

# GEOVISUALIZATION FOR STORM SURGE RISK COMMUNICATION

Thomas R. Allen<sup>a</sup> and Stephen Sanchagrin<sup>b</sup>

<sup>a</sup> Department of Geography, East Carolina University, Greenville, NC 27858 allenth@ecu.edu

<sup>b</sup> Renaissance Computing Institute (RENCI), East Carolina University, Greenville, NC 27858 sanchagrins@ecu.edu

**KEY WORDS:** hurricane, geovisualization, cartography, digital globes, storm surge, downscaling

## ABSTRACT:

With North Carolina being one of the most at risk states in North America for both direct and indirect hurricane strikes it is important that decision makers and the public have the best possible accurate and appropriate information. Emergency managers have expressed interest in new visualization techniques of storm surge in the hopes to better communicate risks and encourage compliance with evacuation of the general public. Two storm surge models, SLOSH (Sea, Lake and Overland Surge from Hurricanes) and ADCIRC (ADvanced CIRCulation), are evaluated for potential to visualize storm surges for risk communication. This project also critically investigates the appropriateness and tradeoffs for spatial characterization within GIS, data models, and data structures. Issues with both models such as grid resolution, temporal resolution, generalization, and storage volumes will be discussed, with emphasis on visualizing in GIS. The future of storm surge visualization will be examined with experimental examples of 3D-storm surge maps, animations, and online applications.

## 1. INTRODUCTION

### 1.1 Hurricane Storm Surge Visualization

Visualizations of forecast storm surges in place-based context are envisioned as an improvement of both risk awareness and communicating impending hazards in emergency situations such as a hurricane evacuation. A continuum of potential visualizations may range from static maps to animated model output to immersive, interactive media. In addition to risk communication for the public, immersive, high-resolution geovisualizations that might allow managers to investigate and explore forecasted surges could reveal threats and improve preparedness and response. Three-dimensional space-time dynamics and computational geovisualization for scientific insights and practical applications alike (Smith et al. 2000; Yuan and Hornsby 2008.) Scientific and visual analytic applications, for example, might include representations of model uncertainty or instability, such as “quality flags” symbolized on the model mesh or grid. Geovisualization encourages analysis for multiple purposes and users, for interpreting spatial patterns, and using new multimedia and communications in a broader informed way among academia, government, and stakeholders (Slocum et al. 2009.) Hence, the challenge is to develop accessible technology that will have proven and robust improvements for risk awareness and communication.

### 1.2 Purpose

This purpose of this project is to critically evaluate existing storm surge models (SLOSH and ADCIRC) in order to identify constraints on their application for risk communication and to explore potential geovisualization. To accomplish this, we address the physical and computational limitations of models, inhibiting factors for spatial representation, and GIS post-processing and cartographic communication. Next, geovisualizations that improve or eclipse the limitations inherent in the status quo approaches to representing model output are

developed and demonstrated, including enhanced resolution (down-scaled) grid output, enforcement of hydrologic connectivity in spatial models of inundation, and web-based, interactive cartography (with and without 3D terrain and contextual representation.)

### 1.3 Storm Surge Models

Storm surge models are often developed by coastal modelers with secondary consideration given to visualization or integration into GIS and other decision-support systems. There are many advantages of taking model output and incorporating into such a system. Various other data layers such as evacuation routes, critical infrastructure, and vulnerable populations can be analyzed in conjunction with this model output.

The SLOSH model is the model most emergency managers use in evacuation decision-making, as well as post landfall for information regarding areas of extent of inundation impacts and timely disaster response (Houston and Powell 1994). The model output is particularly coarse, and provides little assistance in hurricane mitigation. A model has been created to downscale the resolution of the SLOSH output, and to provide a more accurate estimation of inundation. The downscaling of the SLOSH output will be conducted utilizing a variety of input elevation layers to illustrate the flexibility of the model. The downscaled SLOSH output will then be compared against the other currently available SLOSH data products, produce by the NCCGIA, to determine the difference in inundation for a slow moving category 3 storm. Once the difference in inundation area is calculated, a comparison to the NCCGIA data will be completed to determine if there are any discrepancies of critical infrastructure, roads, and at risk populations affected.

