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

JL Woodruff[1], JC Dietrich[1],
D Wirasaet[2], AB Kennedy[2], D Bolster[2],
Z Silver[2], SD Medlin[3], RL Kolar[4]

[1]Dep't of Civil, Construction, and Environmental Engineering, NC State Univ
[2]Dep't of Civil and Environmental Engineering and Earth Sciences, Univ Notre Dame
[3]School of Environmental, Civil, Agricultural, and Mechanical Engineering, Univ Georgia
[4]School of Civil Engineering and Environmental Science, Univ Oklahoma

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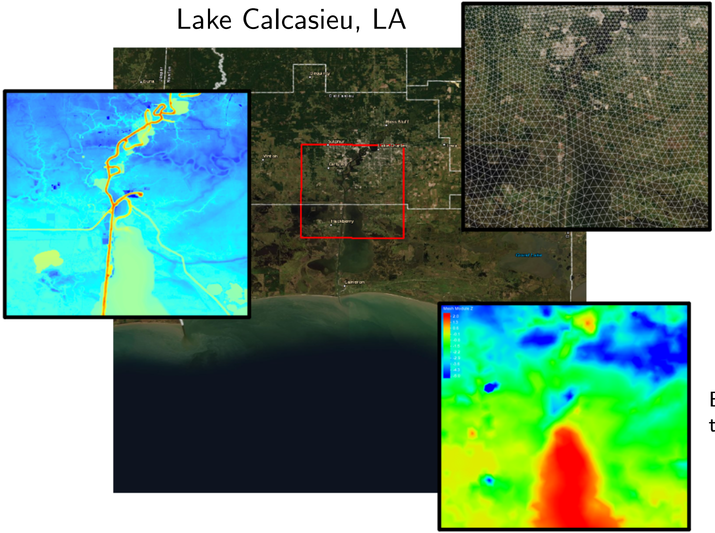
1. Motivation

Loss of Information at Model Scale

Lake Calcasieu, LA

High-resolution DEM with bathy/topo for Bayou Contraband

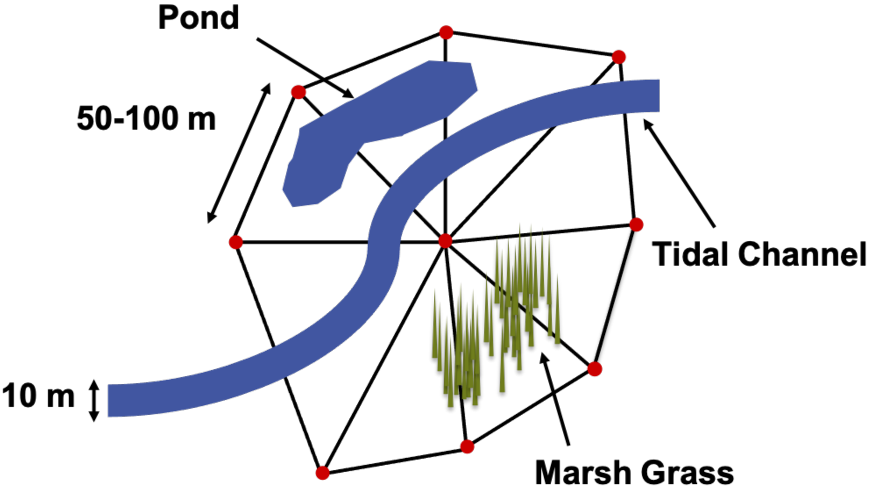


Typical finite-element mesh for coastal flood forecasting

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, current velocities) at the model scale

Selected applications to shallow water flows:

- Defina (2000) corrected advection and partially wet cells
  - → Able to coarsen by 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

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 grid/mesh scale:

$$\langle Q \rangle_G \equiv \frac{1}{A_G} \iint_{A_W} Q \, \mathrm{d}A$$

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

$$\langle Q \rangle_W \equiv \frac{1}{A_W} \iint_{A_W} Q \, \mathrm{d}A$$

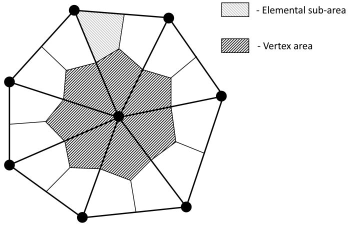
- Where the areas are related by:

$$A_W = \phi A_G$$

We implemented the 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 the continuous-Galerkin, finite-element method on unstructured meshes

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



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

- Example of momentum conservation in x-direction:

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

  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	$\phi = 0$ 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	$C_{M,f} = C_f = gn^2/H^{1/3}$	$C_{M,f} = \langle C_f \rangle_G$
Surface gradient	$C_\zeta = 1$	$C_\zeta = 1$

