Storm Surge Predictions from Ocean- to Subgrid-Scales

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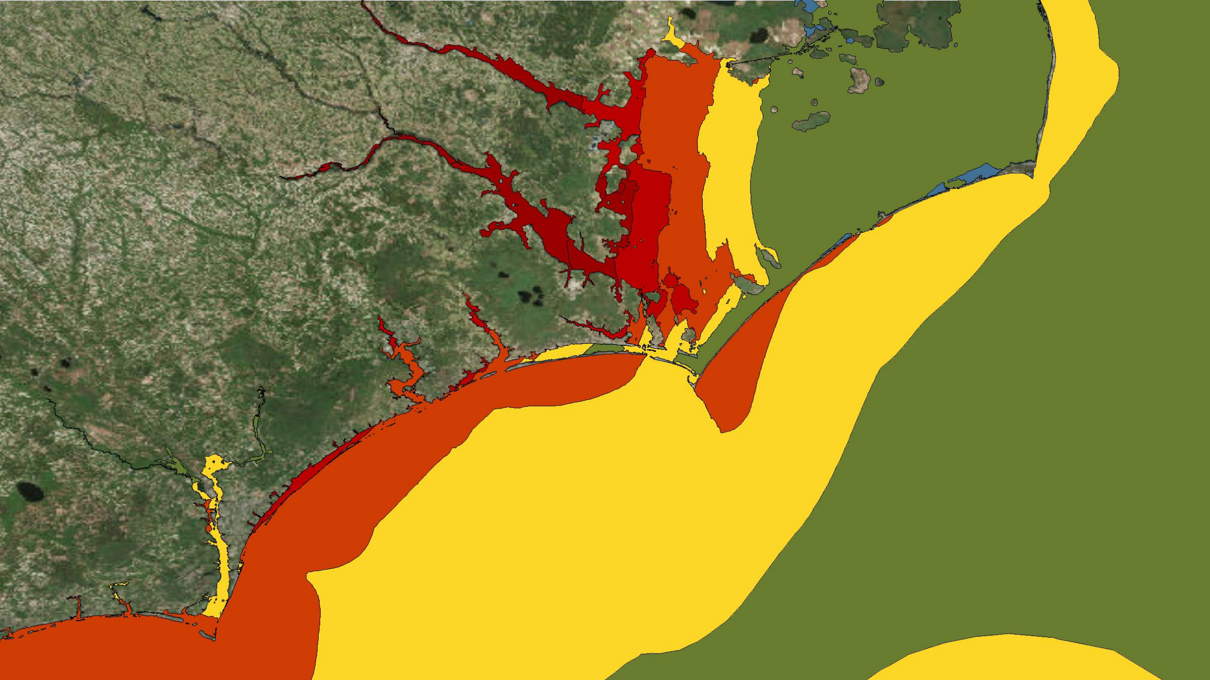


ADvanced CIRCulation (ADCIRC) solves modified forms of the shallow water equations ...

We use ADCIRC to represent the long waves of tides and storm surge

- Solves the generalized wave continuity equation (GWCE) for water levels (ζ):

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

- Solves the depth-averaged momentum equations for currents (U, V):

$$\frac{\mathrm{D}U}{\mathrm{D}t} - fV = -g \frac{\partial}{\partial x} \left[\zeta + \frac{p_s}{g \rho_0} - \alpha \eta \right] + \frac{\tau_{sx} + \tau_{bx}}{\rho_0 H} + \frac{M_x - D_x}{H}$$

$$\frac{\mathrm{D}V}{\mathrm{D}t} + fU = -g \frac{\partial}{\partial y} \left[\zeta + \frac{p_s}{g \rho_0} - \alpha \eta \right] + \frac{\tau_{sy} + \tau_{by}}{\rho_0 H} + \frac{M_y - D_y}{H}$$

… and ADCIRC uses high-resolution in space and time

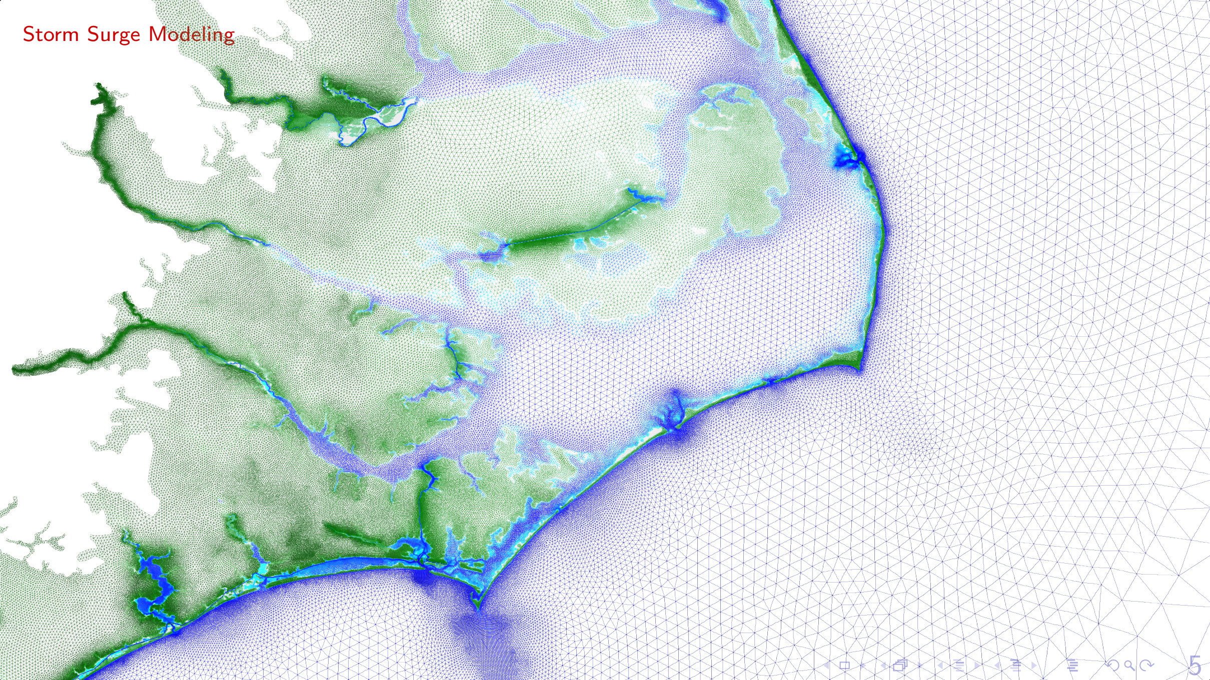
In geographic space:

- Piecewise-linear, continuous, Galerkin finite elements
  - Unique values for (ζ, U, V) at every mesh vertex
- Typical minimum mesh spacings of 10 to 50 m

In time:

- Semi-implicit
  - Implicit solution of GWCE using Jacobi Conjugate Gradient (JCG) solver
  - Explicit solution of momentum equations with lumped mass matrix
- Fully explicit
  - Also possible to use lumped mass matrix for solution of GWCE
- Typical time steps of 0.5 to 10 sec

Storm Surge Modeling

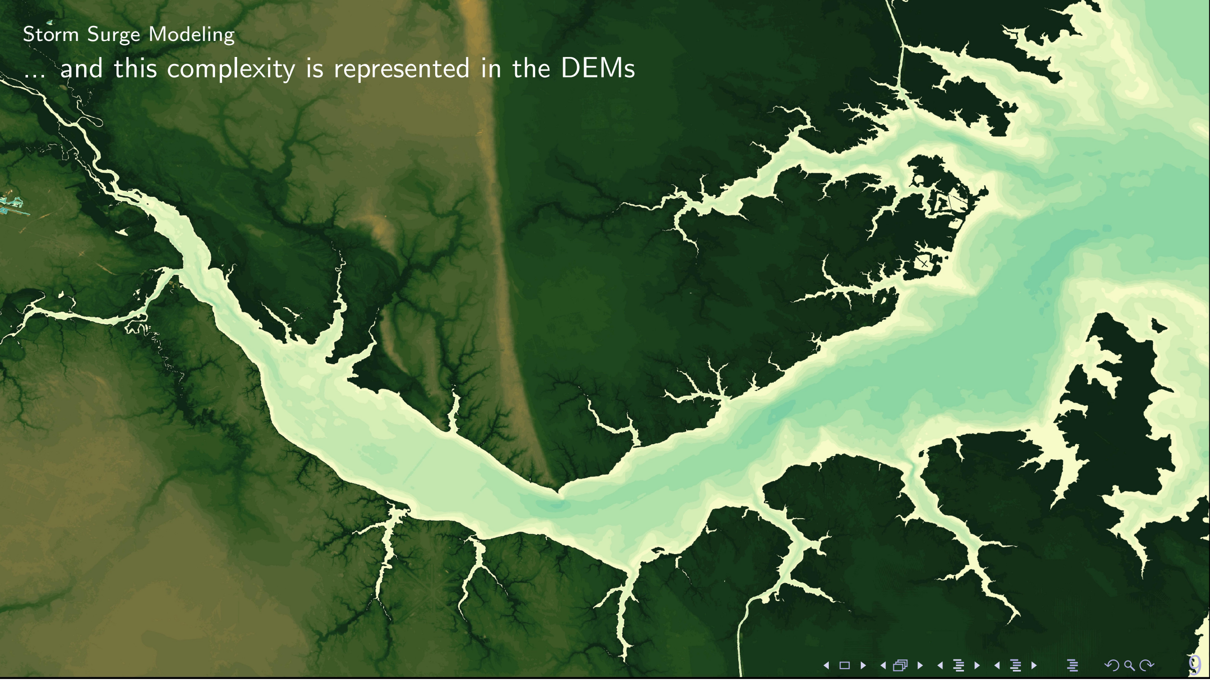


Coastal NC has a wide range of spatial scales ...

... which we can explore by zooming to the Neuse River Estuary ...

... which has a main estuary, smaller channels, floodplains, etc. ...

