NC STATE UNIVERSITY

Hurricane Wave and Storm Surge Forecasting for the Carolina Coast

JC Dietrich[1], R Cyriac[1], RA Luettich Jr[2], JG Fleming[3], BO Blanton[4]

[1]Dep't of Civil, Construction, and Environmental Engineering, NC State University
[2]Institute of Marine Sciences, University of North Carolina at Chapel Hill
[3]Seahorse Coastal Consulting, Morehead City, NC
[4]Renaissance Computing Institute, Chapel Hill, NC

WRCEE Seminar Series
26 September 2014

About Me

North Carolina State University

- Civil, Construction, and Environmental Engineering
    - Assistant Professor: 08/2013 to present

CCEE Department, Mann Hall, NCSU

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University of Texas at Austin

- Institute for Computational Engineering and Sciences
  - Research Associate: 09/2012 to 07/2013
  - Postdoctoral Researcher: 11/2010 to 08/2012

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- Civil Engineering and Geological Sciences
  - Graduate Researcher: 08/2005 to 10/2010

University of Oklahoma

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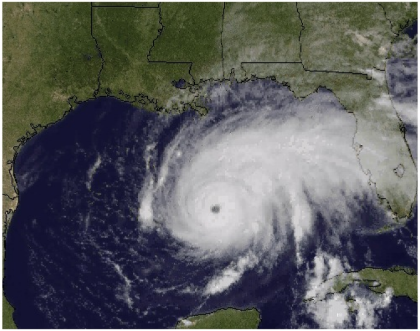
Hurricane Season 2005

Impacts on Southern Louisiana

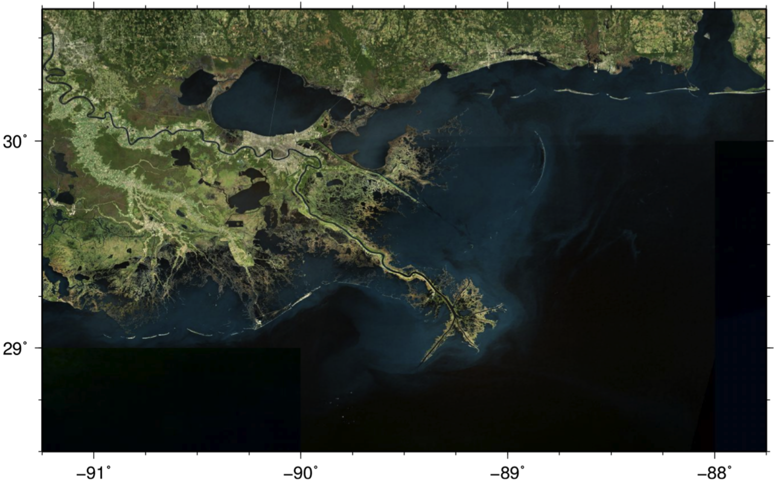
Katrina: 08/28 - 08/29

Rita: 08/28 - 08/29



Hurricane Season 2005

Flooding of New Orleans

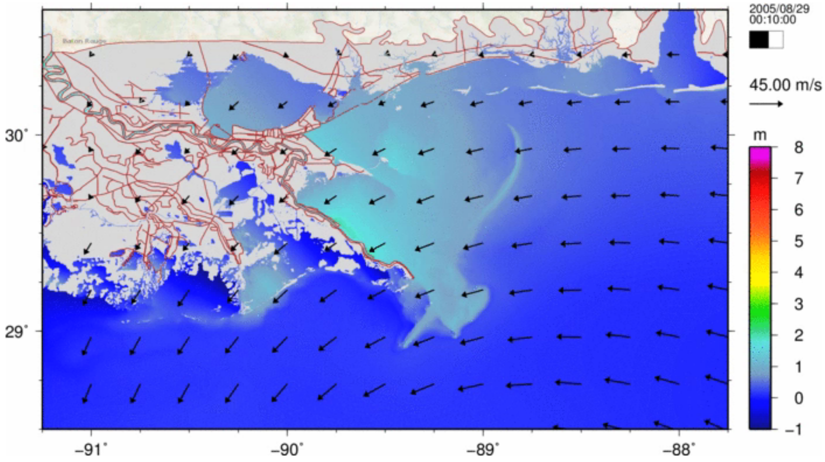


Hurricane Season 2005

Flooding of New Orleans

Hurricane Season 2005

Katrina on 29 August



S Bunya, JC Dietrich, *et al.* (2010). A High-Resolution Coupled Riverine Flow, Tide, Wind, Wind Wave and Storm Surge Model for Southern Louisiana and Mississippi: Part I Model Development and Validation. *Monthly Weather Review*, 138(2), 345-377.

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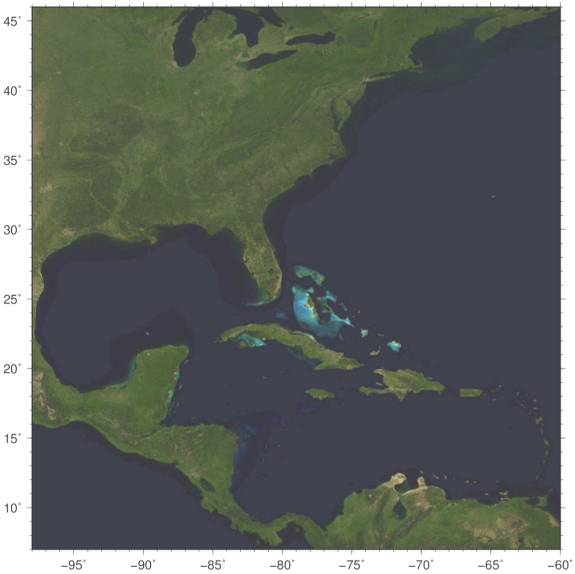
Wide Range of Spatial Scales

Gulf and Atlantic Coasts



Wide Range of Spatial Scales

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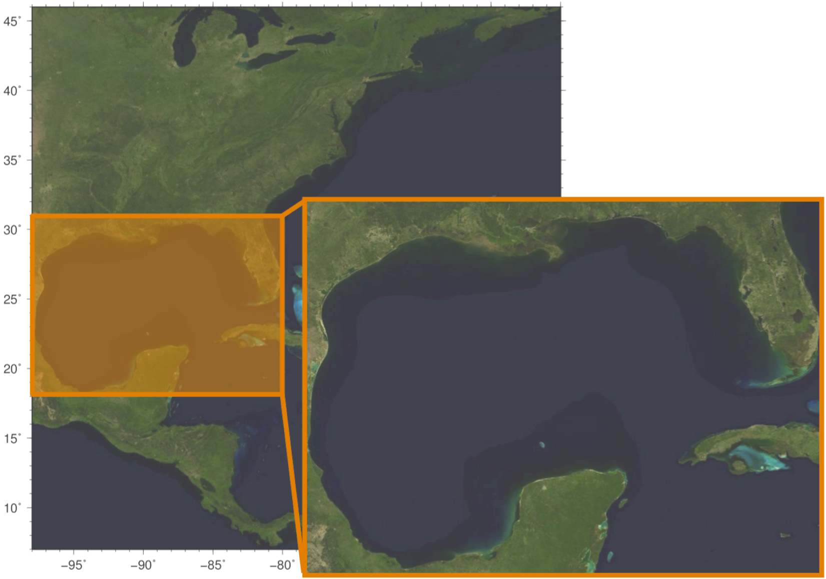

