Hurricane Wave and Storm Surge Forecasting for the North Carolina Coast

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Johnson C Smith University
Charlotte NC, 31 March 2017

COASTAL RESILIENCE CENTER
A U.S. Department of Homeland Security Center of Excellence

Sea Grant
North Carolina

Introduction
- About Me
- Hurricane Season 2005

Predictive Modeling of Coastal Flooding
- Wide Range of Spatial Scales
- Models for Hurricane Waves and Storm Surge
- Engineering Applications

Analyses of Hurricane Matthew (2016)
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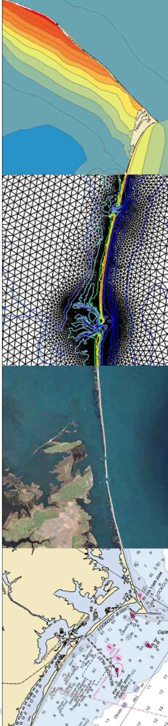
Considering Erosion of Beaches and Dunes
- Exploring Morphodynamics during Isabel (2003)
- Initial Results with XBeach

Summary and Future Work



About Me

North Carolina State University

- Civil, Construction, and Environmental Engineering
  - Assistant Professor: 08/2013 to present

CCEE Department, Mann Hall, NCSU

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  - 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

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  - Undergraduate Researcher: 06/1999 to 05/2004

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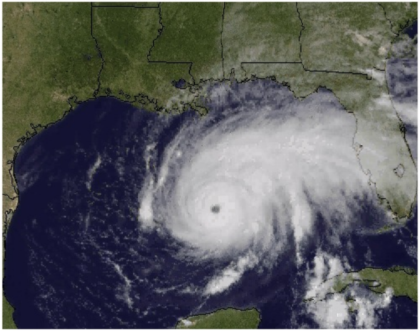
Hurricane Season 2005

Impacts on Southern Louisiana

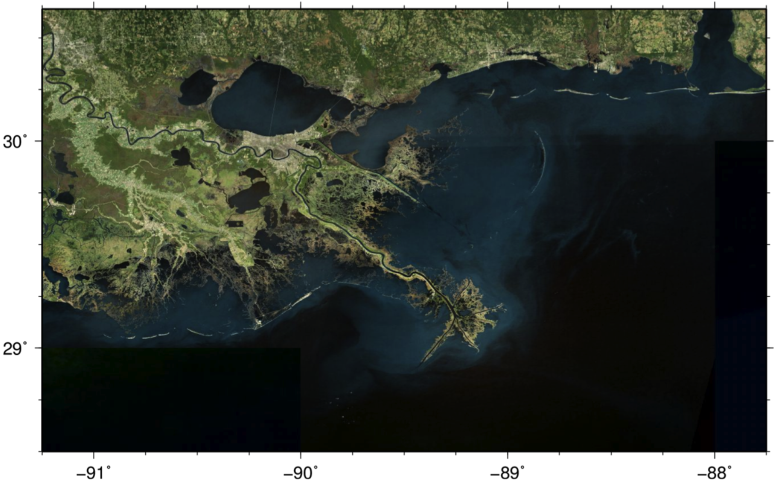
Katrina: 08/28 - 08/29

Rita: 09/22 - 09/24



Hurricane Season 2005

Flooding of New Orleans

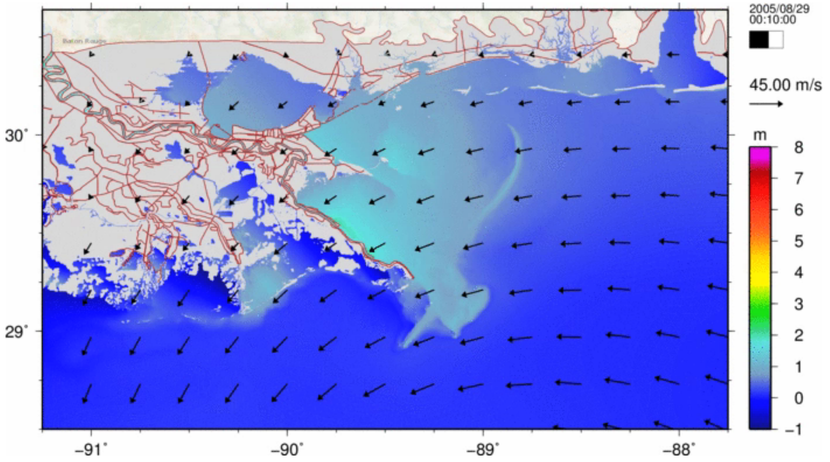


Hurricane Season 2005

Flooding of New Orleans

Hurricane Season 2005

Katrina (2005) on 29 August



S Bunya, JC Dietrich, *et al.* (2010). A High-Resolution Coupled Riverine Flow, Tide, Wind, Wind Wave and Storm Surge Model for Southern Louisiana and Mississippi: Part I – Model Development and Validation. *Monthly Weather Review*, 138(2), 345-377.

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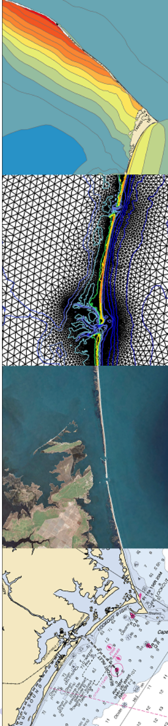
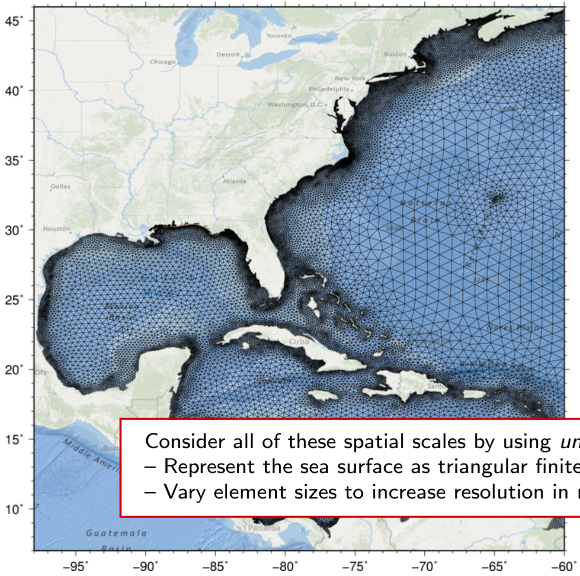


