Coupling of Deterministic and Probabilistic Models for Prediction of Storm-Driven Erosion on Barrier Islands

Ph.D. Defense

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Sea Grant North Carolina

US Army Corps of Engineers®

USCRP US COASTAL RESEARCH PROGRAM

NSF

Acknowledgements

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About Me

I was born in Hamedan, Iran.

Got my B.S. In Civil Engineering at Bu-Ali Sina University.

Earned my M.S. in Civil Engineering with the focus on Coastal Engineering at University of Tehran.

Traveled 6500 miles to pursue my Ph.D.!

Outline

- Introduction
- Motivation and Background
- Objectives
- Coupling Deterministic Models
- Developing Surrogate Model
- Summary and Conclusion

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Storm Impacts

Irene (2011), NC

Arthur (2014), NC

Mitigation Plans

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Motivations

Improve our understanding of:

- Erosion, overwash, and breaching due to storm
- Their contribution to flooding
- Storm impacts on sustainability of nourished beaches

Research Question:

How do individual erosion events contribute to large-scale coastal hazards?

How do individual erosion events contribute to large-scale coastal hazards?

McCall et al. [2010], De-Vet [2014], Kurum and Overton [2013],

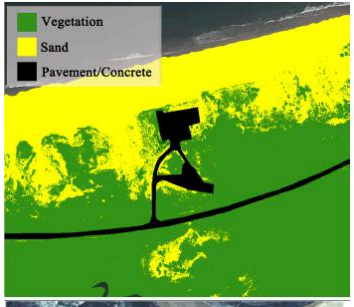
- Storm surge estimation
- Modeled the overwash and dune erosion
- Land cover effects on breaching

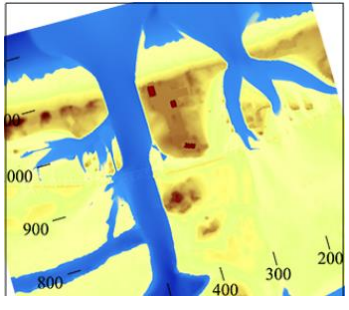
Findings:

- Storm impacts on erosion
- Prediction of erosion is accurate
- Relationship between geomorphology, storm intensity and flooding

Missing gaps:

- Didn't include large-scale impacts
- Breaching contribution to flooding was not considered
- Successive storms' impacts were not considered



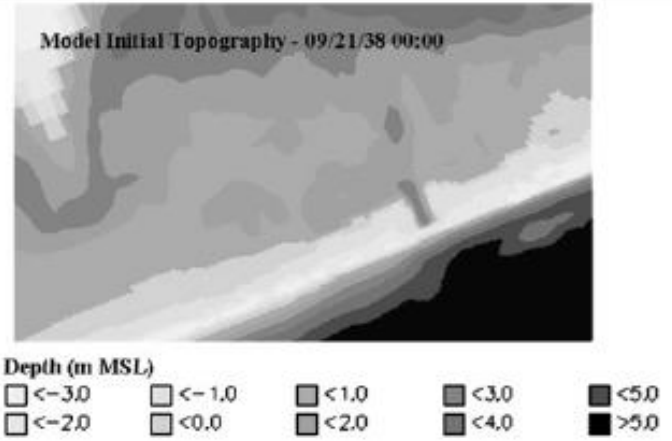


How do individual erosion events contribute to large-scale coastal hazards?

Canizares and Irish [2008]
- Storm-driven erosion and breach
- Coupling ADCIRC, Delft3D, and Sbeach

Findings:
- Beaching can cause flooding
- Suitable for simulating sediment overwash processes once the barrier island is fully inundated

Missing gaps:
- Temporal evolution of the breach are not fully implemented
- Successive storm impacts are not considered

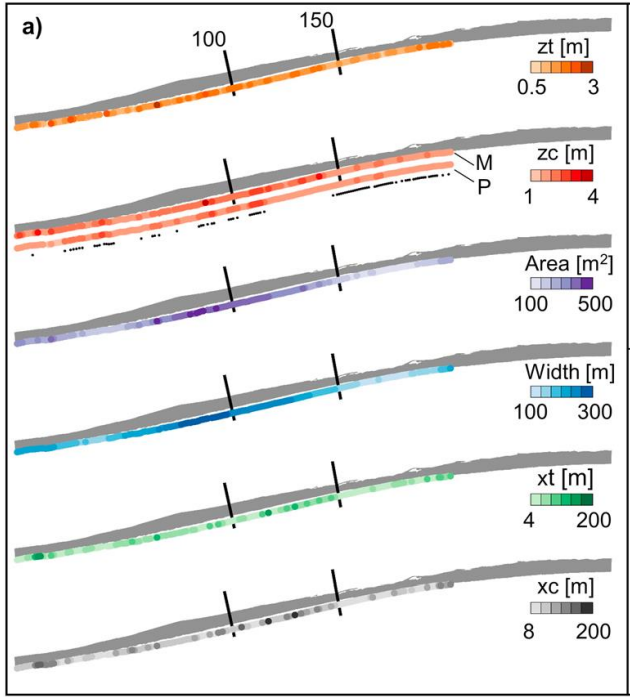


How do individual erosion events contribute to large-scale coastal hazards?

- [Plant et al., 2014], [Santos et al., 2019]
- Shoreline change
- Coastal erosion due to synthetic storms
- Combination of probabilistic and deterministic models
- Based on 100 synthetic storms

Findings:
- Potential of probabilistic models
- Efficiency in predictions

Missing gaps:
- Did not evaluate multiple storms impacts
- Not reliable for a different beach bathymetry



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NC STATE UNIVERSITY

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Objectives

How do individual erosion events contribute to large-scale coastal hazards?

There are missing gaps in our understanding of:

- Morphodynamics of erosion and breaching on large-scale.
- Contributing factors to breaching on the barrier island.
- Contribution of erosion and beaching to flooding in nearby coastal communities.
- Response of nourished beaches to successive storm events

Objectives:

1. Evaluate beach and dune erosion and flooding over a barrier island
2. Evaluate breaching and flooding into a back lagoon
3. Evaluate nourishment performance for multiple storms

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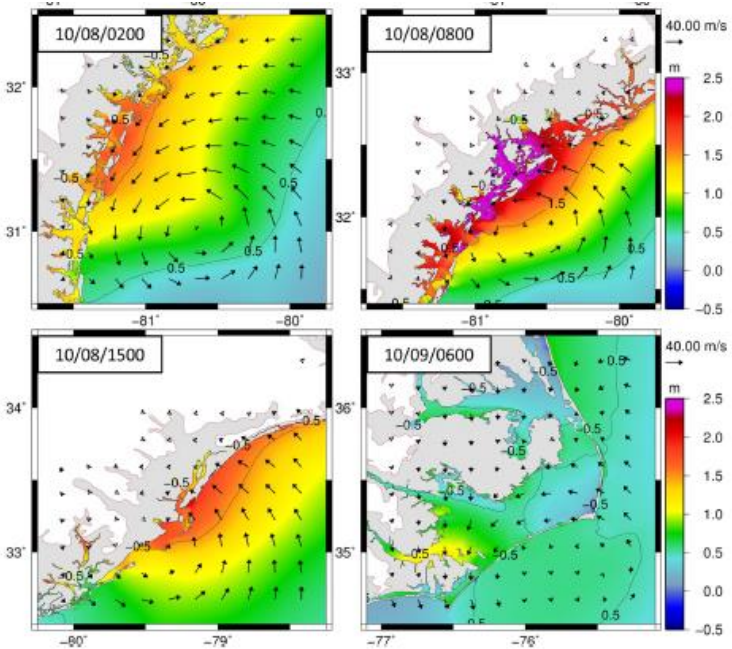
Objective #1

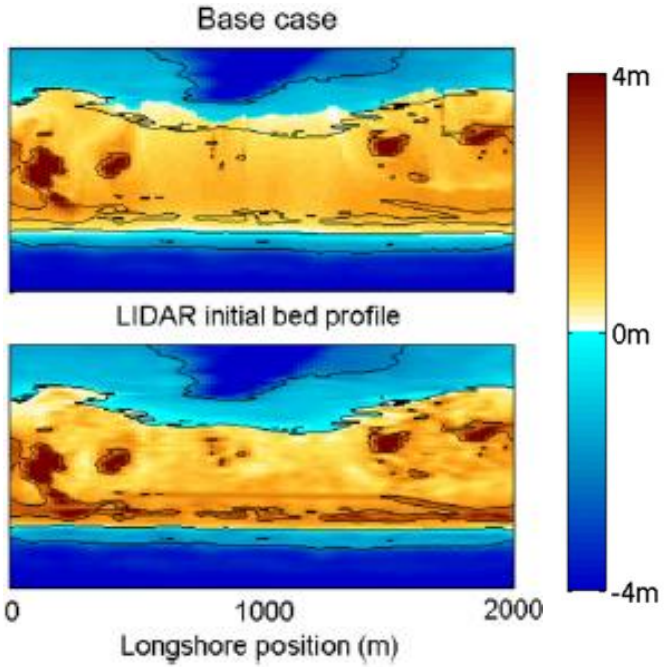
1. Evaluate beach and dune erosion and flooding over a barrier island

   - Model erosion and overwash on a large domain
   - Implement a loose coupling of deterministic models
   - Evaluate the improvement in flooding predictions

