Subgrid Corrections in Finite-Element Models of Storm-Driven Coastal Flooding

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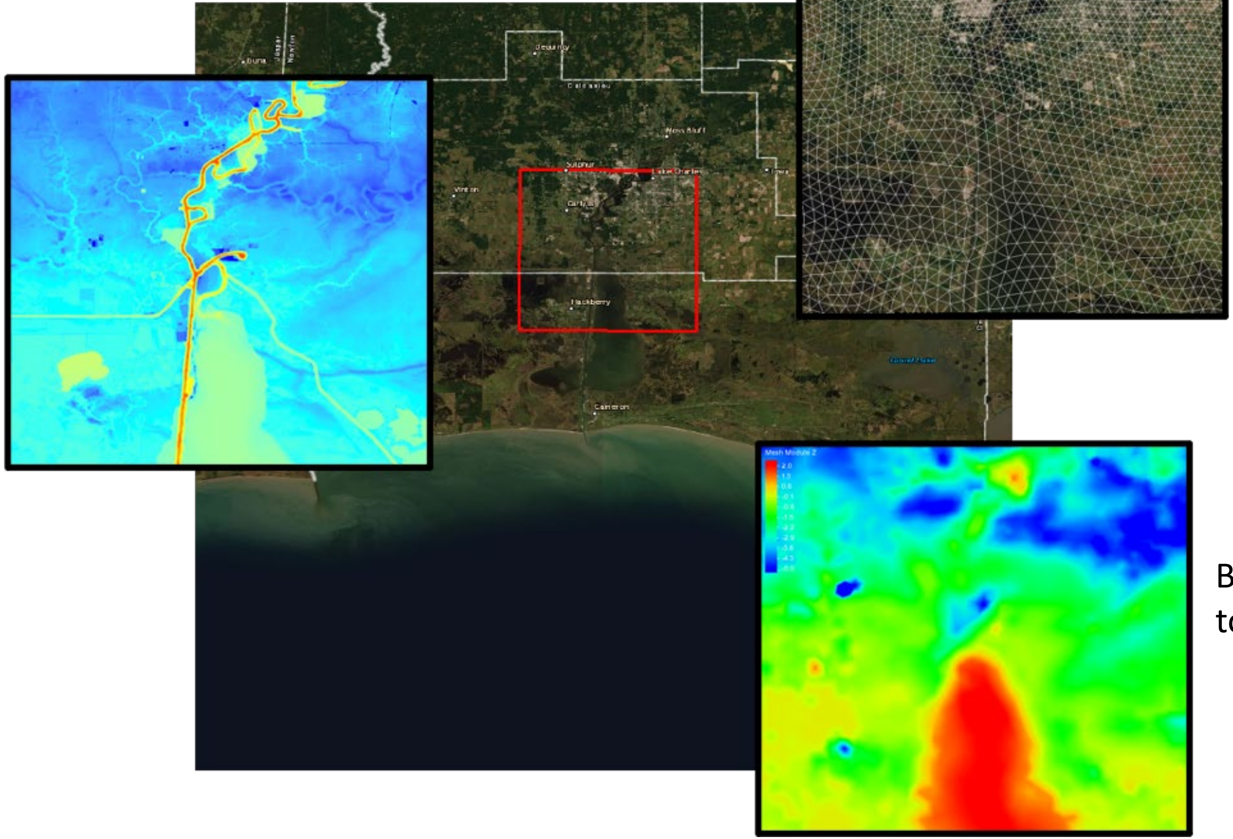
1. Motivation

