Improving Forecasts for Coastal Flooding during Hurricanes

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Center for Sustainable Energy and Environmental Engineering
East Carolina Univ, Virtual Webinar, 12 Apr 2022

NC STATE UNIVERSITY

North Carolina State University

- Civil, Construction, and Environmental Engineering
  - Associate Professor: 08/2019 to Present
  - Assistant Professor: 08/2013 to 08/2019

University of Texas at Austin

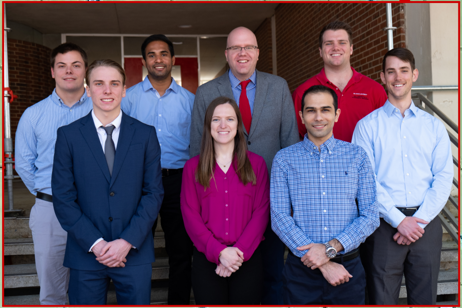
- Institute for Computational Engineering and Sciences
  - Research Associate: 09/2012 to 07/2013
  - Postdoctoral Researcher: 11/2010 to 08/2012

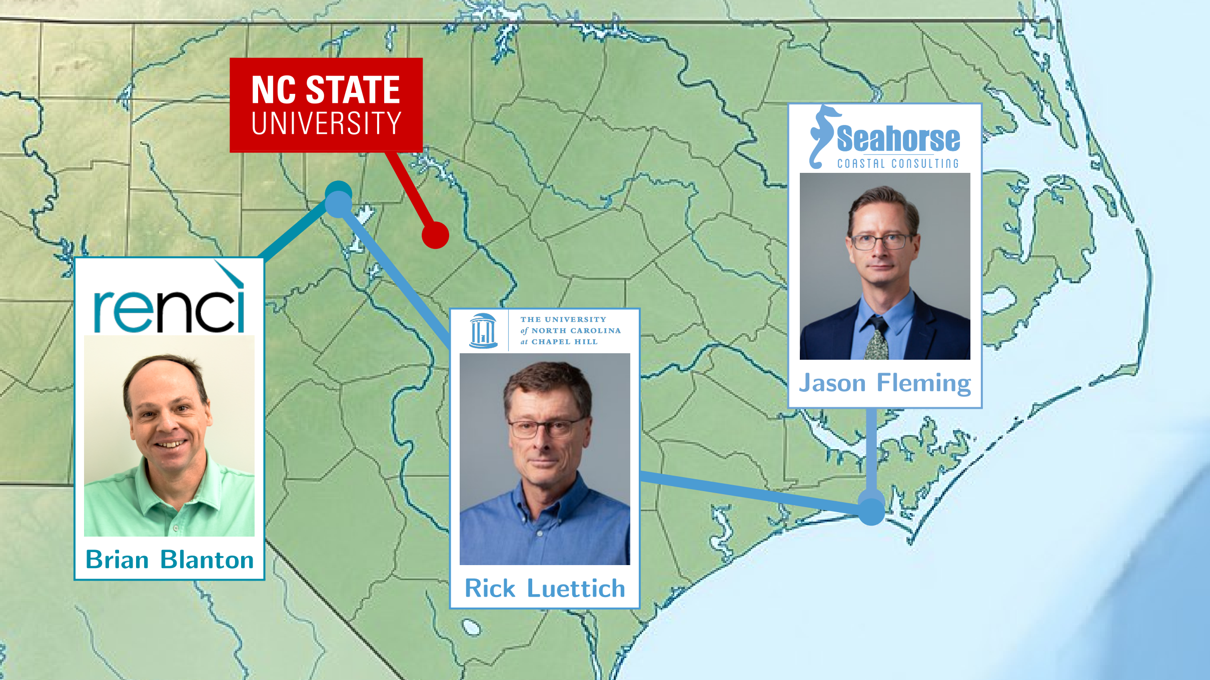
University of Notre Dame

- Civil Engineering and Geological Sciences
  - Graduate Researcher: 08/2005 to 10/2010

University of Oklahoma

- Civil Engineering and Environmental Science
  - Graduate Researcher: 06/2004 to 07/2005
  - Undergraduate Researcher: 06/1999 to 05/2004





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Seahorse
COASTAL CONSULTING
Jason Fleming
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Brian Blanton
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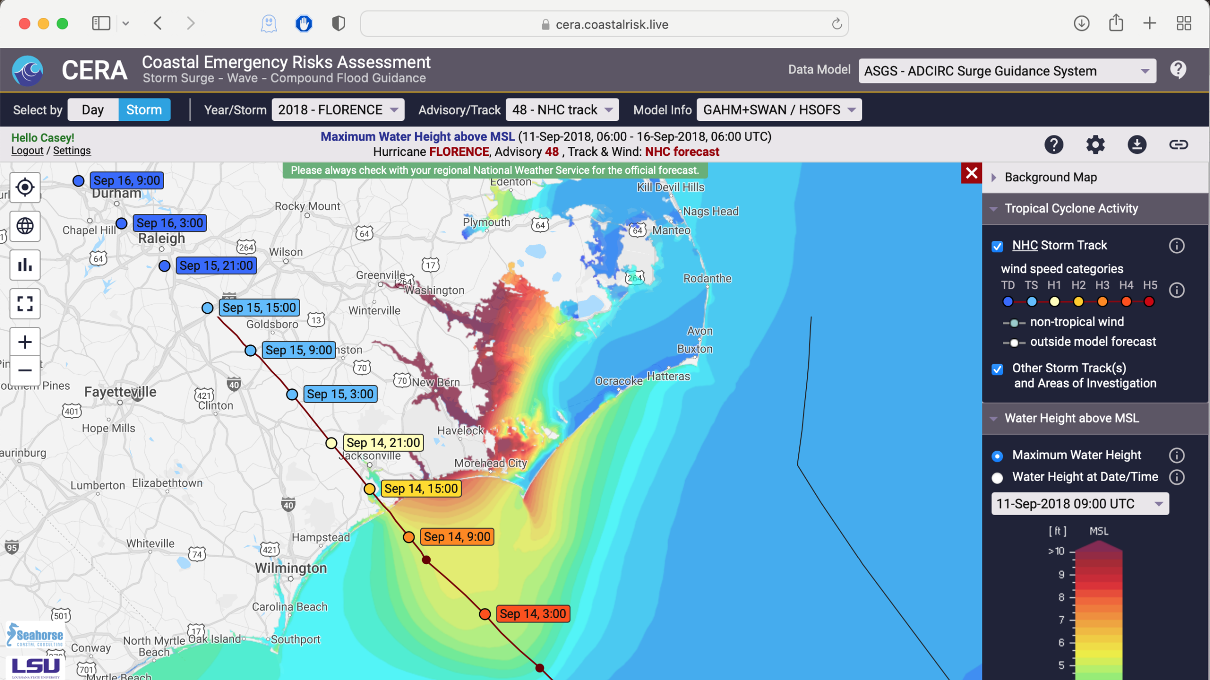
at CHAPEL HILL
Rick Luettich