Wide Range of Spatial Scales

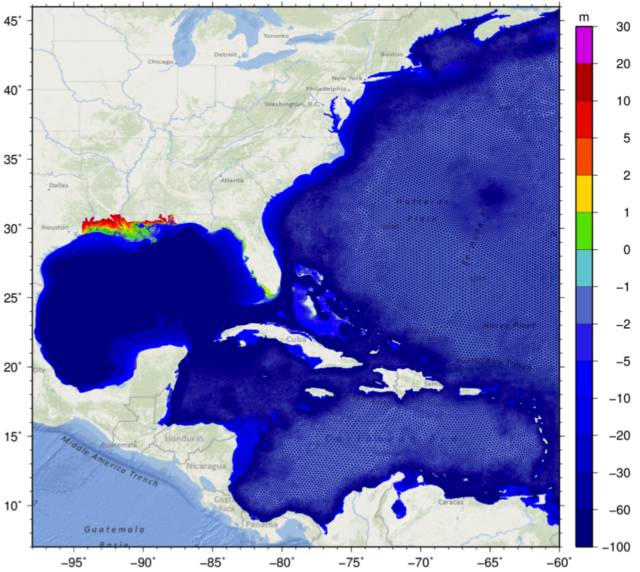
Unstructured, Finite-Element Meshes



Consider all of these spatial scales by using *unstructured meshes*:
– Represent the sea surface as triangular finite elements
– Vary element sizes to increase resolution in regions of interest

Wide Range of Spatial Scales

SL16 Mesh for Southern Louisiana



Wide Range of Spatial Scales

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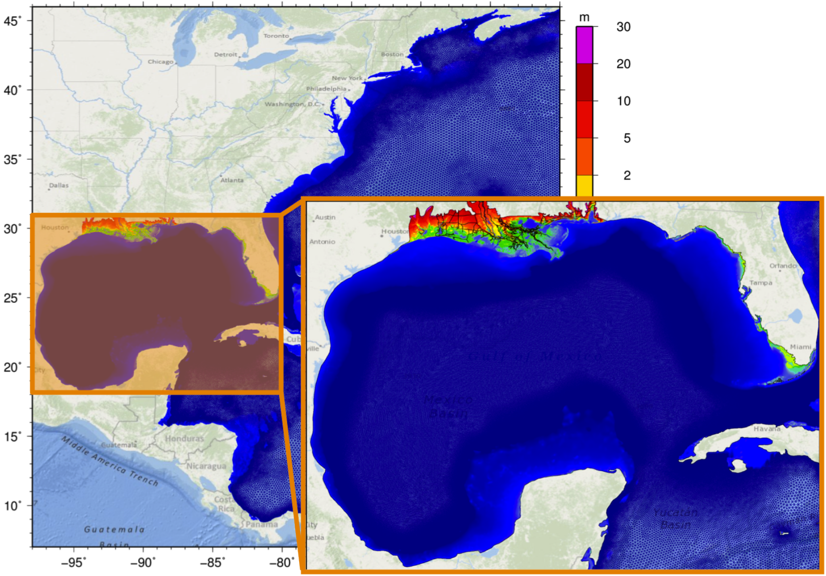

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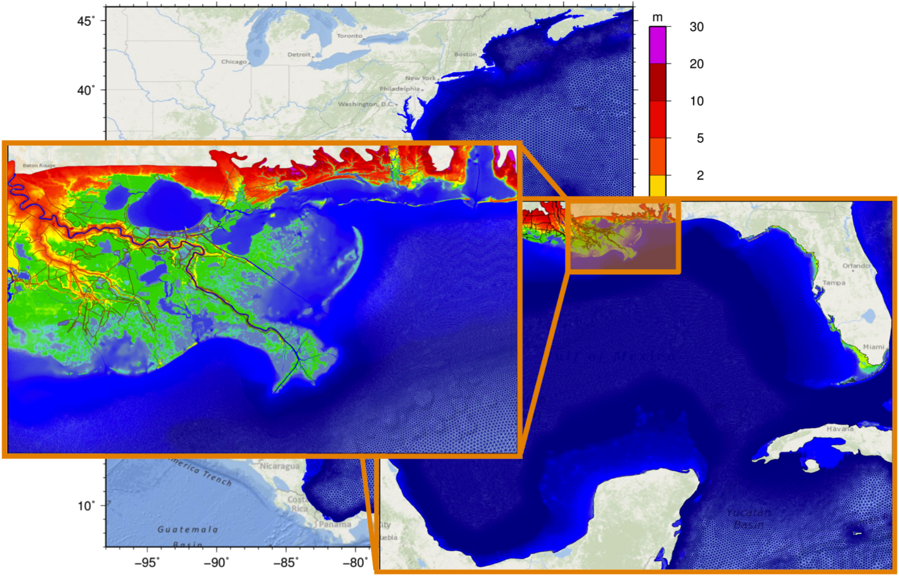

