Hurricane Wave and Storm Surge Modeling: Recent Developments and Forecasting during Hurricane Matthew

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Duke University Marine Lab
Beaufort NC, 12 April 2017

COASTAL RESILIENCE CENTER
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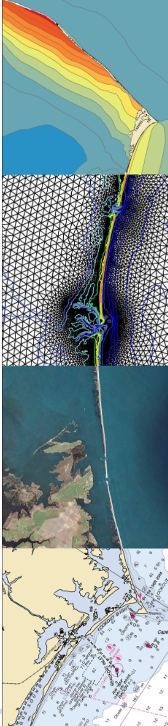
Sea Grant North Carolina



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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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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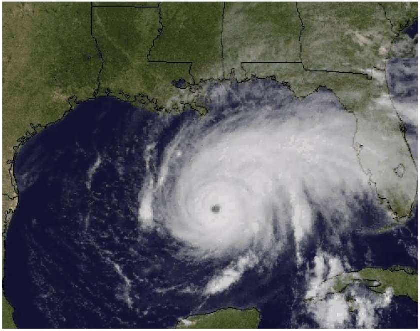
Hurricane Season 2005

Impacts on Southern Louisiana

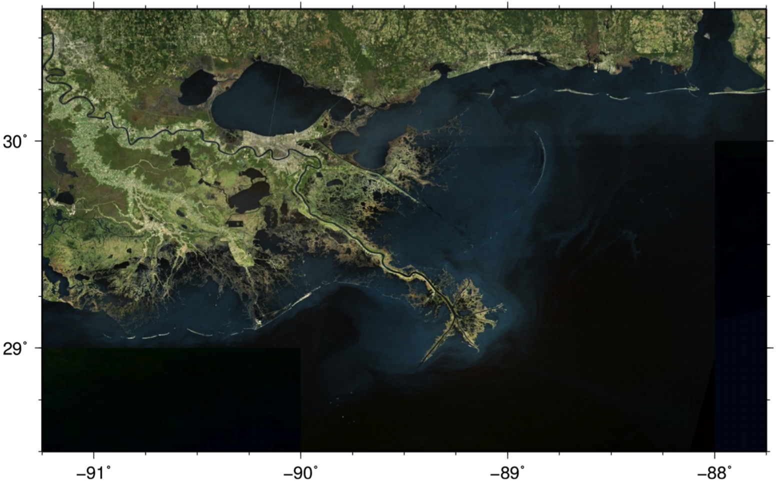
Katrina: 08/28 - 08/29

Rita: 09/22 - 09/24



Hurricane Season 2005

Flooding of New Orleans

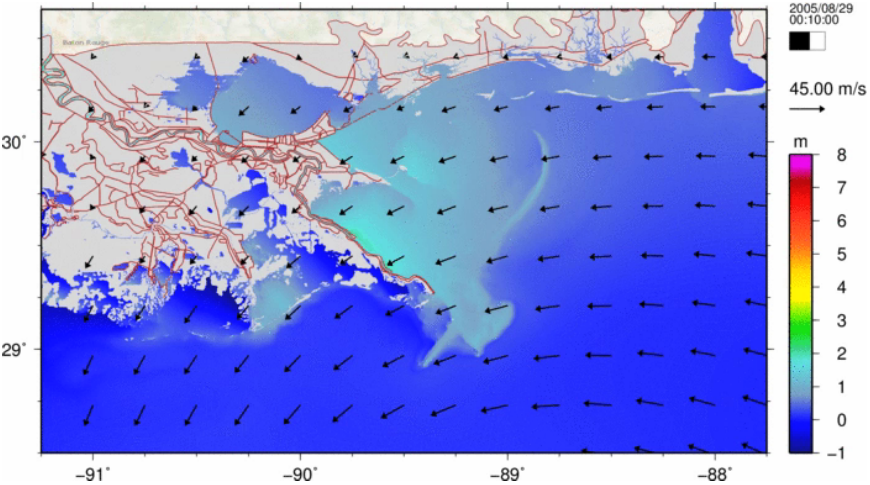


Hurricane Season 2005

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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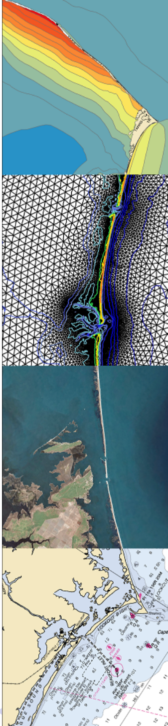
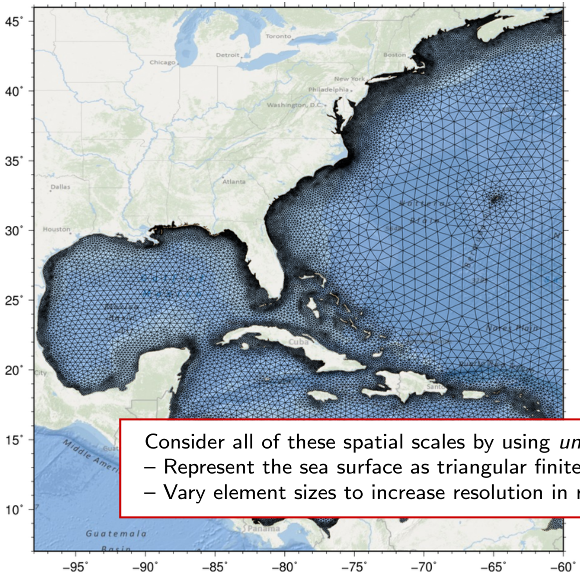