cera.coastalrisk.live
CERA
Coastal Emergency Risks Assessment
Storm Surge - Wave - Compound Flood Guidance
Data Model
ASGS - ADCIRC Surge Guidance System
Select by
Day
Storm
Year/Storm
2018 - FLORENCE
Advisory/Track
48 - NHC track
Model Info
GAHM+SWAN / HSOFS
Hello Casey!
Logout / Settings
Maximum Water Height above MSL (11-Sep-2018, 06:00 - 16-Sep-2018, 06:00 UTC)
Hurricane FLORENCE, Advisory 48 , Track & Wind: NHC forecast
Please always check with your regional National Weather Service for the official forecast.
Sep 16, 9:00
Sep 16, 3:00
Sep 15, 21:00
Sep 15, 15:00
Sep 15, 9:00
Sep 15, 3:00
Sep 14, 21:00
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Durham
Chapel Hill
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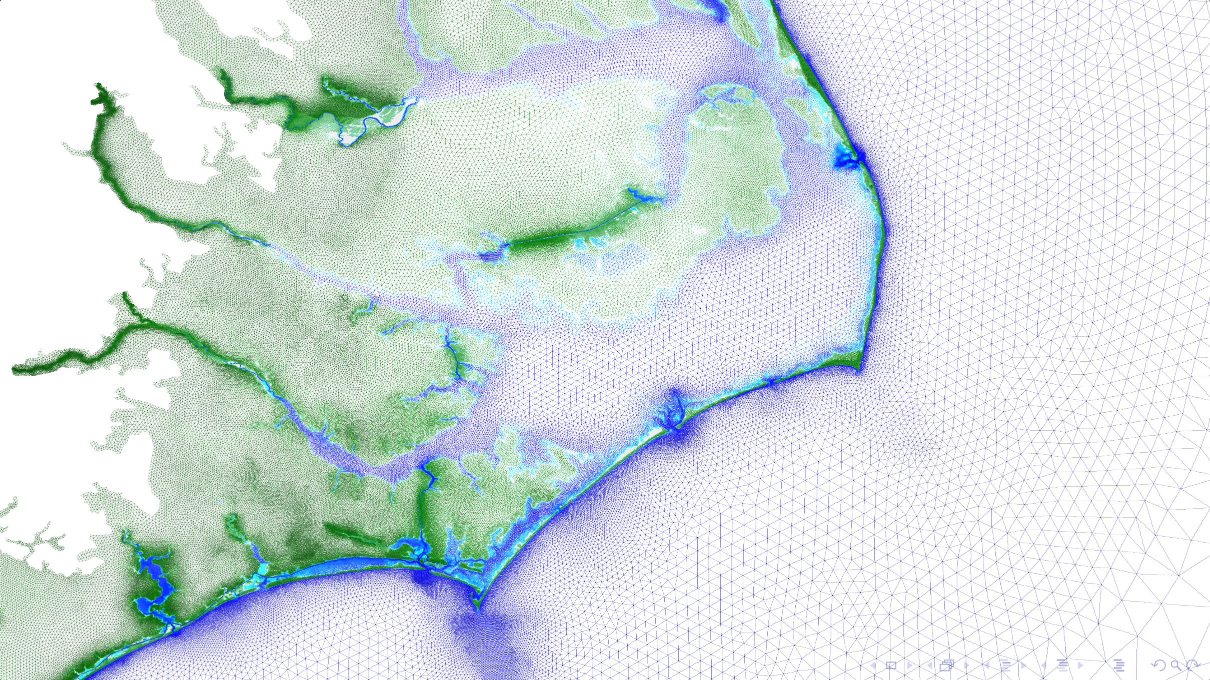
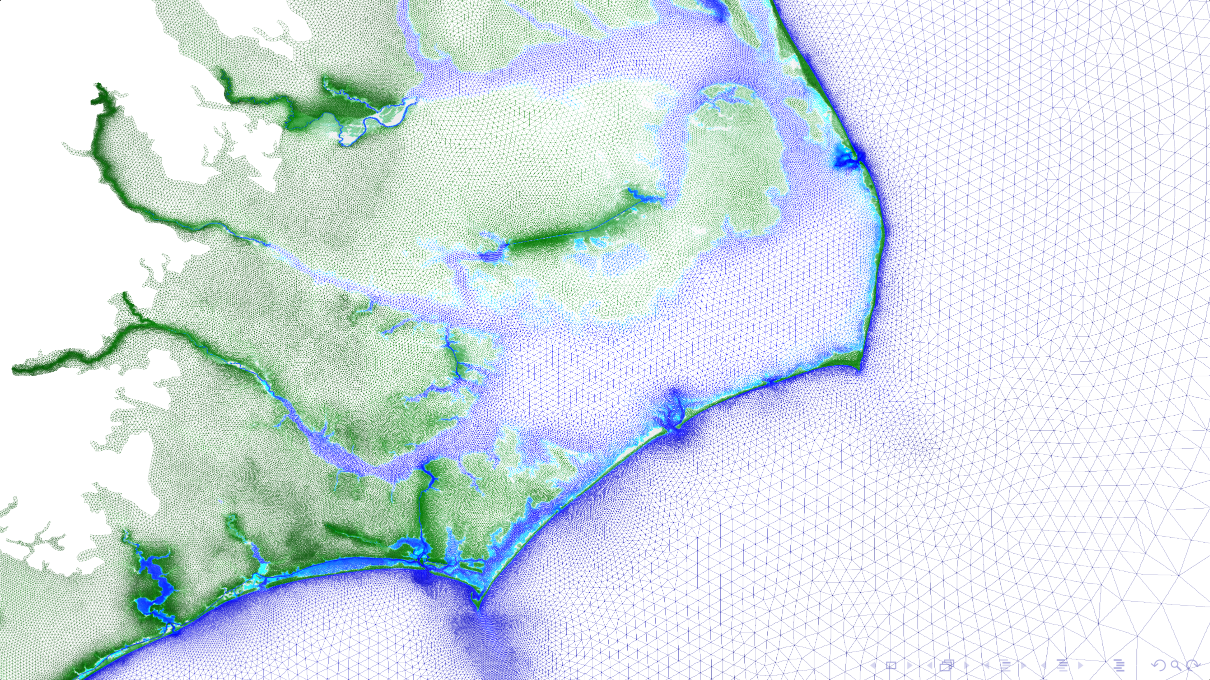
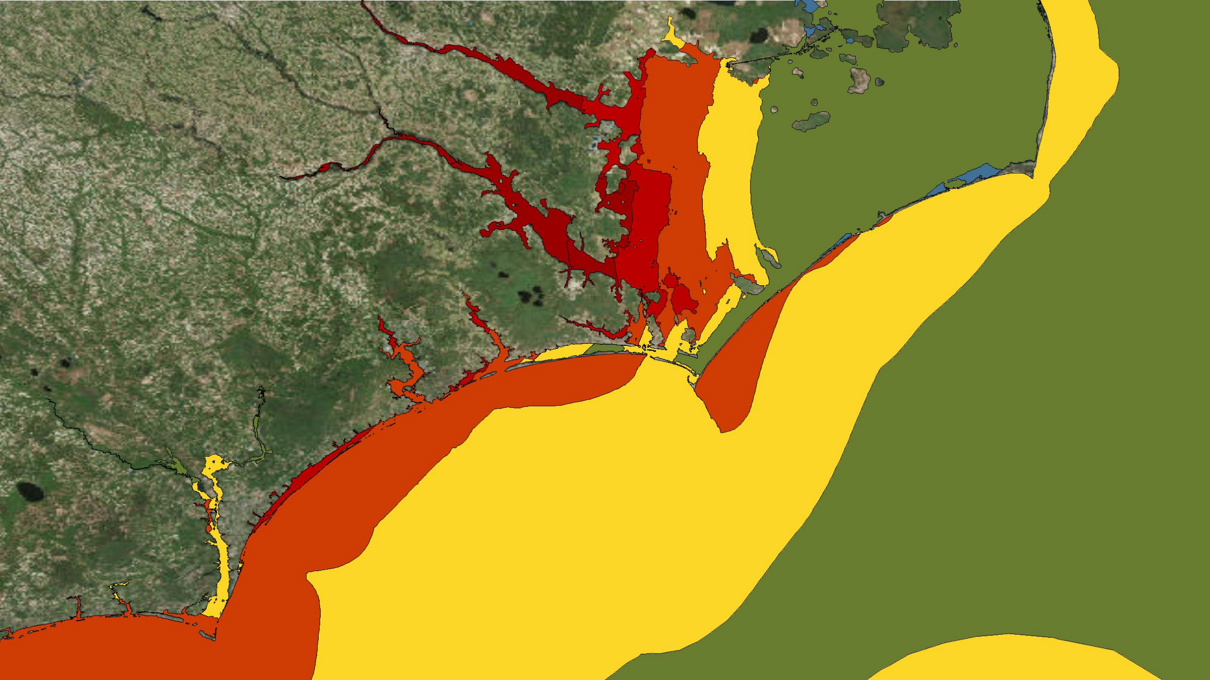
Oak Island
Southport
North Myrtle Beach
Conway
Myrtle Beach
Edenton
Plymouth
Kill Devil Hills
Nags Head
Manteo
Rodanthe
Avon
Buxton
Ocracoke
Hatteras
Background Map
Tropical Cyclone Activity
NHC Storm Track
wind speed categories
TD TS H1 H2 H3 H4 H5
non-tropical wind
outside model forecast
Other Storm Track(s) and Areas of Investigation
Water Height above MSL
Maximum Water Height
Water Height at Date/Time
11-Sep-2018 09:00 UTC
[ft] MSL
>10
9
8
7
6
5
Seahorse
LSU