Wide Range of Spatial Scales

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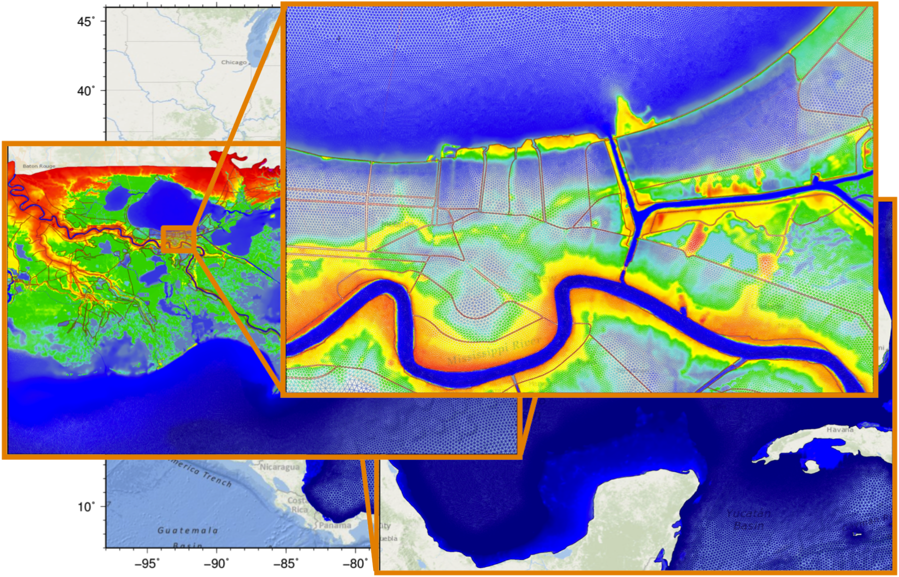
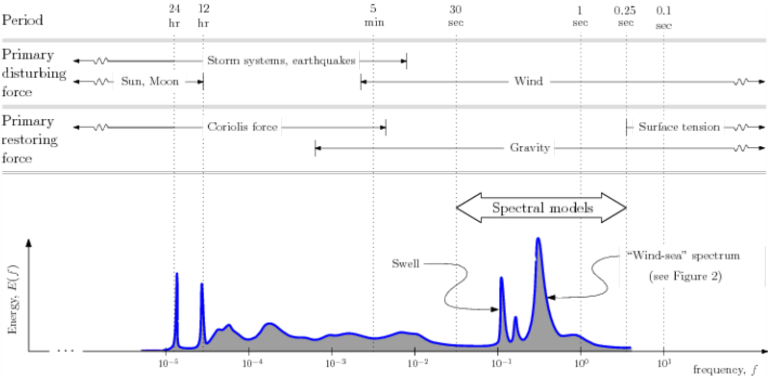


Models for Hurricane Waves and Storm Surge

Temporal Scales

Sea surface can be described with both *long* and *short* waves

- Long waves due to tides, storm surge
- Short waves due to wind (swell and wind-sea)



For short waves, we use SWAN

- Does not represent the phase of each individual wave
    - Conserved quantity is the action density $N(t, x, y, \sigma, \theta)$
    - Can be integrated to compute statistical wave properties

Solves the action balance equation:

$$\frac{\partial N}{\partial t} + \nabla_{\mathbf{x}} \cdot \left[(\mathbf{c}_g + \mathbf{U}) N \right] + \frac{\partial c_\theta N}{\partial \theta} + \frac{\partial c_\sigma N}{\partial \sigma} = 0$$

Solution methods in geographic (x, y) and spectral (σ, θ) spaces:

- Gauss-Seidel in geographic space
- Iterative solution of matrix system in spectral space

For long waves, we use ADCIRC

- Does represent the phases of tides and/or storm surge

Solves the generalized wave continuity equation for water levels ζ:

$$\frac{\partial^2 \zeta}{\partial t^2} + \tau_0 \frac{\partial \zeta}{\partial t} + \frac{\partial \tilde{J}_x}{\partial x} + \frac{\partial \tilde{J}_y}{\partial y} - UH \frac{\partial \tau_0}{\partial x} - VH \frac{\partial \tau_0}{\partial y} = 0$$

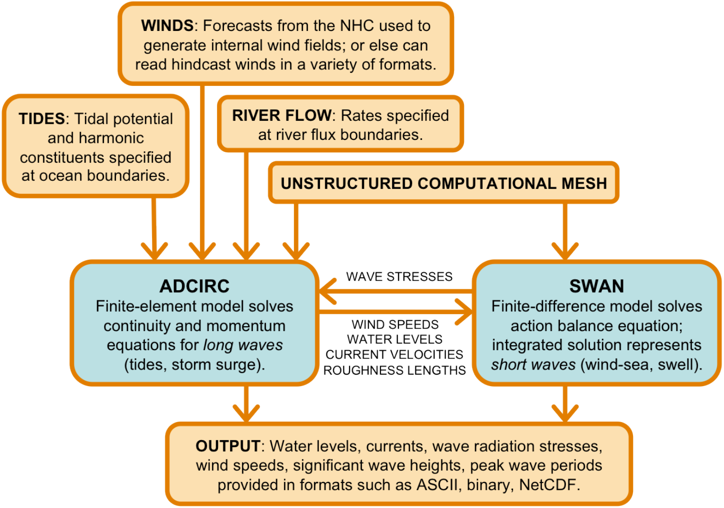
Solves the depth-averaged momentum equations for currents (U, V):

$$\frac{DU}{Dt} - fV = -g \frac{\partial}{\partial x} \left[\zeta + \frac{p_s}{g \rho_0} - \alpha \eta \right] + \frac{\tau_{sx} + \tau_{bx}}{\rho_0 H} + \frac{M_x - D_x}{H}$$

$$\frac{DV}{Dt} + fU = -g \frac{\partial}{\partial y} \left[\zeta + \frac{p_s}{g \rho_0} - \alpha \eta \right] + \frac{\tau_{sy} + \tau_{by}}{\rho_0 H} + \frac{M_y - D_y}{H}$$

Models for Hurricane Waves and Storm Surge

Tight Coupling of SWAN+ADCIRC



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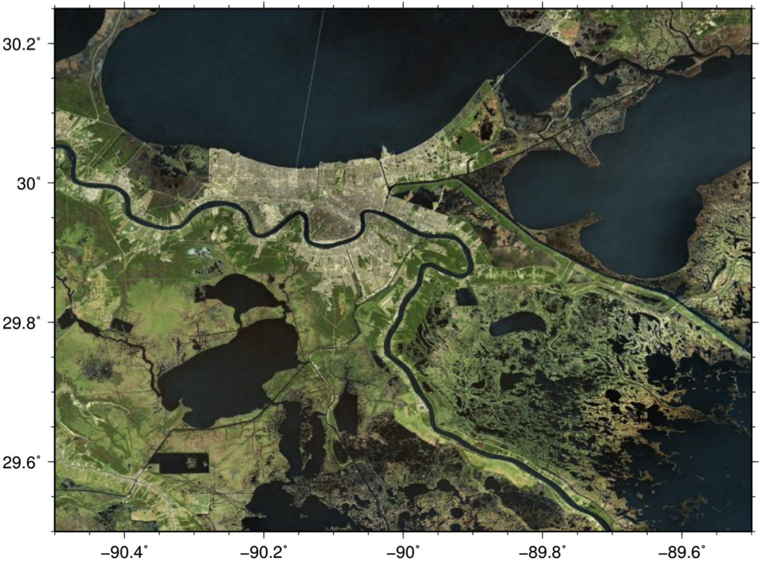
Engineering Applications
Surge Barrier Design with the USACE



