Implementation of a Coupled Storm Surge plus Waves Modeling System at the National Hurricane Center

Cristina Forbes (NOAA/NWS/NHC)
Andre Van der Westhuysen (NOAA/NWS/NCEP)
Craig Mattocks (NOAA/NWS/NHC)
Jamie Rhome (NOAA/NWS/NHC)
Outline

SLOSH+SWAN (SWOSH) Coupled Model
(Sea, Lake, and Overland Surges from Hurricanes + Simulating Waves Nearshore)

- IOOS Testbed 1
- IOOS Testbed 2
- MEOWs/MOMs

Validation Results in Puerto Rico
- Hurricane Georges (1998)
- Hurricane Irene (2011)
- Tropical Storm Erika (2015)
IOOS/SURA Testbed
(Integrated Ocean Observing System/Southeastern Universities Research Association)

Testbed 1: June 1, 2010 - May 31, 2012

- SLOSH+SWAN (SWOSH) coupled model developed by Don Slinn at University of Florida.

- Delivered to NHC in 2011.

- Original code was configured for elliptical basins (egl3), Gulf of Mexico (egm2, egm3) and Sabine Lake (ebp3) and the polar basin Providence/Boston (pv2).

- NHC needed to assess whether coupled model system could use existing infrastructure to create and visualize products.

Cristina Forbes et al. 14th Intl Workshop on Wave Hindcasting & Forecasting & 5th Coastal Hazard Symp. 11/8-13/2015, Key West, FL
Inclusion of Wave Forcing in SLOSH

Prof. Don Slinn, University of Florida, Department of Civil and Coastal Engineering

\[
\frac{\partial \zeta}{\partial t} = -\frac{\partial U}{\partial x} - \frac{\partial V}{\partial y} - \frac{\partial U_{\text{mass flux}}}{\partial x} - \frac{\partial V_{\text{mass flux}}}{\partial y}
\]

Continuity Eqn (2-16)

\[
\frac{\partial U}{\partial t} = -g(h+\zeta) \left[ B_r \frac{\partial (\zeta - \zeta_0)}{\partial x} + B_i \frac{\partial (\zeta - \zeta_0)}{\partial y} \right] + f(A_r V + A_i U) + C_r (\tau_x + \tau_{wx}) - C_i (\tau_y + \tau_{wy}) - \frac{U}{(h+\zeta)} \left[ \frac{\partial U_{\text{mass flux}}}{\partial x} + \frac{\partial V_{\text{mass flux}}}{\partial y} \right]
\]

U Transport Eqn (2-17)

\[
\frac{\partial V}{\partial t} = -g(h+\zeta) \left[ B_r \frac{\partial (\zeta - \zeta_0)}{\partial y} + B_i \frac{\partial (\zeta - \zeta_0)}{\partial x} \right] + f(A_r U + A_i V) + C_r (\tau_y + \tau_{wy}) + C_i (\tau_x + \tau_{wx}) - \frac{V}{(h+\zeta)} \left[ \frac{\partial V_{\text{mass flux}}}{\partial x} + \frac{\partial U_{\text{mass flux}}}{\partial y} \right]
\]

V Transport Eqn (2-18)

\(\tau_{wx}, \tau_{wy}\) – real and imaginary wave radiation stress per unit mass component

Smith (2006)

\(U_{\text{mass flux}}, V_{\text{mass flux}}\) – real and imaginary component of horizontal transport due to mass transport

Cristina Forbes et al. 14th Intl Workshop on Wave Hindcasting & Forecasting & 5th Coastal Hazard Symp. 11/8-13/2015, Key West, FL
MEOWs / MOMs
(Maximum Envelopes of Water / Maximum of MEOWs)

• Hypothetical tracks that take into account the climatology of the region were generated for Puerto Rico at NHC
• 8 directions (WSW, W, WNW, NW, NNW, N, NNE, NE)
• 2 RMWs (20, 35 nm)
• 3 storm motions (5, 15, 25 mph)
• 5 Wind speed intensity categories (1, 2, 3, 4, 5)
• 21 landfall locations, spaced 10 miles apart
• 2 initial water level/datums (Zero, High Tide)
• **Total number of synthetic storms = 10,080**
• MEOWs composited by category, direction, datum, forward speed
• MOMs composited by category and initial water level (or datum)
IOOS/SURA Testbed
(Integrated Ocean Observing System/Southeastern Universities Research Association)

Post Testbed 1:

- Code was modified for Puerto Rico basin (hsj2).