Modeling Tools



ADCIRC+SWAN

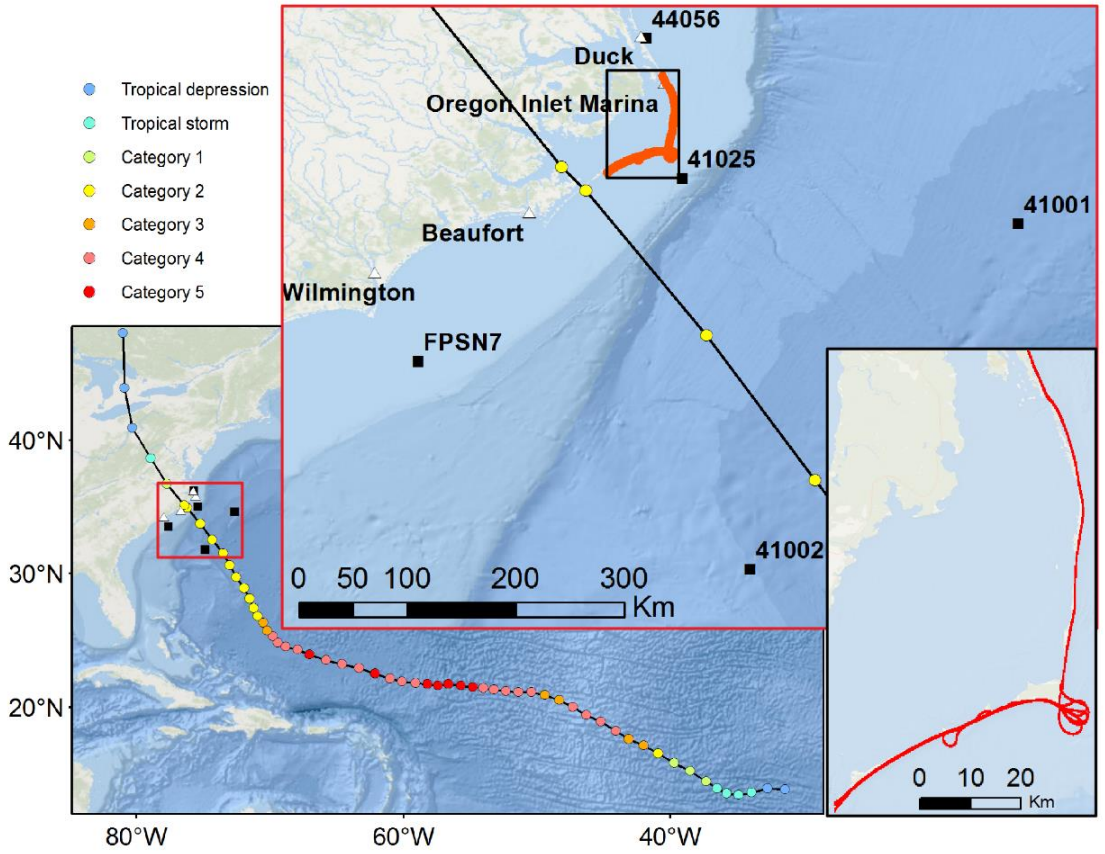


XBeach

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:

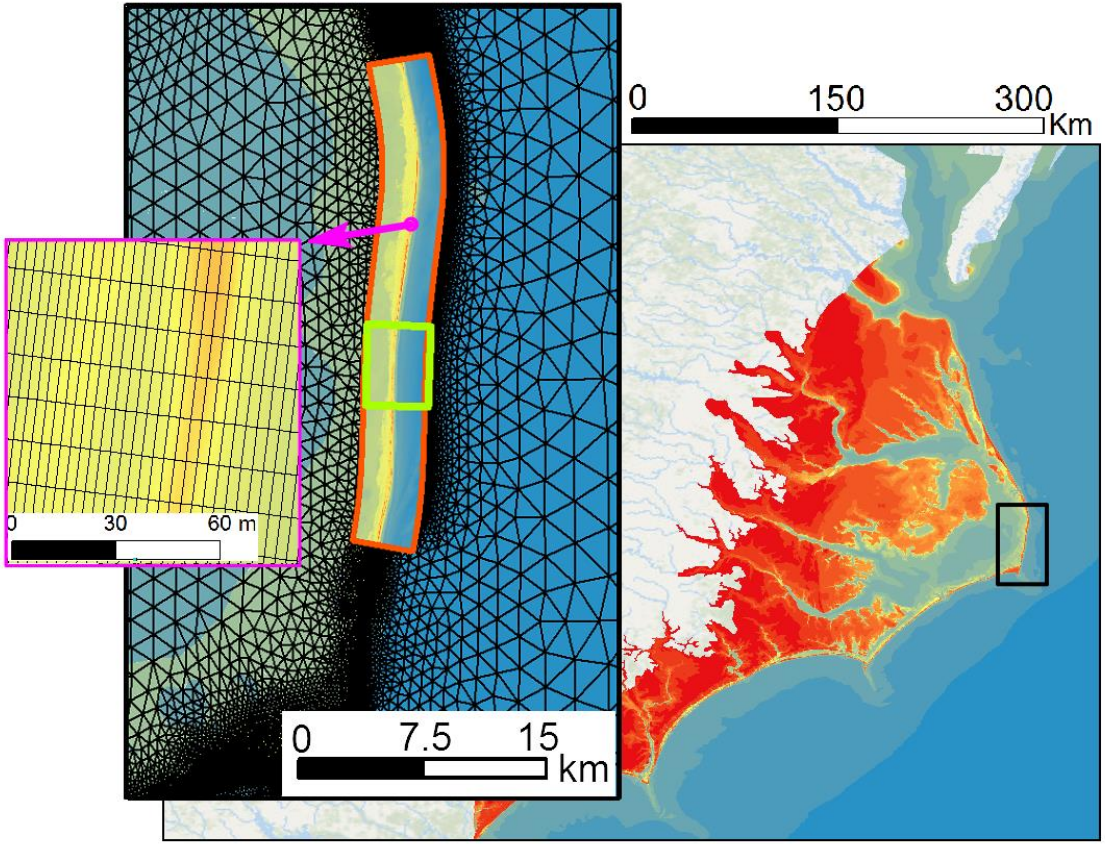
- 30 km domain
- Alongshore: 15 m
- Cross shore: 3-35 m

Topo/Bathy data:

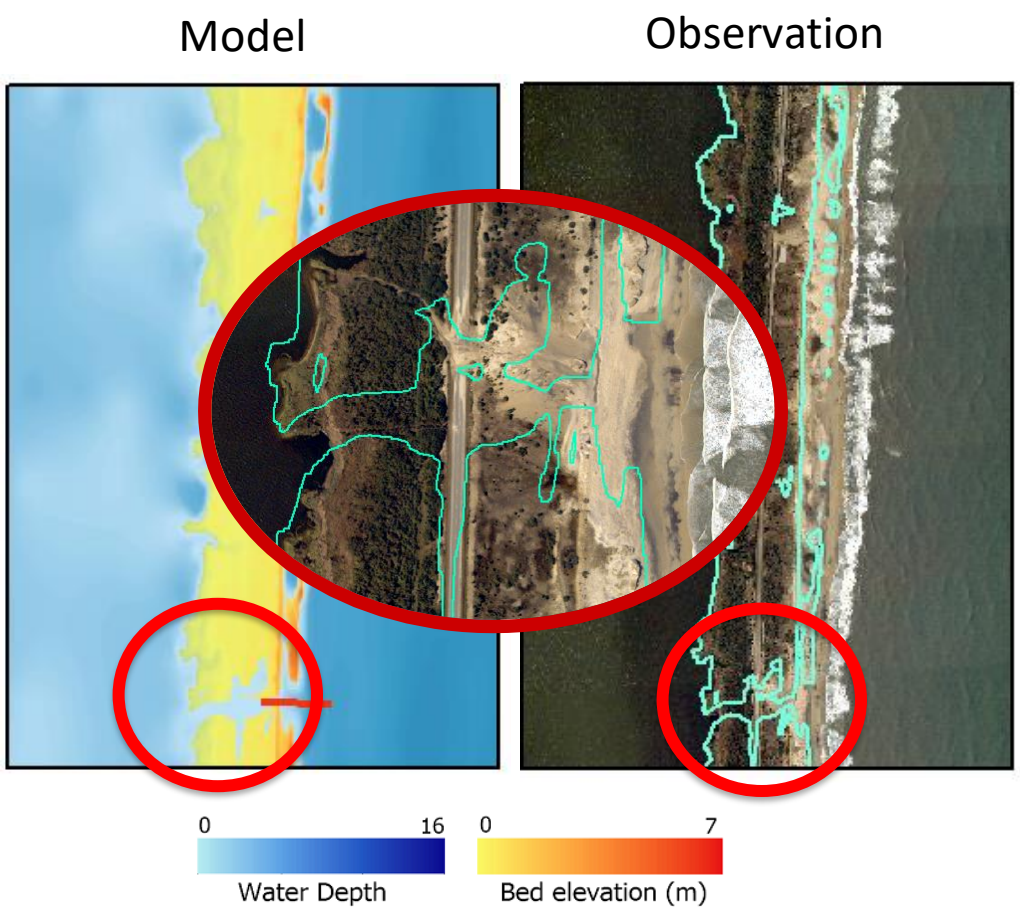
- Pre-storm LiDAR
- NC floodplain mapping DEM

Model setup:

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

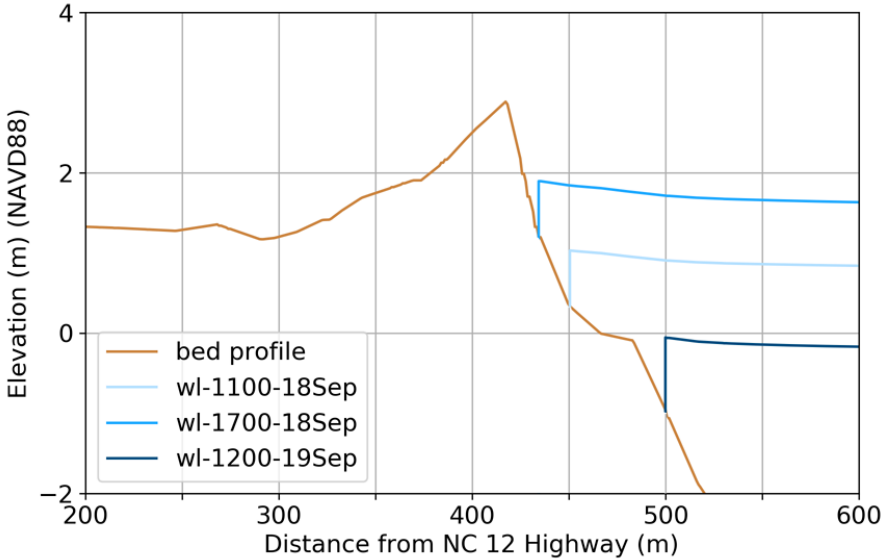


XBeach Prediction

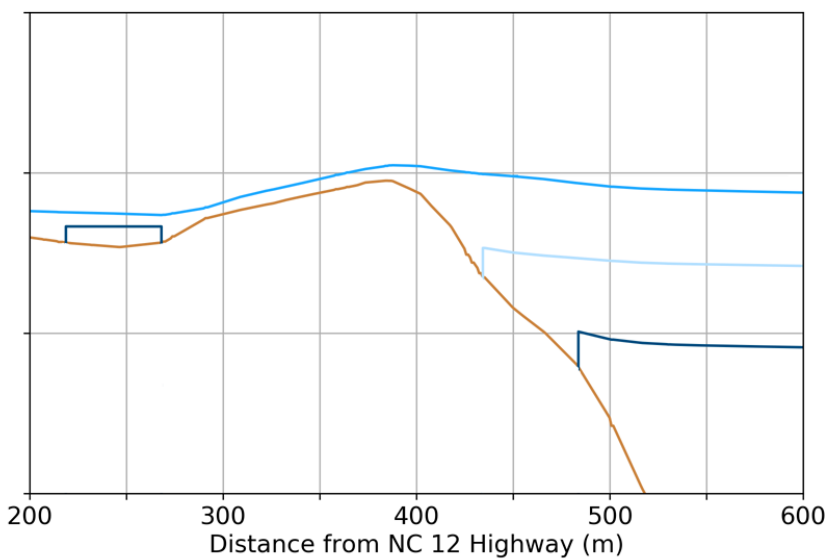


Loose Coupling

Pre-storm topo



XBeach prediction



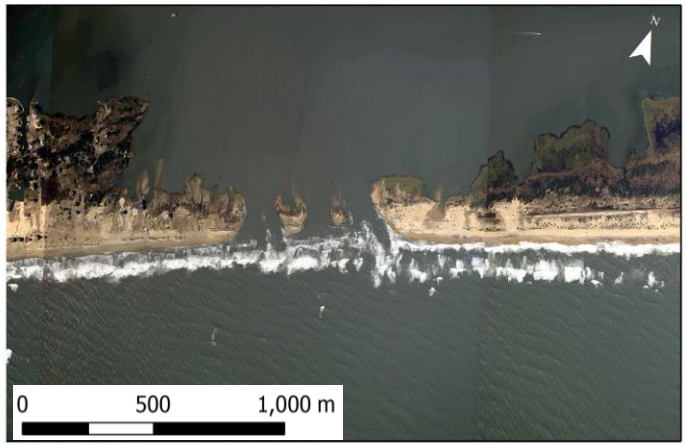
Objective #2

2. Evaluate breaching and flooding into a back lagoon

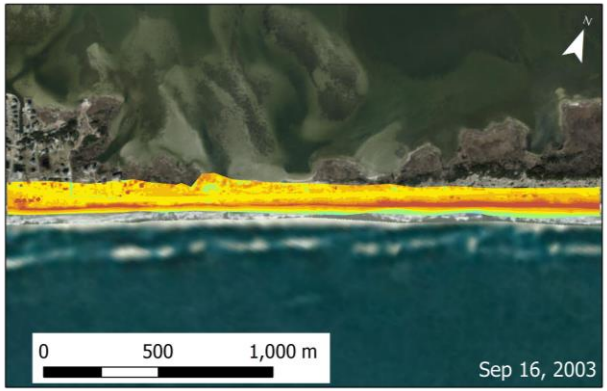
- Model breaching and channel formation
- Evaluate the parameters that cause breaching
- Implement a two-way coupling of deterministic models
- Evaluate the contribution of breaching to large-scale flooding

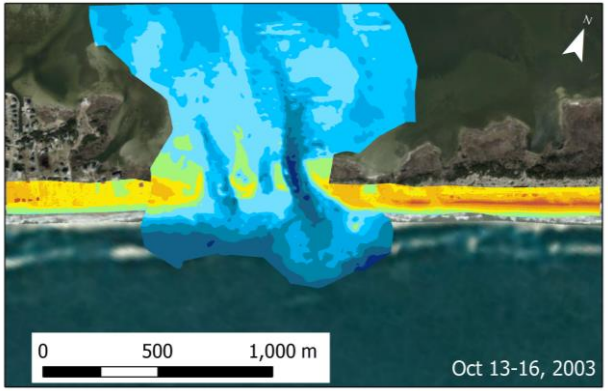
Isabel Inlet

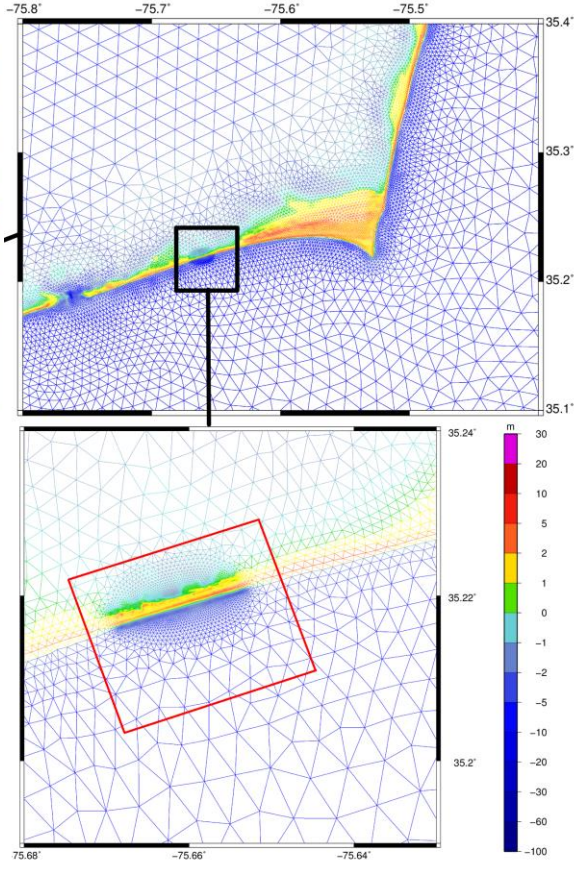
- Three channels
- Total width of 520 m
- Maximum depth of 6 m
- Closed by USACE

