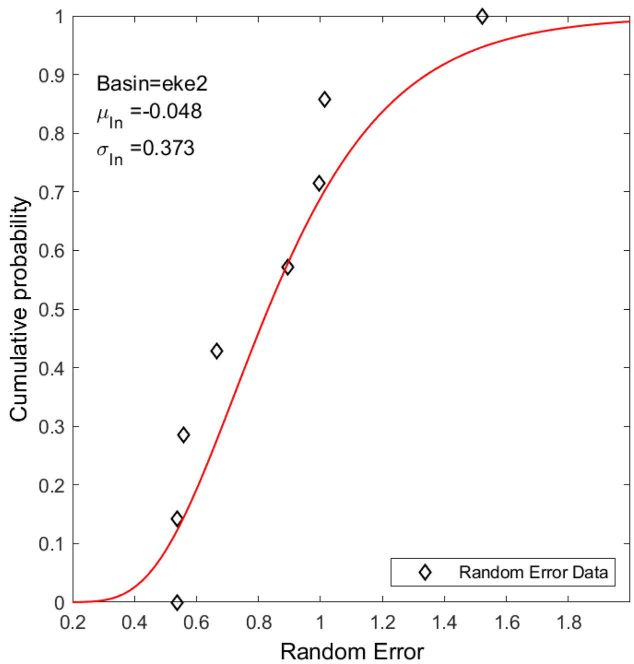


Figure F- 16: Lognormal distribution fit of random errors for ‘eke2’ basin

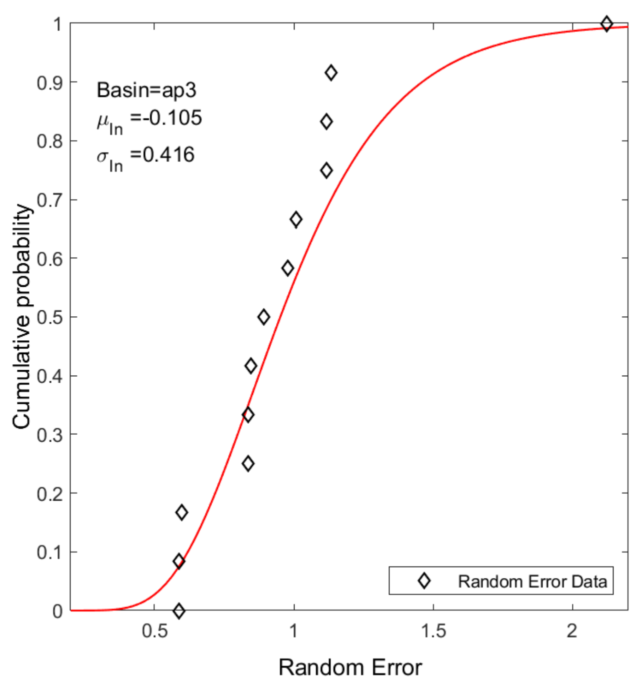


Figure F- 17: Lognormal distribution fit of random errors for ‘ap3’ basin

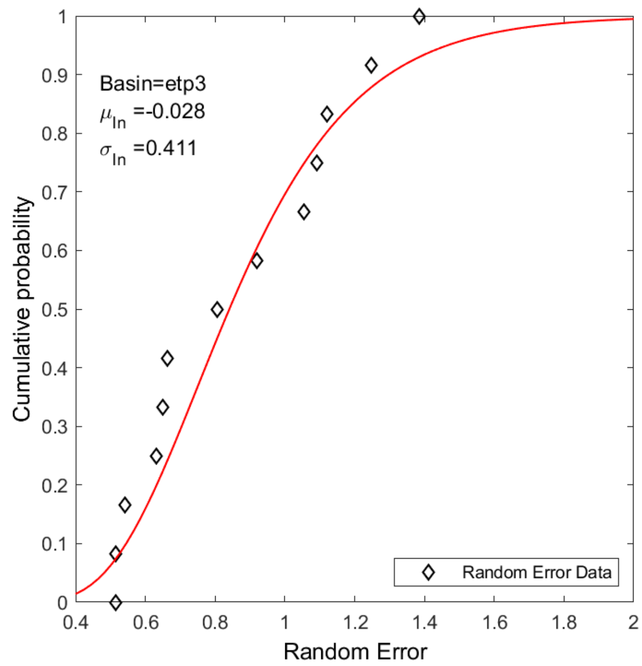


Figure F- 18: Lognormal distribution fit of random errors for ‘etp3’ basin

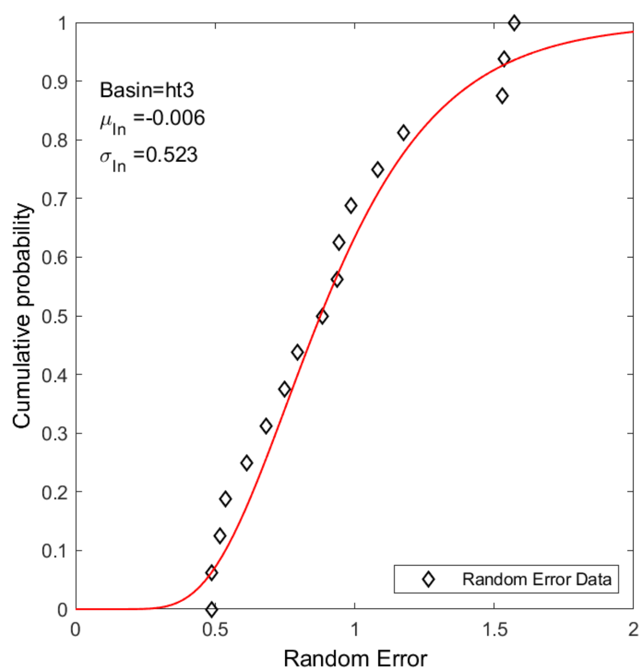


Figure F- 19: Lognormal distribution fit of random errors for ‘ht3’ basin

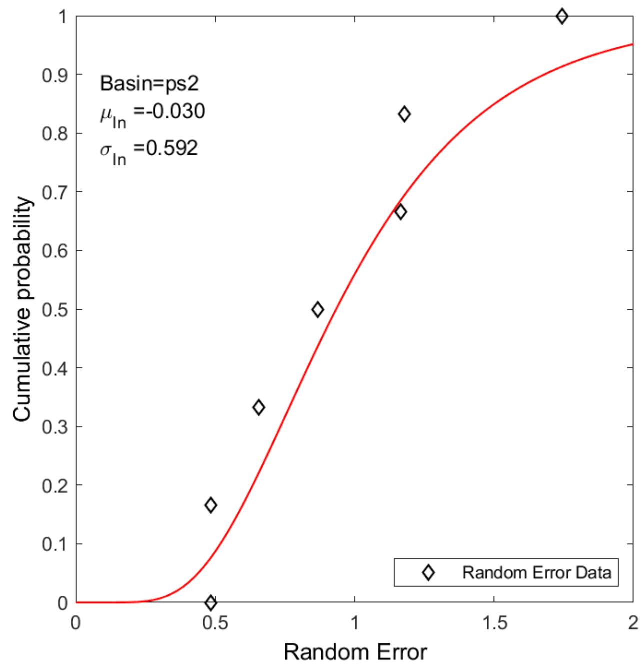


Figure F- 20: Lognormal distribution fit of random errors for ‘ps2’ basin

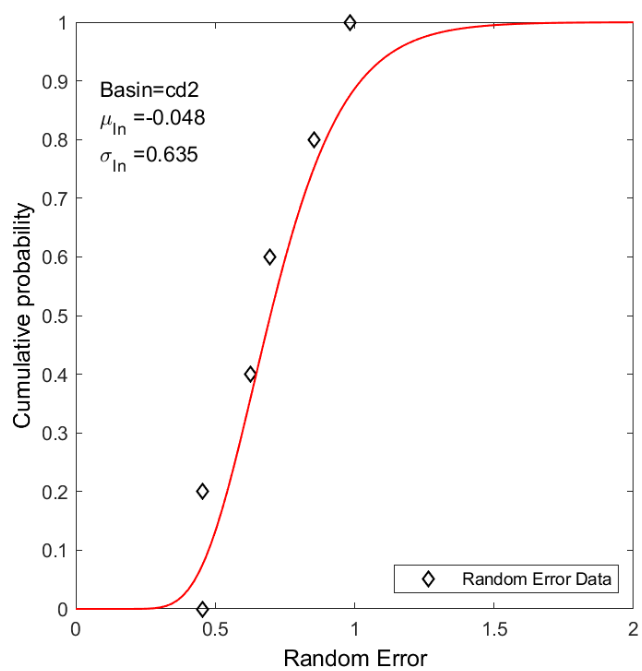


Figure F- 21: Lognormal distribution fit of random errors for ‘cd2’ basin

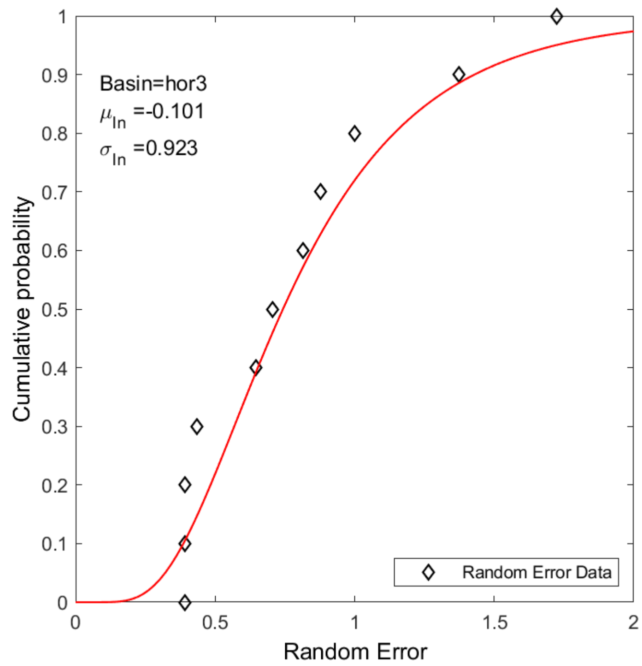


Figure F- 22: Lognormal distribution fit of random errors for ‘hor3’ basin

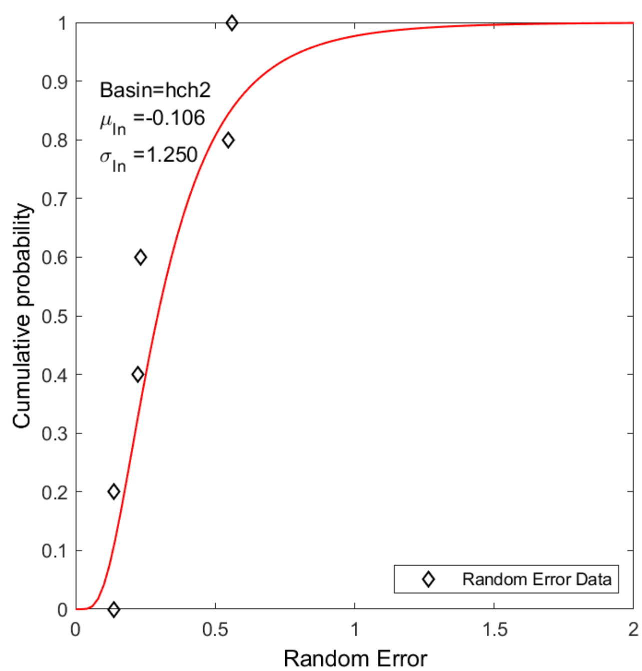


Figure F- 23: Lognormal distribution fit of random errors for ‘hch2’ basin

Appendix G

Visualization Toolbox Code

1. Tool to Create Surge and Wind footprints

```
# --------------------------------------------------------------------------
# create_surge_footprints.py
# Created on: 2019-01-15
#Last Updated on: 2019-02-08

# Written by Sami Mohammed

   # Tool Description:
#This tool plot the surge footprints to a fine resolution by using IDW method of
interpolation
#The aim of the tool is to help visualise the extent of the storm surge with respect to
NAVD88 for individual events

   ## Typical Inputs:
# An event file in csv format (Event_1.csv)
# Preprocessed polygon shape file for the same event (combination of 4 files-
Event_1.dbf, .prj, .shx, .shp)

   ## Expected outputs:
# Folders called as  sfinal(Event_ID)
# A GeoDatabase with the Rasters of surge footprints

   ## Requirements:
# ArcGIS Desktop 10.3 or Higher alongwith Spatial Analyst tool Licensed and enabled
# --------------------------------------------------------------------------

from tkinter import Tk, Label, Button, StringVar

class Viz_tool_gui:
   LABEL_TEXT = [" Starting the Visualization tool "]
   def __init__(self, master):
      self.master = master
      master.title("Viz Tool")


      self.label_index = 0
```

```
        self.label_text = StringVar()
        self.label_text.set(self.LABEL_TEXT[self.label_index])
        self.label = Label(master, textvariable=self.label_text)
        self.label.pack()

        self.surge_button = Button(master, text="Make Surge Footprint",
command=self.surge)
        self.surge_button.pack()

        self.wind_button = Button(master, text="Make Wind Footprint",
command=self.wind)
        self.wind_button.pack()

        self.combined_button = Button(master, text="Make Combined Footprints",
command=self.combined)
        self.combined_button.pack()

        self.close_button = Button(master, text="Quit", command=master.quit)
        self.close_button.pack()

    def surge(self):
        # Import arcpy and other required modules
        import time
        import arcpy
        import os
        from glob import glob
        import shutil