… and this complexity is represented in the DEMs

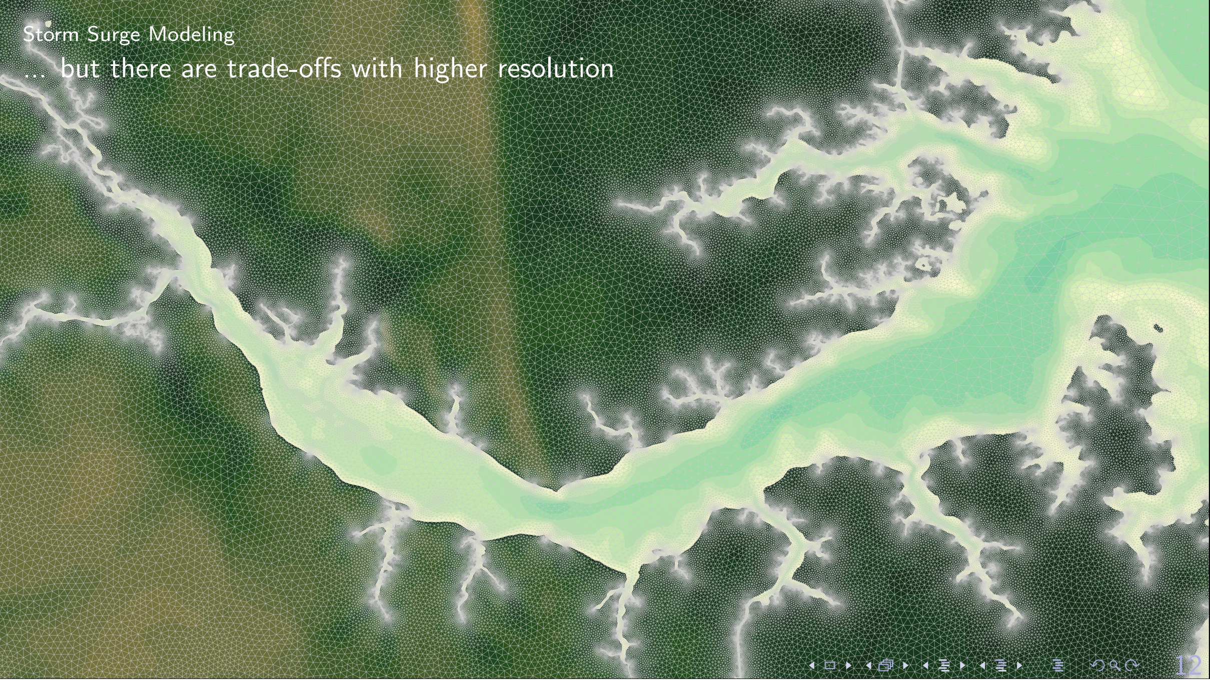


If we are not careful with how we design our mesh ...

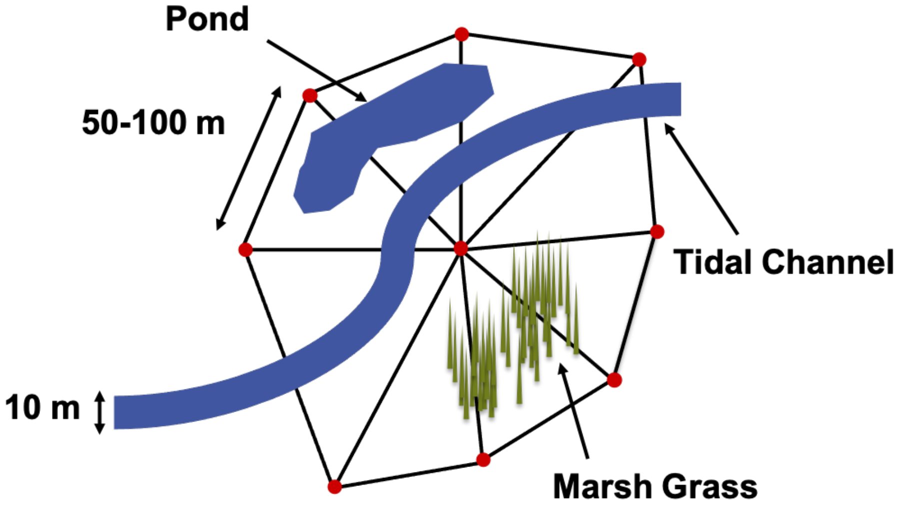
... then we may alias the smaller features ...

Storm Surge Modeling

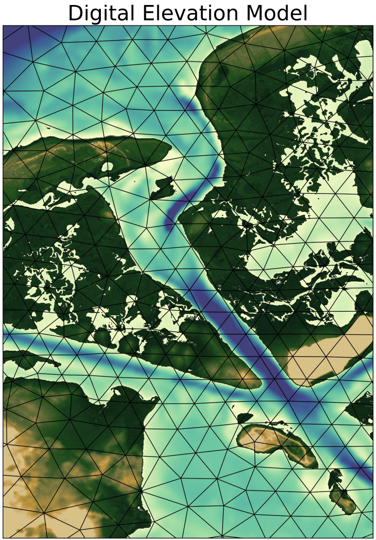
… but there are trade-offs with higher resolution

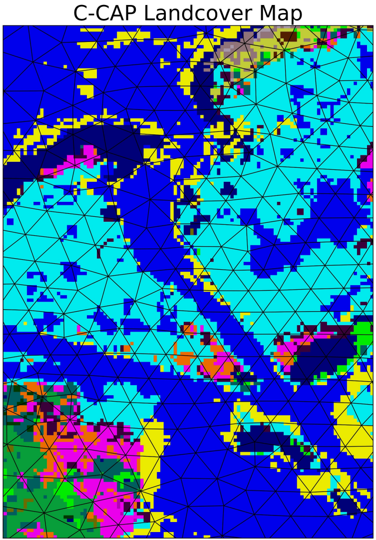


We want to have our cake ...



