NC STATE UNIVERSITY

Forecasting and Mapping of Coastal Flooding during Hurricanes

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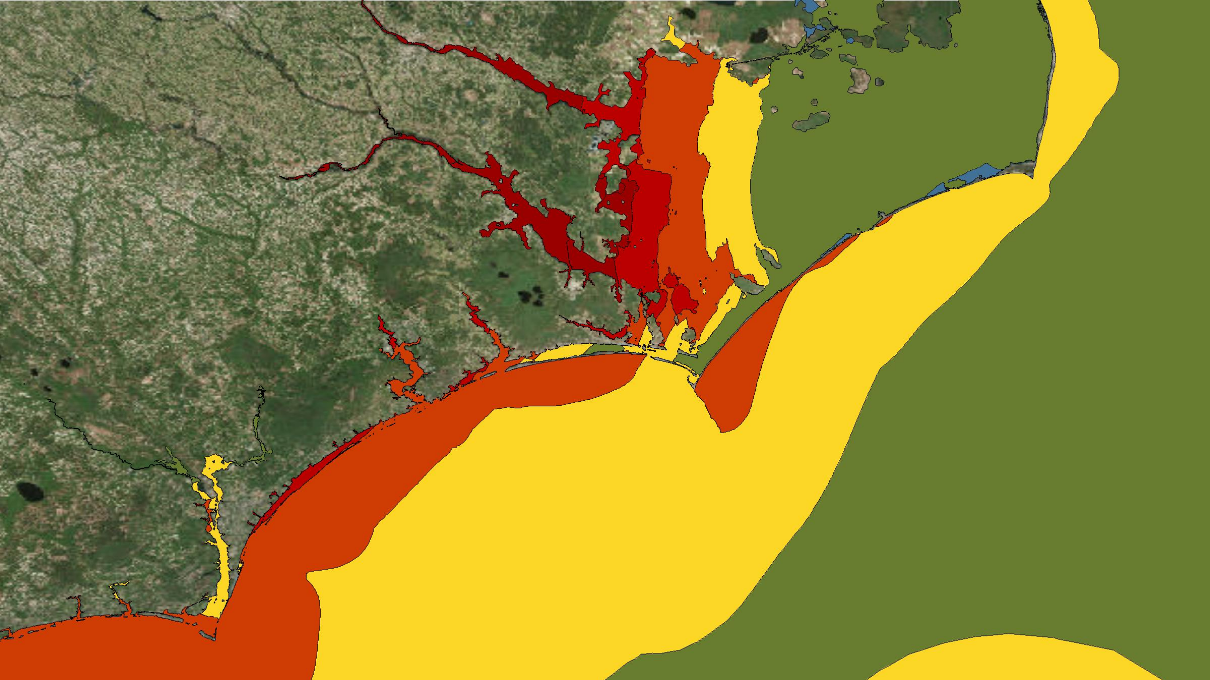
Numerical Analysis Seminar Series
NCSU Dep't of Mathematics, 19 March 2018



Predictive Modeling for Hurricane Waves and Storm Surge

- Wide Range of Spatial Scales
- Waves and Storm Surge
- Engineering Applications

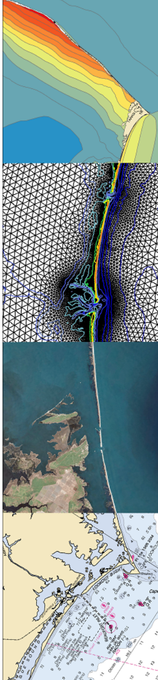
Real-Time Forecasting for North Carolina

- Unstructured, Finite Element Mesh
- Hurricane Florence (2018)

Improving Efficiency via Dynamic Load Balancing

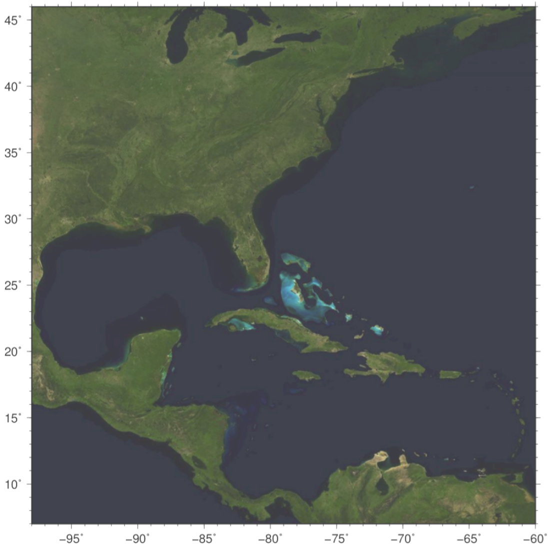
- Domain Decomposition
- Examples of Efficiency Gains

Summary



Wide Range of Spatial Scales

Gulf and Atlantic Coasts



Wide Range of Spatial Scales

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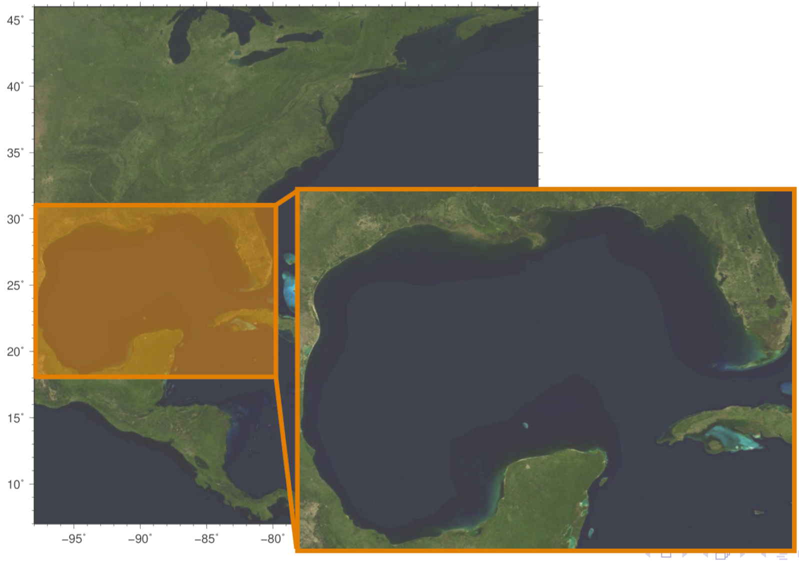

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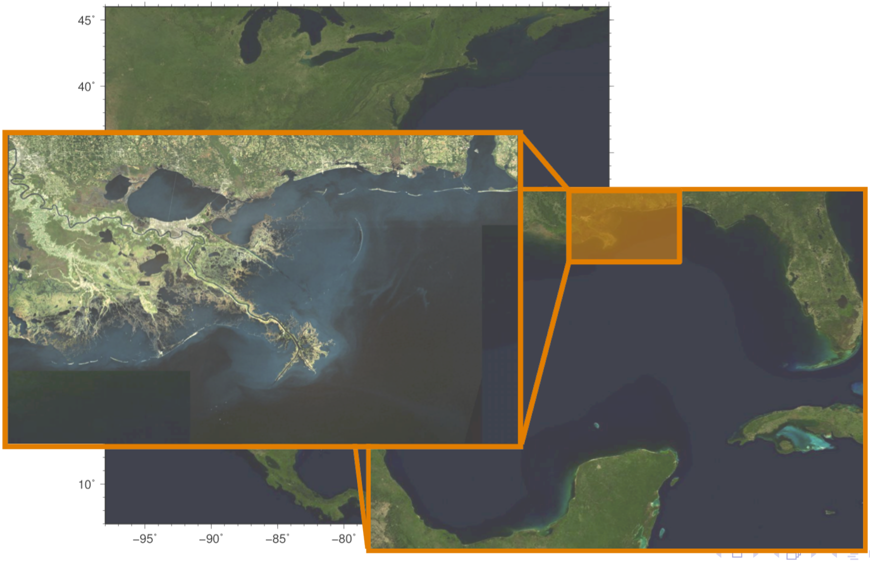
Gulf and Atlantic Coasts