        print("-------- Starting the Surge Visualization Tool ------------")

        def validate_input(inp):
            try:
                inp = int(inp)
            except ValueError:
                print("Could not convert input to integer, try again")
                inp = None
            return inp

        start = time.time()

        # Overwiriting existing files if any
        arcpy.env.overwriteOutput = True

        # Setting up Working directory and Local variables:
        work_dir = os.getcwd()
```

```
    arcpy.env.workspace = work_dir

    number = None
    while number is None:
        number = raw_input("Enter Event ID")
        number = validate_input(number)

    if number == '':
        inp = glob('*.csv')
    else:
        inp = ["Event_"+str(number)+".csv"]

    print(inp)

    # Looping over all the events and performing same tasks for each of them
    for i in inp:
        eve = i.split('_')[1]
        print("-------- Event_ID ------------")
        print(eve)
        event_id = eve.split('.')[0]
        Extension = i.split('.')[1]

        arcpy.CheckOutExtension("spatial")
        Layer_1 = "Layer_1"

    # Making XY Event Layer
        arcpy.MakeXYEventLayer_management("Event_"+event_id + ".csv", "lon",
"lat",
Layer_1,GEOGCS['GCS_WGS_1984',DATUM['D_WGS_1984',SPHEROID['WGS_198
4',6378137.0,298.257223563]],PRIMEM['Greenwich',0.0],UNIT['Degree',0.0174532925
199433]];-400 -400 1000000000;-100000 10000;-100000 10000;8.98315284119522E-
09;0.001;0.001;IsHighPrecision", "")

        # Converting Feature Class to Feature Class

        arcpy.FeatureClassToFeatureClass_conversion(Layer_1, work_dir,
"eveid"+event_id, "", "event_id \"event_id\" true true false 4 Long 0 0
,First,#,Layer_13,event_id,-1,-1;lon \"lon\" true true false 8 Double 0 0
,First,#,Layer_13,lon,-1,-1;lat \"lat\" true true false 8 Double 0 0 ,First,#,Layer_13,lat,-1,-
1;wind_speed \"wind_speed\" true true false 4 Long 0 0 ,First,#,Layer_13,wind_speed,-
1,-1;storm_surge \"storm_surge\" true true false 8 Double 0 0
,First,#,Layer_13,storm_surge,-1,-1", "")

    # Interpolation of surge data to a surface using IDW -----
```

```
        arcpy.gp.Idw_sa( "eveid"+event_id+".shp", "storm_surg", "s_int"+event_id,
"0.001548", "2", "VARIABLE 12", "")

        idw_time = time.time()
        print("----------- Surge Interpolation time --------------")
        print(str(idw_time - start)+" "+"seconds")

        elevRaster_s = arcpy.sa.Raster('s_int'+event_id)
        extent_s = elevRaster_s.extent
        Envelope_s = "%f %f %f %f" %(extent_s.XMin, extent_s.YMin, extent_s.XMax,
extent_s.YMax)

    # Clip Surge to exact extent of the footprint

        arcpy.Clip_management("s_int"+event_id, "%f %f %f %f" %(extent_s.XMin,
extent_s.YMin, extent_s.XMax, extent_s.YMax), "sfinal"+event_id,
"Event_"+event_id+".shp", "0", "ClippingGeometry", "NO_MAINTAIN_EXTENT")

    # Returning the License back to the ArcGIS to be used for next time
        arcpy.CheckInExtension("spatial")

    # Creating a layer with the same color classifcation and scale