… and eat it, too





Long history of subgrid corrections for shallow water flows ...

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

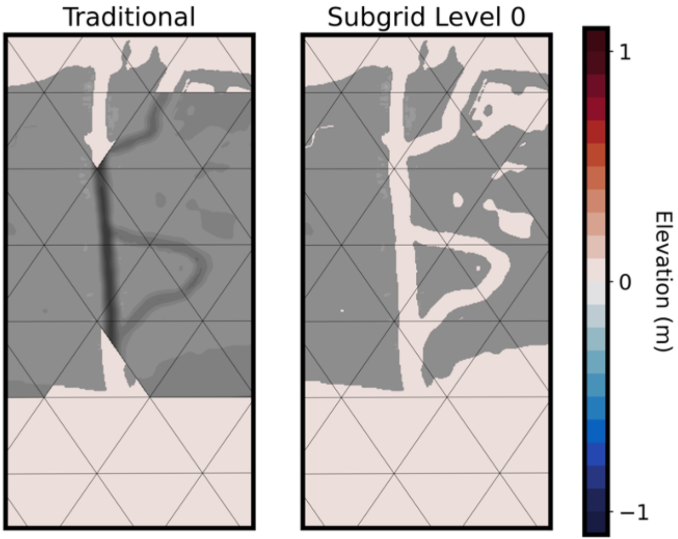
Selected applications to shallow water flows:

- 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

.. and we used subgrid corrections to improve connectivity for ADCIRC



Subgrid Corrections in ADCIRC

- Averaged Equations
- Closure Terms
- Look-up Tables

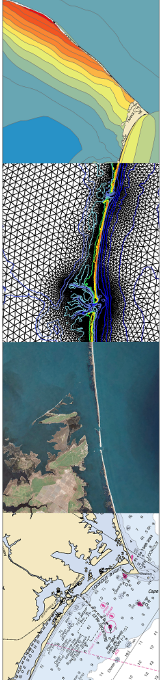
Benefits on Synthetic Test Cases

- Level 0 (Wet Fraction)
- Level 1 (Advection and Bottom Friction)

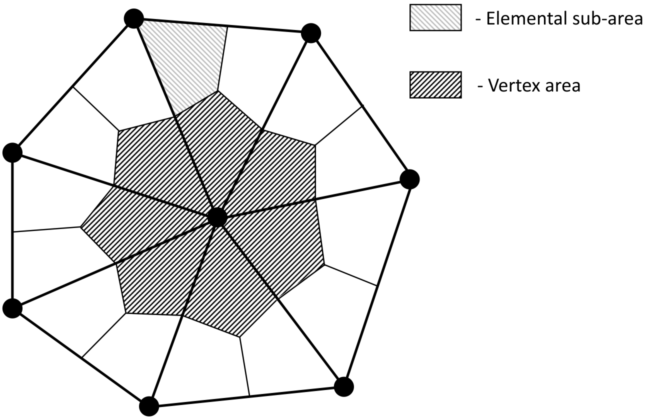
Expansion to Storm Surge on Ocean Scales

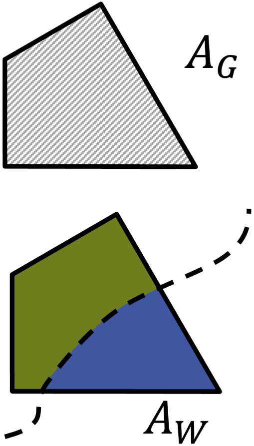
- Matthew (2016) in South Atlantic Bight

Conclusions



Implementation in ADCIRC requires careful definitions of averaging areas





Govering 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:

$$A_W = \phi A_G$$

… and we can simplify the time derivatives …

We can use rules from Whitacker (1985) to interchange differentiation

- We assume away the boundary integrals

For example, to average a time derivative:

$$
\begin{aligned}
\langle \frac{\partial UH}{\partial t} \rangle_G &= \frac{1}{A_G} \iint_{A_W} \frac{\partial UH}{\partial t} \, \mathrm{d}A \\
&= \frac{1}{A_G} \frac{\partial}{\partial t} \iint_{A_W} UH \, \mathrm{d}A - \frac{1}{A_G} \iint_{\Gamma_W} UH \left(U_B \cdot \mathrm{n}_S \right) \, \mathrm{d}S \\
&= \frac{\partial \langle UH \rangle_G}{\partial t}
\end{aligned}
$$

because we assume $H = 0$ on the wet/dry boundary Γ_W

… and we can simplify the spatial derivatives …

The averaging starts similarly for a spatial derivative:

$$
\begin{aligned}
\langle \frac{\partial UUH}{\partial x} \rangle_G &= \frac{1}{A_G} \iint_{A_W} \frac{\partial UUH}{\partial x} \, \mathrm{d}A \\
&= \frac{1}{A_G} \frac{\partial}{\partial x} \iint_{A_W} UUH \, \mathrm{d}A + \frac{1}{A_G} \iint_{\Gamma_W} UUH \, \mathrm{n}_{s,x} \, \mathrm{d}S \\
&= \frac{\partial \langle UUH \rangle_G}{\partial x}
\end{aligned}
$$

but then we also introduce a closure term:

$$
\frac{\partial \langle UUH \rangle_G}{\partial x} = \frac{\partial C_{UU} \langle U \rangle \langle UH \rangle_G}{\partial x}
$$