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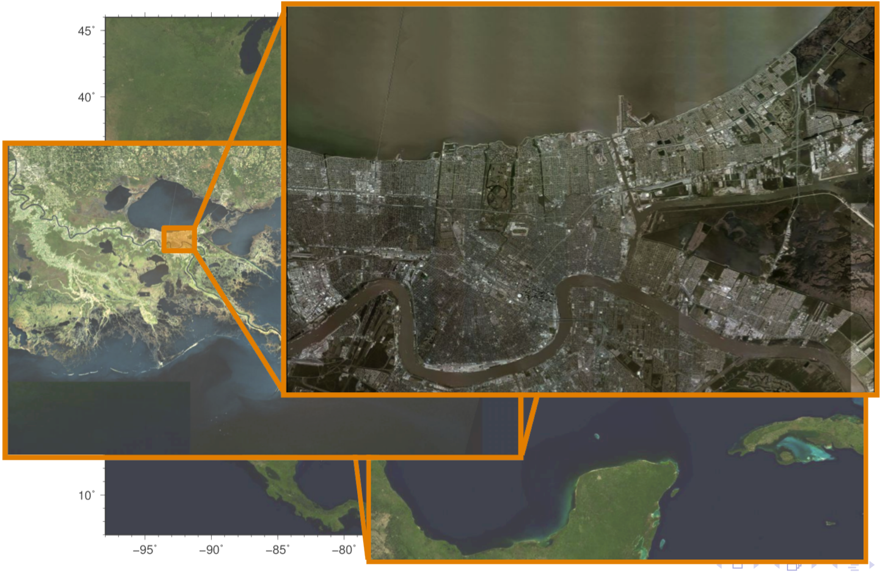
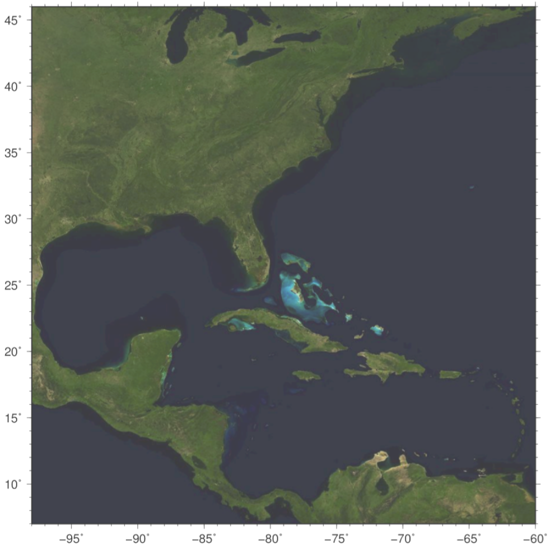


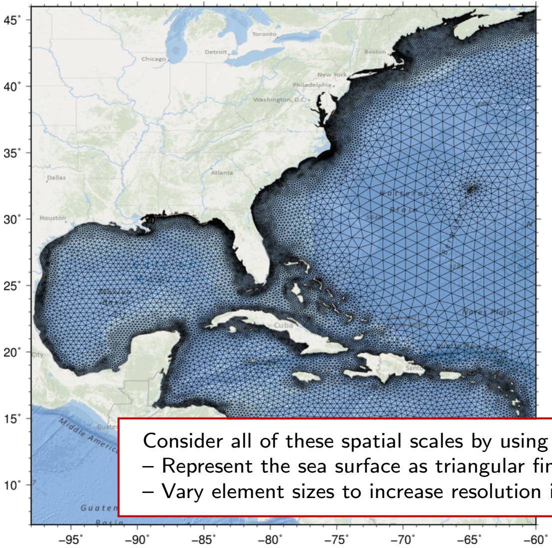
Wide Range of Spatial Scales

Gulf and Atlantic Coasts



Wide Range of Spatial Scales

Unstructured, Finite-Element Meshes



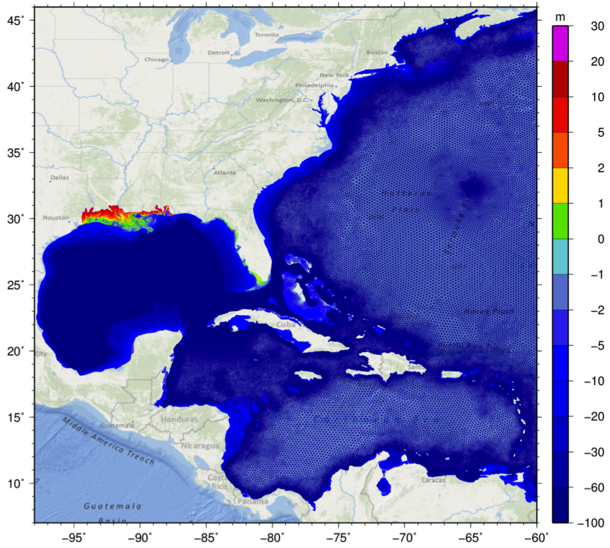
Consider all of these spatial scales by using *unstructured meshes*:

– 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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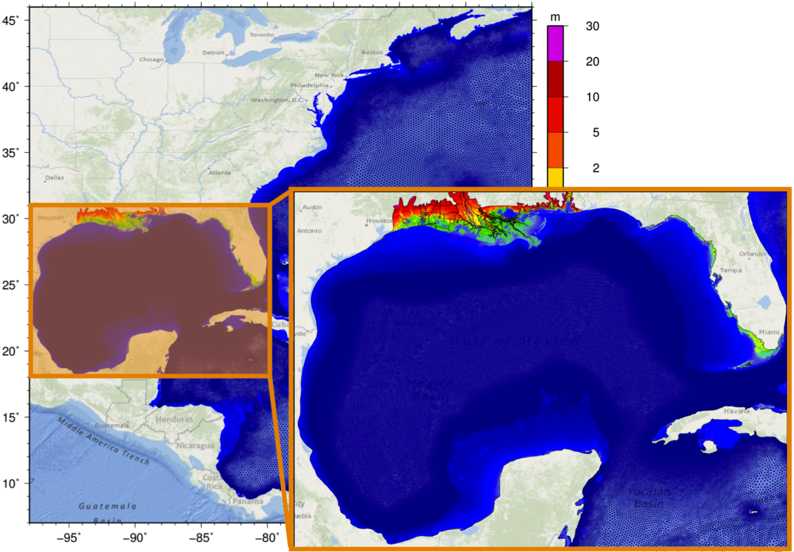

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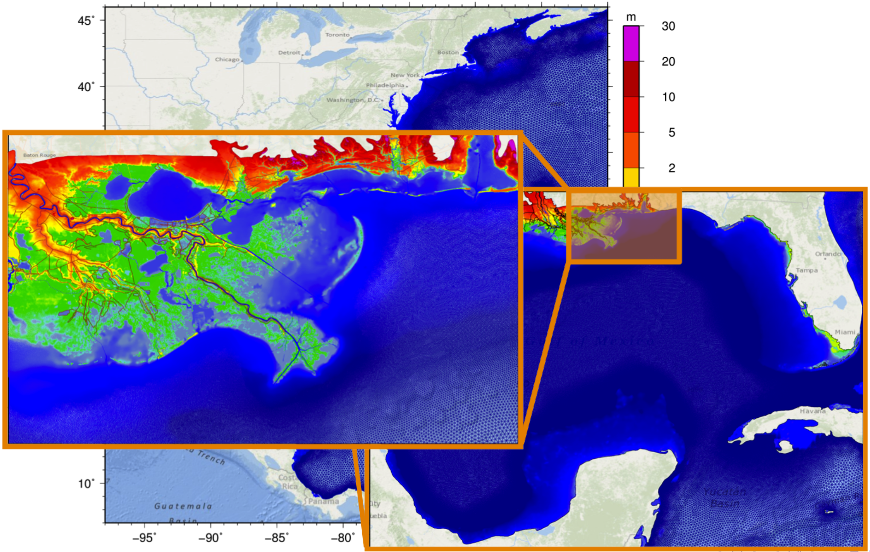