        arcpy.MakeRasterLayer_management(in_raster="sfinal"+event_id,
out_rasterlayer="MakeRas_sfinal"+event_id, where_clause="", envelope=Envelope_s,
band_index="")
        arcpy.SaveToLayerFile_management(in_layer="MakeRas_sfinal"+event_id,
out_layer="slayer"+event_id+".lyr", is_relative_path="RELATIVE",
version="CURRENT")

arcpy.ApplySymbologyFromLayer_management(in_layer="slayer"+event_id+".lyr",
in_symbology_layer="color_s.lyr")

        layer_time = time.time()
        print("----------- Layer creation time --------------")
        print(str(layer_time - idw_time)+" "+"seconds")

    ## Creating a KML file to view it in google earth
        arcpy.LayerToKML_conversion(layer="slayer"+event_id+".lyr",
out_kmz_file="s"+ event_id+"GE.kmz", layer_output_scale="0",
is_composite="NO_COMPOSITE", boundary_box_extent="DEFAULT", \
                              image_size="1024", dpi_of_client="96",
ignore_zvalue="ABSOLUTE")
```

```
    googleearthfile_time = time.time()
    print("----------- Google earth File creation time --------------")
    print(str(googleearthfile_time - layer_time)+" "+"seconds")

    for f in glob("eveid"+event_id+".*"):
        os.remove(f)

    for j in glob("s_int"+event_id+".*"):
        os.remove(j)

process_time = time.time()
print("------------------ Processing time -------------------")
print(str(process_time - start)+"seconds")

# Creating a Geodatabase to store the surge footprints
OutGDB = arcpy.CreateFileGDB_management(work_dir, "surge_footprints.gdb")

mySurgeList = arcpy.ListRasters("sfinal*", "")

newList = []
for x in mySurgeList:
     z1 = os.path.join(work_dir, x)
     newList.append(z1)

inList = (";".join([i for i in newList]))
arcpy.RasterToGeodatabase_conversion(inList, OutGDB)

try:
    os.mkdir("Google_Earth_files_surge")
    os.mkdir("ArcGIS_Layer_files_surge")
except OSError:
    # The directory already existed, nothing to do
    pass

src_fldr = work_dir
kmz_dst_fldr = work_dir+"\\Google_Earth_files_surge"
lyr_dst_fldr = work_dir+"\\ArcGIS_Layer_files_surge"


for kmz_file in glob(src_fldr+"\\*.kmz"):
    shutil.copy2(kmz_file, kmz_dst_fldr);

for lyr_file in glob(src_fldr+"\\s*.lyr"):
    shutil.copy2(lyr_file, lyr_dst_fldr)
```

```
    # Removing the intermediate files

    for j in glob("s*.lyr"):
        os.remove(j)

    for m in glob("s_int*"):
        shutil.rmtree(m, ignore_errors=True)

    for o in glob("info"):
        shutil.rmtree(o, ignore_errors=True)

    for p in glob("s*ge.kmz*"):
        os.remove(p)
        # Removing the intermediate files
    for g in glob("s*.lyr"):
        os.remove(g)

    gdb_time = time.time()
    print("--------------- Surge gdb creation time -------------")
    print(str(gdb_time - process_time)+" "+"seconds")

    end = time.time()
    print("--------------------- Final_time --------------------")
    print(str(end - start)+" "+"seconds")
    print("--------------------- Footprint is ready  --------------------")



def wind(self):
    # Import arcpy and other required modules