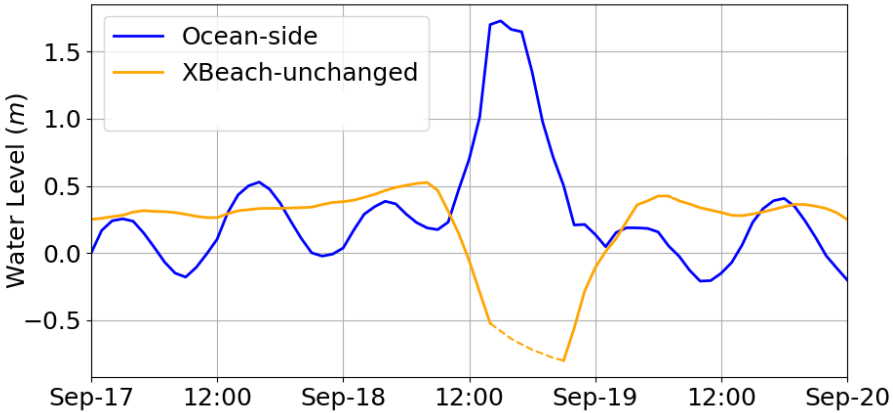


Observed Data

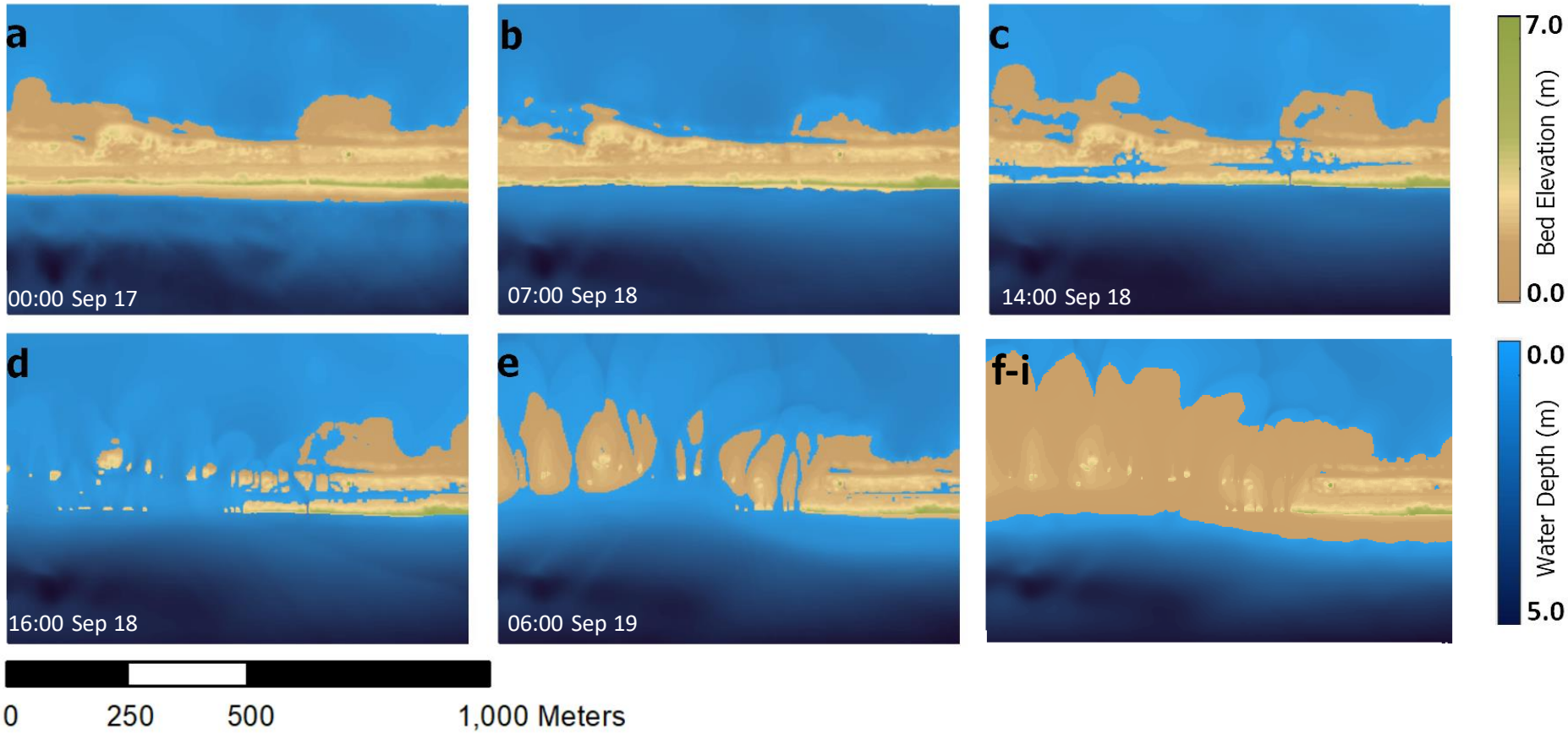




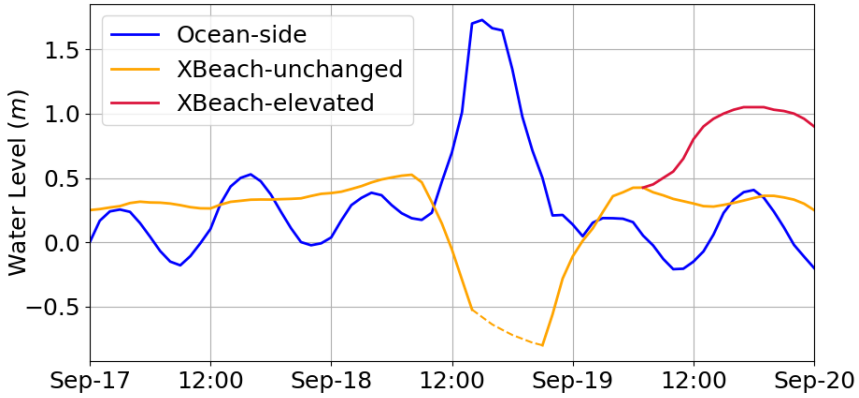


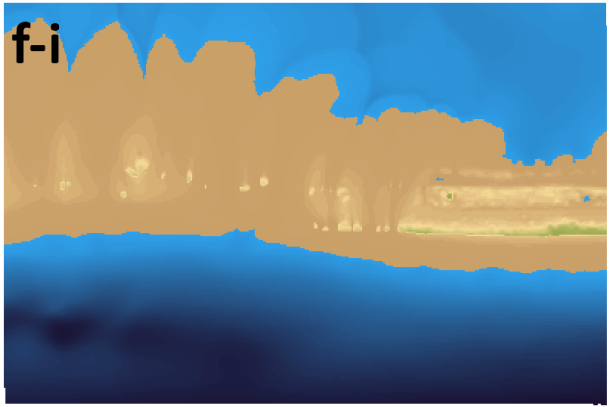


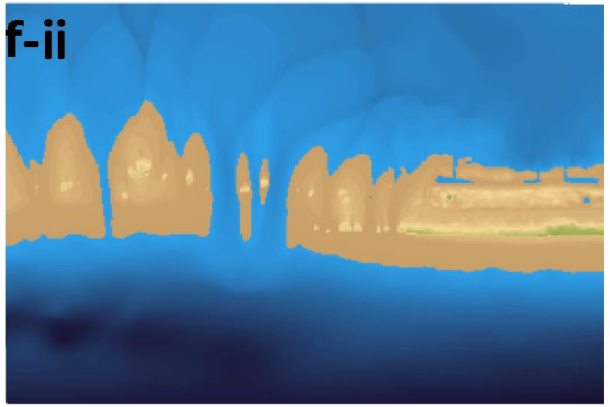
XBeach Results



XBeach Results





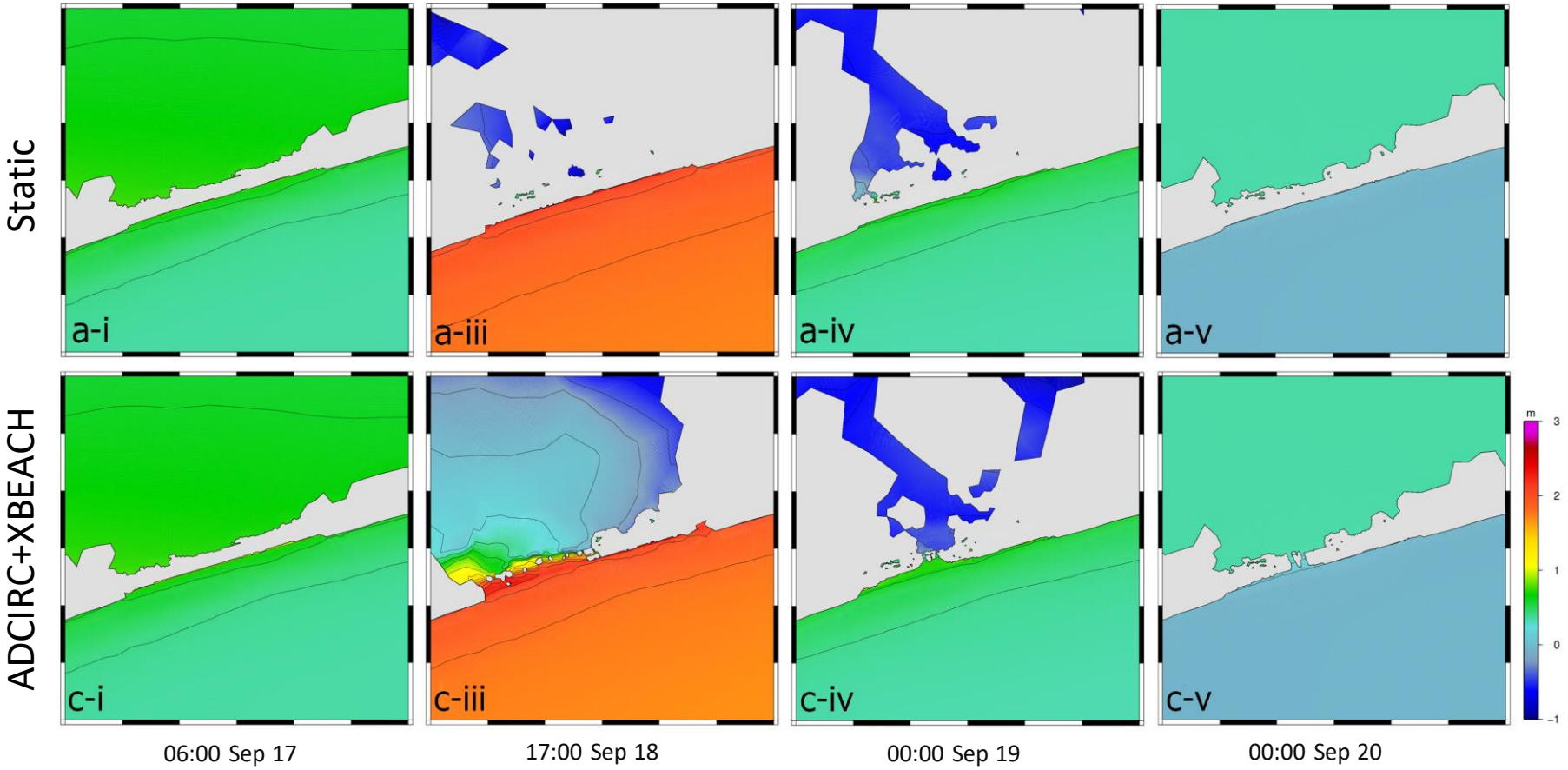


- XBeach is limited. Some processes are missing
- Sub-surface layers can change the results
- The water level has an important role

