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

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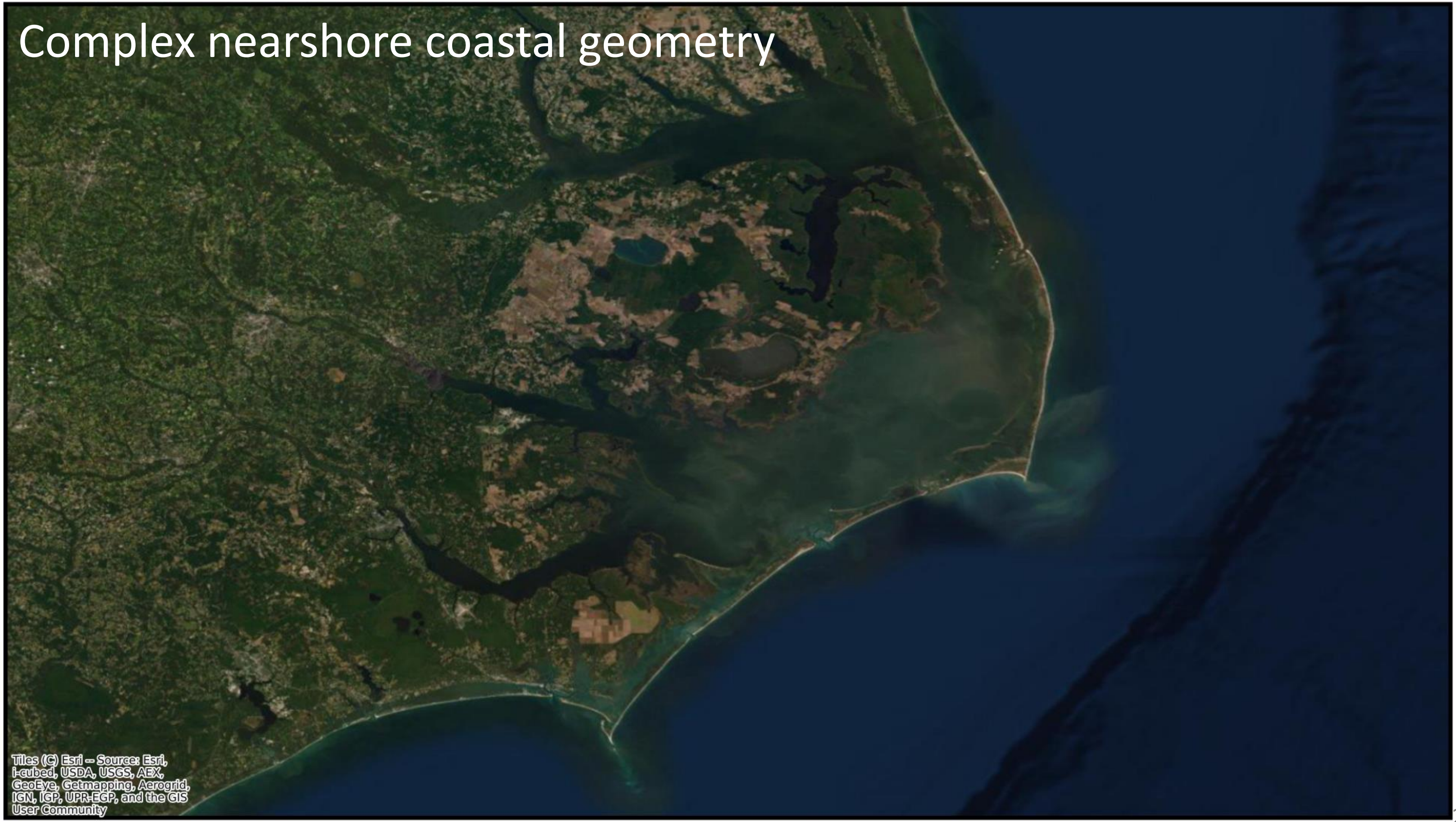
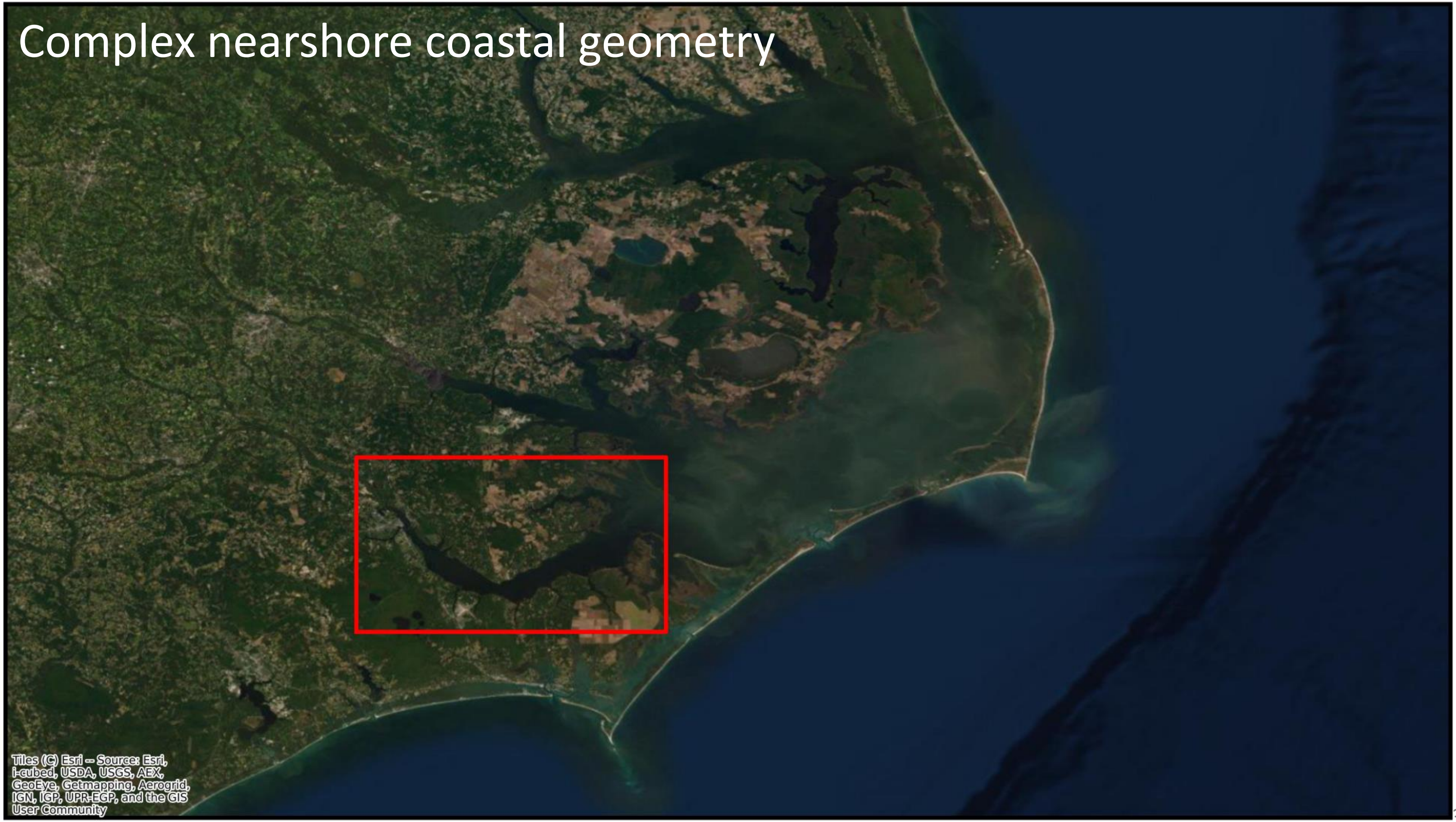
Complex nearshore coastal geometry



