Storm Surge Predictions from Ocean- to Subgrid-Scales

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ADCIRC Users Group Meeting
Baton Rouge, Louisiana, 8-9 Jun 2023

COASTAL RESILIENCE CENTER
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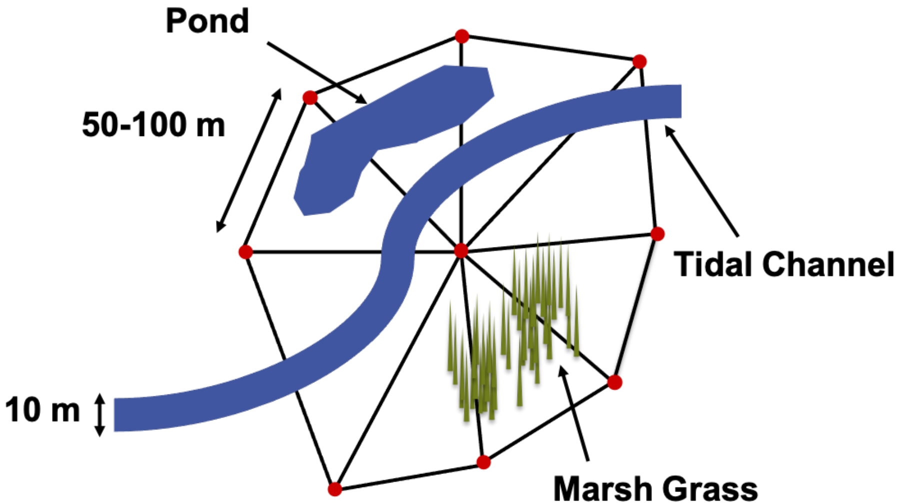
1. Motivation

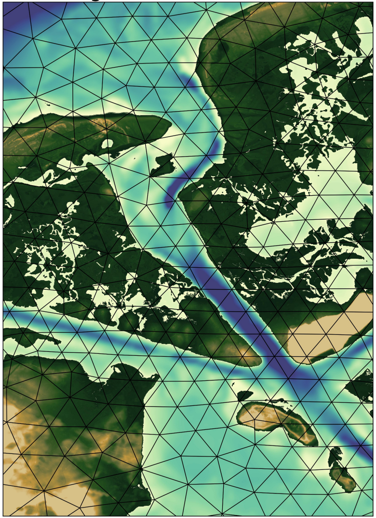
Use Smaller-Scale Information to ‘Correct’ Flows



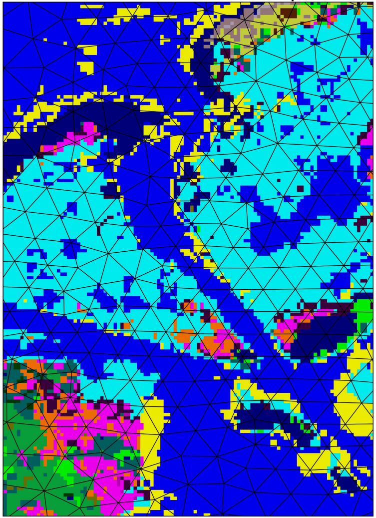
1. Motivation

Rich Datasets for Ground Surface Characteristics Smaller than Grid Scale

Digital Elevation Model



C-CAP Landcover Map



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:

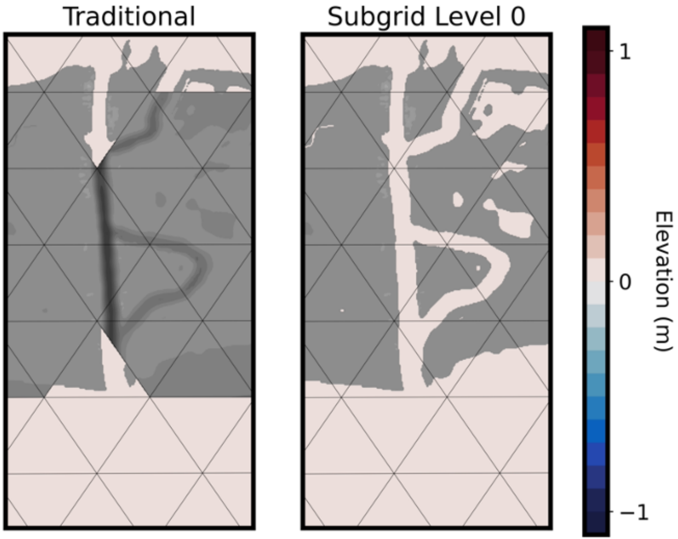
- Defina (2000) corrected advection and partially wet cells
  - → Able to coarsen by factor of 32
- Casulli (2009) and Casulli and Stelling (2011) also corrected partially wet cells
  - → Used lookup tables created from high-resolution elevation data
- Volp (2013) corrected bottom stress
  - → Improved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