Wide Range of Spatial Scales

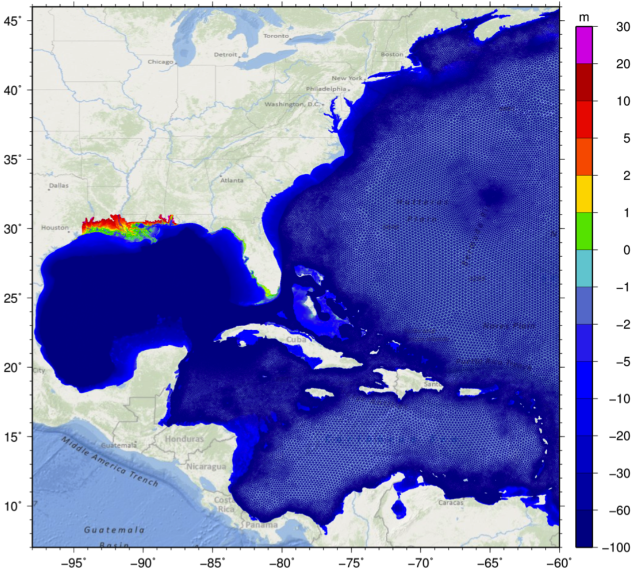
Unstructured, Finite-Element Meshes



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

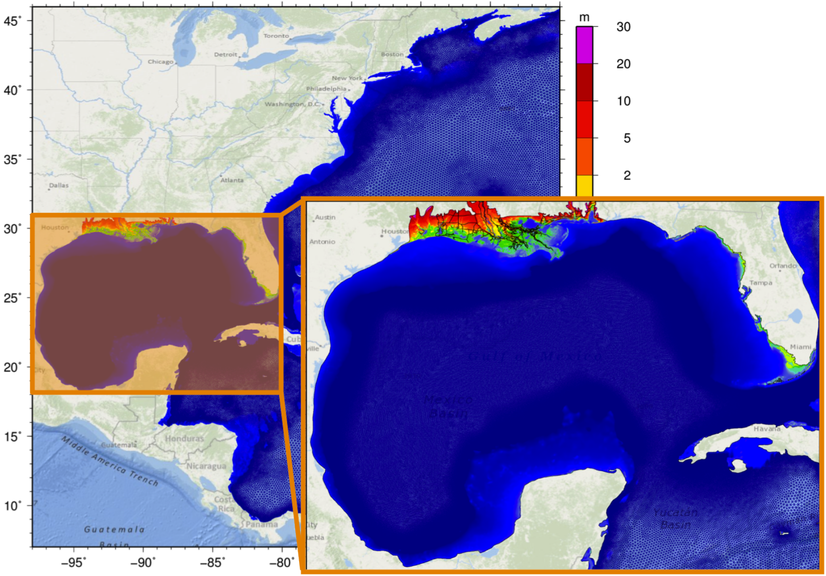
Wide Range of Spatial Scales

SL16 Mesh for Southern Louisiana



Wide Range of Spatial Scales

SL16 Mesh for Southern Louisiana



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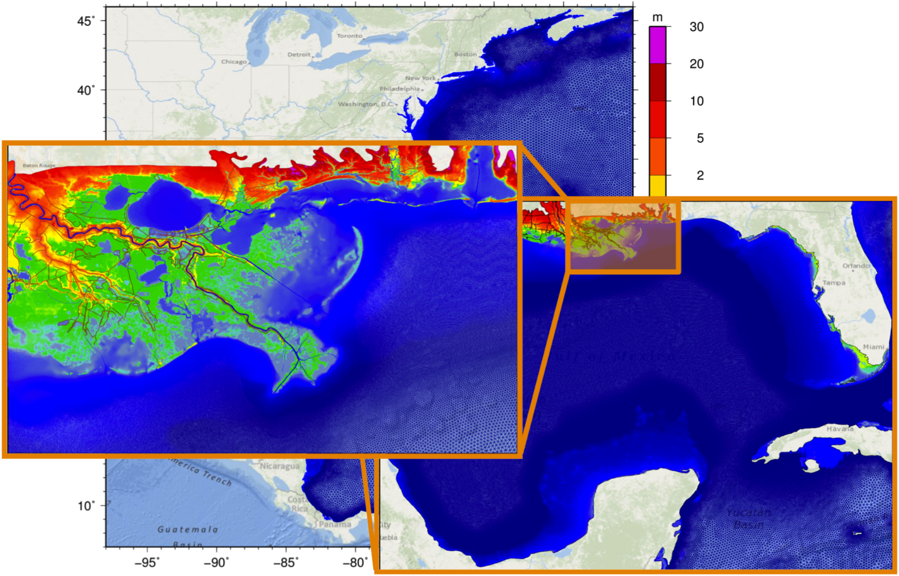

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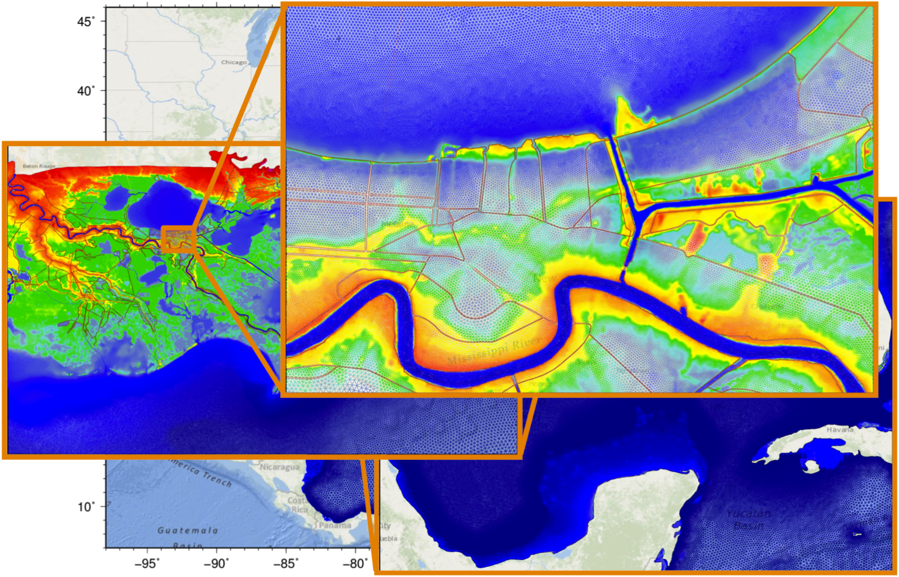
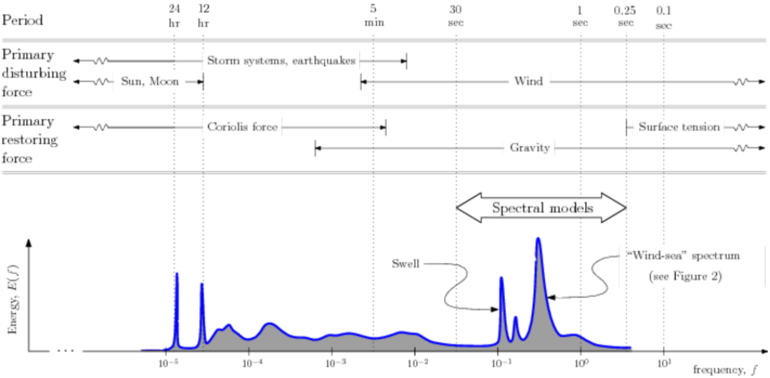