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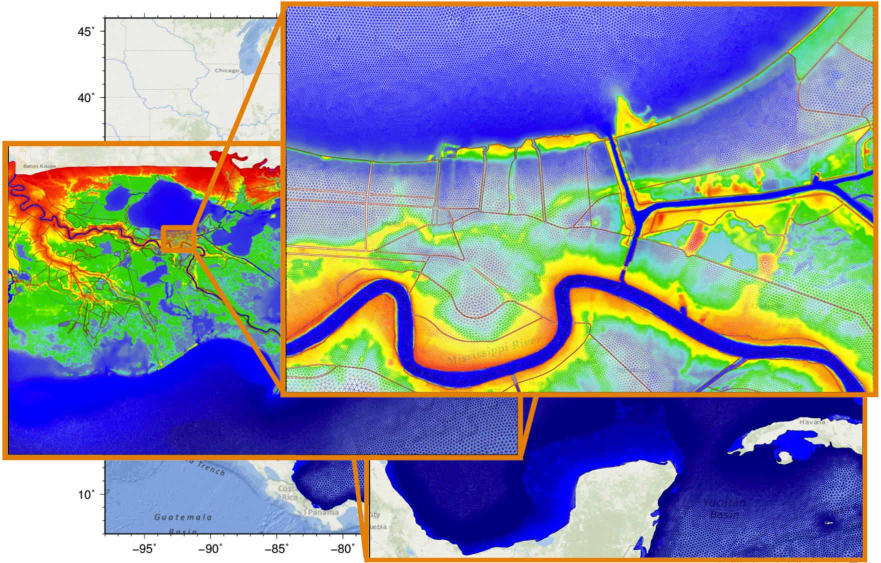
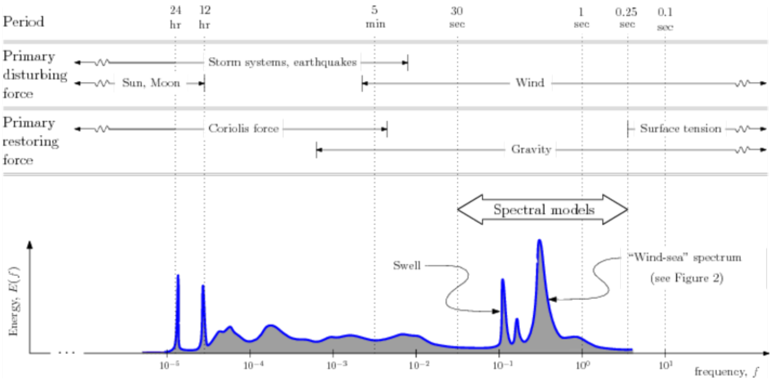


Waves and Storm Surge

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 long waves, we use ADCIRC

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

Solves the generalized wave continuity equation (GWCE) 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):

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

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

In geographic space:

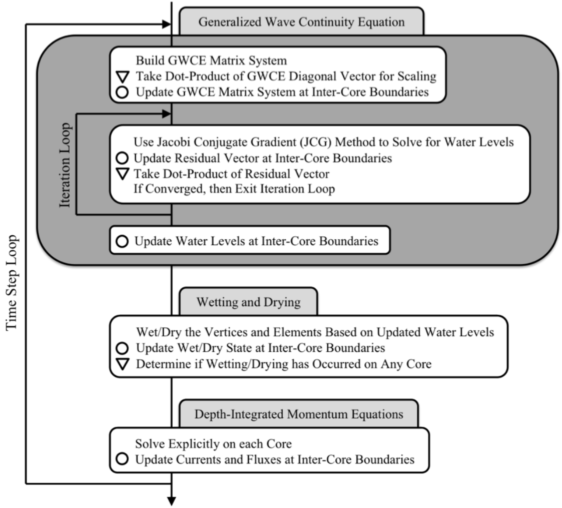
- Piecewise-linear, continuous, Galerkin finite elements
  - Unique values for (ζ, U, V) at every mesh vertex
- Typical minimum mesh spacings of 10 to 50 m

In time:

- Semi-implicit
  - Implicit solution of GWCE using Jacobi Conjugate Gradient (JCG) solver
  - Explicit solution of momentum equations with lumped mass matrix
- Fully explicit
  - Also possible to use lumped mass matrix for solution of GWCE
- Typical time steps of 0.5 to 10 sec

Waves and Storm Surge

ADCIRC Solution Algorithm



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:

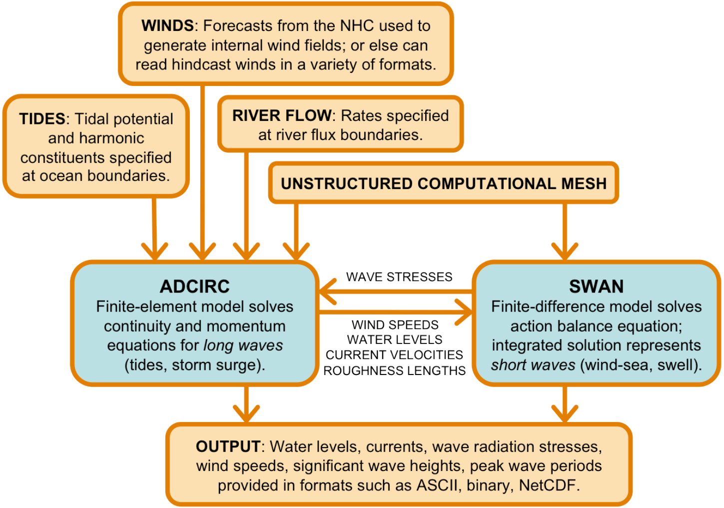
$$\frac{\partial N}{\partial t} + \nabla_{\mathbf{x}} \cdot \left[\left(\mathbf{c}_g + \mathbf{U} \right) N \right] + \frac{\partial c_\theta N}{\partial \theta} + \frac{\partial c_\sigma N}{\partial \sigma} = 0$$