The SLOSH model was originally developed by the Techniques Development Laboratory of the National Weather Service (NWS) as a real-time operational surge forecast that could be run once the appropriate tropical cyclone track and pressure data was available.

The networks of grid points comprising model domains are called SLOSH basins, and have been created for the Atlantic coast, Gulf Coast, Bahamas, Virgin Islands, Puerto Rico, as well as for parts of China and India. Each grid cell in a SLOSH basin has topographic or bathymetric data associated with it. Updates are released as new elevation and bathymetry data for particular basins are provided by the U.S. Geological Survey (USGS) and the National Geophysical Data Center (NGDC). When discussing SLOSH basins it is important to understand that not all SLOSH basins are identical. Depending on the size and location of the particular area of interest one might use a variety of different telescoping grids. The telescoping grid allows for higher detail or resolution in coastal areas and less detail in the open ocean. This reduces computing requirements as compared to structured grids with uniform cells across a model domain.

To obtain the surge levels, the SLOSH model requires a variety of fairly simple meteorological parameters, at specific time intervals. The calculations utilize the latitude and longitude of the storms eye, central atmospheric pressure, the radius of the maximum winds ( $R_{MW}$ ), as well as storm track and speed (Jelensnianski et al. 1992). Colle (2008) notes that surface wind speed is not an input parameter in the SLOSH model calculations, but rather “water levels are forced by an idealized wind field that depends upon the pressure deficit ( $\Delta p$ ) and the radius of maximum wind ( $R_{MW}$ ) from the storm center” (Houston and Powell 1994). Houston and Powell also note that the calculations consider topography and bathymetry, but not astronomical tides, waves or rainfall flooding.

With every model, whether a forecast model or numerical model, there is always going to be some level of inaccuracies or assumptions made. Different models are designed to operate and handle these inaccuracies and assumptions in different ways depending on the end product and the end user. SLOSH is no exception to this generalization, and has its own series of issues and limitations. One issue to be addressed is that of grid type and basin formation. While the telescoping grids are efficient in regard to computational resources, they can fall short when used to model inundation and surge. For example, if the area of interest is a section of hurricane prone Dare County, North Carolina, the size of the cell size is much too coarse to give any sort of accurate prediction of surge. This is due to its distance from the central arc of the grid origin. Figure 1. Illustrates how the cell size increases with the distance for an area of the Pamlico Sound SLOSH basin.

### 1.3 Surge Visualization for Coastal Emergency Management

Coastal emergency managers have begun using visualizations within graphical programs such as *CanVis* (Gold-Kruecke 2007) to portray ground-level inundation from floods and surges. Technologies such as webmap services and GIS portals are now ubiquitous and able to distribute storm surge model such as ADCIRC output and related maps and animations arising from real-time forecasting (Mattocks and Forbes 2008). The Louisiana Geographic Information Center’s 2009 Hurricane Response Mapping portal is one example that links the National Hurricane Center products with locally-developed mapservers (<http://lagic.lsu.edu/hurricanes/>), while the NC Coastal Hazards Portal (NC COHAZ) (<http://www.coastal.geology.ecu.edu/NCCOHAZ>) is an experimental platform that integrates multihazard layers in

separate thematic map interfaces (e.g., coastal erosion, surges, and real-time hazards.) In addition, many local emergency managers have GIS resources and personnel at their disposal who can employ the GIS products from NHC, including SLOSH. In some instances, they may already be using GIS software in operations, such as FEMA HAZUS for loss estimation (Pine et al. 2005.) SLOSH Maximum Envelope of Water (MEOW) and Maximum of Maximum (MOM) of MEOW files are provided with the SLOSH Display System and are able to be readily exported to ESRI shapefile format. The SLOSH Display System provides access to the library of pre-run simulations, including a GUI to query and extract appropriate MEOW or MOM files. The system can be used as a stand-alone decision support tool or in conjunction with other hazard software (HAZUS, Hurrevac, Hurtrack, or within a GIS.)

