Multi-Scale Predictions of Storm-Driven Erosion, Breaching, and Flooding of Barrier Islands

PhD Research Proposal

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U.S. Coastal Research Program

NSF

Acknowledgements

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Outline

- Introduction
  - Barrier islands vulnerability
  - Storm impacts
  - Predicting the impacts
- Proposed Research
  - Objectives
  - Erosion, Breaching, Coupling
  - Hypotheses
- Numerical Models
  - XBeach
  - ADCIRC+SWAN
- Preliminary Results
- Proposed Tasks

Outline

- Introduction
- Proposed Research
- Numerical Models
- Preliminary Results
  - Modeling erosion, overwash and inundation
  - Loose coupling
- Proposed Tasks
  - Island breach modeling
  - Two-way coupling

- **Introduction**
- Proposed Research
- Numerical Models
- Preliminary Results
- Proposed Tasks

Barrier Islands

NC Outer Banks, Hurricane Florence 2018

Storm Impacts

Florence (2018), NC

Irene (2011), NC

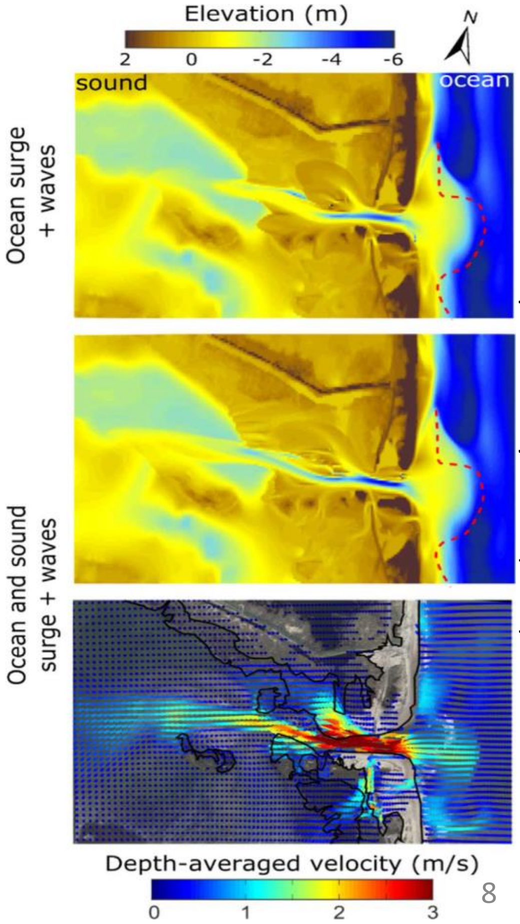
Arthur (2014), NC

Matthew (2016), FL

Modeling Tools

Morphodynamic models:

- Erosion, overwash, sediment transport, etc.
- High-resolution mesh
- Small-scale features
- Small domains

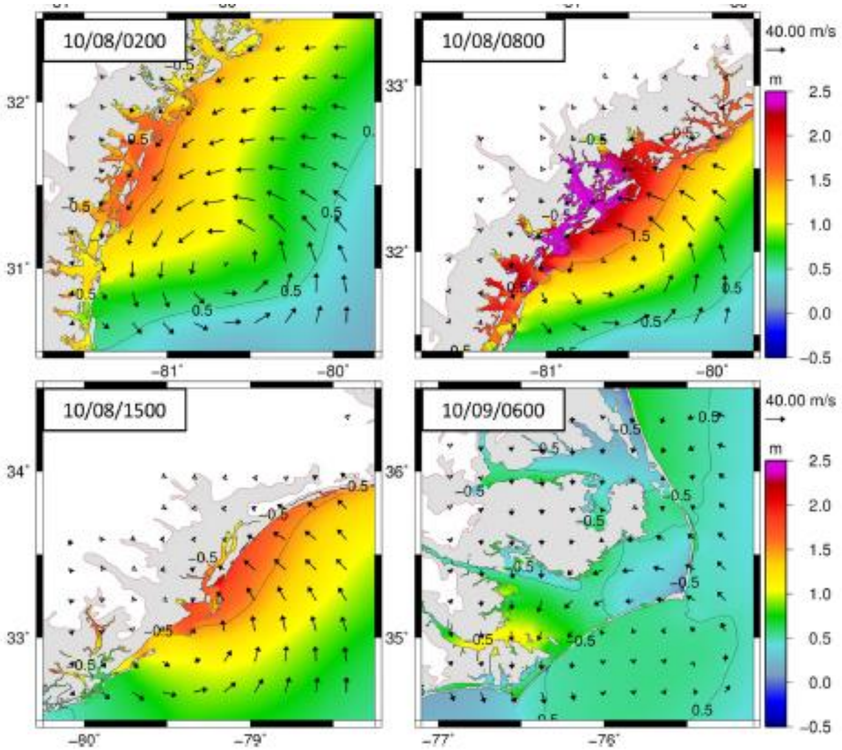


Velasquez Montoya et al. (2018)

Modeling Tools

Storm surge and flooding models:

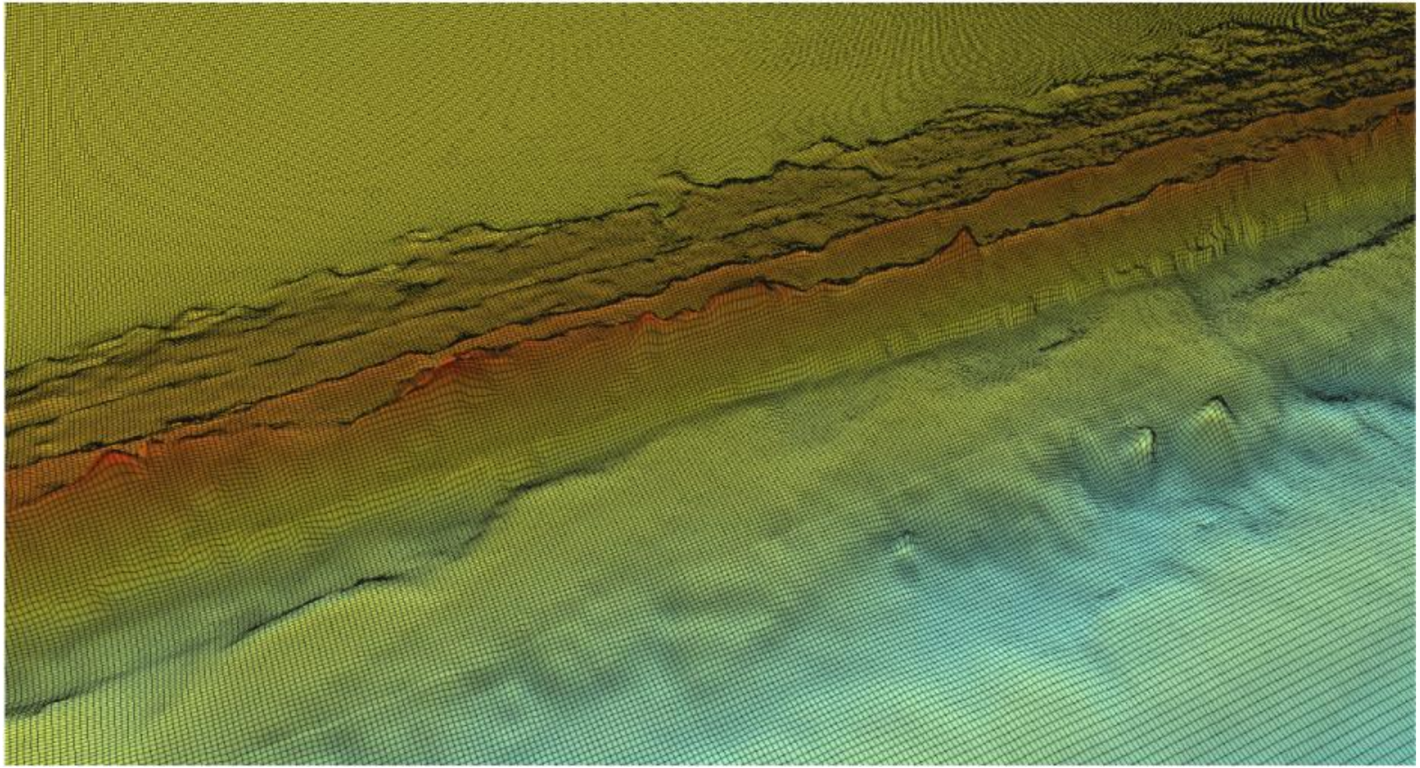
- Tide, wave, current, flooding, etc.
- Large domains
- From back-barrier to open ocean
- Coarse mesh resolution



