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Forecasting and Mapping of Coastal Flooding during Hurricanes

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Fall Technical Conference
ASCE North Carolina Section, Raleigh NC, 26 Sep 2019

Sea Grant North Carolina

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COASTAL RESILIENCE CENTER
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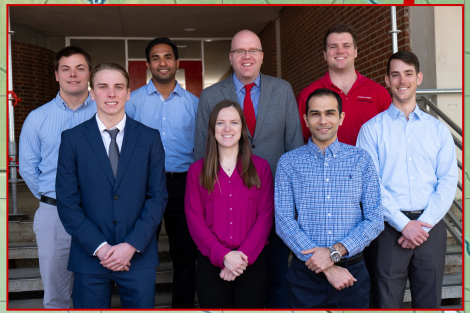

North Carolina State University
- Civil, Construction, and Environmental Engineering
  - Associate Professor: 08/2019 to Present
  - Assistant Professor: 08/2013 to 08/2019

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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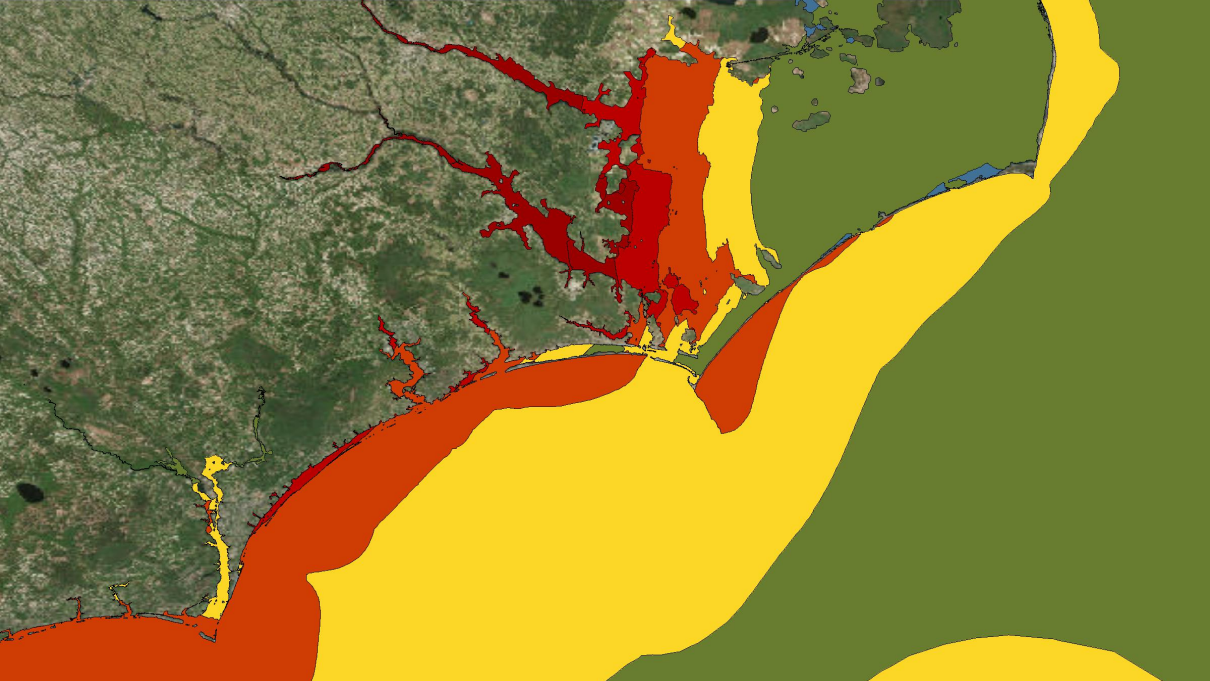
Brian Blanton

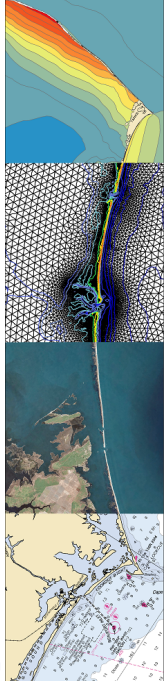
THE UNIVERSITY of NORTH CAROLINA at CHAPEL HILL

Rick Luettich

Seahorse COASTAL CONSULTING

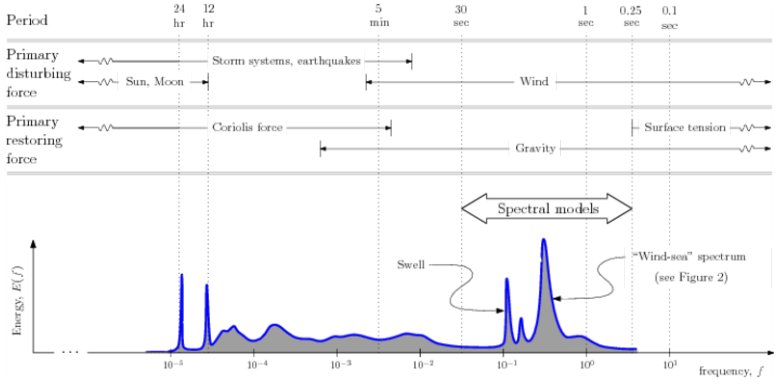
Jason Fleming





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 long waves, we use ADCIRC

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

Solves the generalized wave continuity equation (GWCE) 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):

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

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

In geographic space:

- Piecewise-linear, continuous, Galerkin finite elements
  - Unique values for (ζ, U, V) at every mesh vertex
- Typical minimum mesh spacings of 10 to 50 m

In time:

- Semi-implicit
  - Implicit solution of GWCE using Jacobi Conjugate Gradient (JCG) solver
  - Explicit solution of momentum equations with lumped mass matrix
- Fully explicit
  - Also possible to use lumped mass matrix for solution of GWCE
- Typical time steps of 0.5 to 10 sec

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:

