Improving predictions of coastal flooding via sub-mesh corrections

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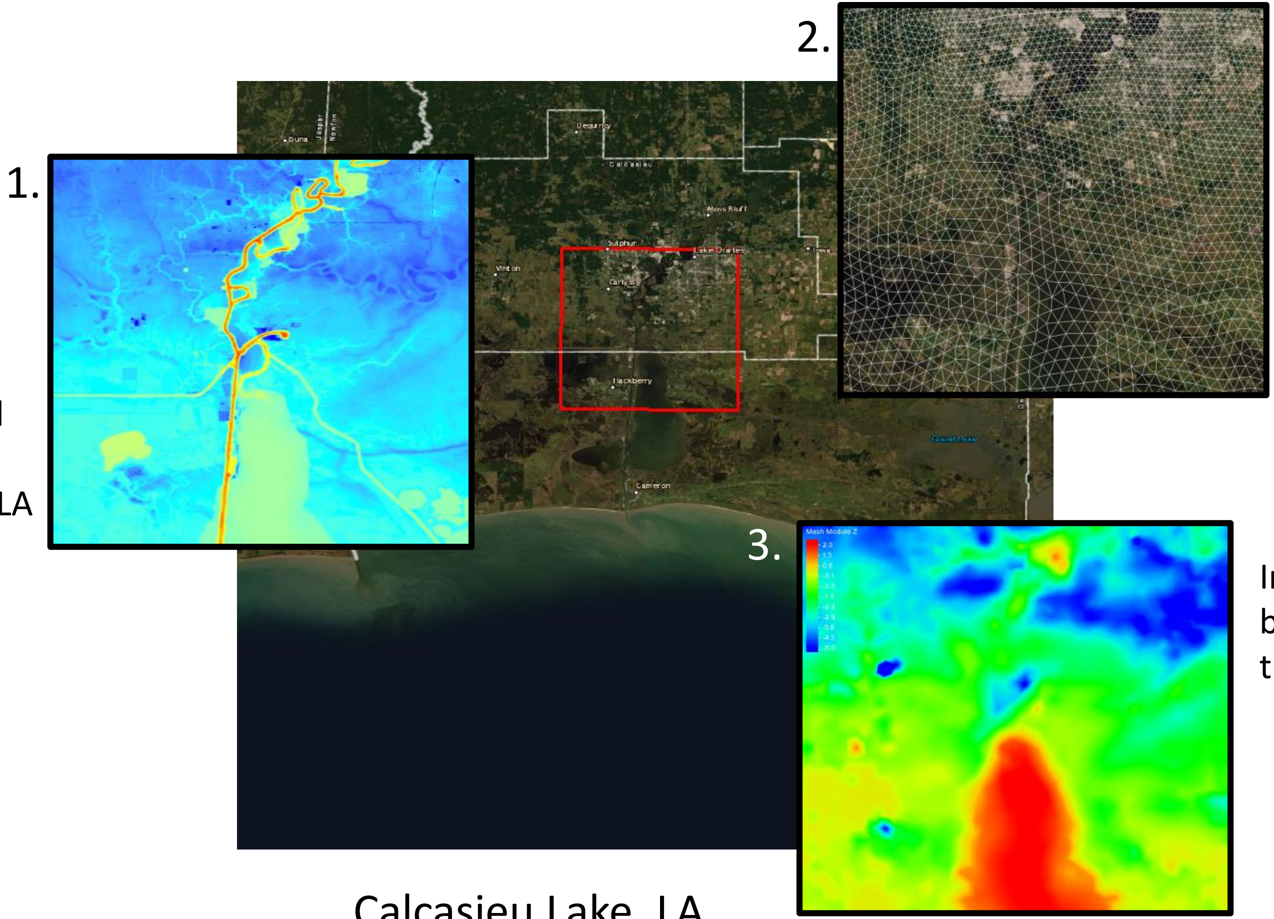
Introduction

- Sub-mesh corrections are incorporated into the ADvanced CIRCulation (ADCIRC) finite element model
- ADCIRC is a state-of-the-art storm surge model that has been used extensively over the last 30 years for coastal flooding predictions

Introduction

- High resolution is computationally **costly**
  - Hinders the speed of ADCIRC runs
  - Delays the forecast predictions
- This study aims to **increase the accuracy and efficiency of ADCIRC** by:
  - Adding sub-mesh correction factors to the governing equations
  - Running on coarsened meshes

High resolution bathymetry of the Bayou Contraband and Northern Calcasieu Lake, LA



NOMAD mesh v1e MSL (HSOFS)

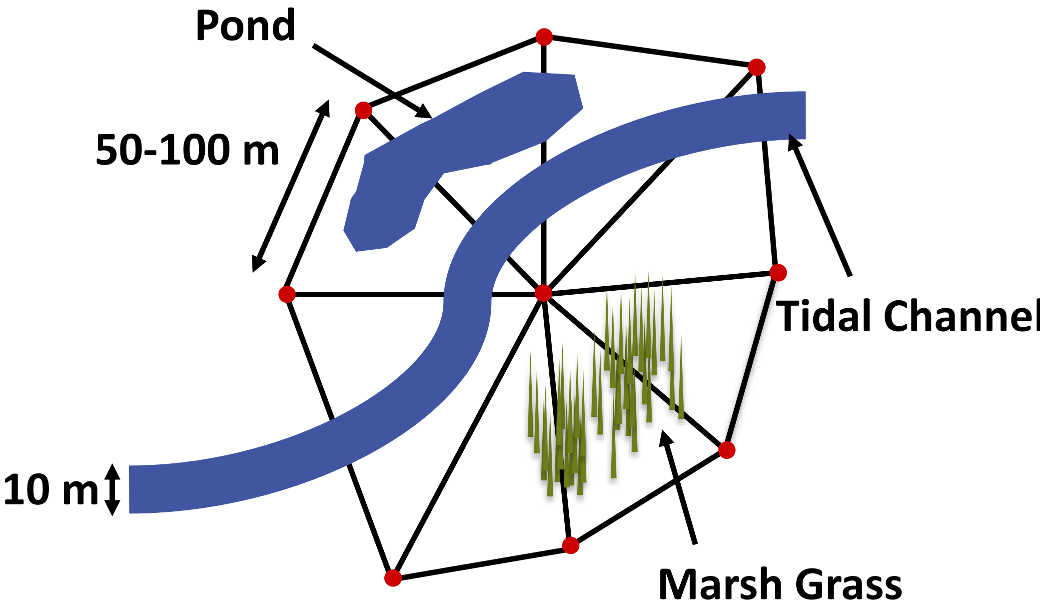
- This mesh is used in real-time forecasting by NOAA and the ADCIRC Prediction System (APS).