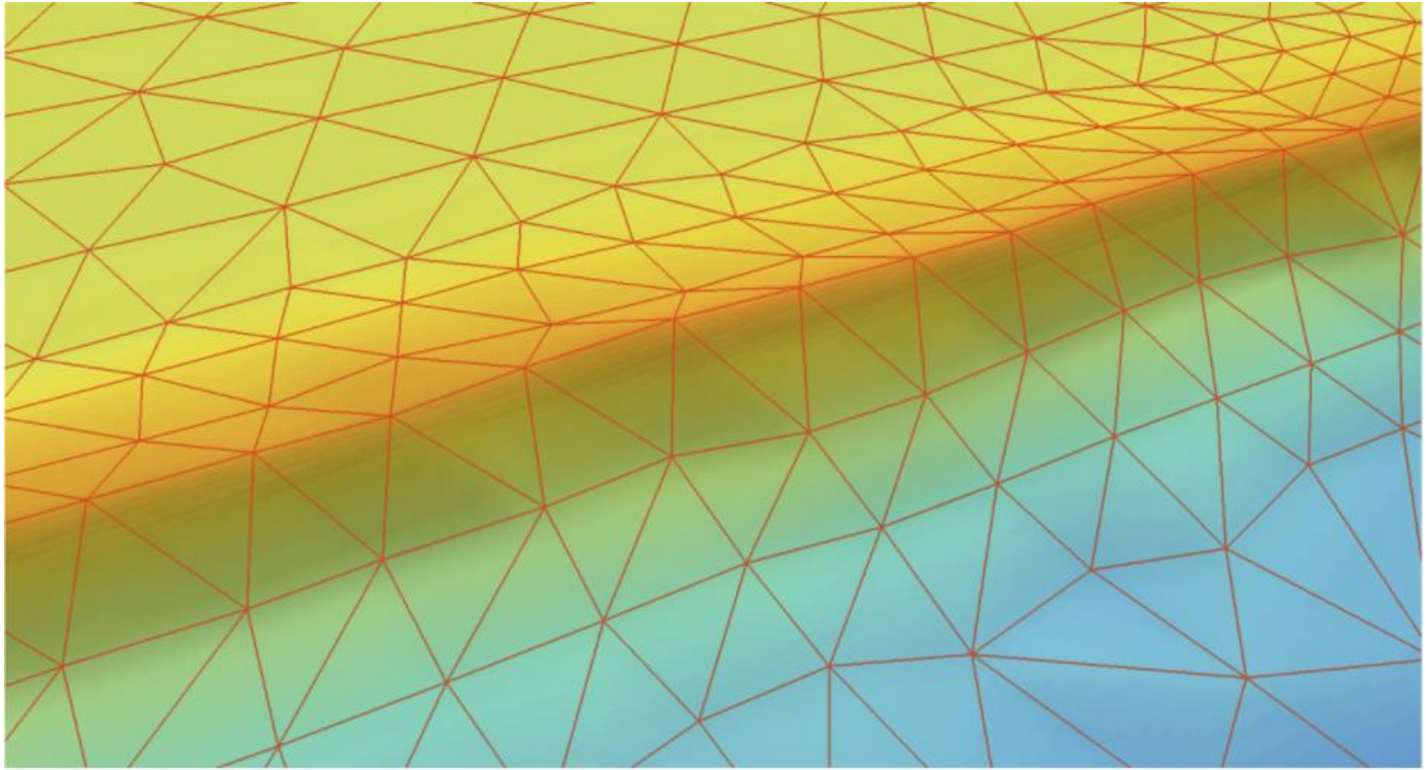
Thomas et al. (2019)

Resolution Difference

Resolution Difference



Resolution Difference



What are the gaps?

- Widely used and very reliable models
- Not connected
- Coastal flooding models
  - Efficient for modeling hydrodynamics on large domain
  - Coarse mesh cannot resolve dune-scale features
  - Do not consider morphology

This is a problem especially when significant erosion occur

Why is it Important?

Connecting the models:

- Improve the accuracy of flooding predictions
- Predict large scale interactions of morphodynamics and hydrodynamic
- Study the damages to infrastructure from both sediment and water

- Introduction
- **Proposed Research**
- Numerical Models
- Preliminary Results
- Proposed Tasks

Objectives

1. Model storm-driven erosion, overwash, and inundation
2. Model breaching and channel formation during storm
3. Bridge the gap between region-scale and Island-scale models

Objectives

1. Model storm-driven erosion, overwash, and inundation

1. Erosion & Overwash

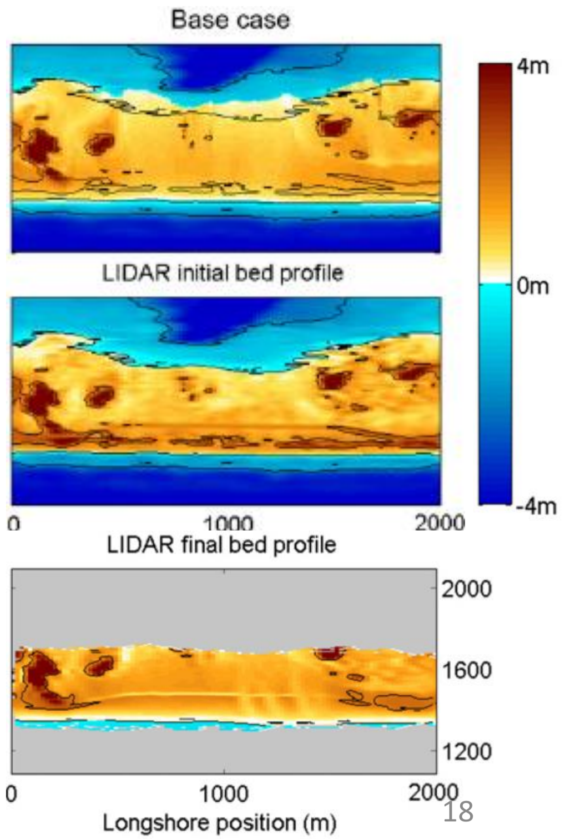
Overton et al. [2004], Clinch et al. [2012], Harter [2017]

- Vulnerable spots, erosion, overwash
- Storm surge estimation

McCall et al. [2010]

- Modeled the overwash in Santa Rosa Island during Hurricane Ivan (2004).
- Small domain size

A. Gharagozlou, J. C. Dietrich, A. Karanci, R. A. Luettich, and M. F. Overton "Storm-driven erosion and inundation of barrier islands from dune- to region-scales." Coastal Engineering, 2019. Submitted.



Objectives

2. Model Breaching and channel formation during storm

2. Modeling Barrier Island Breaching

Breaching:

- Connects back-barrier to the ocean
- Depends on storm properties and topography of the coast
- Impacts the hydrodynamics and morphodynamics of the region

2. Modeling Breaching

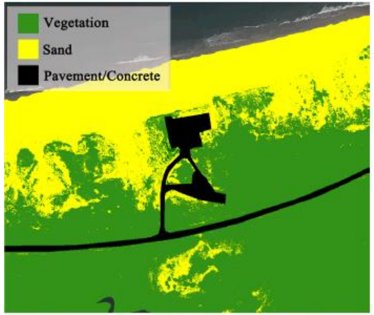
Kraus [2003], De-Vet [2014], Elsayed et al. [2017]

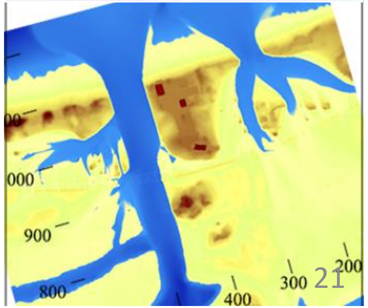
- Breaching, erosion, channel formation
- Physic-based model improvement
- Small domain models

Kurum and Overton [2013]

- Land cover effects on breaching
- Multiple sediment layers
- Different sediment properties (median size and erodability)

- Instead of calibration factors we will use bed friction





2. Modeling Breaching

Research Questions:

How to include the **processes** involved in **breaching**?