Complex nearshore coastal geometry



Complex nearshore coastal geometry

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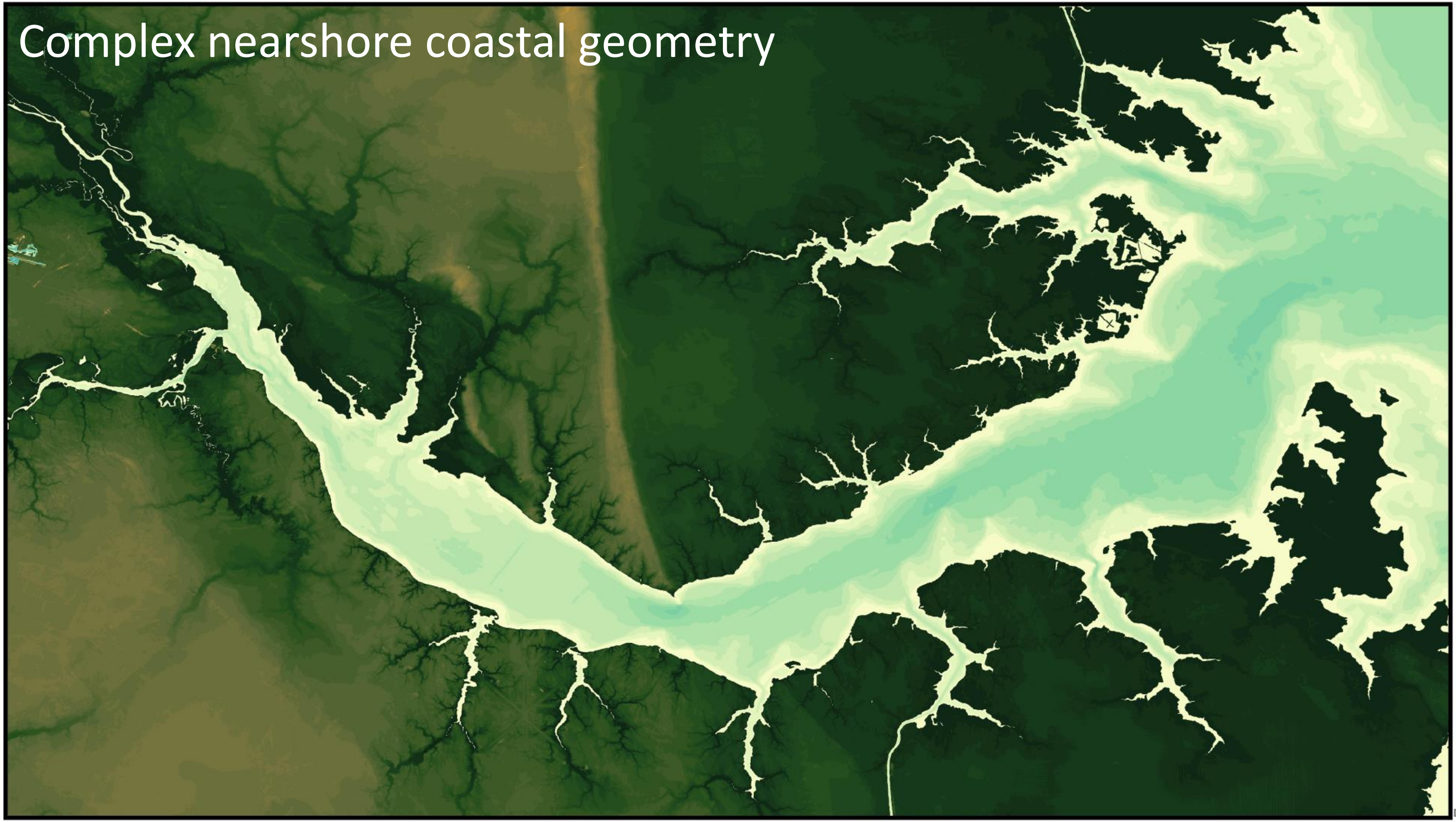
