P2.96 A SIMPLE COASTLINE STORM SURGE MODEL BASED ON PRE-RUN SLOSH OUTPUTS

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1. INTRODUCTION

Storm surge is an abnormal rise of sea level associated with the passage of hurricanes and other severe storms; the rising water often comes with violent force (Harris, 1963). As Hurricane Katrina struck the U.S. in 2005, its storm surge was over twenty feet (6 m) high along the coastline, decimated cities, killed more than a thousand people, and caused economic damage of approximately $40 billion, half of the total estimated hurricane loss (Knabb et al. 2006). To predict such powerful storm surges and to assess their risks, many mathematical models have been developed. They range from simple empirical models to sophisticated numerical ones.

Empirical surge models are relatively easy to develop and simple to apply but have limited capability and are no longer widely applied. They generally use empirical functions to relate peak surge height to the storm pressure deficit, which is the pressure difference between the storm center and its periphery. They tend to calculate only peak surges at the open coastline. Conner et al. (1957) developed an empirical equation to compute peak surge heights for landfalling hurricanes, using observed historical hurricane data and surge heights along open coasts. The equation was obtained as a linear regression to determine peak surge as a function of pressure deficit. Jelesnianski (1972) developed three nomograms from empirical data and theoretical calculations. These allow rapid estimation of peak surge heights. The first nomogram uses pressure deficit and radius to maximum wind to make the initial surge estimation. The other nomograms make corrections for shoaling effects and for direction and speed of storm motion. Hsu (2006) applied these nomograms to estimate the peak surge heights for the 2005 hurricanes Katrina and Rita. His results were in good agreement with observed values.

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Although empirical models can produce reliable estimates for peak surge heights at the open coast, they fail to produce accurate estimates for surge distribution along the coastline and for inland flooding because they are incapable of modeling the complex process of surge formation. Storm surge depends not only on wind speed, pressure deficit, size, translation speed, and moving direction of the storm, but also on coastal bathymetry, topography, barriers, waterways, astronomical tide, and other local geographical features at the landfall area (Harris, 1963). In contrast to empirical models, sophisticated numerical models have succeeded in producing accurate estimates for both coastline surge and for inland flooding. Numerical surge models use hydro-dynamical governing equations to represent the surge formation process and run on a grid system that includes most factors affecting storm surge. One typical such numerical model is the SLOSH model, developed by the National Weather Service (NWS). SLOSH stands for “Sea, Lake, and Overland Surges from Hurricanes” (Jelesnianski et al. 1992). As implied by the name, the SLOSH model computes inland flood triggered by storm surge. NWS has simulated thousands of hypothetical hurricanes using the SLOSH model and loaded the pre-run results into a package called SLOSH Display (FEMA et al. 2003).

Applications of numerical surge models such as SLOSH require intensive computation and extensive training for operational personnel. In many cases, however, simple models are desirable due to time and resource constraints. This paper presents a simple model for computing storm surge along hurricane-prone coastlines of the United States, which is a hybrid of empirical and numerical surge models. This model uses a parametric wind profile model to compute hurricane wind speeds along the coastline and a wind-surge function to derive surge heights. The wind-surge function is based on the pre-run SLOSH outputs by NWS. This model does not involve complex numerical computation but it uses the outputs of the numerical model. This simple coastline storm surge model will be hereafter referred to as the SCSSM model. The rest of this paper will describe in detail the development of the SCSSM model. Section 2 introduces the SLOSH model and its pre-run outputs, which are the basis of the SCSSM model. Section 3 describes the coastline wind profile model, the wind-surge function, and model verification. Section 4 discusses the accuracy and limitations of the SCSSM model. Section 5 summarizes the main features of the model.

2. SLOSH MODEL AND ITS PRE RUN OUTPUTS

This section describes the characteristics of SLOSH model and the SLOSH pre-run outputs in the SLOSH Display package.

2.1 SLOSH model

The SLOSH model employs a set of governing equations, derived from Newtonian fluid motion and continuity laws, to compute the dynamic changes of water level during the passage of a hurricane. It applies a two-dimensional finite difference scheme to solve the governing equations for a grid network comprising a basin. SLOSH uses 38 basins to cover the Gulf and Atlantic coast of the U.S.; Oahu, Hawaii; Puerto Rico; and the Virgin Islands. These basins are constantly updated or new basins are added as more accurate basin data become available (Glahn et al. 2009).