Interpolated bathymetry of the mesh

Calcasieu Lake, LA

Sub-mesh Features

- Sub-mesh features:
  - Hydraulic features that influence flow
  - Exist below the resolution of the mesh
  - Include: small scale channels, ponds, marsh grasses, and roadways



Theory

- The primitive shallow water equations were first averaged using techniques outlined in Kennedy et al. 2019.
- These averaged primitive equations were then transformed into the GWCE and conservative momentum equations ADCIRC uses.

Averaged Variables Theory

- To obtain the averaged variables we integrate inside each element.
- A given dummy variable Q would be averaged as follows:

$$\langle Q \rangle_G \equiv \frac{1}{A_G} \iint_{A_W} Q dA \qquad \& \qquad \langle Q \rangle_W \equiv \frac{1}{A_W} \iint_{A_W} Q dA \qquad \text{Where: } A_W = \phi A_G$$

GWCE Conversion

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

$$\Downarrow$$

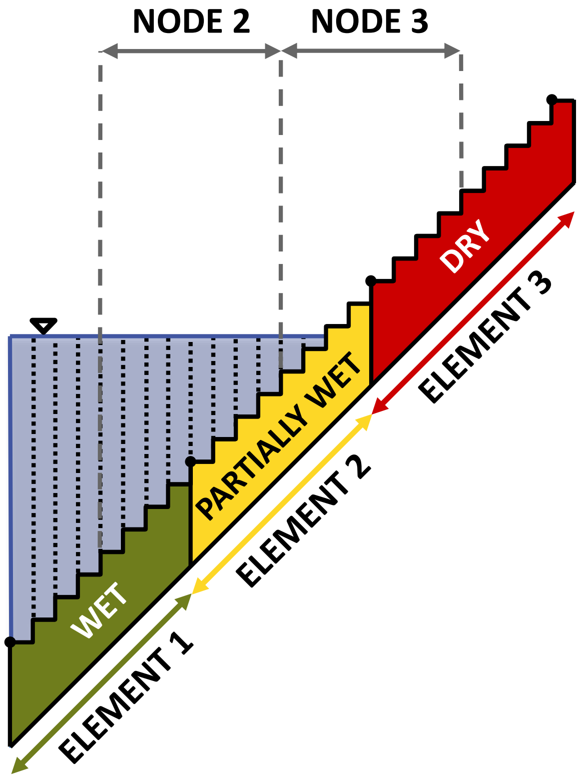
$$\phi \frac{\partial^2 \langle \zeta \rangle_W}{\partial t^2} + \phi \tau_0 \frac{\partial \langle \zeta \rangle_W}{\partial t} + \frac{\partial \langle \tilde{J}_x \rangle_W}{\partial x} + \frac{\partial \langle \tilde{J}_y \rangle_W}{\partial y} - \langle U \rangle_W \langle H \rangle_G \frac{\partial \tau_0}{\partial x} - \langle V \rangle_W \langle H \rangle_G \frac{\partial \tau_0}{\partial y} = 0$$

Where:

- ϕ is the wet area fraction
- Subscripts $\langle \quad \rangle_W$ and $\langle \quad \rangle_G$ mean the variable was averaged over the wet area or whole area respectively

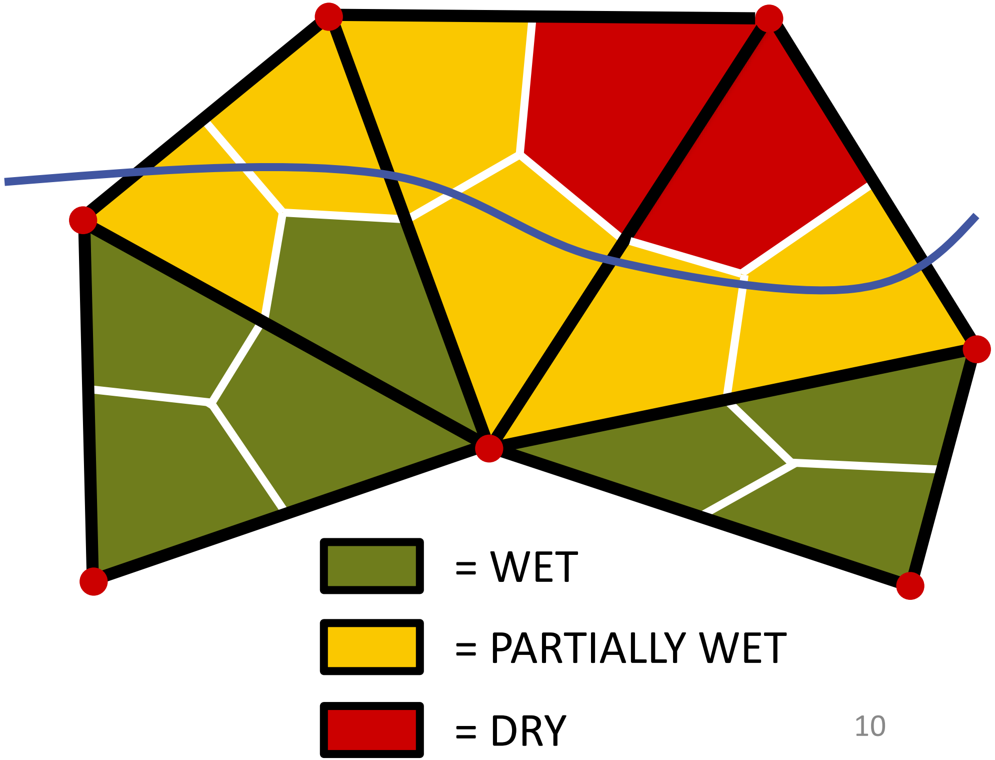
Sub-mesh calculations

- Sub-mesh calculations are performed using a high resolution digital elevation model (DEM) underlying a ADCIRC mesh of coarser resolution.
- Sub-mesh correction factors such as ϕ and $\langle H \rangle_G$ are found by integrating the sub-areas within each element.
- Sub-mesh quantities are pre-computed and read into ADCIRC.