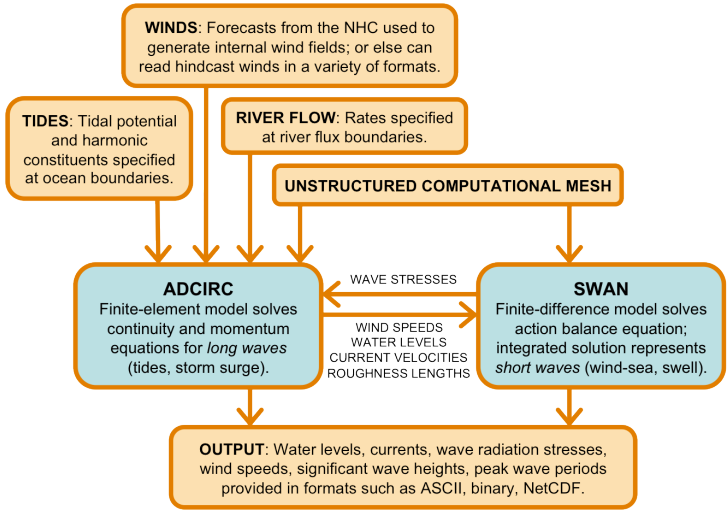
$$\frac{\partial N}{\partial t} + \nabla_{\mathbf{x}} \cdot [(\mathbf{c}_g + \mathbf{U}) N] + \frac{\partial c_\theta N}{\partial \theta} + \frac{\partial c_\sigma N}{\partial \sigma} = 0$$

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

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

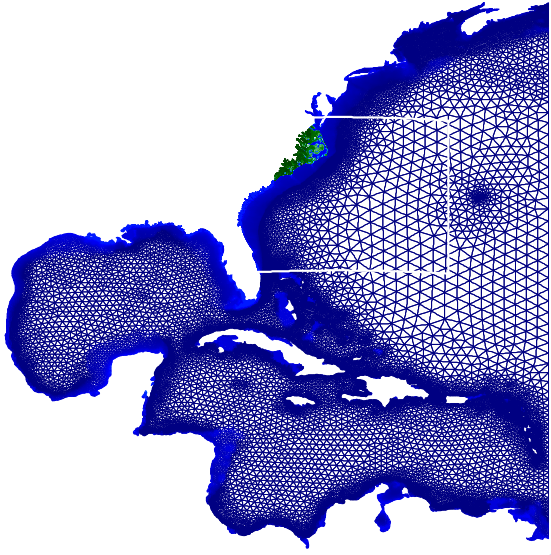
Models for Waves and Coastal Circulation

Tightly-Coupled SWAN+ADCIRC



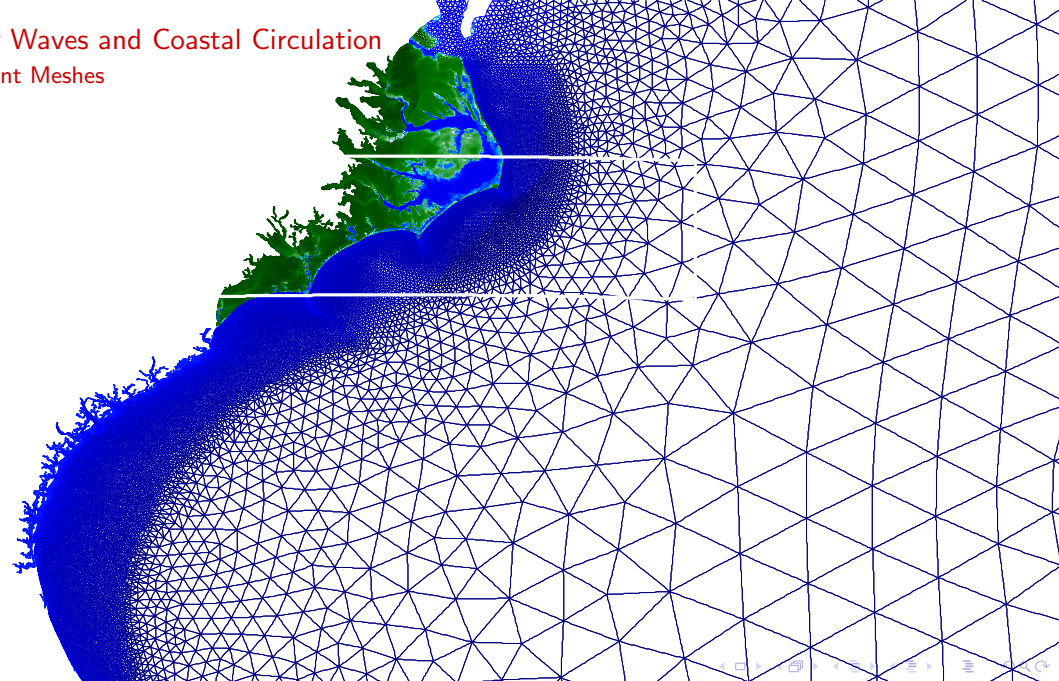
Models for Waves and Coastal Circulation