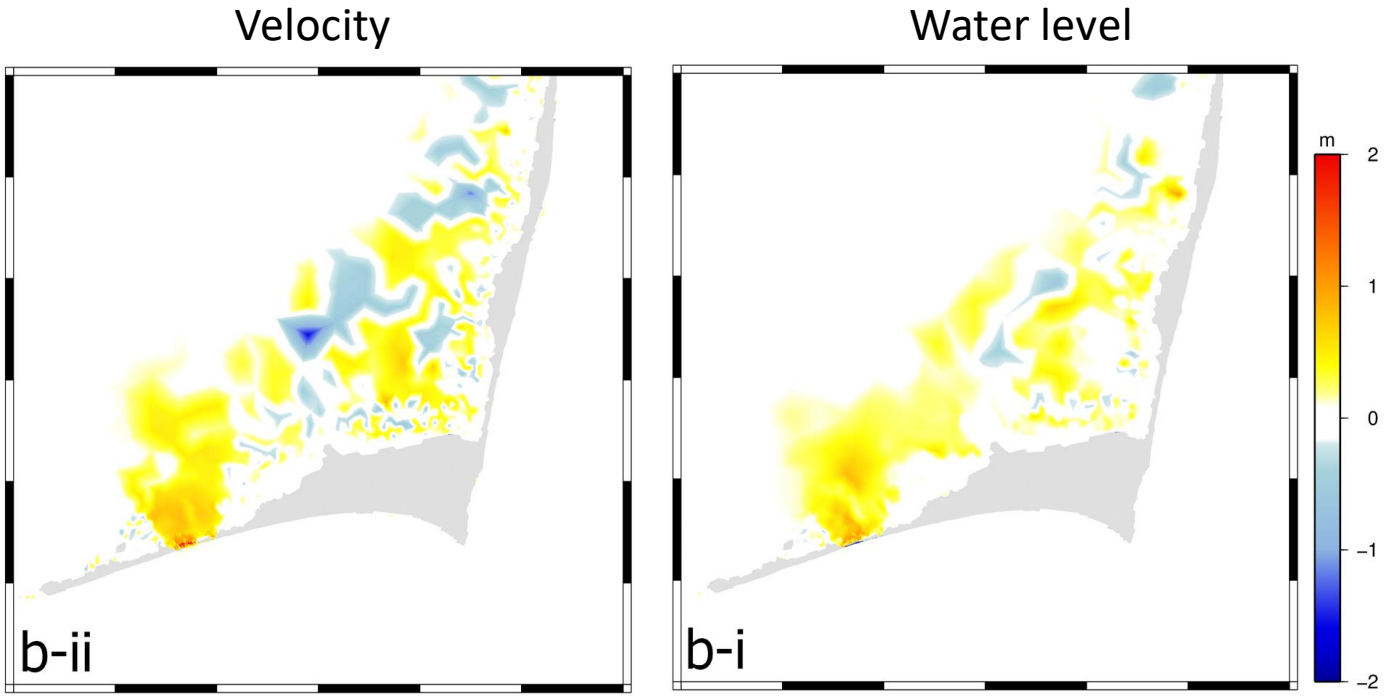
Elevation is updated using Time-Varying Bathymetry module in ADCIRC

1. Static (No change in bathymetry)
2. Dynamic (using XBeach results)
    - Update elevation from hourly outputs of XBeach

Coupling Results



Coupling Results



Conclusion

1. XBeach performance:

- Erosion and overwash predictions match the observation

2. Modeling Breaching:

- Flow from the sound to the ocean has an important role in deepening the breached channels
- XBeach does not include all the physics
- The information about sub-surface layers in the model can improve the results

3. Coupled models:

- Breaching of the barrier island has significant large-scale impacts on the hydrodynamics
- These impacts extend 10 – 13 km in the sound

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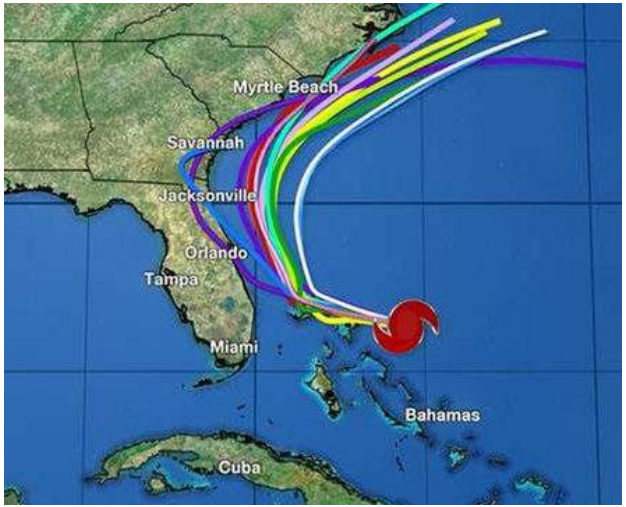
Objective #3

3. Evaluate nourishment performance for multiple storms

- Combine deterministic and probabilistic models to develop a surrogate model
- Include both the storm and bathymetry variation in the model training
- Model the erosion of a nourished beach due to multiple storms
- Quantify surrogate model errors and efficiency

Deterministic models:

- Computationally expensive
- Not suitable for a several storms
- Do not consider uncertainty in futuristic scenarios



Probabilistic models:

- Based on a database of predictions
- Consider a larger number of scenarios
- Improve the computational time

- Include the uncertainty in inputs
- Improve computational time for scenario-based predictions
- Previous studies did not include the variation in beach profiles.
- They only included the storm variables.

Our goal:

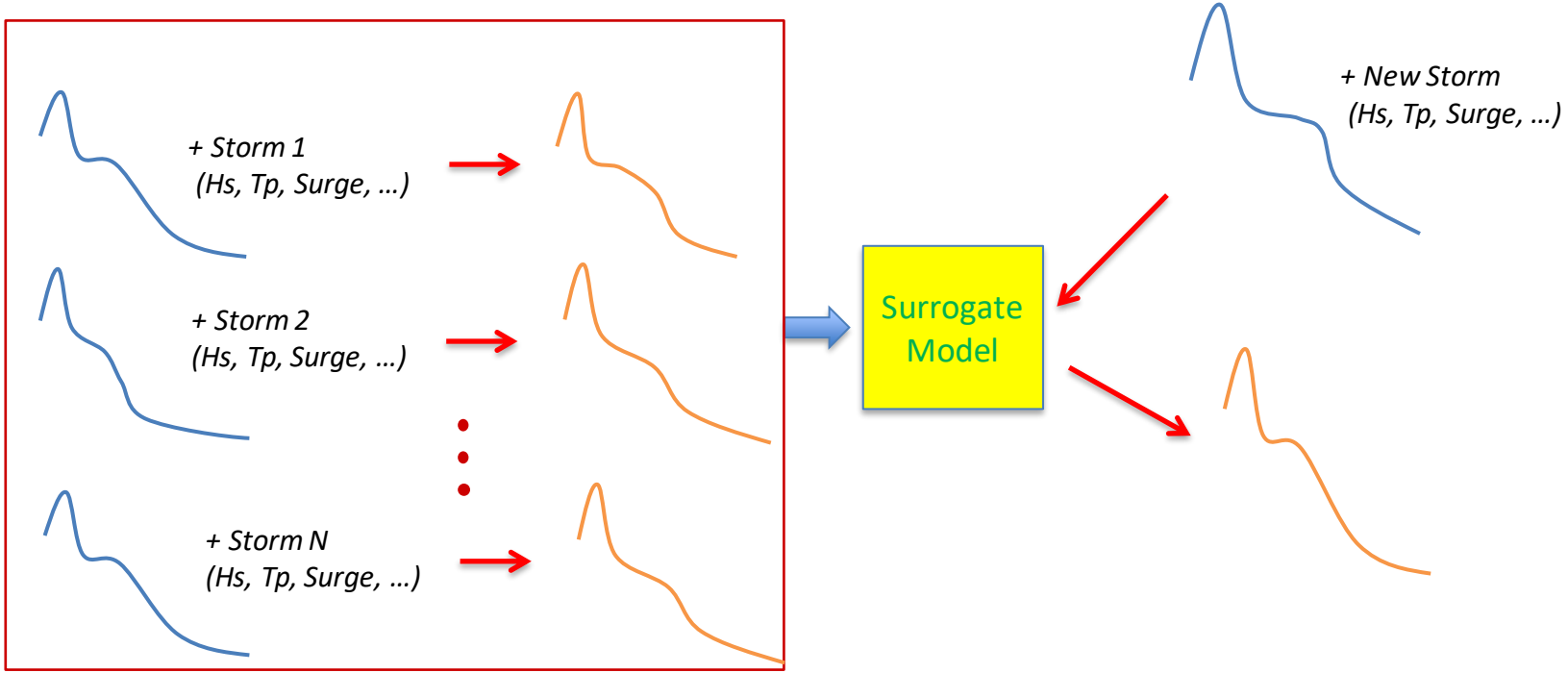
Not just a surrogate for storm parameters To beach/dune response parameters