- Preliminary MEOWs/MOMs were created with hsj2 to see if it would be possible to use the NHC operational infrastructure.

- In partnership with the University of Miami-RSMAS, TeraGrid/Xsede supercomputer resources were used to create MEOWs/MOMs with hsj2.

- Test was successful. MEOWs and MOMs were generated for SLOSH wind-only and SLOSH wind-plus-waves simulations and were visualized in the SLOSH Display.
IOOS/SURA Testbed

Testbed 2: October, 2013 - September 2015

SLOSH code was modified to:
- Allow basins larger than 400x400 grid points,
- Implement new horizontal datum,
- Make hardwired parameters flexible.

Basin development
- Various high-resolution grids were developed and tested,
- Code that generates the GIS shapefiles was modified to produce GRS80 horizontal datum instead of Clarke ellipsoid,
- Code modifications were transitioned to NOAA/MDL for inclusion in master svn codebase.
Evolution of Puerto Rico Basin

(increases in resolution and extent)

1991
- sju: 3,104 m
- 56 x 125

1993
- hsju: 930 m
- 45 x 177

2010
- hsj2: 387 m
- 96 x 353

2014
- hsj5: 91 m
- 333 x 1332

SWAN Domain for SWOSH
- SWAN Grid: 1921 x 1921, 231 m
# Puerto Rico Basin

## Sources of Bathymetry and Topography Data

### Bathymetry

<table>
<thead>
<tr>
<th>Source</th>
<th>Data Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>ETOPO Bedrock</td>
<td>Cell Size 1 arc-minute</td>
</tr>
<tr>
<td>Horizontal Datum World Geodetic System of 1984 (WGS 84) Vertical Datum Sea Level Vertical Units Meters Grid Format Multiple: tiff, xyz</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Source</th>
<th>Cell Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>USCRM</td>
<td>3 arc-seconds (90 m cell size)</td>
</tr>
<tr>
<td>NOS Nav Charts</td>
<td>For channels Variable Res</td>
</tr>
</tbody>
</table>

### Topography

<table>
<thead>
<tr>
<th>Source</th>
<th>Data Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>2004 US Army Corps of Engineers (USACE) Joint Airborne Lidar Bathymetry Technical Center of Expertise (JALBTCX) Puerto Rico Lidar</td>
<td>January 10 - February 8, 2004 Vertical Accuracy 18.6 cm RMS Error</td>
</tr>
<tr>
<td>FEMA ADCIRC Composite DEM for Puerto Rico NOAA National Geophysical Data Center (NGDC) Tsunami Inundation DEMs</td>
<td></td>
</tr>
<tr>
<td>Guayama Ponce Fajardo San Juan Arecibo Mayaguez</td>
<td>20070622 1/3 arc-sec MHW DEM</td>
</tr>
<tr>
<td>20060505 1/3 arc-sec MHW DEM</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Source</th>
<th>Data Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>NED Data</td>
<td>Islands around PR 20140605 30 m</td>
</tr>
</tbody>
</table>
MEOWs/MOMs

- 10,080 simulations of hypothetical storms were run on the Jet supercomputing cluster to produce the MEOWs/MOMs.
- Example MEOW track – SLOSH vs. SWOSH

Cat 3, 15 mph, RMW=20 miles
MEOWs/MOMs

- MEOWs/MOMs are considered by NHC as the best approach for determining the vulnerability of an area to account for the forecast uncertainty and form the basins for the development of the nation’s evacuation zones.