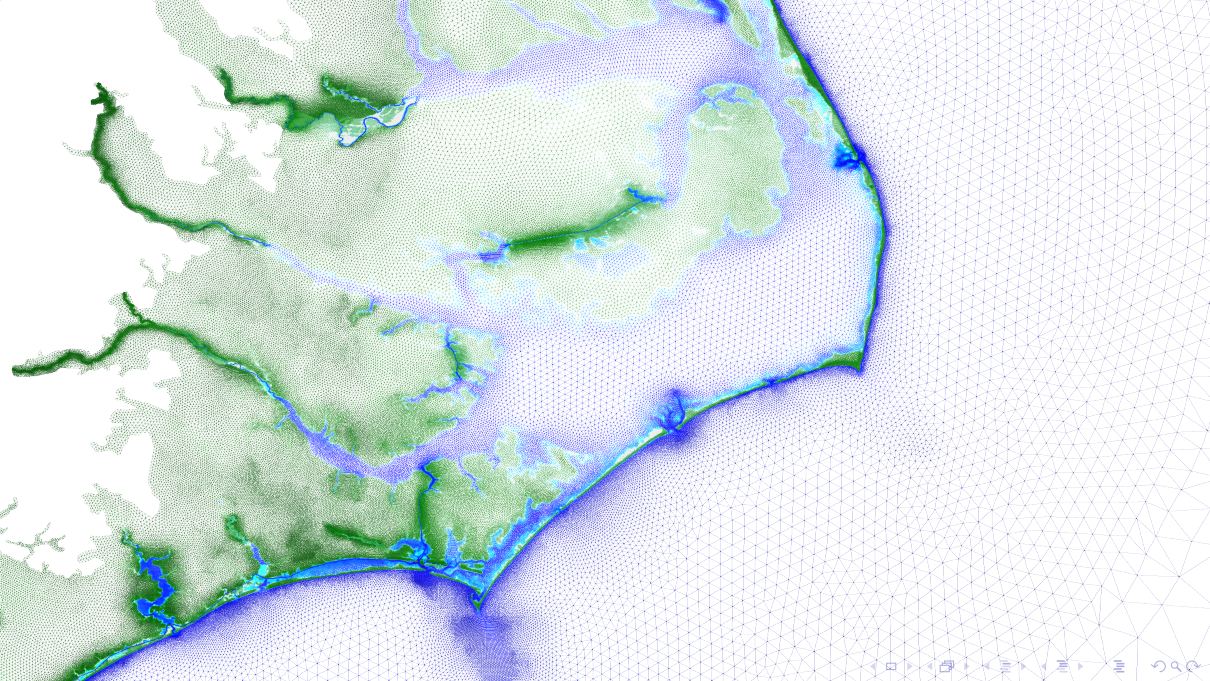
Finite Element Meshes

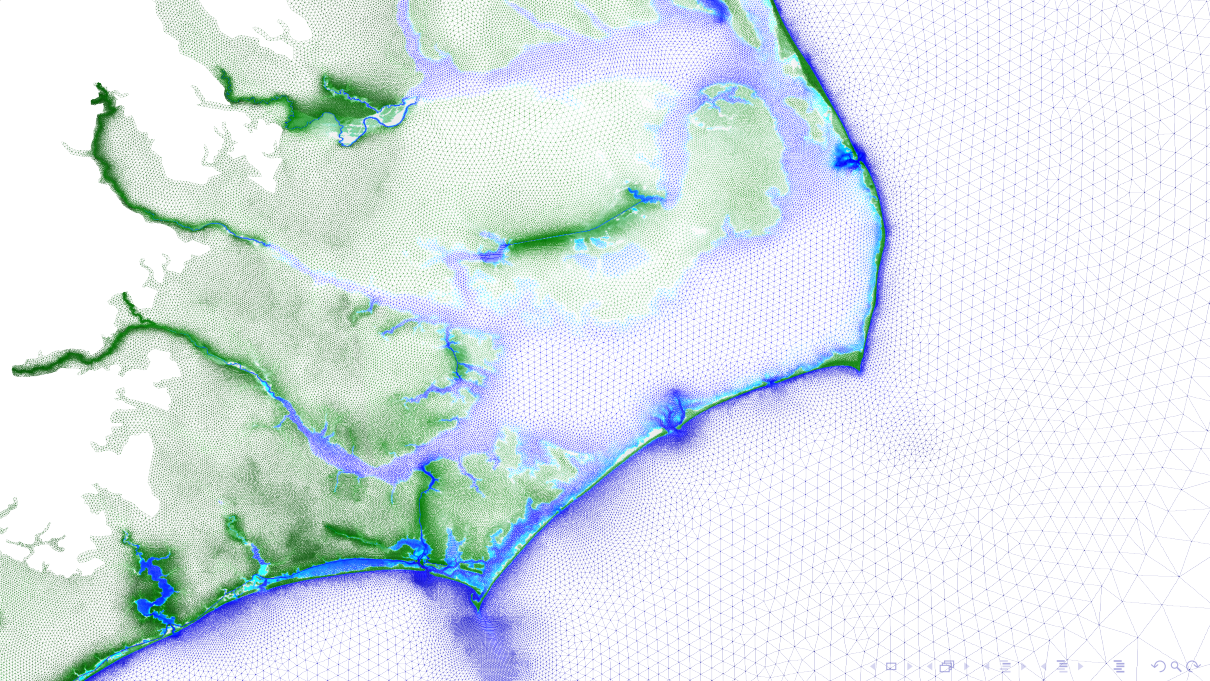


Models for Waves and Coastal Circulation

Finite Element Meshes







SWAN+ADCIRC are used in real-time via the ADCIRC Prediction System (APS)

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

Wind fields from two sources:

- Under normal conditions:
  - Downloaded from NAM model output by NOAA/NCEP
  - Converted into format compatible with SWAN+ADCIRC
- 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 (NCEM, NCDOT, FEMA)
- Share publicly via web service (`www.adcirc.org`)

CERA Coastal Emergency Risks Assessment

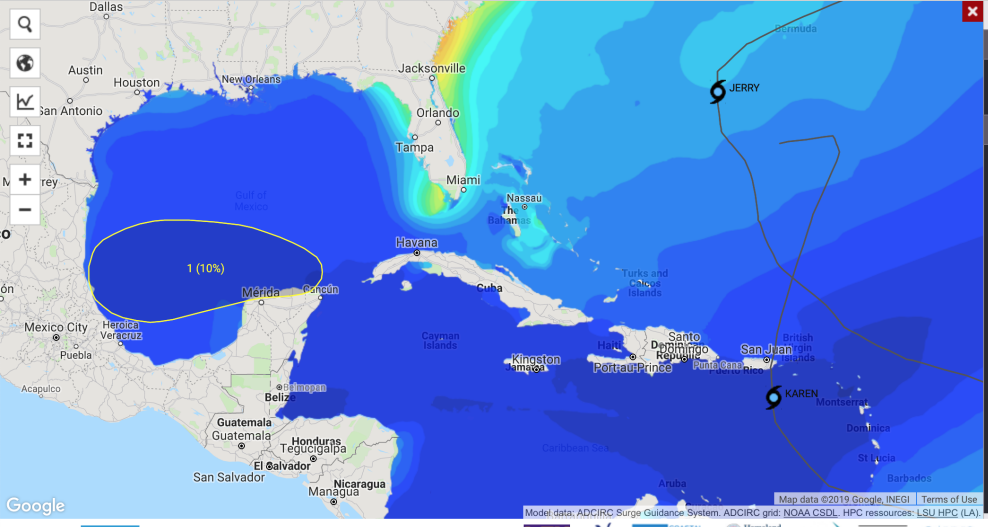
ADCIRC storm surge and wave guidance

NOAA Extratropical Surge & Tide System | ADCIRC Surge Guidance System

Select by: Day | Storm | Day: 24-Sep-2019 | Start Time: 06:00 UTC | Model Info: 12km NAM / HSOFS

Hello Casey!
Logout / Settings

Maximum Water Height above MSL (24-Sep-2019, 06:00 - 27-Sep-2019, 18:00 UTC)



Model data: ADCIRC Surge Guidance System. ADCIRC grid: NOAA CSDL. HPC ressources: LSU HPC (LA).

