NC STATE UNIVERSITY

Hurricane Wave and Storm Surge Forecasting for the North Carolina Coast

JC Dietrich[1], A Thomas[1], A Behnia[2], CN Dawson[2]

[1]Dep't of Civil, Construction, and Environmental Engineering, NC State University
[2]Inst. for Computational Engineering and Sciences, University of Texas at Austin

Dep't of Civil and Environmental Engineering
Jackson State University, Jackson MS, 4 May 2016

COASTAL RESILIENCE CENTER
A U.S. Department of Homeland Security Center of Excellence

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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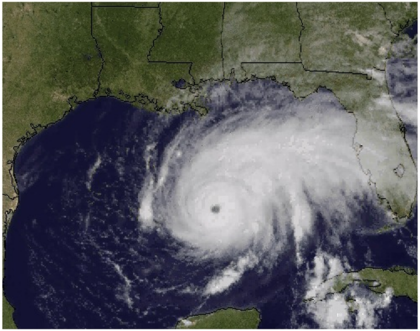
Hurricane Season 2005

Impacts on Southern Louisiana

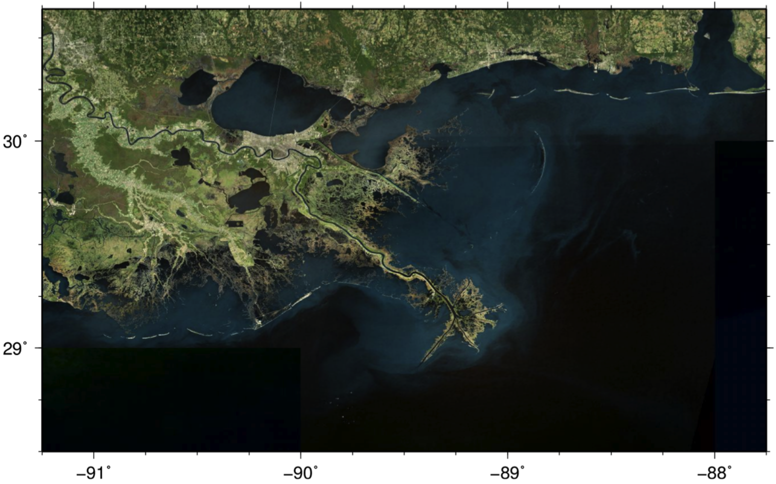
Katrina: 08/28 - 08/29

Rita: 09/22 - 09/24



Hurricane Season 2005

Flooding of New Orleans

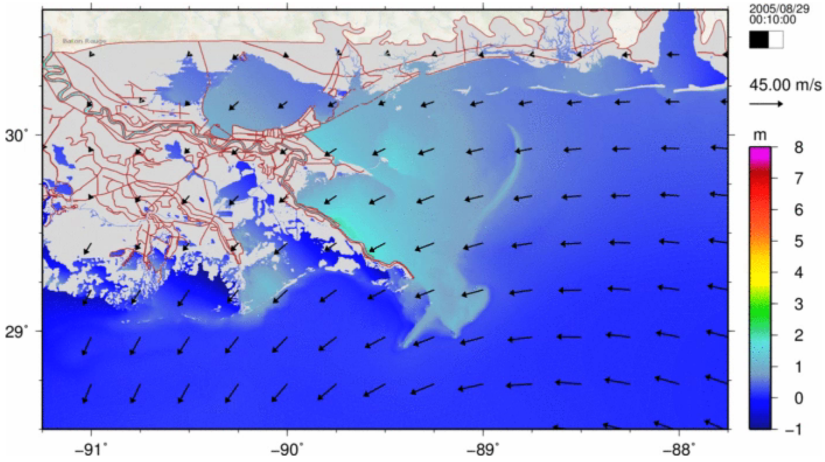


Hurricane Season 2005

Flooding of New Orleans

Hurricane Season 2005

Katrina (2005) 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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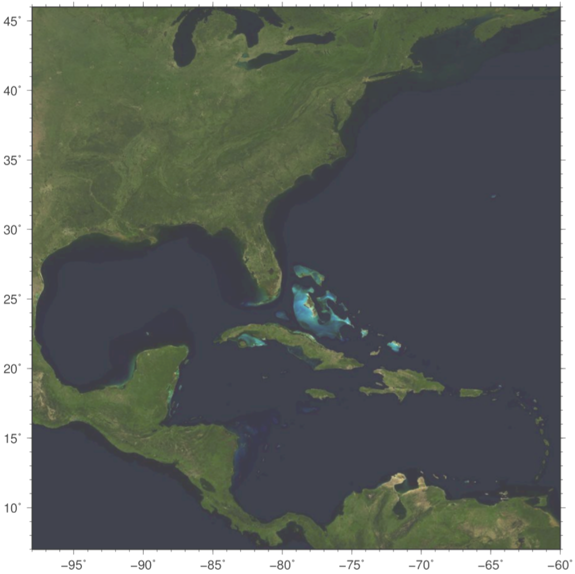
Wide Range of Spatial Scales