Loss of Information at Model Scale

Lake Calcasieu, LA



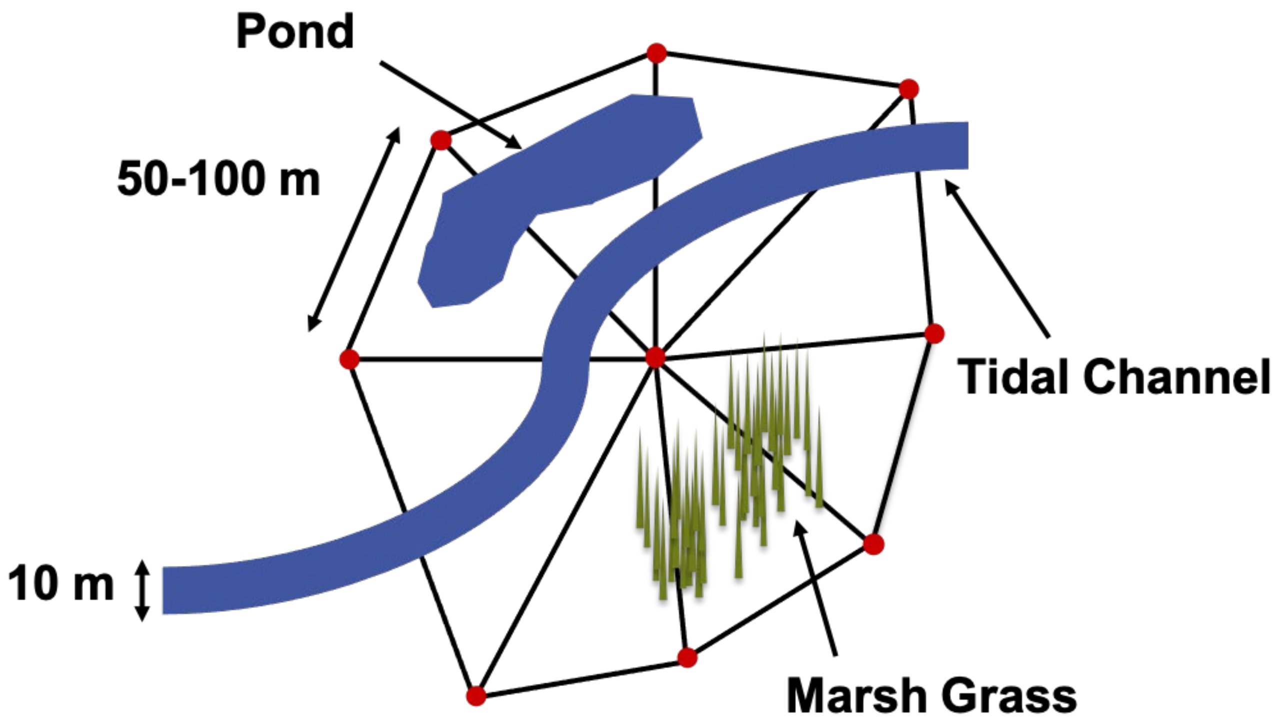
High-resolution DEM with bathy/topo for Bayou Contraband

Typical finite-element mesh for coastal flood forecasting

Bathy/topo aliased to mesh scale

1. Motivation

Use Smaller-Scale Information to ‘Correct’ Flows



2. Methods
Subgrid Corrections

Subgrid corrections use information at smaller scales to 'correct' flow variables (water levels and current velocities) at the model scale

Selected applications to shallow water flows:

- Defina (2000) corrected advection and partially wet cells
  - ➢ Able to coarsen by a factor of 32
- Casulli (2009) and Casulli and Stelling (2011) also corrected partially wet cells
  - ➢ Used lookup tables created from high-resolution elevation data
- Volp (2013) corrected bottom stress
  - ➢ Improved discharge and water surface slope relative to high-resolution counterparts

Able to coarsen the model resolution and still represent small-scale flow pathways and barriers

- ➢ Higher accuracy at same resolution, higher efficiency at coarser resolution

2. Methods
Averaged Variables

Shallow water equations are averaged to the model scale, e.g. Kennedy *et al.* (2019)

A given flow variable Q can be averaged:

- To the gird/mesh scale:

$$\langle Q \rangle_G \equiv \frac{1}{A_G} \iint_{A_W} Q \, dA$$

- To only the wet part of the grid/mesh scale:

$$\langle Q \rangle_W \equiv \frac{1}{A_W} \iint_{A_W} Q \, dA$$

- Where the areas are related by:

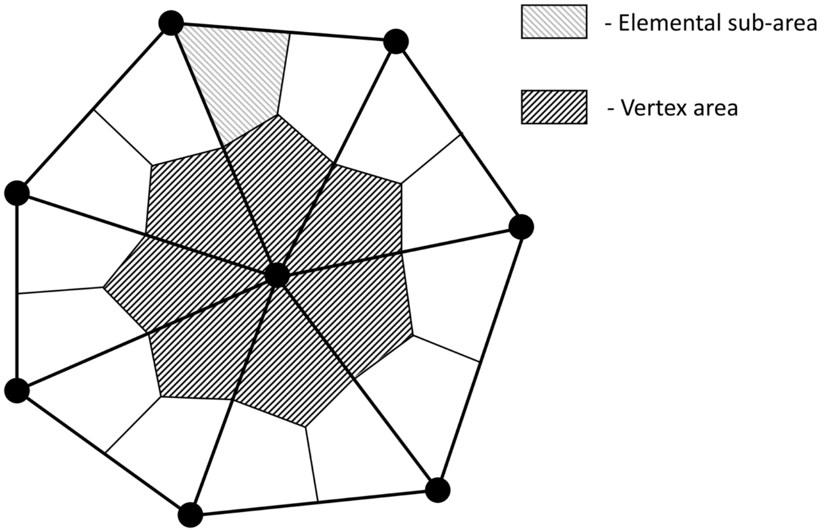
$$A_W = \phi A_G$$

2. Methods
Implementation in ADCIRC

We implemented subgrid corrections in ADvanced CIRCulation (ADCIRC)