Background Map

Tropical Cyclone Activity

- [x] storm tracks and areas of investigation

Water Height above MSL

- (•) Maximum Water Height
- ( ) Water Height at Date/Time

24-Sep-2019 09:00 UTC

[ft] MSL

>7.5
7
6.5
6
5.5
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0

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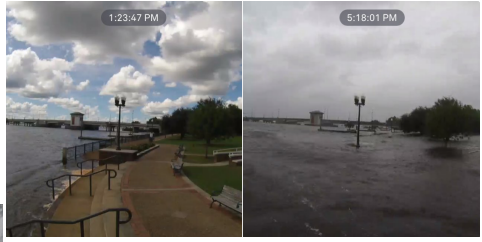
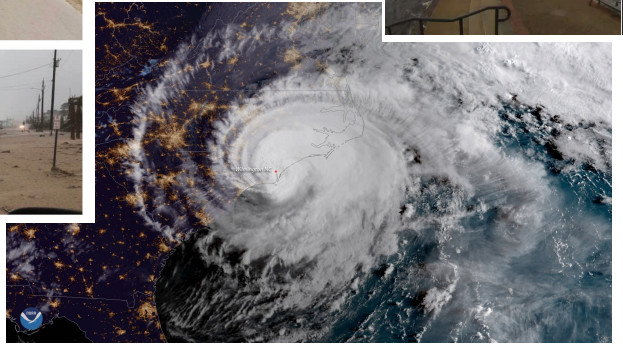
Florence (2018)

Extensive Impacts to Coastal NC

Surf City NC (@AdamWGME)

Union Point in New Bern NC (@NWSEastern)



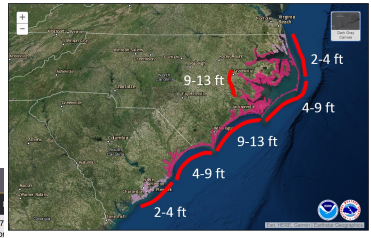


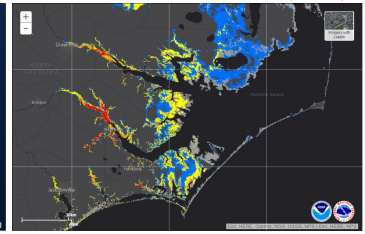
Florence making landfall on Fri Sep 14 (@NOAASatellites)

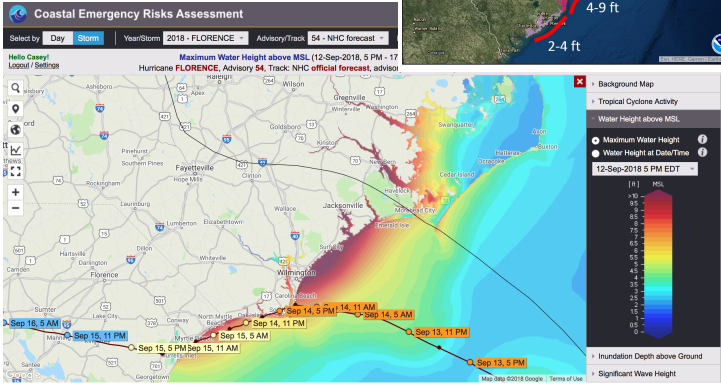
Florence (2018)

Forecasts of Storm Surge

Surge and flooding guidance from the National Hurricane Center (NHC)



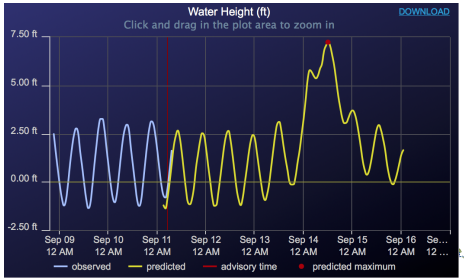




ADCIRC maximum water levels for Advisory 54 (CERA)

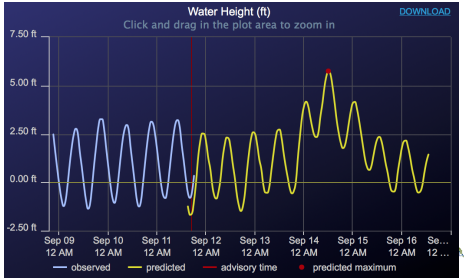
Florence (2018)

Adv 48 – Sep 11 Tue 5am



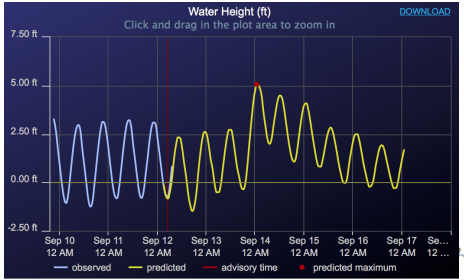
Florence (2018)

Adv 50 – Sep 11 Tue 5pm



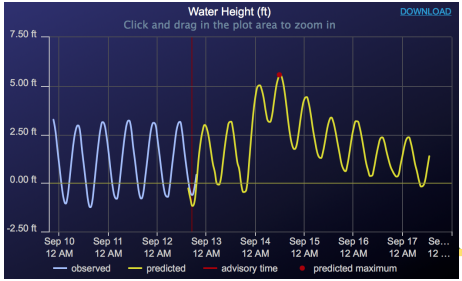
Florence (2018)

Adv 52 – Sep 12 Wed 5am



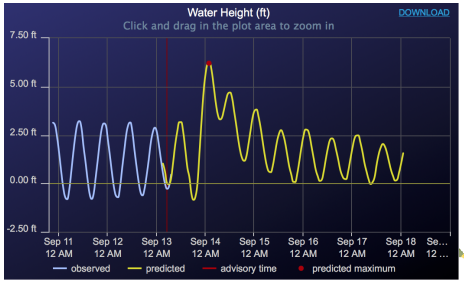
Florence (2018)