    import time
    import arcpy
    import os
    from glob import glob
    import shutil
    print("-------- Starting the Wind Footprint Visualization tool ------------")


    def validate_input(inp):
        try:
            inp = int(inp)
        except ValueError:
            print("Could not convert input to integer, try again")
```

```
        inp = None
    return inp

start = time.time()

# Overwiriting existing files if any
arcpy.env.overwriteOutput = True

# Setting up Working directory and Local variables:
work_dir = os.getcwd()
arcpy.env.workspace = work_dir

number = None
while number is None:
    number = raw_input("Enter Event ID")
    number = validate_input(number)

if number == '':
    inp = glob('*.csv')
else:
    inp = ["Event_"+str(number)+".csv"]

print(inp)

# Looping over all the events and performing same tasks for each of them
for i in inp:
    eve = i.split('_')[1]
    print("-------- Event_ID ------------")
    print(eve)
    event_id = eve.split('.')[0]
    Extension = i.split('.')[1]

    arcpy.CheckOutExtension("spatial")
    Layer_1 = "Layer_1"

# Making XY Event Layer
    arcpy.MakeXYEventLayer_management("Event_"+event_id + ".csv", "lon",
"lat",
Layer_1,"GEOGCS['GCS_WGS_1984',DATUM['D_WGS_1984',SPHEROID['WGS_19
84',6378137.0,298.257223563]],PRIMEM['Greenwich',0.0],UNIT['Degree',0.017453292
5199433]];-400 -400 1000000000;-100000 10000;-100000 10000;8.98315284119522E-
09;0.001;0.001;IsHighPrecision", "")

# Converting Feature Class to Feature Class
```

```
        arcpy.FeatureClassToFeatureClass_conversion(Layer_1, work_dir,
"eveid"+event_id, "", "event_id \"event_id\" true true false 4 Long 0 0
,First,#,Layer_13,event_id,-1,-1;lon \"lon\" true true false 8 Double 0 0
,First,#,Layer_13,lon,-1,-1;lat \"lat\" true true false 8 Double 0 0 ,First,#,Layer_13,lat,-1,-
1;wind_speed \"wind_speed\" true true false 4 Long 0 0 ,First,#,Layer_13,wind_speed,-
1,-1;storm_surge \"storm_surge\" true true false 8 Double 0 0
,First,#,Layer_13,storm_surge,-1,-1", "")

    # Interpolation of surge data to a surface using IDW -----
        arcpy.gp.Idw_sa( "eveid"+event_id+".shp", "wind_speed",
"w_int"+event_id,"0.001548", "2", "VARIABLE 12", "")

        idw_time = time.time()
        print("----------- Wind Interpolation time --------------")
        print(str(idw_time - start)+" "+"seconds")

        elevRaster_w = arcpy.sa.Raster('w_int'+event_id)
        extent_w = elevRaster_w.extent
        Envelope_w = "%f %f %f %f" %(extent_w.XMin, extent_w.YMin,
extent_w.XMax, extent_w.YMax)

    # Clip Surge to exact extent of the footprint
        arcpy.Clip_management("w_int"+event_id, "%f %f %f %f" %(extent_w.XMin,
extent_w.YMin, extent_w.XMax, extent_w.YMax), "wfinal"+event_id,
"Event_"+event_id+".shp", "0", "ClippingGeometry", "NO_MAINTAIN_EXTENT")

    # Returning the License back to the ArcGIS to be used for next time
        arcpy.CheckInExtension("spatial")

    # Creating a layer with the same color classifcation and scale

        arcpy.MakeRasterLayer_management(in_raster="wfinal"+event_id,