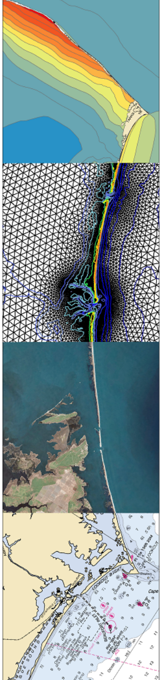






1. How to Represent Channels / Barriers Smaller than the Mesh?
    1.1. Motivation
    1.2. Methods
    1.3. Calcasieu Lake LA
    1.4. Conclusions

2. How to Predict Flooding due to Erosion of Beaches / Dunes?
    2.1. Motivation
    2.2. Methods
    2.3. Isabel Inlet
    2.4. Conclusions



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

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D Wirasaet[2], AB Kennedy[2], D Bolster[2],
Z Silver[2], SD Medlin[3], RL Kolar[4]

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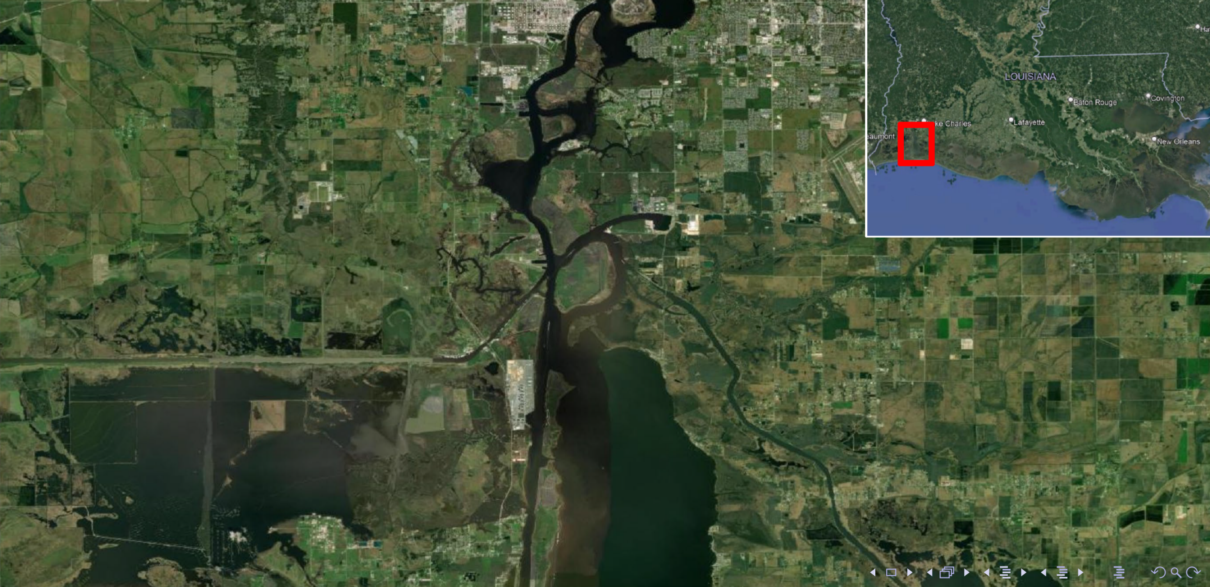
1.1. Motivation