But storm + initial beach/dune parameters To beach/dune response parameters

Surrogate model

Surrogate model:

Probabilistic model that learns how to predict like a deterministic model using machine learning tools

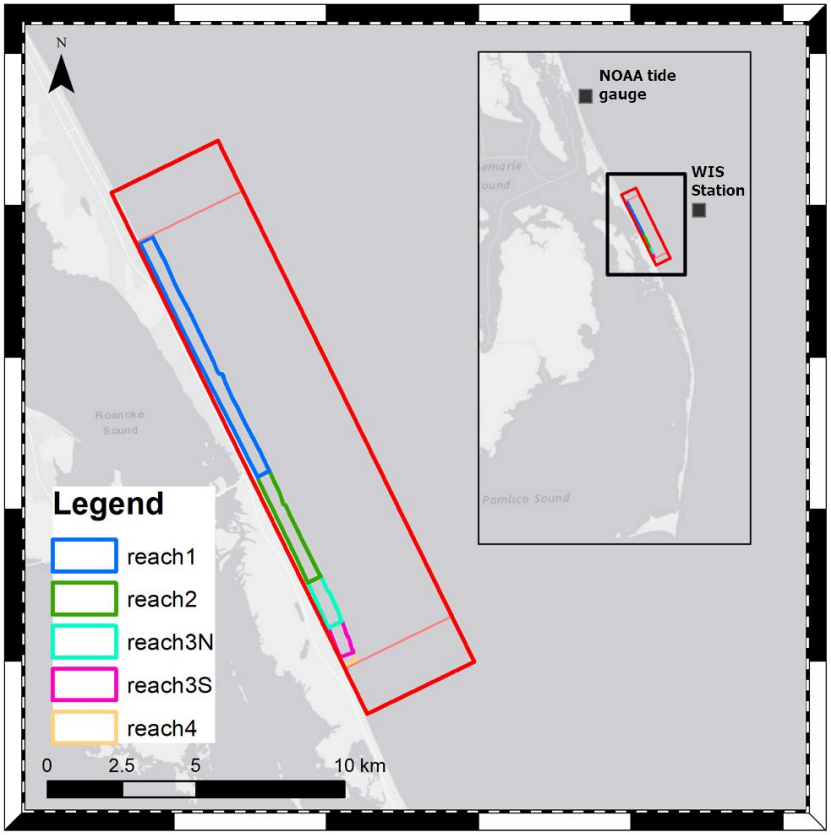


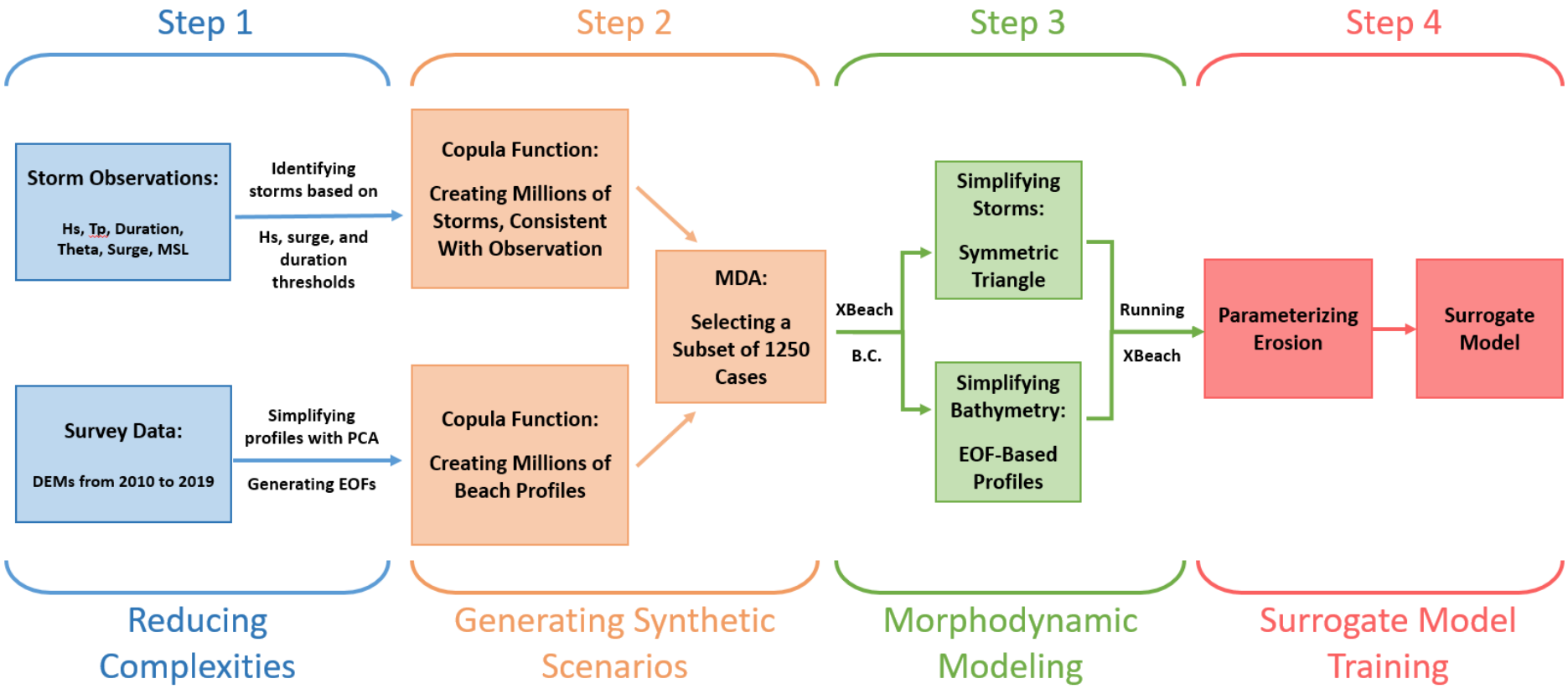
Study Area

More than 15 surveys between 2010 & 2019

Beach nourishment in 2011 & 2019

More than 40 years of storm observation data




Step 1
Step 2
Step 3
Step 4
Storm Observations:
Hs, Tp, Duration, Theta, Surge, MSL
Identifying storms based on
Hs, surge, and duration thresholds
Copula Function:
Creating Millions of Storms, Consistent With Observation
Survey Data:
DEMs from 2010 to 2019
Simplifying profiles with PCA
Generating EOFs
Copula Function:
Creating Millions of Beach Profiles
MDA:
Selecting a Subset of 1250 Cases
XBeach
B.C.
Simplifying Storms:
Symmetric Triangle
Simplifying Bathymetry:
EOF-Based Profiles
Running
XBeach
Parameterizing Erosion
Surrogate Model
Reducing Complexities
Generating Synthetic Scenarios
Morphodynamic Modeling
Surrogate Model Training

Step 1

Storm Observations:

Hs, Tp, Duration, Theta, Surge, MSL

Identifying storms based on

Hs, surge, and duration thresholds

Survey Data:

DEMs from 2010 to 2019

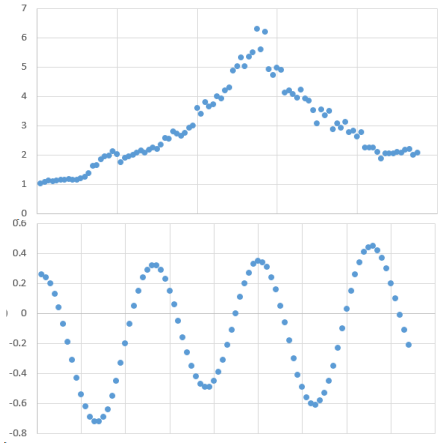
Simplifying profiles with PCA

Generating EOFs

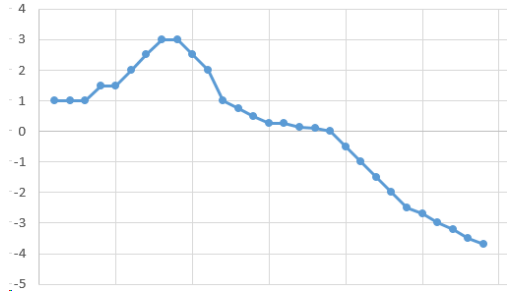
Reducing Complexities

Hs

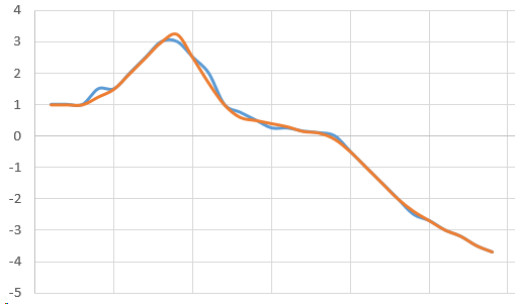
η



Hs, Tp, θ, η, duration



Principal Components



Step 1

Storm Observations:

Hs, Tp, Duration, Theta, Surge, MSL

Identifying storms based on

Hs, surge, and duration thresholds

Hs

η

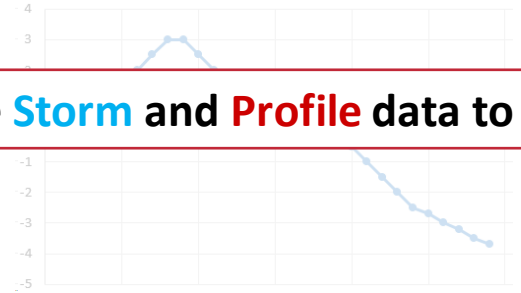
Hs, Tp, θ, η, duration

Survey Data:

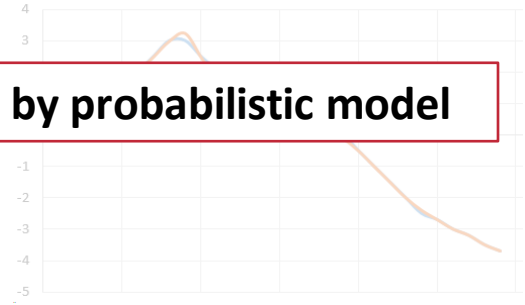
DEMs from 2010 to 2019

Simplifying profiles with PCA

Generating EOFs



Principal Components



Reducing Complexities

We parameterize Storm and Profile data to be used by probabilistic model

Step 2

Copula Function:

Creating Millions of Storms, Consistent With Observation

MDA:

Selecting a Subset of 1250 Cases

Copula Function:

Creating Millions of Beach Profiles

Generating Synthetic Scenarios

Hs	Tp	D	η	Dur
2.5	8.5	80	0.6	80
4.5	14	60	1.4	120
2.5	10	45	1.0	90
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800 observed storms

Hs	Tp	D	η	Dur
1.5	9.5	75	0.8	60
5.5	12	38	1.2	100
3.5	10	100	0.5	50
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1000000 synthetic storms

Hs	Tp	D	η	Dur
5.5	12	38	1.2	100
3.5	10	100	0.5	50
2.0	11	30	1.0	95
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1250 most dissimilar storms

Step 2

Copula Function:

Creating Millions of Storms, Consistent With Observation

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Generating Synthetic Scenarios

Hs	Tp	D	η	Dur
2.5	8.5	80	0.6	80
4.5	14	60	1.4	120
2.5	10	45	1.0	90

800 observed storms

Hs	Tp	D	η	Dur
1.5	9.5	75	0.8	60
5.5	12	38	1.2	100
3.5	10	100	0.5	50

1000000 synthetic storms

Hs	Tp	D	η	Dur
5.5	12	38	1.2	100
3.5	10	100	0.5	50
2.0	11	30	1.0	95

1250 most dissimilar storms

Synthetic scenarios are representative of realistic storm and profile condition

Step 3

Simplifying Storms: Symmetric Triangle

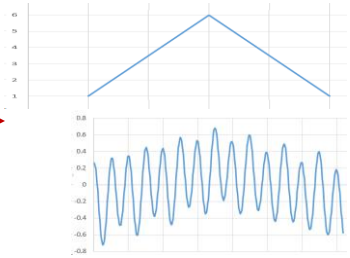
XBeach B.C.

Running XBeach

Simplifying Bathymetry: EOF-Based Profiles

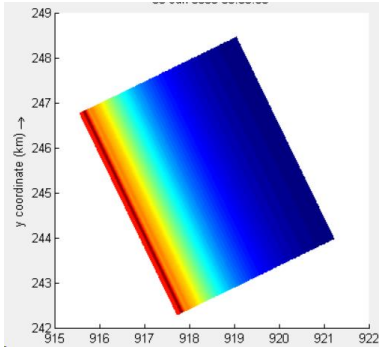
Morphodynamic Modeling

Hs, Tp, θ, η, duration, MSL →



Symmetric triangular

Principal componenet →



XBeach Model

Step 3

Hs, Tp, θ, η, duration, MSL

Symmetric triangular

XBeach Model

Simplifying Storms:

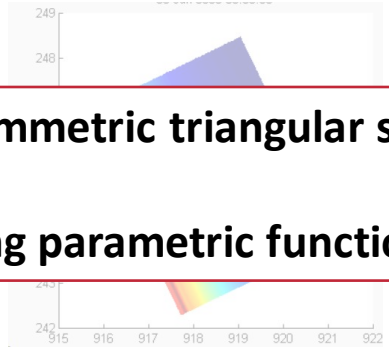
Symmetric Triangle

XBeach B.C.

Running XBeach

Simplifying Bathymetry:

EOF-Based Profiles



Morphodynamic Modeling

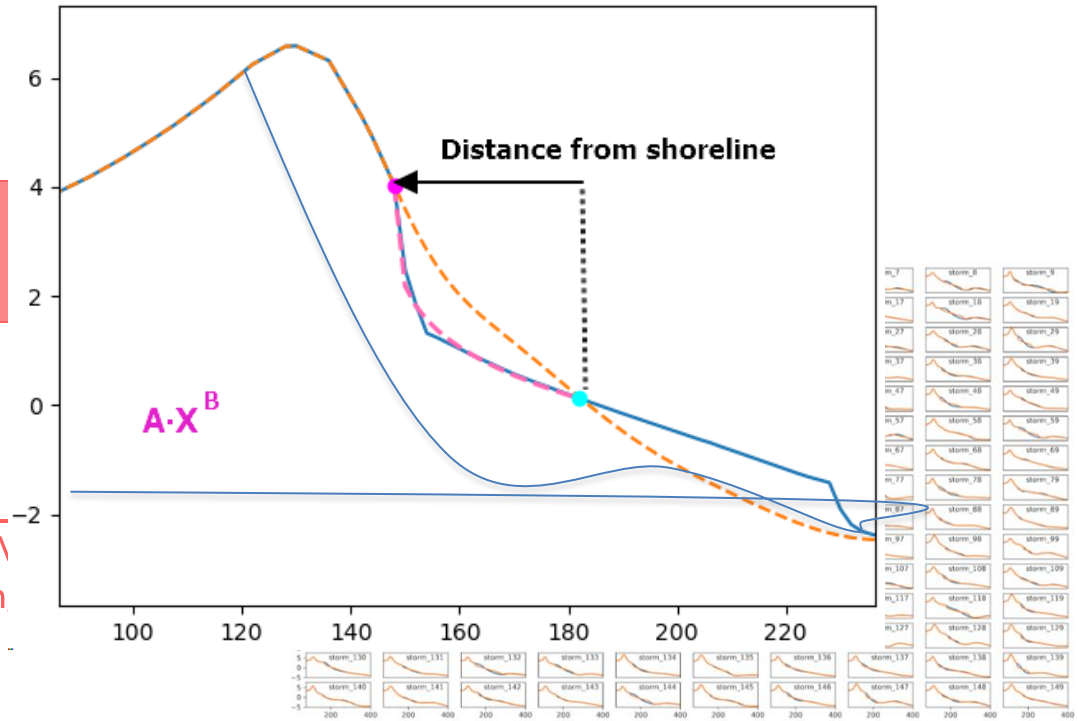
We simplify Storms using Symmetric triangular shape