out_rasterlayer="MakeRas_wfinal"+event_id, where_clause="", envelope=Envelope_w,
band_index="")
        arcpy.SaveToLayerFile_management(in_layer="MakeRas_wfinal"+event_id,
out_layer="wlayer"+event_id+".lyr", is_relative_path="RELATIVE",
version="CURRENT")

arcpy.ApplySymbologyFromLayer_management(in_layer="wlayer"+event_id+".lyr",
in_symbology_layer="color_w.lyr")

        layer_time = time.time()
        print("----------- Layer creation time --------------")
        print(str(layer_time - idw_time)+" "+"seconds")
```

```
    ## Creating a KML file to view it in google earth
        arcpy.LayerToKML_conversion(layer="wlayer"+event_id+".lyr",
out_kmz_file="w"+ event_id+"GE.kmz", layer_output_scale="0",
is_composite="NO_COMPOSITE", boundary_box_extent="DEFAULT",
image_size="1024", dpi_of_client="96", ignore_zvalue="ABSOLUTE")

        googleearthfile_time = time.time()
        print("----------- Google earth File creation time --------------")
        print(str(googleearthfile_time - layer_time)+" "+"seconds")

        for f in glob("eveid"+event_id+".*"):
            os.remove(f)

        for j in glob("w_int"+event_id+".*"):
            os.remove(j)

    process_time = time.time()
    print("------------------ Processing time -------------------")
    print(str(process_time - start)+"seconds")

    # Creating a Geodatabase to store the surge footprints
    OutGDB = arcpy.CreateFileGDB_management(work_dir, "wind_footprints.gdb")

    myWindList = arcpy.ListRasters("wfinal*", "")

    newList = []
    for x in myWindList:
        z1 = os.path.join(work_dir, x)
        newList.append(z1)

    inList = (";".join([i for i in newList]))
    arcpy.RasterToGeodatabase_conversion(inList, OutGDB)

    try:
        os.mkdir("Google_Earth_files_wind")
        os.mkdir("ArcGIS_Layer_files_wind")
    except OSError:
        # The directory already existed, nothing to do
        pass

    src_fldr = work_dir
    kmz_dst_fldr = work_dir+"\\Google_Earth_files_wind"
    lyr_dst_fldr = work_dir+"\\ArcGIS_Layer_files_wind"
```

```
    for kmz_file in glob(src_fldr+"\\*.kmz"):
        shutil.copy2(kmz_file, kmz_dst_fldr);

    for lyr_file in glob(src_fldr+"\\w*.lyr"):
        shutil.copy2(lyr_file, lyr_dst_fldr)

    # Removing the intermediate files

    for j in glob("w*.lyr"):
        os.remove(j)

    for m in glob("w_int*"):
        shutil.rmtree(m, ignore_errors=True)

    for o in glob("info"):
        shutil.rmtree(o, ignore_errors=True)

    for p in glob("w*ge.kmz*"):
        os.remove(p)
        # Removing the intermediate files
    for g in glob("w*.lyr"):
        os.remove(g)

    gdb_time = time.time()
    print("--------------- Wind gdb creation time -------------")
    print(str(gdb_time - process_time)+" "+"seconds")

    end = time.time()
    print("--------------------- Final_time --------------------")
    print(str(end - start)+" "+"seconds")
    print("--------------------- Footprint is ready  --------------------")


def combined(self):
    # Import arcpy and other required modules