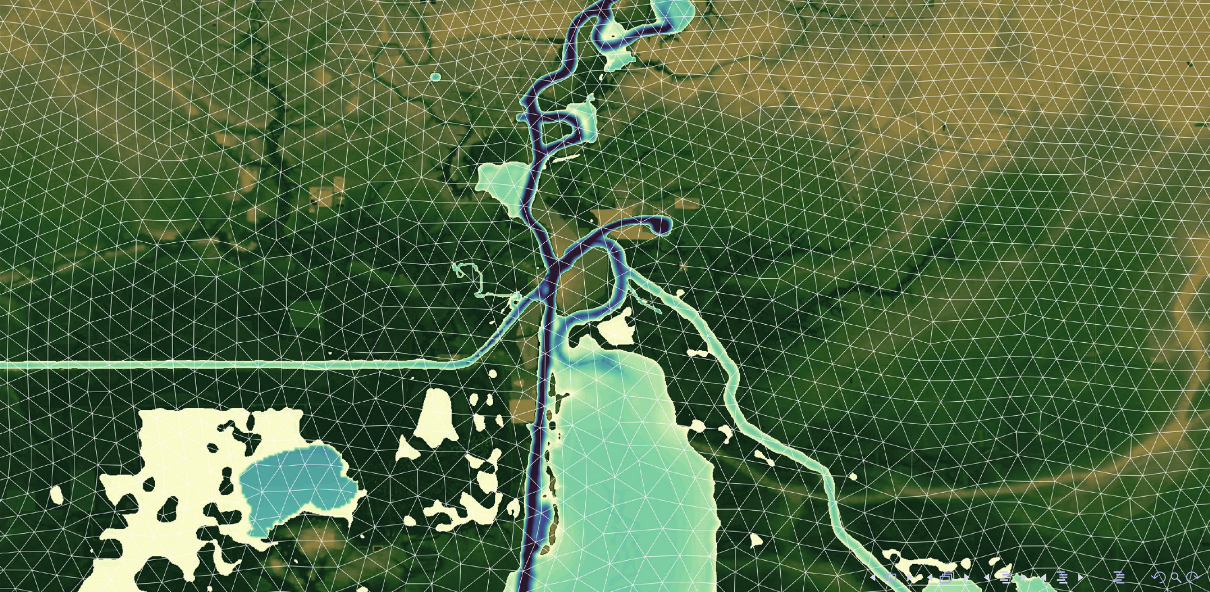
Loss of Information at Model Scale



1.1. Motivation

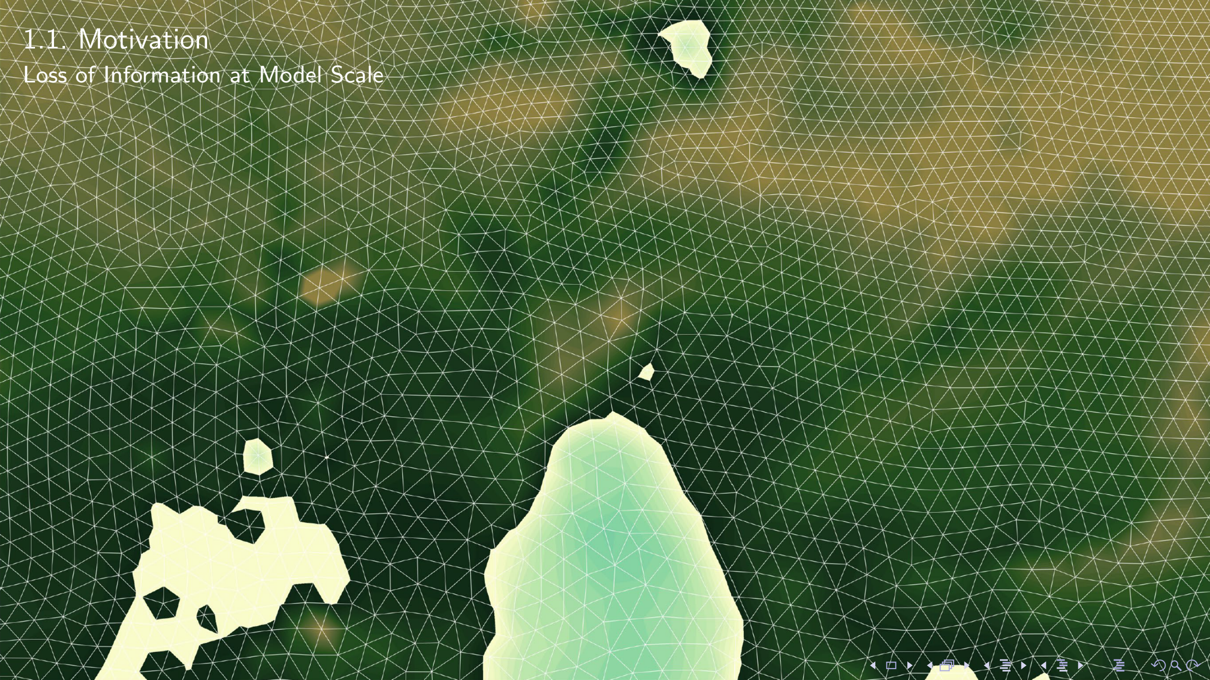
Loss of Information at Model Scale

Loss of Information at Model Scale



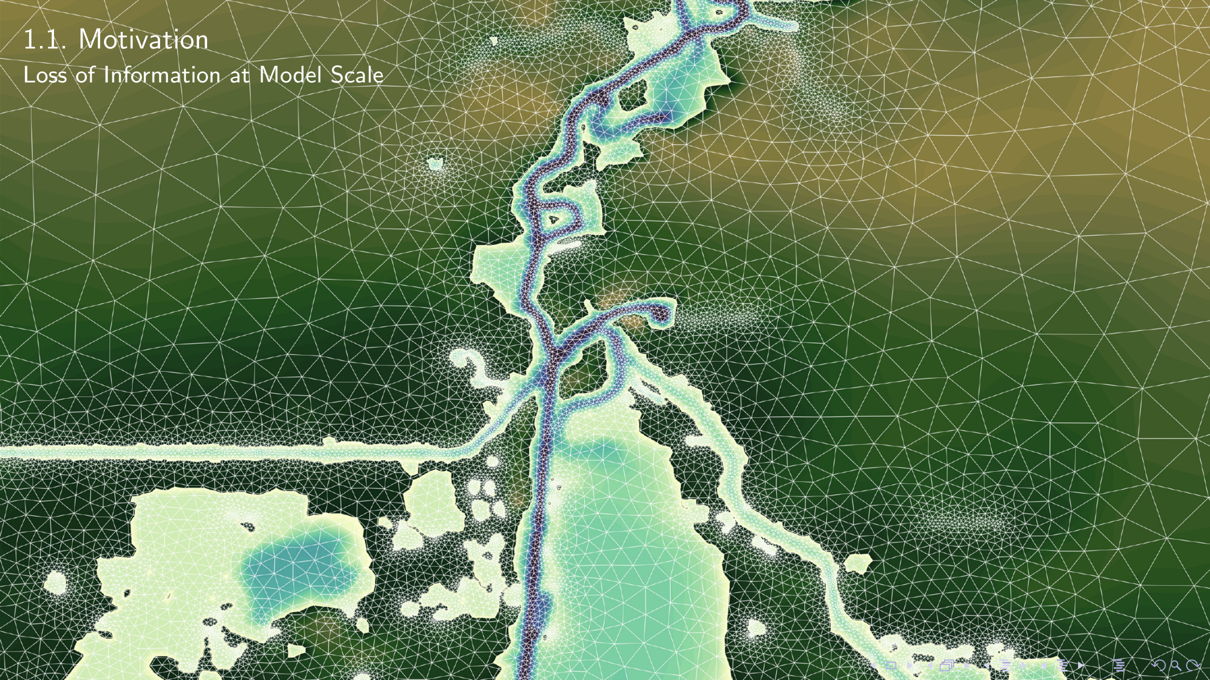
1.1. Motivation

Loss of Information at Model Scale



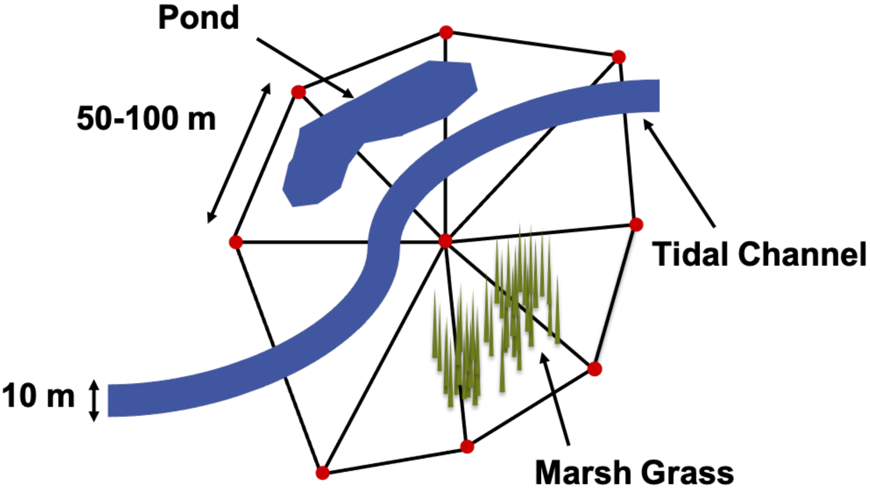
1.1. Motivation

Loss of Information at Model Scale



1.1. Motivation

Use Smaller-Scale Information to 'Correct' Flows



1.2. 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:

$$A_W = \phi A_G$$

Averaged Governing Equations for ADCIRC

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

- Example of momentum conservation in x-direction:

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

  in which the red coefficients are new closure terms

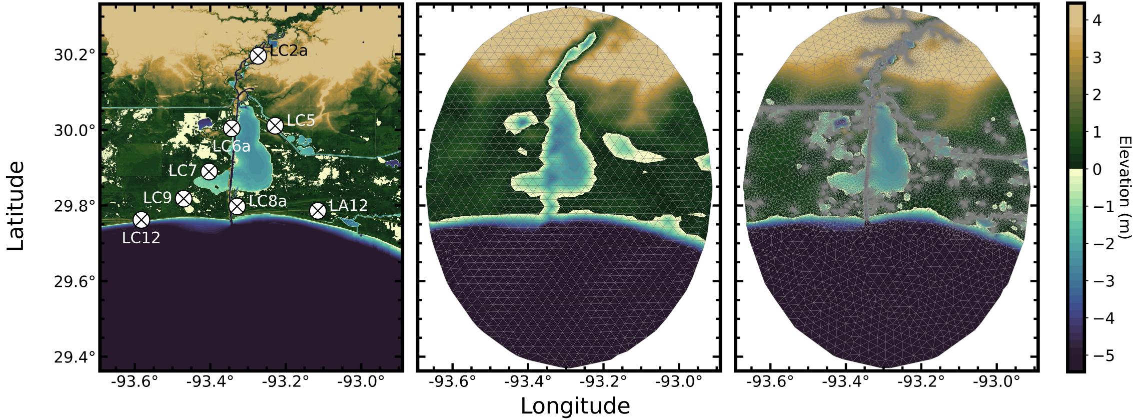
- Similarly for momentum conservation in y-direction, mass conservation

1.3. Calcasieu Lake LA

Meshes and Station Locations

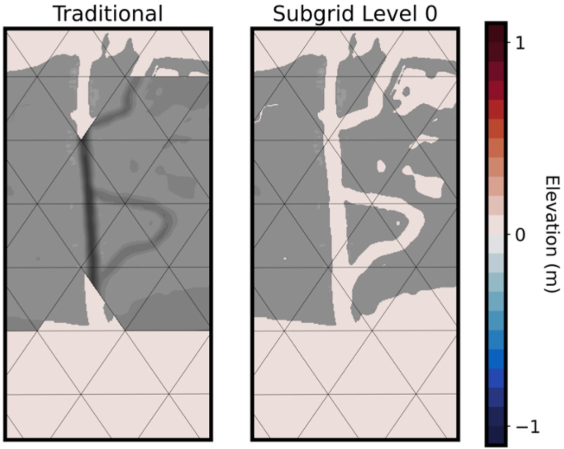
Coarse:
1,236 vertices
2,370 elements

Fine:
40,816 vertices
81,321 elements



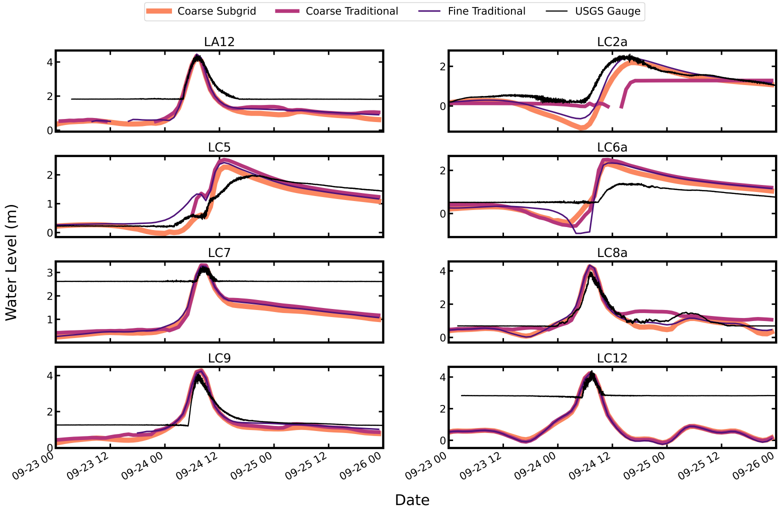
1.3. Calcasieu Lake LA

Improvements for Channel Connectivity



1.3. Calcasieu Lake LA

Tides and Storm Surge at Stations

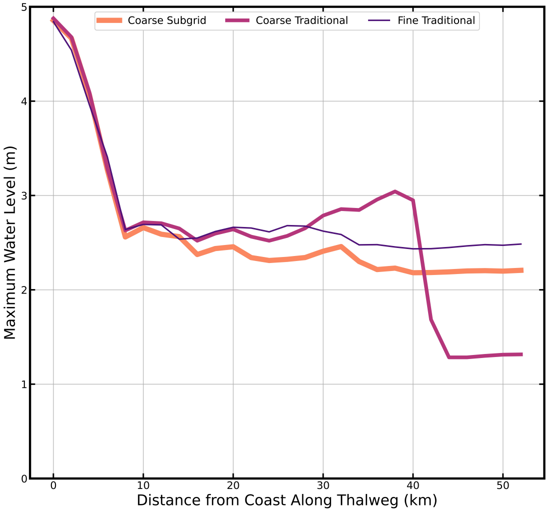


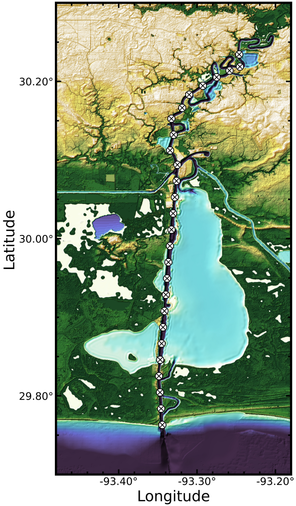
Differences (m) in peak water levels at observation stations