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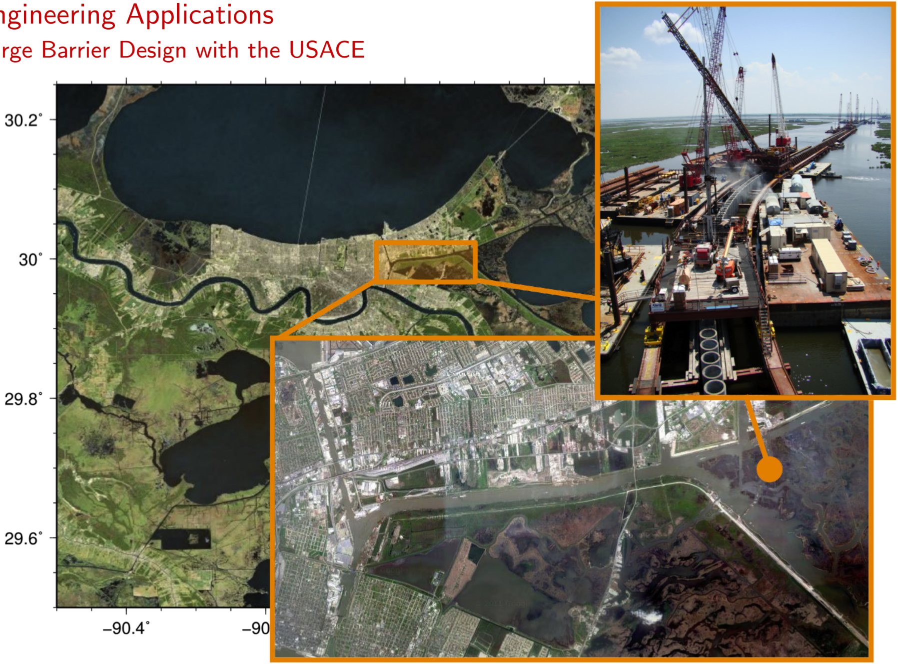

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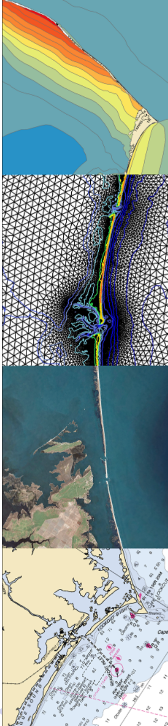


SWAN+ADCIRC can be employed in real-time via the ASGS

- **Everything happens automatically**
  - Models are initialized, run and processed by Perl scripts

Wind fields from two sources:

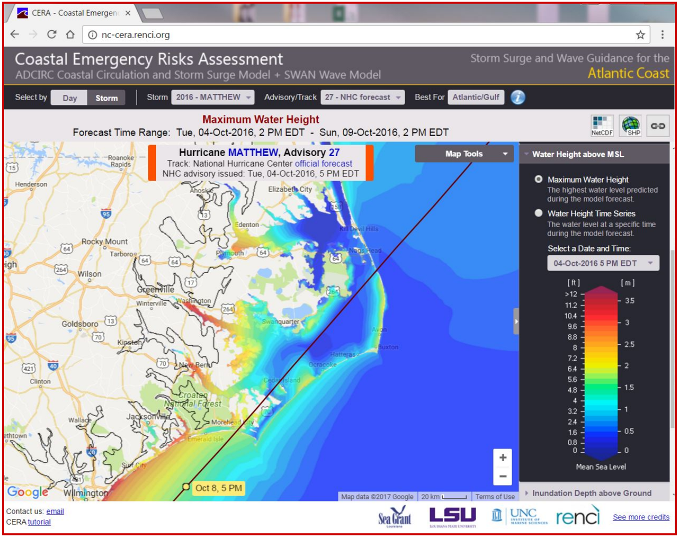
1. Under normal conditions:
   - Downloaded from NAM model output by NOAA/NCEP
   - Converted into format compatible with SWAN+ADCIRC
2. Under hurricane conditions:
   - Download advisories from NOAA/NHC
   - Generate wind field using parametric model (Holland, 1980)

Guidance can be shared in multiple formats:

- Raster images (JPG, PNG, etc.)
- Geo-referenced raster images (Google Earth, GIS)
- Web service (`nc-cera.renci.org`)