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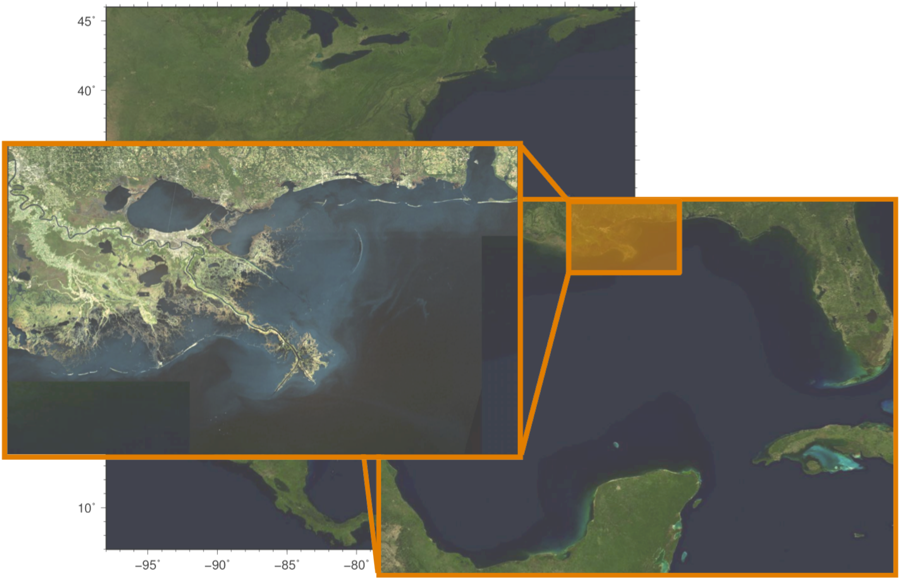

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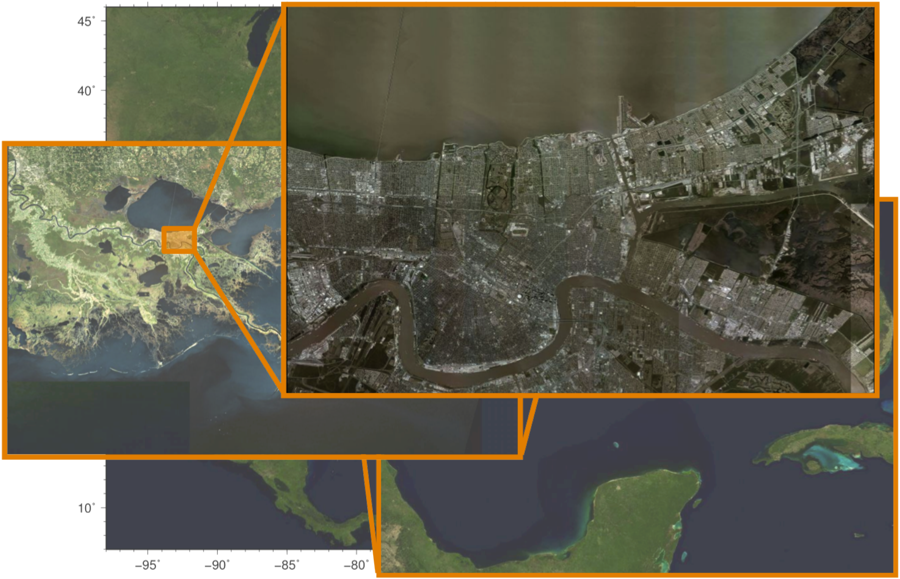
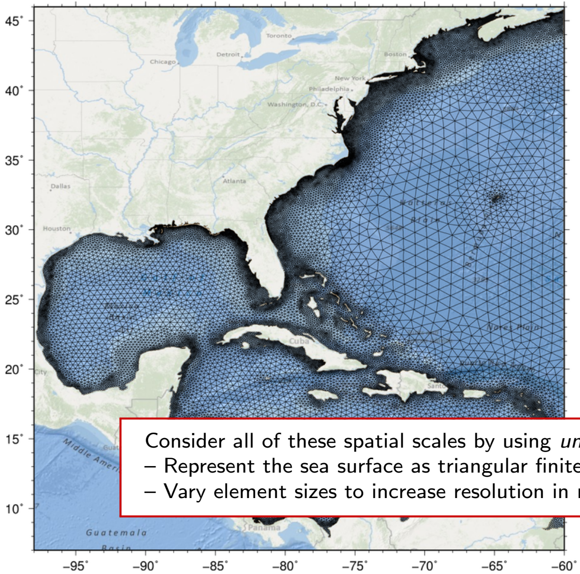


Wide Range of Spatial Scales

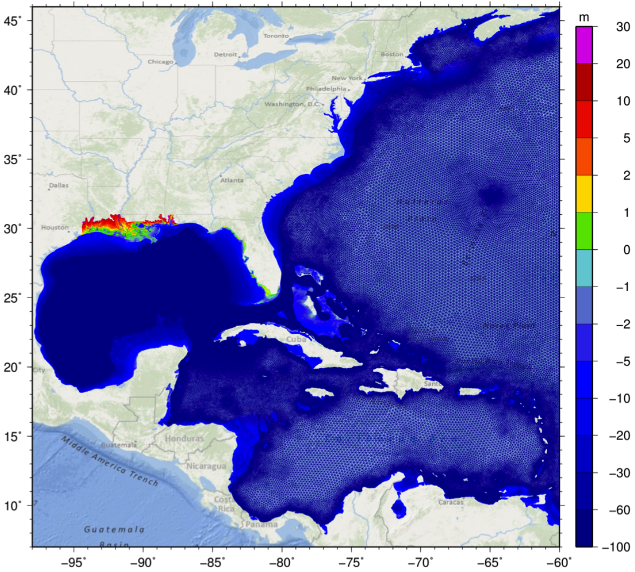
Unstructured, Finite-Element Meshes



Consider all of these spatial scales by using *unstructured meshes*:
– Represent the sea surface as triangular finite elements
– Vary element sizes to increase resolution in regions of interest