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

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

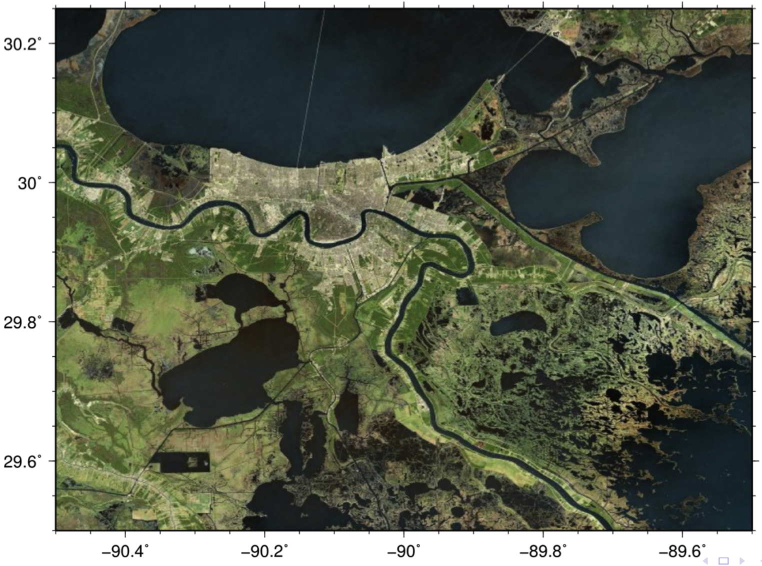
Waves and Storm Surge

Tight Coupling of SWAN+ADCIRC



Engineering Applications

Surge Barrier Design with the USACE



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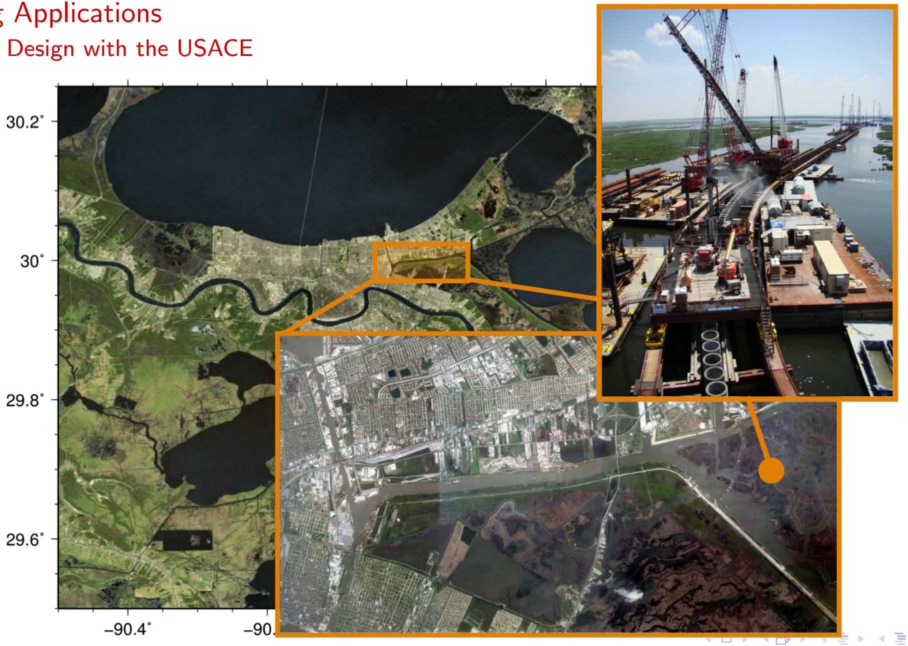
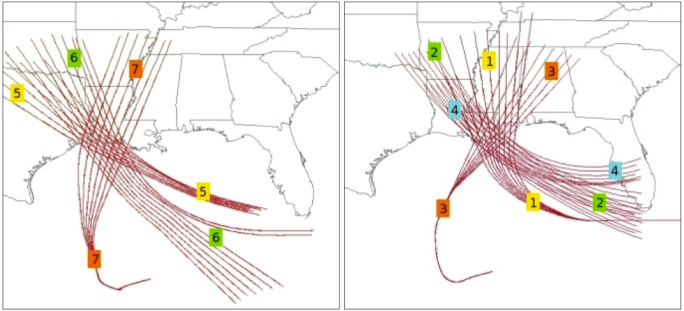


Joint Probability Method with Optimal Sampling (JPM-OS):

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



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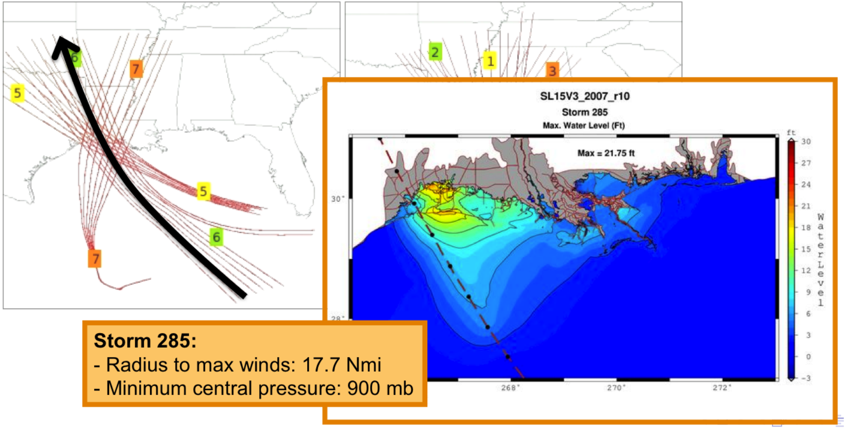
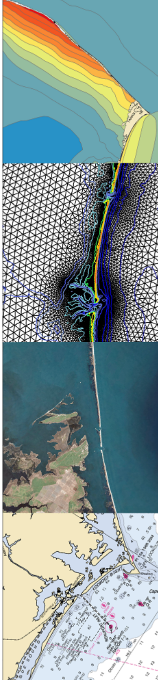
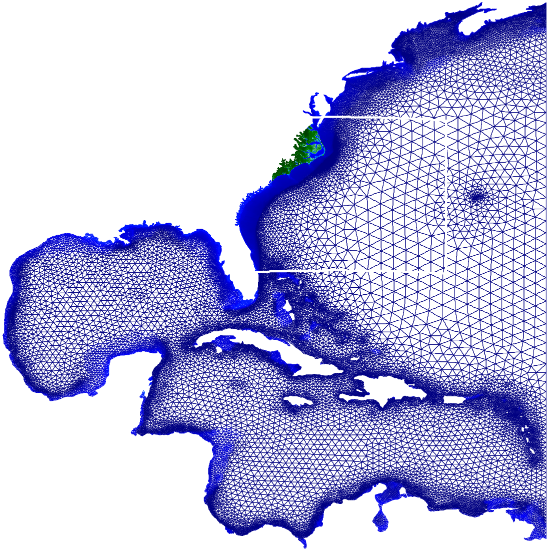