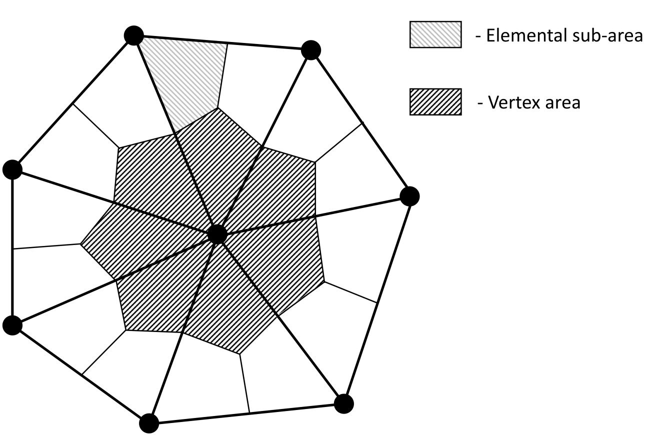
1. Motivation

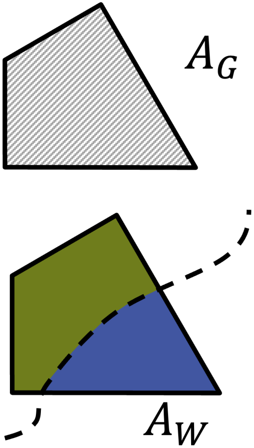
Improvements for Connectivity to Inland Regions



2. Methods

Implementation in ADCIRC requires Careful Definitions of Averaging Areas





Shallow Water Equations are Averaged to the Model Scale

A given flow variable Q can be averaged, e.g. Kennedy *et al.* (2019):

- 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:

$$A_W = \phi A_G$$

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

- Example of momentum conservation in x-direction:

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

  in which the red coefficients are new closure terms

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

Closure Terms have Levels of Complexity

We used 'Level 0' and 'Level 1' closures:

		Conventional	Level 0	Level 1
Wet/dry	ϕ	0 or 1	A_W/A_G	A_W/A_G
Advection	$C_{UU}, C_{VU}, C_{UV}, C_{VV}$	1	1	$\frac{1}{\langle H \rangle_W} \langle H^2/C_f \rangle_W R_v^2$
Friction	$C_{M,f}$	$C_f = gn^2/H^{1/3}$	$\langle C_f \rangle_W$	$\langle H \rangle_W R_v^2$
Surface gradient	C_ζ	1	1	1

Note the differences for the wet/dry status, advection, and friction terms

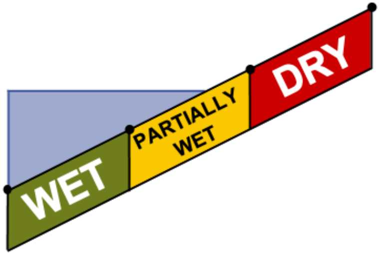
- Level-0 only changes the wet/dry status to allow partially wet cells/elements
- Level-1 adds corrections for advection and friction