Adv 54 – Sep 12 Wed 5pm



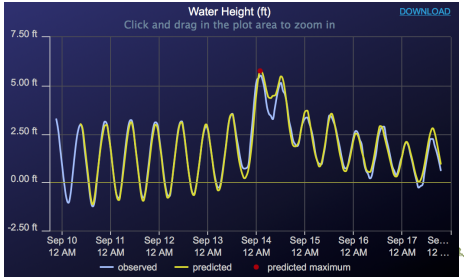
Florence (2018)

Adv 56 – Sep 13 Thu 5am



Florence (2018)

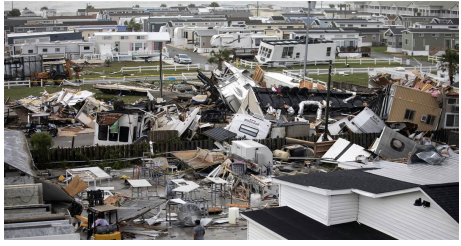
Best-Track Hindcast



Dorian (2019)

Extensive Impacts to Coastal NC

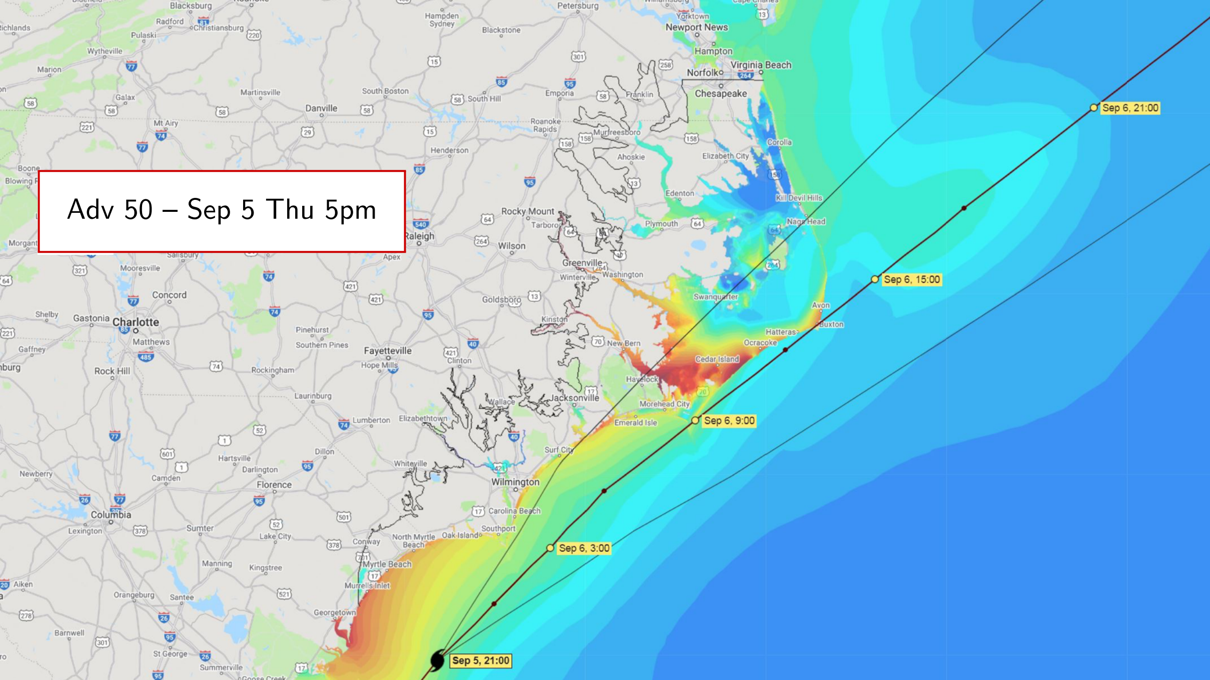
Waterspout tornado in Emerald Isle NC



Post-storm cleanup on NC-12 near Pea Island

Overland flooding on Ocracoke Island NC

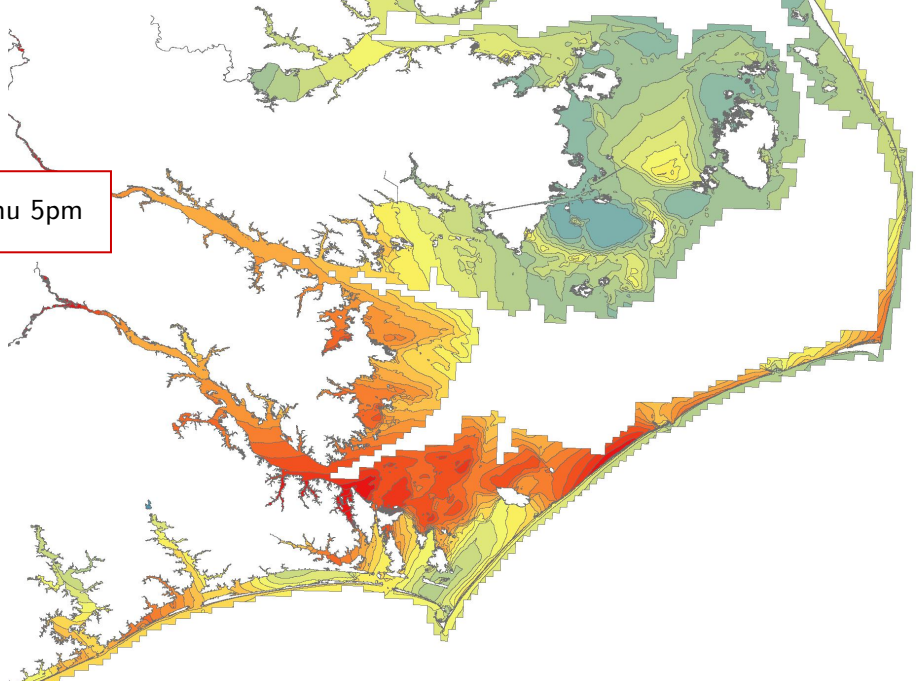
Adv 50 – Sep 5 Thu 5pm



Dorian (2019)