- Widely used for predictions of coastal circulation, storm surge, and flooding during storms
- Solves modified forms of the shallow-water equations by using continuous-Galerkin, finite-element method on unstructured meshes

This required a careful definition of vertex- and element-based averaging areas:



Averaged Governing Equations for ADCIRC

For this study, its governing equations were averaged to the mesh scale

- Example of momentum conservation in *x*-direction:

$$\frac{\partial \langle UH \rangle_G}{\partial t} + \frac{\partial C_{UU} \langle U \rangle \langle UH \rangle_G}{\partial x} + \frac{\partial C_{VU} \langle V \rangle \langle UH \rangle_G}{\partial y} - f \langle VH \rangle_G$$
$$= -\mathrm{g} C_\zeta \langle H \rangle_G \frac{\partial \langle \zeta \rangle_W}{\partial x} - g \langle H \rangle_G \frac{\partial P_A}{\partial x} + \phi \left\langle \frac{\tau_{sx}}{\rho_0} \right\rangle_W$$
$$- C_{M,f} \frac{|\langle U \rangle| \langle UH \rangle_G}{\langle H \rangle_W} + \frac{\partial}{\partial x} \tilde{E}_H \frac{\partial \langle UH \rangle_G}{\partial x} + \frac{\partial}{\partial y} \tilde{E}_H \frac{\partial \langle UH \rangle_G}{\partial y}$$

in which the red coefficients are new closure terms

- Similarly for momentum conservation in *y*-direction, mass conservation

We used a so-called 'Level 0' closure:

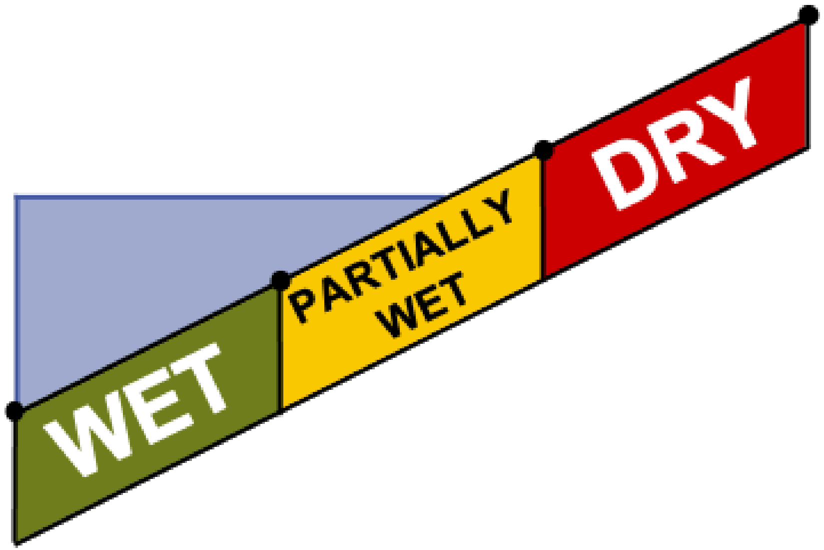
	Traditional	Level 0
Wet/dry	$\phi = 0 \text{ or } 1$	$\phi = A_W / A_G$
Advection	$C_{UU} = C_{VU} = C_{UV} = C_{VV} = 1$	$C_{UU} = C_{VU} = C_{UV} = C_{VV} = 1$
Friction	$C_{M,f} = C_f = gn^2/H^{1/3}$	$C_{M,f} = \langle C_f \rangle_W$
Surface Gradient	$C_\zeta = 1$	$C_\zeta = 1$