- MEOWs/MOMs were delivered to NOAA’s Meteorological Development Laboratory (MDL) in May 2015 for distribution.
SWOSH Validation
Tropical Cyclone Tracks
Verification Stations

NOAA Stations

<table>
<thead>
<tr>
<th>N</th>
<th>Stn ID</th>
<th>Station Name</th>
<th>Lon (deg)</th>
<th>Lat (deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>9755371</td>
<td>San Juan, PR</td>
<td>-66.1164</td>
<td>18.4589</td>
</tr>
<tr>
<td>2</td>
<td>9759110</td>
<td>Magueyes Island, PR</td>
<td>-67.0464</td>
<td>17.9701</td>
</tr>
<tr>
<td>3</td>
<td>9751401</td>
<td>Lime Tree Bay, VI</td>
<td>-64.7538</td>
<td>17.6947</td>
</tr>
<tr>
<td>4</td>
<td>9751639</td>
<td>Charlotte Amalie, VI</td>
<td>-64.9200</td>
<td>18.3358</td>
</tr>
<tr>
<td>5</td>
<td>9757809</td>
<td>Arecibo, PR</td>
<td>-66.7024</td>
<td>18.4805</td>
</tr>
<tr>
<td>6</td>
<td>9754228</td>
<td>Yabucoa Harbor, PR</td>
<td>-65.8330</td>
<td>18.0551</td>
</tr>
<tr>
<td>7</td>
<td>9759938</td>
<td>Mona Island, PR</td>
<td>-67.9385</td>
<td>18.0899</td>
</tr>
<tr>
<td>8</td>
<td>9751364</td>
<td>Christiansd H, St Croix, VI</td>
<td>-64.7050</td>
<td>17.7500</td>
</tr>
<tr>
<td>9</td>
<td>9752695</td>
<td>Esperanza, Viegues Island, PR</td>
<td>-65.4714</td>
<td>18.0939</td>
</tr>
<tr>
<td>10</td>
<td>9753216</td>
<td>Fajardo, PR</td>
<td>-65.6311</td>
<td>18.3352</td>
</tr>
<tr>
<td>11</td>
<td>9752619</td>
<td>Isabel Segunda, Viequez Is., PR</td>
<td>-65.4438</td>
<td>18.1525</td>
</tr>
<tr>
<td>12</td>
<td>9751381</td>
<td>Lameshur Bay, St John, VI</td>
<td>-64.7242</td>
<td>18.3182</td>
</tr>
<tr>
<td>13</td>
<td>9759394</td>
<td>Mayaguez, PR</td>
<td>-67.1600</td>
<td>18.2200</td>
</tr>
<tr>
<td>14</td>
<td>9759412</td>
<td>Aguadilla, PR</td>
<td>-67.1646</td>
<td>18.4566</td>
</tr>
</tbody>
</table>
Hurricane Georges (1998)
Hurricane Georges (1998)

- **Genesis**: Cape Verde storm formed from large African wave on Sept 17, 1998
- **Peak Winds**: 155 mph (250 kph) Cat 4, wide wind field - 300 mi (490 km) TS force winds
- **Lowest Pressure**: 937 mb
- **Lives Lost**: 604 (most in Hispanola)
- **Damage Est.**: $14.1 billion
- **Landfall (PR)**: Sept. 21 as Cat 3 with 129 mph (208 kph) gusts, 3 tornadoes, crossed entire island (weakened to Cat 1 over mountains, reintensified to Cat 1), 8 deaths, $2.8 billion in damage, catastrophic damage to electrical system, roads, crops
- **Storm Surge**: 10 ft (3 m) at Fajardo along northeast coast
- **Waves**: Reports of 20 ft (6 m) at landfall in PR and 13.1 ft (4m) by a ship nearby.
- **Peak Rainfall**: 240 inches (6,096) mm, mountain flooding, river overflows
Max Water Level
SLOSH vs. SWOSH
Hurricane Georges
Max Water Level
SLOSH vs. SWOSH
Hurricane Georges
Differences in Max Water Level
SLOSH vs. SWOSH
Hurricane Georges