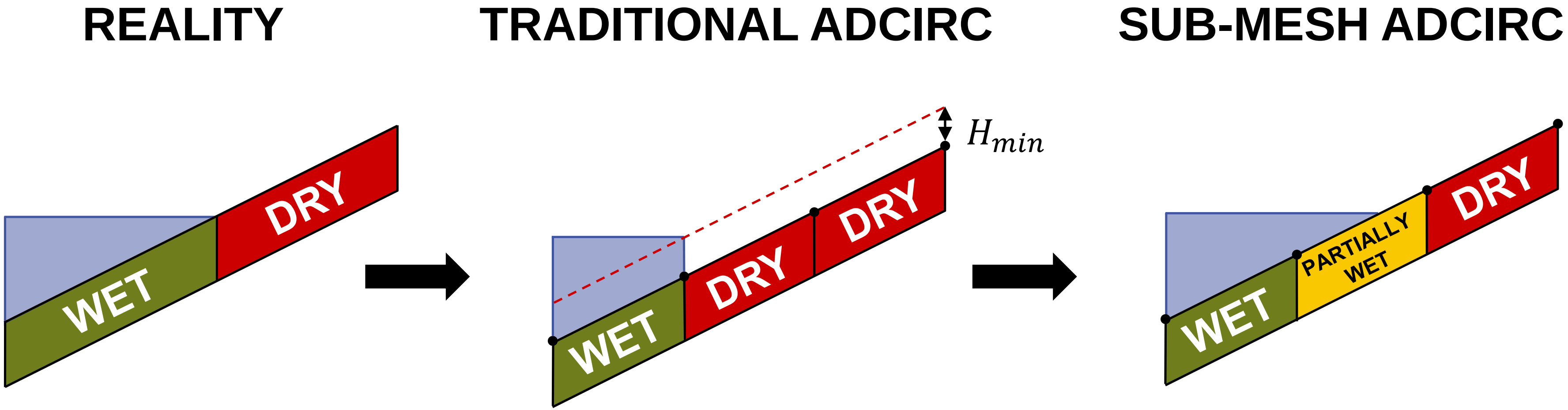


Sub-mesh in 2D

- In 2D the elements are split up into 3 sub-areas.
- Sub-mesh calculations are performed based on the DEM lying beneath the mesh for each sub-area within the element.



Wetting and Drying



Wetting and Drying Algorithm

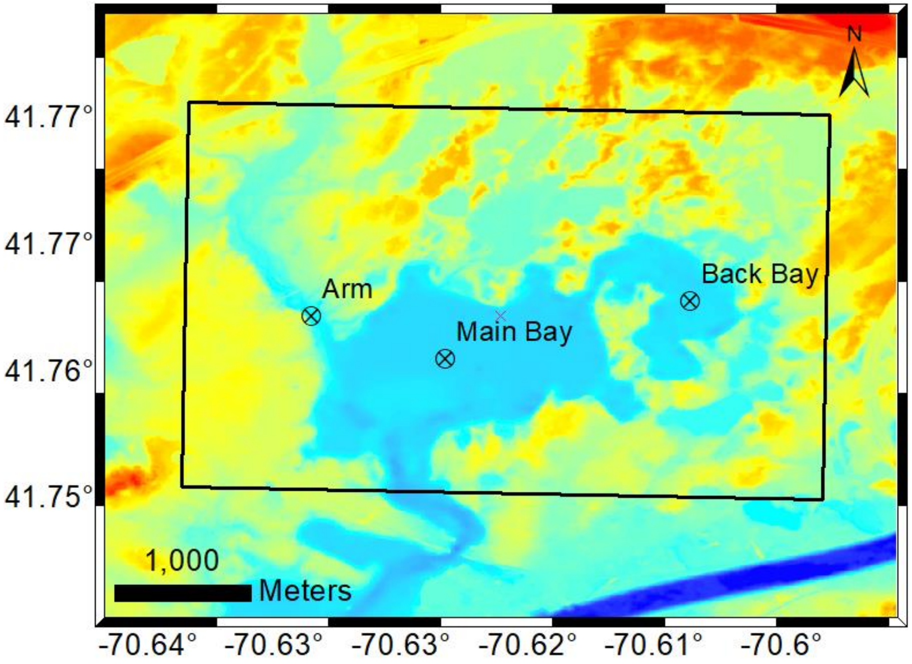
BEGIN Wetting and Drying → **COMPUTE** averaged variables ϕ, $\langle H \rangle_G$, $\langle H \rangle_W$ → **EVALUATE** wet/dry state $\phi \geq \phi_{dry}$ → **END** Wetting and Drying

Test Domains

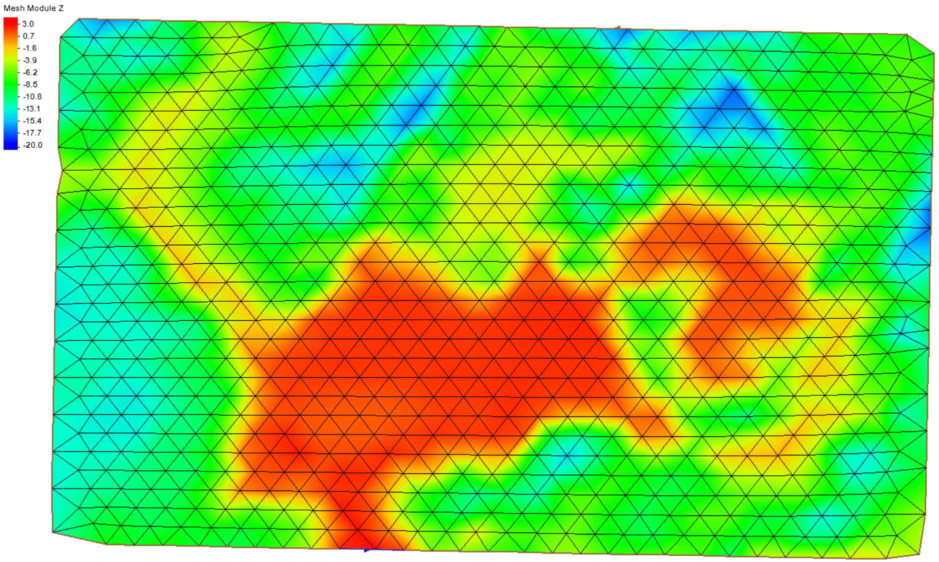
- Two domains were used to test the viability of the sub-mesh additions in ADCIRC:
  1. Buttermilk Bay, Massachusetts
  2. Calcasieu Lake, Louisiana