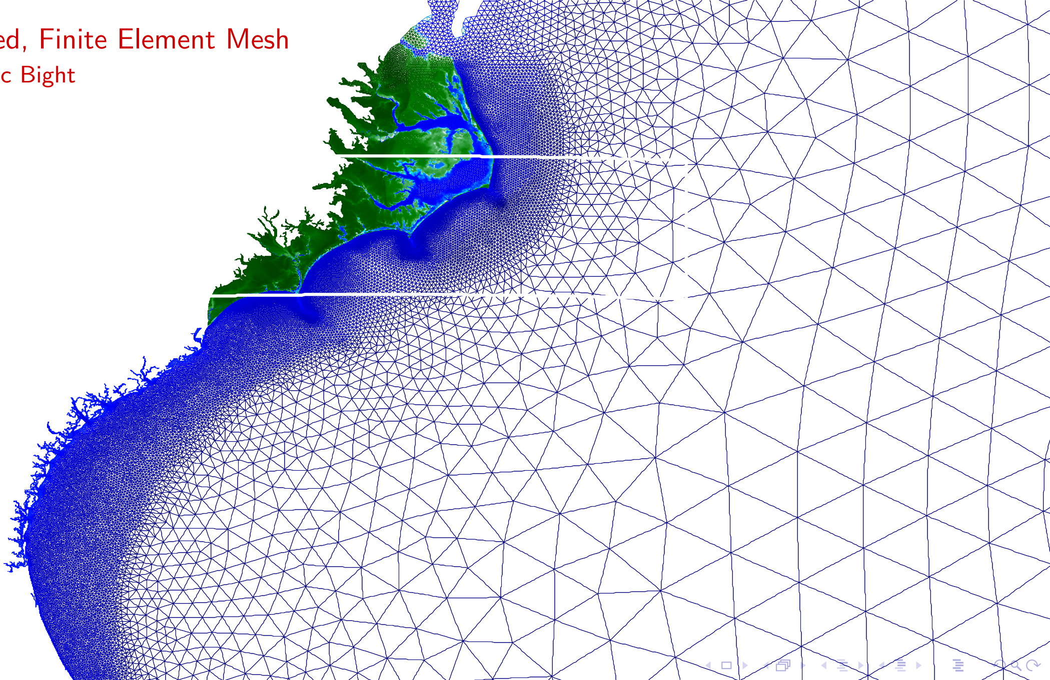
Unstructured, Finite Element Mesh

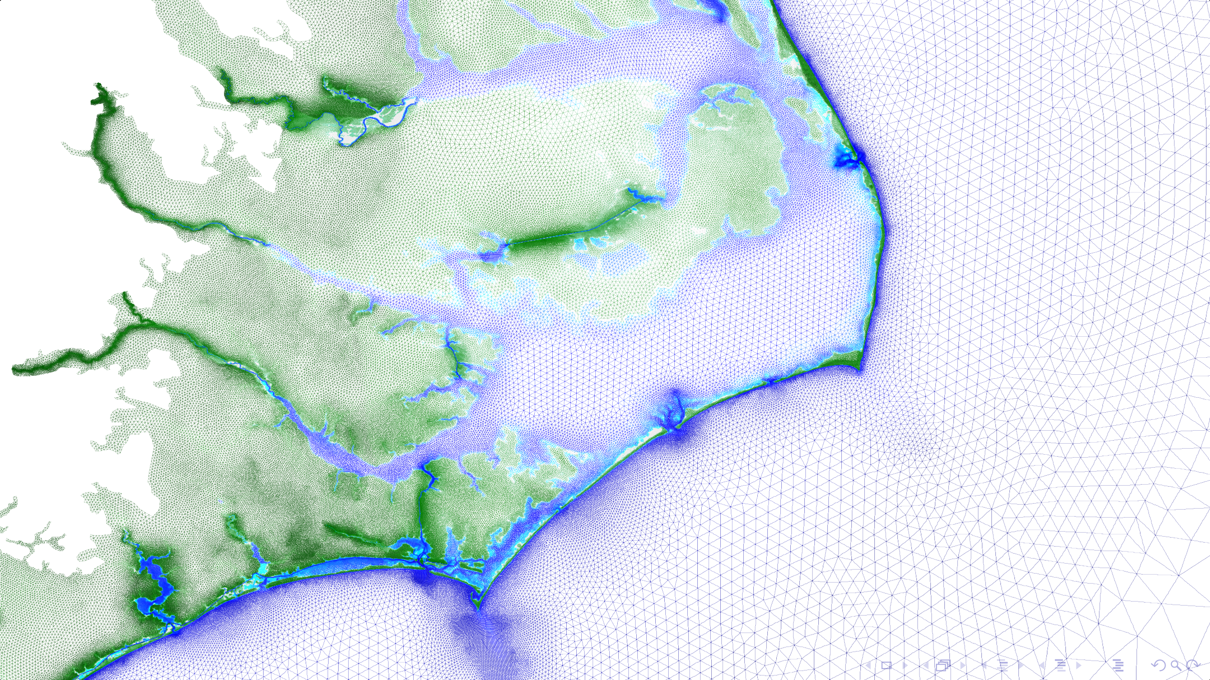
Western North Atlantic Ocean



Unstructured, Finite Element Mesh

South Atlantic Bight



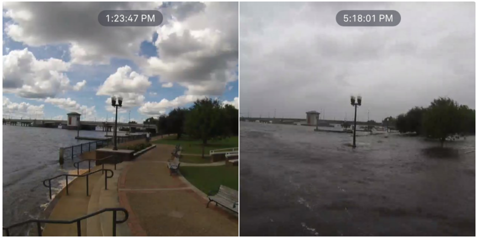


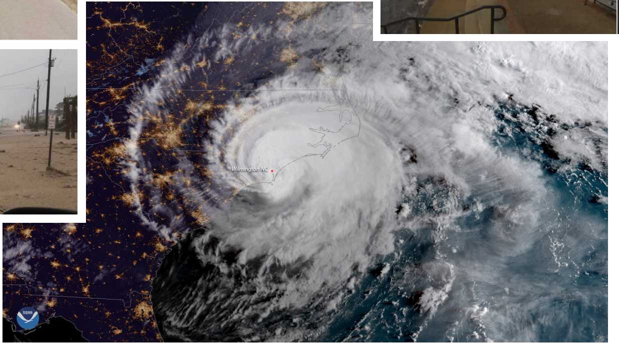
Hurricane Florence (2018)

Extensive Impacts to Coastal NC

Surf City NC (@AdamWGME)

Union Point in New Bern NC (@NWSEastern)



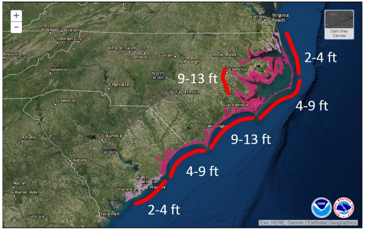


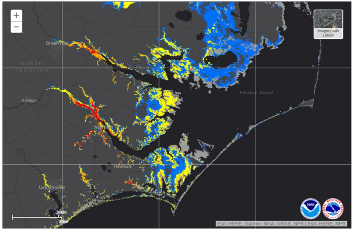
Florence making landfall on Fri Sep 14 (@NOAASatellites)

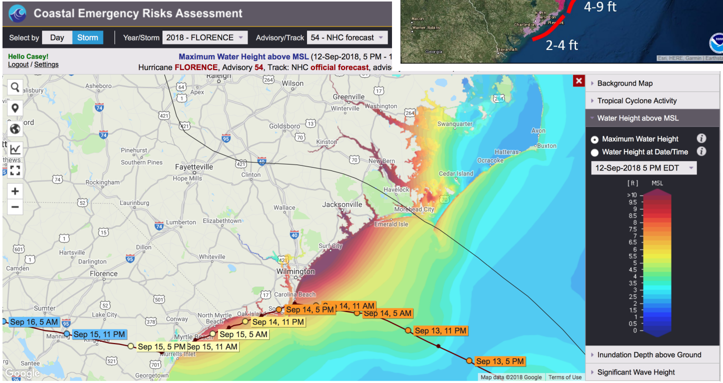
Hurricane Florence (2018)

Forecasts of Storm Surge

Surge and flooding guidance from the National Hurricane Center (NHC)







ADCIRC maximum water levels for Advisory 54 (CERA)

Hurricane Florence (2018)
ADCIRC Surge Guidance System (ASGS)

SWAN+ADCIRC can be employed in real-time

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

Wind fields from two sources:

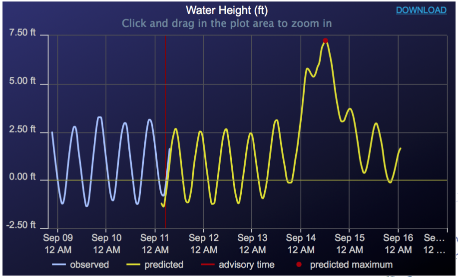
- Under normal conditions:
  - Downloaded from NAM model output by NOAA/NCEP
  - Converted into format compatible with SWAN+ADCIRC
- Under storm conditions:
  - Download advisories from NOAA/NHC
  - Generate wind fields using parametric model (Holland, 1980)

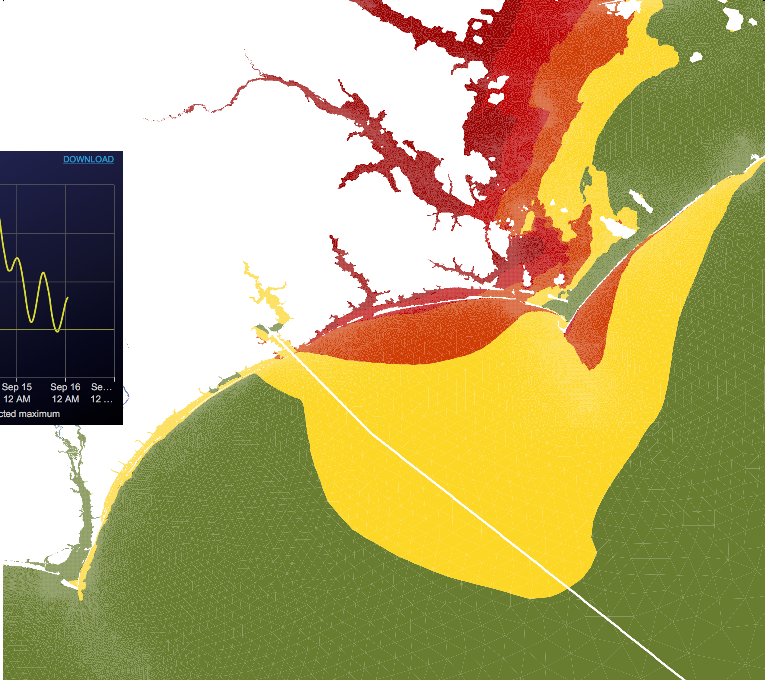
Guidance can be shared in multiple formats:

- Send directly to stakeholders (NC Emergency Management)
- Share publicly via web service (`http://www.adcirc.org`)

Hurricane Florence (2018)

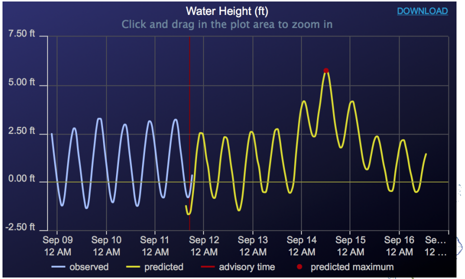
Adv 48 – Sep 11 Tue 5am

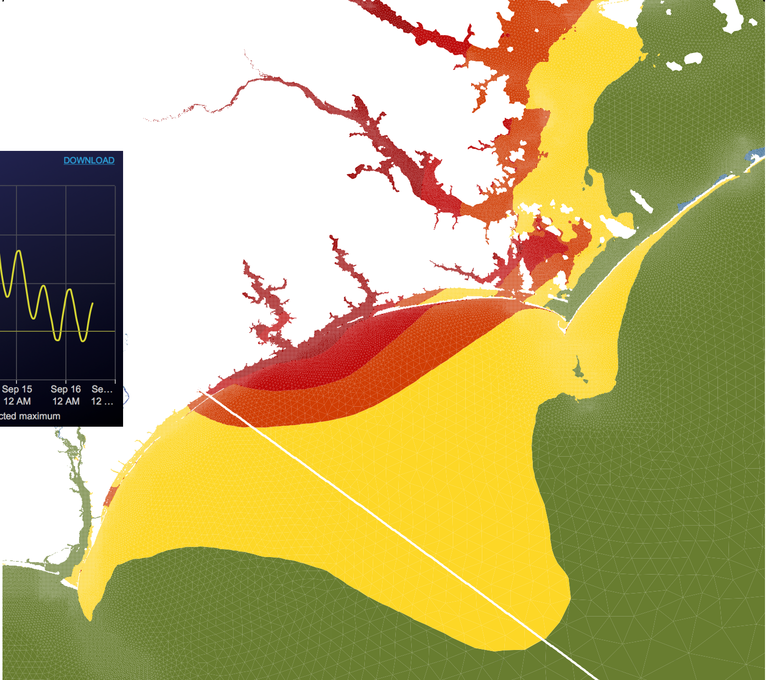




Hurricane Florence (2018)

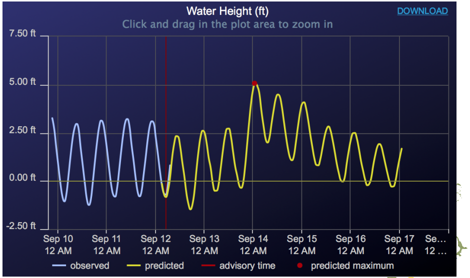
Adv 50 – Sep 11 Tue 5pm

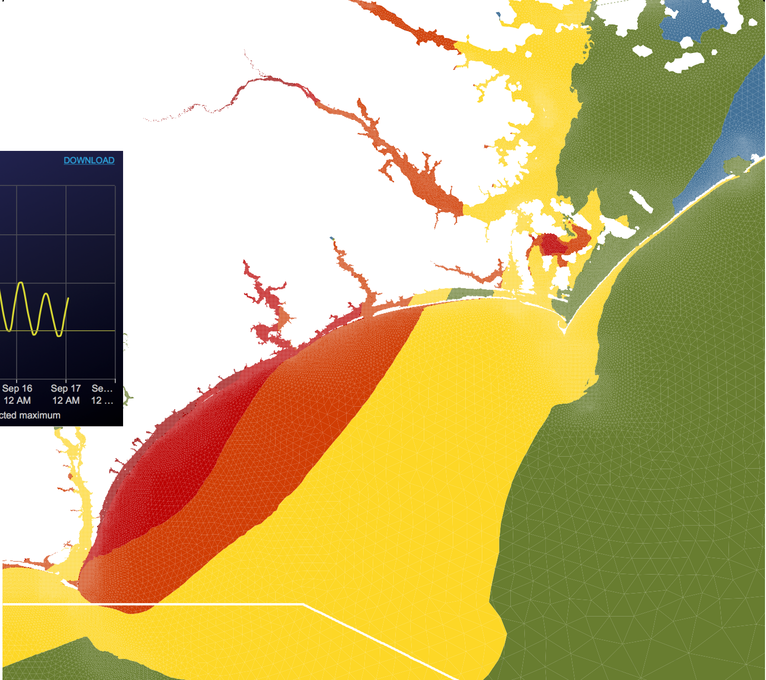




Hurricane Florence (2018)

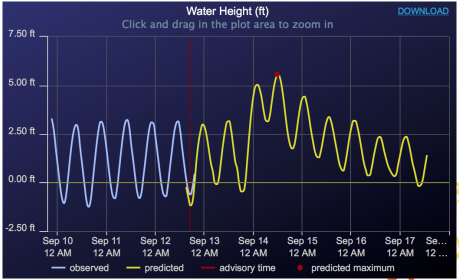
Adv 52 – Sep 12 Wed 5am

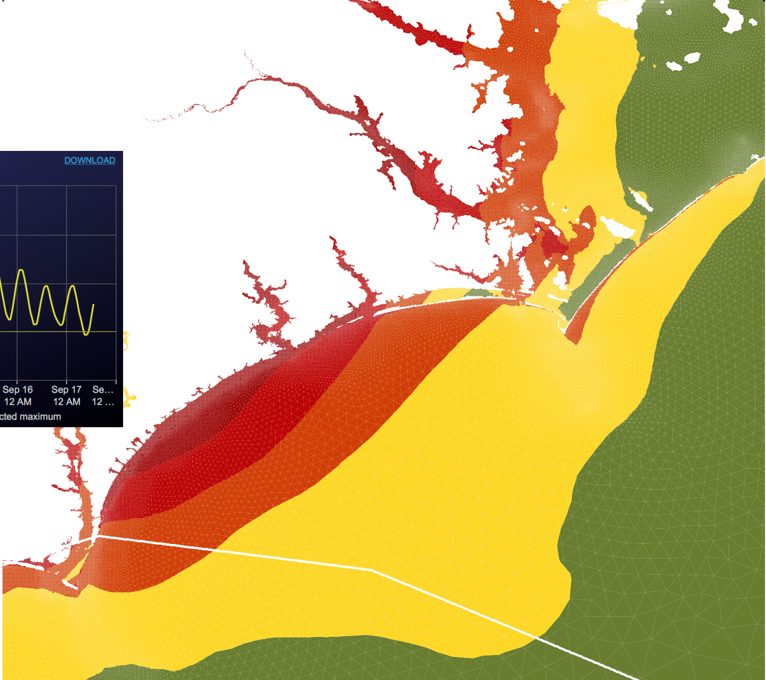




Hurricane Florence (2018)