Note the differences for the wet/dry status and friction term

- Higher-level closures will be explored in future work

This allows for partially wet cells/elements

- Better connectivity through small-scale flow pathways



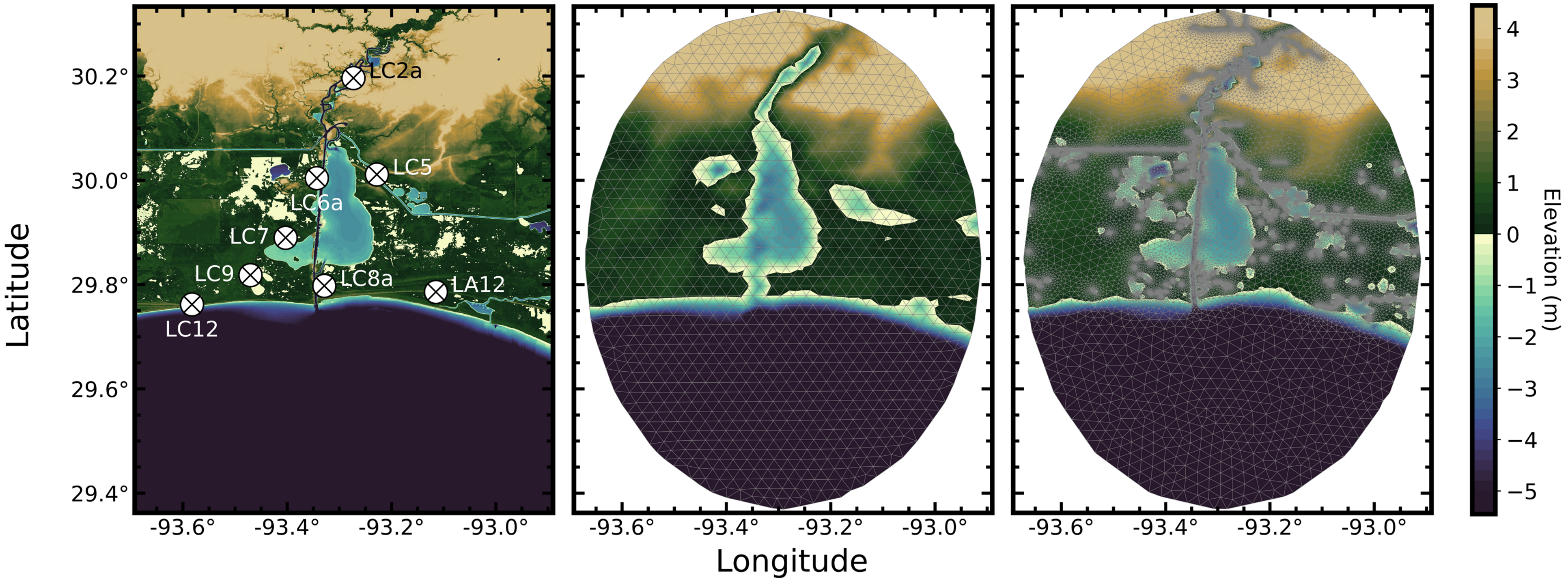
This required a major revision to ADCIRC's wet/dry algorithm

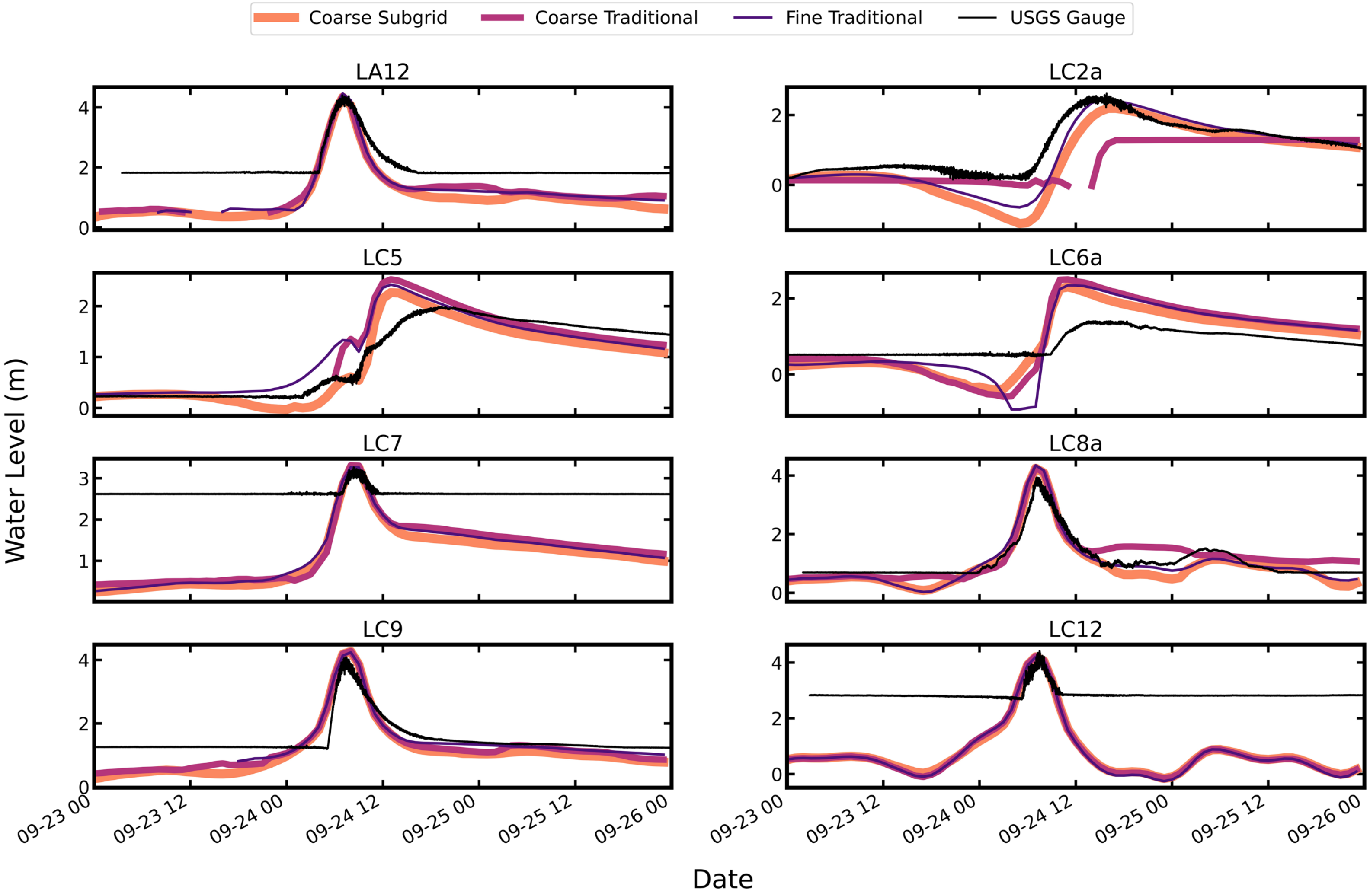
- Removed extensive logic to compare water levels and velocities between vertices