    import time
    import arcpy
    import os
    from glob import glob
    import shutil
    print("-------- Starting the Combined Footprint Visualization tool ------------")
```

```
def validate_input(inp):
    try:
        inp = int(inp)
    except ValueError:
        print("Could not convert input to integer, try again")
        inp = None
    return inp

start = time.time()

# Overwiriting existing files if any
arcpy.env.overwriteOutput = True

# Setting up Working directory and Local variables:
work_dir = os.getcwd()
arcpy.env.workspace = work_dir

number = None
while number is None:
    number = raw_input("Enter Event ID")
    number = validate_input(number)

if number == '':
    inp = glob('*.csv')
else:
    inp = ["Event_"+str(number)+".csv"]

print(inp)

# Looping over all the events and performing same tasks for each of them
for i in inp:
    eve = i.split('_')[1]
    print("-------- Event_ID ------------")
    print(eve)
    event_id = eve.split('.')[0]
    Extension = i.split('.')[1]

    arcpy.CheckOutExtension("spatial")
    Layer_1 = "Layer_1"

# Making XY Event Layer
    arcpy.MakeXYEventLayer_management("Event_"+event_id + ".csv", "lon",
"lat", Layer_1,
```

```
"GEOGCS['GCS_WGS_1984',DATUM['D_WGS_1984',SPHEROID['WGS_1984',6378
137.0,298.257223563]],PRIMEM['Greenwich',0.0],UNIT['Degree',0.0174532925199433
]];-400 -400 1000000000;-100000 10000;-100000 10000;8.98315284119522E-
09;0.001;0.001;IsHighPrecision", "")
    # Converting Feature Class to Feature Class
        arcpy.FeatureClassToFeatureClass_conversion(Layer_1, work_dir,
"eveid"+event_id, "", "event_id \"event_id\" true true false 4 Long 0 0
,First,#,Layer_13,event_id,-1,-1;lon \"lon\" true true false 8 Double 0 0
,First,#,Layer_13,lon,-1,-1;lat \"lat\" true true false 8 Double 0 0 ,First,#,Layer_13,lat,-1,-
1;wind_speed \"wind_speed\" true true false 4 Long 0 0 ,First,#,Layer_13,wind_speed,-
1,-1;storm_surge \"storm_surge\" true true false 8 Double 0 0
,First,#,Layer_13,storm_surge,-1,-1", "")

    # Interpolation of wind data to a surface using IDW ----- You can read more about
methods of interpolation on arcgis blog and choose a different one too.
        arcpy.gp.Idw_sa( "eveid"+event_id+".shp", "wind_speed", "w_int"+event_id,
"0.001548", "2", "VARIABLE 12", "")

        idw_time_wind = time.time()
        print("----------- Wind Interpolation time --------------")
        print(str(idw_time_wind - start)+" "+"seconds")

    # Interpolation of surge data to a surface using IDW -----
        arcpy.gp.Idw_sa( "eveid"+event_id+".shp", "storm_surg", "s_int"+event_id,
"0.001548", "2", "VARIABLE 12", "")
        idw_time_surge = time.time()
        print("----------- Surge Interpolation time in seconds --------------")
        print(str(idw_time_surge - idw_time_wind)+" "+"seconds")

    # Reading in raster file to get the extent/bounds of the Wind and Surge
        elevRaster_w = arcpy.sa.Raster('w_int'+event_id)
        extent_w = elevRaster_w.extent
        Envelope_w = "%f %f %f %f" %(extent_w.XMin, extent_w.YMin,