2. Methods

Subgrid Corrections allow for Partially Wet Cells/Elements

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

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

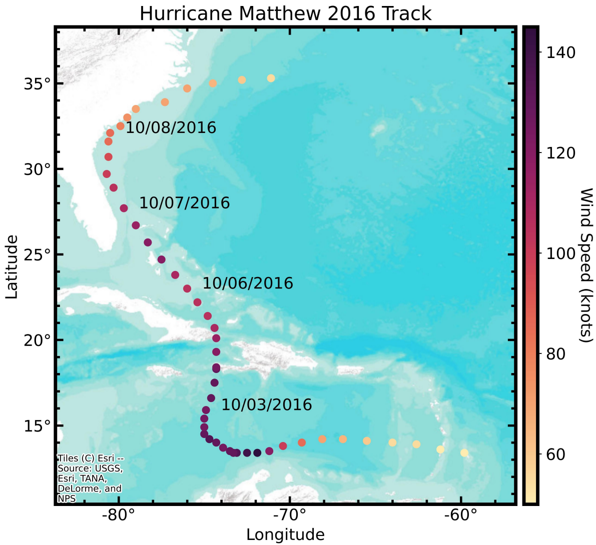


Now the status is determined solely by the total water depth:

$$\langle H \rangle_G > \langle H \rangle_{G_{min}} = 0.1 \text{ m}$$

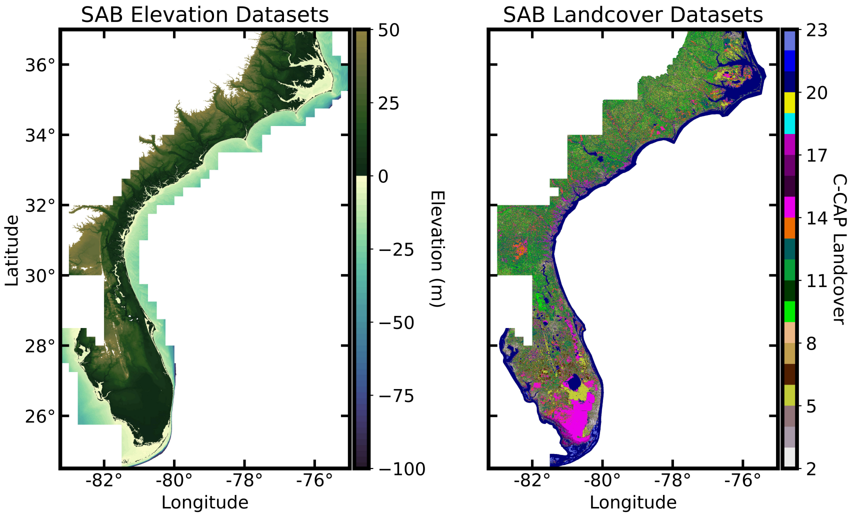
3. Results

Widespread Effects of Hurricane Matthew (2016)