Gulf and Atlantic Coasts



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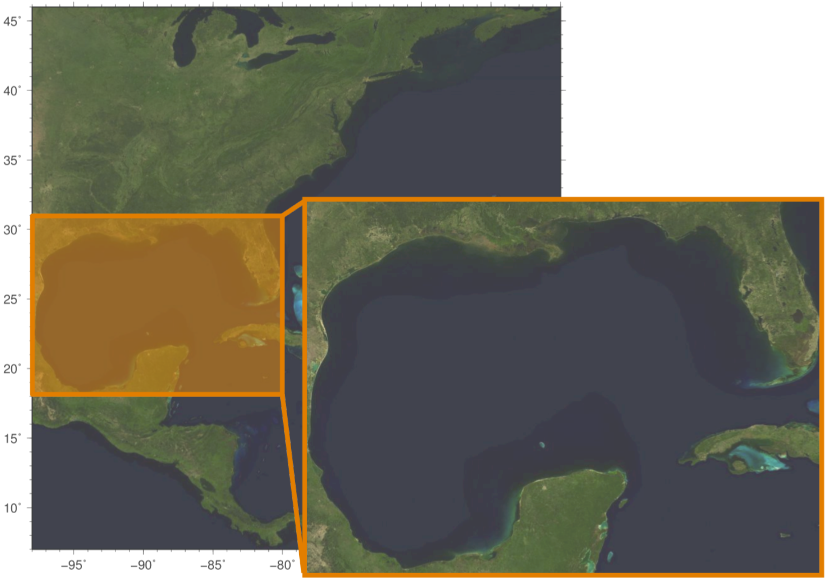

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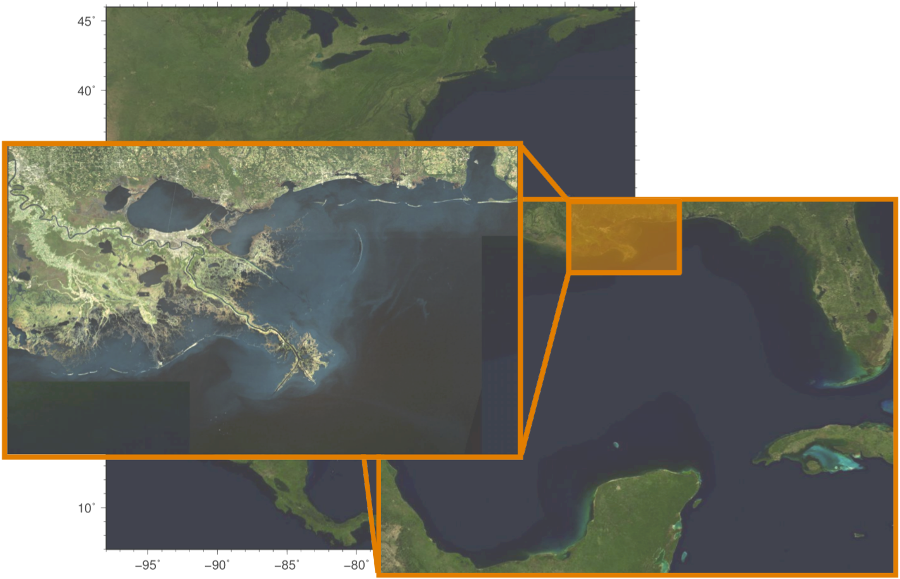

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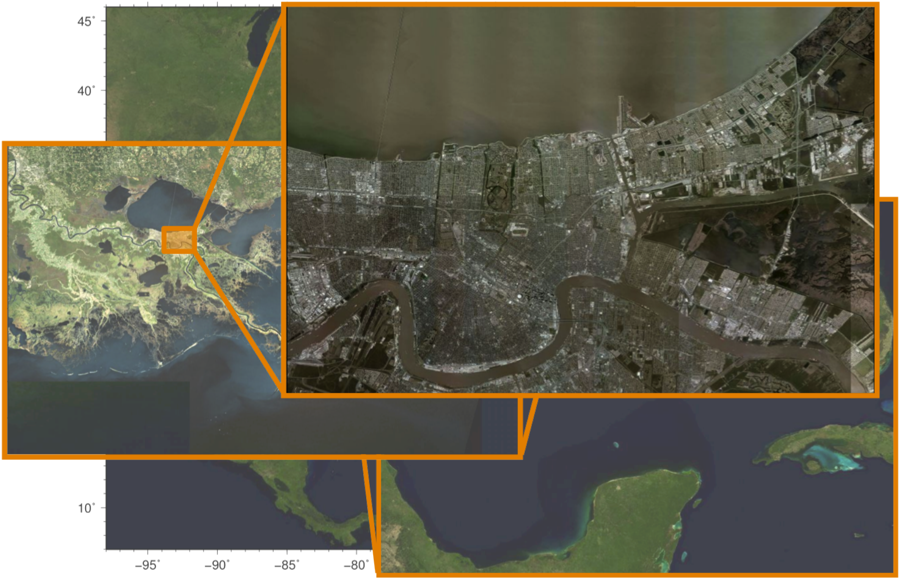
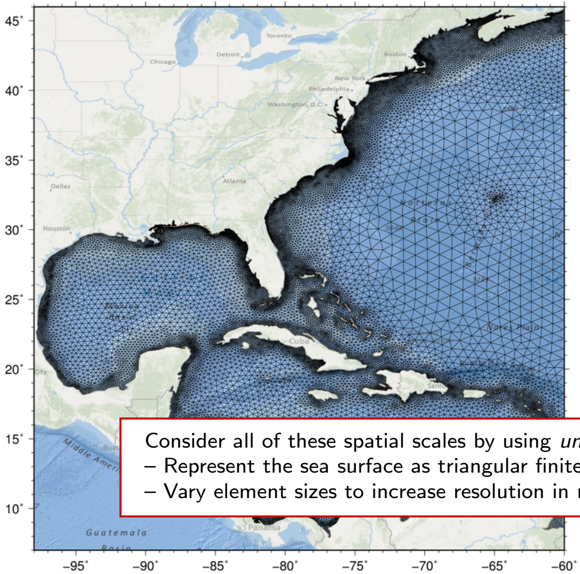