Difference in Water Level
Max = 0.91 m

Percentage Difference in Water Level
Max = 100% (pink dots)
10-20% increase from waves

Cristina Forbes et al. 14th Intl Workshop on Wave Hindcasting & Forecasting & 5th Coastal Hazard Symp. 11/8-13/2015, Key West, FL
Significant Wave Height Verification
Hurricane Georges
Summary
SLOSH vs. SWOSH
Hurricane Georges

<table>
<thead>
<tr>
<th>Stn ID</th>
<th>Time of Max Elev (day)</th>
<th>Max Elev (m)</th>
<th>RMS</th>
<th>CORR</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Obs</td>
<td>SL</td>
<td>SW</td>
<td>Obs</td>
</tr>
<tr>
<td>9755371</td>
<td>21.9833</td>
<td>21.96</td>
<td>21.98</td>
<td>.710</td>
</tr>
<tr>
<td>9759110</td>
<td>22.2083</td>
<td>22.24</td>
<td>22.24</td>
<td>.646</td>
</tr>
<tr>
<td>9751401</td>
<td>21.7583</td>
<td>21.74</td>
<td>21.74</td>
<td>.565</td>
</tr>
<tr>
<td>9751639</td>
<td>21.9125</td>
<td>21.89</td>
<td>21.87</td>
<td>.612</td>
</tr>
</tbody>
</table>

7% increase at San Juan, PR
RMSE = 5 to 10 cm
CORR = .66 to .91
Impact of Waves

Hurricane Georges (1998)

Number of Cells > 100%

Increase in Above Ground Water Level Due to Waves (Percent)

Log (Number of Cells)

1311

197

4

8

Cristina Forbes, NHC
Hurricane Irene (2011)
Hurricane Irene (2011)

- **Genesis**: Hurricane recon aircraft, investigating tropical wave east of Lesser Antilles, found small low-level circulation center SW of large convective burst on Aug. 20, 2011
- **Peak Winds**: 120 mph (195 kph) Cat 3 in the Bahamas
- **Lowest Pressure**: 940 mb
- **Lives Lost**: 49
- **Damage Est.**: $17.45 billion
- **Landfall (PR)**: Aug. 21 with 70 mph (110 kph) winds, strengthened to Cat 1 as it traversed the island
- **Storm Surge**: 1.62 ft (0.5 m) in Esperanza, Vieques
- **Storm Tide**: 2.58 ft in Fajardo (0.8 m)
- **Waves**: 12.5 ft (3.8 m) in San Juan and St. John buoys
- **Peak Rainfall**: 22.09 inches (561 mm) in Gurabo
Max Water Level
SLOSH vs. SWOSH
Hurricane Irene
Max Water Level
SLOSH vs. SWOSH
Hurricane Irene
Differences in Max Water Level
SLOSH vs. SWOSH
Hurricane Irene

Difference in Water Level
Max = 0.73 m

Percentage Difference in Water Level
Max = 100% (pink dots)
10-40% increase from waves

Cristina Forbes et al. 14th Intl Workshop on Wave Hindcasting & Forecasting & 5th Coastal Hazard Symp. 11/8-13/2015, Key West, FL
SWAN Max Significant Wave Height
Hurricane Irene

Max SWH = 7.11 m
(23.3 ft)
Error Cones
SLOSH vs. SWOSH
Hurricane Irene

Wind Only

Wind + Waves

Cristina Forbes et al. 14th Intl Workshop on Wave Hindcasting & Forecasting & 5th Coastal Hazard Symp. 11/8-13/2015, Key West, FL
## Summary