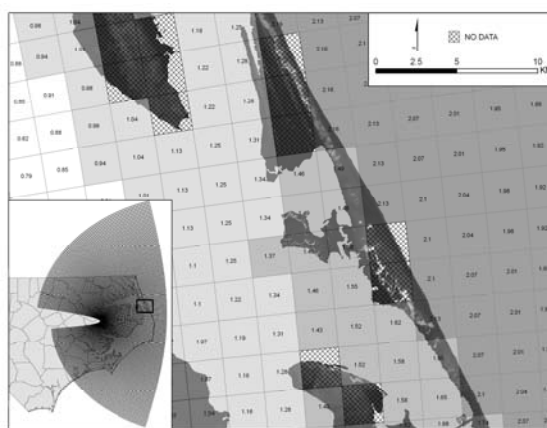


Figure 1. Pamlico basin SLOSH grid (inset) and a portion of the northern Outer Banks, illustrating telescoping grid scale, overlapping sound and ocean cells.

To obtain the surge levels, the SLOSH model requires a variety of fairly simple meteorological parameters, at specific time intervals. The calculations utilize the latitude and longitude storms eye, central atmospheric pressure, the radius of the maximum winds ( $R_{MW}$ ), as well as storm track and speed (Jelenskii et, al 1986). Colle (2008) notes that surface wind speed is not an input parameter in the SLOSH model calculations, but rather “water levels are forced by an idealized wind field that depends upon the pressure deficit and the radius of maximum wind ( $R_{MW}$ ) from the storm center”(Houston and Powell 1994). The calculations consider topography and bathymetry but not astronomical tides, waves or flooding.

### 1.4 Issues and Limitations

With every model, whether a forecast model or numerical model, there is always going to be some level of inaccuracies or assumptions made. Different models are designed to operate and handle these inaccuracies and assumptions in different ways depending on the end product and the end user. SLOSH is no exception to this generalization, and has its own series of issues and limitations. The limitations discussed are issues with grid type/basin formation, and environmental parameters.

### **Grid Spatial Resolution**

The first issue to be addressed is that of grid type and basin formation. While the telescoping grids are suited to limited computational resources for running the model, they can fall short when used to visualize surge inundation. For example, if the area of interest is a section of Dare County, North Carolina, a highly hurricane prone area, the size of the cell size is much too coarse for a site-specific visualization of surge, primarily owing to increasing cell size with distance from the central arc of the grid origin. This poses a limitation for an emergency manager who is using the SLOSH output to identify problem areas, or susceptible impacts and evacuation. Later, we evaluate a method to down-scale and visualize these sensitivities.

### **Processes and Forecast Storm Tracks**

The limitations of the model remain a concern, particularly the need to simultaneously account for wave heights and astronomical tides and riverine water level forcings that are not included in the model. Nonetheless, a set of MEOW grids are derived from hundreds of scenarios of storm tracks (varying direction of landfall), as well as varying forward speeds and tides (mean and high). Forward speed scenarios predict surges in scenarios of 5, 10, or 15 mph, an improvement over earlier "slow" (<18mph) and "fast" (>18mph) speeds. Overall planning further benefits from the simpler derivation of MOMs files, which characterize the maximum of MEOWs and provide a consistent worst case picture of storm surges possible for given intensities (Saffir-Simpson category 1-2, 3, and 4-5), notwithstanding limitations still remaining on antecedent riverine precipitation input, astronomical tides and waves.

Physical processes are incompletely represented in SLOSH, while temporal applications require use of pre-run models for 'worst case' estimates or reliance on single-run deterministic track runs (dependent and highly sensitive to track or intensity forecast errors.) Thus, while SLOSH remains the National Weather Service's *de facto* standard, it is also commonly interpreted in conjunction with forecasts from ADCIRC based on deterministic runs within ca. 24 hours of a landfall. The limitations of the model remain a concern, particularly the need to simultaneously account for wave heights and astronomical tides and riverine water level forcing that are not included in the model. Nonetheless, a set of Maximum Envelopes of Water (MEOWs) grids are derived from hundreds of scenarios of storm tracks (varying direction of landfall), as well as varying forward speeds and tides (mean and high). Forward speed scenarios predict surges in scenarios of 5, 10, or 15 mph, an improvement over earlier "slow" (<18mph) and "fast" (>18mph) speeds. Overall planning further benefits from the simpler derivation of Maximum of Maximums (MOMs) files, which characterize the maximum of MEOWs and provide a consistent worst case picture of storm surges possible for given intensities (Saffir-Simpson category 1-2, 3, and 4-5), notwithstanding limitations still remaining on antecedent riverine precipitation input, astronomical tides and waves. SLOSH MEOW and MOM files are provided with the SLOSH Display System and are able to be readily exported to ESRI shapefile format. The Display System provides access to the library of pre-run simulations, including a GUI to query and extract appropriate MEOW or MOM files. The system can be used as a stand-alone decision support tool or in

conjunction with other hazard software (HAZUS, Hurrevac, Hurtrack, or GIS, for instance.)