extent_w.XMax, extent_w.YMax)

        elevRaster_s = arcpy.sa.Raster('s_int'+event_id)
        extent_s = elevRaster_s.extent
        Envelope_s = "%f %f %f %f" %(extent_s.XMin, extent_s.YMin, extent_s.XMax,
extent_s.YMax)

    # Clip Wind to exact extent of the footprint
        arcpy.Clip_management("w_int"+event_id, Envelope_w, "wfinal"+event_id,
"Event_"+event_id+".shp", "0", "ClippingGeometry", "NO_MAINTAIN_EXTENT")
```

```
        # Clip Surge to exact extent of the footprint
            arcpy.Clip_management("s_int"+event_id, Envelope_s, "sfinal"+event_id,
"Event_"+event_id+".shp", "0", "ClippingGeometry", "NO_MAINTAIN_EXTENT")

        # Creating a layer with the same color classifcation and scale

            arcpy.MakeRasterLayer_management(in_raster="wfinal"+event_id,
out_rasterlayer="MakeRas_wfinal"+event_id, where_clause="", envelope=Envelope_w,
band_index="")
            arcpy.SaveToLayerFile_management(in_layer="MakeRas_wfinal"+event_id,
out_layer="wlayer"+event_id+".lyr", is_relative_path="RELATIVE",
version="CURRENT")

arcpy.ApplySymbologyFromLayer_management(in_layer="wlayer"+event_id+".lyr",
in_symbology_layer="color_w.lyr")

            wind_layer_time = time.time()
            print("-----------Wind Layer creation time --------------")
            print(str(wind_layer_time - idw_time_surge)+" "+"seconds")

        # Creating a layer with the same color classifcation and scale

            arcpy.MakeRasterLayer_management(in_raster="sfinal"+event_id,
out_rasterlayer="MakeRas_sfinal"+event_id, where_clause="", envelope=Envelope_s,
band_index="")
            arcpy.SaveToLayerFile_management(in_layer="MakeRas_sfinal"+event_id,
out_layer="slayer"+event_id+".lyr", is_relative_path="RELATIVE",
version="CURRENT")

arcpy.ApplySymbologyFromLayer_management(in_layer="slayer"+event_id+".lyr",
in_symbology_layer="color_s.lyr")

            surge_layer_time = time.time()
            print("----------- Surge Layer creation time --------------")
            print(str(surge_layer_time - wind_layer_time)+" "+"seconds")

        ## Creating a KML file to view it in google earth
            arcpy.LayerToKML_conversion(layer="wlayer"+event_id+".lyr",
out_kmz_file="w"+ event_id+"GE.kmz", layer_output_scale="0",
is_composite="NO_COMPOSITE",
boundary_box_extent="DEFAULT",image_size="1024", dpi_of_client="96",
ignore_zvalue="ABSOLUTE")

            googleearthfile_w_time = time.time()
```

```
    print("----------- Google earth files for wind --------------")
    print(str(googleearthfile_w_time - surge_layer_time)+" "+"seconds")

  ## Creating a KML file to view it in google earth
    arcpy.LayerToKML_conversion(layer="slayer"+event_id+".lyr",
out_kmz_file="s"+ event_id+"GE.kmz", layer_output_scale="0",
is_composite="NO_COMPOSITE", boundary_box_extent="DEFAULT",
image_size="1024", dpi_of_client="96", ignore_zvalue="ABSOLUTE")

    googleearthfile_s_time = time.time()
    print("----------- Google earth files for surge --------------")
    print(str(googleearthfile_s_time - googleearthfile_w_time)+" "+"seconds")