Real-Time Forecasting during Hurricane Matthew

Coastal Emergency Risks Assessment (CERA): `nc-cera.renci.org`



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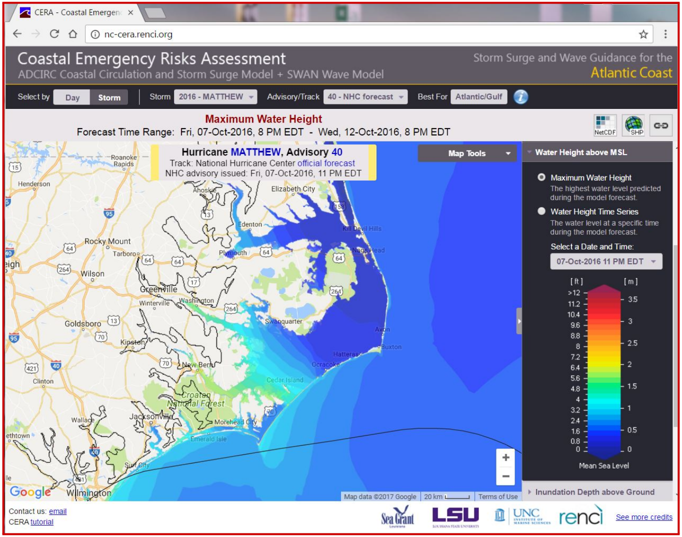
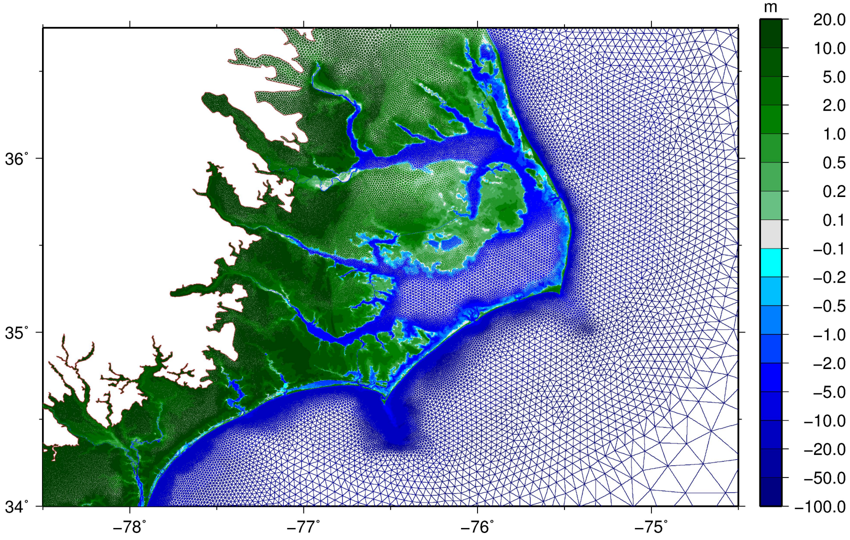
Coastal Emergency Risks Assessment (CERA): `nc-cera.renci.org`



Real-Time Forecasting during Hurricane Matthew

High-Resolution Mesh for North Carolina – NC9



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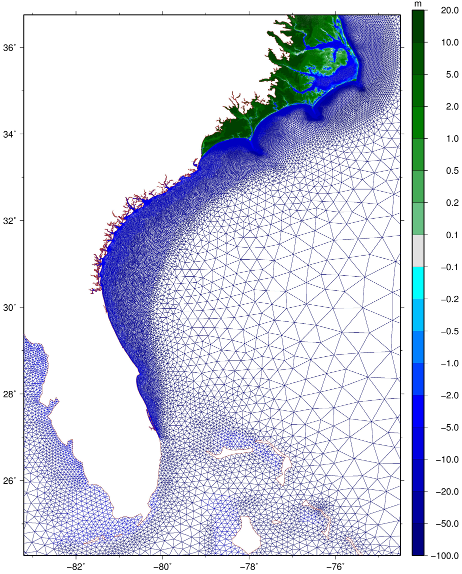
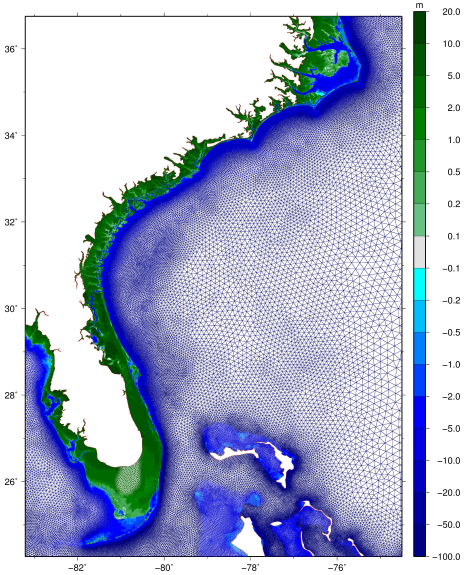


Real-Time Forecasting during Hurricane Matthew

Large-Domain Mesh for the U.S. Gulf and Atlantic Coasts – HSOFS



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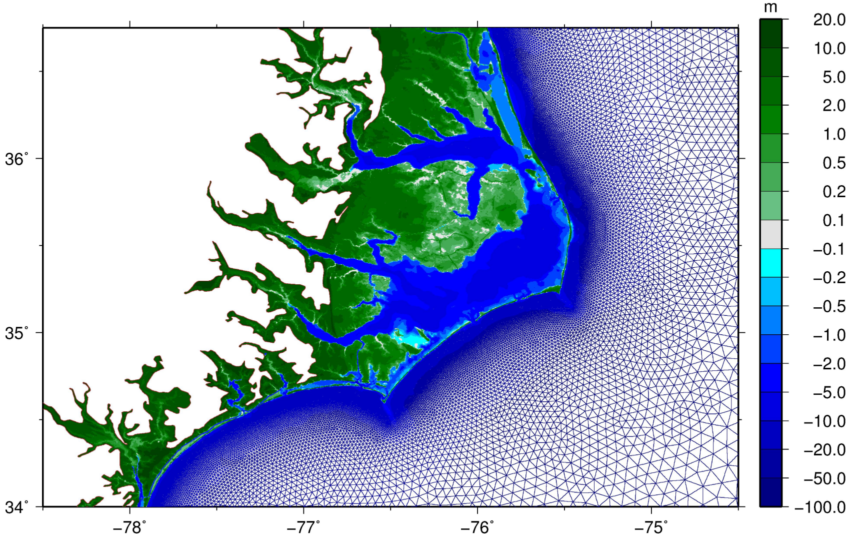
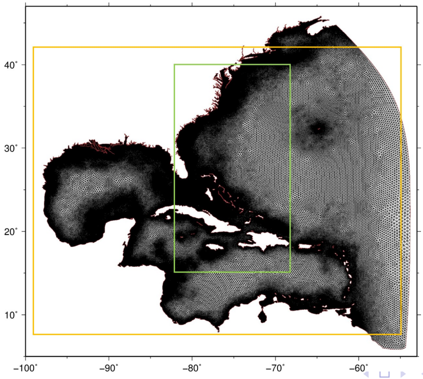
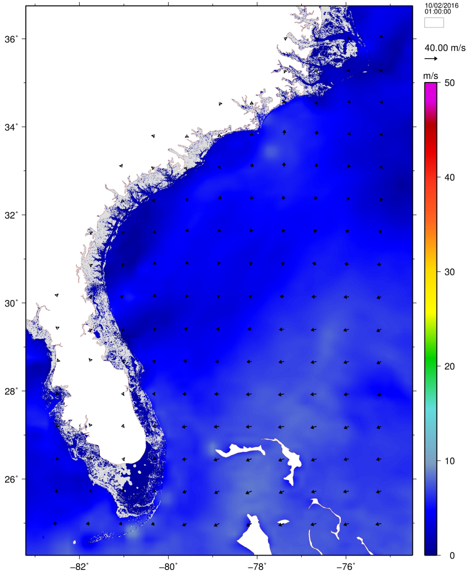