	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

1.3. Calcasieu Lake LA

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	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

→ But it gives comparable results to a mesh that is 33 times coarser

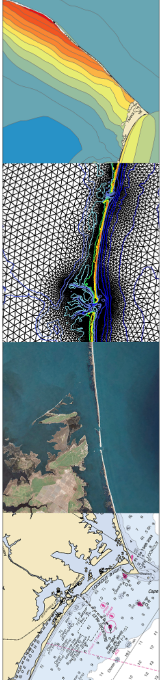
1.4. Conclusions
Subgrid ADCIRC

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



1.4. Conclusions

Recent Manuscript in *Ocean Modelling*

Ocean Modelling 167 (2021) 101887

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

Check for updates

Johnathan L. Woodruff [a,*], J.C. Dietrich [a], D. Wirasaet [b], A.B. Kennedy [b], D. Bolster [b], Z. Silver [b], S.D. Medlin [a], R.L. Kolar [c]

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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 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.

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2. How to Predict Flooding due to Erosion of Beaches / Dunes?
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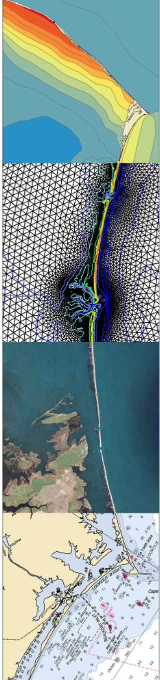


Formation of a Barrier Island Breach and its Contributions to Lagoonal Circulation

A Gharagozlou[1], JC Dietrich[1],
TC Massey[2], DL Anderson[1], JF Gorski[1], MF Overton[1]

[1]Dep't of Civil, Construction, and Environmental Engineering, NC State Univ
[2]Coastal and Hydraulics Laboratory, U.S. Army Engineer Research and Development Center

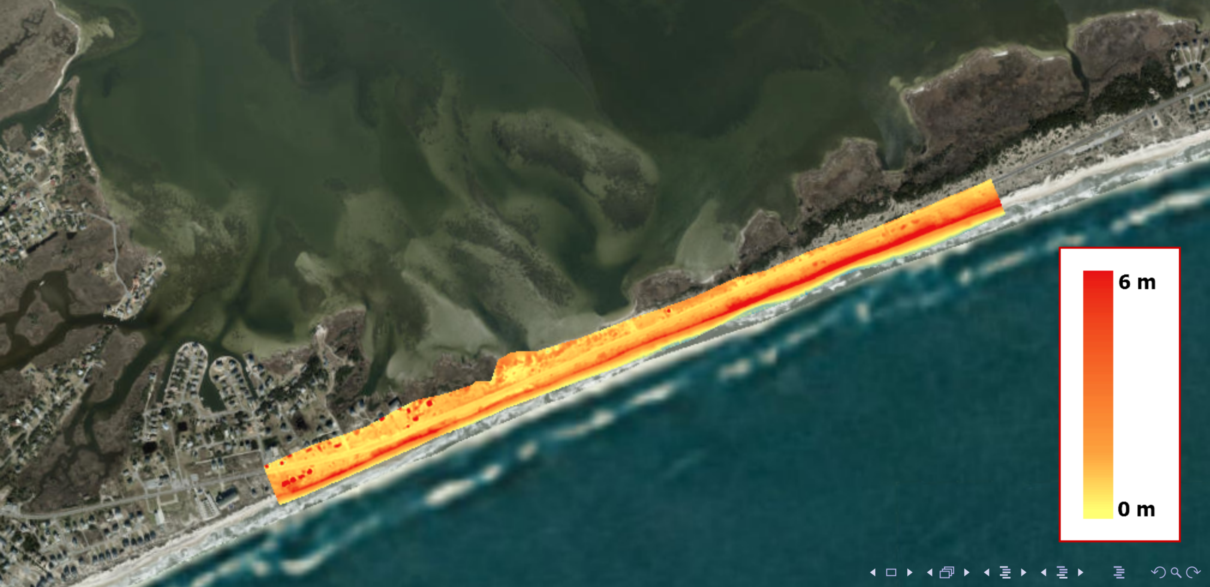
USCRP

2.1. Motivation

Isabel Inlet (2003)

2.1. Motivation

Pre-Storm Ground Surface



2.1. Motivation

Post-Storm Ground Surface

2.2. Methods

Model Coupling

Our wave/surge models are limited:

- Bathymetry and topography are static
- No consideration of beach erosion, dune breaching, new flow pathways, etc.
- Flooding impacts are limited behind the dunes

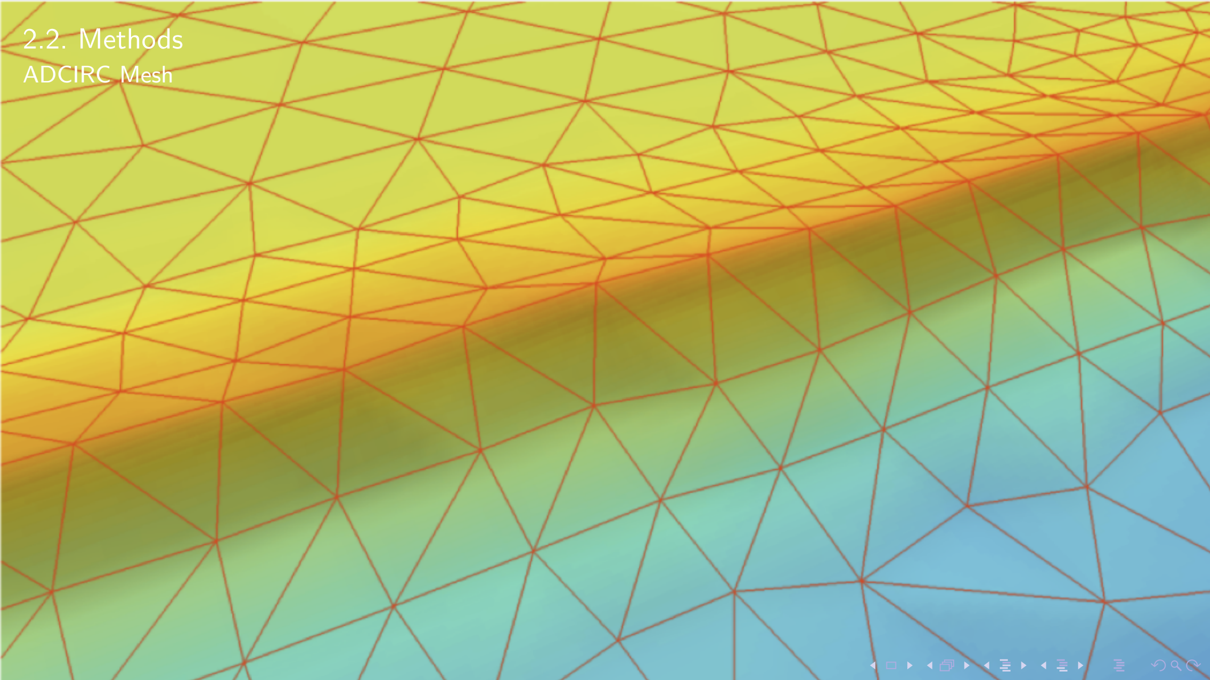
We are coupling with XBeach (eXtreme Beach):