Buttermilk Bay

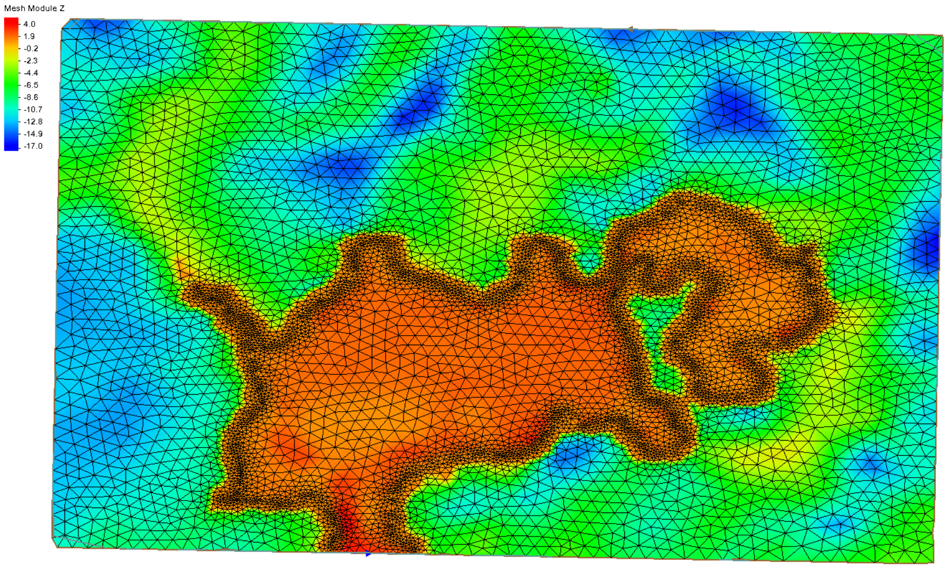
- Manning's n = 0.022
- Forced with 1 m sinusoidal tidal signal
- Water levels taken at points denoted by ⊗
- Sub-mesh bathymetry 3 m resolution.
- 5% ϕ cutoff