Wide Range of Spatial Scales

SL16 Mesh for Southern Louisiana



Wide Range of Spatial Scales

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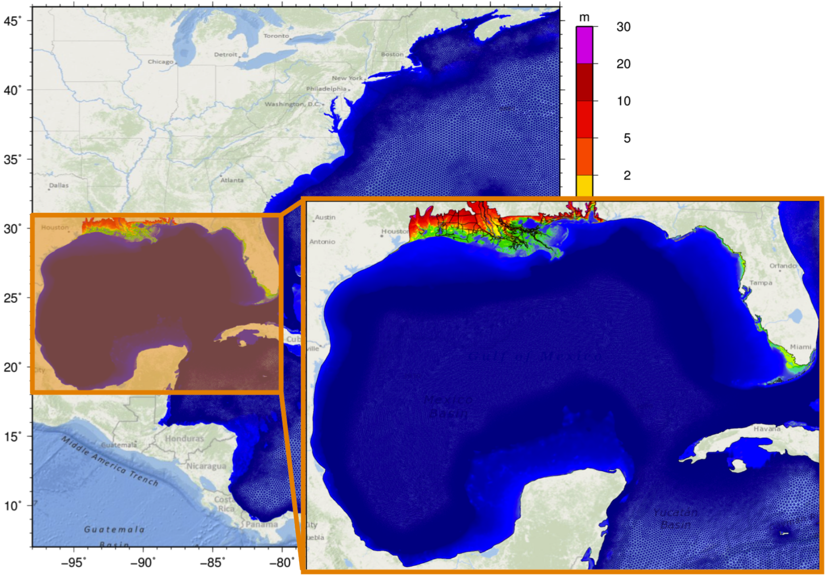

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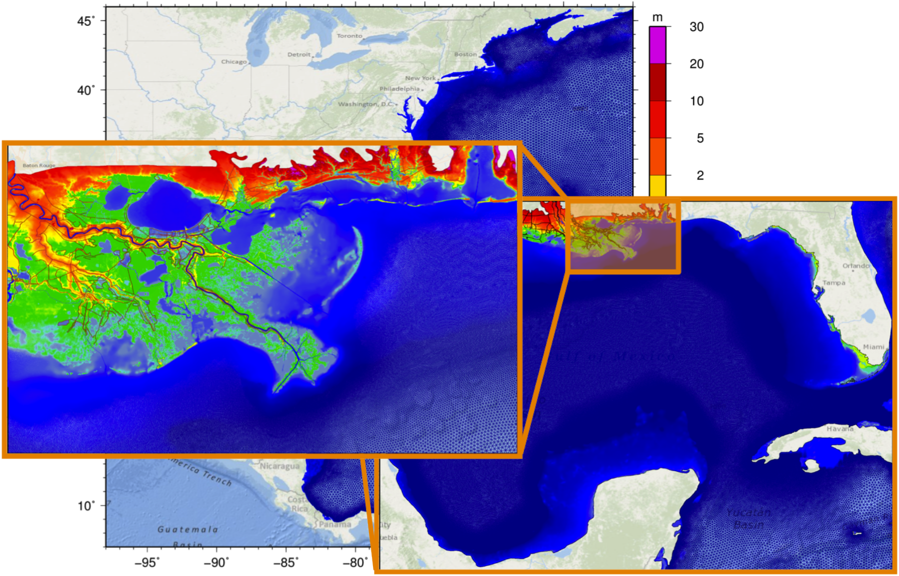

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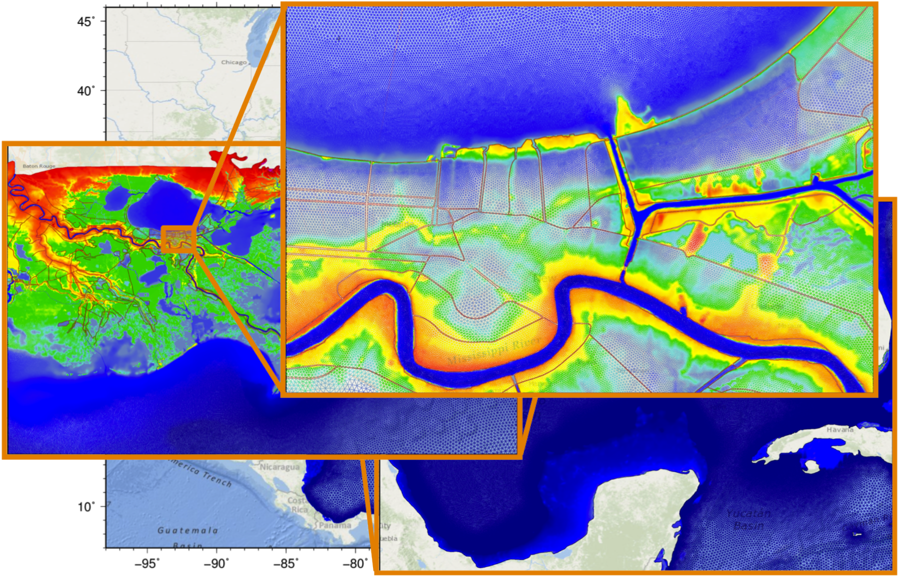
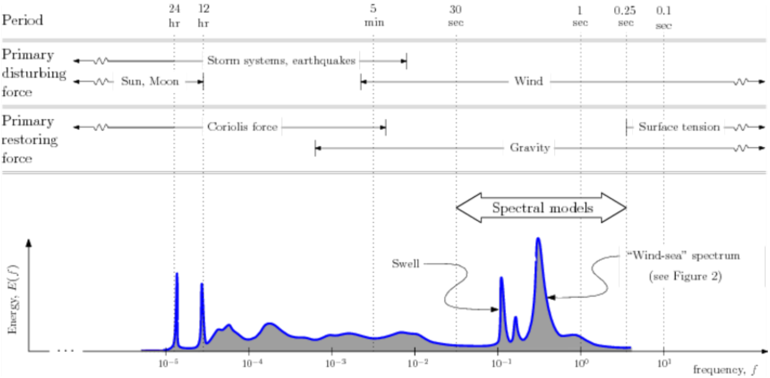


Waves and Storm Surge
Temporal Scales

Sea surface can be described with both *long* and *short* waves

- Long waves due to tides, storm surge
- Short waves due to wind (swell and wind-sea)



For short waves, we use SWAN

- Does not represent the phase of each individual wave
  - Conserved quantity is the action density $N(t, x, y, \sigma, \theta)$
  - Can be integrated to compute statistical wave properties