Wide Range of Spatial Scales

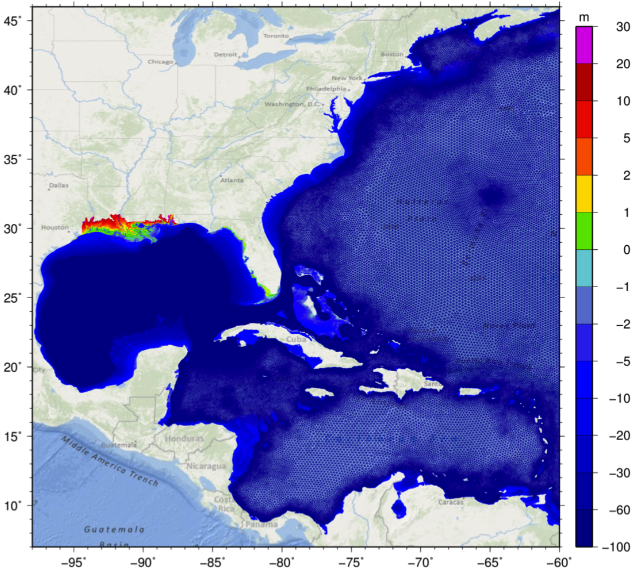
Unstructured, Finite-Element Meshes



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



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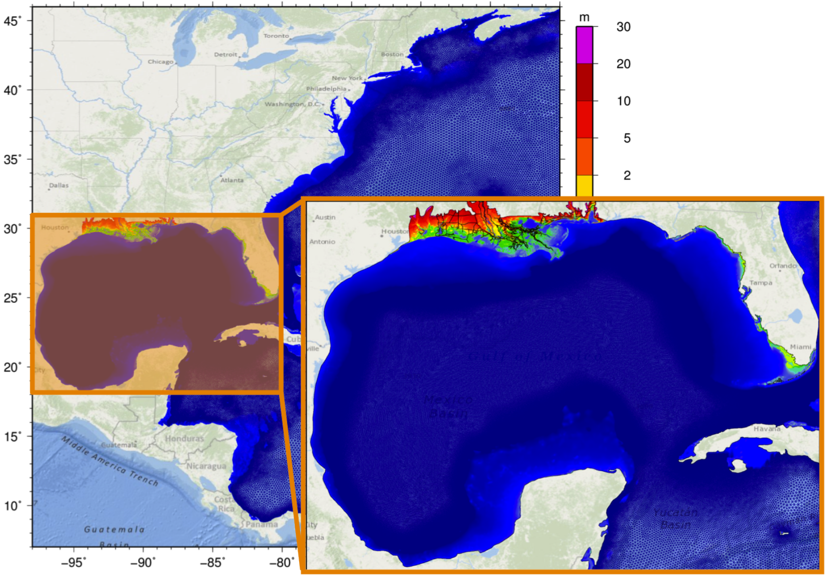

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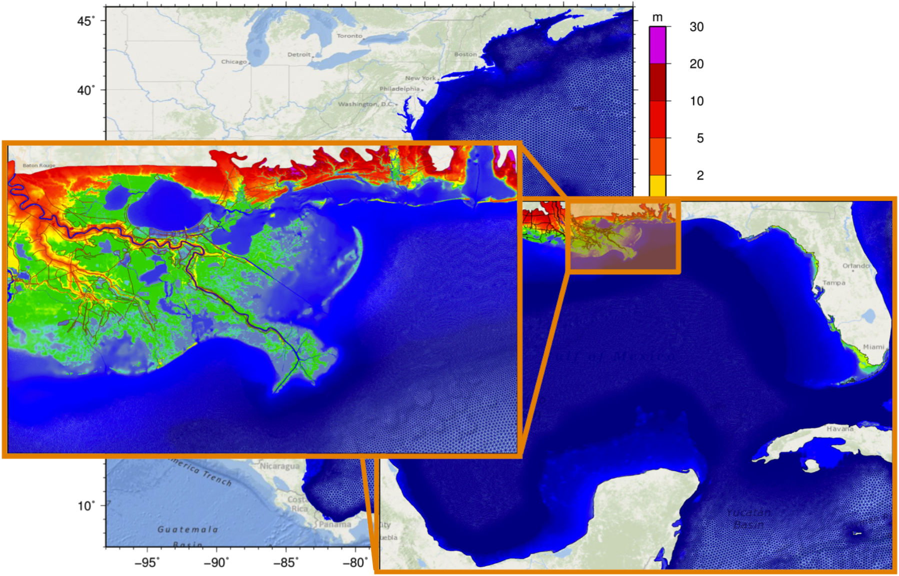

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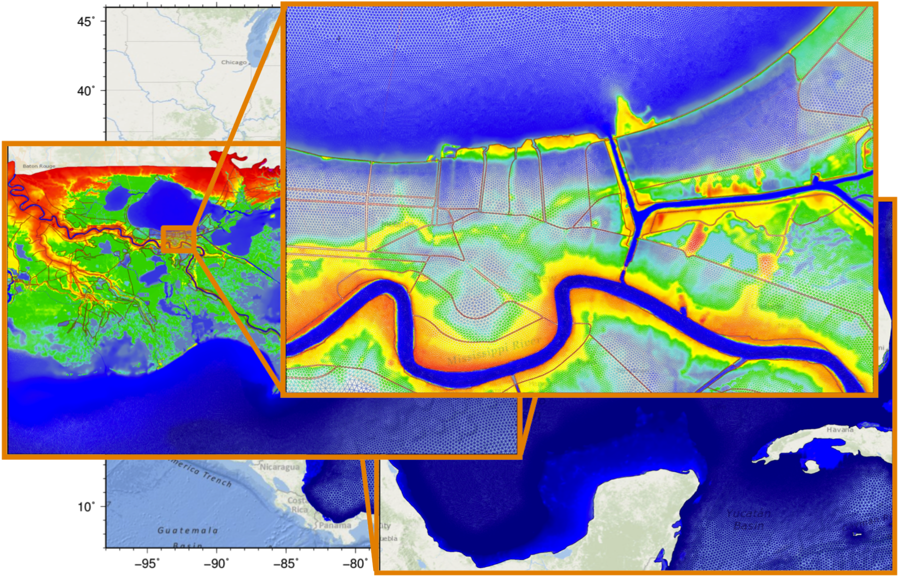
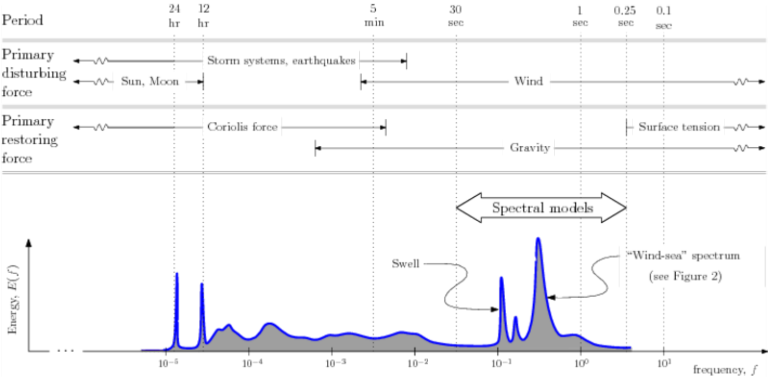