How to predict the **location** and **size** of the breach?

How to apply the predictions on a **large-scale domain**?

2. Modeling Breaching

Hypothesis 1:
The **accurate location and shape** of breaching and channelization during a storm can be predicted only if information about **the land cover and sub-layers** are included.

Hypothesis 2:
If we include a large-extent domain on the barrier island, significant **large-scale impacts** of breaching on water levels, flow velocities, and sediment transport can be studied.

Hypothesis 3:
Via targeted coarsening of the mesh resolution, the **computational time** will be improved while the **accuracy** of the **predictions in large scale** will be maintained.

Objectives

3. Bridge the gap between region-scale and Island-scale models

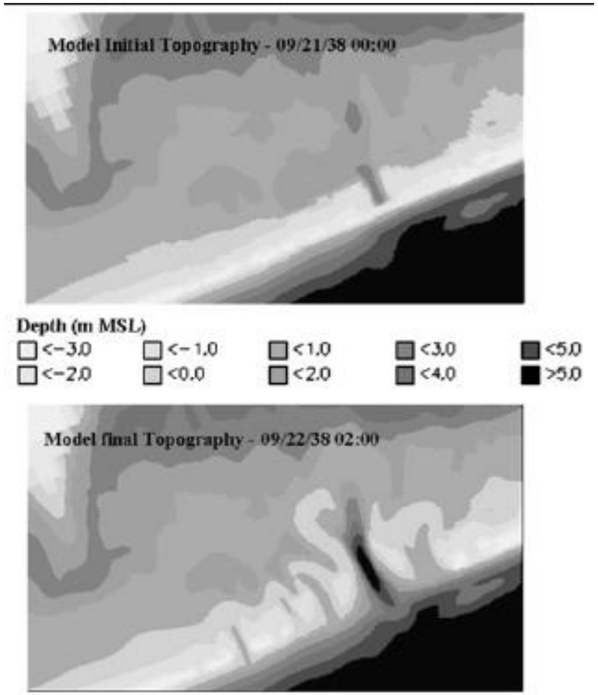
3. Coupling

Suh et al. [2015, 2017]

- One-way coupling
- Small domain

Cañizares and Irish [2008]

- Storm-driven erosion and breaching
- Coupling ADCIRC, Delft3D, and SBeach
- Suitable for simulating sediment overwash processes once the barrier island is fully inundated.



3. Coupling

Research Questions:

How to **connect** the **morphodynamics and hydrodynamics** during the storm on **local** and **regional** scales?

How **temporal and spatial resolution** requirements for coupling impact the predictions?

3. Coupling

Hypothesis 4:
The prediction of flooding extents and large-scale impacts of storm on back-barrier hydrodynamics will be improved if **ADCIRC and XBeach** models are coupled and the bathymetry predictions are **updated dynamically**.

Hypothesis 5:
In case of extensive breaching and channel formation, the **frequency and duration** of ground surface update has a significant impact on flooding predictions and can be modeled correctly if the **temporal evolution** of the breach is represented accurately.

- Introduction
- Proposed Research
- **Numerical Models**
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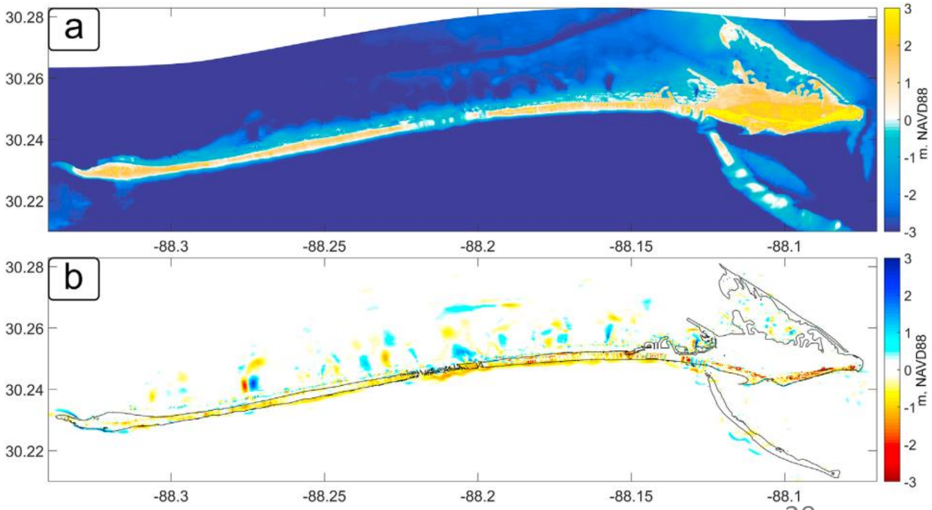
XBeach

Xbeach (Roelvink [2009])

- Nearshore hydrodynamics and morphodynamics
- Depth-averaged shallow water equations, Short-wave action balance
- Infragravity waves
- Dune face avalanching
- Structured mesh
- Typical domain size of 2—20 km
- Typical resolution of 2—20 m

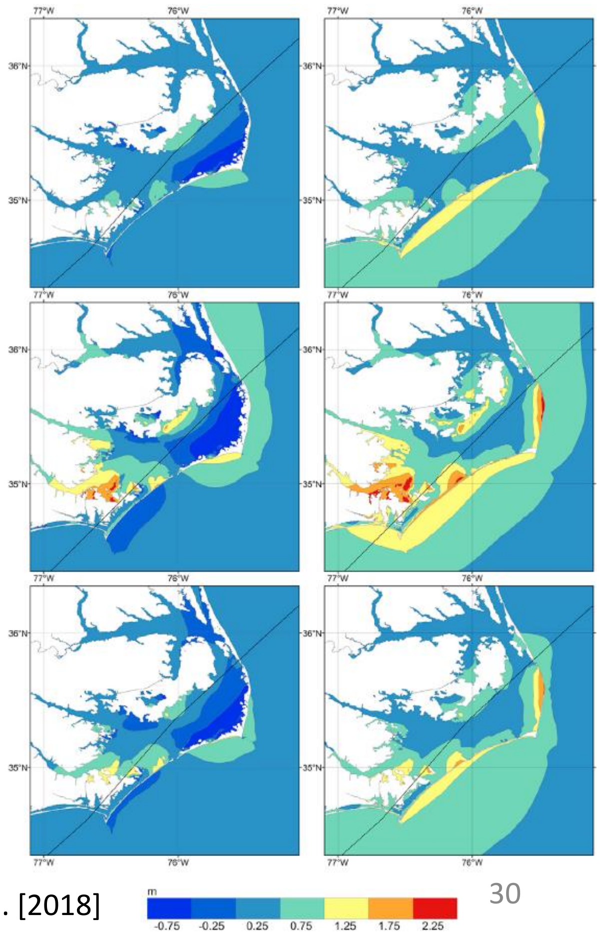


Passeri et al. [2018]

ADCIRC+SWAN

ADCIRC+SWAN (Luettich et al [1992], Dietrich et al. [2013], Booij et al [1999])

- Powerful tool for flooding and storm surge modeling
- Finite-element model
- Shallow water equations, Wave action density equation
- Flexible, unstructured meshes
- Typical minimum resolution of 50—100 m



Cyriac et al. [2018]

- Introduction
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Motivations for Modeling Erosion

- Predict storm-driven erosion over large domains
- Develop techniques for coarsening predictions and coupling back to flooding models

Goals:

1. Validate XBeach erosion predictions on larger domains
   - Quantify model performance on 30-km of Hatteras Island during Isabel