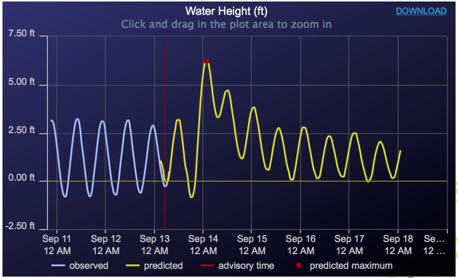
Adv 54 – Sep 12 Wed 5pm

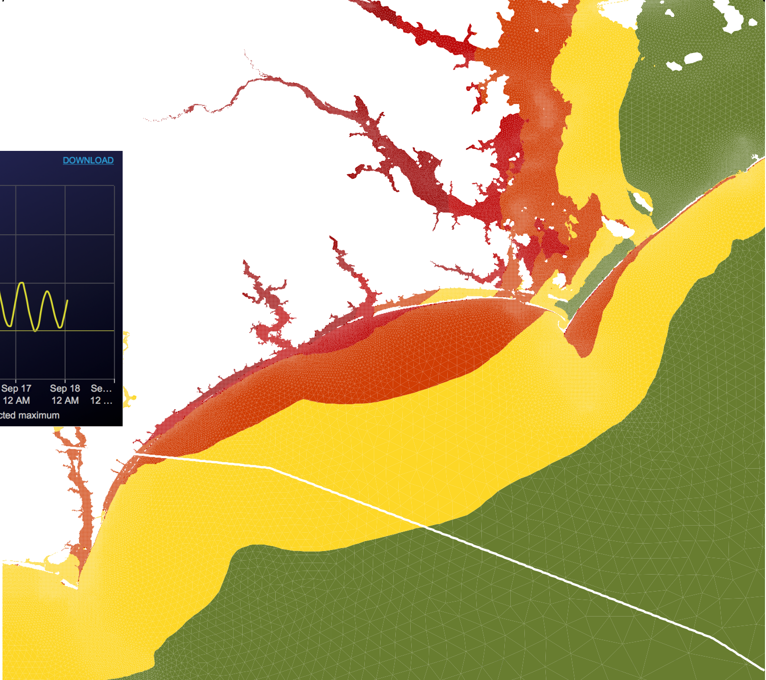




Hurricane Florence (2018)

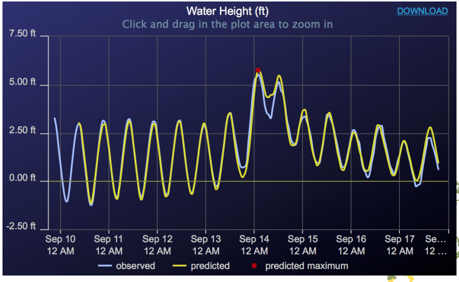
Adv 56 – Sep 13 Thu 5am

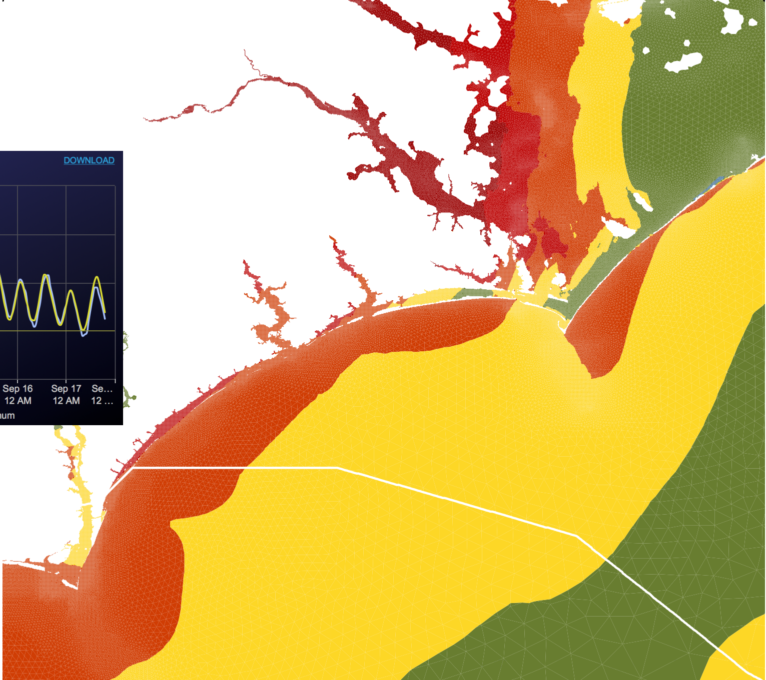




Hurricane Florence (2018)

Best-Track Hindcast





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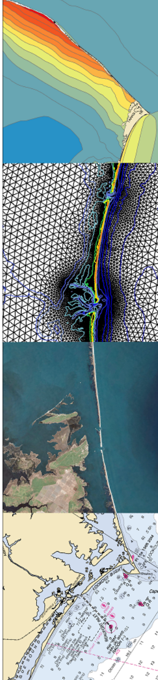
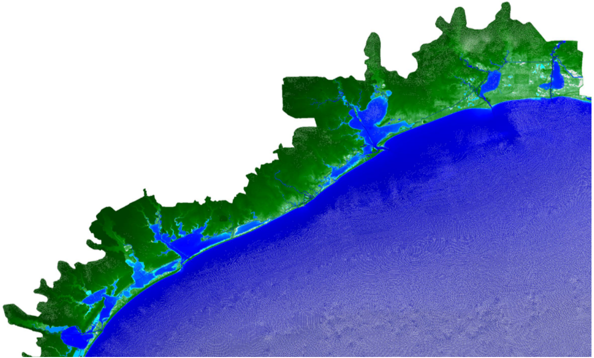


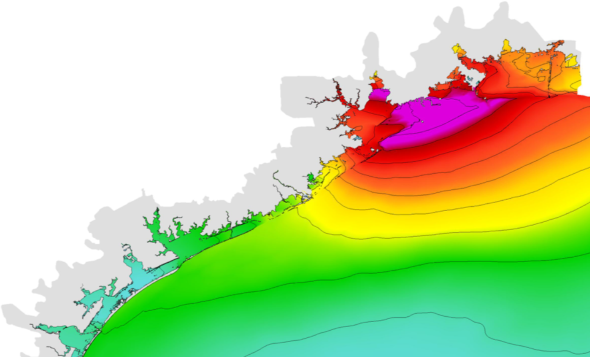
Domain Decomposition

What About the Dry Regions?

Example ADCIRC simulation for Hurricane Ike (2008):

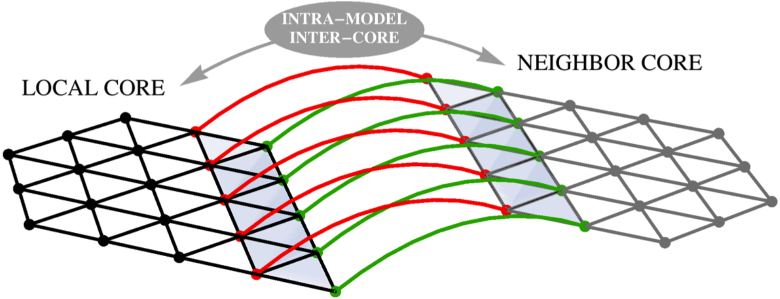
- The mesh (on left) includes floodplains along the entire Texas coastline
- About 1/2 is wet at the start, and only 2/3 is wet at the peak inundation (on right)
- **What can we do with the 1/3 of the mesh that is never used?**