### **Currency and Near-Real-time Utility**

Another limitation of the SLOSH output is the lack of real-time wind field predictions or measurements. The wind models used by SLOSH can vary greatly from the storm's actual wind field in time, space, and magnitude. This was the case for hurricane Emily in 1993 when the eye wall crossed eastern Pamlico Sound in North Carolina causing very strong surface winds, and as a result the SLOSH model "...significantly underestimated the surface winds and resulting storm surge observed on the Pamlico Sound side of Cape Hatteras"(Houston et al. 1999). In other comparisons of the SLOSH model wind fields with observed winds, Houston and Powell (1996) concluded that the use of the NOAA Hurricane Research Division's real-time wind field data could be used to improve upon the SLOSH model's estimated values.

### **Surge Height, Inundation, and Uncertainty**

The accuracy of SLOSH is limited. Surge heights are represented by a rule-of-thumb of +/- 20% accuracy of predicted maximum surge height. For instance, a prediction of 15 feet surge would really produce a range prediction of 12-8 feet. Since SLOSH data computes storm tide elevations in National Geodetic Vertical Datum 1929, it is at least cumbersome to recomputed values to match extensive LiDAR DEMs in vertical meters and North American Vertical Datum 1988 (feet or meters.) By design, SLOSH does not incorporate fine-scale geomorphic features and potential inundation thresholds, such as the breaching of inlets in barrier islands, dunes, or engineered features such as levees.) The grid resolution of SLOSH is variable but is relatively coarse, with most cells on the order of 1 mile x 1 mile. Elevations for grid cells are based the averages of underlying DEMs, such that the actual cell may have non-normal distribution of elevation. Levee areas or areas protected by natural ridges may result in confusing generalization. Furthermore, flooding in SLOSH cells is considered aspatially, wherein each cell is flooded as if it were inundated irrespective of direction of flooding.

To assess the impacts of errors in elevation models as it relates to the downscaling model, a Monte Carlo simulation was utilized. The primary goal of the downscaling model is to predict the area of inundation by utilizing the SLOSH model output and a DEM. Liu notes that the degree of positional error is related to the uncertainty in vertical and horizontal measurements in addition to issues surrounding datum conversion, projections, and interpolation methods. Lui later notes however that due to the dense sampling of LiDAR points, projection and interpolation errors are negligible (Lui 2007). The 2008 NOAA IOCM data used provided a horizontal accuracy of +/- 2.0m and a vertical accuracy of +/-0.30m. These errors may cause the position of the inundation zone to fluctuate either landward or seaward. Lui continues by noting that "the error inflation factor is determined by the foreshore slope. For each beach with a gentle surface slope, a slight vertical error will be amplified and translated to a larger error" (Lui 2007.) This larger spatial error could result in poor decision making the face of an extreme coastal event.

## 2. METHODS

This project uses SLOSH and NC LiDAR elevation data. The SLOSH data are obtained from two sources, the SLOSH Display Package distributed by NOAA NHC and the downscaled NC Center for Geographic Information and Analysis (NCCGIA) data from NC OneMap online GIS repository. The SLOSH data from NOAA is used in the downscaling model, and represents the Maximum of the Maximum Envelope of Water (MEOW) or MOM. The SLOSH MOM data is a “worst case” scenario, in which multiple hurricane tracks are used, with landfall occurring from multiple directions, for a given storm category and speed (Jelenianski 2007). Elevation data was obtained from the North Carolina Flood Plain Mapping program, in a variety of spatial resolutions (NC Floodplain Mapping Program uses 50ft, 20ft, and 10ft. resampled elevation grids.)