Waves and Storm Surge

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:

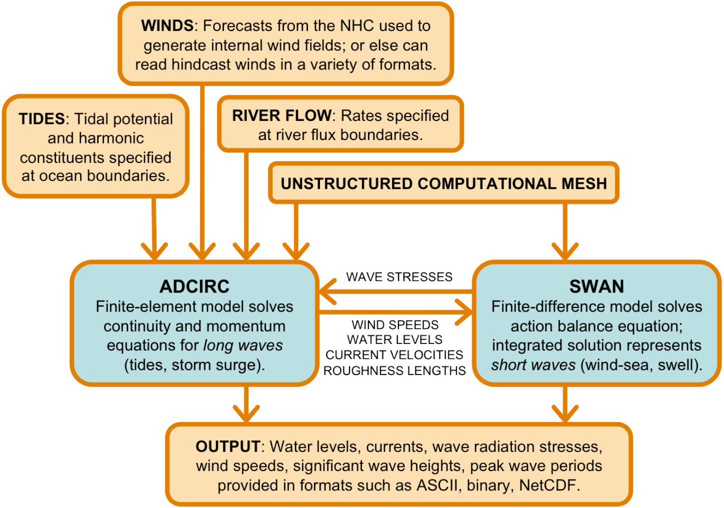
$$\frac{\partial^2 \zeta}{\partial t^2} + \tau_0 \frac{\partial \zeta}{\partial t} + \frac{\partial \tilde{J}_x}{\partial x} + \frac{\partial \tilde{J}_y}{\partial y} - UH \frac{\partial \tau_0}{\partial x} - VH \frac{\partial \tau_0}{\partial y} = 0$$

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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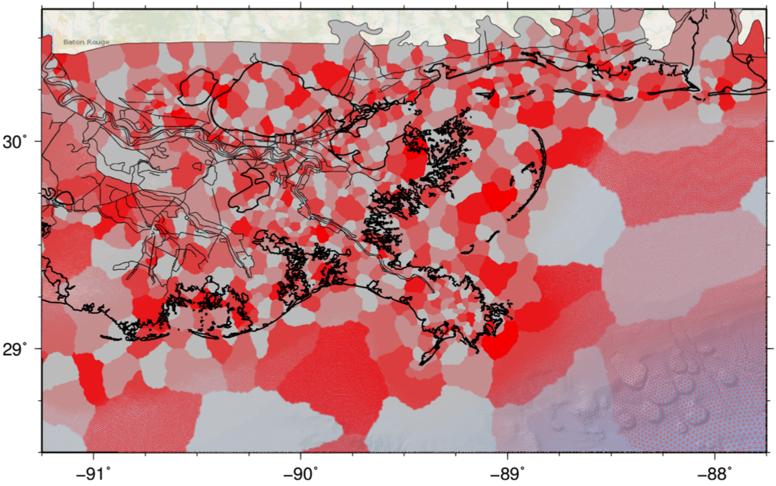
Tight Coupling of SWAN+ADCIRC
Domain Decomposition

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

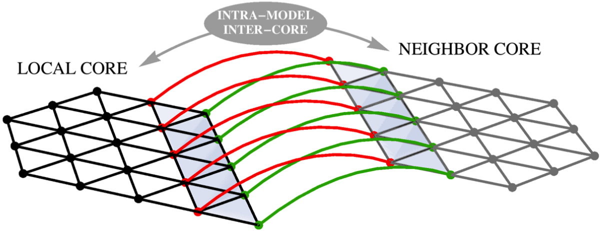
- Each computational core works on its own sub-mesh



