STORM TIDE HINDCASTS FOR HURRICANE HUGO: INTO AN ESTUARINE AND RIVERINE SYSTEM

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ABSTRACT

This paper presents simulated storm tides from a hindcast of Hurricane Hugo (1989). Water surface elevations are obtained from computations performed with the hydrodynamic ADCIRC-2DDI numerical code.

Four different two-dimensional finite element domains are developed in order to assess the surge-tide-streamflow interaction within an estuarine and riverine system. Two domains include inland topography, i.e., several observed inundated areas along the coast and relevant riverine floodplains.

Results at three locations are presented; at Charleston harbor, where Hugo made landfall, Bulls Bay, where the highest water elevations were observed, and at the inlet of the Winyah Bay estuary, the mouth of the Waccamaw river. The simulated results show good agreement with the recorded storm data and the observed high water elevations. A slight phasing error is recognized. Our numerical results reveal that including inundated areas and floodplains in our finite element mesh is of vital importance in order to represent the storm tide response best along the coast reach of interest and within the Waccamaw riverine systems.

1. INTRODUCTION

Hurricanes remain the single costliest and most devastating of all storms. Most of the catastrophe results from storm surge produced during these events. In recent years, the unprecedented destruction by several hurricanes along the South Carolina coast highlights the importance of developing a capability to model the interaction between storm surge, atmospheric tide, and streamflow. Advanced numerical models, like ADCIRC, are capable of enhancing the understanding of hydrodynamic behavior along coastal areas during such storm events.

The present paper focuses on studying storm tide generation by Hurricane Hugo in 1989 along the South Carolina coast. The region of interest (Figure 1) includes the Winyah Bay northeast of Charleston, the Waccamaw River up to Conway and the Atlantic Intracoastal Waterway (AIW) within the Grand Strand (Myrtle Beach).

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Four different two-dimensional finite element models are developed in order to evaluate the surge-tide-streamflow interaction. Each of the computational regions comprises a semicircular mesh encompassing the South Carolina coast and the continental shelf.

In the following sections, the history of Hurricane Hugo, the hydrodynamic model used, the different finite element meshes applied, and the simulated results will be presented and discussed.

Figure 1 Bathymetric Contours (a) Computational Domain, (b) Inset Confluence Atlantic Intracoastal and Waccamaw River, and (c) Inset Winyah Bay Inlet.

2. HURRICANE HUGO

Hurricane Hugo (1989) was the strongest storm to strike the United States since 1969. It was also one of the costliest in U.S. history accounting for $9.7 billion in damages. The hurricane directly caused 49 fatalities. South Carolina suffered the greatest number of deaths with 13 lives lost. More than 200,000 families were affected with homes destroyed or damaged (DOC, 1990).

Hugo was initially formed as a tropical depression within the Atlantic Ocean, approximately 200 km south of Cape Verde Islands (Figure 2) on September 10, 1989. The tropical storm reached full strength on September 15, with wind speeds of 305 km/h at an altitude of 460 m, and surface wind speeds of 260 km/h making Hugo a Category 5 hurricane (DOC, 1990). In the following days the cyclone hit the Virgin Islands, Puerto Rico, and the Bahamas. On September 21, Hugo developed a hurricane eye of more than 65 km in diameter. At the zero hour on September 22, the hurricane made landfall just east of Charleston. The storm hit at an angle nearly perpendicular to the coast.

The storm tides within Bulls Bay reached an elevation of about 6 m. At Winyah Bay, the highest elevations of approximately 3.7 m occurred near the middle of the bay. The gaging station at Charleston harbor recorded storm tides of 3.7 m (Schuck-Kolben and Cherry, 1995).
3. HYDRODYNAMIC MODEL DESCRIPTION

The computations were performed using the hydrodynamic finite element model ADCIRC-2DDI (Advanced Circulation model for oceanic, coastal, and estuarine waters – Two Dimensional Depth Integrated option) (Luettich et al., 1992). ADCIRC utilizes the vertically averaged equations of mass and momentum conservation, subject to the hydrostatic pressure approximation. In order to solve the depth-averaged shallow water equations the original continuity equation is replaced by the generalized wave-continuity equation. The equation is obtained by reformulating the continuity equation (Luettich et al., 1992). The forcings included in the model are tidal elevations at the open ocean boundary, surface pressure, and wind shear stress. ADCIRC computes the water elevations by applying triangular finite elements. The domains subject to inundation and overtopping the wetting and drying feature is employed.

4. METEOROLOGICAL FORCING

The forcing included for the storm tide generation are surface pressure, surface shear stress due to wind, and astronomical tide forcings at the open water boundaries. In addition, overland and streamflows are included in the model run.