The grid system expresses basin physical characteristics such as inland topography, bathymetry of coastal area, configuration of coastline, and continental shelves. Channels, waterways, and significant natural and man-made barriers are included as sub-grid elements to increase accuracy. This grid system enables the SLOSH model to generate surge heights along the coastline, simulate inland flooding, compute routing of storm surge into bays, estuaries, or river basins, and allow the overtopping of barriers and flow through barrier gaps (Jelesnianski et al. 1992).

The SLOSH governing equations are driven by a parametric wind field model that requires only a few meteorological inputs. They are selected in a way to make it possible for them to be forecasted operationally so that SLOSH can be used for real-time surge forecasting (Jelesnianski et al. 1992). The input parameters include: (1) storm positions every 6 hours; (2) central pressure deficit; and (3) radius to maximum wind. The radius to maximum wind is defined as the distance between the storm center and the location where the maximum wind occurs. The six-hour storm positions implicitly include direction and speed of the storm motion. In addition, the initial water level is also required for surge height calculation.

The SLOSH model produces two types of outputs: surge profile and surge envelope. The surge profile is formed by surge heights at every grid location in a basin at a particular moment, which produces sequential snapshots. The envelope represents the highest surge level at every grid location during the passage of the hurricane regardless of occurring time. The maximum surge heights at coastline locations form the surge envelope along the coastline. Hereafter, surge height at a location will refer to the maximum surge height at that location during the passage of the storm.

SLOSH produces reasonably accurate estimates for maximum surge heights, as supported by many validation cases. Comparisons with historical hurricanes showed that the SLOSH model estimates were within ±20% of the observed values (Jelesnianski et al. 1992). Good agreement was also reported by Jarvinen and Lawrence (1985), who used SLOSH to compute surge heights for 10 historical hurricanes and compared them with 523 observed values.

2.2 SLOSH pre-run output package

NWS has used the SLOSH model to simulate thousands of hypothetical hurricanes at each basin along the Gulf and

East coasts of the United States, and distributed the results in the SLOSH Display package. The composite of SLOSH pre-outputs in this package is the basis for the development of the simple coastline surge model described in this paper.

The SLOSH Display program includes two SLOSH composites: (1) Maximum Envelope of Water (MEOW) elevation and (2) the Maximum of MEOW (MOM). A large number of MEOWs were generated in each basin and they are identified by the combination of hurricane category, landfall direction, translational speed, and initial tide level. Each MEOW is created with a group of parallel hurricanes, about 10 miles apart, of the same category, storm direction, translational speed, and initial tide level (Taylor, 2009; FEMA et al. 2003). The category ranges from 1 to 5, as defined by the Saffir-Simpson Scale (Simpson, 1974) using the minimum central pressure. Table 1 shows the central pressures for each category and corresponding pressure deficits by using peripheral pressure of 1010 mb (FEMA et al., 2006). Storm directions at landfall are selected from 16 directions with interval of 22.5^0, as shown in the lower left corner of Fig. 1. The coastline orientation actually determines the number of storm directions selected for MEOW generation in each basin. The selected translational speeds represent the climatological values and they are 5 or 10 mph apart depending on basin latitudes. In addition, each MEOW also specifies a tide level, high tide or mean tide. Overall, MEOW represents the highest surge value for the group of parallel hurricanes with the specified category, storm direction, translation speed, and initial tide level.

The number of MEOWs for a typical SLOSH basin can reach hundreds and the number of hypothetical hurricanes to generate them may attain thousands. For example, if three translational speeds, eight storm directions, and two tide levels are simulated for each of the five categories, the total number of MEOWs for the basin will be 240. If each MEOW is created with a group of 20 parallel hypothetical hurricanes, the number of hurricanes to produce these MEOWs will be 4800. Figure 1 shows a SLOSH MEOW image at Pensacola Bay, Florida, where surge levels are displayed by colors and the parallel lines with arrows indicate hurricane tracks and their directions.