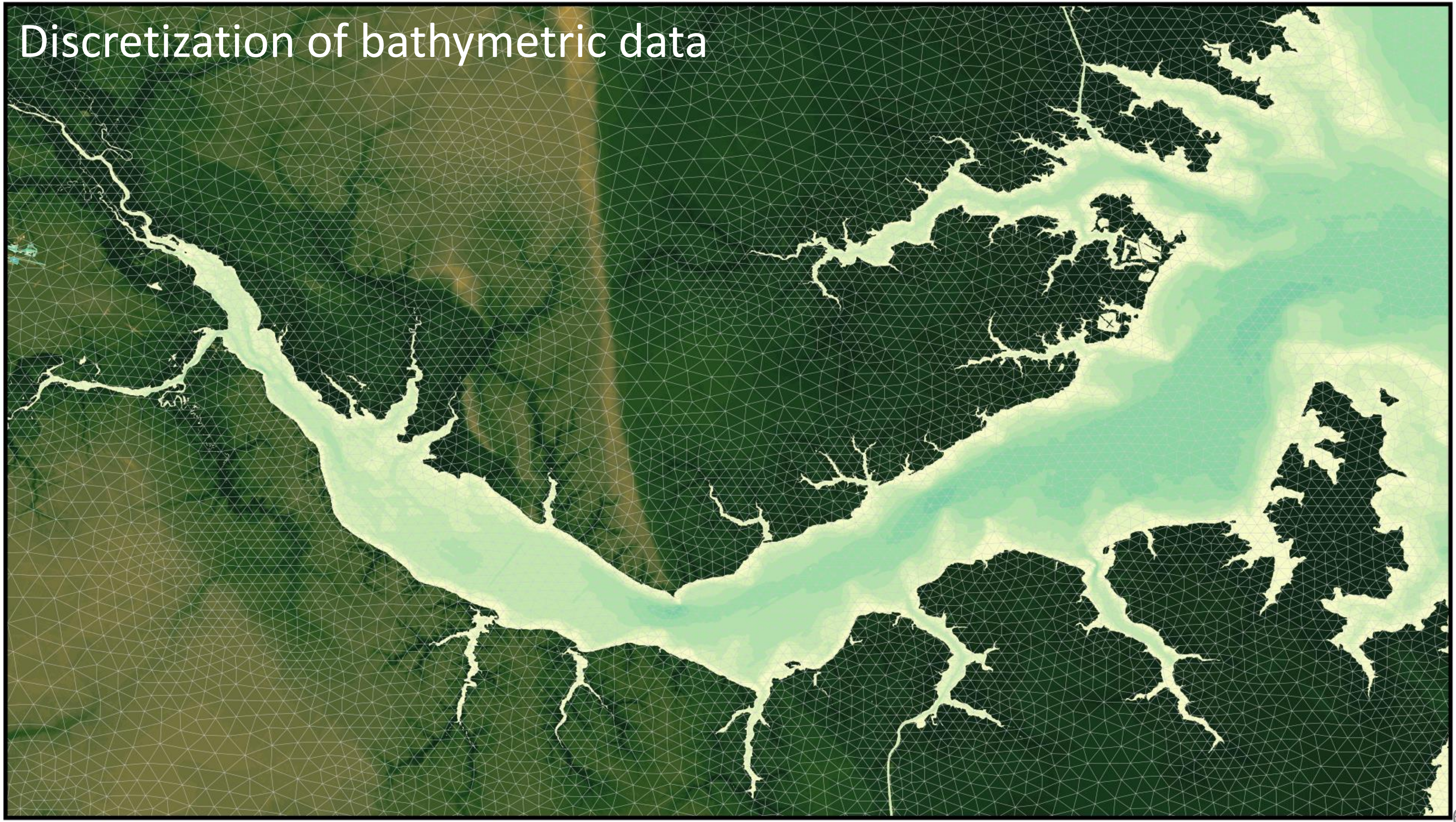
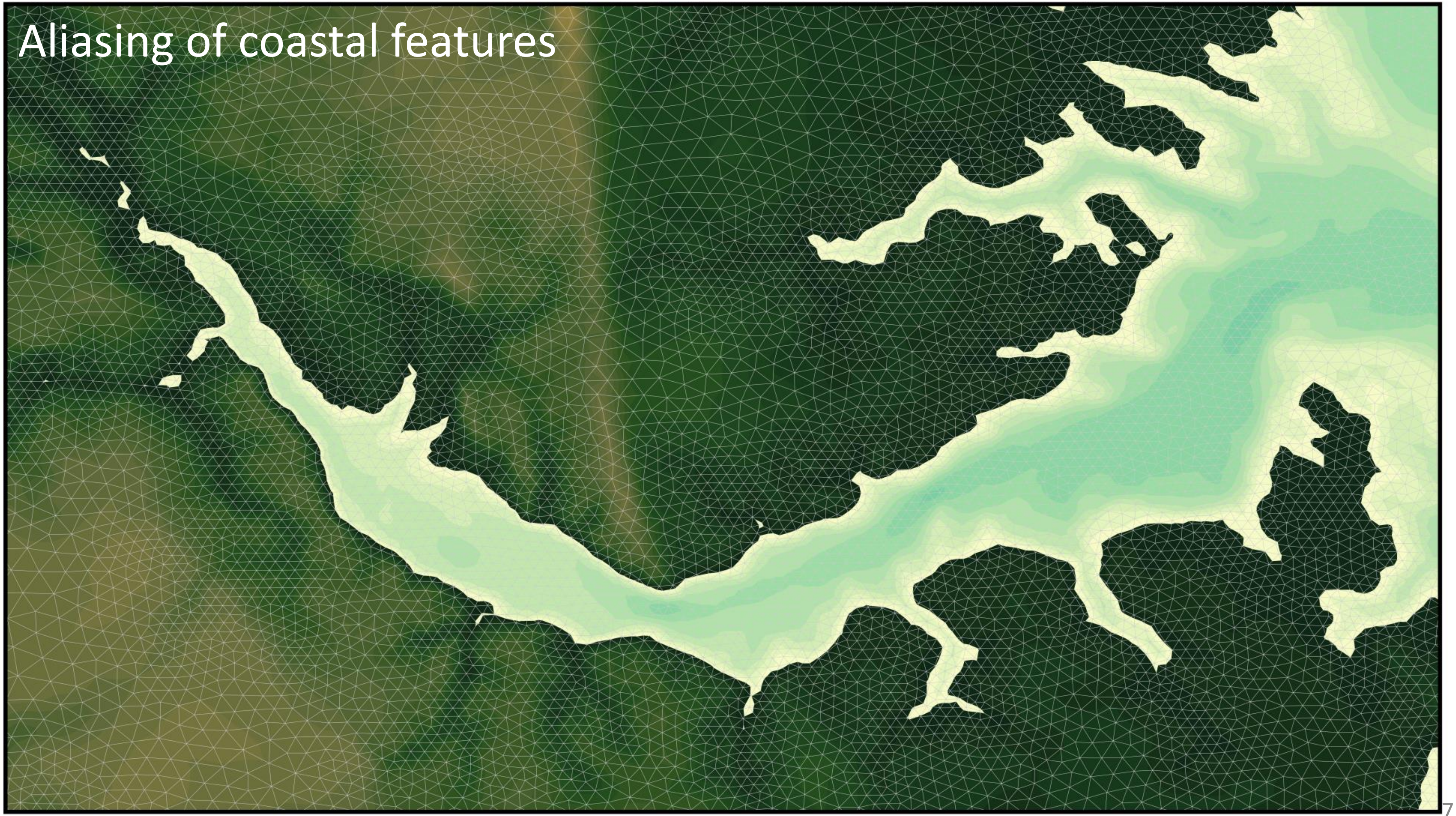
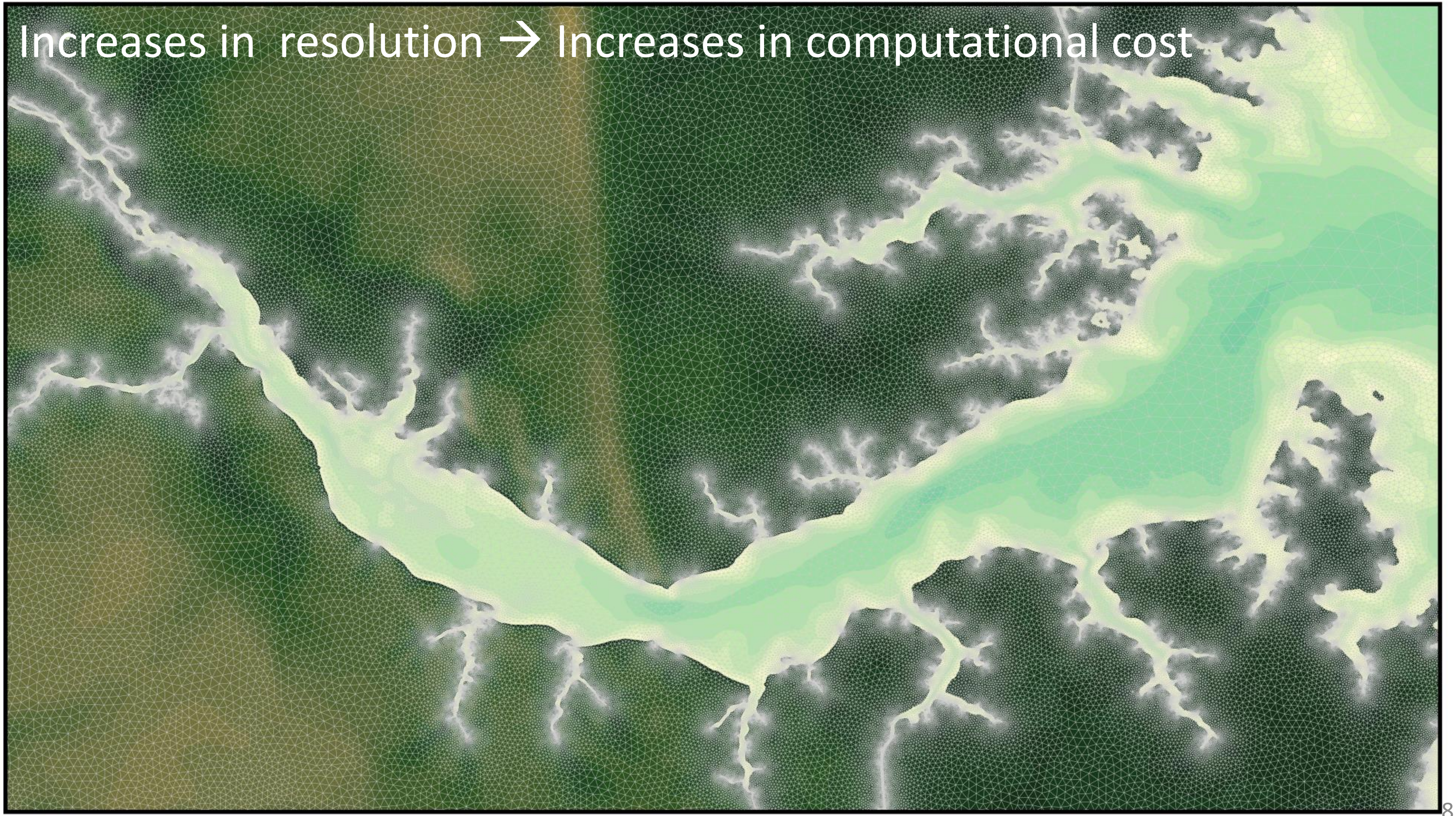