Flooding Guidance

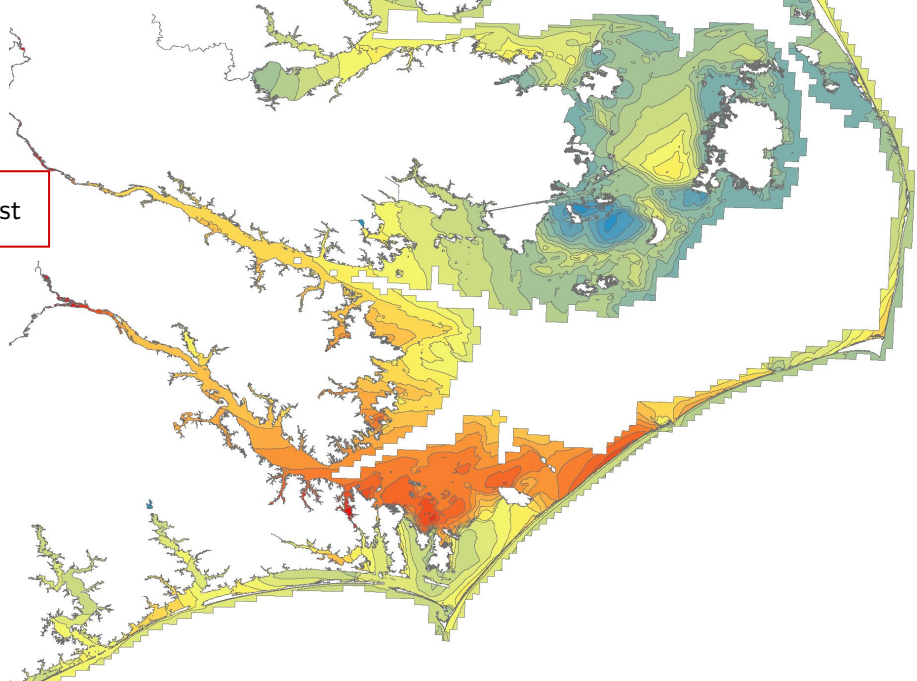
Adv 50 – Sep 5 Thu 5pm

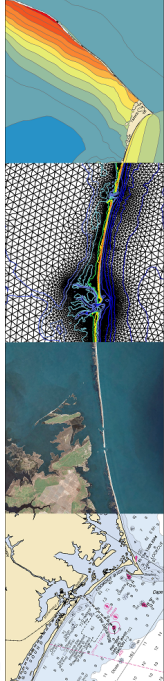


Dorian (2019)

Flooding Guidance

Best-Track Hindcast





1. Downscaling of Flooding Guidance for Decision Support

Motivation & Methods

We want to enhance the flooding guidance we provide to our partners

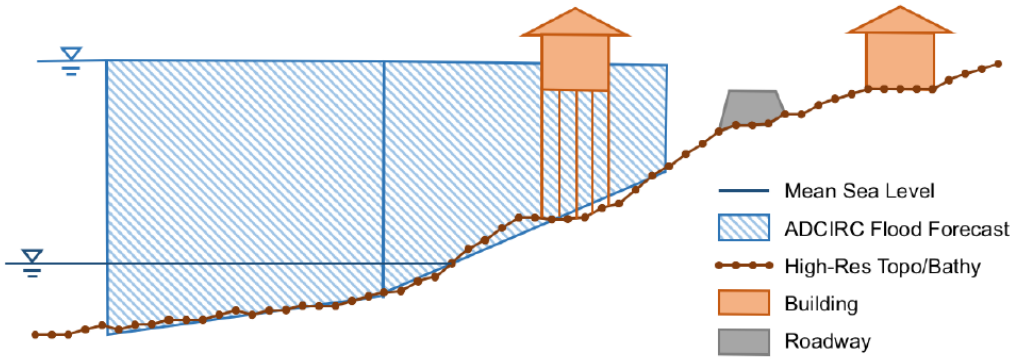
- We were providing water levels at our model resolution
  - Use an unstructured *mesh* with unequal spacings
  - More than 600K points
  - Minimum spacing of about 50 to 100 m
- Partners wanted to combine with other datasets
  - Use a structured *raster* with equal spacing
  - More than 400M cells
  - High-resolution topography with spacings of 50 ft (or smaller!)

Need to do two things:

- *Downscale* – Increase resolution to match their high-resolution topography datasets
- *Extrapolate* – Extend our flooding guidance into smaller-scale coastal regions

1. Downscaling of Flooding Guidance for Decision Support

Motivation & Methods



We used the Geographic Resources Analysis Support System (GRASS):

- Available as open-source software (`https://grass.osgeo.org`)
- Developed by Prof. Mitasova and researchers in the Center for Geospatial Analytics
- Extremely fast for raster processing

Then the general steps were:

- Interpolate ADCIRC points to raster at resolution of DEM (50 ft)
- Extrapolate water levels into small-scale channels and floodplains
  - Expand the raster outward only where the water levels are higher than the ground
  - Remove isolated (not hydraulically-connected) cells
- Convert the new "grown" raster to polygon format for distribution

1. Downscaling of Flooding Guidance for Decision Support

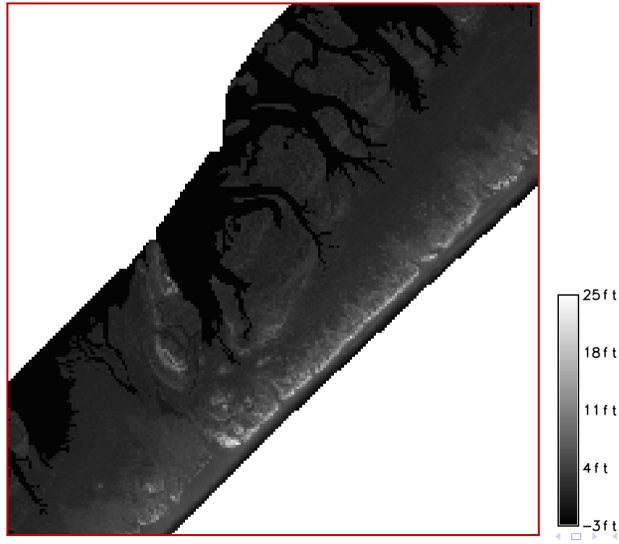
Examples for Matthew (2016) and Dorian (2019)