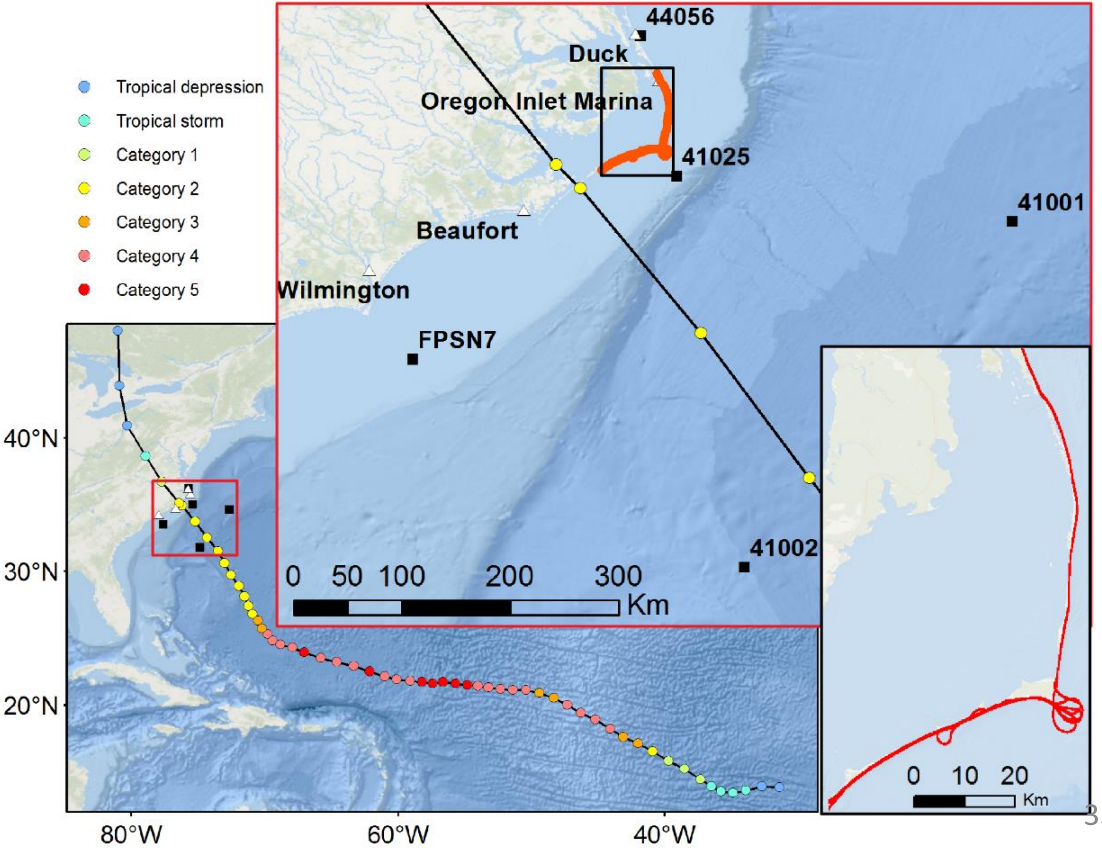
2. Evaluate XBeach accuracy at coarser resolution
   - What happens if we use a coarser mesh?

3. Loose coupling XBeach and ADCIRC
   - What are implications as a hydraulic control to stop or allow flooding?
   - How ADCIRC predictions change with updated topography?

Hurricane Isabel

- Survey width: 250-300 m
- High resolution LiDAR: 2m
- Covering large extent
- Erosion, overwash, and breaching
- Pre- and post-storm data:

  16 Sep — 21 Sep 2003



Study Area

Computational grid:

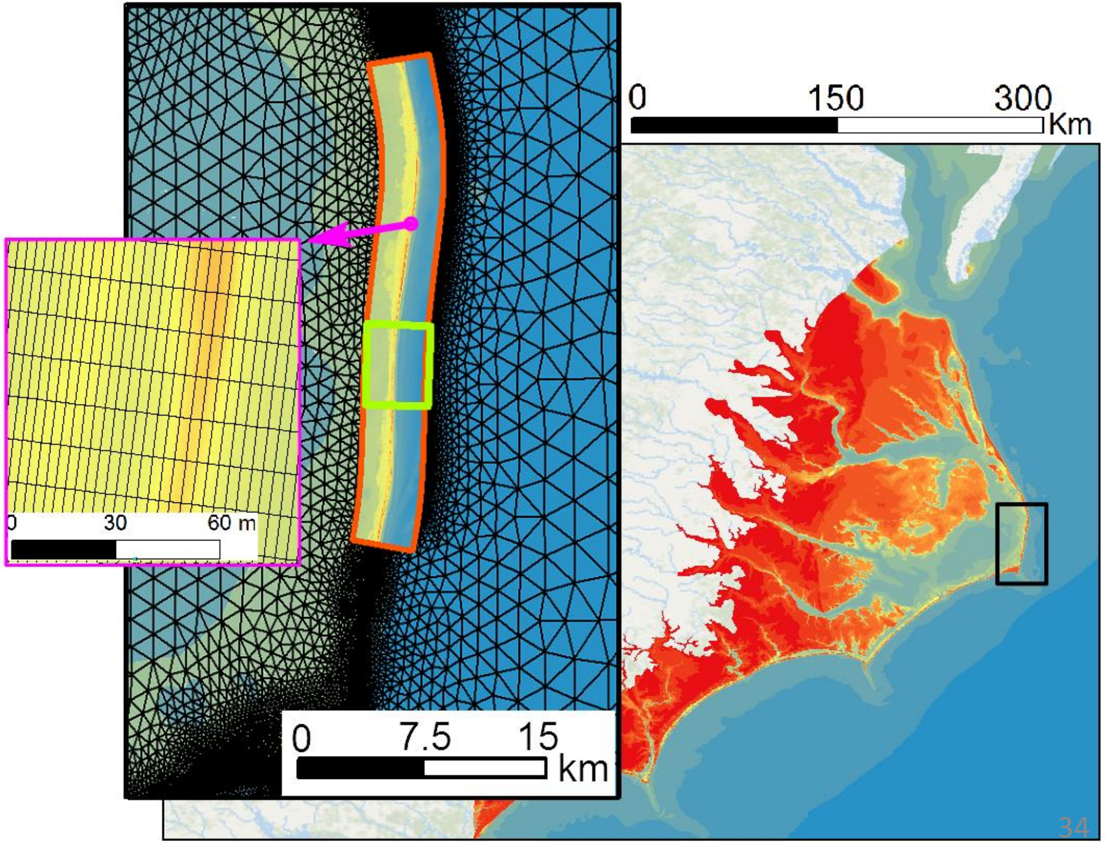
- Alongshore: 15 m
- Cross shore: 3-35 m

Topo/Bathy data:

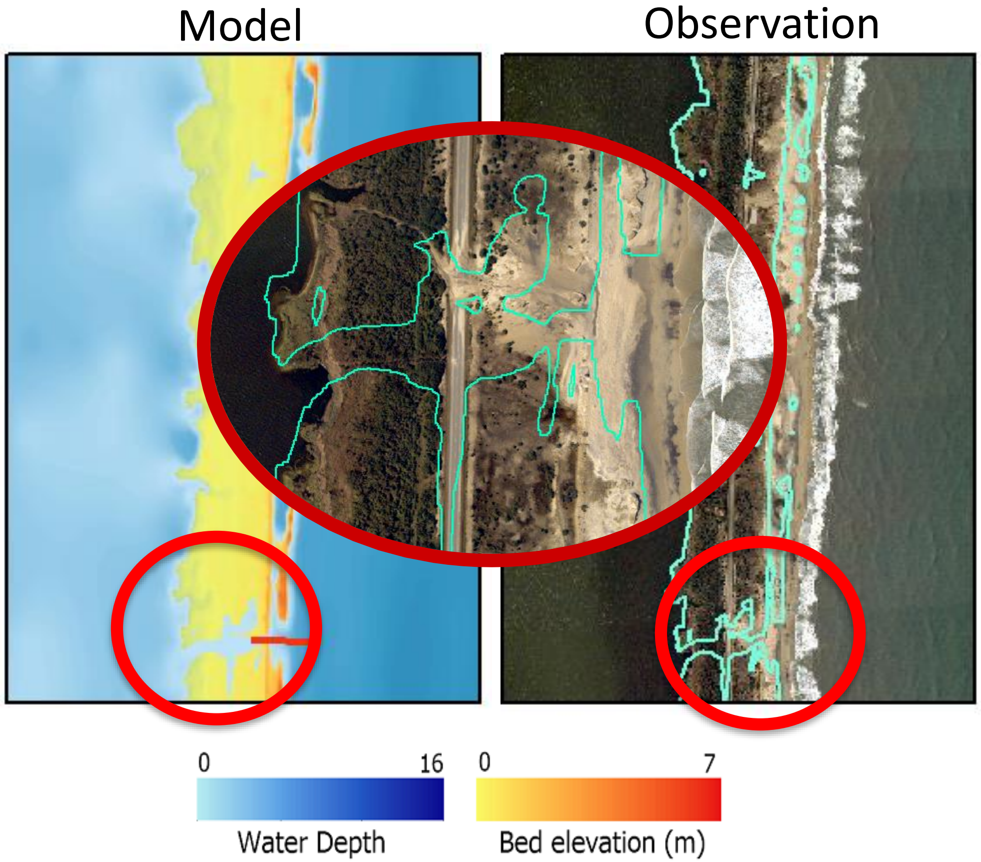
- Pre-storm LiDAR
- NC floodplain mapping DEM