### Spatial Analysis and Downscaling

Spatial methods applied include a combination of vector and raster based analysis, as well as automation utilizing ArcGIS Model builder. The downscaling model has the flexibility of incorporating a user defined elevation grid, allowing future iterations of the model to estimate inundation as new data becomes available. This is a substantial improvement over the historical method of producing downscaled inundation maps, which were frequently created by hand digitizing USGS topographic maps. The model also allows for the input of deterministic SLOSH model output from the NHC in the event of an actual storm, giving emergency managers a more accurate prediction for area inundation, and as a result the affected populations and evacuations routes.

The vast majority of inundation models to date allow for interior sections of land to flood as the water levels rise, that in reality have no connection to a water source (sound or ocean), also known as hydro-connectivity. This method is typically referred to as the “bathtub model”, and provides inaccurate assumptions. Hydro-connectivity is established in the model by utilizing a cost distance function, with inundation *only* allowed from a source raster of water locations (i.e., sound or ocean), a rule that improves results over a single pixel or contour-based bathtub inundation.

The output from that model is currently a raster data. Once the downscaling has been completed map algebra calculations will be used to compare difference in inundation between the three elevation resolutions, and ultimately compared to a rasterized NCCGIA data. The analysis will be conducted for Dare County, North Carolina, with emphasis placed on Roanoke Island and the city of Nags Head.

### Geovisualizations

In addition to official updates from the NWS other groups have worked with model output in an effort to refine the resolution for better visualization, and more accurate representation of inundation. South of Kitty Hawk North Carolina for example the cell size is not always appropriate for the visualization. It was seen in Figure 1. how an entire SLOSH cell may cover portion of the barrier island, and for this particular example (SLOSH category 2, fast-moving MOM) that stretch of barrier island would be inundated with between 1-2 meters of water.

The NCCGIA inundation SLOSH inundation polygons are aggregated using then available 1:24,000 USGS topographic maps (ca. 5ft. interval). Areal interpolation was used to create an overlay to delimit inundation according to lumped categories 1 and 2, category 3, and categories 4 and 5 hurricanes. The result was a polygon file which shows relatively fine detail of inundation as in Figure 2. However, these elevation data have been vastly eclipsed by LiDAR bare earth models with 15cm vertical accuracy and 10 to 20 m spatial resolution.

### Monte Carlo Error Modeling

The procedure used in the assessment of accuracy errors in the prediction of inundation area was very similar to those used by Lui. First the level of error and uncertainty of the source elevation model were determined. Then utilizing a pseudo-random number generator and the bound of potential error determined earlier 30 random permutations were created. All 30 of these permutations had similar statistics as far as their mean and standard deviations and were therefore within the realm of possible error. The inundation model was then run on each of the 30 permutations and their differences noted.

## 3. RESULTS

To exploit the availability of LiDAR DEMs, the model we implemented accepts either the raw MEOW/MOM data or deterministic runs as they become available and output similar results. The advantage of this dataset is the added option of including new high accuracy LIDAR DEM's as they become available and the biggest advantage of utilizing the deterministic runs as they are made available by the NWS. The model utilizes the SLOSH, LiDAR DEMs, and water raster as inputs, and computes a Cost Distance function with enforced hydro-connectivity to sound or ocean flooding source. The inundation can only originate from open water sources and eliminates the existence of non-connected inundation polygons associated with “bathtub” models. Model output from three different elevation grids (50ft, 20ft, and 10ft resolution) generated similar results. These inundation grids were overlaid with the NCCGIA interpolated contour-based approach. Results from the 20ft downscaled inundation model versus the NCCGIA method are shown in Figure 2, illustrating where the NCCGIA surge expects inundation extent on Roanoke Island relative to data indicated in LiDAR DEMs. There are areas on the barrier island in Nags Head shown in blue that indicate probable flooding in the LiDAR data that are not indicated in the interpolated NCCGIA polygons. Areas of agreement on inundation in this category 2 MOM scenario are shown in purple.