All necessary wind data was computed and provided by Oceanweather Inc. (http://www.oceanweather.com) using a tropical wind model established and described by Cox and Cardone (2000). An exponential pressure law is employed in order to compute a circularly symmetric pressure field located at the center of the storm. The wind speeds are computed by equations of horizontal motion and vertically averaged through the planetary boundary layer. Wind speeds and atmospheric pressure are then interpolated to each node of the finite element mesh at each specified time step. For this study, the translation wind speed to wind stress is accomplished by applying the relationship proposed by Garratt (1977) integrated in the ADCIRC code.
5. FINITE ELEMENT MODEL DEVELOPMENT

Four finite element models (Figure 3, 4, 5, and 6) are developed. Each domain includes a semicircular mesh that encloses the South Carolina coast and the continental shelf. The mesh within the Atlantic Ocean and the majority of the continental shelf remains the same for all domains. Slight grid alterations had to be made along the coast and estuaries, insignificant to the computational results.

The first mesh SC-1 (Figure 3) contains the Winyah Bay only. The second SC-1-FP (FP stands for floodplain) (Figure 4) uses the Winyah Bay and inland topography. A third mesh SC-2 (Figure 5) incorporates the Winyah Bay, Waccamaw River, and AIW. Finally, a fourth SC-2-FP (Figure 6) utilizes the Winyah Bay, Waccamaw River, AIW and inland topography. An inset figure is presented, next to each finite element mesh showing a study domain detail.

The two domains with inland topography include several observed inundated areas along the South Carolina coast, and relevant floodplains. Islands within the riverine system are incorporated in the mesh as well. The same applies for barrier islands within the reach of interest (Charleston to Winyah Bay). The maximum element size for all meshes is 14 km. Table 1 summarizes and displays the characteristic of the four meshes engaged in this study.

Figure 3 Computational Domain (a) SC-1, no Floodplain and (b) Inset Study Domain.

Figure 4 Computational Domain (a) SC-1-FP, with Floodplain and (b) Inset Study Domain.
Table 1 Characteristics of the Model Meshes.

<table>
<thead>
<tr>
<th>Domain</th>
<th>Including Floodplain</th>
<th>Nodes</th>
<th>Elements</th>
<th>Smallest Mesh Size</th>
<th>Figure</th>
</tr>
</thead>
<tbody>
<tr>
<td>SC-1</td>
<td>No</td>
<td>10,400</td>
<td>19,000</td>
<td>65 m</td>
<td>3</td>
</tr>
<tr>
<td>SC-1-FP</td>
<td>Yes</td>
<td>14,500</td>
<td>27,600</td>
<td>65 m</td>
<td>4</td>
</tr>
<tr>
<td>SC-2</td>
<td>No</td>
<td>34,000</td>
<td>56,300</td>
<td>9 m</td>
<td>5</td>
</tr>
<tr>
<td>SC-2-FP</td>
<td>Yes</td>
<td>117,900</td>
<td>227,000</td>
<td>9 m</td>
<td>6</td>
</tr>
</tbody>
</table>

Figure 5 Computational Domain (a) SC-2, no Floodplain and (b) Inset Study Domain.

Figure 6 Computational Domain (a) SC-2-FP, with Floodplain and (b) Inset Study Domain.
5.1 Building the Computational Mesh

The shoreline and riverbanks are obtained from the National Geophysical Data Center (NGDC) Coastline Extractor at http://rimmer.ngdc.noaa.gov/coast/. A semi-circular arc is used to define the open ocean boundary, with endpoints at Hilton Head Island, South Carolina and Cape Fear, North Carolina.

In order to discretize the riverine system, a mesh of at least three elements across the river channel is used to ensure proper generation and propagation of the storm surge wave throughout the scheme. This especially proves important to a riverine system with an extended upstream body, i.e., including the Waccamaw River and AIW. Furthermore, three elements across guarantee the best representation of the parabolic or trapezoidal shape of the river cross sections.

Both domains including the floodplains; SC-1-FP and SC-2-FP are based on the previous developed meshes SC-1 and SC-2. The appending of the meshes is established by defining an inland boundary, far enough inland from the river and coastline boundary that covers the observed inundation areas. Large portions of pertinent tributaries basins (Great Pee Dee River, Black River, Sampit River, and Santee River) are included within these boundaries as well. Information regarding inundated areas, during Hurricane Hugo, is retrieved from anecdotal records, depicted inundation areas, surveyed high water mark maps and topographic maps from the U.S. Geological Survey (USGS) agency. It proved to be very useful to have the maps on CD-ROM available (http://www.maptech.com). Background images are generated and read in to the mesh generation tool box of Surface-water Modeling System (SMS).