Tight Coupling of SWAN+ADCIRC

Parallel Communication

Communication between cores at sub-mesh boundaries



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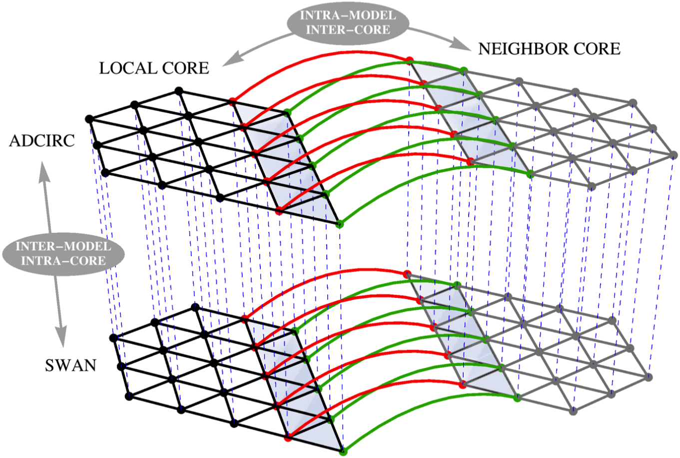
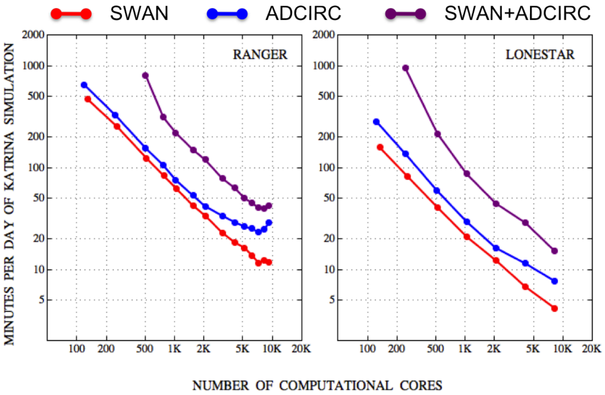


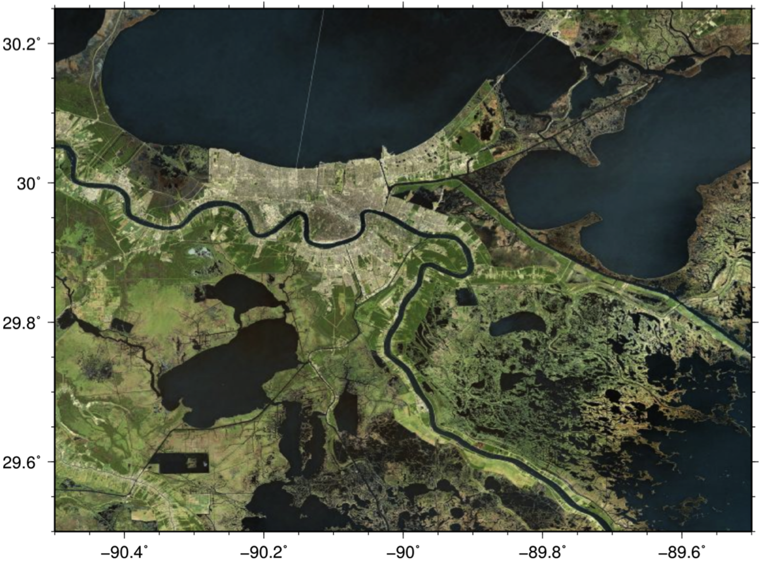
Tight Coupling of SWAN+ADCIRC
Parallel Scaling



	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)

Engineering Applications

Surge Barrier Design with the USACE



Engineering Applications

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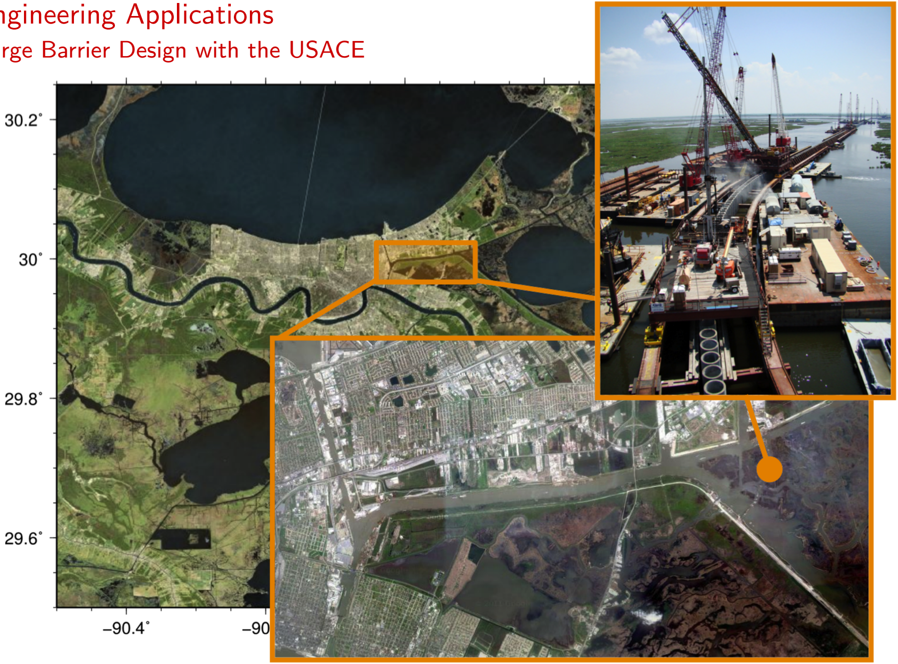
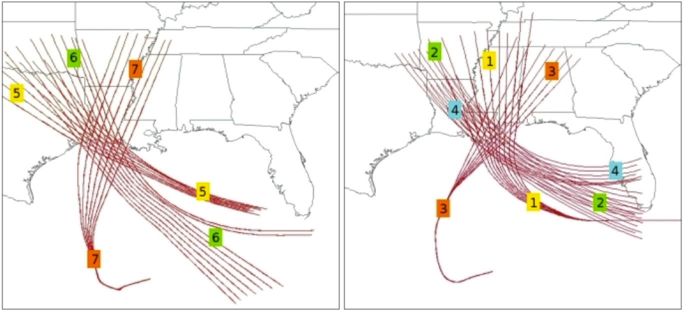