Consider the enhanced guidance on Carteret County

- One of 32 NC coastal counties that includes at least some part of the ADCIRC mesh
- Chosen for its complexity; contains barrier islands, estuaries, low-lying topography

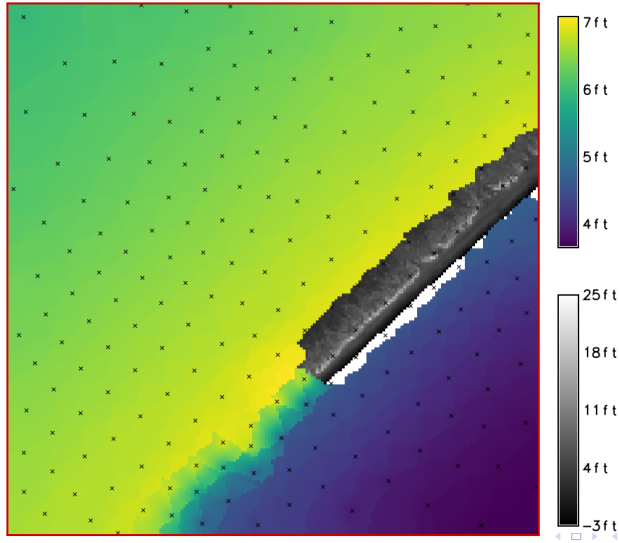
1. Downscaling of Flooding Guidance for Decision Support

Examples for Matthew (2016) and Dorian (2019)



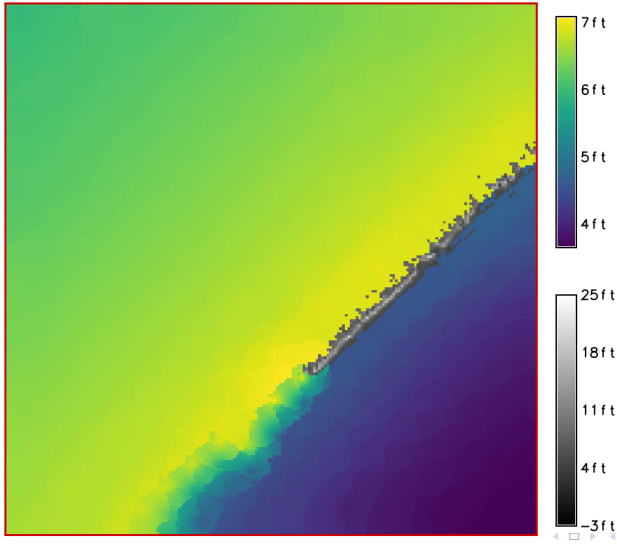
1. Downscaling of Flooding Guidance for Decision Support

Examples for Matthew (2016) and Dorian (2019)



1. Downscaling of Flooding Guidance for Decision Support

Examples for Matthew (2016) and Dorian (2019)



1. Downscaling of Flooding Guidance for Decision Support

Examples for Matthew (2016) and Dorian (2019)

We are now providing the enhanced guidance to our partners

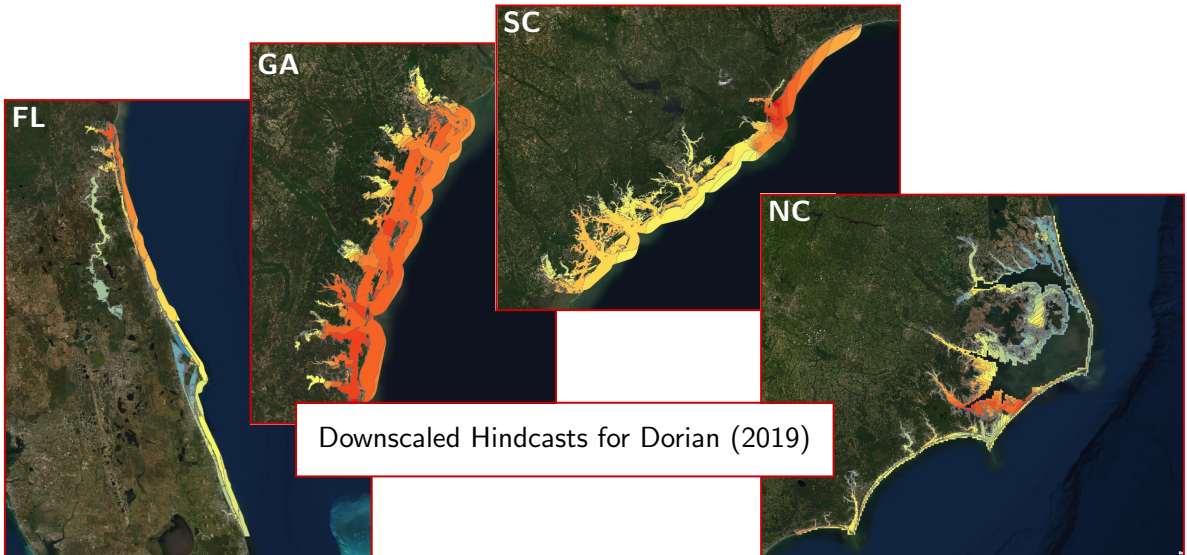
- During hurricane season, we use an automated script on our cluster at NCSU:
  - Detects when ADCIRC results are posted to the archive
  - Downloads the maximum water levels
  - Runs the enhanced-resolution process
- Recent storms:
  - 2017 – Harvey & Irma
  - 2018 – Florence & Michael
  - 2019 – Dorian

Recent enhancements to the downscaling script

- Generalized to work for ADCIRC flooding guidance in any region, on any DEM
- Integrated within *Kalpana* and released as open-source (`ccht.ccee.ncsu.edu`)

1. Downscaling of Flooding Guidance for Decision Support

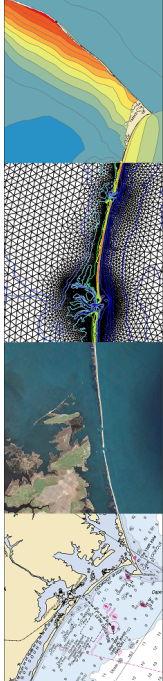
Examples for Matthew (2016) and Dorian (2019)