Table 1. Central pressures and pressure deficit of simulated hurricanes for MEOW

Category	Actual Hurricane (mb)	Modeled Hurricane (mb)	Pressure Deficit (mb)
1	1010–980	990	Δp=20
2	979–965	970	Δp=40
3	964-945	950	Δp=60
4	944-920	930	Δp=80
5	<920	910	Δp=100

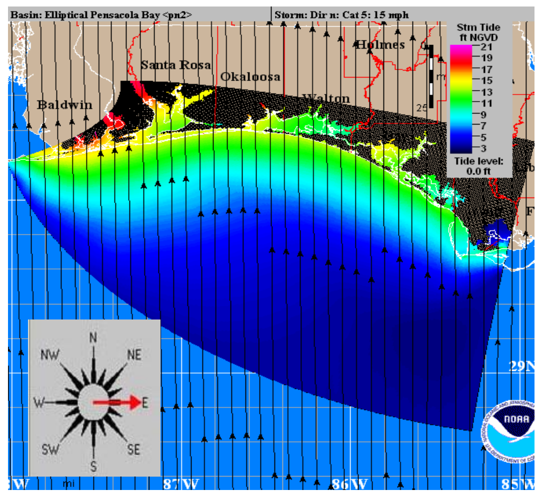

Figure 1. An image of SLOSH MEOW output at Pensacola Bay, Florida (Taylor, 2009)

3. MODEL DEVELOPMENT

The simple coastline surge model includes two major components: an empirical wind profile model for computing wind speeds along the coastline, and the coastline wind-surge function based on SLOSH MEOWs. This section describes these two components and the model verification.

3.1 Coastline wind profile model

The coastline wind profile model is a modification of the Kaplan-DeMaria (1995) empirical wind model for coastline locations. Wind speeds are calculated by

$$V = V_x\left(\frac{r}{r_{\max}}\right)\exp\left\{\frac{1}{\alpha}\left[1-\left(\frac{r}{r_{\max}}\right)^{\alpha}\right]\right\} \pm cs \quad r \geq r_{\max} \quad (1)$$

$$V = V_x \pm \left(\frac{r}{r_{\max}}\right)cs \quad r < r_{\max} \quad (2)$$

where $V_x = M_x - cs$ is the symmetric maximum wind, M_x is the maximum wind, *cs* is the translational speed, *V* is the wind speed at a location with a distance *r* from the storm track, r_{max} is the radius of maximum wind, and α is a profile parameter. The storm profile parameter determines how fast the wind speed decays as the distance from the storm track increases. The positive sign is for locations on the right of the hurricane track; the negative sign is for locations on the left. The wind field is symmetric if the translational speed *cs* is zero. The value of the translational speed determines the asymmetry of the wind field by placing stronger wind on the right.

3.2 Coastline wind-surge relationship

The coastline wind-surge function is designed to relate wind speed to the surge height at a coastline location by assuming that the surge height is a function of wind speed. This assumption seems to consider only the most important factor of the surge formation process—wind; but this function implicitly includes effects of storm direction, translational speed, initial tide level, and effects of important local geographical features such as bathymetry, topography, barriers, and waterways which are modeled in the SLOSH grids. To achieve this result, the wind-surge function is derived by a linear interpolation of the surge heights from SLOSH MEOWs. The details of the derivation are given below.

Let the wind-surge function have the following form,

$$G(X) = F_{H,X}(V, X) \quad (3)$$

In this equation, *X* represents the coordinates of a coastline location, latitude and longitude. *G(X)* is the surge height at the location *X*. The general function $F_{H,X}$ maps the wind speed *V* at location *X* to the surge height. The wind speed *V* can be computed using the wind profile model equations 1 and 2. The subscript *H* and *X* indicate that function $F_{H,X}$ is defined for a given hurricane (*H*) and for a given location (*X*). The function $F_{H,X}$ at a location changes for different hurricanes even if they may produce the same wind speed at the location. The function $F_{H,X}$ also changes at different locations for a given hurricane and the changes are due to the variation in wind speed at different locations. In other words, the function has to be defined for each location and for each hurricane. Therefore, the function reflects implicitly the parameters that define the hurricane and the local geographical conditions that define the location. So the wind-surge function is not just a function that simply relates the wind speed to surge height, but it include effects of local geographical features and hurricane parameters.

This function can be extremely complicated because, as explained before, surge heights are determined by many factors. However, SLOSH MEOWs provide an excellent opportunity for a simple method of linear interpolation to approximate the function. To approximate the function $F_{H,X}$ (*V,X*) for a hurricane at a coastline location, we choose the basin where the hurricane makes landfall, the MEOWs that have the storm direction and translational speed closest to those of the hurricane, and the initial tide level closest to the tide level at the time when the hurricane approaches the coastline. For the selected storm direction, translational speed, and initial tide, there are five MEOW surge heights at the location, one from each hurricane category. We assume that these five surge heights represent five samples of the wind-surge function expressed in equation 3. This is the fundamental assumption in the development of the simple coastline surge model.