Engineering Applications
Floodplain Risk Maps for FEMA

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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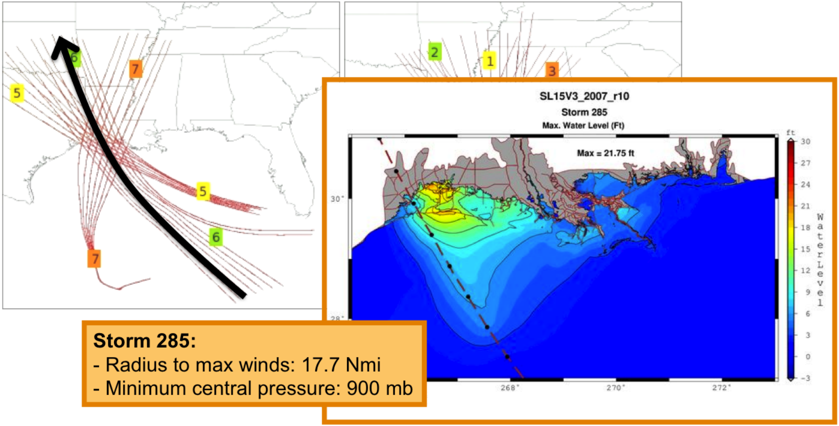


In North Carolina, the guidance is available from the Coastal Emergency Risks Assessment (CERA) team:

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

Updated often with new guidance:

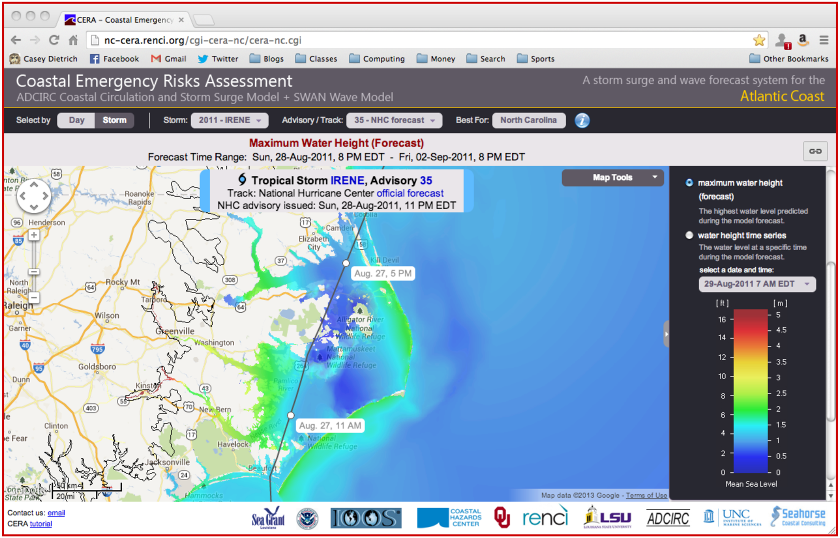
- Normal conditions with base meteorology from NOAA/NCEP
- Extreme conditions with storm advisories from NOAA/NHC

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

Real-Time Forecasting

Example during Irene (2011): `nc-cera.renci.org`



Motivation:

- Predictive models are costly
- Hundreds or even thousands of CPUs, hours of wall-clock time
- Why spend resources on regions that are never flooded by the storm?

Dynamic load balancing:

- Assign an equal amount of wet regions to each core
- Reallocate computational resources to improve parallel efficiency
- Each core will be responsible for developing its own subdomain

Initial attempts:

- Optimize the initial domain decomposition
- Decomposition is still static for now

Dynamic Load Balancing
History of Domain Decomposition in ADCIRC

We use METIS to decompose our domain

- Separate library, written in C, developed at Univ. Minnesota
- Weights based on the number of edges connected to each vertex
- METIS tries to equalize the weights across the subdomains

Our preprocessor (`adcprep`) was written about 15-18 years ago

- Our domains were entirely wet – oceans and coastal regions
- No floodplains or dry regions to consider in the decomposition
- Initial decomposition was static

Need to revise the domain decomposition

- Equal amounts of wet and dry to each core
- Make ADCIRC skip computations on dry vertices

Dynamic Load Balancing

Changes to adcprep Preprocessor

Now METIS is called twice

- Called first to decompose only the wet regions
- Called again to decompose only the dry regions

Each core is assigned one wet region, and one dry region

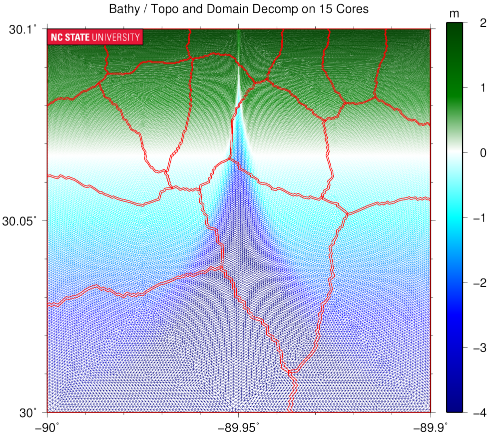
- This way, each core will be contributing to the workload
- Work is balanced at start of simulation
- May become imbalanced due to wetting / drying during simulation

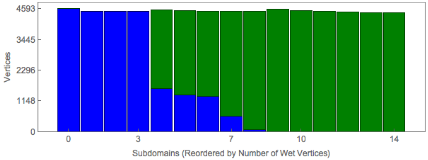
No guarantee that each core's wet and dry regions will be connected

- One core may have two subdomains that are far from each other
- Potential problem for large domains – we are increasing the communication

Test Case 1 – Ideal Channel and Floodplain

Initial Domain Decomposition





First test case is channel and floodplain:
- Ideal mesh: 64,415 vertices
- Shallow depths from −4m to +2m
- Tidal range from −1m to +1m

So we expect a lot of wetting/drying:
- Roughly 1/3 of the domain by size
- More of the domain by resolution

Initial decomposition is sub-optimal:
- 4 cores start fully wet
- 5 cores start partly wet/dry
- 6 cores start fully dry