- Highly-accurate fields for surface pressures and wind velocities from Ocean Weather Inc. (OWI)
- Fields provided on multiple grids:
  - Basin: Gulf and western Atlantic, resolution of 0.25°
  - Regional: US east coast to Virginia, resolution of 0.05°



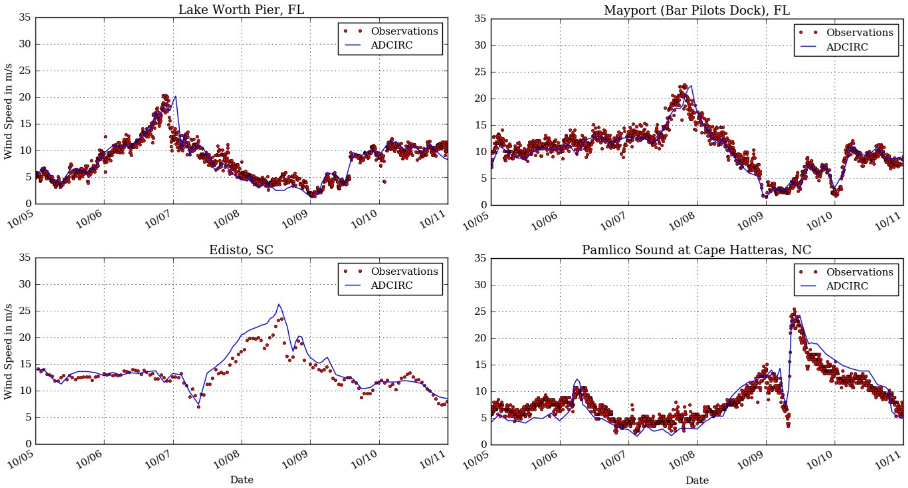
Best-Possible Hindcast of Hurricane Matthew

Evolution of Winds Along US East Coast – HSOFS



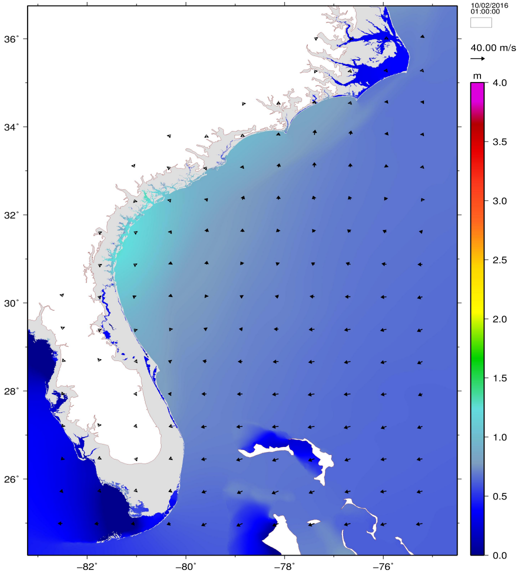
Best-Possible Hindcast of Hurricane Matthew

Wind Speed Comparison from South to North



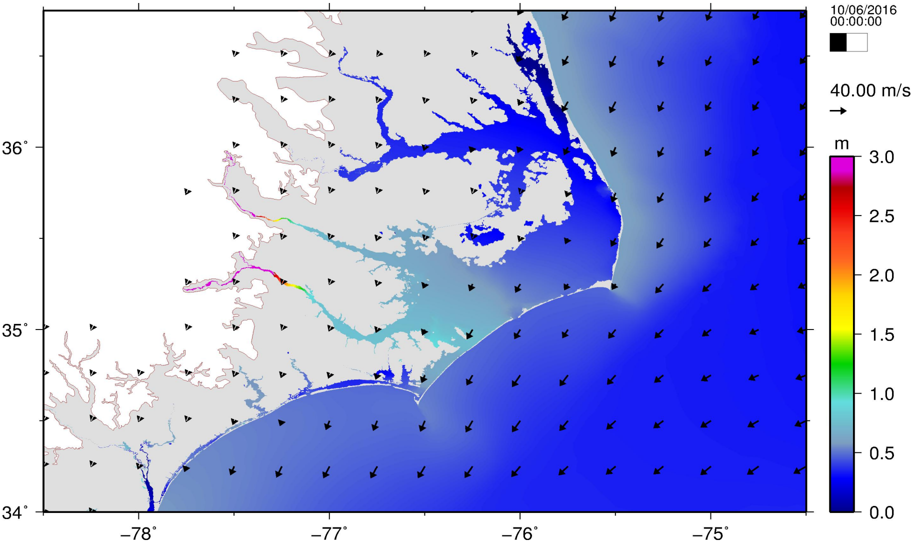
Best-Possible Hindcast of Hurricane Matthew

Evolution of Water Levels Along the US East Coast – HSOFS



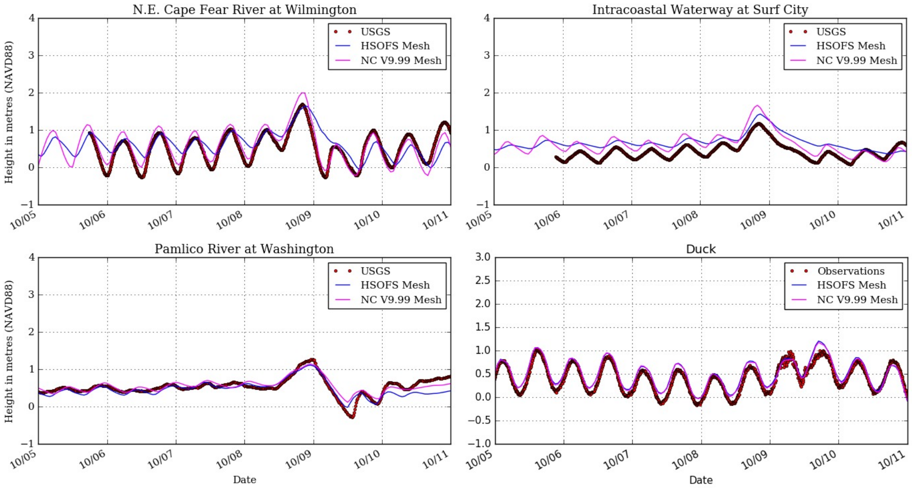
Best-Possible Hindcast of Hurricane Matthew

Evolution of Water Levels in North Carolina – NC9



Best-Possible Hindcast of Hurricane Matthew

Water Level Comparison from South to North



How does mesh resolution affect the model performance?