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

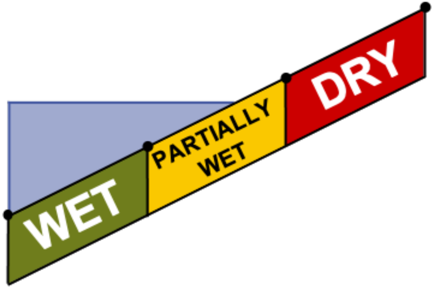
$\rightarrow$ Higher-level closures will be explored in future work

2. Methods

Partially Wet Cells/Elements

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

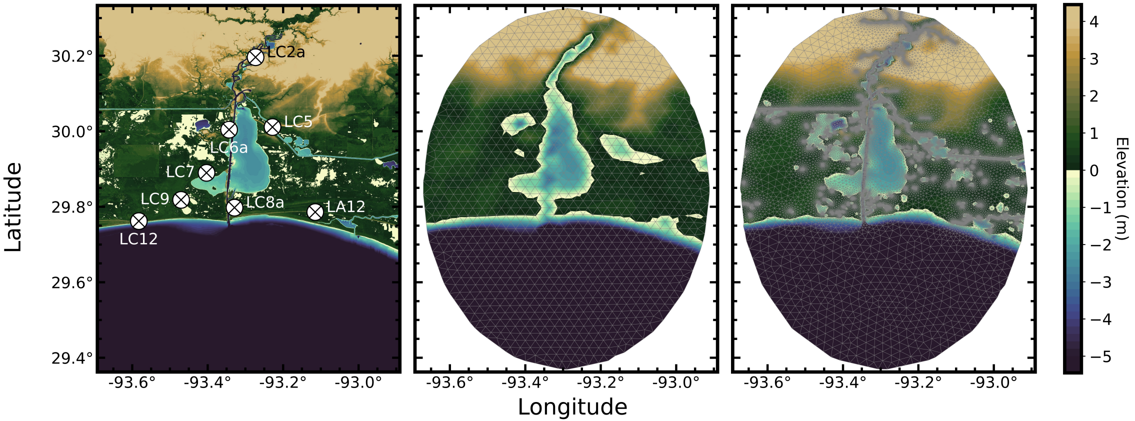
→ Removed extensive logic to compare water levels, velocities between vertices