- Open-source model developed in the Netherlands
- Capable of simulating hydrodynamic and morphodynamic processes
- Applied typically at beach scales (a few kilometers)

2.2. Methods

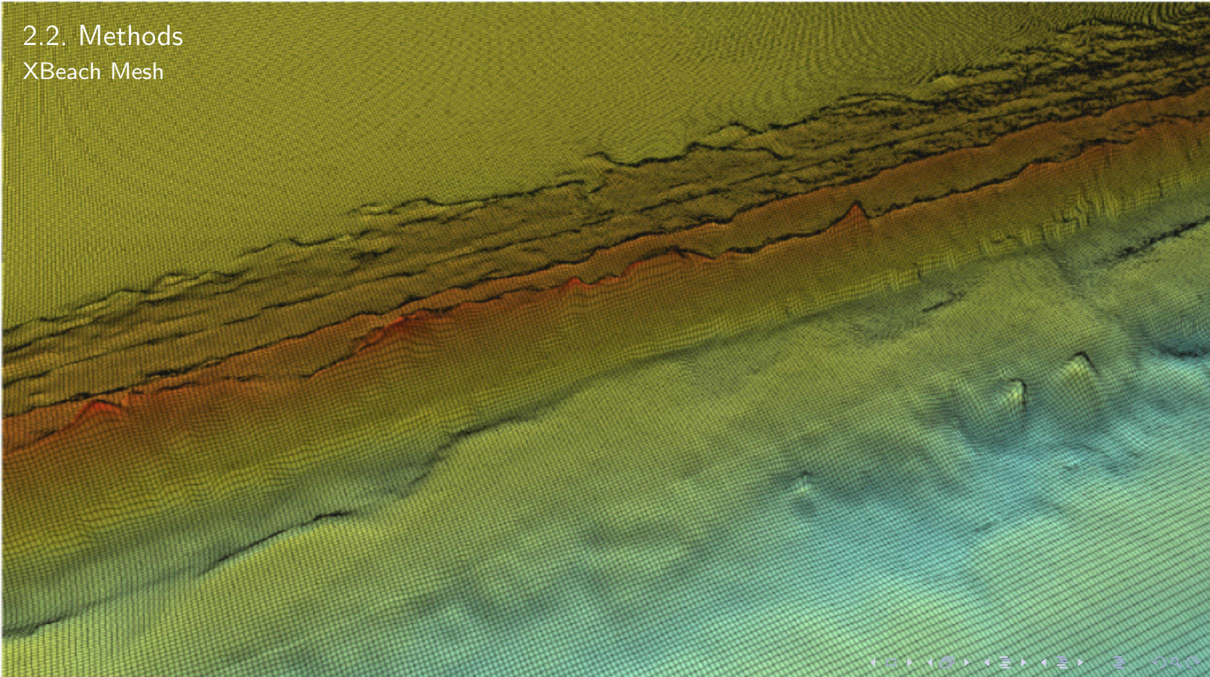
Aerial Photo of Hatteras Island

2.2. Methods
ADCIRC Mesh



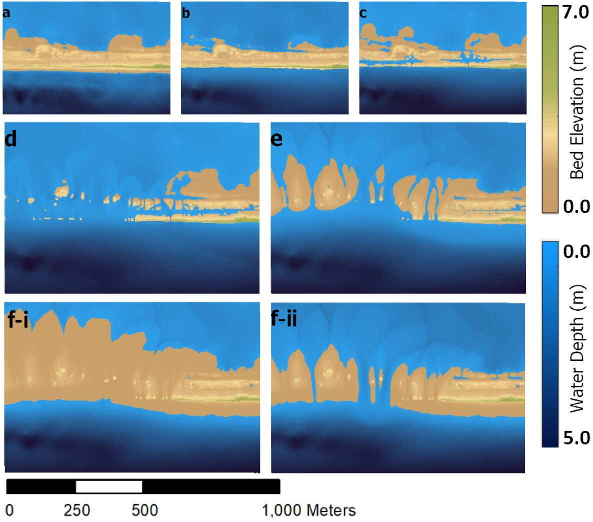
2.2. Methods

XBeach Mesh



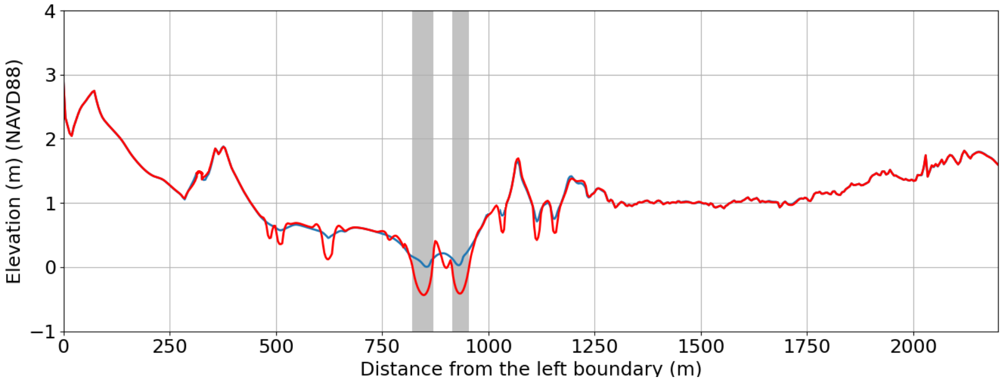
2.3. Isabel Inlet

Formation of Isabel Inlet



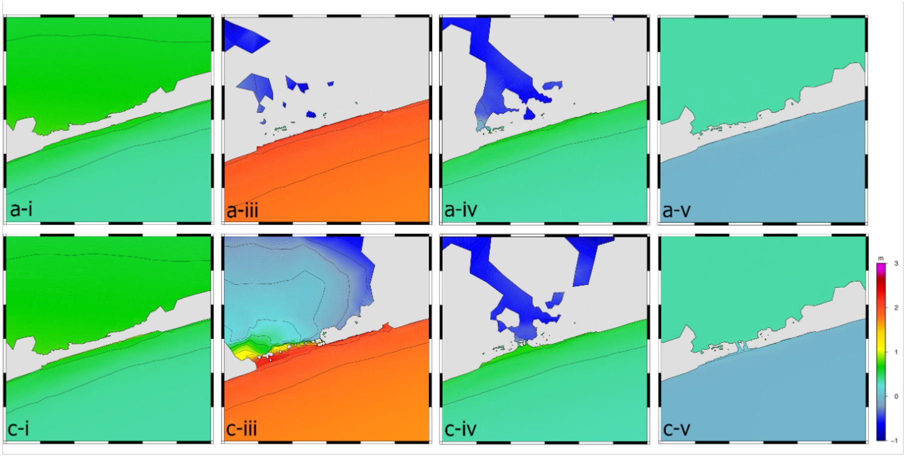
2.3. Isabel Inlet

Deeper Breaches



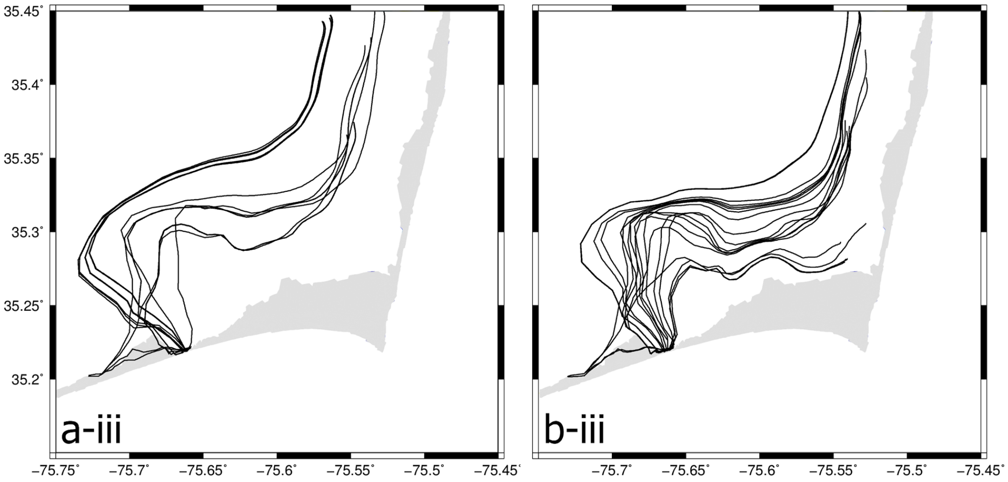
2.3. Isabel Inlet

Static vs Coupled Flooding Predictions



2.3. Isabel Inlet

Large-Scale Effects on Lagoonal Circulation



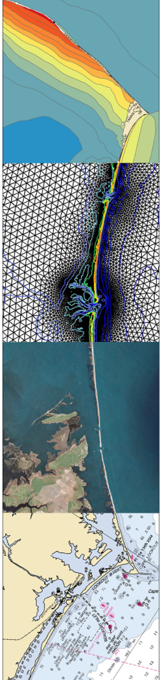
2.4. Conclusions
Subgrid ADCIRC

The main contributions of this study are:

1. XBeach could predict the initiation and location of the breach
   - → Not able to predict number and full depths of breaches
2. Flow from sound to ocean helps to deepen the breached channels
   - → Artificially raised water levels to make this happen
3. Breaching of the barrier island has significant effects on large-scale
   - → Flooding extends 10 to 13 km into sound

Ongoing efforts are focused on:

- Expanding to the full U.S. coastline
- Automating for real-time forecasting



Recent Manuscript in *Estuarine, Coastal and Shelf Science*

Estuarine, Coastal and Shelf Science 262 (2021) 107593

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Formation of a barrier island breach and its contributions to lagoonal circulation

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ARTICLE INFO

Keywords:
Hatteras Island
Hurricane Isabel
XBeach
ADCIRC+SWAN

ABSTRACT

Barrier islands are a primary coastal defense and often experience erosion during storms. When they fail due to storm-induced breaching, there can be significant changes to the small- and large-scale hydrodynamics and morphodynamics of the region. In this study, we explore the formation of a breach on Hatteras Island, North Carolina, during Isabel (2003) and the subsequent flooding into Pamlico Sound. Two-way coupling of high-fidelity, high-resolution numerical models for coastal erosion and flooding enables a better understanding of the formation of the breach, as well as scenarios of the breach's effects on the circulation in the region. The breach connecting the ocean to the sound formed during the day of landfall. It is shown that, during the