Simulation of 4 days:
- Eight tidal cycles
- Extensive wetting and drying
- Some cores are always dry

Wall-clock time of $\sim$ 17.8 min

Test Case 1 – Ideal Channel and Floodplain

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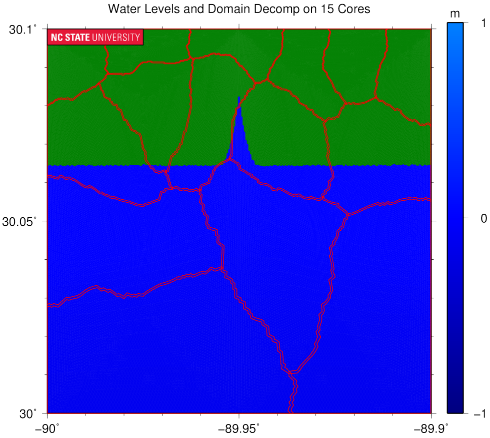

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Optimizing Initial Decomposition for Wet Vertices

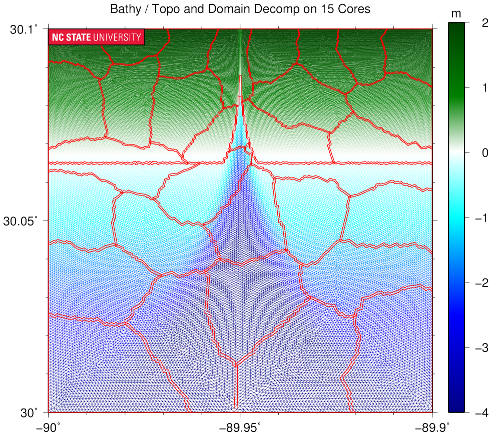
We optimized the decomposition:
- All cores are both wet and dry

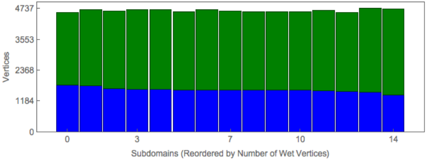
Changes to `adcprep`:
- METIS called twice
- Weights only on vertices (not edges)
- Separate subdomains for wet and dry

For example, core 0000:
- Wet region with 1591 vertices
- Dry region with 3013 vertices
- Not guaranteed to connect

Now every core is contributing
- Still imbalances during tidal cycle

Wall-clock time of $\sim$ 13.1 min
- Speedup of **26 percent**





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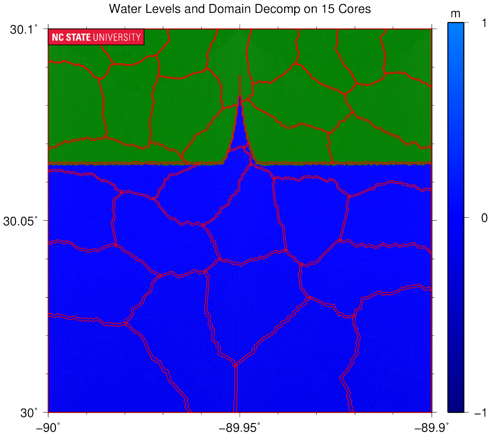
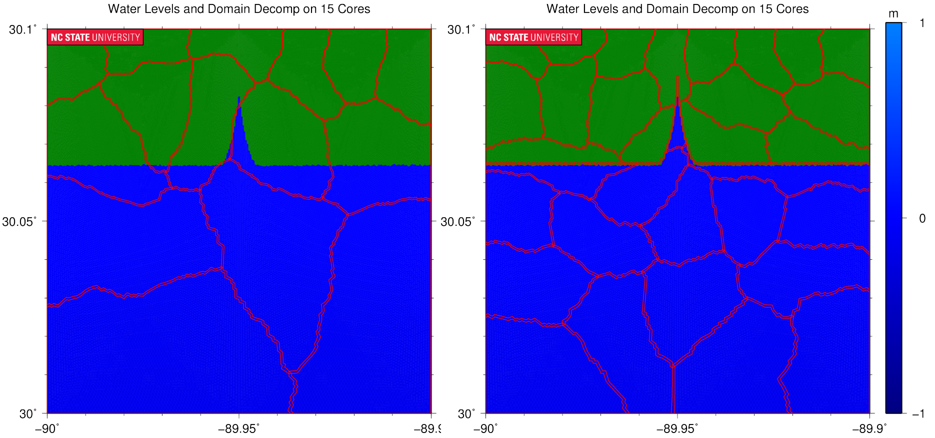


Test Case 1 – Ideal Channel and Floodplain

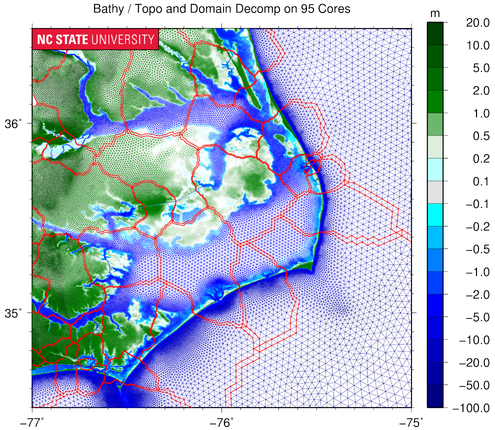
Water Level Comparison and Timings

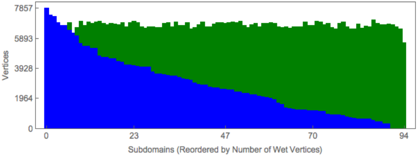


Test	Code Version	Cores	CPU-hr	% Change
Wet/Dry	ADCIRC v52.22	15	4.46	
	+ load balancing		3.29	– **26.3**