Discretization of bathymetric data

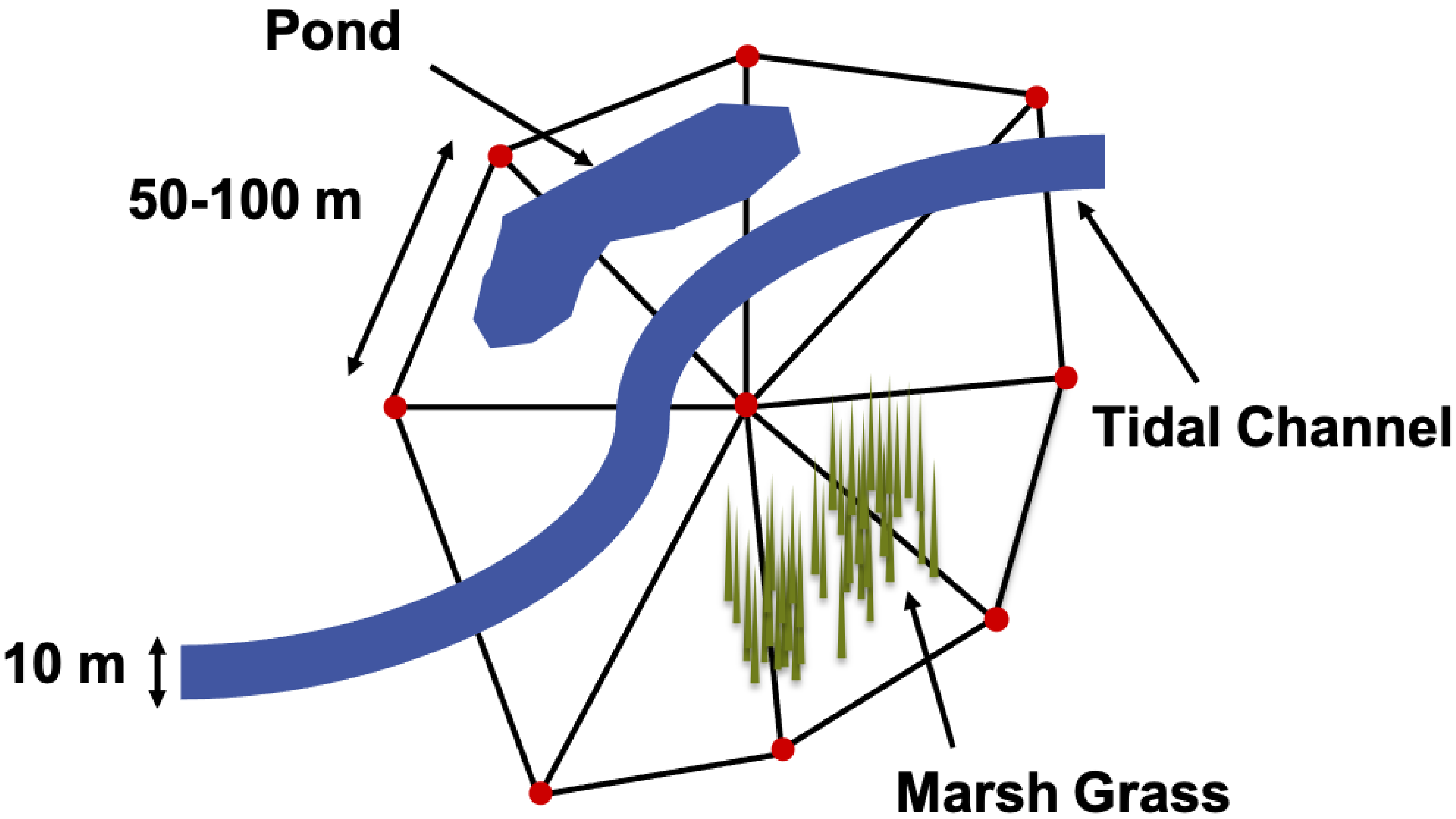


Aliasing of coastal features




Increases in resolution → Increases in computational cost

Unresolved subgrid-scale features



Previous subgrid studies

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

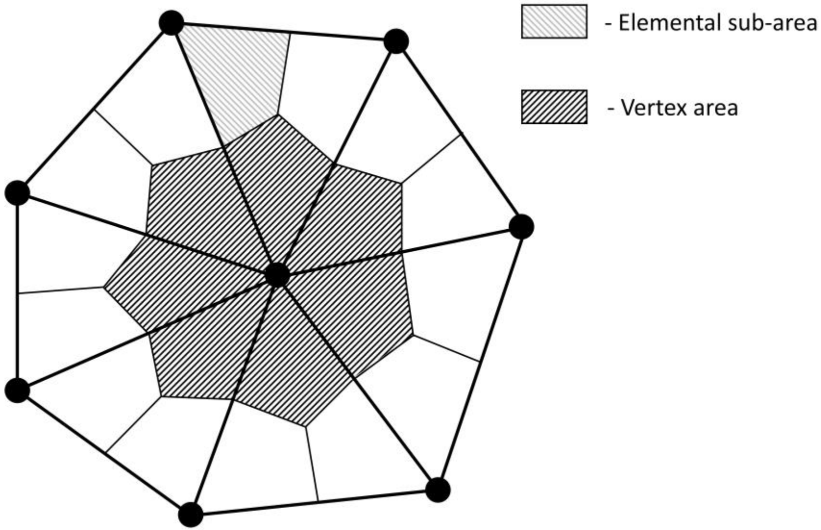
- ➢ Higher accuracy at same resolution, higher efficiency at coarser resolution

Implementation into the ADCIRC model

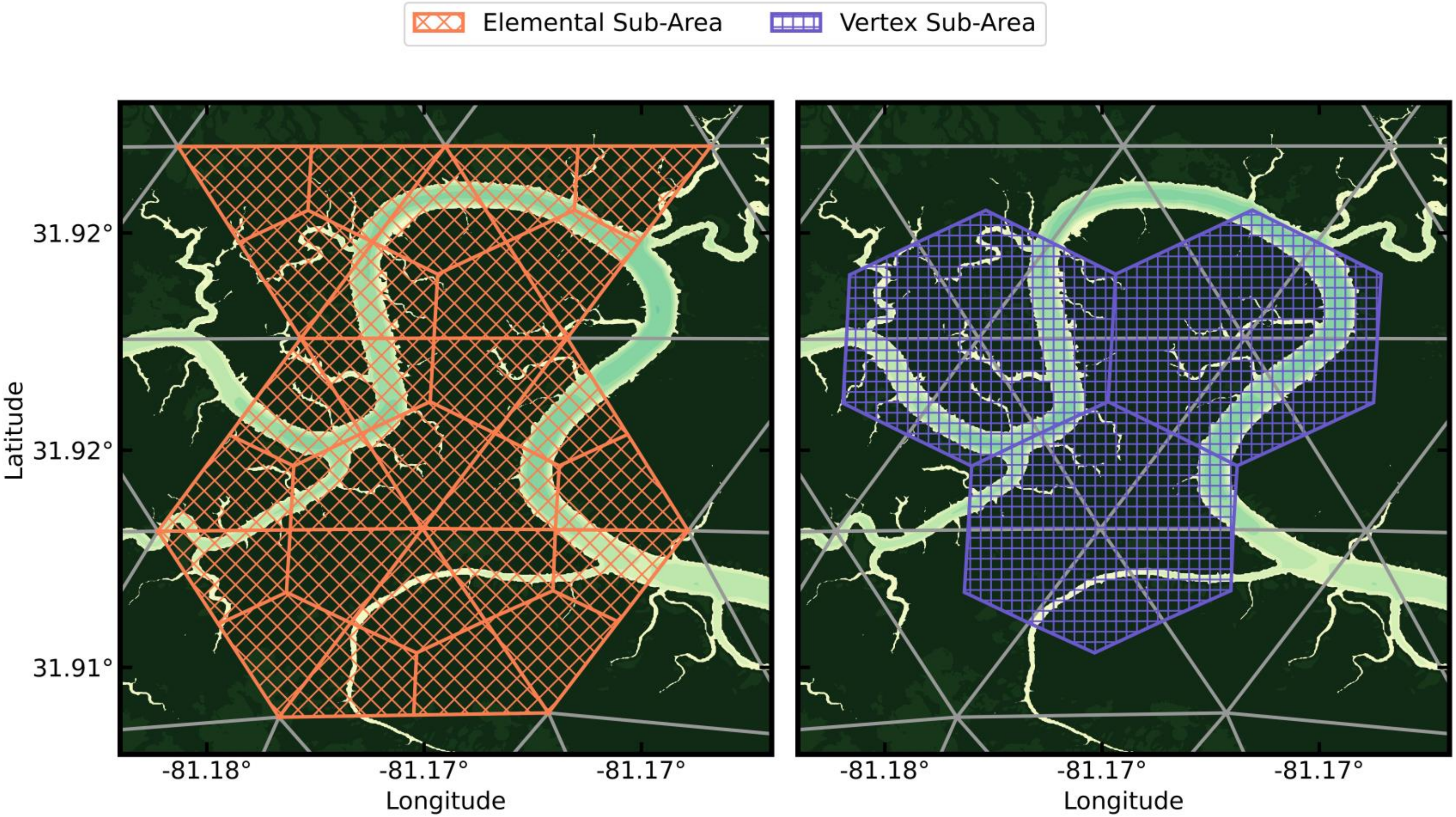
We implemented subgrid corrections in ADvanced CIRCulation (ADCIRC)