Model setup:

- Simple model with minimal tuning
- To expand to other regions
- Waves and water levels from ADCIRC+SWAN



1. XBeach Validation

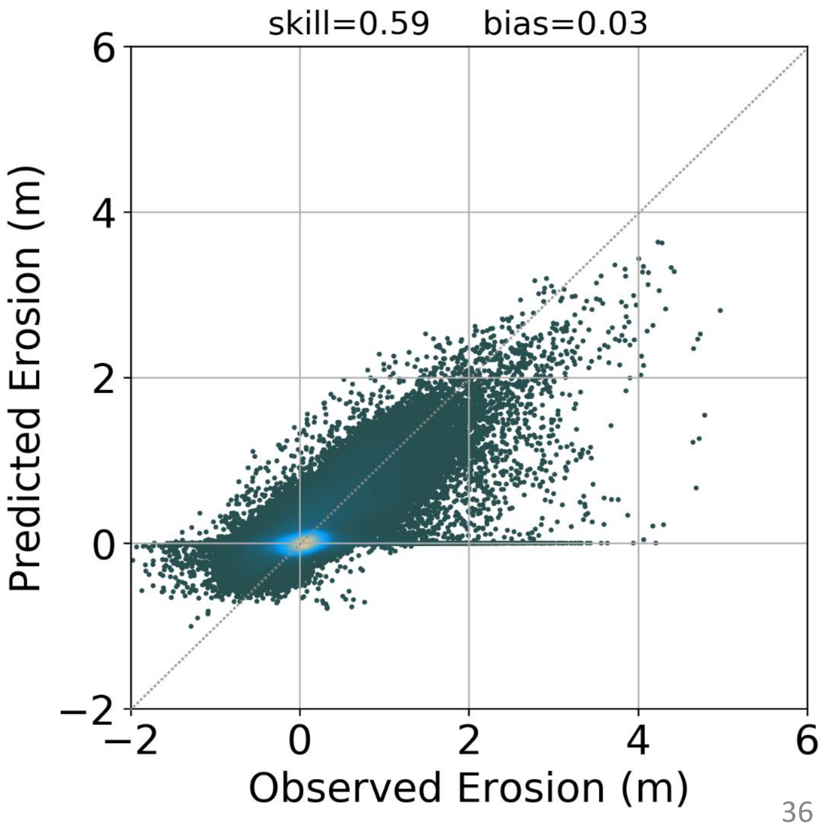


1. XBeach Validation

Skill Score (Sutherland et al. [2004])

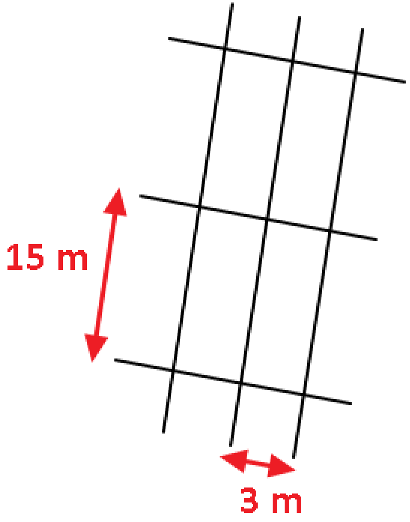
$$Skill = 1 - \frac{\sum_{i=1}^{N} \left(dz_{b_{LIDAR,i}} - dz_{b_{XBeach,i}}\right)^2}{\sum_{i=1}^{N} \left(dz_{b_{LIDAR,i}}\right)^2}$$

- Skill Score > 0.5 is “Excellent”
- Model Skill Score = 0.59



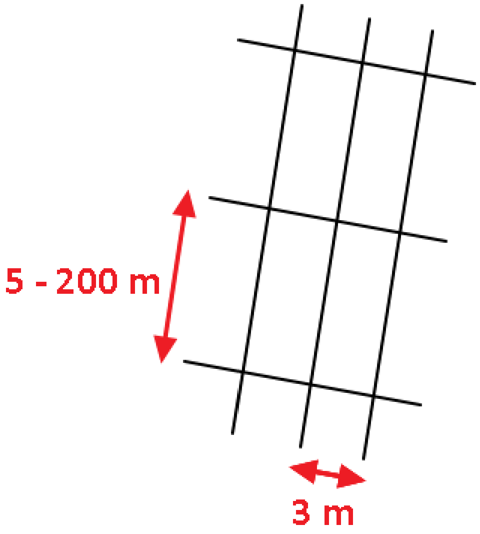
2. Resolution Sensitivity

- Changing mesh spacing on smaller domain
  - Alongshore
  - Cross-shore
- Sensitivity of Skill Score to resolution



2. Resolution Sensitivity

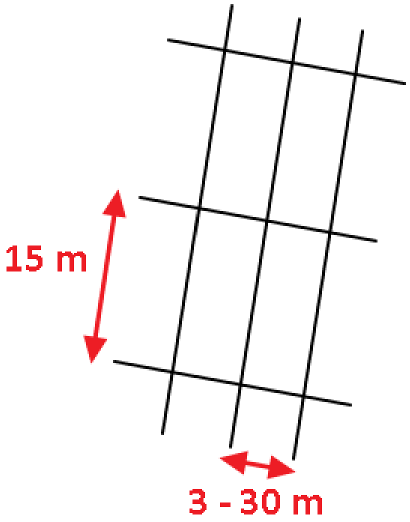
- Alongshore spacing



Mesh	Skill	Bias
5m	0.68	-0.06
10m	0.69	-0.07
15m	0.68	-0.06
20m	0.69	-0.06
30m	0.69	-0.06
50m	0.67	-0.05
100m	0.69	-0.03
200m	0.69	-0.03