Solves the action balance equation:

$$\frac{\partial N}{\partial t} + \nabla_{\mathbf{x}} \cdot \left[(\mathbf{c}_g + \mathbf{U}) N \right] + \frac{\partial c_\theta N}{\partial \theta} + \frac{\partial c_\sigma N}{\partial \sigma} = 0$$

Solution methods in geographic (x, y) and spectral (σ, θ) spaces:

- Gauss-Seidel in geographic space
- Iterative solution of matrix system in spectral space

For long waves, we use ADCIRC

- Does represent the phases of tides and/or storm surge

Solves the generalized wave continuity equation for water levels ζ:

$$\frac{\partial^2 \zeta}{\partial t^2} + \tau_0 \frac{\partial \zeta}{\partial t} + \frac{\partial \tilde{J}_x}{\partial x} + \frac{\partial \tilde{J}_y}{\partial y} - UH \frac{\partial \tau_0}{\partial x} - VH \frac{\partial \tau_0}{\partial y} = 0$$

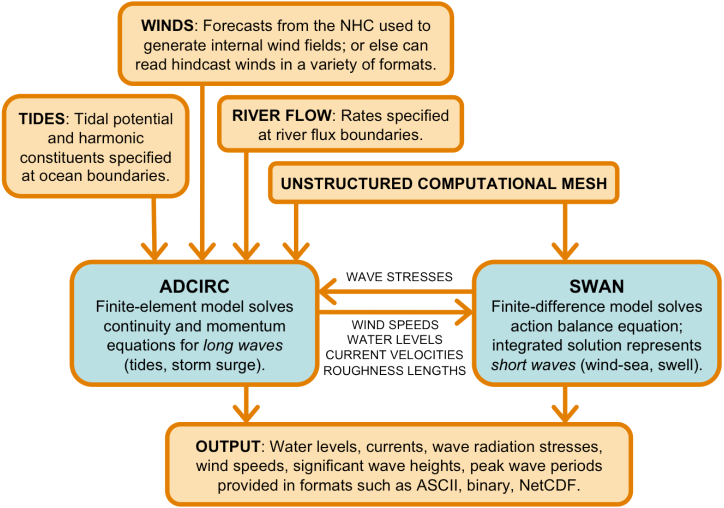
Solves the depth-averaged momentum equations for currents (U, V):

$$\frac{DU}{Dt} - fV = -g \frac{\partial}{\partial x} \left[\zeta + \frac{p_s}{g \rho_0} - \alpha \eta \right] + \frac{\tau_{sx} + \tau_{bx}}{\rho_0 H} + \frac{M_x - D_x}{H}$$

$$\frac{DV}{Dt} + fU = -g \frac{\partial}{\partial y} \left[\zeta + \frac{p_s}{g \rho_0} - \alpha \eta \right] + \frac{\tau_{sy} + \tau_{by}}{\rho_0 H} + \frac{M_y - D_y}{H}$$

Tight Coupling of SWAN+ADCIRC

Flow Chart



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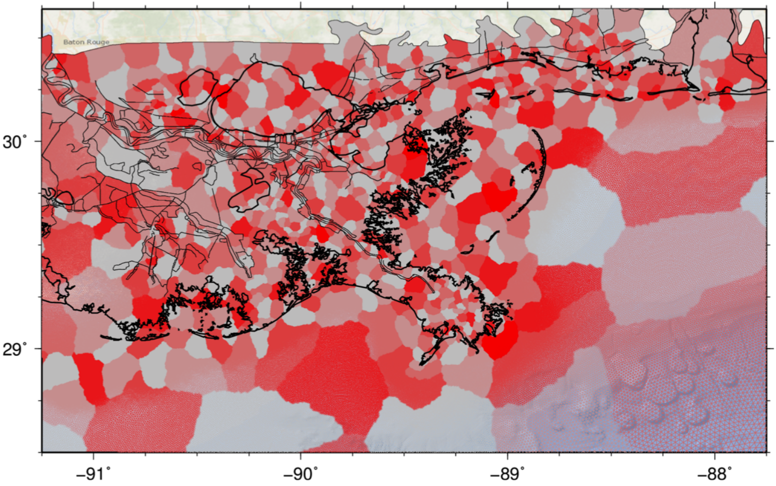
Tight Coupling of SWAN+ADCIRC

Domain Decomposition

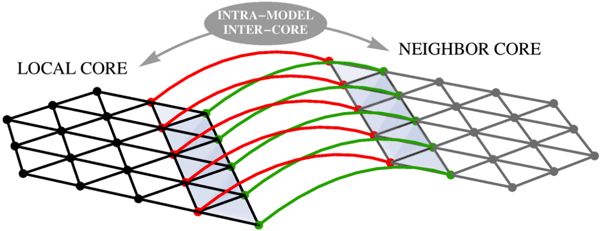
Large-scale problem is cut into thousands of small-scale problems

- Each computational core works on its own sub-mesh



Tight Coupling of SWAN+ADCIRC
Parallel Communication

Communication between cores at sub-mesh boundaries



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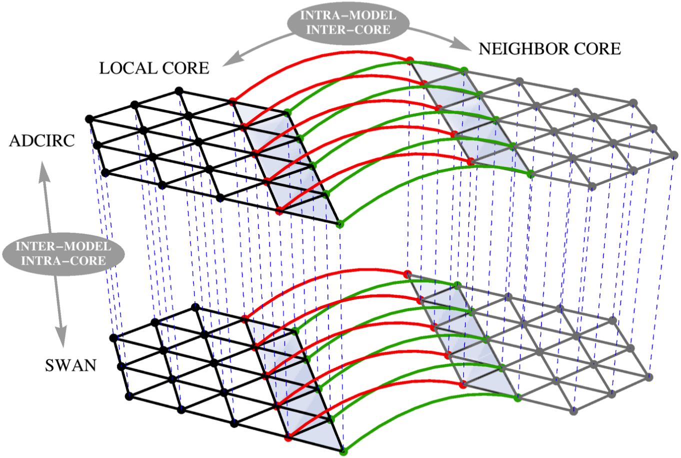
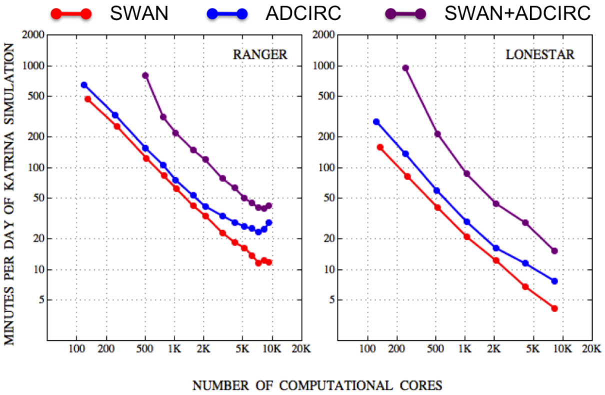