- 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:



Elemental vs. vertex averaged areas

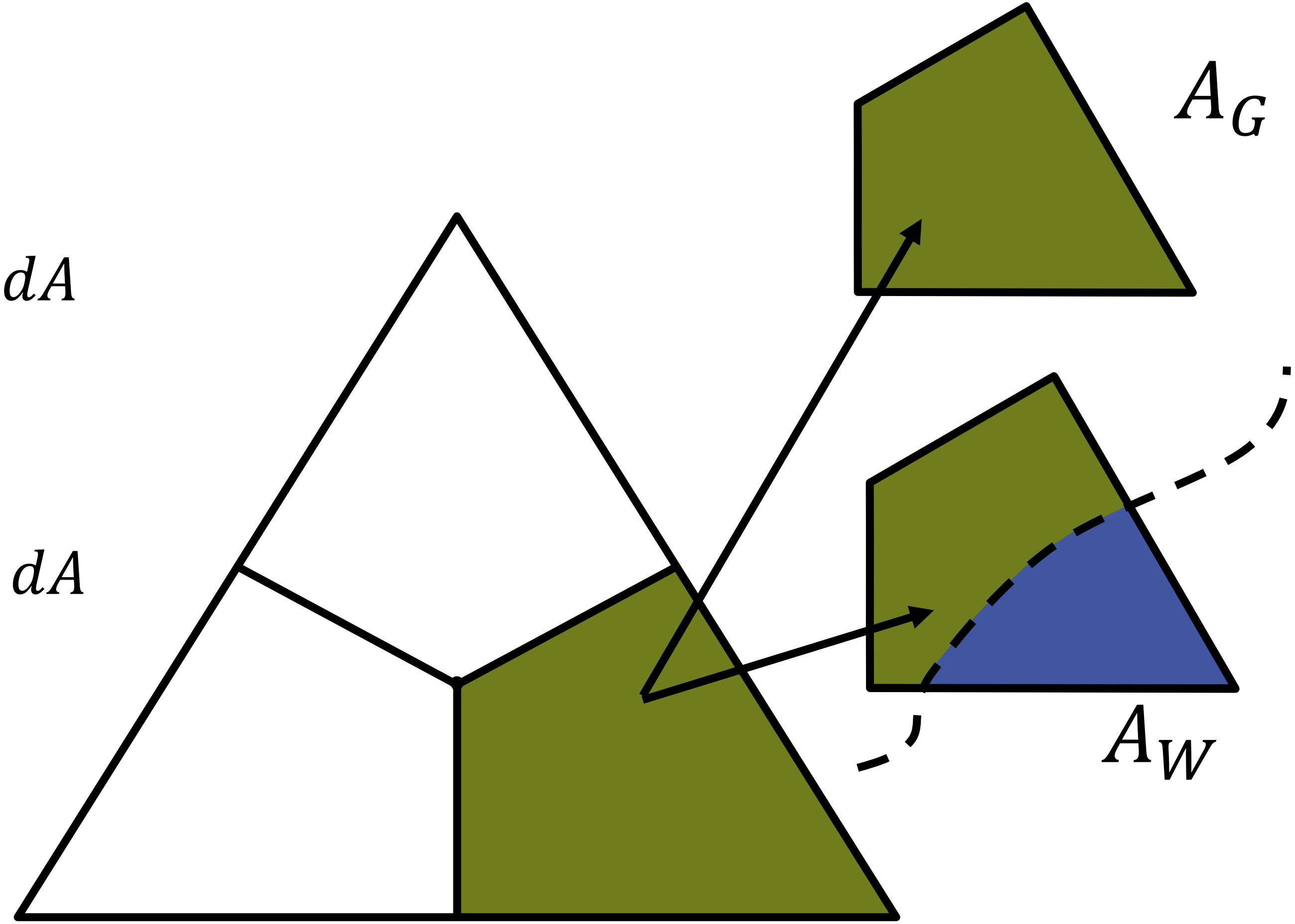


Averaging areas

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

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

$$\phi = A_W / A_G$$



Averaged momentum equation

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

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

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

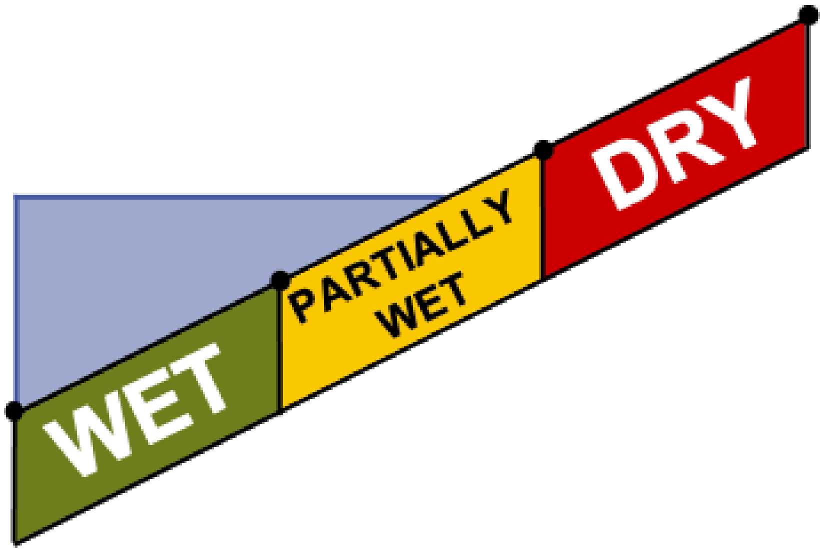
in which the red coefficients are new closure terms

- Similarly for momentum conservation in *y*-direction

Changes to the wet/dry algorithm

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

Closure coefficients for Traditional and Level 0 closures

At first 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	$C_{M,f} = C_f = gn^2/H^{1/3}$	$C_{M,f} = \langle C_f \rangle_W$
Surface Gradient	$C_\zeta = 1$	$C_\zeta = 1$

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

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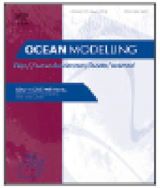

Subgrid corrections in finite-element modeling of storm-driven coastal flooding

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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 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.