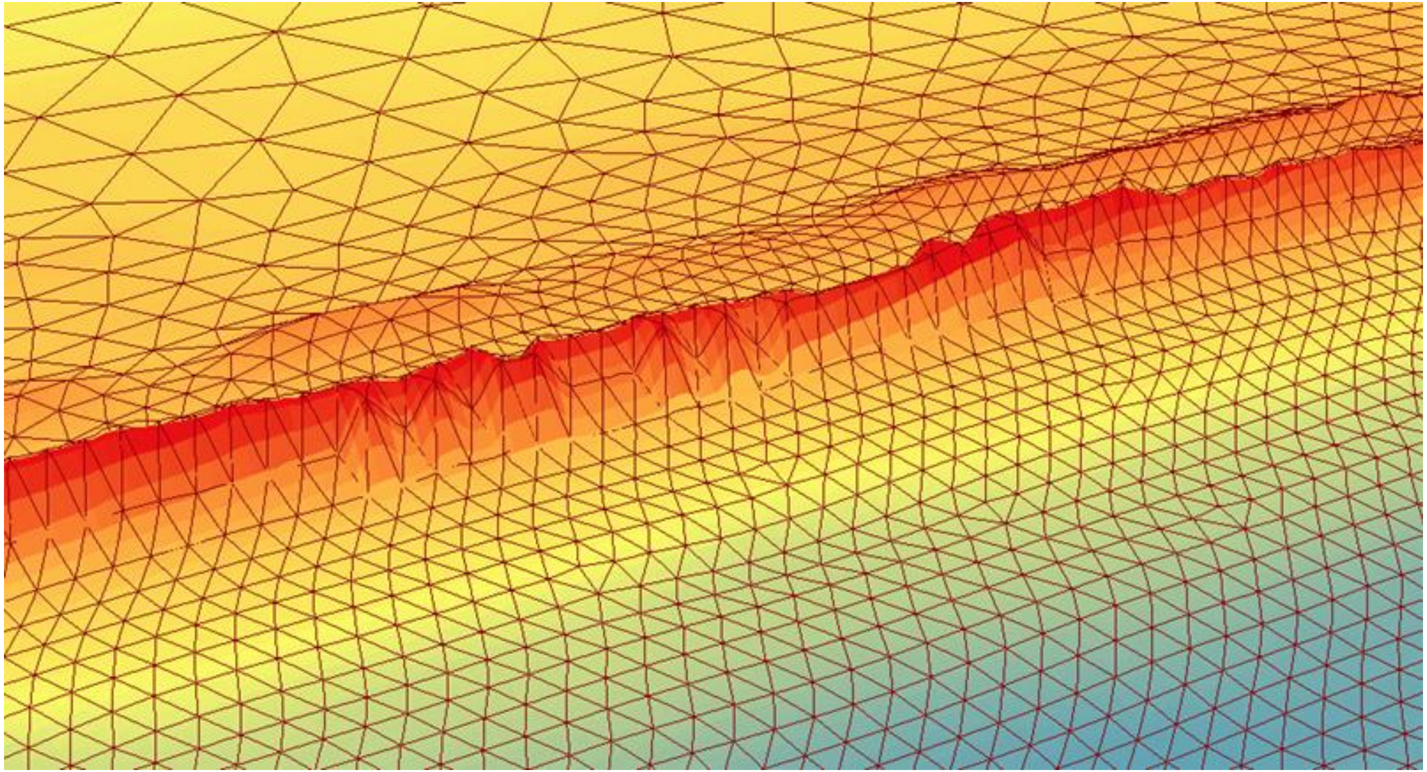
2. Resolution Sensitivity

- Cross-shore spacing



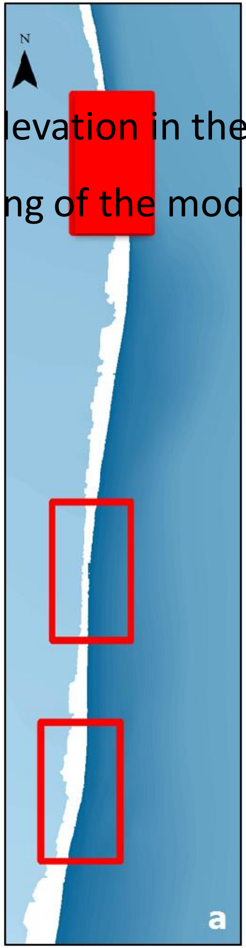
Mesh	Skill	Bias
3m	0.68	-0.06
5m	0.60	-0.05
10m	0.51	-0.03
15m	0.27	-0.03
30m	0.07	0.33

3. Loose Coupling

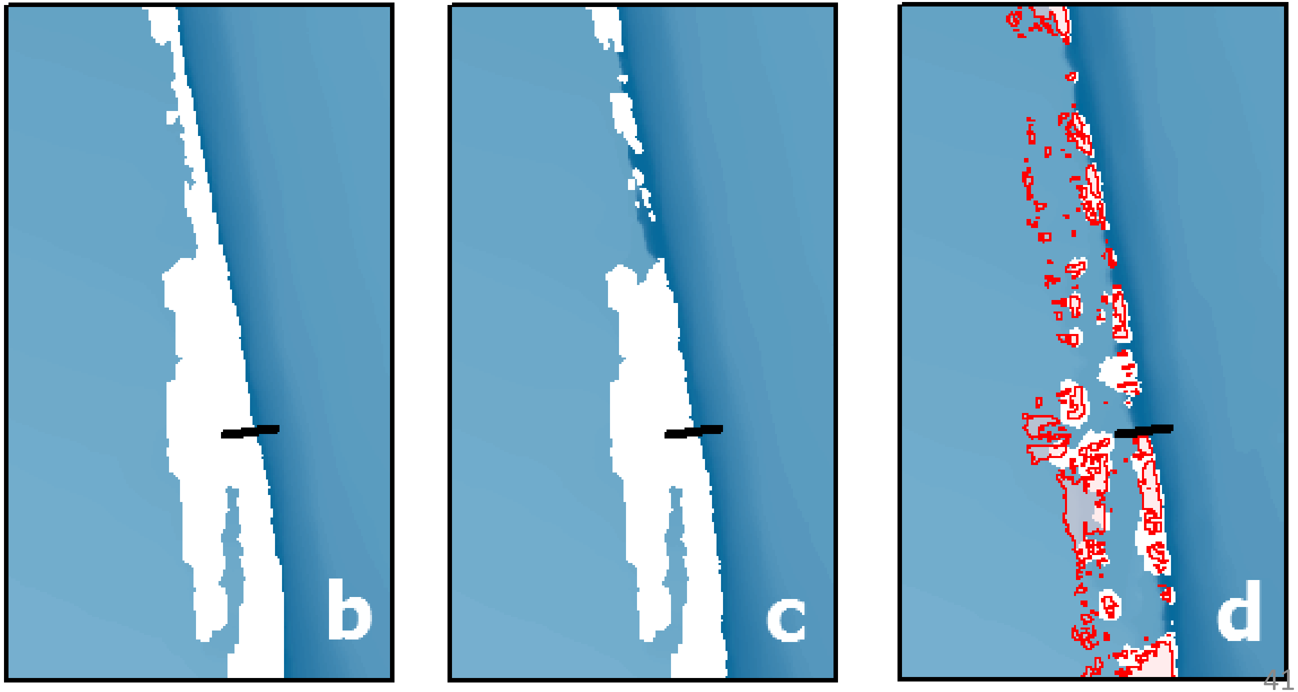


3. Loose Coupling

Mesh elevation in the beginning of the model:

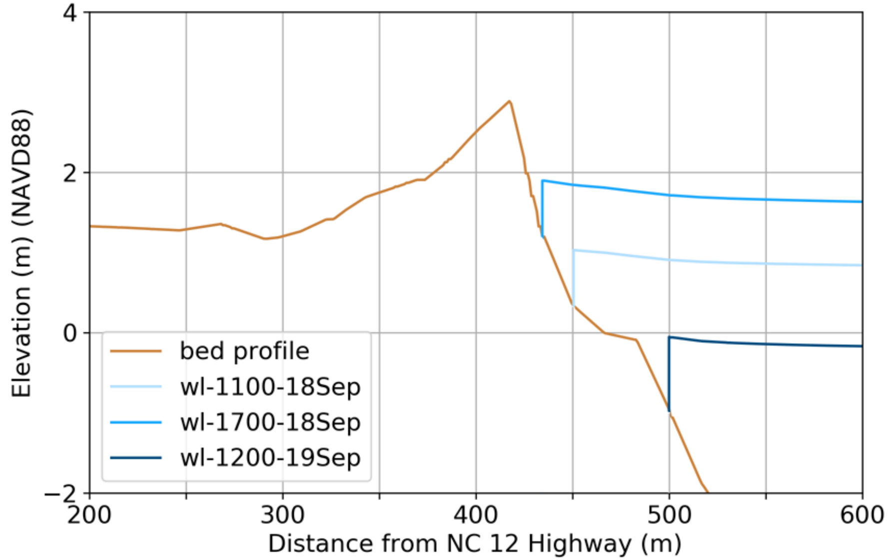


Observed pre-storm | Observed post-storm | XBeach prediction

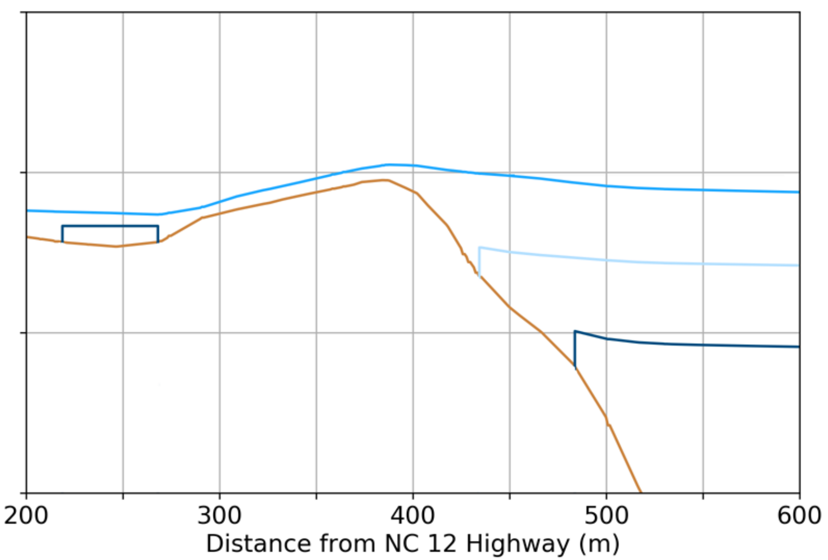


3. Loose Coupling

Pre-storm topo



XBeach prediction



Conclusion

1. XBeach performance:

- Model performance on 30 km domain is very encouraging
- Beach profile, Erosion events, flooding extents match post-storm observation