... to derive the averaged governing equations for ADCIRC

We apply these averaging rules to every term in the governing equations

– 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

We can assign closures with 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

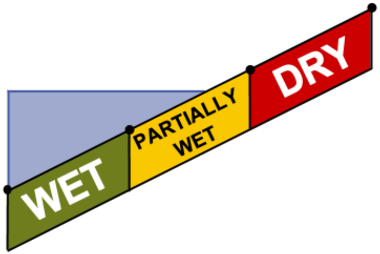
– Level 0 only changes the wet/dry status to allow partially wet cells/elements

– Level 1 adds corrections for advection and friction

… and these closures allow for partially wet elements/areas

Level-0 closures required a major revision to ADCIRC's wet/dry algorithm

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



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

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

Closures and averaged values can be pre-computed and stored in look-up tables ...

Following variables depend on subgrid information:

- Elements: $\langle H \rangle_G$, C_{UU}, C_{VU}, C_{UV}, C_{VV}, ϕ
- Vertices: $\langle H \rangle_G$, $\langle H \rangle_W$, $C_{M,f}$, ϕ

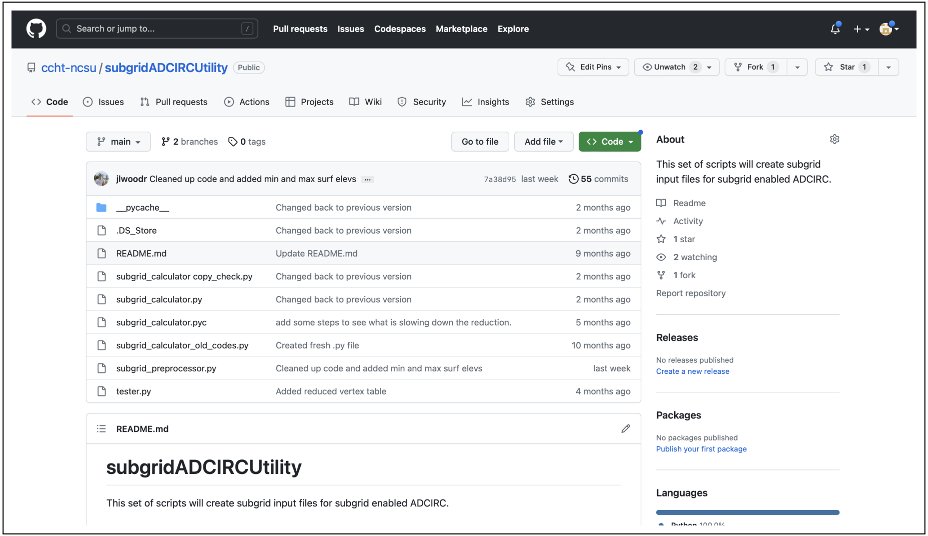
We can pre-compute these variables:

- Pick a range of possible water levels, e.g. $\langle \zeta \rangle_W = -5$ to 5 m
- For each possible $\langle \zeta \rangle_W$, compute other variables based on high-resolution elevation and landcover raster datasets
- Store variables in look-up tables for use during the simulation

We reduced file sizes by using a range of possible wet-area fractions, $\phi = 0$ to 1

Look-up Tables

... by using an open-source subgrid calculator



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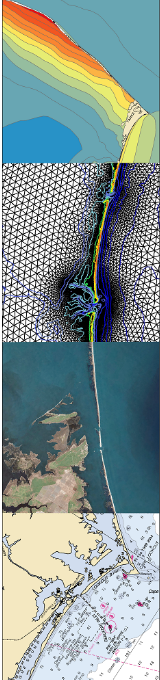
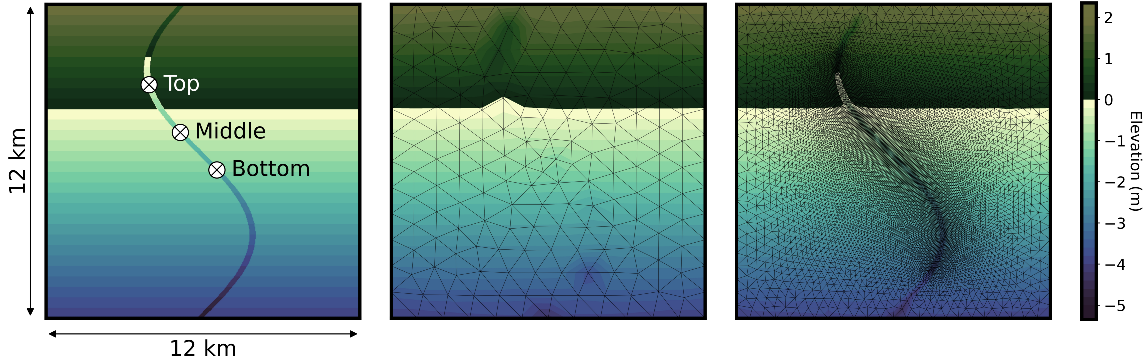
Conclusions



Partially wet elements are important ...