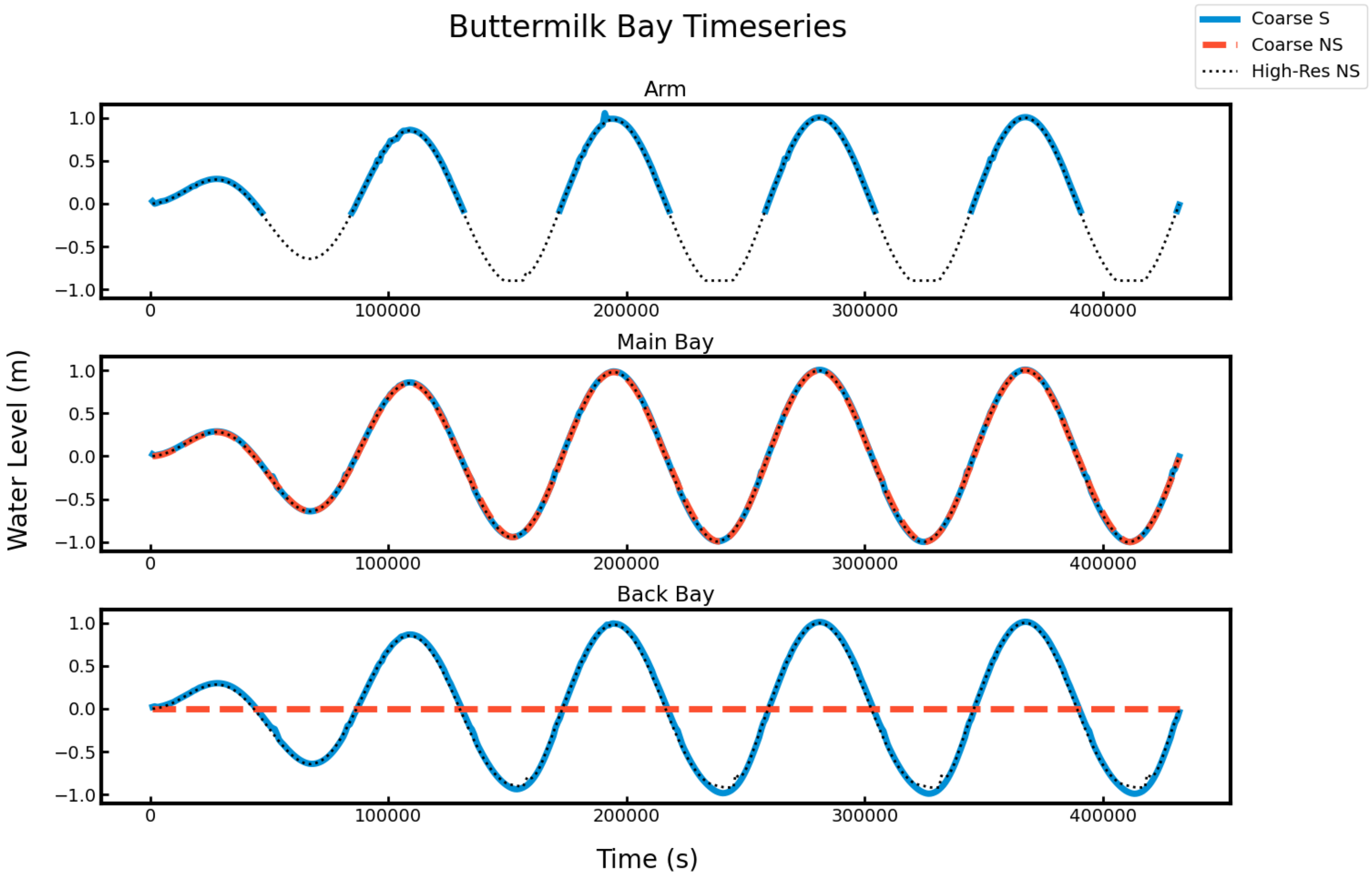
Buttermilk Bay

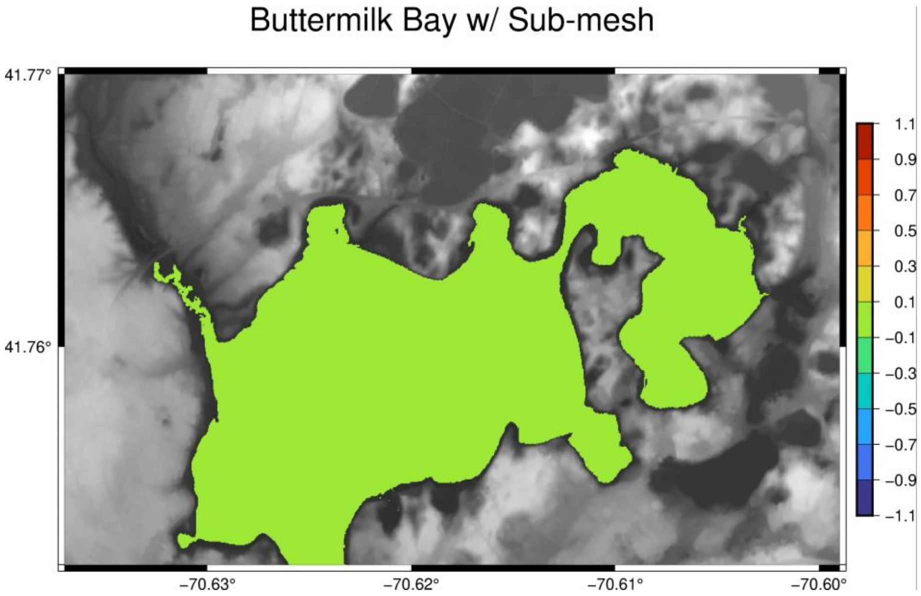


Vertices: 830 Elements: 1,569

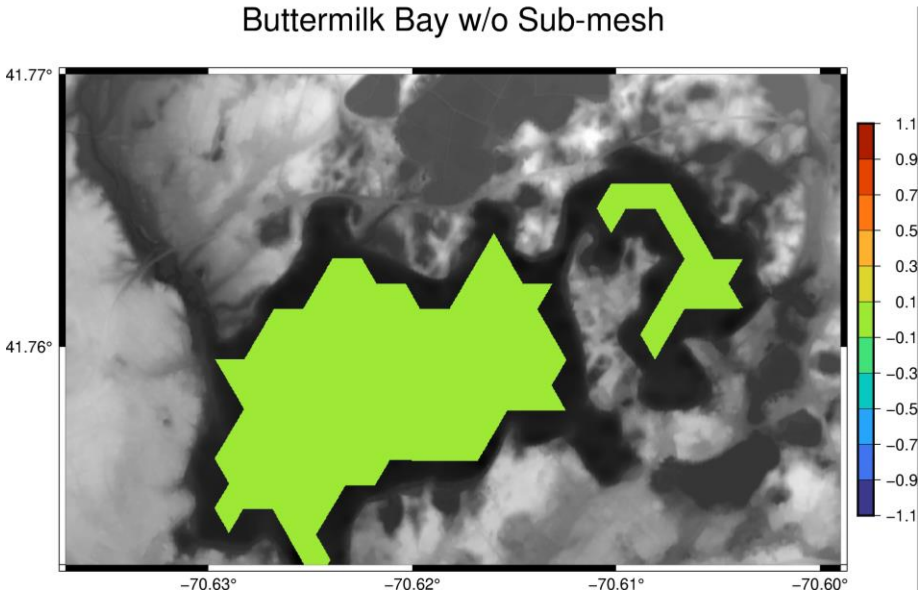


Vertices: 4,795 Elements: 9,412


Buttermilk Bay Timeseries
Coarse S
Coarse NS
High-Res NS
Arm
Main Bay
Back Bay
Water Level (m)
Time (s)
1.0
0.5
0.0
−0.5
−1.0
0
100000
200000
300000
400000



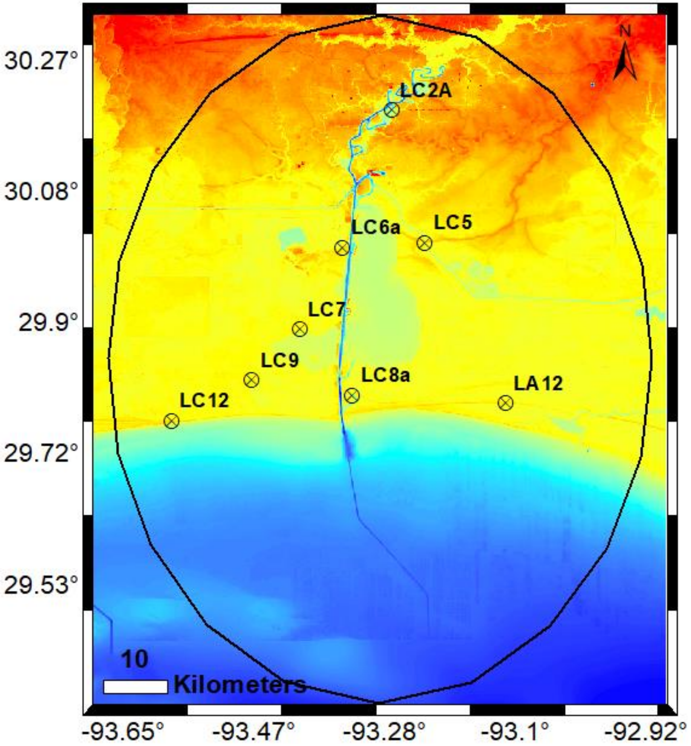
Buttermilk Bay w/ Sub-mesh
41.77°
41.76°
–70.63°
–70.62°
–70.61°
–70.60°
1.1
0.9
0.7
0.5
0.3
0.1
–0.1
–0.3
–0.5
–0.7
–0.9
–1.1