storm, overwash and inundation from the ocean led to deterioration of the beach and dunes, and then after the storm, the creation of channels through the island was sensitive to elevated water levels in the lagoon. Then flooding scenarios are considered in which the ground surface of the hydrodynamic model was (a) static, updated with the (b) pre- and post-storm observations, and updated dynamically with (c) erosion model predictions and (d) erosion model predictions with elevated lagoon-side water levels. The model results show that the breach has region-scale effects on flooding that extend 10 to 13 km into the lagoon, increasing the local water levels by as much as 1.5 m. These results have implications for similar island-lagoon systems threatened by storms.

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ADCIRC is a system of computer programs for solving time dependent, free surface circulation and tran... problems in two and three dimensions. These programs utilize the finite element method in space allow... the use of highly flexible, unstructured grids. Typical ADCIRC applications have included:

- prediction of storm surge and flooding
- modeling tides and wind driven circulation
- larval transport studies
- near shore marine operations
- dredging feasibility and material disposal studies

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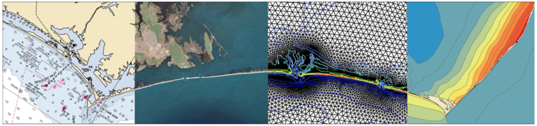
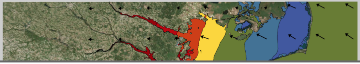
Coastal & Computational Hydraulics Team



What We Do | Join Our Team | FigureGen | Kalpana | SWAN+ADCIRC

Welcome to the CCHT! We develop computational models for wind waves and coastal circulation, and then apply these models to high-resolution simulations of ocean behavior. Our goals are to understand how coastlines are threatened during storms, how materials are transported in the coastal environment, and how to communicate these hazard risks for use in decision support. Our research spans the disciplines of coastal engineering, numerical methods, computational mathematics, and high-performance computing.



MEET OUR TEAM

Faculty
- **Casey Dietrich** | Posts | CV

Post-Doctoral Researchers
- **Dylan Anderson** | Posts | CV

Graduate Students
- **Ajimon Thomas** | Posts | CV
- **Alireza Gharagozlou** | Posts | CV
- **Johnathan Woodruff** | Posts | CV
- **Autumn Poisson** | Posts | CV
- **Carter Rucker** | Posts | CV

Undergraduate Students
- Chloe Stokes
- Carter Howe