Sub-Mesh Corrections for Efficient Predictions of Storm-Driven Coastal Flooding

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1. Motivation Loss of Information at Model Scale

High-resolution DEM with bathy/topo for Bayou Contraband



Typical finiteelement 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
 - $\rightarrow\,$ Able to coarsen by factor of 32
- Casulli (2009) and Casulli and Stelling (2011) also corrected partially wet cells
 - $\rightarrow\,$ Used lookup tables created from high-resolution elevation data
- Volp (2013) corrected bottom stress
 - $\rightarrow\,$ 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

 $\rightarrow\,$ 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 grid/mesh scale:

$$\langle Q \rangle_G \equiv rac{1}{A_G} \iint_{A_W} Q \; \mathrm{d}A$$

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

$$\langle Q
angle_W \equiv rac{1}{A_W} \iint_{A_W} Q \; \mathrm{d}A$$

- Where the areas are related by:

$$A_W = \phi A_G$$

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2. Methods

Implementation in ADCIRC

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:



2. Methods

Averaged Governing Equations for ADCIRC

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

- Example of momentum conservation in x-direction:

$$\frac{\partial \langle UH \rangle_{G}}{\partial t} + \frac{\partial C_{UU} \langle U \rangle \langle UH \rangle_{G}}{\partial x} + \frac{\partial C_{VU} \langle V \rangle \langle UH \rangle_{G}}{\partial y} - f \langle VH \rangle_{G}$$
$$= -g C_{\zeta} \langle H \rangle_{G} \frac{\partial \langle \zeta \rangle_{W}}{\partial x} - g \langle H \rangle_{G} \frac{\partial P_{A}}{\partial x} + \phi \langle \frac{\tau_{sx}}{\rho_{0}} \rangle_{W}$$
$$- C_{M,f} \frac{|\langle U \rangle| \langle UH \rangle_{G}}{\langle H \rangle_{W}} + \frac{\partial}{\partial x} \tilde{E}_{h} \frac{\partial \langle UH \rangle_{G}}{\partial x} + \frac{\partial}{\partial y} \tilde{E}_{h} \frac{\partial \langle UH \rangle_{G}}{\partial y}$$

in which the red coefficients are new closure terms

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

2. Methods

Closures

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	$C_{M,f}=C_f=gn^2/H^{1/3}$	$C_{M,f} = \langle C_f angle_G$
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

 $\rightarrow\,$ Better connectivity through small-scale flow pathways



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

 $\rightarrow\,$ Removed extensive logic to compare water levels, velocities between vertices

3. Results Meshes and Station Locations

30.2°

 Coarse:
 Fine:

 1,236 vertices
 40,816 vertices

 2,370 elements
 81,321 elements



Improvements at Wet/Dry Interface



Tides and Storm Surge at Stations



Date

Accuracy 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

Improvements for Channel Connectivity



Maximum Water Levels along Main Channel



Efficiency

Wall-clock times (sec) for three test cases

- All tests run in serial on same hardware

	Coarse Subgrid	Coarse Traditional	Fine Traditional
Winding Channel	62	107	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
 - $\rightarrow\,$ First application with hurricane-strength forcing
- 2. Increases in accuracy and hydraulic connectivity on coarsened meshes
 - $\rightarrow\,$ Peak surge within 0.5 m at top of Bayou Contraband
- 3. Efficiency gains on coarsened meshes
 - $\rightarrow\,$ 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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