The five samples constitute the basis for the linear interpolation to approximate the wind-surge function. If we let index *I* indicate the hurricane category, the five samples can be expressed as

$$G_I(X) = F_{H,X}(V_I, X) \quad I = 1,2,3,4,5 \qquad (4)$$

where $G_I(X)$ is the MEOW surge height of category I at the location X, V_I is the maximum wind speed of category I hurricane. The hurricane category is defined by the central pressure deficit as shown in Table 1. We use a pressure-wind relationship by Landsea et al. (2004) to compute the maximum wind speed from the pressure deficit,

$$V_I = 14.172(\Delta p_I)^{0.4778} \qquad (5)$$

where Δp_I is the pressure deficit used for SLOSH MEOW for category I in mb and V_I is 1-min surface sustained wind in kt. Using the five pairs of wind speed and surge height, we can easily build a piecewise linear function by interpolation to approximate the wind-surge function at the location. Fig. 2 shows an example of the linearly interpolated wind-surge function for a coast location using SLOSH MEOWs. The data points are the MEOW surge heights and wind speeds corresponding to the five hurricane categories. Extrapolations on both ends of the piecewise linear curve will be used to calculate surge heights for wind speeds which are lower than category 1 or higher than category 5.

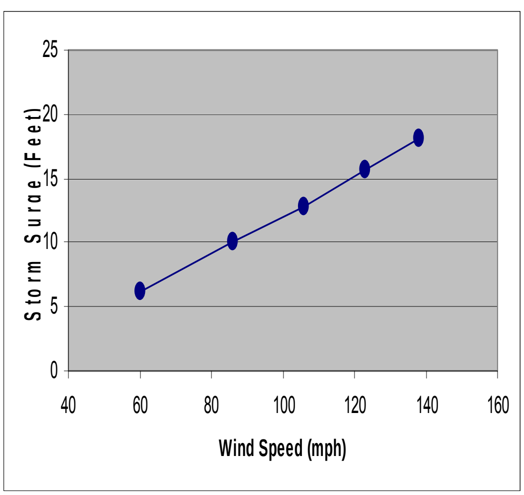

Figure 2. Piecewise linear wind-surge function for a location.

3.3 Model Verification

The model has been verified preliminarily with two hurricanes, 1989 Hugo and 1992 Andrew, in comparison with the SLOSH model. We selected these two hurricanes because their SLOSH surge estimates were included in the SLOSH program provided by NWS. At locations on the open coastline, the SCSSM consistently re-produced surge height estimates by the SLOSH model.

The SCSSM model requires hurricane parameters and SLOSH MEOWs identified by the parameters to compute surge heights along the open coastline. The computation includes five steps. First, determine the parameters that describe the hurricane at landfall. These parameters include the maximum wind speed, central pressure, storm direction, translational speed, and initial tide level. The maximum wind speed can be obtained by equation 5 using the pressure deficit. In this verification, we selected the same parameters for the two hurricanes as those used in the SLOSH program in order to have a consistent comparison. Second, identify SLOSH MEOWs for each hurricane category so that the storm direction, translational speed, and initial tide level associated with the MEOWs are closest to the parameters of the land-falling hurricane. Third, construct the wind-surge function by linear interpolation for the coastline locations of interest. Fourth, compute wind speeds at the locations using the wind profile model. Finally, use the piecewise linear wind-surge function at each location to obtain the estimated surge heights.

Figures 3 and 4 compare the SCSSM and the SLOSH model for surge height estimates along the open coastline for the two hurricanes. The data points in these figures represent surge heights at locations along the open coastline. More locations on the right side of the hurricanes track are selected than those on the left, because we are more interested in the high surge heights that tend to occur on the right side.

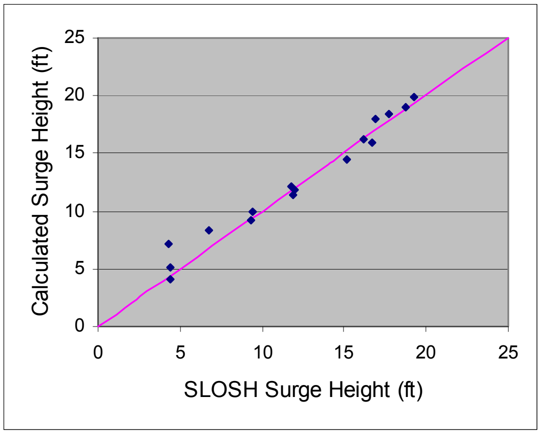

Figure 3. Comparison of surge heights by SLOSH and by the SCSSM for 1989 Hugo.