Elevation data within the Atlantic Ocean, Waccamaw River, AIW, and inland areas is obtained from the National Geophysical Data Center (NGDC) Coastal Relief CD-ROM, Volume 2. The CD-ROM includes a gridded database that merges 3-arc second digital elevation maps (DEM), established by USGS, to a large collection of hydrographic sounding data, collected by the National Ocean Service (NOS) and other institutions. After the construction of the finite element mesh, the elevation data is interpolated onto the nodes of the mesh. The final “floodplain mesh” (Figure 4 and 6) is accomplished by deleting all nodes with elevations exceeding 6.1 m.

5.2 Computational Model Setup

The total simulation time is 1.75 days (September 20, 1989, 6 p.m. to September 22, 12 p.m.). Eight tidal elevation forcings (K1, M2, M4, M6, N2, O1, S2, and Steady) are applied at the open boundaries. Meteorological forcings (wind speed and surface pressure) are read in to the mesh every 15 minutes. The simulations are begun from a cold start. Boundary forcings are ramped over a period of 0.5 days. The minimum depth of wetting and drying elements (only for SC-1-FP and SC-2-FP) is set at 0.01 m. The bottom friction coefficient, Cr, is set at 0.0025, eddy viscosity at 5.00 m2/s. The time steps for each domain are presented in Table 2.

5.3 Computational Performance

The storm tide simulations are performed in the Compaq Water Resources Simulations Laboratory, at the University of Central Florida, Orlando (http://cwrsl.cecs.ucf.edu/). The laboratory is equipped with a twelve-unit cluster, each unit contains a 600 MHz processor. These machines can be run in serial or as a high-speed parallel system. Running simulations on all twelve processors splits the mesh into twelve sub-domains that are post-processed to one domain after computation. Table 2 shows the recorded run time for each finite element mesh. Note that the “Adjusted Run Time” value relates the effective run time to an equivalent one-processor run time. A linear speedup relationship between run time and number of processors is achieved and therefore applied to these calculations.
Table 2 Computational Model Setup and Performance.

<table>
<thead>
<tr>
<th>Domain</th>
<th>Nodes</th>
<th>No. of Processors</th>
<th>Time Step</th>
<th>Run Time</th>
<th>Adjusted Run Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>SC-1</td>
<td>10,400</td>
<td>1</td>
<td>6 s</td>
<td>45 min</td>
<td>45 min</td>
</tr>
<tr>
<td>SC-1-FP</td>
<td>14,500</td>
<td>1</td>
<td>6 s</td>
<td>60 min</td>
<td>60 min</td>
</tr>
<tr>
<td>SC-2</td>
<td>34,000</td>
<td>12</td>
<td>0.6 s</td>
<td>2 hr 15 min</td>
<td>27 hr 45 min</td>
</tr>
<tr>
<td>SC-2-FP</td>
<td>117,900</td>
<td>12</td>
<td>0.6 s</td>
<td>8 hr</td>
<td>96 hr</td>
</tr>
</tbody>
</table>

6. RESULTS AND DISCUSSIONS

6.1 Charleston Harbor

Figure 8 displays results from a hindcast of Hurricane Hugo. Deviation from mean sea level (MSL) is plotted against time. The thick line represents historical data recorded at the Charleston, South Carolina tide gage. The four other curves (see legend for symbols) allow distinctions to be drawn between the four separate model domains. Since the storm surge hit at approximately high tide it is important to note that all domains accurately captured the tidal signal leading up to the storm surge event. A slight phasing error is recognized.

The domains that do not include inundated areas and floodplains (Figure 8, SC-1; square symbol and SC-2; triangular symbol) resulted in the highest peak for the storm tide. This is reasonable when one considers that no-flow boundary conditions were imposed for these domains, which result in the water mass constrained within infinite vertical walls at all shorelines. While the two domains that include inland topography, i.e., SC-1-FP, and SC-2-FP, and therefore utilize wetting and drying of elements, produce less peak surge, they provide a more accurate representation of the recession of the storm tide hydrograph. Note how the SC-1 (Winyah Bay Only) and SC-2 (Waccamaw River and AIW) domains have a slightly lower recession and result in an artificial second peak.

Figure 8 Storm tide hydrograph Hurricane Hugo at Charleston harbor tide gage, South Carolina.
None of the models accurately capture the rising limb of the storm tide hydrograph. At the zero hour on 9/22/1989 (Figure 8) the historical data is above MSL. All four domains produced a rising limb that begins up to nearly one meter below MSL. This hindcast shortcoming is due to an absence of wave run-up.