Models for Hurricane Waves and Storm Surge
Temporal Scales

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:

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

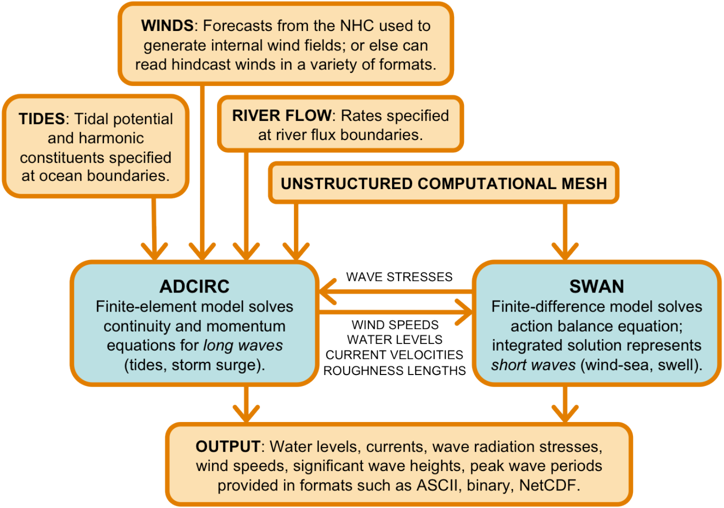
Solves the depth-averaged momentum equations for currents (U, V):

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

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

Models for Hurricane Waves and Storm Surge

Tight Coupling of SWAN+ADCIRC



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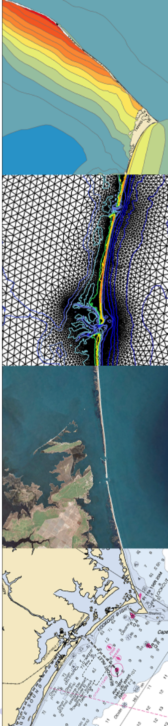


SWAN+ADCIRC can be employed in real-time via the ASGS

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

Wind fields from two sources:

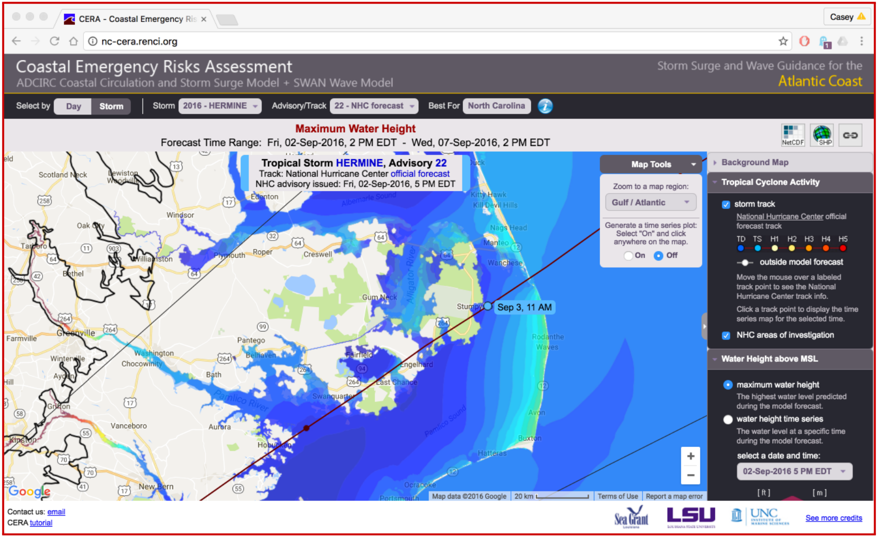
1. Under normal conditions:
   - Downloaded from NAM model output by NOAA/NCEP
   - Converted into format compatible with SWAN+ADCIRC
2. Under hurricane conditions:
   - Download advisories from NOAA/NHC
   - Generate wind field using parametric model (Holland, 1980)

Guidance can be shared in multiple formats:

- Send directly to stakeholders (NC Emergency Management)
- Share publicly via web service (`www.adcirc.org`)

Real-Time Forecasting during Hurricane Hermine

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



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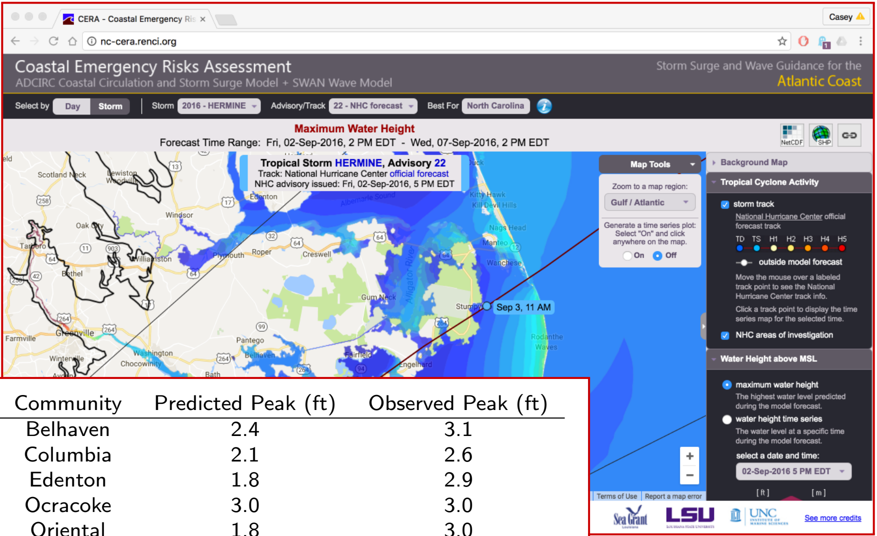