https://doi.org/10.1016/j.ocemod.2021.101887

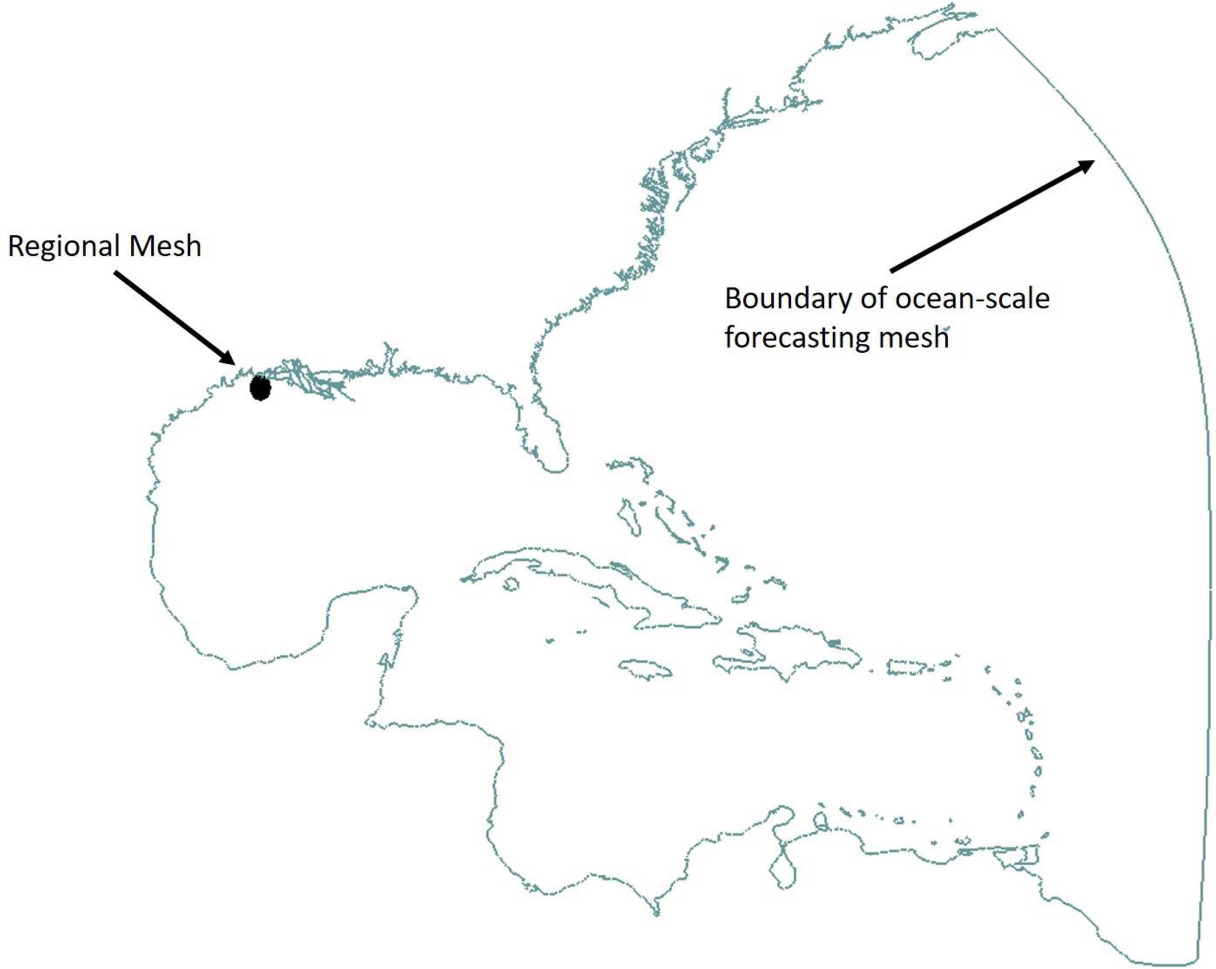
Higher-level corrections to subgrid ADCIRC

	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	$C_\zeta = 1$	$C_\zeta = 1$

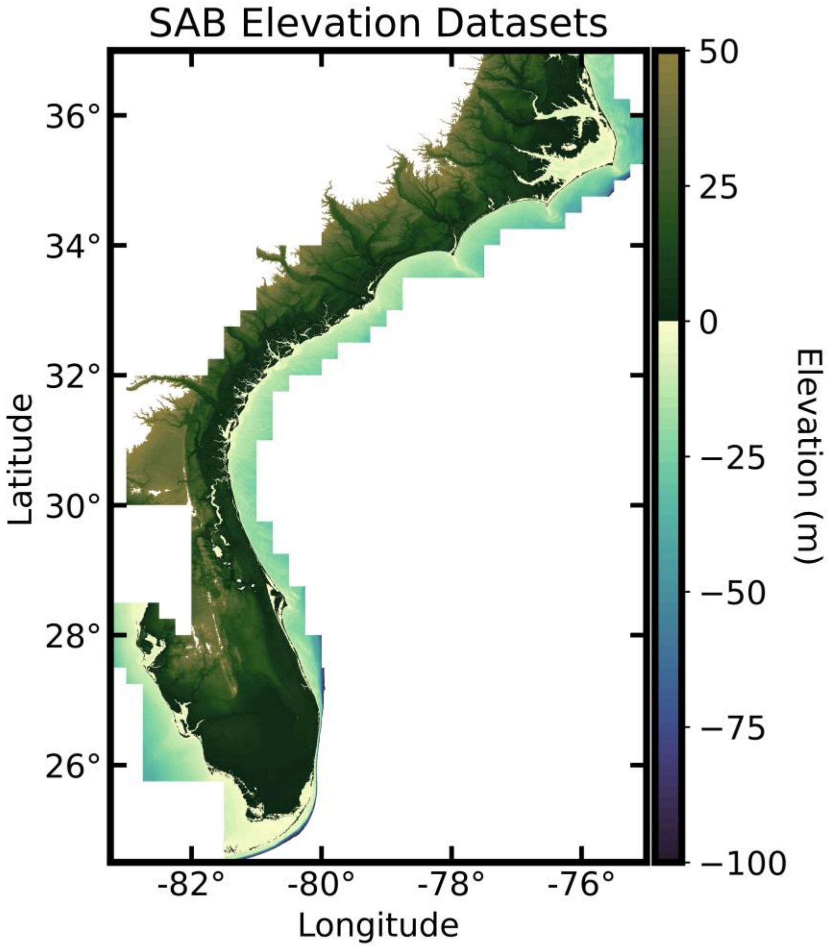
Where: $R_v^2 = \dfrac{\langle H \rangle_W}{\left\langle H^{3/2} C_f^{-1/2} \right\rangle_W}$

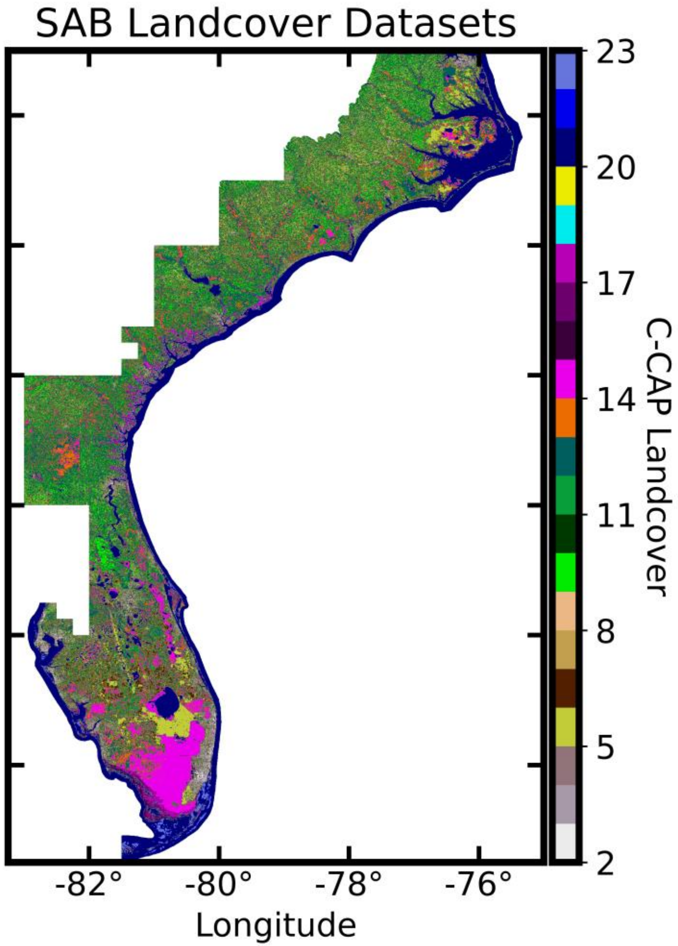
These Level 1 corrections are intended to correct inaccuracies in friction and advection predictions