Tight Coupling of SWAN+ADCIRC

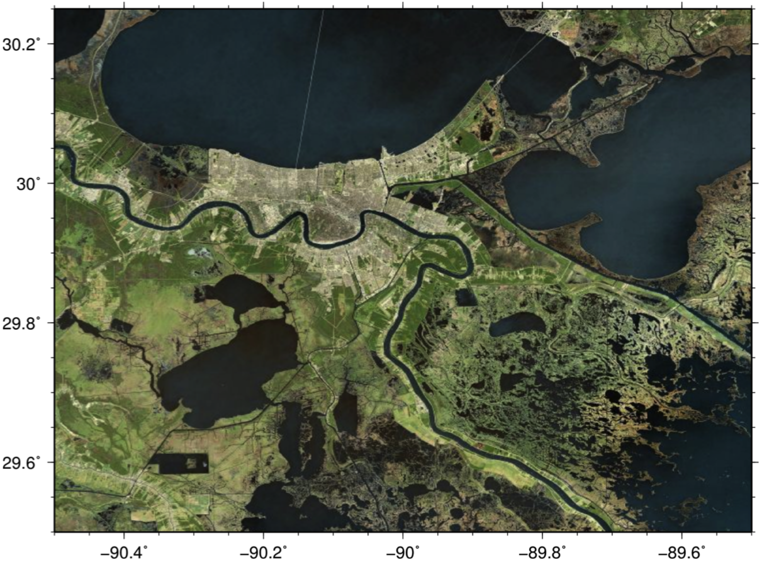
Parallel Scaling



	TACC Ranger	TACC Lonestar
Node	Sun Blade x6420	Dell PowerEdge M610
CPU	4 Quad-core AMD Opteron 8356	2 Six-core Xeon 5680
Frequency	2.3 GHz	3.33 GHz
Architecture	AMD K10 (Barcelona)	Intel Nehalem (Westmere-EP)

Validation for Hurricane Gustav (2008)

Near Flooding of New Orleans



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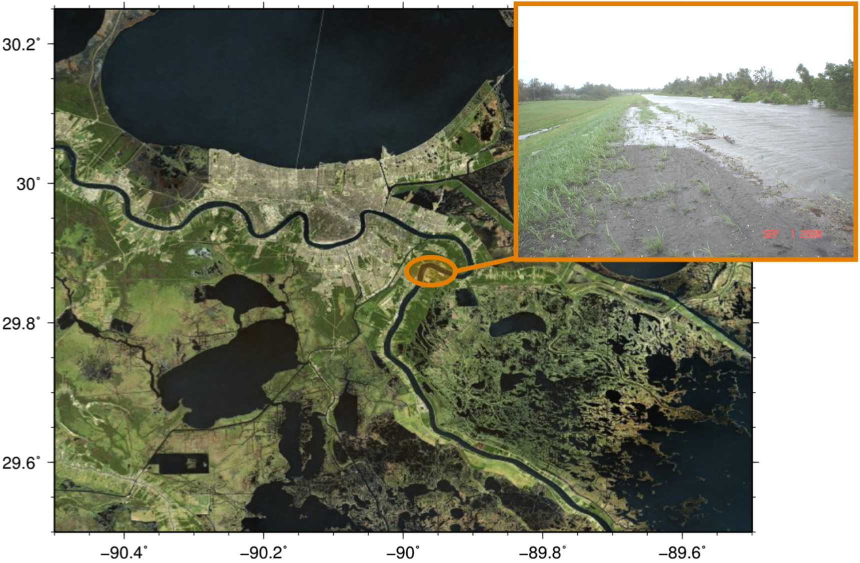

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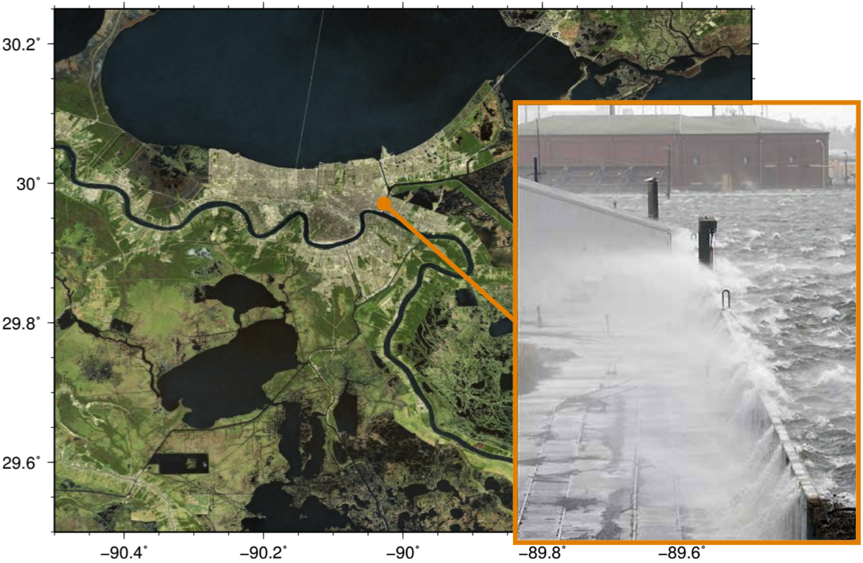
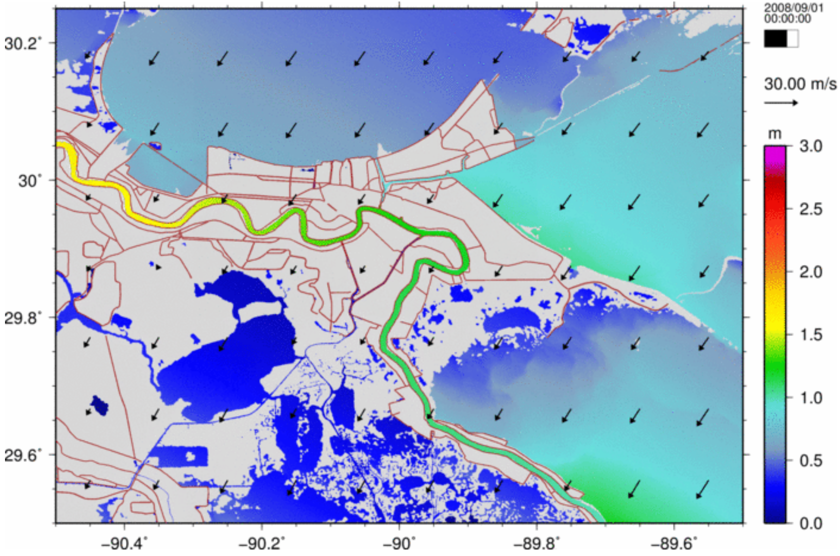