Community	Predicted Peak (ft)	Observed Peak (ft)
Belhaven	2.4	3.1
Columbia	2.1	2.6
Edenton	1.8	2.9
Ocracoke	3.0	3.0
Oriental	1.8	3.0

Real-Time Forecasting during Hurricane Matthew

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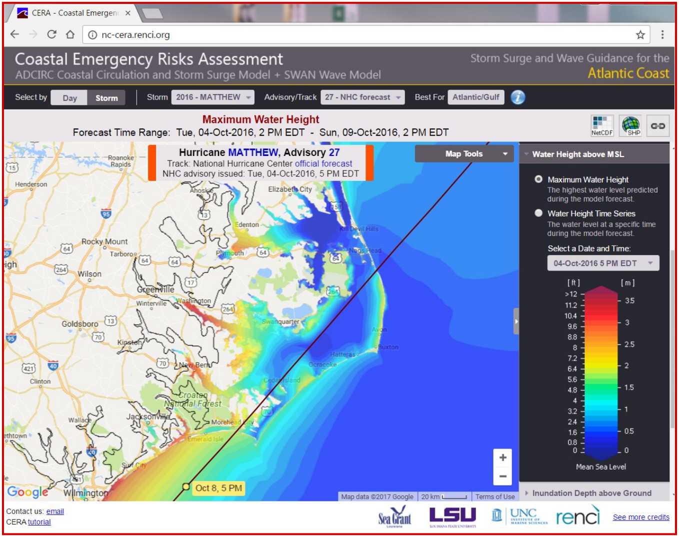

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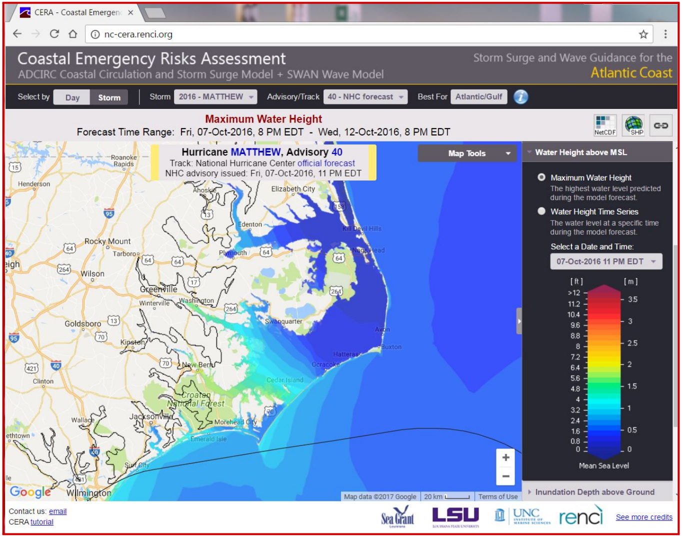
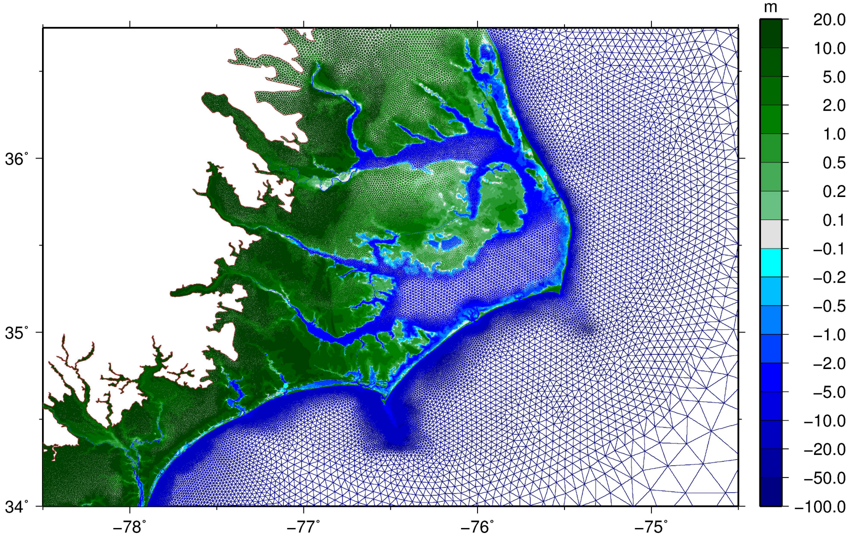


Real-Time Forecasting during Hurricane Matthew

High-Resolution Mesh for North Carolina – NC9



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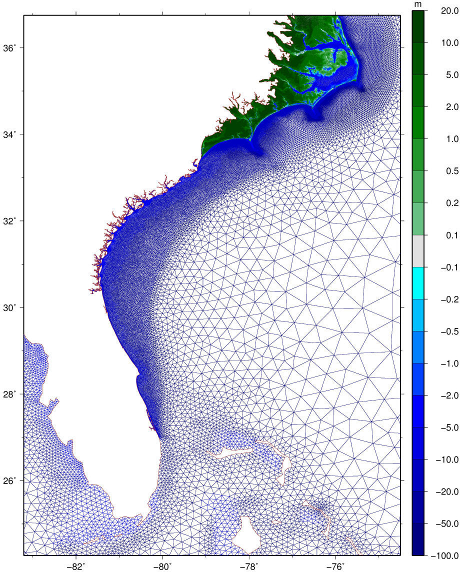
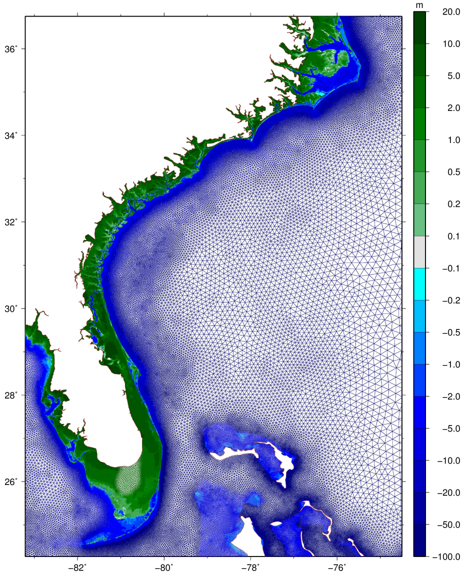