2. XBeach mesh resolution:

- Skill score is not sensitive to alongshore mesh spacing
- Skill score gets worse as the cross-shore mesh resolution increases

3. ADCIRC-updated topo/bathy:

- Beach and dune erosion contribute to flooding predictions
- Results match the prediction in XBeach and post-storm observation

Limitations

1. Lack of Island Breaching:

- During Isabel, an inlet was formed near Cape Hatteras
- Channel formation can contribute to surge and flooding
- The morphodynamics of breaching should be included in the model

2. Loose one-way coupling:

- Static approach was used to update the bathymetry
- Predictions did not account for temporal evolution of the surface
- ADCIRC starts with a topography that has been already affected by the storm
- Two-way coupling is needed to update the surface dynamically

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Region-Scale Predictions of Breaching

Isabel Inlet (2003)

- Three channels
- Total width of 520 m
- Maximum depth of 6 m
- Closed by USACE

Region-Scale Predictions of Breaching

Study Area and Computational Meshes

- 2-km and 15-km domains
- Minimum resolution
    - Alongshore: 2 m (5, 10 m)
    - Cross-shore: 2m (5, 10 m)

- Maximum alongshore spacing: 10 m (20, 30 m)

Hypotheses

Hypothesis 1: Modeling shape of the breach using land cover and sub-layer impacts.

Hypothesis 2: Studying the significant large-scale impacts of breaching

Hypothesis 3: Mesh coarsening and improving the computational time

Region-Scale Predictions of Breaching

Modeling the breach

Idealized domain (T1 tests)

- Uniform bathymetry (2-km domain)

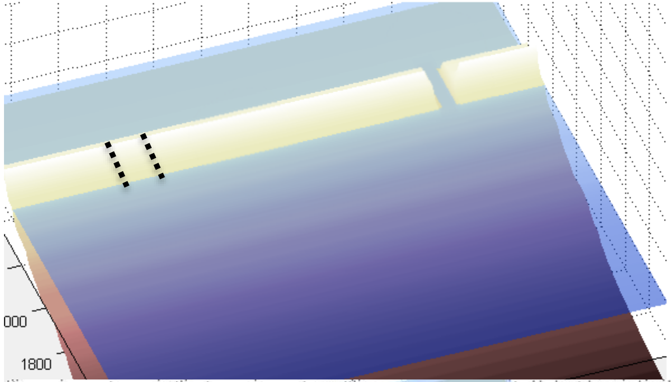
Realistic domain (T2 tests)

- Real topo/bathymetry (2-km and 15-km domains)

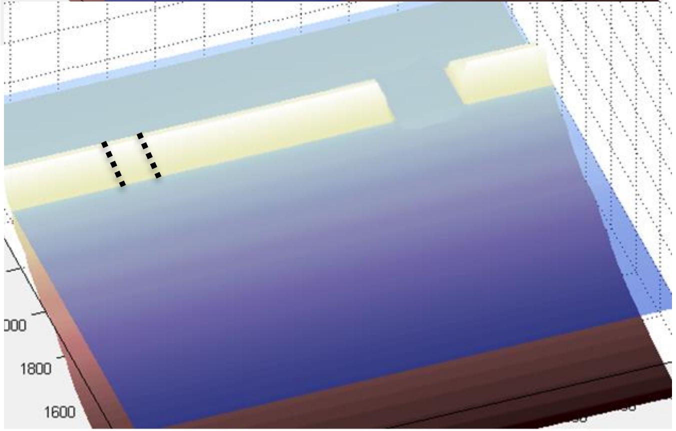
- Land cover (H1)
- Sub-layer (H1)
- Land cover + sub-layer (H1)
- Mesh resolution sensitivity (H3)
- Multi-scale impacts of pre-existing channel (H1, H2)
- Multi-scale impacts of Hindering the breaching (H1, H2)