3. Results
Meshes and Station Locations

Coarse:
1,236 vertices
2,370 elements

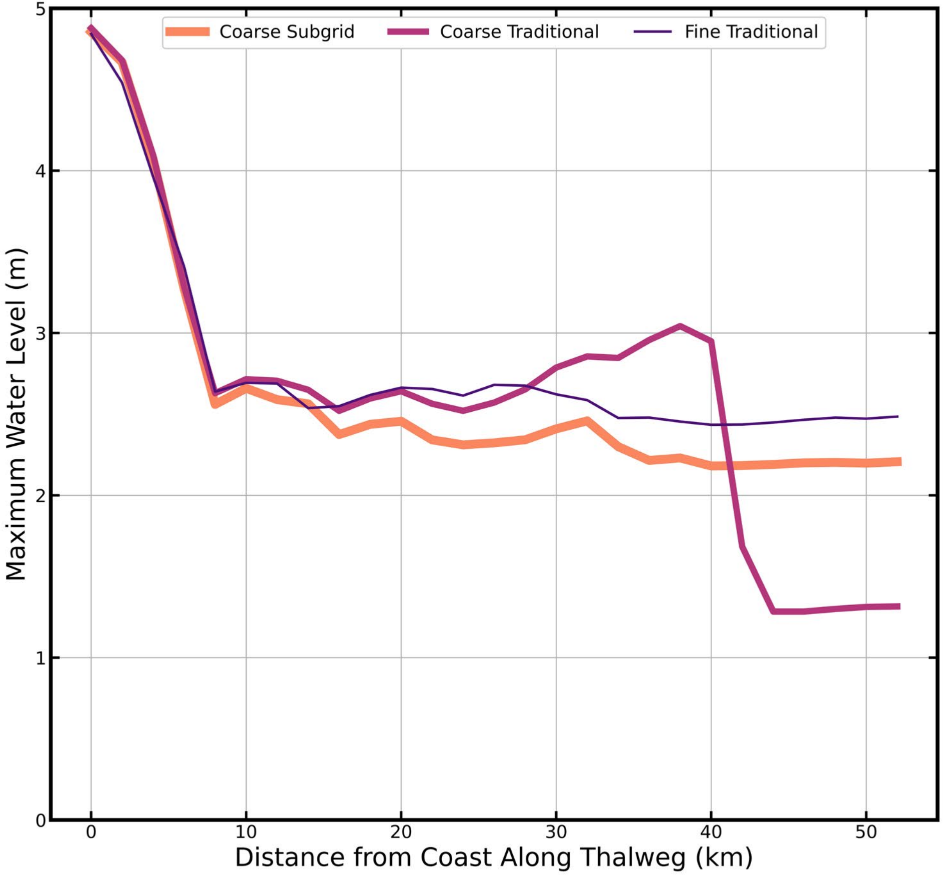
Fine:
40,816 vertices
81,321 elements

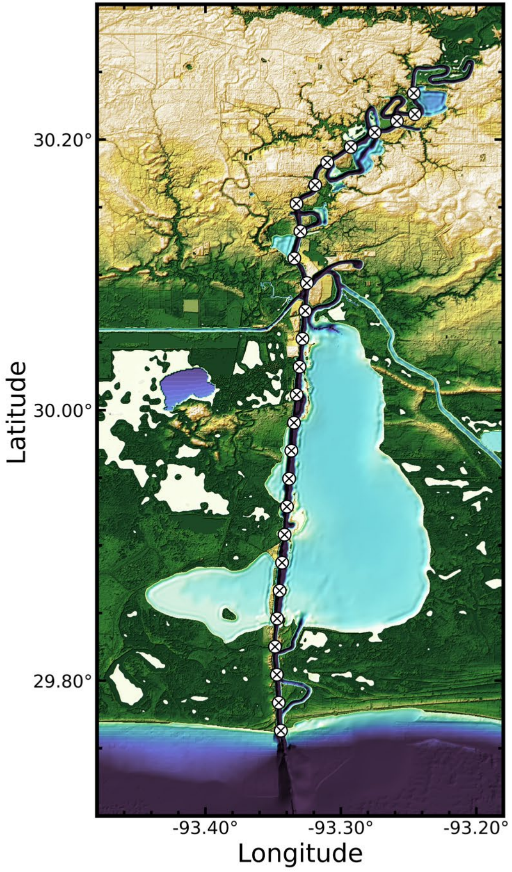