Real-Time Forecasting during Hurricane Matthew

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



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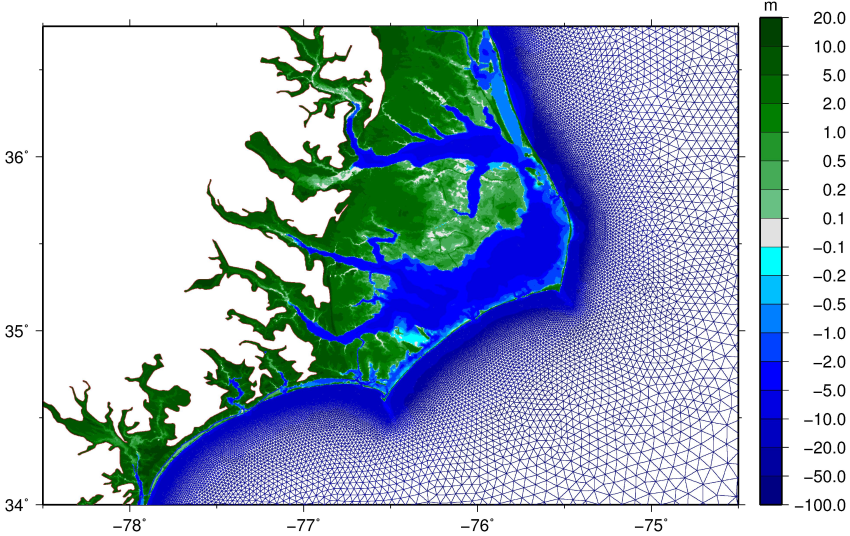
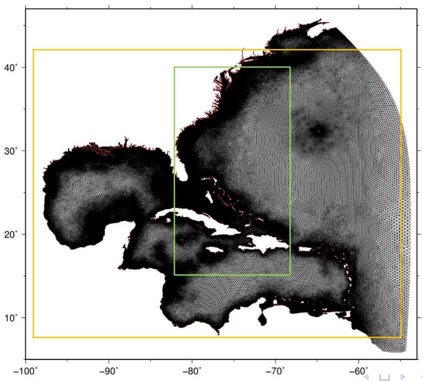


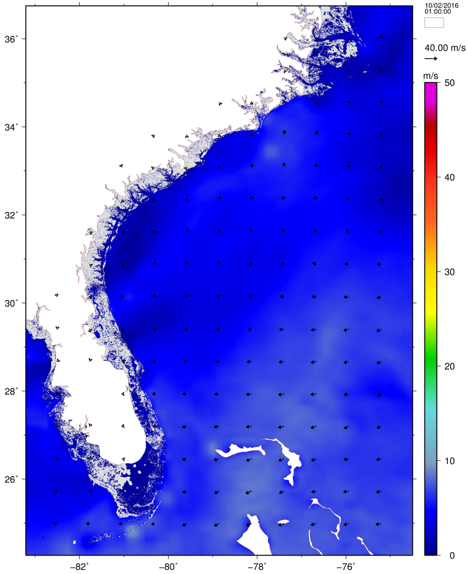
OceanWeather Inc. (OWI)

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



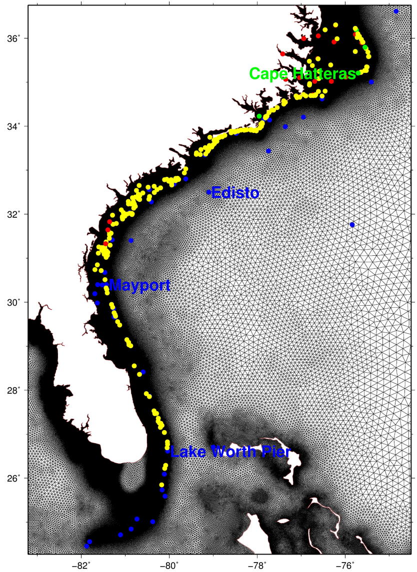
Best-Possible Hindcast of Hurricane Matthew

Evolution of Winds Along US East Coast – HSOFS



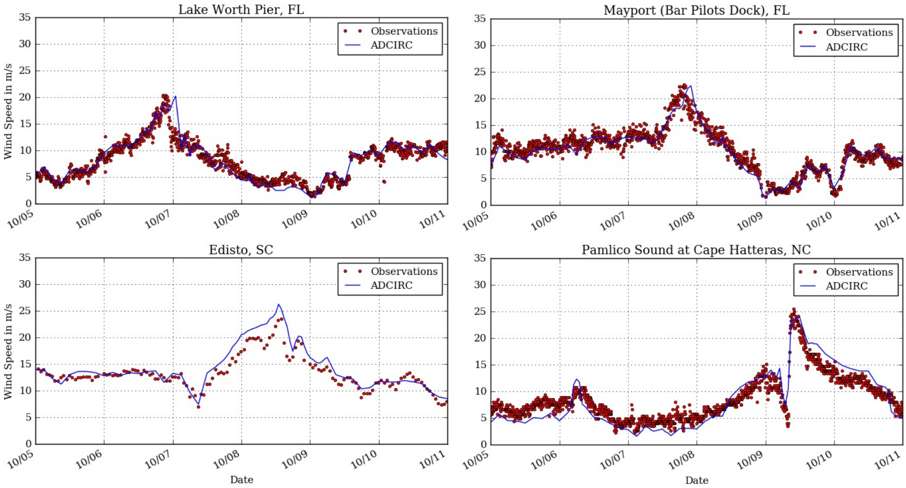
Best-Possible Hindcast of Hurricane Matthew