Region-Scale Predictions of Breaching

T1-5: Pre-existing 50-m channel

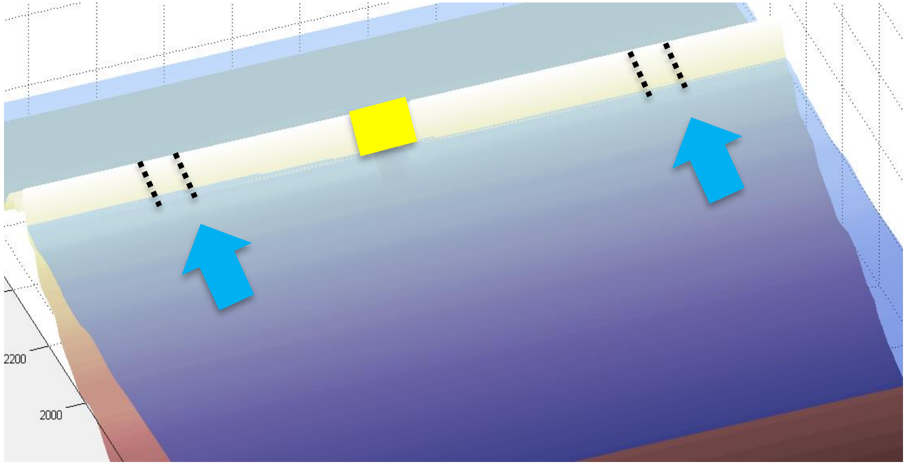


T1-6: Pre-existing 300-m channel



Region-Scale Predictions of Breaching

T2-5: Breaching will be hindered



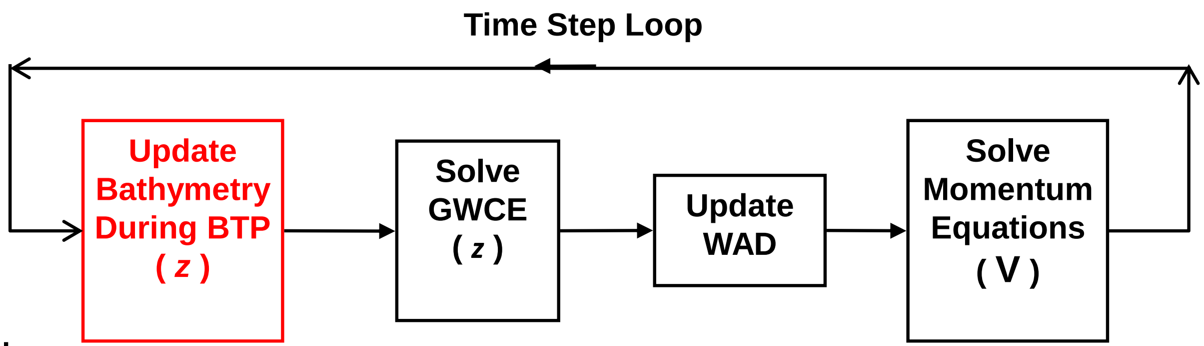
Coupling ADCIRC and XBeach

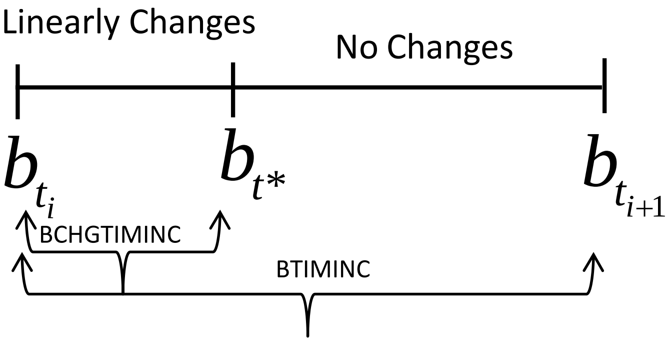
Time-varying bathymetry update

Two-way coupling

Implemented in ADCIRC

by Dr. Chris Massey





Hypotheses

Hypothesis 4: Two-way coupling of models with temporal bathymetry update

Hypothesis 5: Evaluating the temporal resolution requirements

Coupling ADCIRC and XBeach

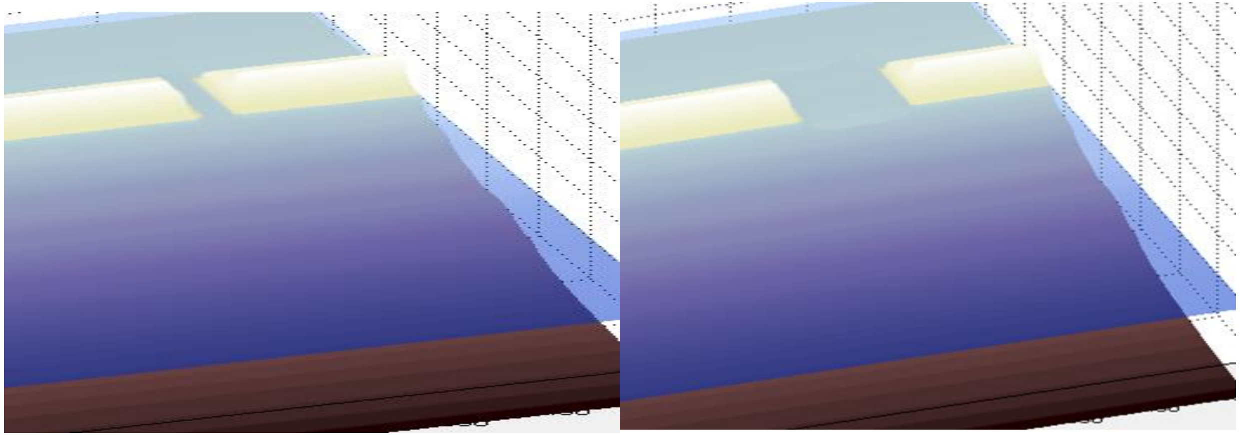
Coupling models
- **Idealized domain (T3 tests)**
- **Realistic domain (T4 tests)**

- Loose coupling (H4)
- Two-way coupling (H4)
- Varying temporal resolution (H5)
- Linear surface update (H5)
- Changing breach size (H4,5)
- Changing lagoon size (H4,5)
- Blocking the existing inlets (4)

Region-Scale Predictions of Breaching

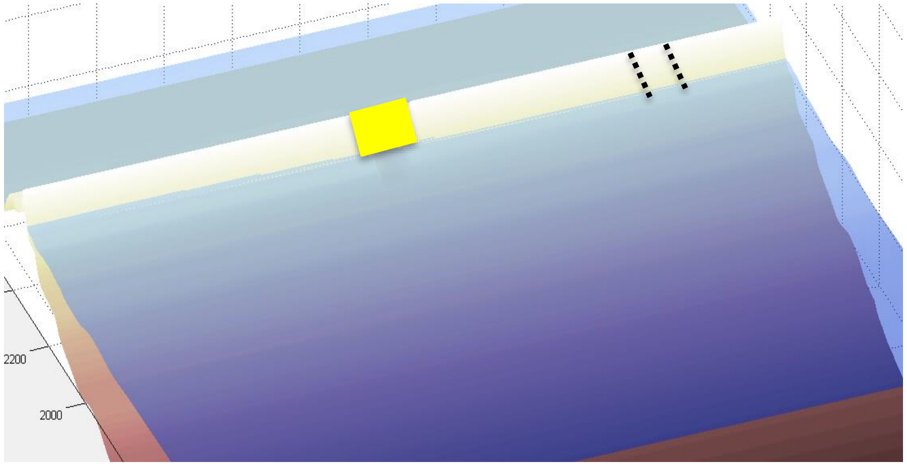
T3-3: Ground surface update every 1, 3, 5, 10 hours

T3-4: Size of the breach (Depth and width) will be doubled

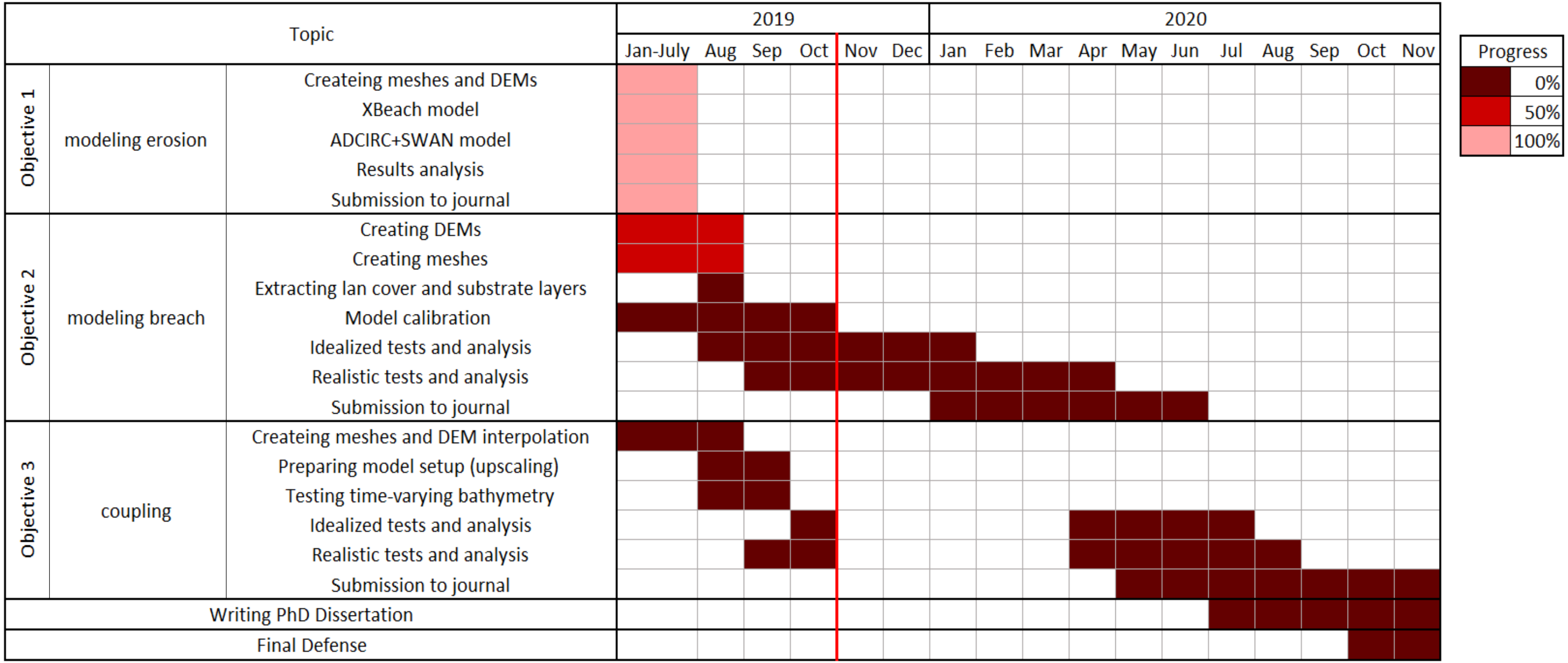


Region-Scale Predictions of Breaching

T4-4: The existing inlets along the barrier island will be blocked



Plan of Work


Topic
2019
2020
Jan-July
Aug
Sep
Oct
Nov
Dec
Jan
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Mar
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Nov
Objective 1
modeling erosion
Createing meshes and DEMs
XBeach model
ADCIRC+SWAN model
Results analysis
Submission to journal
Objective 2
modeling breach
Creating DEMs
Creating meshes
Extracting lan cover and substrate layers
Model calibration
Idealized tests and analysis
Realistic tests and analysis
Submission to journal
Objective 3
coupling
Createing meshes and DEM interpolation
Preparing model setup (upscaling)
Testing time-varying bathymetry
Idealized tests and analysis
Realistic tests and analysis
Submission to journal
Writing PhD Dissertation
Final Defense
Progress
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Summary

- Need to study the large-scale and small-scale storm impacts
- We use ADCIRC+SWAN and XBeach
  - Erosion, overwash, flooding
  - Barrier island breaching
  - Connecting the models

- Two-way coupled modeling approach
- Predicting multi-scale morphodynamics and hydrodynamic impacts
- Improving the flooding predictions
- Preliminary step toward real-time predictions of morpho- and hydrodynamics during storm
- Contributing to the literature

Thank You!