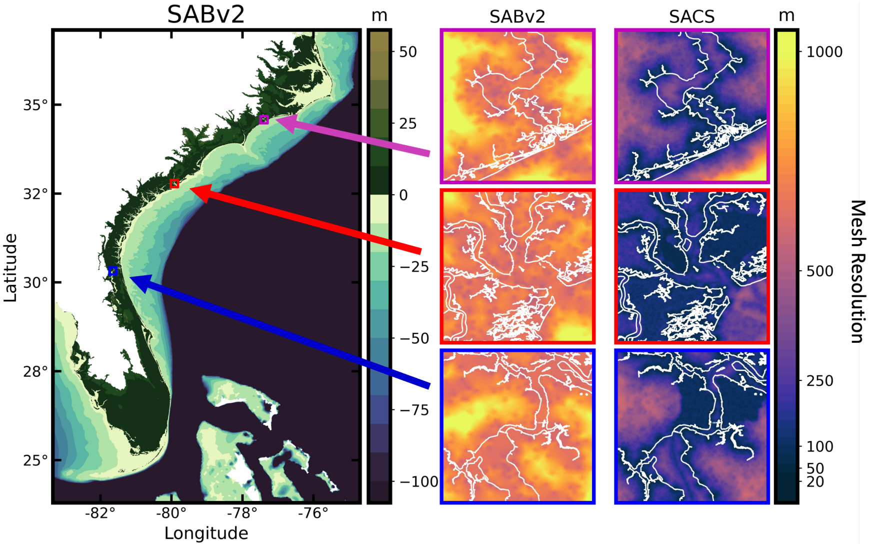
3. Results

South Atlantic Bight described by 830 Datasets and 197 GB



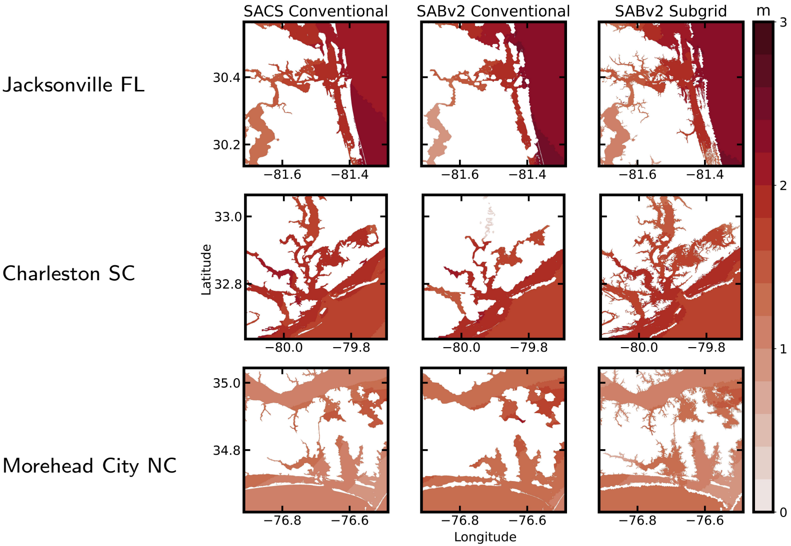
3. Results

'Forecast-Grade' Mesh with 770K Vertices and Minimum Resolution of 500 m



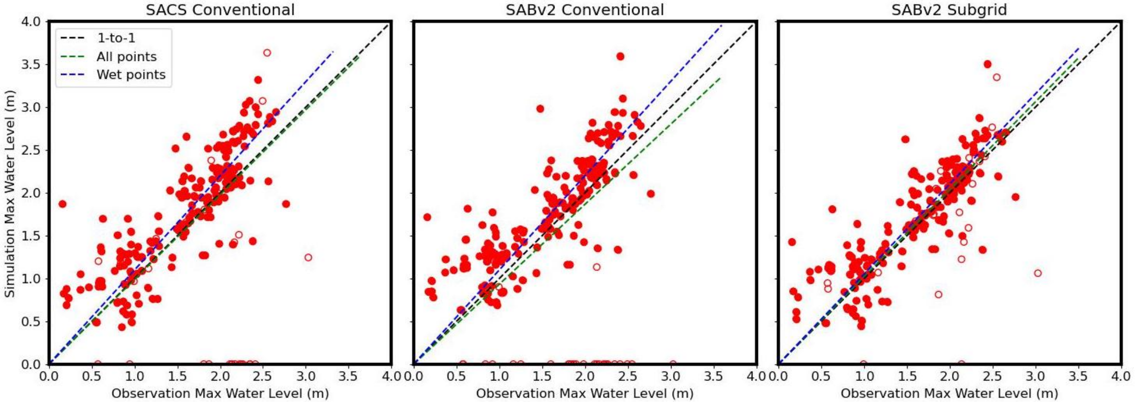
3. Results

Matthew (2016) Flooding Extents are Similar to SACS Mesh that is 15 Times Larger



3. Results

Flooding at More Locations, and Better Match to Observed Peaks



$E_{RMS} = 0.41$ m	$E_{RMS} = 0.43$ m	$E_{RMS} = 0.35$ m
$R^2 = 0.56$	$R^2 = 0.53$	$R^2 = 0.68$
$m = 1.10$	$m = 1.10$	$m = 1.05$