Atmospheric Stations for US East Coast



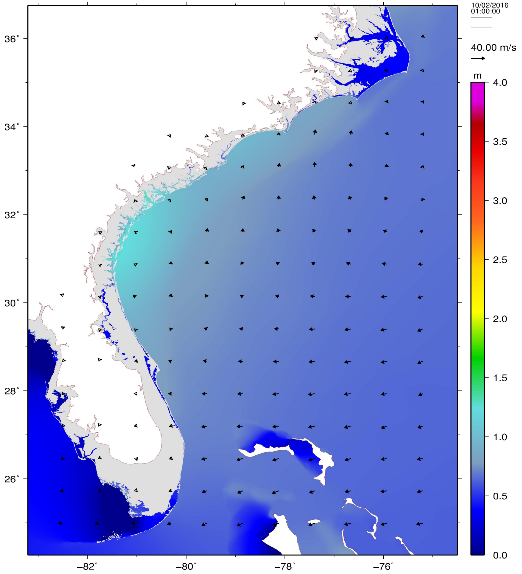
Best-Possible Hindcast of Hurricane Matthew

Wind Speed Comparison from South to North



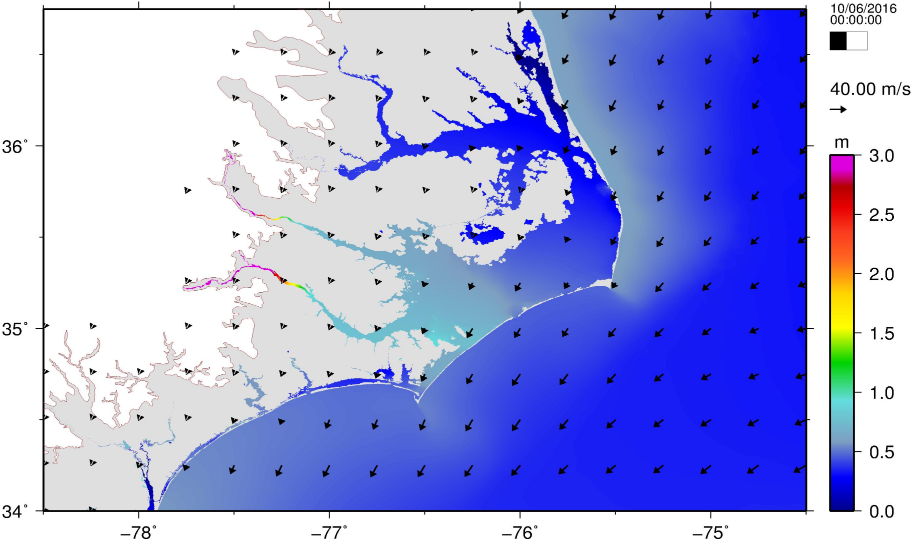
Best-Possible Hindcast of Hurricane Matthew

Evolution of Water Levels Along the US East Coast – HSOFS



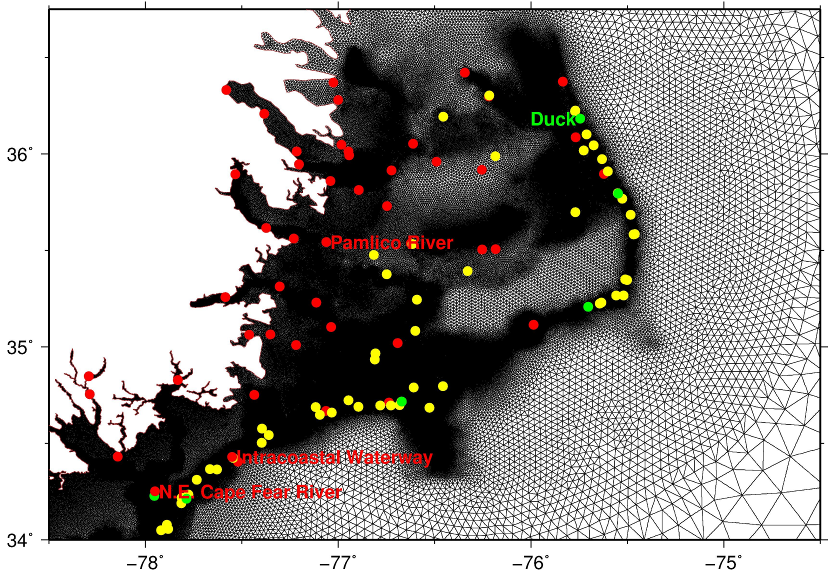
Best-Possible Hindcast of Hurricane Matthew

Evolution of Water Levels in North Carolina – NC9



Best-Possible Hindcast of Hurricane Matthew

Observations of Water Levels in North Carolina



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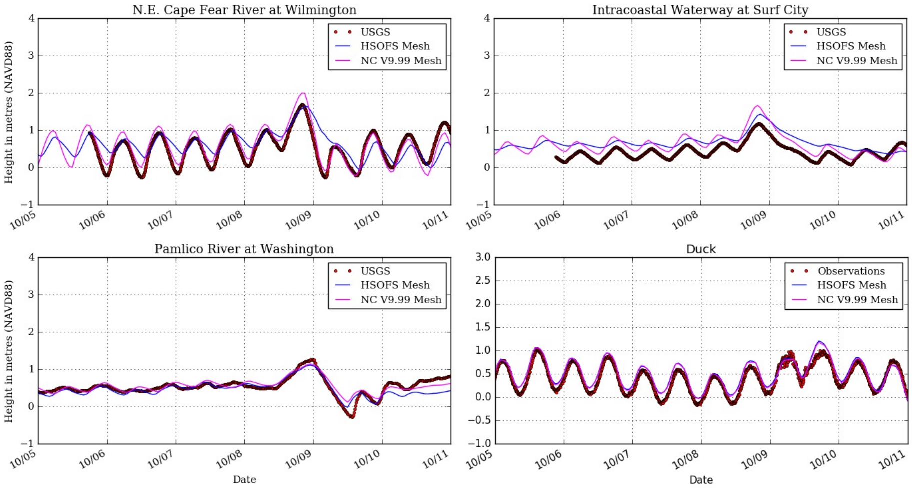


Best-Possible Hindcast of Hurricane Matthew

Quantifying the Effect of Mesh Resolution

How does mesh resolution affect the model performance?