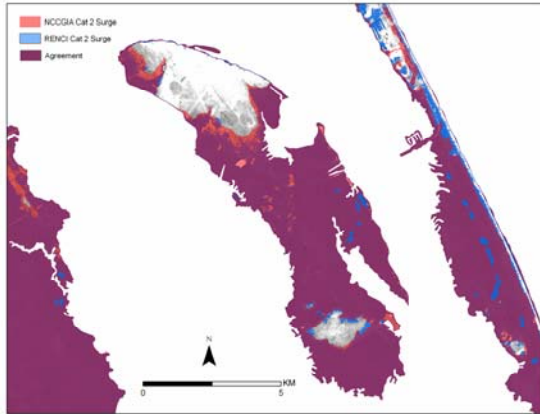


Figure 2. Comparison of NCCGIA inundation versus downscaled SLOSH MOM for LiDAR DEMs.

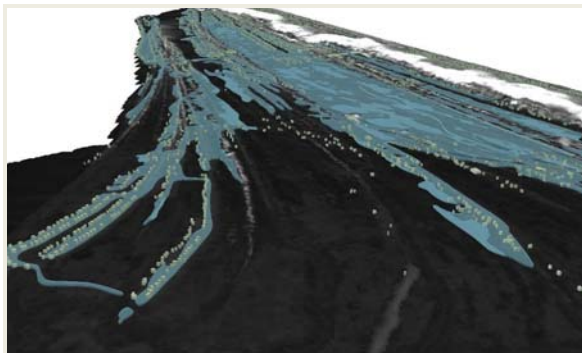


Figure 3. Visualization of a SLOSH MOM for category 1-2 storm in Kitty Hawk, NC, using NCCGIA polygon inundation and extruded county building footprints.

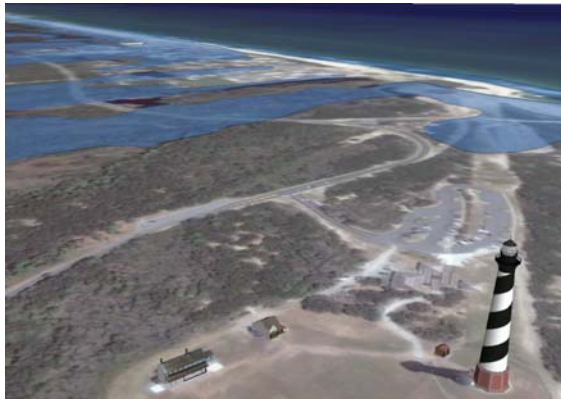


Figure 4. 3D storm surge visualization in GoogleEarth using downscaled SLOSH MOM (category 3, fast-moving) and building models developed in-house and streaming from the Google 3D warehouse.

Our visualization of the resulting downscaled SLOSH MOMs with LiDAR DEMs are also illustrated for a site at Cape Hatteras, NC (Figure 4.) This area depicts our combination of GoogleEarth image and terrain data with Google Sketchup 3D Community Warehouse (lighthouse) and our custom 3D building models. The sample graphic is drawn from a library of static images,

animations, and interactive KML files available on a prototype website for public risk awareness, the SurgeVis site (<http://nccohaz.ecu.edu/stormvis/index.html>).

Error in the LiDAR DEM could result in marged differences in predicted inundation. Over most of the tested area on Roanoke Island, there is marginal spatial variation in the inundation area. However, some unusual patterns are evident where there is likely an underlying representation limit. In low-relief coastal plain landscapes and barrier islands, features such as salt marshes, shrub and maritime forests, canals and drainage ditches, and narrow features such as dune crests may ultimately restrict the accuracy of inundation. In our study area one area present a drastically different inundation zonation in the simulation.

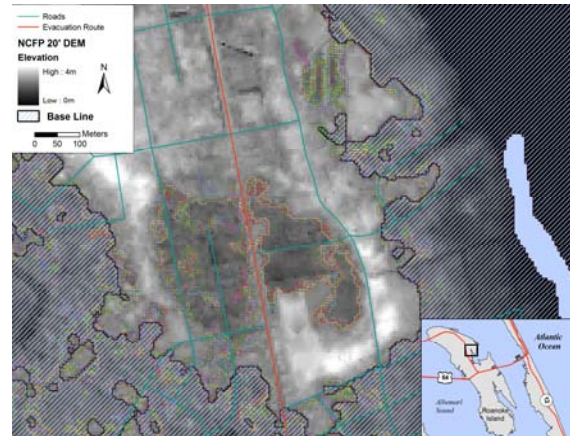


Figure 5. Simulated surge inundations using a Monte Carlo approach to error and iterative downscaling of SLOSH MOMs for a category 2 fast-moving storm, Roanoke Island, NC. Individual simulations are shown as different colors, with isolated extensive areas of the center being inundated under only a few cases, arising from uncertainty in the lower portion of the DEM.