3. Results

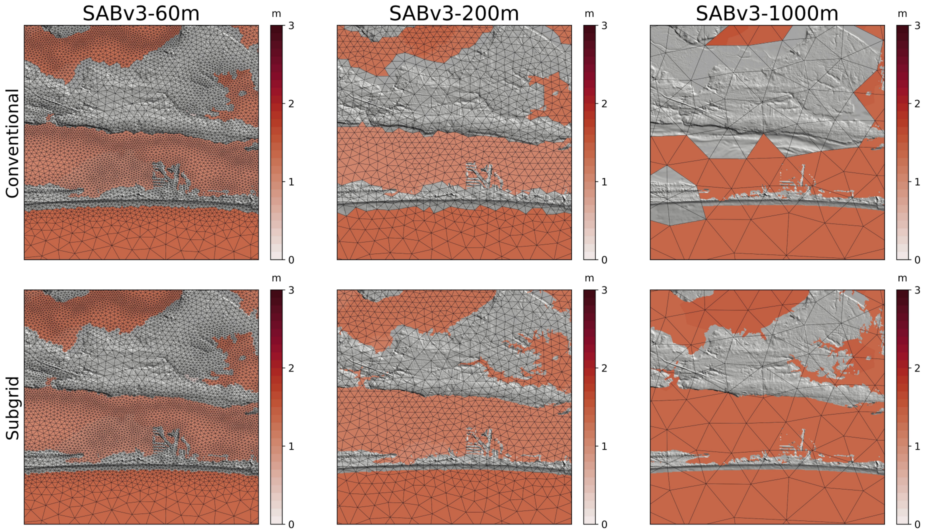
Subgrid ADCIRC has Overhead, but Offers Significant Speed-ups

Wall-Clock Time (CPU-hr)	
SACS Conventional	5860
SABv2 Conventional	386
SABv2 Subgrid	433

Wall-Clock Time Ratio	
SABv2 Subgrid / SABv2 Conventional	1.12
SACS Conventional / SABv2 Subgrid	13.55

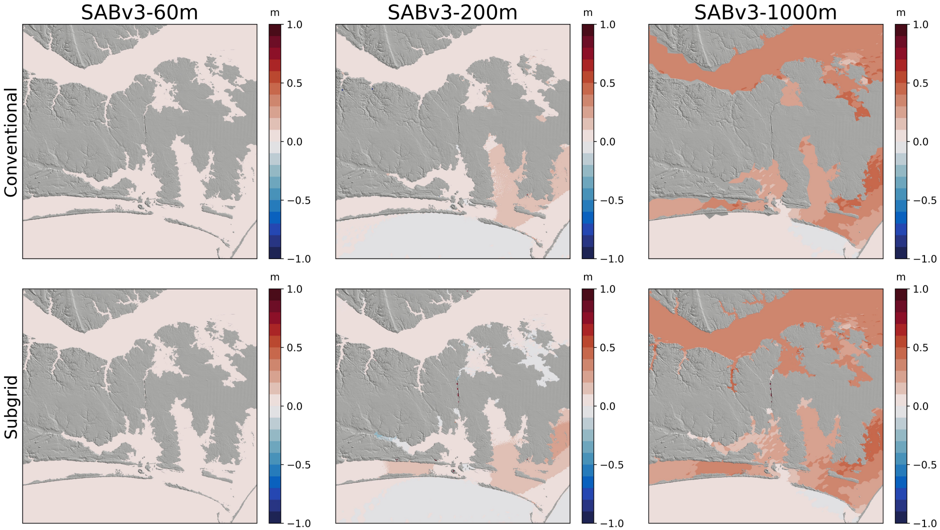
3. Results

How Coarse is Too Coarse?