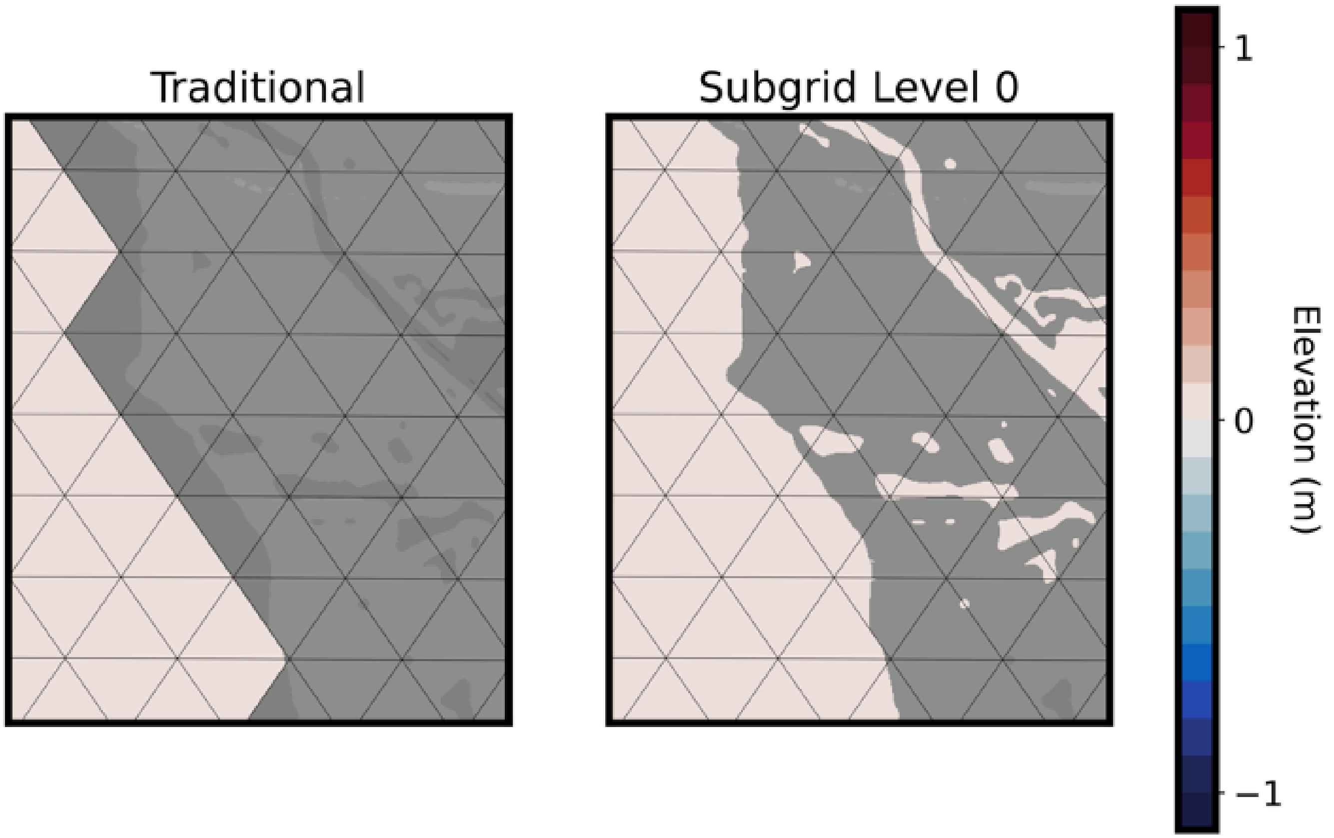
Coarse Subgrid
Coarse Traditional
Fine Traditional
USGS Gauge
LA12
LC2a
LC5
LC6a
LC7
LC8a
LC9
LC12
Water Level (m)
09-23 00
09-23 12
09-24 00
09-24 12
09-25 00
09-25 12
09-26 00
Date