Validation for Hurricane Gustav (2008)

Day of Landfall



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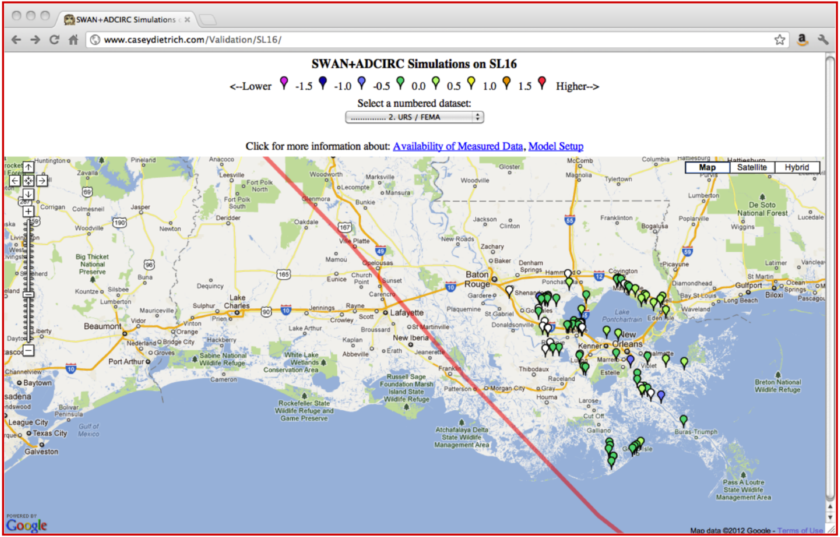
High-Water Marks



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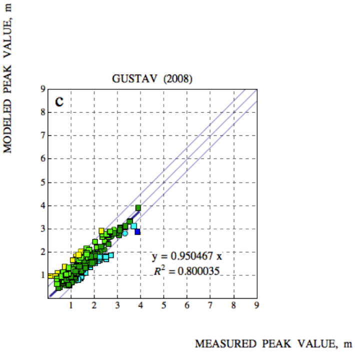

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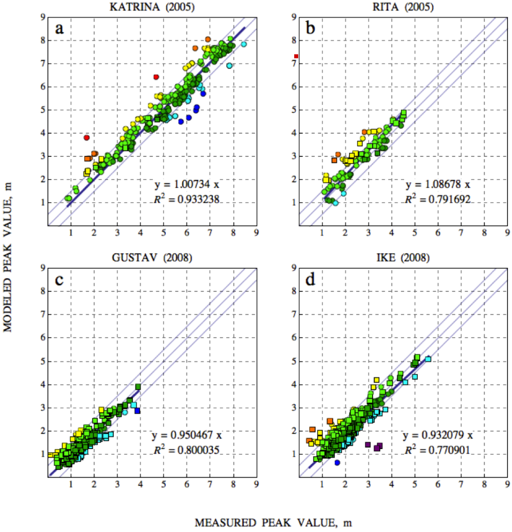

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Applications – Surge Barrier Design – USACE

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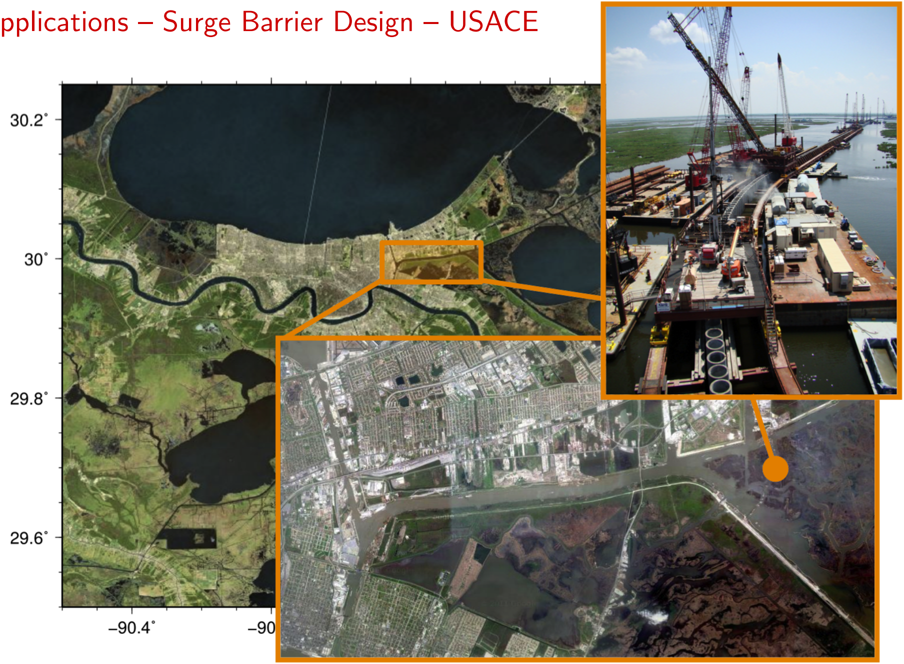
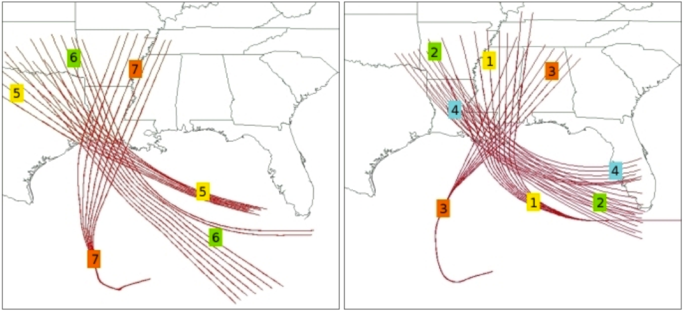


Applications – Floodplain Risk Maps – FEMA

Joint Probability Method with Optimal Sampling (JPM-OS):

- Hypothetical storms with varying characteristics
- Combine results to develop 100-yr flood maps



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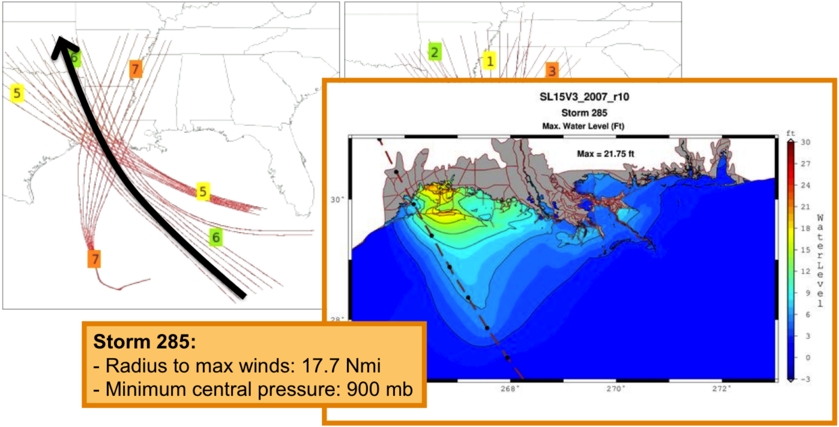