  # Removing the intermediate files
    for f in glob("eveid"+event_id+".*"):
      os.remove(f)

    for g in glob("w_int"+event_id+".*"):
      os.remove(g)

    for j in glob("s_int"+event_id+".*"):
      os.remove(j)

  # Returning the License back to the ArcGIS to be used for next time
  arcpy.CheckInExtension("spatial")


  process_time = time.time()
  print("------------------ Processing time -------------------")
  print(str(process_time - start)+" "+"seconds")

  OutGDB = arcpy.CreateFileGDB_management(work_dir, "footprints.gdb")

  mySurgeList = arcpy.ListRasters("sfinal*", "")
  myWindList = arcpy.ListRasters("wfinal*", "")

  newList = []
  for x in mySurgeList:
     z1 = os.path.join(work_dir, x)
     newList.append(z1)

  for y in myWindList:
     z2 = os.path.join(work_dir, y)
```

```
    newList.append(z2)

inList = (";".join([i for i in newList]))
arcpy.RasterToGeodatabase_conversion(inList, OutGDB)

# -------------------------------------------------------------------------------

try:
   os.mkdir("Google_Earth_files_wind")
   os.mkdir("ArcGIS_Layer_files_wind")
   os.mkdir("Google_Earth_files_surge")
   os.mkdir("ArcGIS_Layer_files_surge")
except OSError:
   # The directory already existed, nothing to do
   pass

src_fldr = work_dir
wkmz_dst_fldr = work_dir+"\\Google_Earth_files_wind"
wlyr_dst_fldr = work_dir+"\\ArcGIS_Layer_files_wind"
skmz_dst_fldr = work_dir+"\\Google_Earth_files_surge"
slyr_dst_fldr = work_dir+"\\ArcGIS_Layer_files_surge"


for wkmz_file in glob(src_fldr+"\\w*.kmz"):
   shutil.copy2(wkmz_file, wkmz_dst_fldr);

for wlyr_file in glob(src_fldr+"\\w*.lyr"):
   shutil.copy2(wlyr_file, wlyr_dst_fldr)

for skmz_file in glob(src_fldr+"\\s*.kmz"):
   shutil.copy2(skmz_file, skmz_dst_fldr);

for slyr_file in glob(src_fldr+"\\s*.lyr"):
   shutil.copy2(slyr_file, slyr_dst_fldr)


# Removing the intermediate files
for h in glob("w*.lyr"):
   os.remove(h)

for i in glob("w*ge.kmz*"):
   os.remove(i)

for j in glob("s*.lyr"):
```

```
            os.remove(j)

        for k in glob("wfinal*"):
            shutil.rmtree(k, ignore_errors=True)

        for l in glob("sfinal*"):
            shutil.rmtree(l, ignore_errors=True)

        for m in glob("s_int*"):
            shutil.rmtree(m, ignore_errors=True)

        for n in glob("w_int*"):
            shutil.rmtree(n, ignore_errors=True)

        for o in glob("info"):
            shutil.rmtree(o, ignore_errors=True)

        for p in glob("s*ge.kmz*"):
            os.remove(p)

        gdb_time = time.time()
        print("--------------- Combined gdb creation time -------------")
        print(str(gdb_time - process_time)+" "+"seconds")

        end = time.time()
        print("--------------------- Final_time --------------------")
        print(str(end - start)+" "+"seconds")

        print("---------------------Wind and Surge Footprints Are Ready  --------------------")

root = Tk()
my_gui = Viz_tool_gui(root)
root.mainloop()
```

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