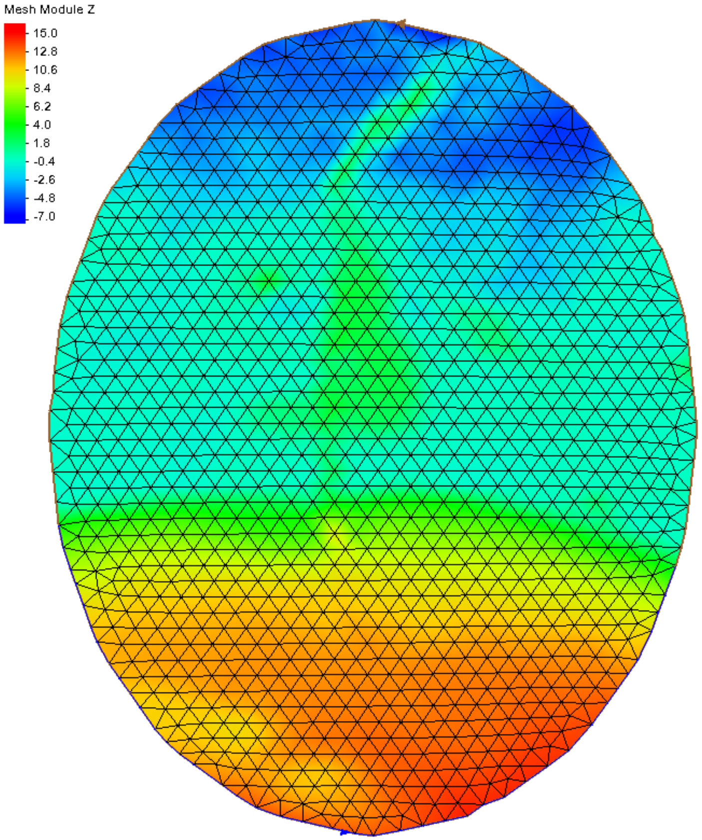


Buttermilk Bay w/o Sub-mesh
41.77°
41.76°
–70.63°
–70.62°
–70.61°
–70.60°
1.1
0.9
0.7
0.5
0.3
0.1
–0.1
–0.3
–0.5
–0.7
–0.9
–1.1

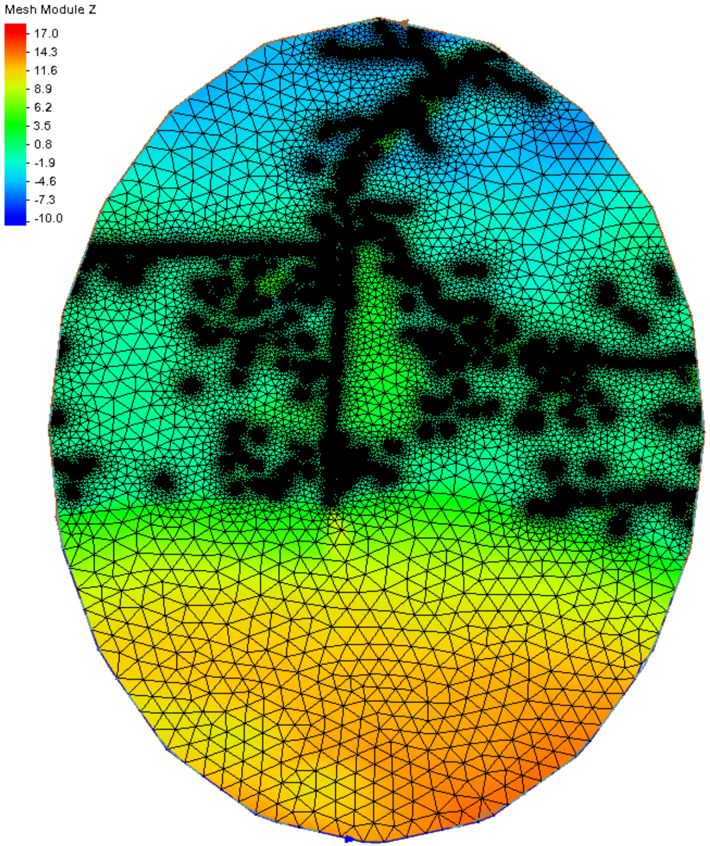
Calcasieu Lake

- Interpolate mesh properties from SL16 mesh
- Force ocean boundary with Rita Hurricane simulation run on SL16 mesh
- Use GAHM vortex winds over entire domain
- 10% ϕ cutoff
- 8 gauge locations to validate simulation results

