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

PhD Research Proposal
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Acknowledgements

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Outline

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• Predicting the impacts
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• ADCIRC+SWAN
Outline

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• Proposed Tasks

  • Modeling erosion, overwash and inundation
  • Loose coupling

  • Island breach modeling
  • Two-way coupling
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Barrier Islands

NC Outer Banks, Hurricane Florence 2018
Storm Impacts

Florence (2018), NC

Irene (2011), NC

Arthur (2014), NC

Matthew (2016), FL
Morphodynamic models:

- Erosion, overwash, sediment transport, etc.
- High-resolution mesh
- Small-scale features
- Small domains
Storm surge and flooding models:

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

2. Model Breaching and channel formation during storm
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**?
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

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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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• **Preliminary Results**

• Proposed Tasks
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
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

Observation Model

Introduction Proposed Research Numerical Models Preliminary Results Proposed Tasks

Proposed Tasks

35
1. XBeach Validation

**Skill Score** (Sutherland et al. [2004])

\[
Skill = 1 - \frac{\sum_{i=1}^{N} (dz_{b,\text{LIDAR},i} - dz_{b,\text{XBeach},i})^2}{\sum_{i=1}^{N} (dz_{b,\text{LIDAR},i})^2}
\]

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

![Graph showing skill score and bias](image)
2. Resolution Sensitivity

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

- Alongshore spacing

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<thead>
<tr>
<th>Mesh</th>
<th>Skill</th>
<th>Bias</th>
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<td>30m</td>
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<td>50m</td>
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<tr>
<td>200m</td>
<td>0.69</td>
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</table>
2. Resolution Sensitivity

- Cross-shore spacing

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<tr>
<td>30m</td>
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</table>
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
• Introduction

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• **Proposed Tasks**
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)

Proposed Tasks

- 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
T2-5: Breaching will be hindered
Coupling ADCIRC and XBeach

Time-varying bathymetry update

Two-way coupling

Implemented in ADCIRC by Dr. Chris Massey

Linearly Changes

\[ b_{t_i} \rightarrow b_{t^*} \rightarrow b_{t_{i+1}} \]

No Changes

Time Step Loop

Update Bathymetry During BTP \((z)\)

Solve GWCE \((z)\)

Update WAD

Solve Momentum Equations \((V)\)
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

<table>
<thead>
<tr>
<th>Topic</th>
<th>2019</th>
<th>2020</th>
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<tbody>
<tr>
<td></td>
<td>Jan-Jul</td>
<td>Aug Sep</td>
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<tr>
<td>Objective 1: modeling erosion</td>
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<td>Creating meshes and DEMs</td>
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<td>ADCIRC+SWAN model</td>
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<td>Results analysis</td>
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<td>Creating DEMs</td>
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<td>Extracting Jan cover and substrate layers</td>
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<td>Model calibration</td>
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<td>Idealized tests and analysis</td>
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<td>Objective 3: coupling</td>
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<td>Creating meshes and DEM interpolation</td>
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<td>Preparing model setup (upscaling)</td>
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<td>Testing time-varying bathymetry</td>
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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!