Expansion to ocean-scale storm surge modelling



Increases to size and quantity of subgrid datasets





Improvements to the pre-processor code

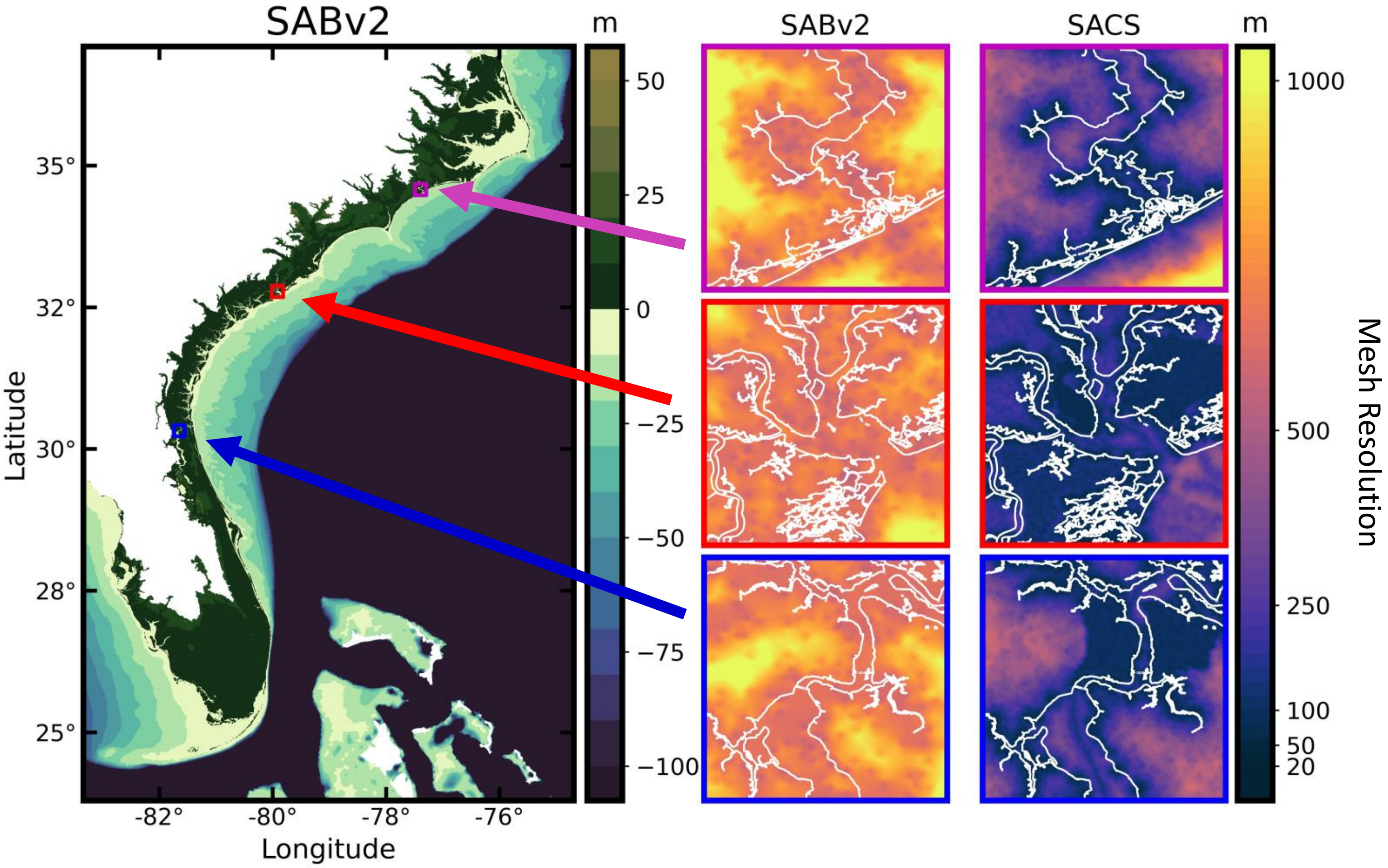
Expansion of *subgrid corrections* to a ocean-scale mesh covering the entire South Atlantic Bight required:

- A total of 832 elevation and landcover data sets ranging from 3 - 30 m resolution.
- The 832 datasets are around 190 GB of elevation and landcover data
- Modification to the subgrid calculator code to incorporate Graphical Processing Units (GPUs) to speed up computations.
- Reduction in the lookup table size to reduce memory usage while the code is running.

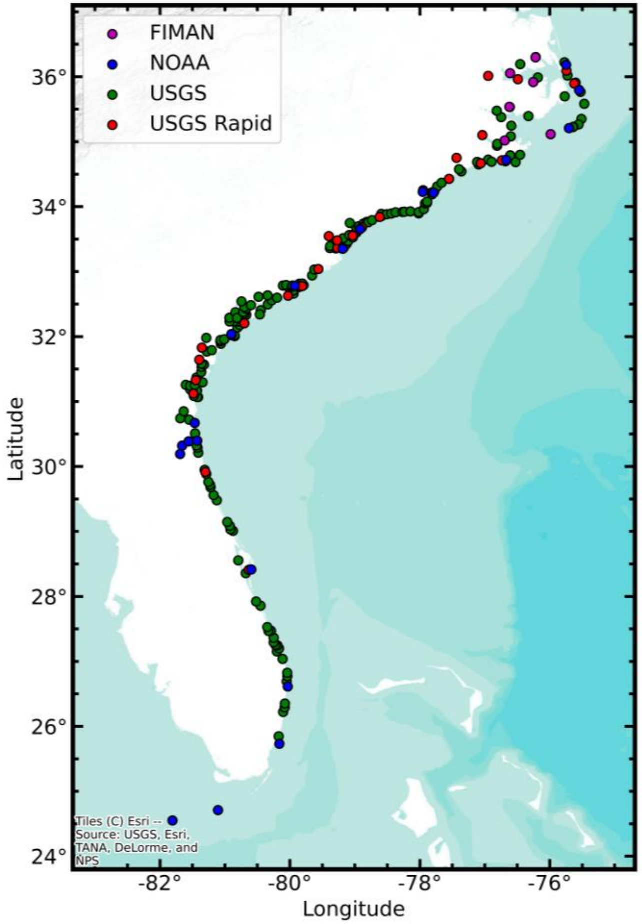
The subgrid processor code is available with and example at:

https://github.com/ccht-ncsu/subgridADCIRCUtility

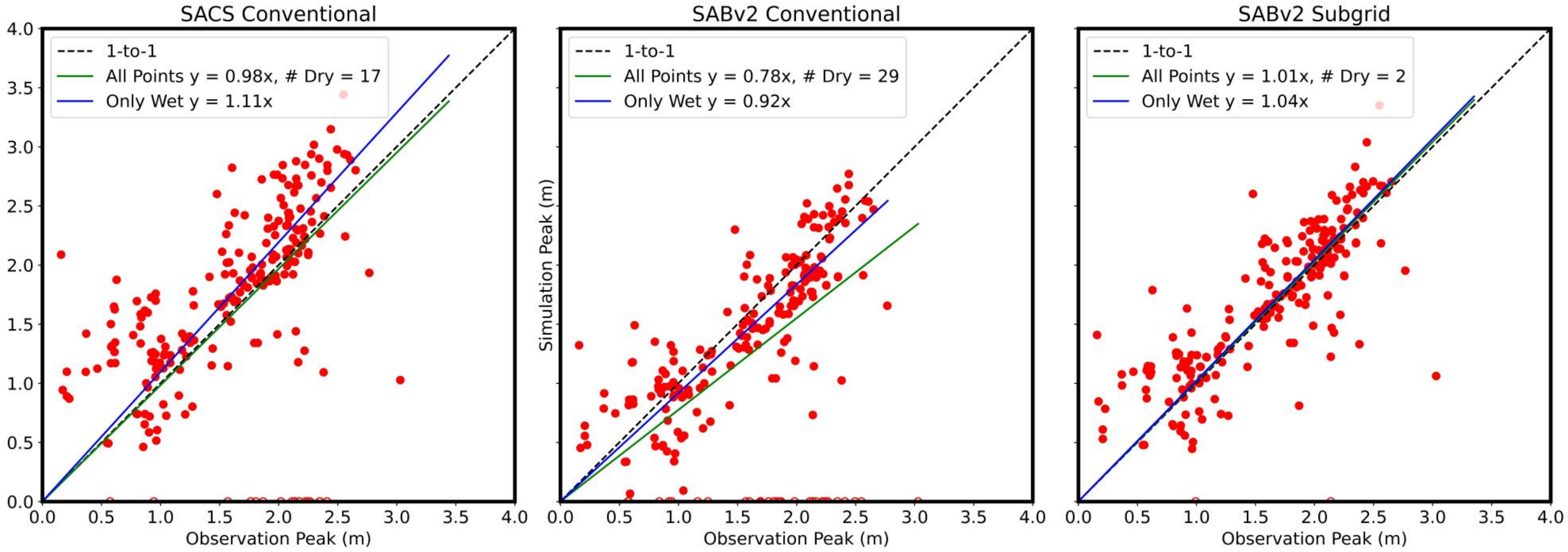
Testing on ocean-scale mesh with emphasis on the South Atlantic Bight