2. Results
Maximum Water Levels along Main Channel





3. Results
Improvements at the Wet/Dry Interface



Wall-clock times (sec) for three test cases

- All tests run in serial on same hardware

	Coarse Subgrid	Coarse Traditional	Fine Traditional
Winding Channel	107	62	5,787
Buttermilk Bay	508	277	4,176
Calcasieu Lake	5,248	3,728	167,514

Subgrid ADCIRC is slightly slower on the same mesh

- But it gives comparable results to a mesh that is 33 times coarser

4. Current Work
Higher Level Closures

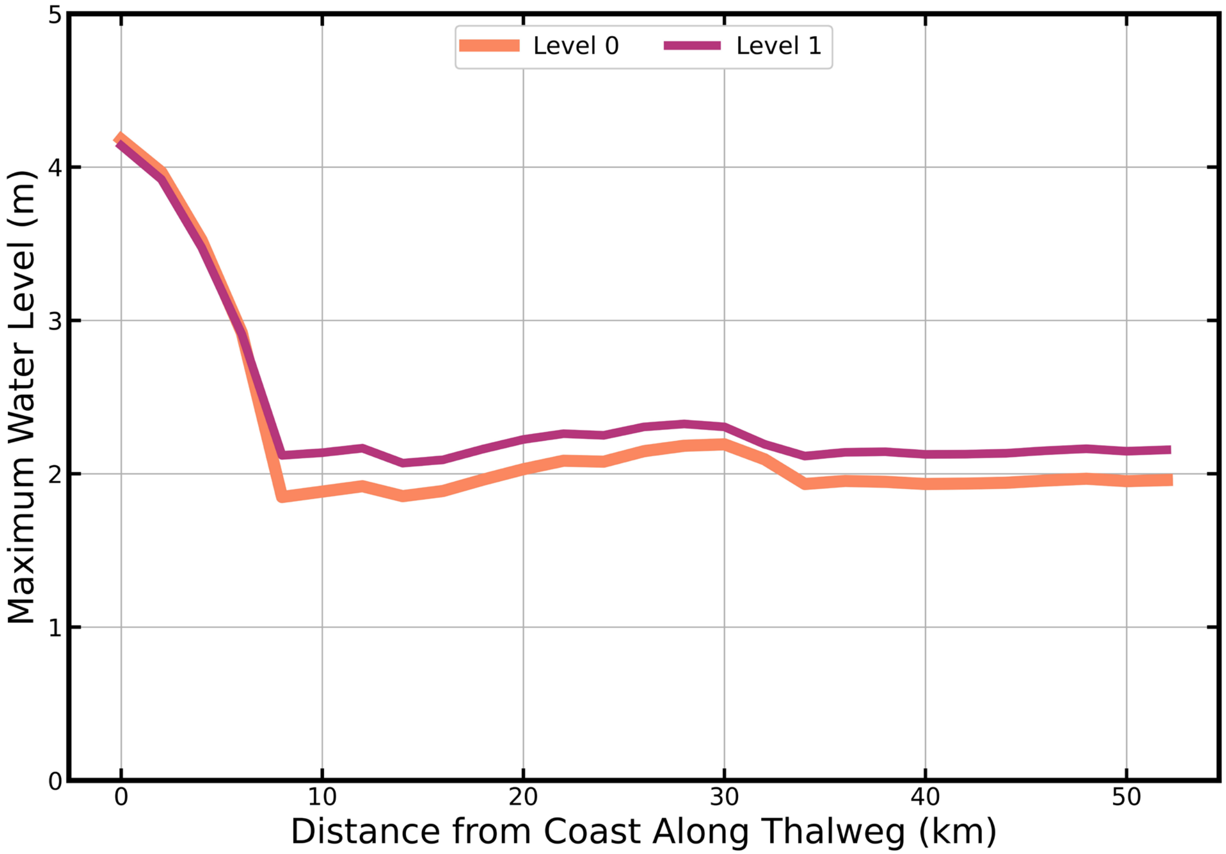
	Level 0	Level 1
Wet/dry	$\phi = A_W/A_G$	$\phi = A_W/A_G$
Advection	$C_{UU} = C_{VU} = C_{UV} = C_{VV} = 1$	$C_{UU} = C_{VU} = C_{UV} = C_{VV} = \frac{1}{\langle H \rangle_W} \left\langle \frac{H^2}{C_f} \right\rangle_W R_v^2$
Friction	$C_{M,f} = \langle C_f \rangle_W$	$C_{M,f} = \langle H \rangle_W R_v^2$
Surface Gradient	$C_\zeta = 1$	$C_\zeta = 1$