#### 4. CONCLUSION

As presented in the agreement table there are certainly discrepancies in inundation zones. This could possibly lead emergency managers to make decisions based upon potentially inaccurate data. Future accuracy assessments need to be made for the downscaled inundation models to ensure accurate representation of the extent of flooding. Even though the area of inundation between the two models is close to 95% three main advantages of the more recent GIS based model have been identified, all relating to model flexibility.

In the event of an actual hurricane landfall the SLOSH deterministic runs could be input to the model resulting in a more accurate representation, rather than inundation zones based off the SLSOH MOM output. This is a clear advantage over a static map, that only predicts a “worst case” scenario, and would allow the emergency managers to actually pinpoint key areas and infrastructure that would be effected for a given storm and track. Another advantage of the GIS based model is the ability to incorporate additional elevation data as it becomes available. Currently, elevation models do not typically incorporate features



such as ditches and water management canals that can greatly alter inundation zones.

The last advantage is the ability for the model to ingest a variety of inundation model output. Experimental runs are currently being conducted utilizing output from the Advanced CIRCulation (ADCIRC) model. The ADCIRC model offers a variety of improvements over the SLOSH model, but still has some of the same key issues with regards to visualization.

In conclusion the downscaling GIS SLOSH model produces results similar to previous contouring and manual digitizing techniques. Although a preliminary Monte Carlo analysis of variability of inundation using introduced error suggests broad fidelity of inundation zones, there are selected areas of moderately high uncertainty. More work is needed to assess the accuracy of these downscaling models using actual storm data. Nonetheless, the GIS model offers many advantages, primarily in model flexibility with inputs and cartography. With further work, emergency managers and the public will have improved information at hand for risk awareness and communication.

## REFERENCES

- Colle, B., F. Buonaiuto, M. Bowman, R. Wilson, R. Flood, R. Hunter, A. Mintz, and D. Hill. 2008. New York City's vulnerability to coastal flooding. American Meteorological Society. June 2008.
- Houston, S., M. Powell. 1994. Observed and modeled wind and water-level response from Tropical Storm Marco (1990). Weather and Forecasting, March 1994.
- Jelesnianski, C., J. Chen, W. Shaffer, and A.D. Taylor. 2007. NOAA Sea Lake and Overland Surge from Hurricanes (SLOSH) Storm Surge CD. May 9, 2007.
- Jelesnianski, C., J. Chen, and W. Shaffer. 1992. NOAA Technical Report NWS 48: SLOSH: Sea Lake and Overland Surge from Hurricanes. April 2007.
- Jelesnianski, C., J. Chen, W. Shaffer, and A.D. Taylor. 2007. NOAA Sea Lake and Overland Surge from Hurricanes (SLOSH) Storm Surge CD. May 9, 2007.
- Mattocks, C. and C. Forbes. 2008. A real-time, event-triggered storm surge forecasting system for the state of North Carolina. Ocean Modelling, 25:95-119.
- Pine, J.C., H. Mashriqui, S. Pedro, and J. Meyer. 2005. Hazard mitigation planning using HAZUS-MH flood and wind hazards. *Journal of Emergency Management*, 2:11-16.
- Slocum, T., R. McMaster, F.C. Kessler, and H.H. Howard. 2009. *Thematic Cartography and Geovisualization*, Third edition, Prentice Hall, Upper Saddle River, 561pp.
- Smith, G.M., T. Spencer, and I. Möller. 2000. Visualization of coastal dynamics: Scolt Head Island, North Norfolk, England. *Estuarine, Coastal, and Shelf Science*, 50:137-142.
- Yuan, M. and K.S. Hornsby. 2008. Computation and Visualization for Understanding Dynamics in Geographic Domains: A Research Agenda, University Consortium for Geographic Information Science, CRC Press, Boca Raton, 112pp.