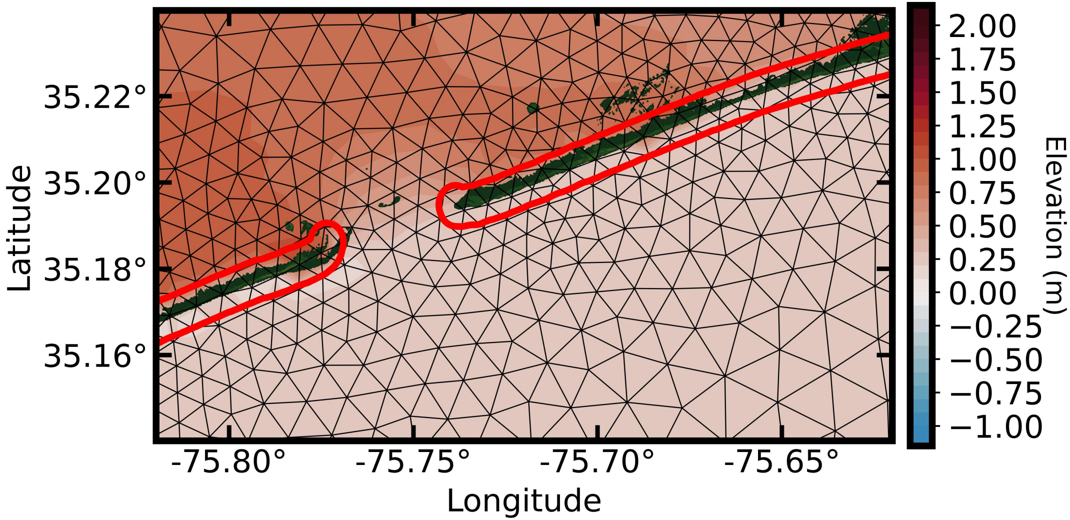
3. Results

Need to Align Vertices with Flow-Blocking Features



3. Results

Enforce a Higher Wetting Criteria at High Points?



4. Conclusions

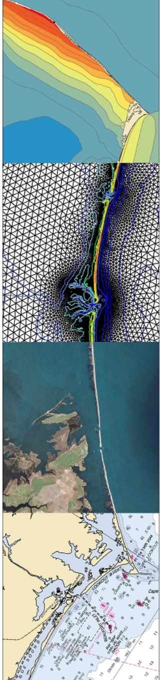
Subgrid ADCIRC

The main contributions of this research are:

1. Subgrid corrections were added to ADCIRC
   → Hurricane-strength forcing on ocean domains
2. Increases in accuracy and hydraulic connectivity on coarsened meshes
   → Flooding to more locations in South Atlantic Bight, better match to observations during Matthew (2016)
3. Efficiency gains on coarsened meshes
   → Speed-ups by factors of 13+

Future efforts should focus on:

- Optimizing code to reduce overhead
- New applications



4. Conclusions

Recent Manuscripts describe Johnathan's PhD Research

Ocean Modelling 167 (2021) 101887

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ELSEVIER

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

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ARTICLE INFO

Keywords:
Storm surge
Subgrid
ADCIRC
Wetting and drying
Shallow water equations

ABSTRACT

Coastal flooding models are used to predict the timing and magnitude
real-time forecasting and long-term design. However, there is a need f
represent flow pathways and barriers at the scales of critical infrastru
subgrid corrections, which use information at smaller scales to 'correct' t
velocities) averaged over the mesh scale. Recent studies have shown a
of magnitude, with the ability to decrease further if the model time ste
In this study, subgrid corrections are added to a widely used, finit
to better understand how they can improve the accuracy and effic
performance of the model, with and without subgrid corrections, is ev
in a synthetic domain and a small bay in Massachusetts, as well as a sc
and storm surge in southwest Louisiana. In these tests we observed tha
model speed by 10 to 50 times, while still representing flow through ch
locations.

10.1016/j.ocemod.2021.101887

10.1007/s11069-023-05975-2

Natural Hazards
https://doi.org/10.1007/s11069-023-05975-2

ORIGINAL PAPER

Check for updates

Storm surge predictions from ocean to subgrid scales

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Received: 25 October 2022 / Accepted: 30 March 2023

Abstract

The inland propagation of storm surge caused by tropical cyclones depends on large and small waterways to connect the open ocean to inland bays, estuaries, and floodplains. Numerical models for storm surge require these waterways and their surrounding topography to be resolved sufficiently, which can require millions of computational cells for flooding simulations on a large (ocean scale) computational domain, leading to higher demands for computational resources and longer wall-clock times for simulations. Alternatively, the governing shallow water equations can be modified to introduce subgrid corrections that allow coarser and cheaper simulations with comparable accuracy. In this study, subgrid corrections are extended for the first time to simulations at the ocean scale. Higher-level

4. Conclusions

Subgrid Lookup Calculator available on Github