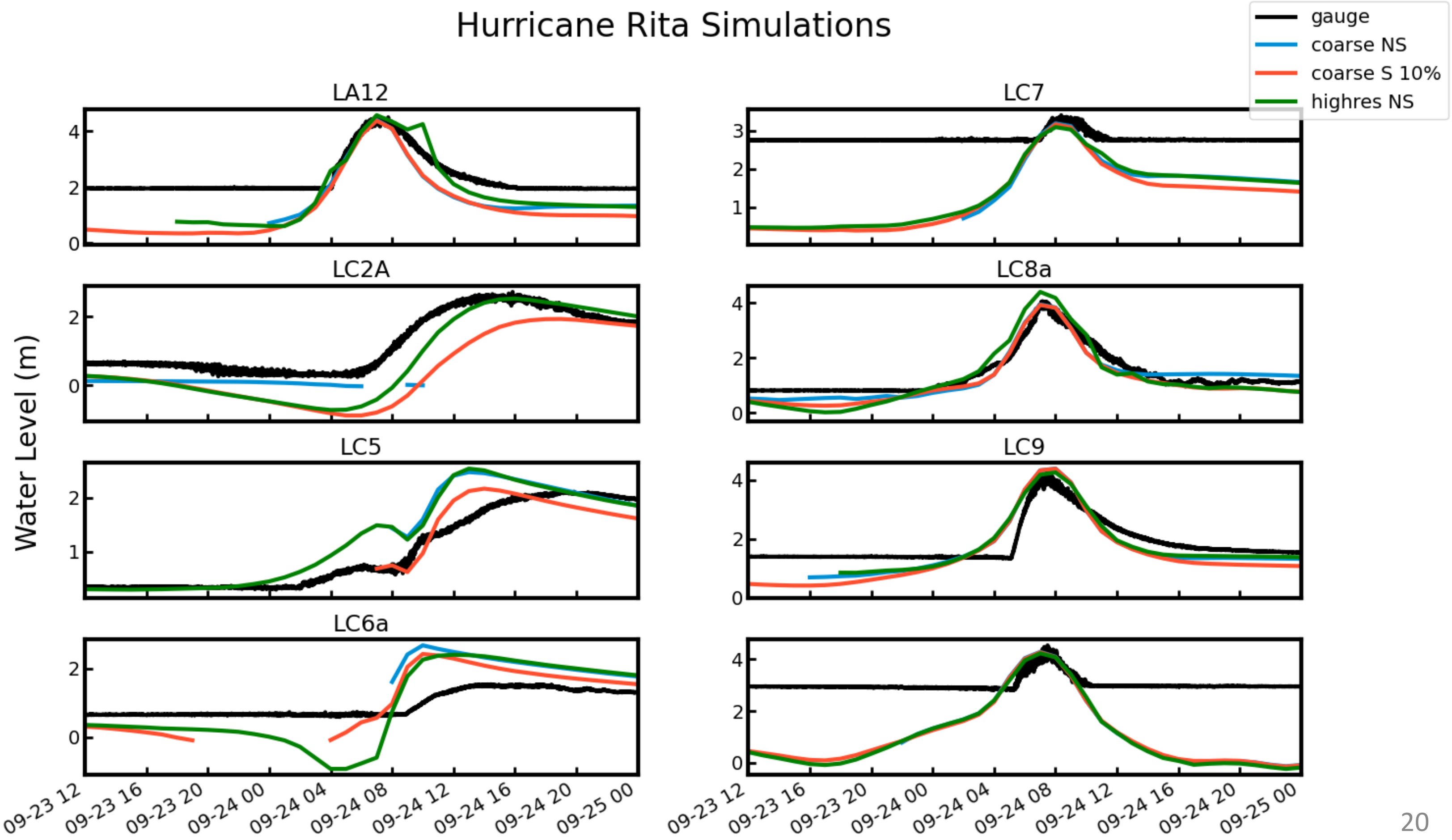


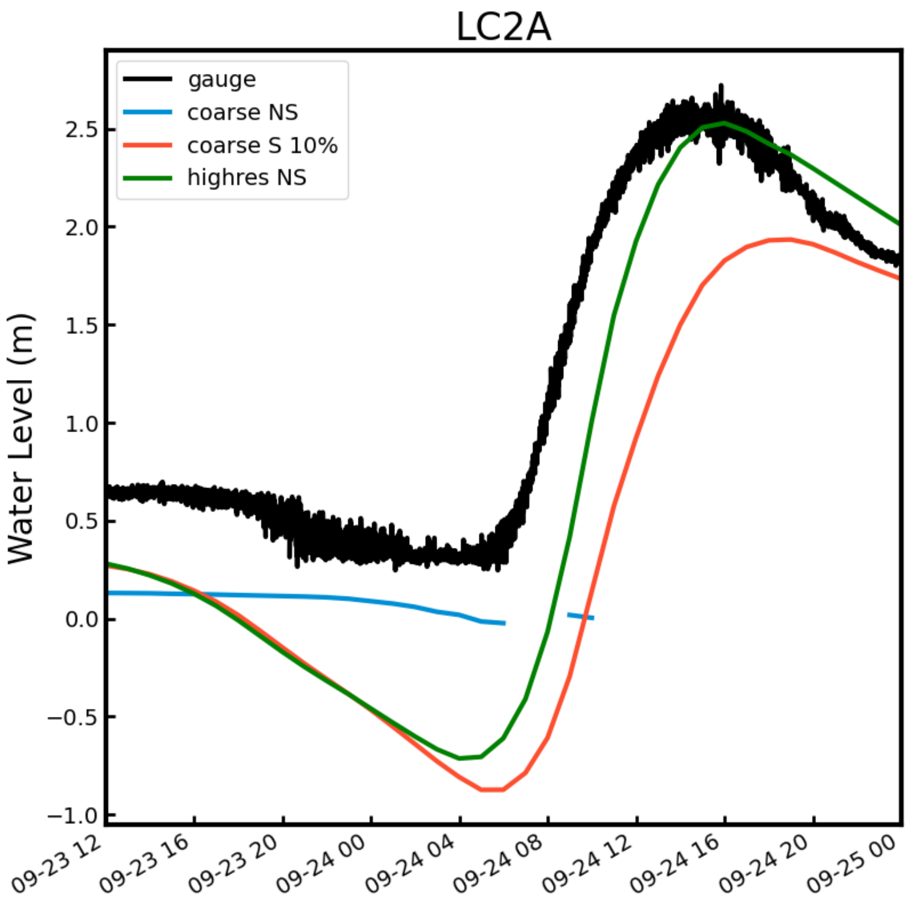


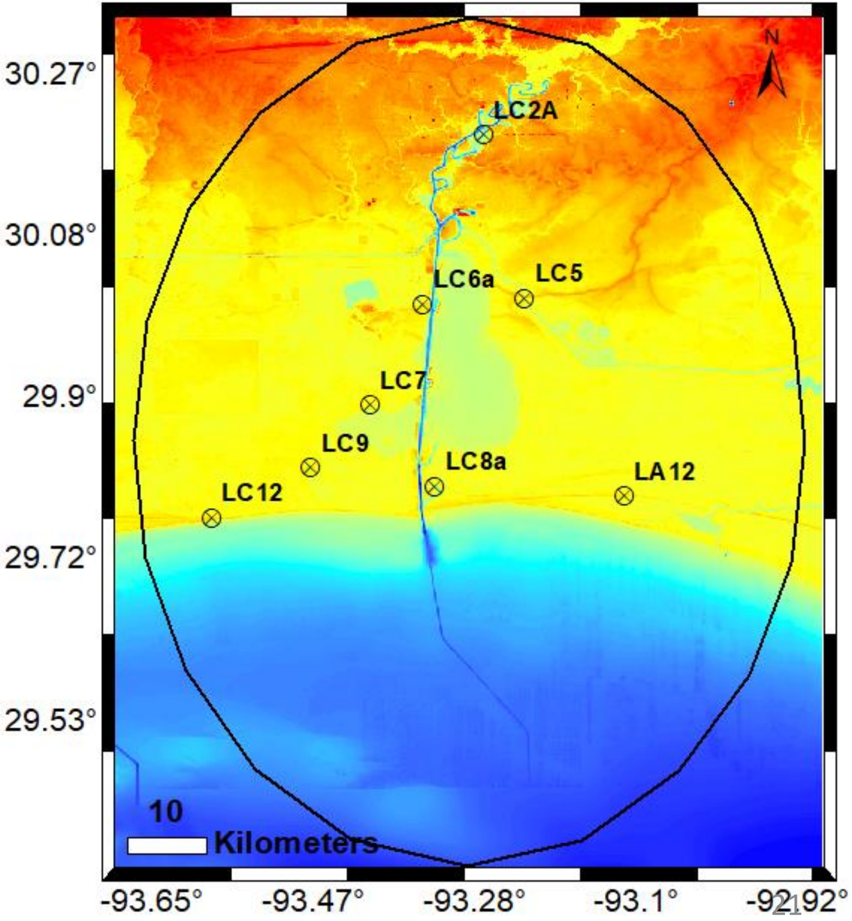
Vertices: 1,236 Elements: 2,370

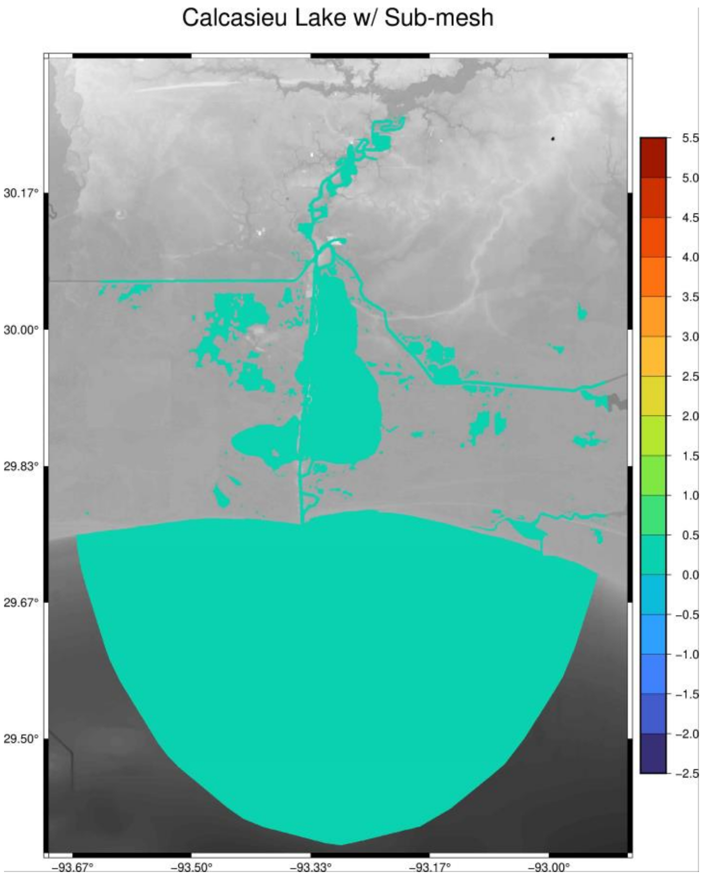


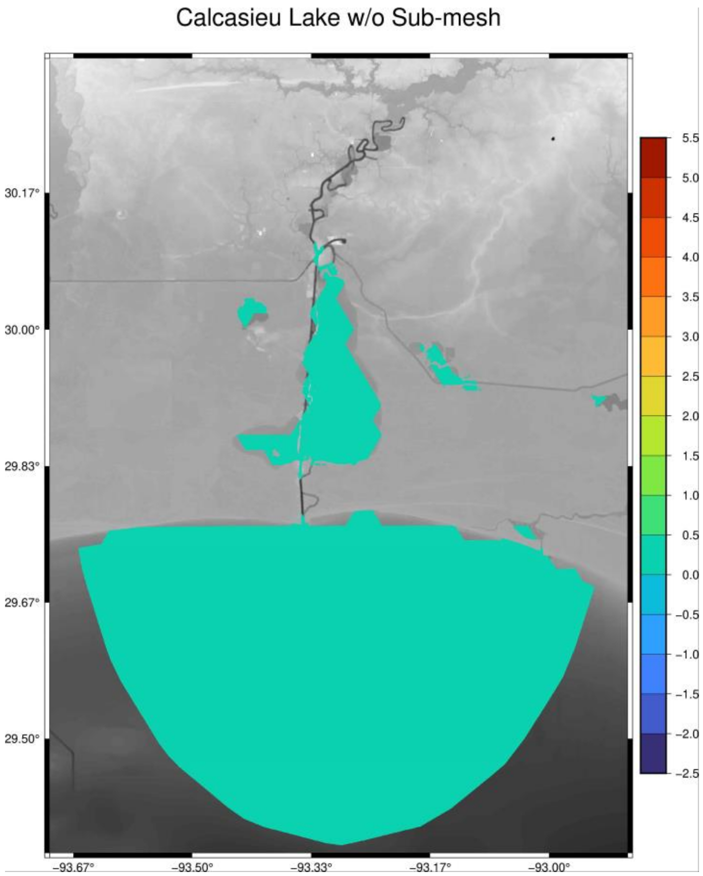
Vertices: 40,816 Elements: 81,321


Hurricane Rita Simulations
gauge
coarse NS
coarse S 10%
highres NS
LA12
LC7
LC2A
LC8a
LC5
LC9
LC6a
Water Level (m)
09-23 12
09-23 16
09-23 20
09-24 00
09-24 04
09-24 08
09-24 12
09-24 16
09-24 20
09-25 00


LC2A
gauge
coarse NS
coarse S 10%
highres NS
Water Level (m)
2.5
2.0
1.5
1.0
0.5
0.0
−0.5
−1.0
09-23 12
09-23 16
09-23 20
09-24 00
09-24 04
09-24 08
09-24 12
09-24 16
09-24 20
09-25 00


30.27°
30.08°
29.9°
29.72°
29.53°
N
LC2A
LC6a
LC5
LC7
LC9
LC8a
LA12
LC12
10
Kilometers
-93.65°
-93.47°
-93.28°
-93.1°
-92.92°


Calcasieu Lake w/ Sub-mesh
30.17°
30.00°
29.83°
29.67°
29.50°
−93.67°
−93.50°
−93.33°
−93.17°
−93.00°
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
−0.5
−1.0
−1.5
−2.0
−2.5


Calcasieu Lake w/o Sub-mesh
30.17°
30.00°
29.83°
29.67°
29.50°
−93.67°
−93.50°
−93.33°
−93.17°
−93.00°
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
−0.5
−1.0
−1.5
−2.0
−2.5

Future Work

- Are sub-mesh corrections a viable option for storm surge forecasting?
  - Need to test on ocean scale mesh.
- Can we further improve the sub-mesh results by adding more corrections?
  - Can we incorporate cell clones?
- Develop a user-friendly display program to showcase sub-mesh results.

Thank you

Questions?

Thank you to the National Science Foundation for sponsoring this research