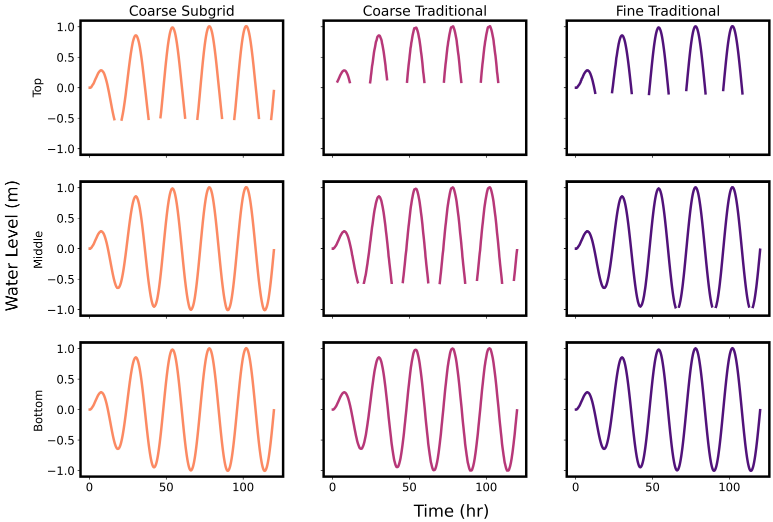
Consider a winding channel:

- Channel width 250 m and depth 1 m below surrounding topography
- Meshes: coarse (1000 m) and fine (minimum 10 m)
- Tides from south boundary with amplitude 1 m



Level 0 (Wet Fraction)

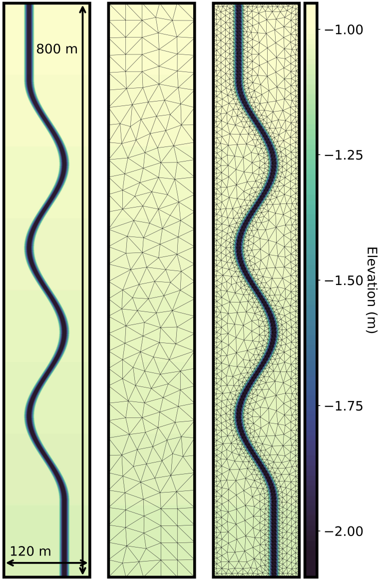
… because they allow tides to propagate further into the channel



Higher-level closures are sometimes important ...

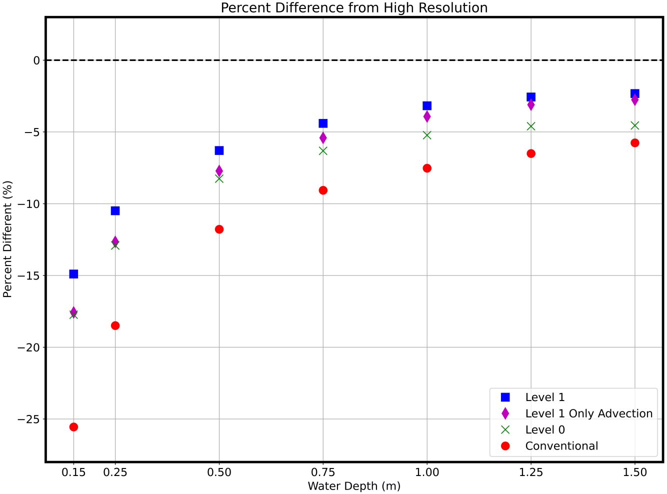
Consider another winding channel:

- Channel width 5 m and depth 1 m below surrounding
- Meshes: coarse (24 m) and fine (minimum 5 m)
- Constant flow by specifying water depths



Level 1 (Advection and Bottom Friction)

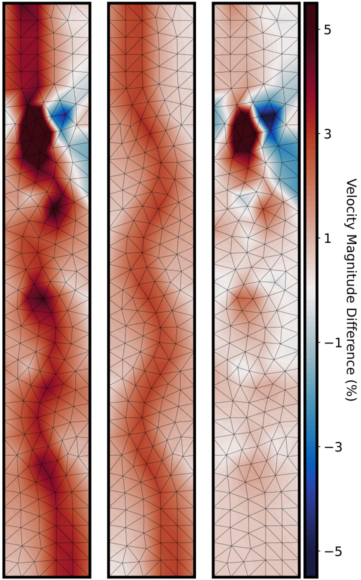
… depending on the overall flow depth …



… and the local flow velocities

Velocity magnitude differences due to:

- Advection and bottom friction
- Only bottom friction
- Only advection



- Subgrid Corrections in ADCIRC
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  - Look-up Tables
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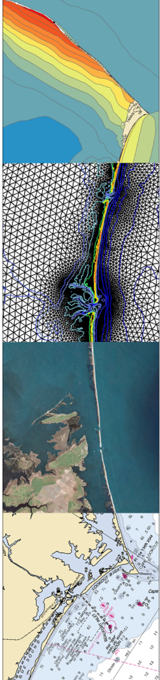
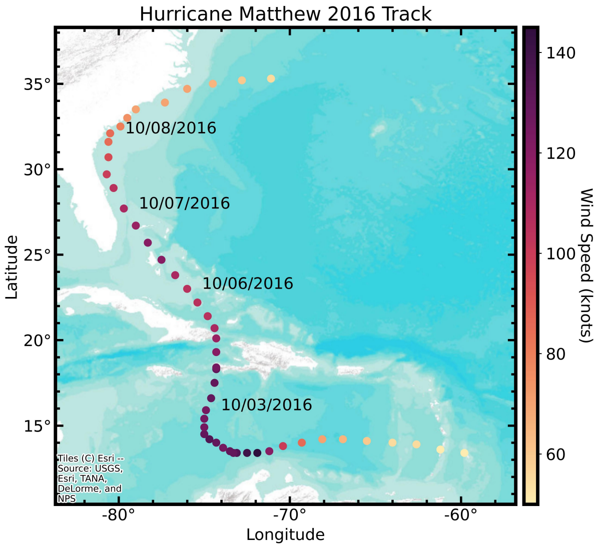
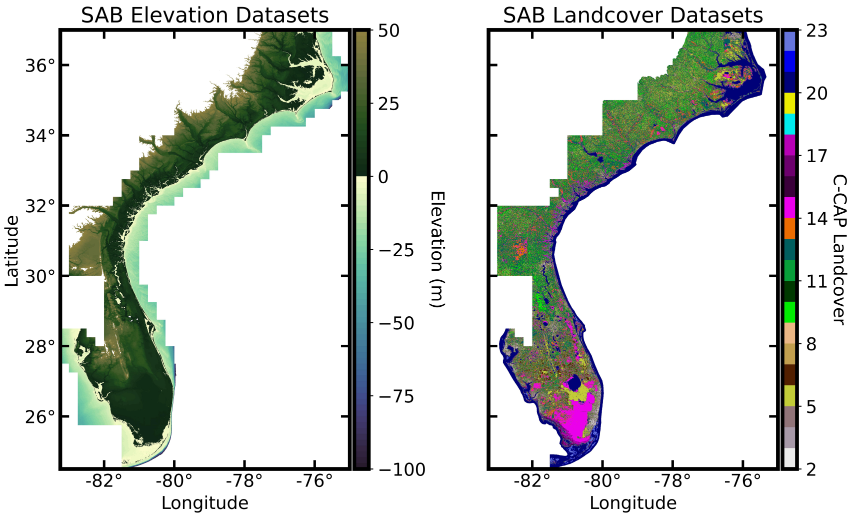
- **Expansion to Storm Surge on Ocean Scales**
  - Matthew (2016) in South Atlantic Bight
- Conclusions



Widespread flooding along South Atlantic Bight (SAB)