- Comparison to wind speeds:

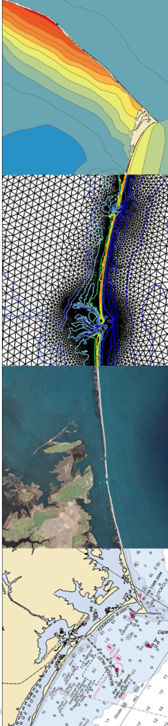
Mesh	Stations	RMSE (m/s)
HSOFS	108	1.944
HSOFS	33	2.260
NC9	33	2.367

- 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

- How can we improve for future years?



Considering Erosion of Beaches and Dunes

eXtreme Beach (XBeach): `xbeach.org`

Our forecast system is limited:

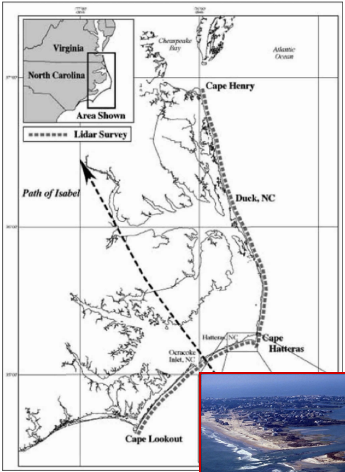
- Bathymetry and topography are fixed / constant
- No consideration of beach erosion, dune breaching, etc.
- Flooding impacts are limited behind the dunes

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

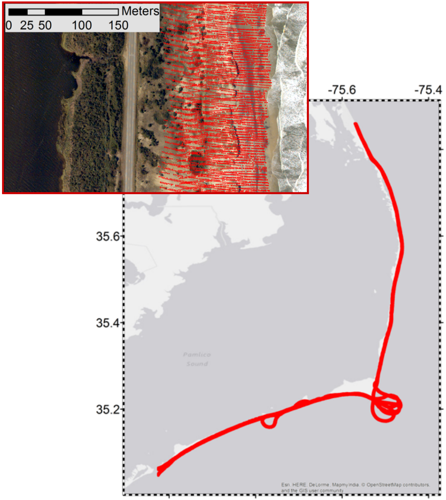
- Most powerful hurricane in 2003
- Made landfall on the Outer Banks on 18 Sep as Category 2 hurricane
- Caused overwash, dune breaching, and infrastructure destruction
- NC-12 closed at identified hotspots
- Major breaching occurred northeast of Hatteras Inlet

Exploring Morphodynamics during Isabel (2003)

Pre- and Post-Storm LiDAR Data

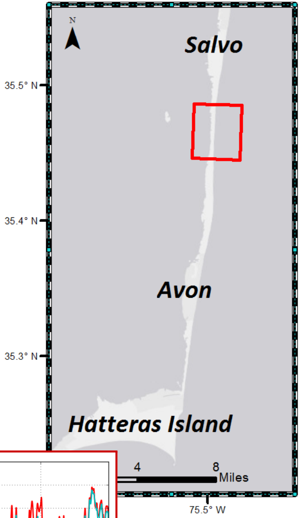
Available LiDAR data:

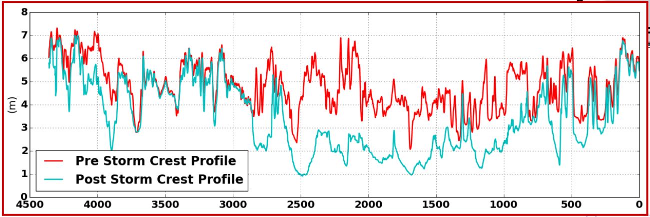
- Pre- and post-storm data sets available from the NASA / USGS Experimental Advanced Airborne Research LiDAR
  - 16 Sep 2003
  - 21 Sep 2003
- Coverage of Outer Banks from Ocracoke Inlet to Oregon Inlet
- Surveyed width of 250-300 m
- Resolution of 2 m
- Only the topographic data are used, due to water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

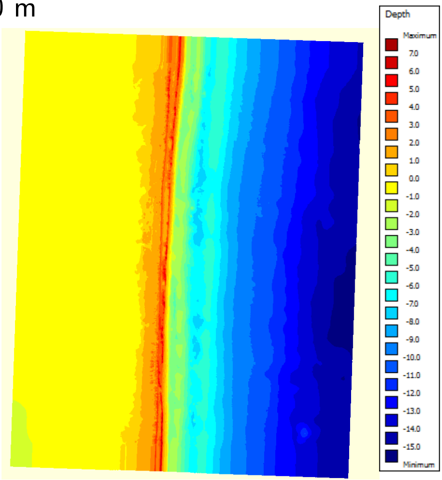
- Pre-storm LiDAR with 1 m resolution
- NC flood mapping DEM with 10 m resolution

Converting to computational mesh:

- Total of 990 $\times$ 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

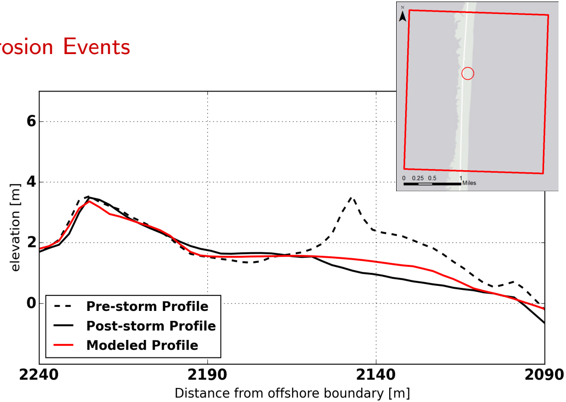


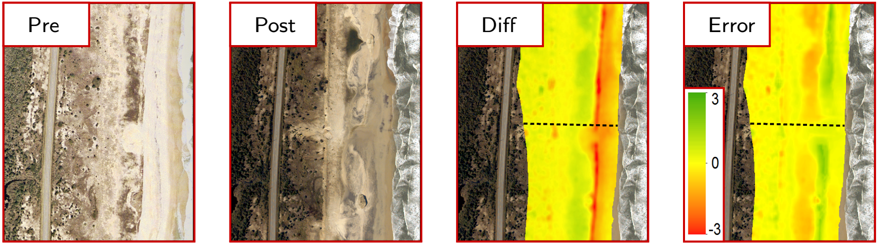
Initial Results with XBeach

XBeach Profiles at Major Dune Erosion Events

Dune Erosion Event #1:

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



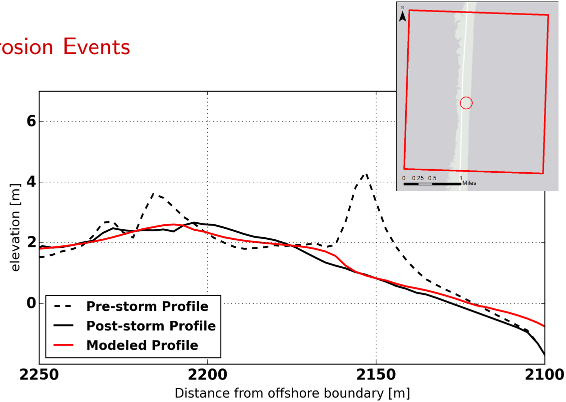


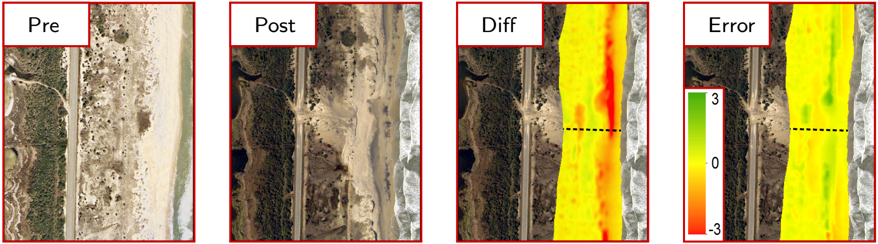
Initial Results with XBeach

XBeach Profiles at Major Dune Erosion Events

Dune Erosion Event #2:

- Removal of first and second dunes
- The erosion and overwash modeled correctly



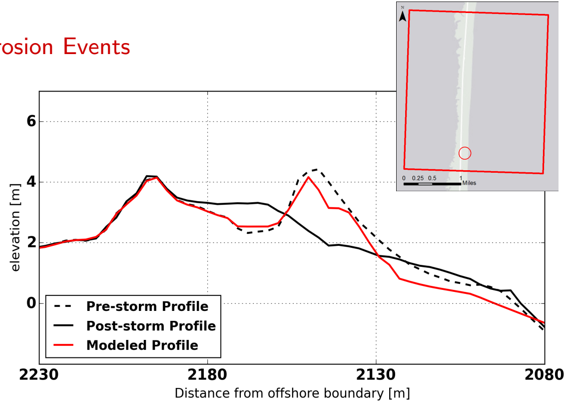


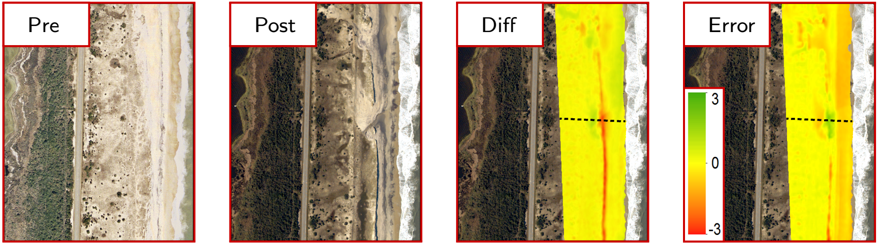
Initial Results with XBeach

XBeach Profiles at Major Dune Erosion Events

Dune Erosion Event #3:

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



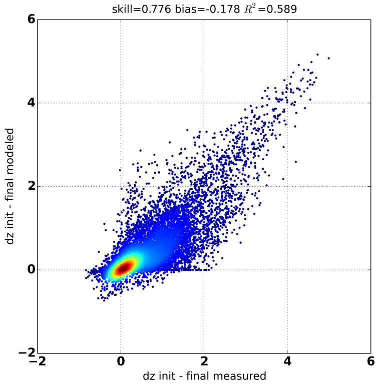


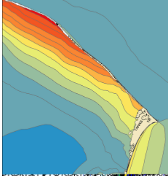
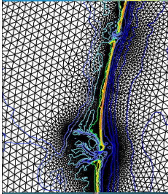
Initial Results with XBeach

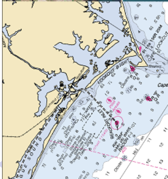
Model Accuracy

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





Summary and Future Work

Predictive Models for Waves, Flooding, and Beach Morphodynamics

Real-time forecasting for coastal North Carolina:

- Available at: `www.adcirc.org`
- Hurricane Matthew (2016)
  - 47 advisories were issued during the storm
  - Flooding impacts along the U.S. East Coast
  - Hindcasts on meshes with difference coverage, resolution
  - Water level predictions within 1 ft

Working with XBeach to simulate beach and dune erosion:

- Preliminary results are encouraging
  - Developing model for Hatteras Island
  - Improving accuracy for complex erosion patterns
- Need to couple with wave and surge models
  - Revised topography to improve flood predictions