SWAN+ADCIRC can be employed in real-time via the ASGS

- **Everything happens automatically**
  - Models are initialized, run and processed by Perl scripts

Wind fields from two sources:

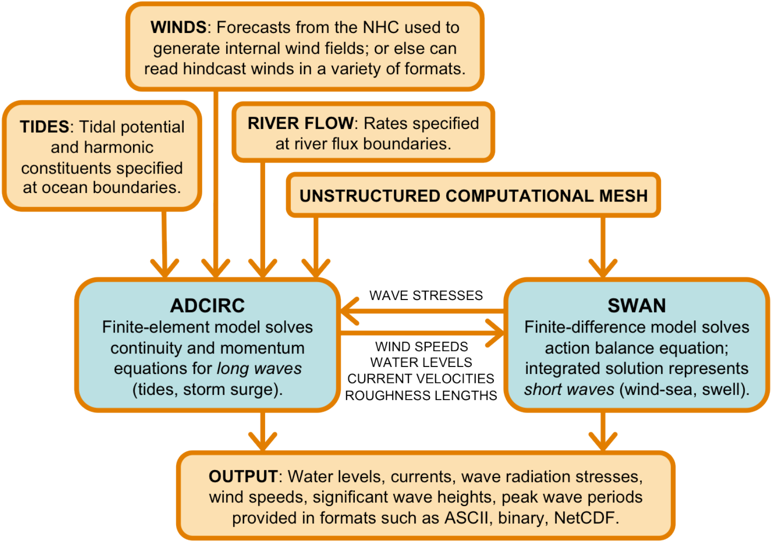
1. Under normal conditions:
   - Downloaded from NAM model output by NOAA/NCEP
   - Converted into format compatible with SWAN+ADCIRC
2. Under hurricane conditions:
   - Download advisories from NOAA/NHC
   - Generate wind field using parametric model (Holland, 1980)

Guidance can be shared in multiple formats:

- Raster images (JPG, PNG, etc.)
- Geo-referenced raster images (Google Earth, GIS)
- Web service (`coastalemergency.org`)

ADCIRC Surge Guidance System (ASGS)

Flow Chart



ADCIRC Surge Guidance System (ASGS)

Development Teams

University of North Carolina at Chapel Hill

- Provide forecasts for Carolina and surrounding states via Google Maps application (`nc-cera.renci.org`)
- Guidance during Irene (2011) prompted Coast Guard to shift operations to avoid flooding of operations center

Louisiana State University

- Provide forecasts for Louisiana and northern Gulf states via Google Maps application (`cera.cct.lsu.edu`)

University of Texas at Austin

- Provide forecasts for storms impacting Texas coastline; partnerships with Texas State Operations Center
- During Isaac (2012), guidance shared with NWS offices in Fort Worth, Tallahassee and Miami

Strengthening Guidance for North Carolina

Web-Based Guidance

In North Carolina, the guidance is available from the Coastal Emergency Risks Assessment (CERA) team:

- Shared via Web portal: `nc-cera.renci.org`

Updated often with new guidance:

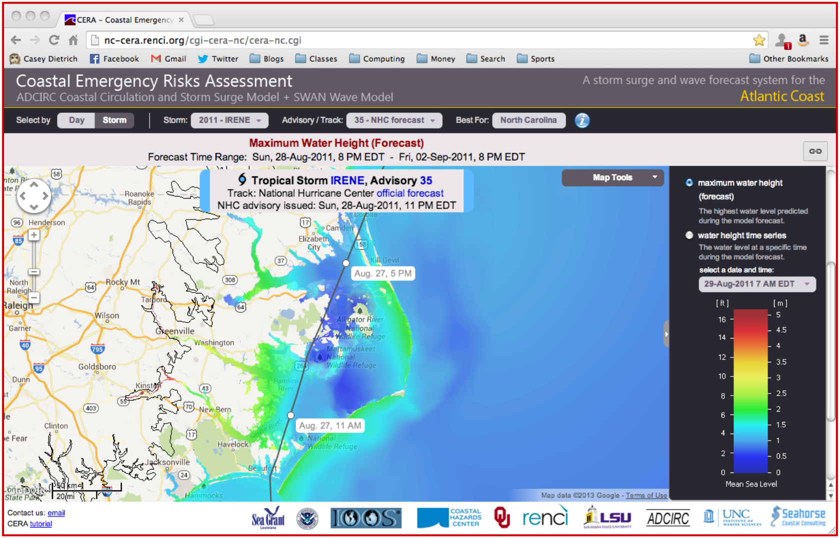
- Normal conditions with base meteorology from NOAA/NCEP
- Extreme conditions with storm advisories from NOAA/NHC

Guidance is interactive within Google Maps:

- View results as a time series or as maxima
- Select layers for:
  - Water levels (above MSL or above ground)
  - Waves (significant heights, peak periods)
  - Wind speeds
  - Hydrographs at NOAA/NOS gage stations

Strengthening Guidance for North Carolina

Example during Hurricane Irene (2011)



Some partners prefer guidance in other formats:

- Polygon-based formats:
  - Shapefiles and ancillary files for GIS
  - KML files for Google Earth
- These files can be overlaid with information from other sources

We developed Python-based scripts to convert SWAN+ADCIRC output

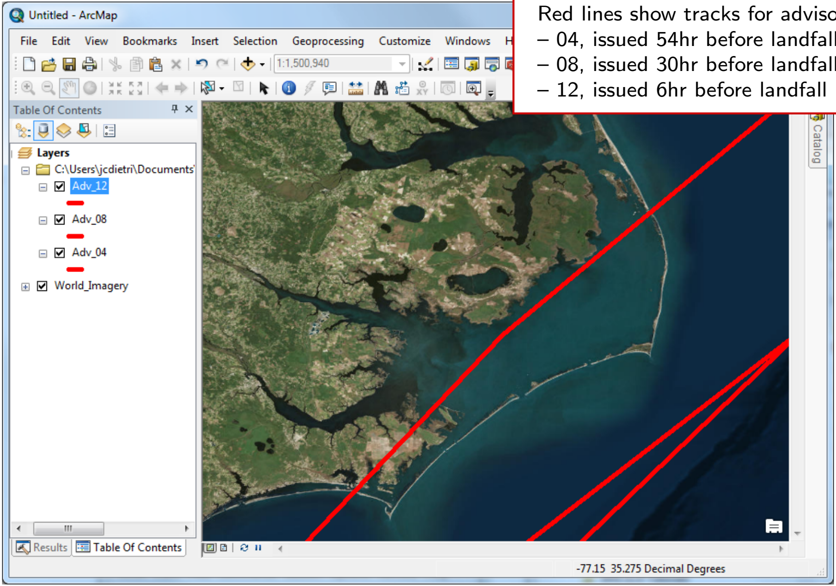
- Based on older scripts from BO Blanton, RA Luettich Jr
- Expanded to consider time series information, KML formats