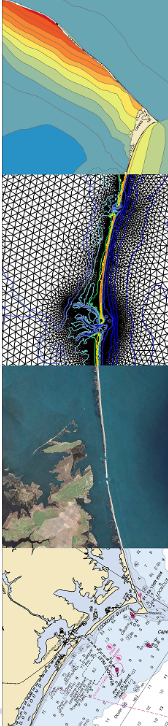
– Comparison to wind speeds:

Mesh	Stations	RMSE (m/s)
HSOFS	108	1.944
HSOFS	33	2.260
NC9	33	2.367

– Comparison to water levels:

Mesh	Stations	RMSE (m)
HSOFS	310	0.295
HSOFS	90	0.264
NC9	90	0.240

Water level predictions are improving when we have better resolution



Considering Erosion of Beaches and Dunes

eXtreme Beach (XBeach): `xbeach.org`

Our forecast system is limited:

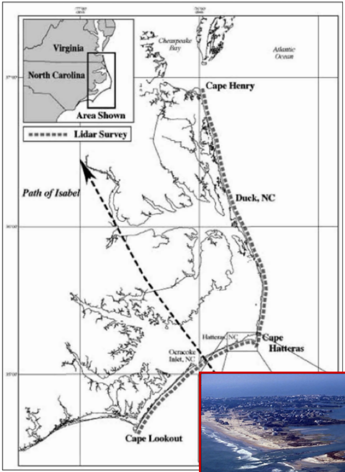
- Bathymetry and topography are fixed / constant
- No consideration of beach erosion, dune breaching, etc.
- Flooding impacts are limited behind the dunes

With support from NC Sea Grant, we are coupling with XBeach:

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

Exploring Morphodynamics during Isabel (2003)

Extensive Erosion and Breaching



We examine storm impacts during Isabel

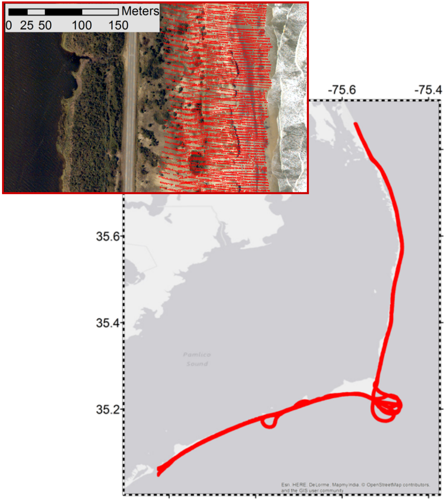
- Most powerful hurricane in 2003
- Made landfall on the Outer Banks on 18 Sep as Category 2 hurricane
- Caused overwash, dune breaching, and infrastructure destruction
- NC-12 closed at identified hotspots
- Major breaching occurred northeast of Hatteras Inlet

Exploring Morphodynamics during Isabel (2003)

Pre- and Post-Storm LiDAR Data

Available LiDAR data:

- Pre- and post-storm data sets available from the NASA / USGS Experimental Advanced Airborne Research LiDAR
  - 16 Sep 2003
  - 21 Sep 2003
- Coverage of Outer Banks from Ocracoke Inlet to Oregon Inlet
- Surveyed width of 250-300 m
- Resolution of 2 m
- Only the topographic data are used, due to water turbidity in bathymetric regions

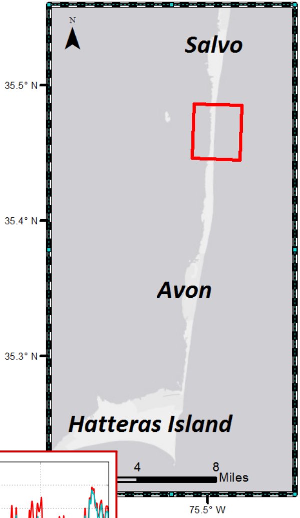


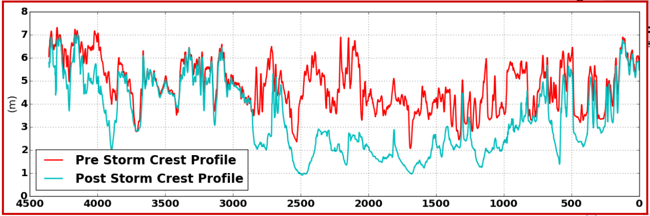
Exploring Morphodynamics during Isabel (2003)

Storm Impacts in Study Area

Alongshore crest elevation change:

- Study area between Avon and Salvo
  - Distance of about 4.3 km
- Elevation changes at pre-storm crest line
  - Average = 1.5 m
  - Maximum = 5.6 m
- Total of 8 major dune erosion events
  - All wider than 15 m





Initial Results with XBeach

Generating Mesh for XBeach Simulations

Combining data sets:

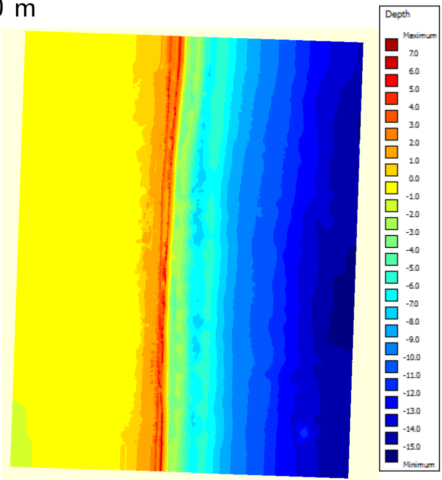
- Pre-storm LiDAR with 1 m resolution
- NC flood mapping DEM with 10 m resolution

Converting to computational mesh:

- Total of 990 × 440 cells
- Cell widths:
  - Alongshore = 15 m
  - Cross-shore
    - At offshore boundary = 30 m
    - At shoreline = 3 m

Need to assign values:

- Waves and water levels
- Sediment properties

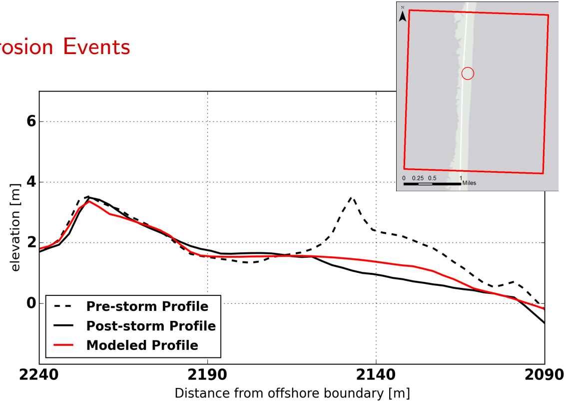


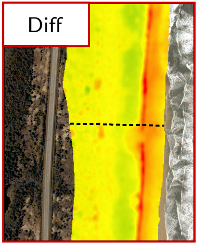
Initial Results with XBeach

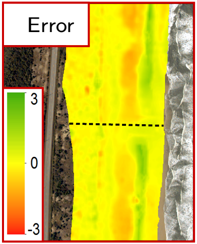
XBeach Profiles at Major Dune Erosion Events

Dune Erosion Event #1:

- First dune removal modeled perfectly
- No changes to profile behind first dune





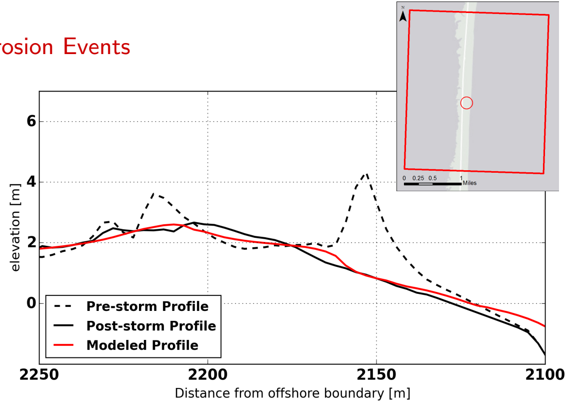


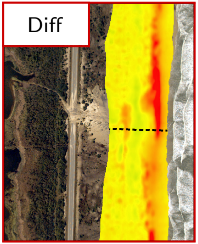
Initial Results with XBeach

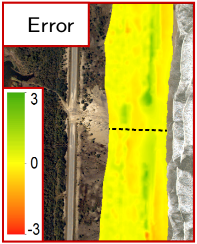
XBeach Profiles at Major Dune Erosion Events

Dune Erosion Event #2:

1. Removal of first and second dunes
2. The erosion and overwash modeled correctly





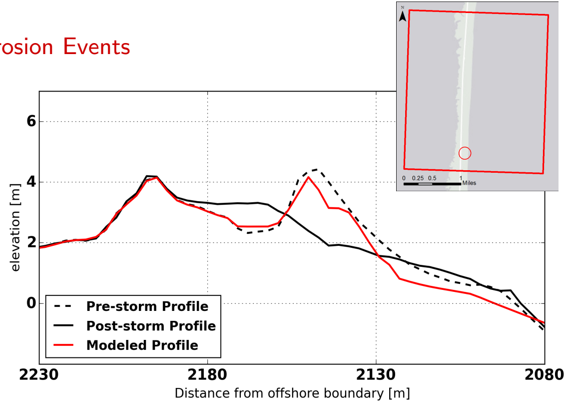


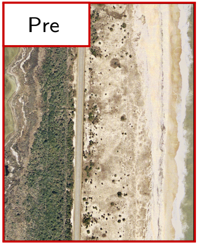
Initial Results with XBeach

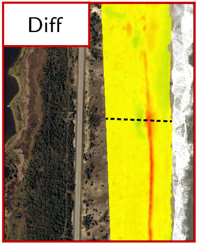
XBeach Profiles at Major Dune Erosion Events

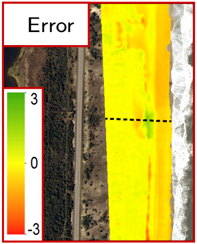
Dune Erosion Event #3:

- Inaccurate model result
- Too much erosion on the beach
- First dune is not removed







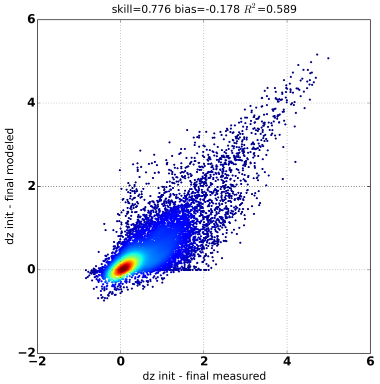


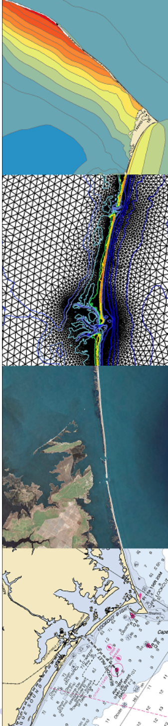
Initial Results with XBeach

Model Accuracy

Skill Score:

- Compares measured to modeled elevation change
- Skill score greater than 0.5 is "Excellent"
- Modeled profiles match observations: scatter points close to 1:1





Real-time forecasting for coastal North Carolina:

- Available several times per day at: `nc-cera.renci.org`
- Hurricane Matthew (2016)
  - 47 advisories were issued during the storm
  - Measurements were collected all along the U.S. East Coast
  - Hindcasts on meshes with difference coverage, resolution
  - Prediction errors decrease for higher resolution meshes

Working with XBeach to simulate beach and dune erosion:

- Preliminary results are encouraging
  - Developing model for large domain: 18 km of Hatteras Island
  - Improving accuracy for more complex erosion patterns and breaching
- Need to couple with ADCIRC
  - Revised topography to improve flood predictions