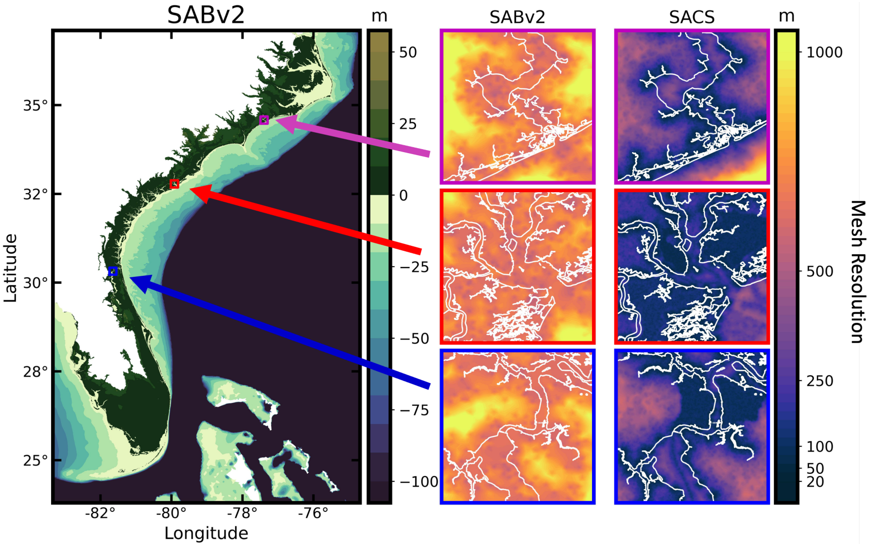


Elevation and landcover described by 830 datasets and 197 GB



Matthew (2016) in South Atlantic Bight

'Forecast-grade' mesh with 770K vertices and minimum resolution of 500 m

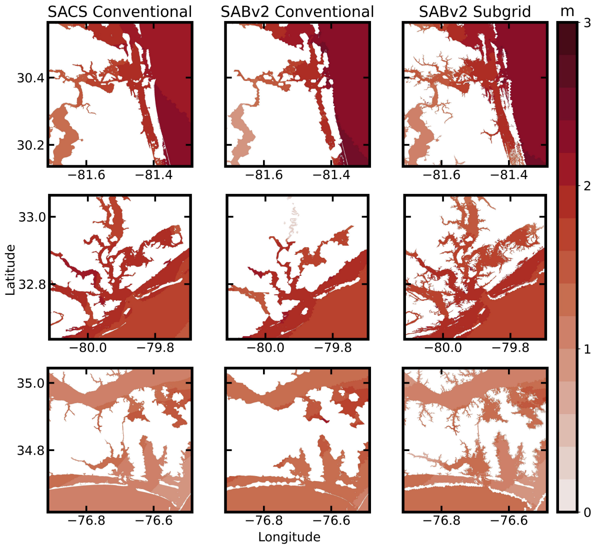


Flooding extents are similar to SACS mesh that is 15 times larger

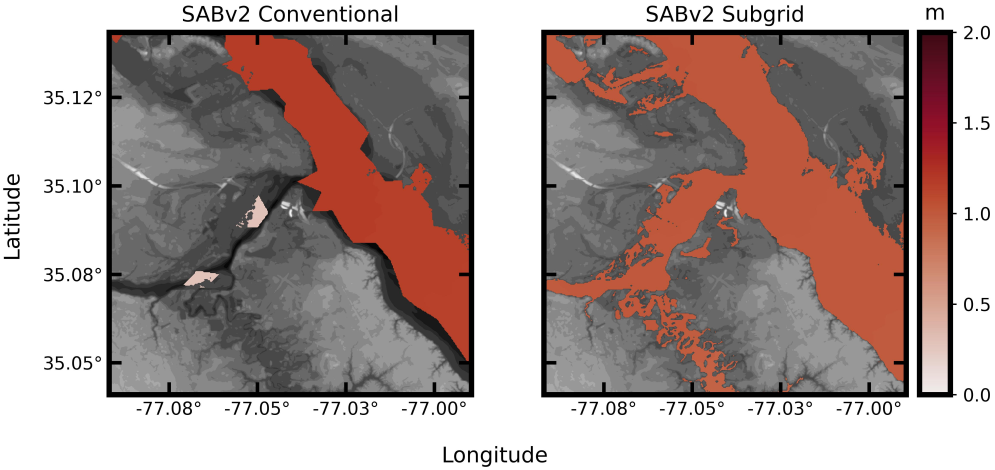
Jacksonville FL

Charleston SC

Morehead City NC

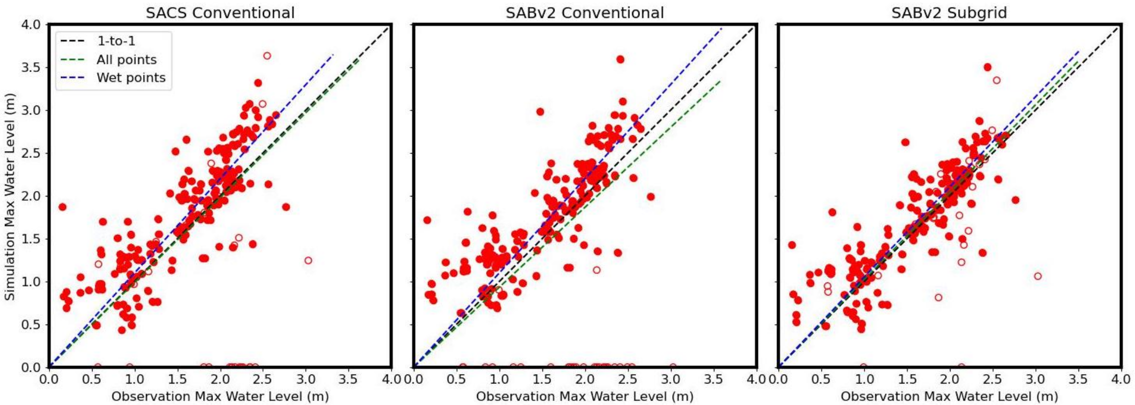


Improved connectivity to far-inland regions like New Bern NC



Matthew (2016) in South Atlantic Bight

Flooding at more locations, and better match to observed peaks



$E_{\mathrm{RMS}} = 0.41$ m
$R^2 = 0.56$
$m = 1.10$

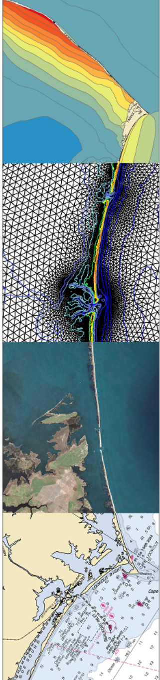
$E_{\mathrm{RMS}} = 0.43$ m
$R^2 = 0.53$
$m = 1.10$

$E_{\mathrm{RMS}} = 0.35$ m
$R^2 = 0.68$
$m = 1.05$

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



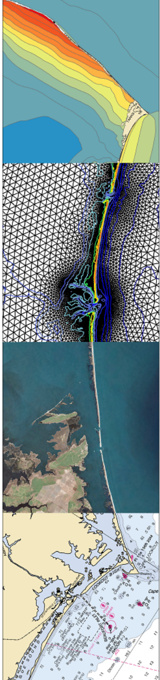
Subgrid ADCIRC

The main contributions of this research are:

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

Future efforts should focus on:

- Optimizing code to reduce overhead
- New applications



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

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ABSTRACT

Coastal flooding models are used to predict the timing and magnitude real-time forecasting and long-term design. However, there is a need fo 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.

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10.1007/s11069-023-05975-2

Natural Hazards
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ORIGINAL PAPER

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Storm surge predictions from ocean to subgrid scales

Johnathan Woodruff[1] · J. C. Dietrich[1] · D. Wirasaet[2] · A. B. Kennedy[2] · D. Bolster[2]

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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