Now sharing guidance in developmental formats with partners at NWS offices, state and local emergency management teams

- **Guidance products are generated and shared automatically**
- Goal – Integrate these products as downloads from NC-CERA

Strengthening Guidance for North Carolina

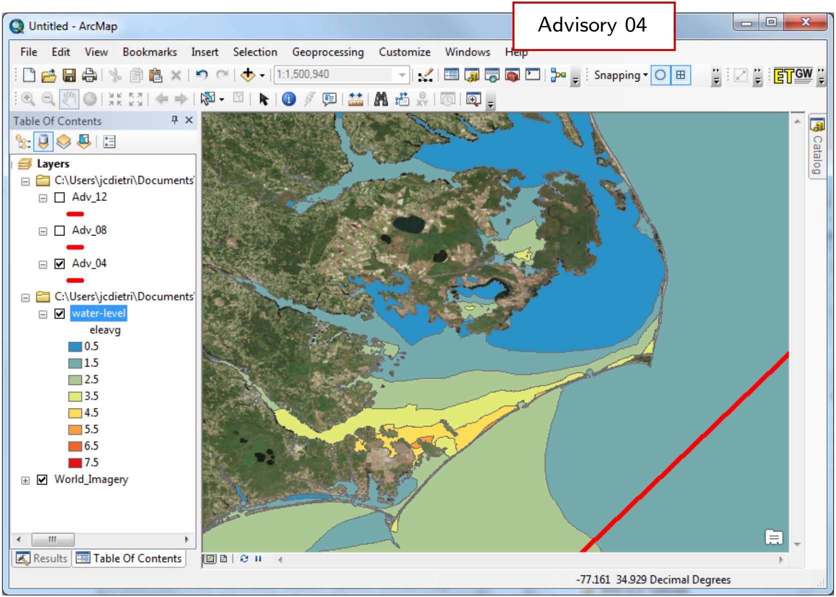
Maximum Water Levels during Hurricane Arthur (2014)



Red lines show tracks for advisories:
- 04, issued 54hr before landfall
- 08, issued 30hr before landfall
- 12, issued 6hr before landfall

Strengthening Guidance for North Carolina

Maximum Water Levels during Hurricane Arthur (2014)



Strengthening Guidance for North Carolina

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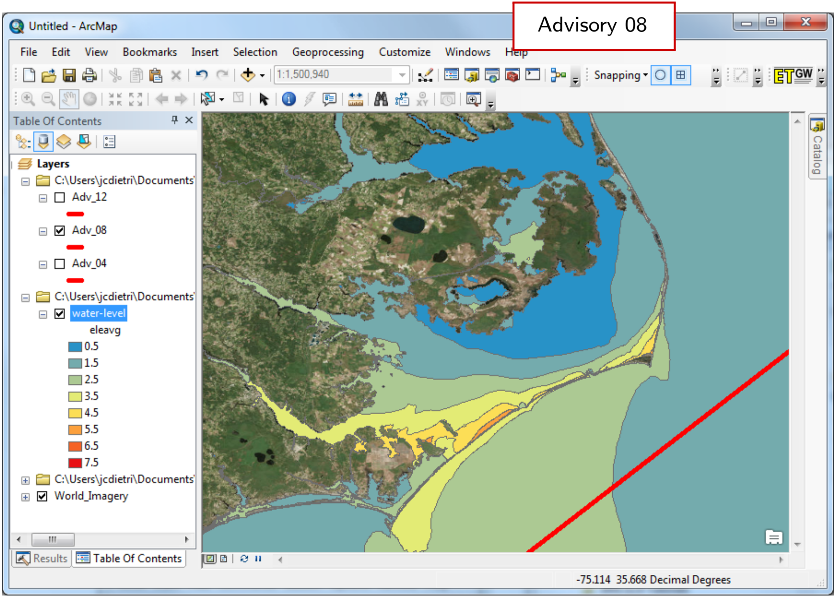

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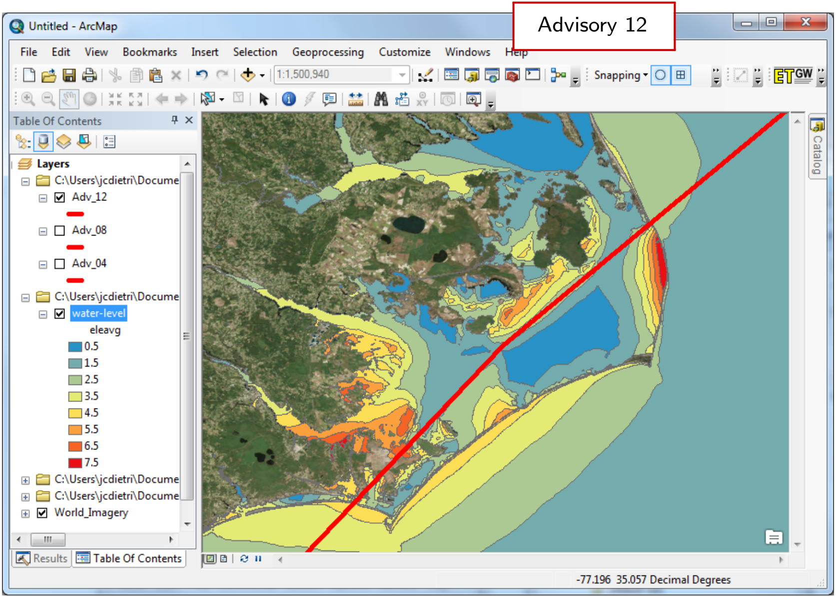

Summary

High-resolution models for southern Louisiana:

- Resolution varies from kilometers to meters in unstructured mesh
- Tight coupling of SWAN+ADCIRC
- Validation to wealth of measurement data

Real-time forecasting for Texas and North Carolina:

- Useful information despite track uncertainties
  - Arthur (2014) in NC
- CERA Web-based guidance for NC coast
- Expanding guidance to GIS and KML formats