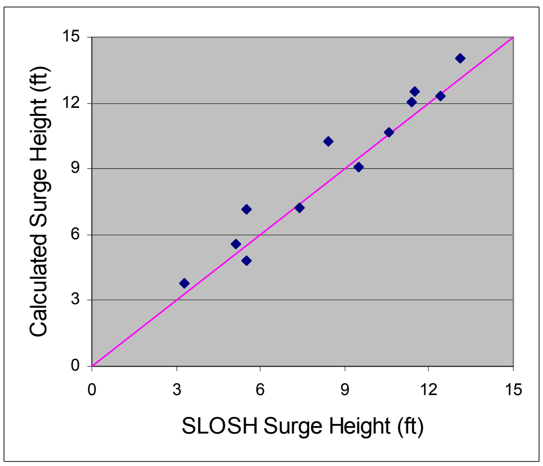

Figure 4. Comparison of surge heights by SLOSH and by the SCSSM for 1992 Andrew.

4. DISCUSSION

We have made many assumptions and approximations in the development of the SCSSM model to take advantages of the SLOSH MEOWs. These approximations introduce errors in the model and limitations to its applications. The model errors discussed here are relative to the SLOSH model instead of the observed surge values of actual hurricanes.

As the most important assumption, we assume that there is a wind-surge function relating wind speed to surge height at an open coastline location and that this function can be obtained by linearly interpolating the SLOSH MEOW values of five hurricane categories. There are several approximations in this assumption. First, we approximate the complex dynamic relationship between the surge height and hurricane wind by a simple function of wind speed. Although the function incorporates many factors considered by SLOSH MEOW, it does not fully account for the effects of some other important factors. For example, it does not consider the effect of hurricane size because SLOSH MEOWs were generated with the same radius to maximum winds. Hurricane size is generally represented by the radius to maximum wind in parametric wind field models. On the other hand, the general SLOSH model considers the effect of hurricane size by including the radius to maximum wind as an input parameter to its wind field model. Irish et al. (2008) showed that hurricane size has a strong influence on surge height. Secondly, the selected SLOSH MEOWs cannot have the exact same storm direction, translational speed, and initial tide level as those of the hurricane of interest. The samples derived from these SLOSH MEOWs are not the true samples of the wind-surge function for the hurricane but we used them as the true samples. Thirdly, we approximate the wind-surge function by a linear interpolation even though the relationship between surge and wind speed is highly non-linear (Irish et al. 2008). However, the model verification shows that even with these approximations the model still performs well relative to the SLOSH estimates.

The SCSSM model has its limitations in addition to those of the SLOSH model and the SLOSH Display package. The model was developed only for surge estimation along open coastline. It does not compute water elevations for inland flooding. It cannot compute the surge time series, either. Since it was developed with the SLOSH Display package, the model covers only regions that the package includes. In addition, the model was developed for landfalling hurricanes, not for by-passing hurricanes and coastal winter storms like Nor’easters. Because of these limitations, the SCSSM model cannot replace powerful numerical models for applications involving estimation of inland flooding.

The SCSSM model, however, has its own advantages: simple to understand, easy to use, and efficient to apply. It can be used to make quick and approximate predictions of surge distribution along a coastline for a hurricane approaching landfall. It can be applied to effectively and efficiently assess coastal surge risks involving computations for tens of thousands of synthetic hurricanes. The model provides an alternative for applications where simple empirical models fail to meet the needs and where the use of complex numerical models is restricted by time and resource constraints.

5. CONCLUSIONS

A simple coastline storm surge model (SCSSM) has been developed to make estimates of surge heights in hurricane-prone sections of the coastline of the United States. The model uses an empirical wind profile model to compute wind speeds at coastline locations and derives surge estimates by relating the wind speeds to surge heights through wind-surge functions. For every coastline location where the surge height is estimated, a wind-surge function is obtained by linearly interpolating the surge values of SLOSH MEOWs at the location. These SLOSH MEOWs are composites of pre-run SLOSH surge estimates contained in the SLOSH Display package produced by the National Weather Service. The SCSSM model is basically a combination of empirical and numerical models.

This combination enables the SCSSM model to be applied as an alternative between the traditional empirical models and the sophisticated numerical models. SCSSM enhances traditional empirical models by a unique way of taking advantage of the results from a complex numerical model. It expands the capability of traditional empirical models with increased accuracy. Its efficiency and effectiveness make it a useful tool for assessing the storm surge risk involving computation of tens of thousands of synthetic hurricanes.

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