**SLOSH vs. SWOSH**

**Hurricane Irene**

<table>
<thead>
<tr>
<th>Stn ID</th>
<th>Time of Max Elev (day)</th>
<th>Max Elev (m)</th>
<th>RMS</th>
<th>CORR</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Obs</td>
<td>SL</td>
<td>SW</td>
<td>Obs</td>
</tr>
<tr>
<td>9755371</td>
<td>22.28</td>
<td>21.74</td>
<td>22.26</td>
<td>.316</td>
</tr>
<tr>
<td>9759110</td>
<td>22.96</td>
<td>21.90</td>
<td>22.96</td>
<td>.223</td>
</tr>
<tr>
<td>9751401</td>
<td>22.01</td>
<td>21.90</td>
<td>21.92</td>
<td>.359</td>
</tr>
<tr>
<td>9751639</td>
<td>22.19</td>
<td>22.06</td>
<td>22.10</td>
<td>.318</td>
</tr>
<tr>
<td>9757809</td>
<td>22.74</td>
<td>21.76</td>
<td>21.74</td>
<td>.312</td>
</tr>
<tr>
<td>9754228</td>
<td>23.18</td>
<td>21.86</td>
<td>22.92</td>
<td>.298</td>
</tr>
<tr>
<td>9759938</td>
<td>23.01</td>
<td>21.87</td>
<td>21.87</td>
<td>.265</td>
</tr>
<tr>
<td>9751364</td>
<td>21.91</td>
<td>21.85</td>
<td>21.88</td>
<td>.384</td>
</tr>
<tr>
<td>9752695</td>
<td>22.21</td>
<td>22.17</td>
<td>22.17</td>
<td>.463</td>
</tr>
<tr>
<td>9753216</td>
<td>22.23</td>
<td>22.18</td>
<td>22.19</td>
<td>.567</td>
</tr>
<tr>
<td><strong>9752619</strong></td>
<td><strong>21.82</strong></td>
<td><strong>22.03</strong></td>
<td><strong>22.02</strong></td>
<td><strong>.330</strong></td>
</tr>
<tr>
<td>9751381</td>
<td>28.81</td>
<td>21.96</td>
<td>21.92</td>
<td>.281</td>
</tr>
<tr>
<td>9759394</td>
<td>22.79</td>
<td>21.72</td>
<td>22.81</td>
<td>.316</td>
</tr>
<tr>
<td>9759412</td>
<td>22.76</td>
<td>21.73</td>
<td>21.72</td>
<td>.257</td>
</tr>
</tbody>
</table>

RMSE=2 to 10 cm
CORR=.81 to .98

30% increase at Isabel Segunda
Impact of Waves

Hurricane Irene (2011)

Number of Cells > 100%

33

Log (Number of Cells)

1566

135

159

114

15

Increase in Above Ground Water Level Due to Waves (Percent)

Cristina Forbes, NHC
Tropical Storm Erika (2015)
Tropical Storm Erika (2015)

- **Genesis:** Developed from westward-moving tropical wave east of Lesser Antilles. Slow to intensify, disorganized due to wind shear, moved rapidly westward. Designated as a tropical storm when a well-defined circulation revealed by ASCAT (radar scatterometer) pass early on Aug 25, 2015.
- **Peak Winds:** 50 mph (85 kph)
- **Lowest Pressure:** 1003 mb
- **Lives Lost:** 36
- **Damage Est:** $511.7 million
- **Landfall (PR):** None – passed south of island
- **Storm Tide:** 1.6 ft (0.49 m)
- **Waves:** 15.1 ft (4.6 m) in St. John, VI
- **Peak Rainfall:** 7.67 inches (195 mm) southeast, in Cavey Mountain Range
Max Water Level
SLOSH vs. SWOSH
TS Erika
Max Water Level
SLOSH vs. SWOSH
TS Erika

Cristina Forbes et al. 14th Intl Workshop on Wave Hindcasting & Forecasting & 5th Coastal Hazard Symp. 11/8-13/2015, Key West, FL
Differences in Max Water Level
SLOSH vs. SWOSH
TS Erika

Difference in Water Level
Max = 0.33 m

Percentage Difference in Water Level
Max = 100% (pink dots)
10-20% increase from waves