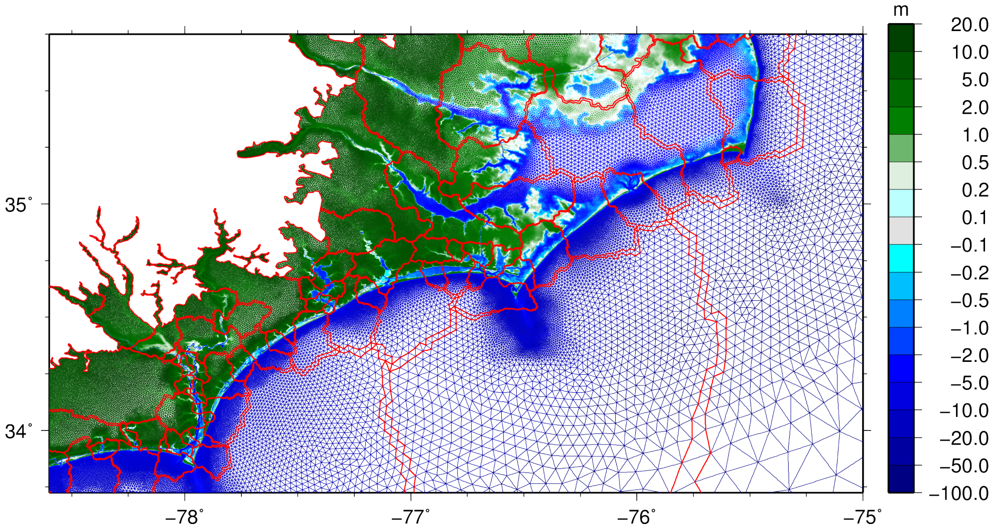
Domain Decomposition

Schematic of Parallel Communication



Domain Decomposition

Example for Realistic Domain



Domain Decomposition

Integration with Zoltan Library

Working closely with the Notre Dame team

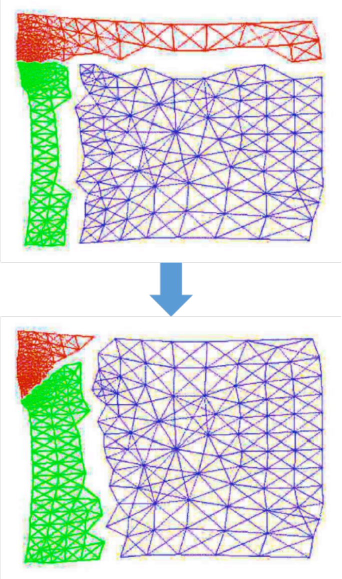
- Keith Roberts, Joannes Westerink

Integrated the **Zoltan toolkit** with ADCIRC

- Parallel, dynamic load balancing
- At checkpoints, rebalance for latest workload
- Migrate information between CPUs

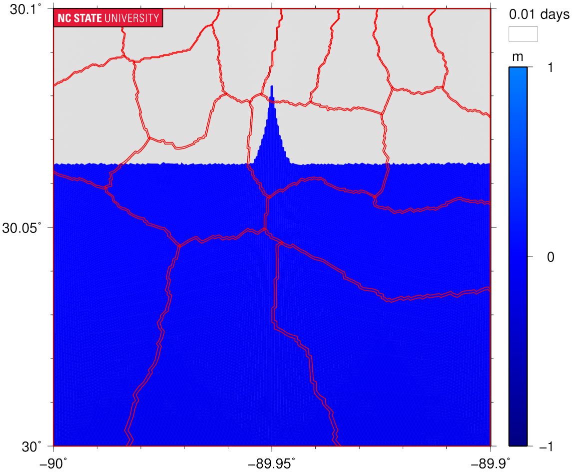
Progress in the past year:

- Streamlined the migration
- Hardened the integration
- Expanded the testing



Examples of Efficiency Gains

Simple Tide in Idealized Channel



Simple channel and floodplain

- Depths from -4 m to +2 m
- Tidal range from -1 m to +1 m
- Expect a lot of wetting and drying

Initial decomposition is sub-optimal

- 4 CPUs start fully wet
- 5 CPUs start partly wet/dry
- 6 CPUs start fully dry

Wall-clock time of about 17.6 min

Examples of Efficiency Gains

Simple Tide in Idealized Channel

Now the workload is rebalanced

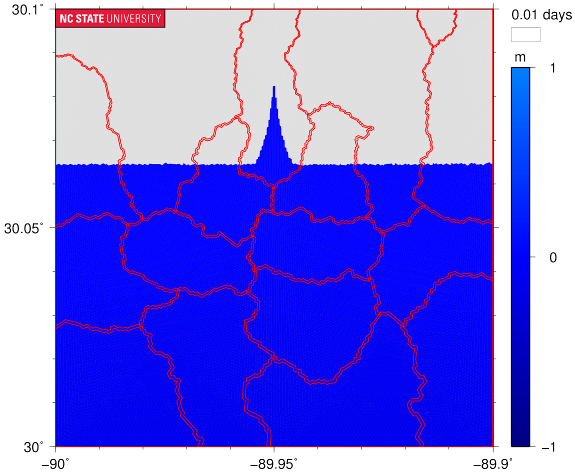
- Total of 28 migration events
- Total of 11 sec doing migration

Rebalancing during first tidal cycle

- Need to weigh cost vs benefit
- If an element is in the inter-tidal zone, then keep it wet

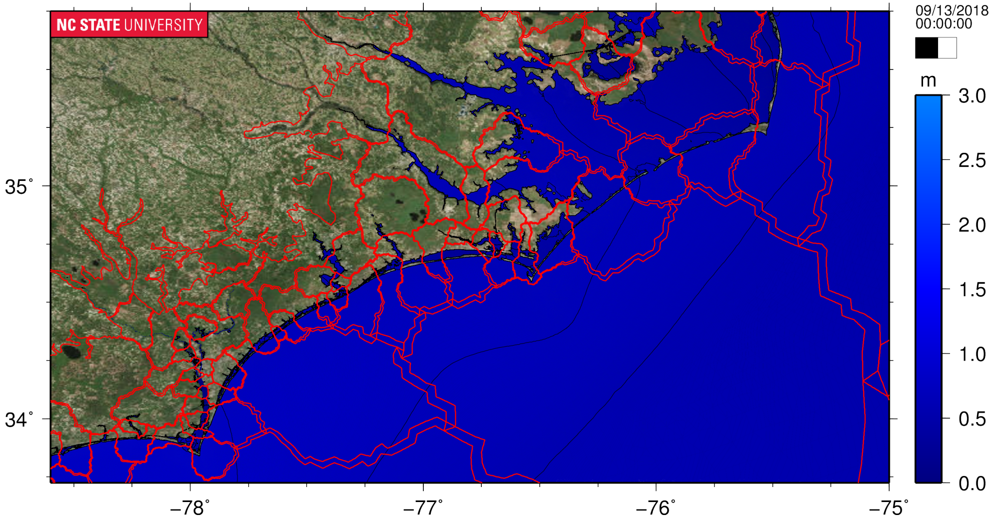
Wall-clock time of 11.2 min

- **Speed-up of 36 percent!**



Examples of Efficiency Gains

Florence (2008) in North Carolina



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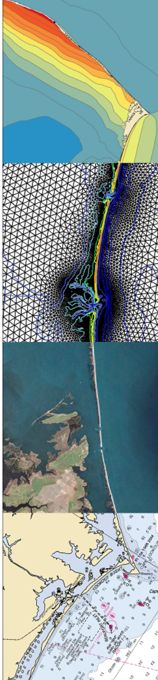

Summary

Forecasting and Mapping of Coastal Flooding during Hurricanes

Real-time forecasting for coastal North Carolina:

- Available at: `www.adcirc.org`
- Matthew (2016), Harvey & Irma (2017), Florence & Matthew (2018)
  - Providing guidance for multiple states
  - Every advisory and perturbations
- Working with NCEM to support their decision-making

Dynamic load balancing:

- Need to weigh cost vs benefit
  - Revised to minimize number of rebalances
  - Careful to select buffer between wet/dry
- Timings are encouraging
  - Large speed-ups (near theoretical) without sacrificing accuracy