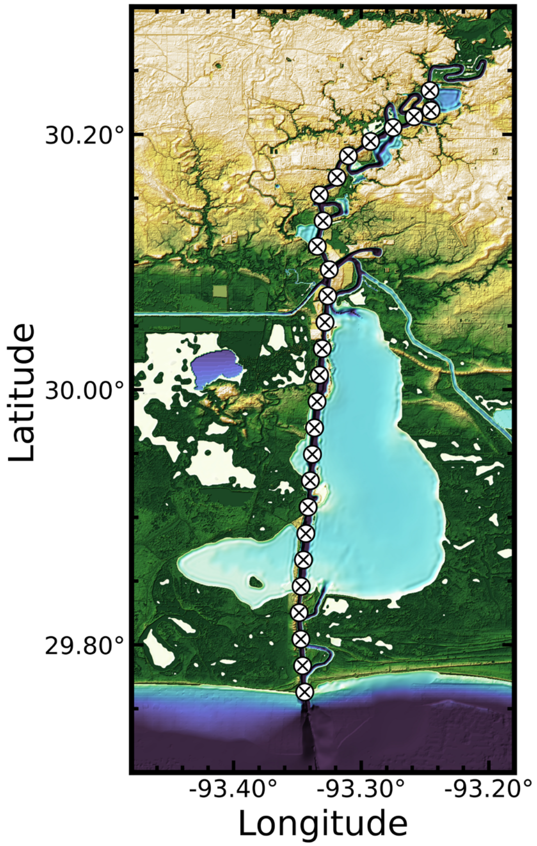
Where: $R_v^2 = \frac{\langle H \rangle_W}{\left\langle H^{3/2} C_f^{-1/2} \right\rangle_W}$

These Level 1 corrections are intended to correct inaccuracies in friction and advection predictions

4. Current Work

Improvements in Water Level Predictions





The main contribution of this study are:

1. Subgrid corrections were added to ADCIRC
   - First application with hurricane-strength forcing
2. Increases in accuracy and hydraulic connectivity on coarsened meshes
   - Peak surge within 0.5 m at top of Bayou Contraband
3. Efficiency gains on coarsened meshes
   - Speed-ups by factors of 30+

Ongoing efforts are focused on:

- Implementing higher-level corrections for friction and advection
- Scaling the subgrid ADCIRC to storm simulations on large domains

5. Conclusions and Future Work

Published Paper in *Ocean Modelling*

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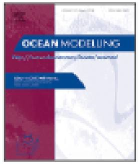

Subgrid corrections in finite-element modeling of storm-driven coastal flooding

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A R T I C L E I N F O

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ADCIRC
Wetting and drying
Shallow water equations

A B S T R A C T

Coastal flooding models are used to predict the timing and magnitude of inundation during storms, both for real-time forecasting and long-term design. However, there is a need for faster flooding predictions that also represent flow pathways and barriers at the scales of critical infrastructure. This need can be addressed via subgrid corrections, which use information at smaller scales to 'correct' the flow variables (water levels, current velocities) averaged over the mesh scale. Recent studies have shown a decrease in run time by 1 to 2 orders of magnitude, with the ability to decrease further if the model time step is also increased.

In this study, subgrid corrections are added to a widely used, finite-element-based, shallow water model to better understand how they can improve the accuracy and efficiency of inundation predictions. The performance of the model, with and without subgrid corrections, is evaluated on scenarios of tidal flooding in a synthetic domain and a small bay in Massachusetts, as well as a scenario with a real atmospheric forcing and storm surge in southwest Louisiana. In these tests we observed that the subgrid corrections can increase model speed by 10 to 50 times, while still representing flow through channels below the mesh scale to inland locations.

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