Cristina Forbes et al. 14th Intl Workshop on Wave Hindcasting & Forecasting & 5th Coastal Hazard Symp. 11/8-13/2015, Key West, FL
Error Cones
SLOSH vs. SWOSH
TS Erika

Wind Only

Wind + Waves

Model High
Model Low
Model Fast
Model Slow

Cristina Forbes et al. 14th Intl Workshop on Wave Hindcasting & Forecasting & 5th Coastal Hazard Symp. 11/8-13/2015, Key West, FL
## Summary

**SLOSH vs. SWOSH**

**TS Erika**

### Hurricane Erika (2015) IWL=.5

<table>
<thead>
<tr>
<th>Stn ID</th>
<th>Time of Max Elev (day)</th>
<th>Max Elev (m)</th>
<th>RMS</th>
<th>CORR</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Obs</td>
<td>SL</td>
<td>SW</td>
<td>Obs</td>
</tr>
<tr>
<td>9755371</td>
<td>27.97</td>
<td>27.94</td>
<td>27.93</td>
<td>.490</td>
</tr>
<tr>
<td>9759110</td>
<td>29.08</td>
<td>28</td>
<td>28</td>
<td>.357</td>
</tr>
<tr>
<td>9751401</td>
<td>28.09</td>
<td>27.98</td>
<td>27.98</td>
<td>.406</td>
</tr>
<tr>
<td>9751639</td>
<td>28.05</td>
<td>27.94</td>
<td>27.94</td>
<td>.415</td>
</tr>
<tr>
<td>9757809</td>
<td>27.92</td>
<td>27.93</td>
<td>29</td>
<td>.479</td>
</tr>
<tr>
<td>9754228</td>
<td>28.13</td>
<td>27.99</td>
<td>27.99</td>
<td>.400</td>
</tr>
<tr>
<td>9759938</td>
<td>28.08</td>
<td>27.99</td>
<td>27.99</td>
<td>.329</td>
</tr>
<tr>
<td>9751364</td>
<td>27.99</td>
<td>27.94</td>
<td>27.94</td>
<td>.321</td>
</tr>
<tr>
<td>9752695</td>
<td>28.09</td>
<td>27.98</td>
<td>27.99</td>
<td>.345</td>
</tr>
<tr>
<td>9753216</td>
<td>27.97</td>
<td>27.94</td>
<td>27.94</td>
<td>.487</td>
</tr>
<tr>
<td>9752619</td>
<td>28.02</td>
<td>27.96</td>
<td>27.97</td>
<td>.433</td>
</tr>
<tr>
<td>9751381</td>
<td>28.05</td>
<td>27.94</td>
<td>27.94</td>
<td>.403</td>
</tr>
</tbody>
</table>

RMSE=4 to 8 cm
CORR=.75 to .96

7% increase at Arecibo, PR
Impact of Waves

Tropical Storm Erika (2015)

Number of Cells > 100%

Increase in Above Ground Water Level Due to Waves (Percent)

Log (Number of Cells)

311
306
11
6

Cristina Forbes, NHC

Cristina Forbes et al. 14th Intl Workshop on Wave Hindcasting & Forecasting & 5th Coastal Hazard Symp. 11/8-13/2015, Key West, FL
Summary

- SLOSH + SWAN coupled model was implemented at NHC.
- Puerto Rico MEOW/MOM composites were completed and delivered to NOAA/MDL for archival and distribution.
- Validation of the SWOSH model was performed with Hurricane Georges (1998), Hurricane Irene (2011) and Tropical Storm Erika (2015).
- This analysis will provide a platform for future modeling and forecasting improvements which will support evacuation planning in locations where waves are important.
Future Work

- Validations of SWOSH with other storms will be performed.
- Validations of SWAN-predicted significant wave height, direction and period against observations will be conducted.
- Sensitivity studies with different SWAN input parameters will be carried out to determine the optimum parameters to use for SWOSH.
- Inclusion of boundary conditions in will be considered for implementation and validation.
Thank you!