Storm surge simulation of Matthew (2016) on SABv2 mesh



Validation of ocean-scale subgrid results



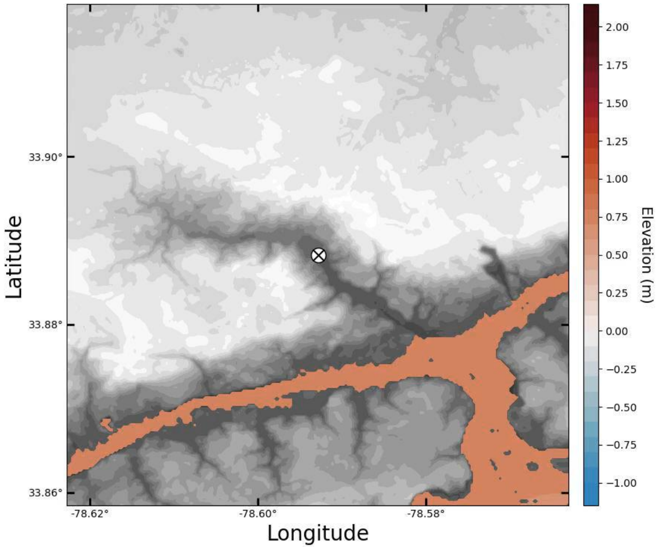
Efficiency of subgrid model at the ocean-scale

Wall-clock times (sec) for three test cases

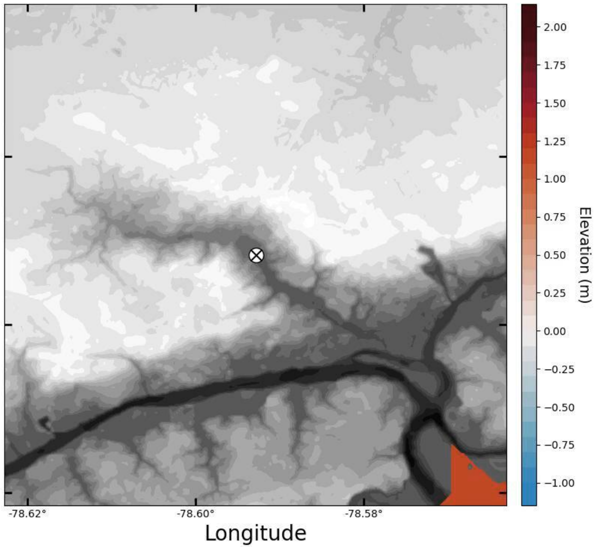
- All tests run on 144 cores on the same hardware
- The subgrid additions increased computational expense by **2x***
  but ran **7x** faster than the SACS Conventional Model

Simulation	Wall-Clock Time (sec)
SACS Conventional	160,511
SABv2 Conventional	10,919
SABv2 Subgrid	22,829

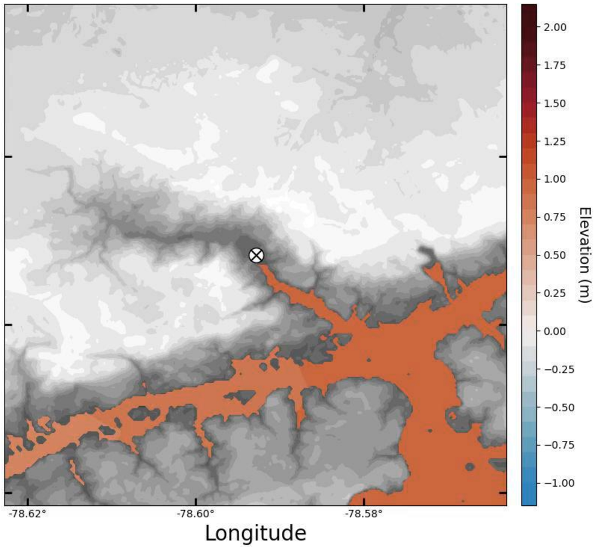
SACS Conventional



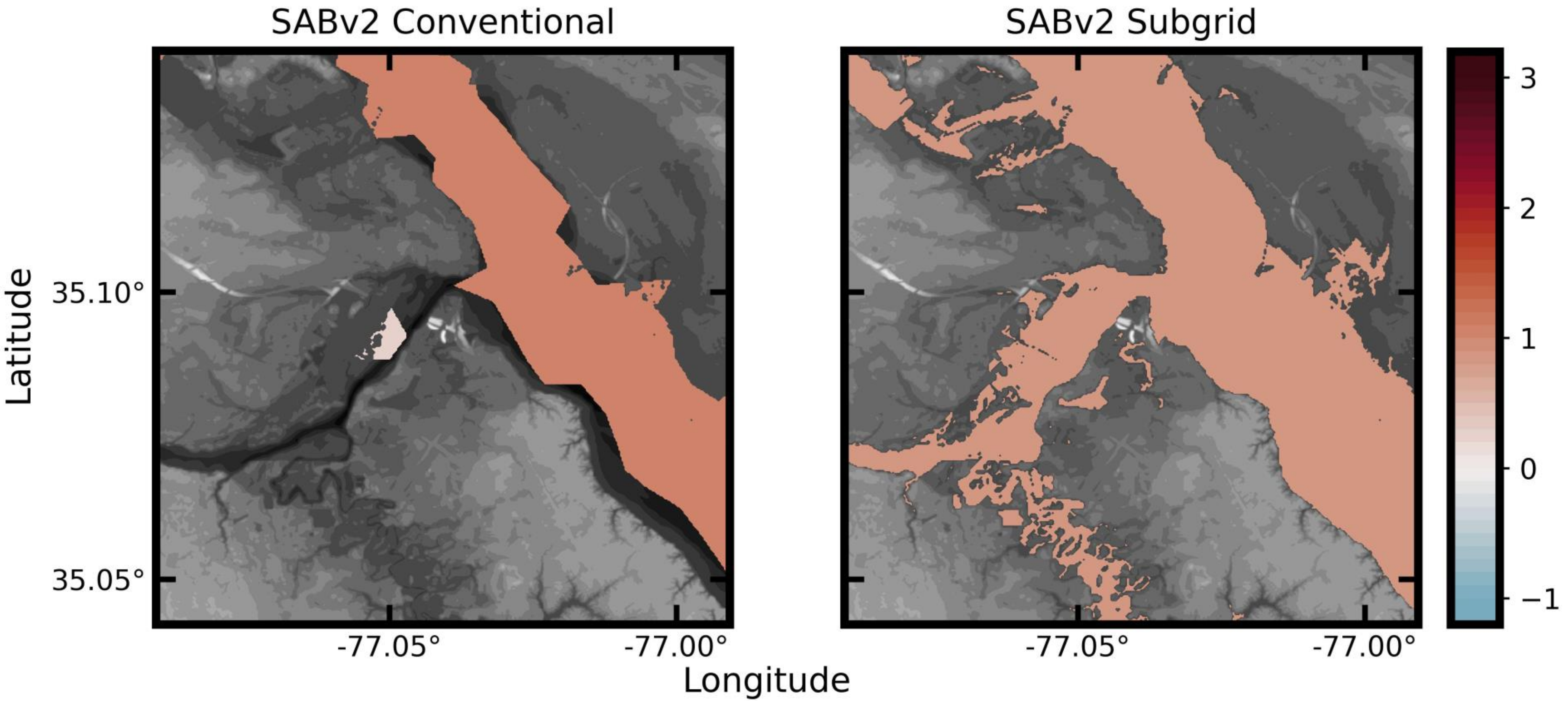
SABv2 Conventional



SABv2 Subgrid



Improvements to hydraulic connectivity and wet/dry front



Conclusions/discussion

The main contribution of this study are:

1. Subgrid corrections were added to ADCIRC
    - First application with hurricane-strength forcing
2. Inclusion of Level 1 Corrections in subgrid ADCIRC
    - Improvements to bottom friction and advection representations
3. Expansion of subgrid ADCIRC to the ocean-scale
    - Testing and validation for Hurricane Matthew (2016)
    - Improvements to lookup table pre-processor code

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Thank you!