3. Results

Meshes and Station Locations

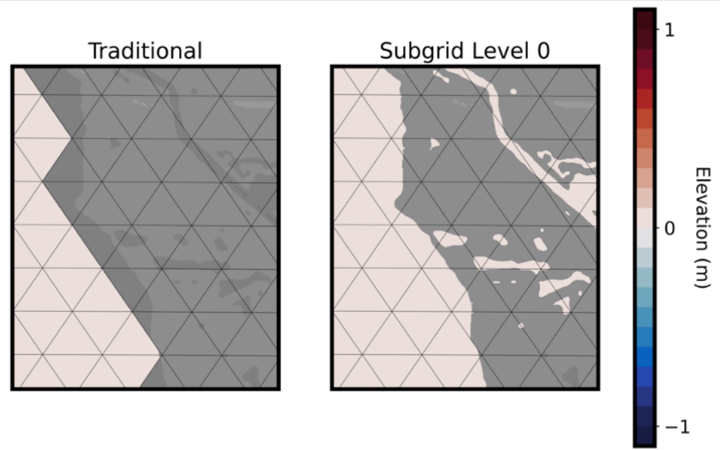
Coarse:
1,236 vertices
2,370 elements

Fine:
40,816 vertices
81,321 elements



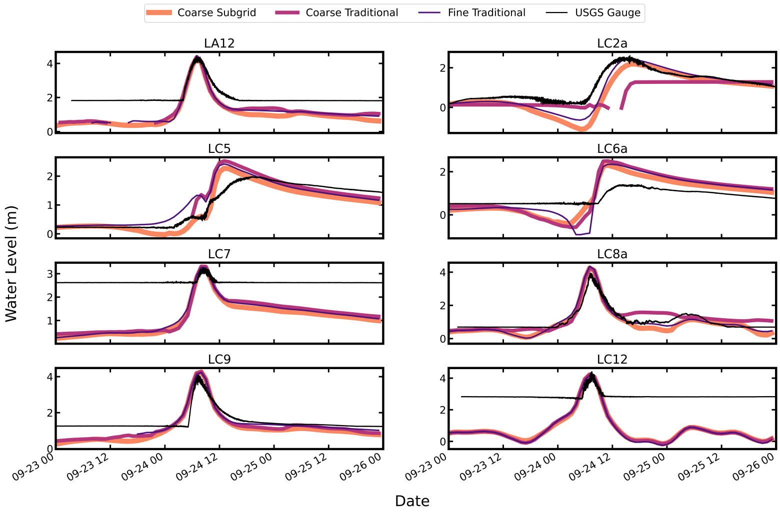
3. Results

Improvements at Wet/Dry Interface



3. Results

Tides and Storm Surge at Stations

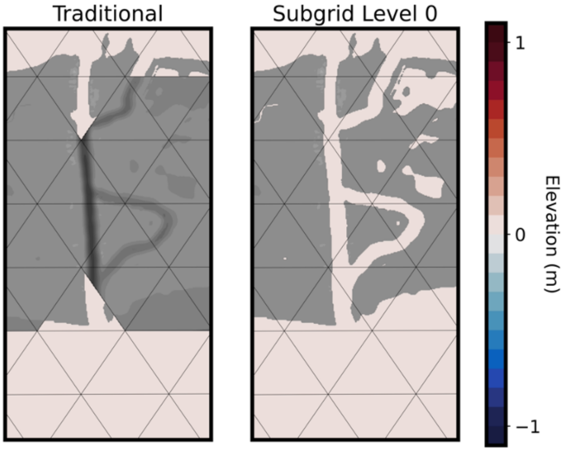


Differences (m) in peak water levels at observation stations

	Coarse Subgrid	Coarse Traditional	Fine Traditional
LA12	0.065	0.028	0.060
LC2a	0.423	1.328	0.152
LC5	0.281	0.538	0.435
LC6a	0.898	1.095	0.940
LC7	0.006	0.048	0.002
LC8a	0.312	0.327	0.412
LC9	0.180	0.192	0.155
LC12	0.202	0.182	0.206

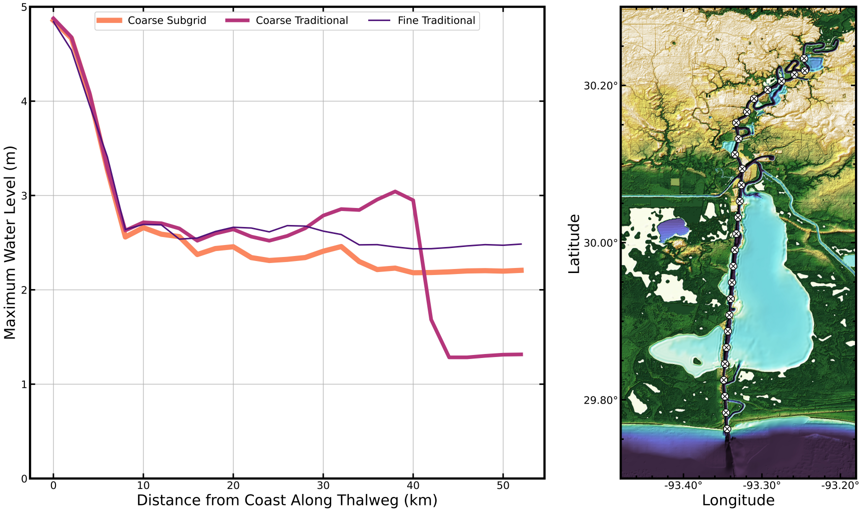
3. Results

Improvements for Channel Connectivity



3. Results

Maximum Water Levels along Main Channel



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

$\rightarrow$ But it gives comparable results to a mesh that is 33 times coarser

4. Conclusions and Future Work

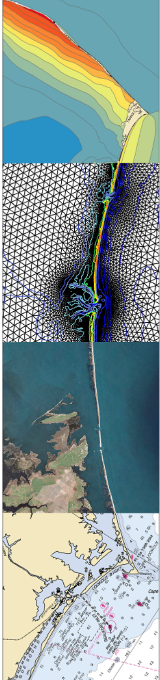
Subgrid ADCIRC

The main contributions 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 simulation on large domains



4. Conclusions and Future Work

Upcoming Manuscript in *Ocean Modelling*

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Johnathan L. Woodruff[a,1], JC Dietrich[a],
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Z Silver[b], SD Medlin[a], RL Kolar[c]

[a]*Department of Civil, Construction, and Environmental Engineering, North Carolina State University, 2501 Stinson Drive, Raleigh, North Carolina, 27607*
[b]*Department of Civil and Environmental Engineering and Earth Science, University of Notre Dame, South Bend, Indiana, 46556*
[c]*School of Civil Engineering and Environmental Science, University of Oklahoma, Norman, Oklahoma, 73019*

Abstract

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