We simplify bathymetry using parametric functions

Step 4

Parameterizing Erosion

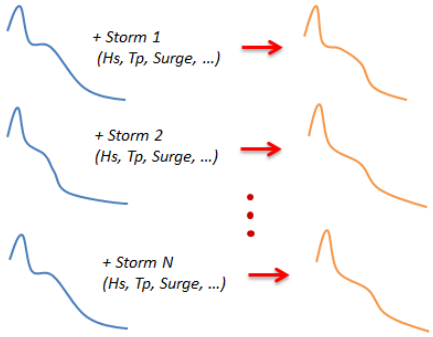
Surrogate M
Trainin

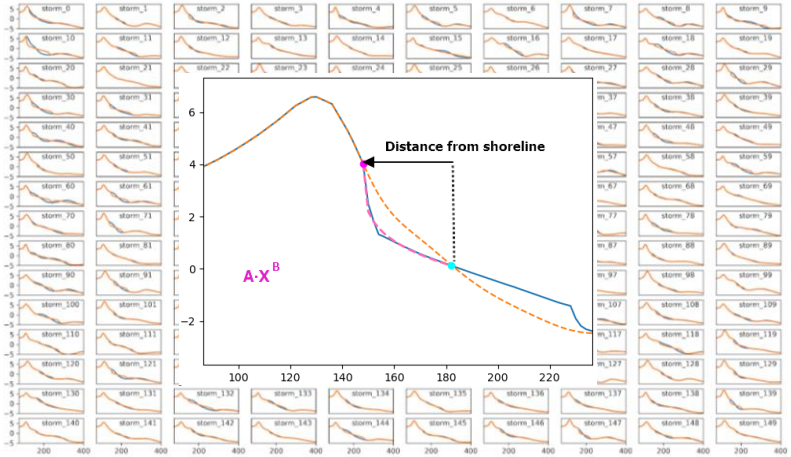


Step 4

Parameterizing Erosion → Surrogate Model

Surrogate Model Training



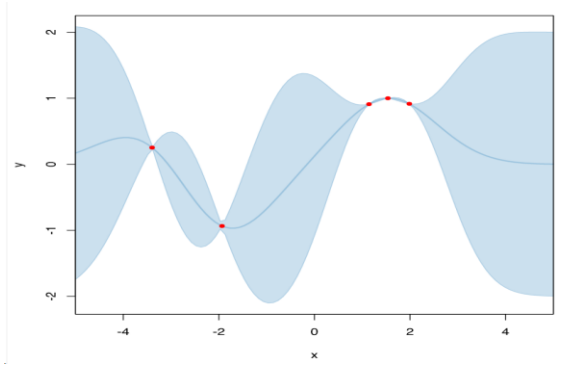


Step 4

Parameterizing Erosion → Surrogate Model

Surrogate Model Training

Parameterized Profile
Parameterized Storm
Parameterized Erosion



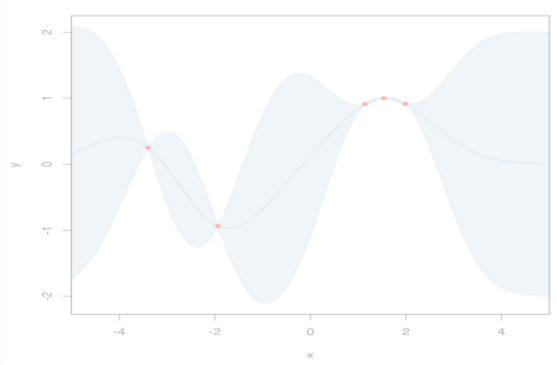
Gaussian Process Regression

Step 4

Parameterizing Erosion → Surrogate Model

Surrogate Model Training

Parameterized Profile
Parameterized Storm
Parameterized Erosion



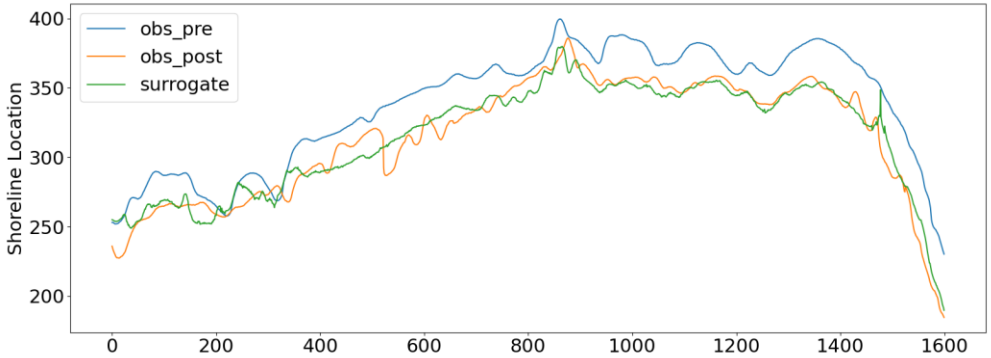
Gaussian Process Regression

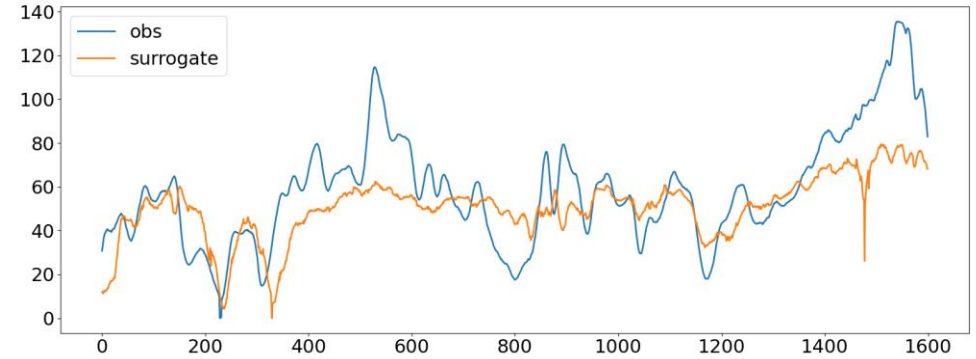
We used parameterized form of Profiles, Storms, and Erosion to train the Surrogate model

2019 Storms

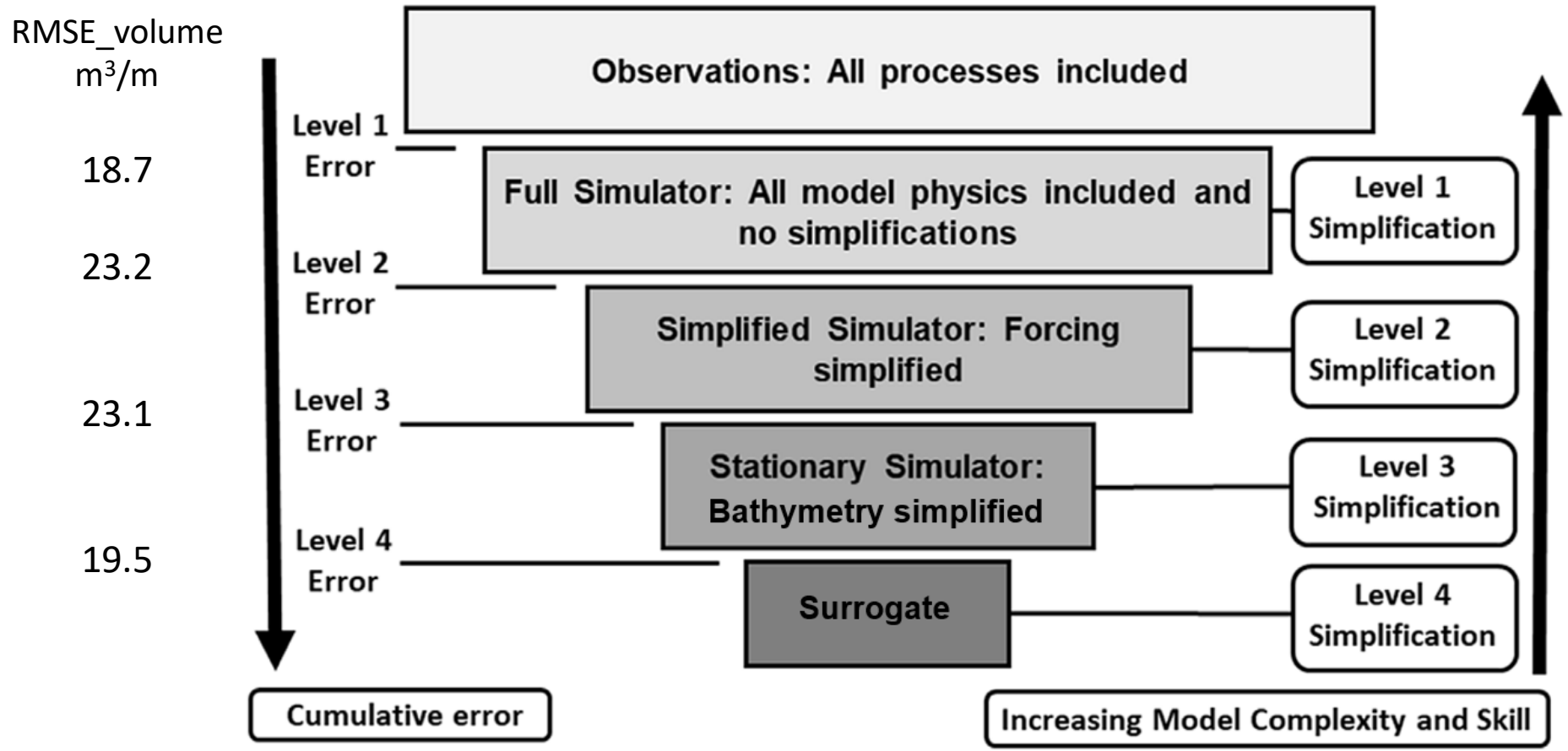
Application to realistic scenario:

- 4 storms in 2019
- Between August and November
- Predictions matches XBeach and Observation
- Under-predicted the erosion in the south
- Took only 20 seconds to run





Model Errors



Conclusion

1. Surrogate model development:

- The bathymetry variation was included, therefore the model can be used for any beach state
- The model can be used for studying multiple storm impacts

2. Accuracy:

- Predictions match the observation and the RMS error in erosion volume is 19.5 m^3/m
- The main portion of this error comes from XBeach model (18.7 m^3/m)
- The model under-estimates the erosion when significant erosion occur.

3. Efficiency:

- The model can produce results within a few seconds while it takes more than 40 hours for XBeach

Outline

- Introduction
- Motivation and Background
- Objectives
- Coupling Deterministic Models
- Developing Surrogate Model
- Summary and Conclusion

Summary

1. Evaluate beach and dune erosion and flooding over a barrier island
   - Successfully predicted the overwash and dune erosion on a very large domain
   - Loose coupling show improvement in the flooding prediction

2. Evaluate breaching and flooding into a back lagoon
   - Water level on the sound deepens the channels
   - XBeach need to include more physics to model the breach
   - Further model setup can improve the predictions
   - Two-way coupling showed that morphodynamics have significant large-scale impacts on flooding

3. Evaluate nourishment performance for multiple storms
   - Surrogate model is an efficient and accurate tool to predict multiple storm impacts on the nourished beaches
   - Including the bathymetry variation allows the model to be applied to any beach state
   - The main errors in the model derive from deterministic predictions
   - The scarp parameterization needs further improvement to capture extensive erosion

Future work

Erosion and breaching:

- Recalibrating XBeach
- Adding more physics to the model
- Adding land-cover, vegetation, sub-surface layers

Surrogate model:

- Reduce the number of scenarios
- Rework the scarp parameterization
- Recalibrating XBeach model


THANK YOU