Test Case 2 – Hurricane Irene (2011) on NC9

Initial Domain Decomposition





Second test case is Irene (2011):
- NC9 mesh: 622,946 vertices

Should be a lot of wetting/drying:
- Roughly 1/2 of domain starts dry
- Flooding of NC coastal regions

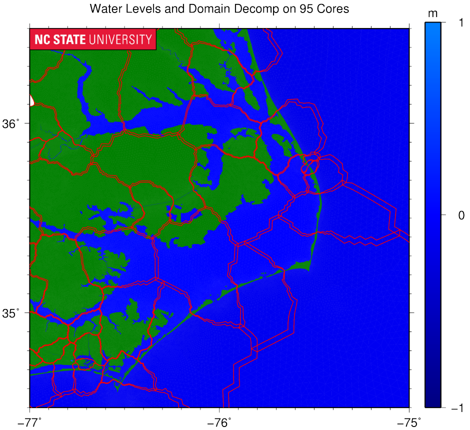
Initial decomposition is sub-optimal:
- Only 7 cores start fully wet
- Most cores are mostly dry

Simulation of 8 days:
- Initial flooding in SW Pamlico Sound
- Sound-side flooding of Hatteras Island

Wall-clock time of 3.52 hr

Test Case 2 – Hurricane Irene (2011) on NC9

Initial Domain Decomposition



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Test Case 2 – Hurricane Irene (2011) on NC9

Optimizing Initial Decomposition for Wet Vertices

We optimized the decomposition:
- All cores are both wet and dry
- Domain boundaries follow shoreline
- Channels separate from floodplains

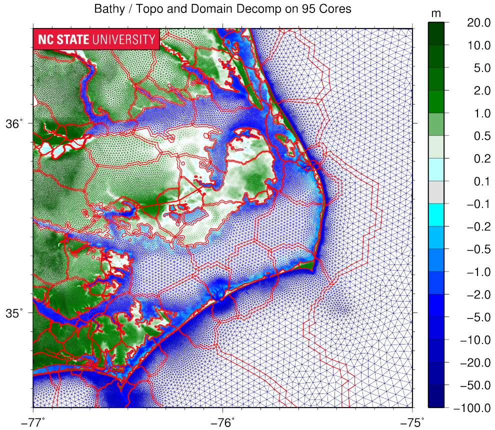
Domain not decomposed equally:
- Some cores have more wet / dry
- Reflects complexity of mesh

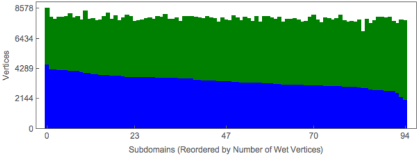
For example, core 0000:
- Wet region with 2274 vertices
- Dry region with 5479 vertices

For example, core 0001:
- Wet region with 3066 vertices
- Dry region with 4766 vertices

Now every core is contributing
- Still imbalances during storm

Wall-clock time of $\sim$ 2.77 hr
- Speedup of **21 percent**





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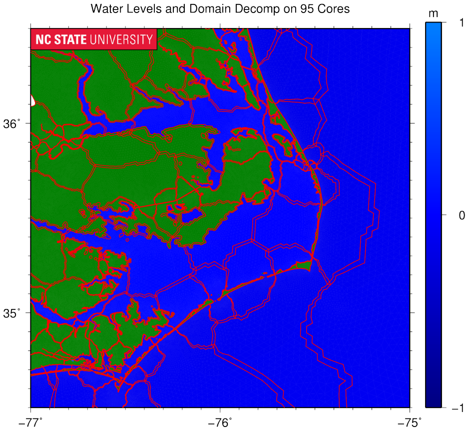

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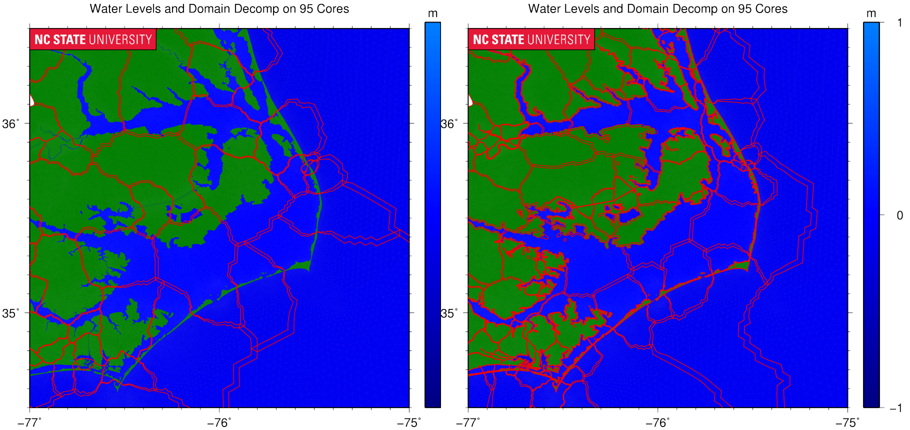

Test	Code Version	Cores	CPU-hr	% Change
Tides	ADCIRC v52.22	15	259.2	
	+ load balancing		210.7	**– 18.7**
Irene	ADCIRC v52.22	96	334.3	
	+ load balancing		263.3	**– 21.2**

Summary and Future Work

Improving the Efficiency of Wave and Surge Models

Tight coupling of SWAN+ADCIRC

- Resolution varies from kilometers to meters in unstructured mesh
- Domain decomposition to assign problem to 1000s of cores
- Spplications – surge barriers, flooding risk maps, forecasting

Dynamic load balancing

- Initial speed-up of 20 percent
- Revise `adcprep` so it can be called as a subroutine from ADCIRC

Obvious benefits for end users

- Faster forecasts for decision support for emergency managers
- Better utilize resources for larger studies for engineering design