6.2 Bulls Bay

Figure 9 shows the computed hydrographs at Bulls Bay, South Carolina. Historical data is not available for this location. The calculated elevations are verified with surveyed and estimated high water marks. After a major hurricane, the U.S. Army Corps of Engineers (USACE) evaluates high water marks and maps the inundated areas. According to their survey, the storm tides reached an elevation of approximately 6.0 m above MSL within Bulls Bay. The highest peaks of 6.2 m occurred inland just northeast of the bay.

The hydrographs show clearly that the two meshes SC-1 and SC-2 produce higher peaks (4.8 m and 5.0 m) than the SC-1-FP and SC-2-FP meshes (4.2 m and 4.1 m). The lower peak computation with inland areas included is reasonable, since the inland areas allow the water mass to spread out into the floodplains. A discrepancy is also noted for the recession curves. The curves representing the SC-1-FP and SC-2-FP models have a higher recession limb because the inland areas hold the storm tide longer. An artificial second peak produced by the SC-1 and SC-2 models is indicated. These peaks are a result of a sloshing effect caused by the no-flow boundary conditions at the shoreline.

None of the model computes water elevations of 6 m above MSL within Bulls Bay. Nevertheless, the computer animation of the inland storm tide, northeast of Bulls Bay, indicates peaks of about 6.0 m and higher above MSL. These elevations are in accordance with the surveyed watermarks by USACE. Questions remain about how accurate water elevations are estimated within large bays during hurricane events.

![Figure 9 Storm tide hydrograph Hurricane Hugo at Bulls Bay, South Carolina.](image-url)
6.3 Winyah Bay Inlet

Figure 10 exhibits the generated hydrographs at Winyah Bay Inlet, South Carolina. Due to the lack of historical data anecdotal information and surveyed high water marks are used to assess the computed results.

Jetties that extend eastward from the inlet confine the entrance to Winyah Bay. Near its mouth, the bay is protected by a massive barrier island, which has dunes higher than 12 m above MSL. The high storm tide stage near the middle of the Winyah Bay was probably the result of the storm tide entering the bay in the vicinity of North Inlet, a former entrance to the bay, where barrier island elevation are lower (Schuck-Kolben and Cherry, 1995). In addition, water surged in overland from southwest causing a further increase in water stages. At Winyah Bay Inlet, the highest reported storm peak was about 3.7 m above MSL.

Again, a clear distinction can be made between the hydrographs computed with or without inland topography. This time, dissimilar to the previous two locations, including the floodplains and inundation areas causes an increase in water elevations. The SC-1-FP and SC-2-FP meshes show peaks of about 3.3 m to 3.4 m above MSL, while the SC-1 and SC-2 meshes demonstrate high elevations of 3.0 m above MSL. It is noticed that the SC-1-FP and SC-2-FP graphs show an increase in water stages at the end of the recession limb. This is produced due to water backflow that surged in to the bay from the north and southwest and can be captured by the models that include the floodplains. A slight phasing shift is observed in the SC-1-FP model.

7. CONCLUSIONS

The ADCIRC-2DDI numerical model is applied in order to simulate the storm tides generated by Hurricane Hugo (1989) in South Carolina, USA. Four different modeling meshes are presented and their results discussed. Simulated storm tide elevations are compared with the recorded water stages at Charleston and verified with surveyed high water marks at two other locations; Bulls Bay and Winyah Bay inlet. All model domains used in this study show fair to good consensus with the reported data.

Figure 10 Storm tide hydrograph Hurricane Hugo at Winyah Bay Inlet, South Carolina.
All plotted hydrographs related to the four different meshes show clear distinction between the models including inland topography (SC-1-FP, Figure 4, and SC-2-FP, Figure 6) and the models without inland topography (SC-1, Figure 3, and SC-2, Figure 5). The inland topography meshes obviously achieve better results where inland inundation occurred. Inundation either causes a decrease in water elevations, at Bulls Bay, or an increase, at Winyah Bay Inlet. At locations, like Charleston harbor, where the riverine system is highly canalized and overtopping is restrained by means of flood control structures along the shore, this effect is not as evident.

It has to be emphasized that Hurricane Hugo hit at an angle nearly perpendicular to the coast, therefore generating very high storm surges. We note that comparing our models with different hurricanes, e.g., Hurricane Floyd (1999) that paralleled the coast, may cause storm tide elevations that might not show such distinction between the different model hydrographs. This potentially different outcome indicates future work to be completed.

In the final analysis, the results show that ADCIRC is capable of accurately predicting storm tides generated by hurricanes along the South Carolina coast. Future work will explore coupling a short wave model with ADCIRC-2DDI. The choice between accuracy, as displayed in Figure 8 to 10, and computational efficiency, as indicated by Table 2, will be dependent on individual modeling demands.

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REFERENCES


Surface-water Modeling System (SMS). Surface-water modeling system reference manual. Brigham Young University, Environmental Modeling Research Laboratory, Provo, UT.