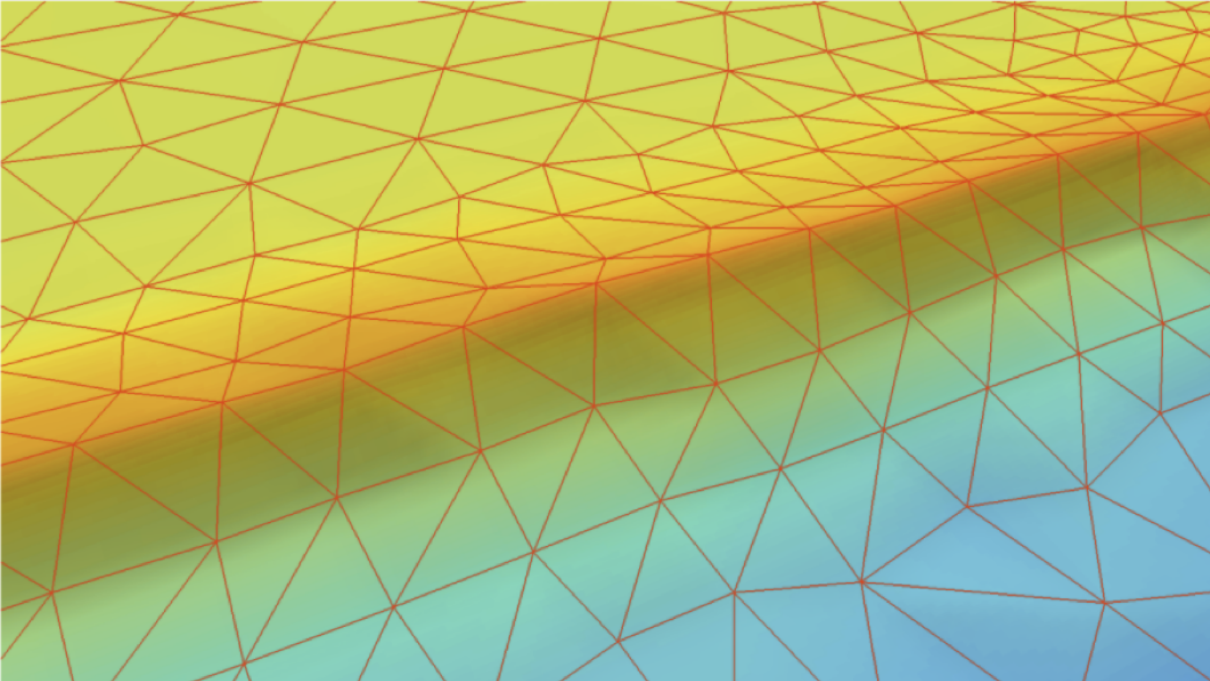


Downscaled Hindcasts for Dorian (2019)

This work has motivated our ongoing research:

- Can we be smarter about the downscaling?
  - Better parallelization of GRASS GIS techniques
  - Can the water surface slope be used in the extrapolation?
  - Can we account for friction losses due to varying land cover?
- Can we use the downscaling to replace the expensive parts of ADCIRC?
  - Coarsen the mesh in ADCIRC, and then add complexities in post-processing
  - Faster overall run-times
  - This is the focus of our NSF PREEVENTS project





2. Predictions of Coastal Erosion

Motivation & Methods

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

We are coupling with XBeach (eXtreme Beach):

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

Mechanics of Coupling:

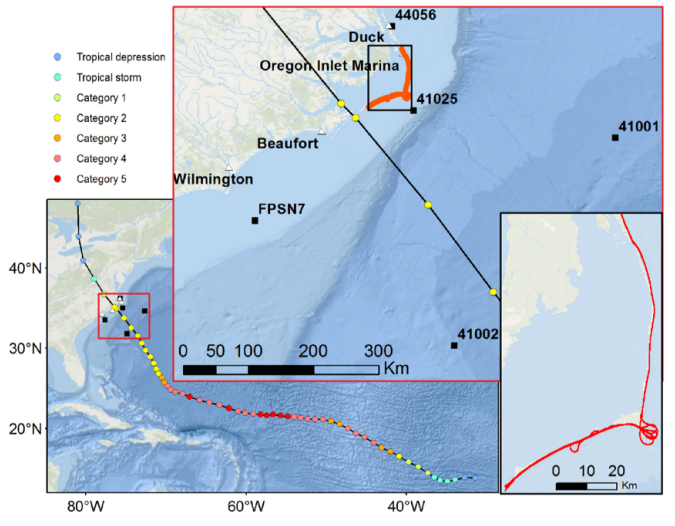
- Predict storm-driven erosion over large domains
- Develop techniques for coarsening predictions and coupling back to flooding models

Goals:

1. Validate XBeach erosion predictions on larger domains
   - Quantify model performance on 30-km of Hatteras Island during Isabel
2. Loose coupling of XBeach and ADCIRC
   - What are implications as a hydraulic control to stop or allow flooding?
   - How will ADCIRC predictions change with updated topography?

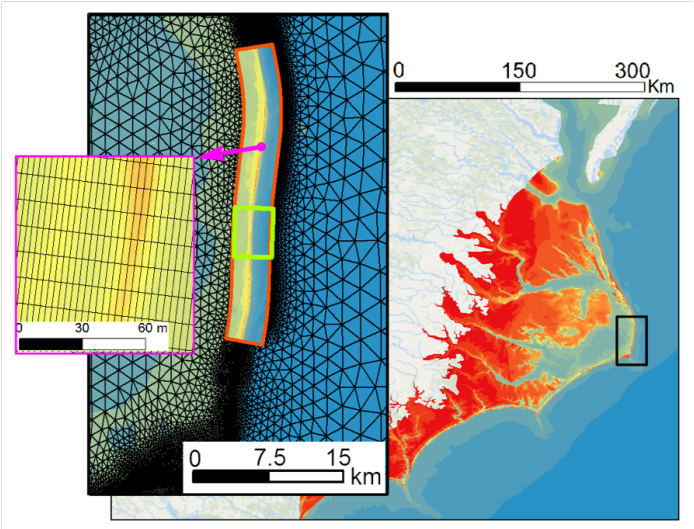
2. Predictions of Coastal Erosion

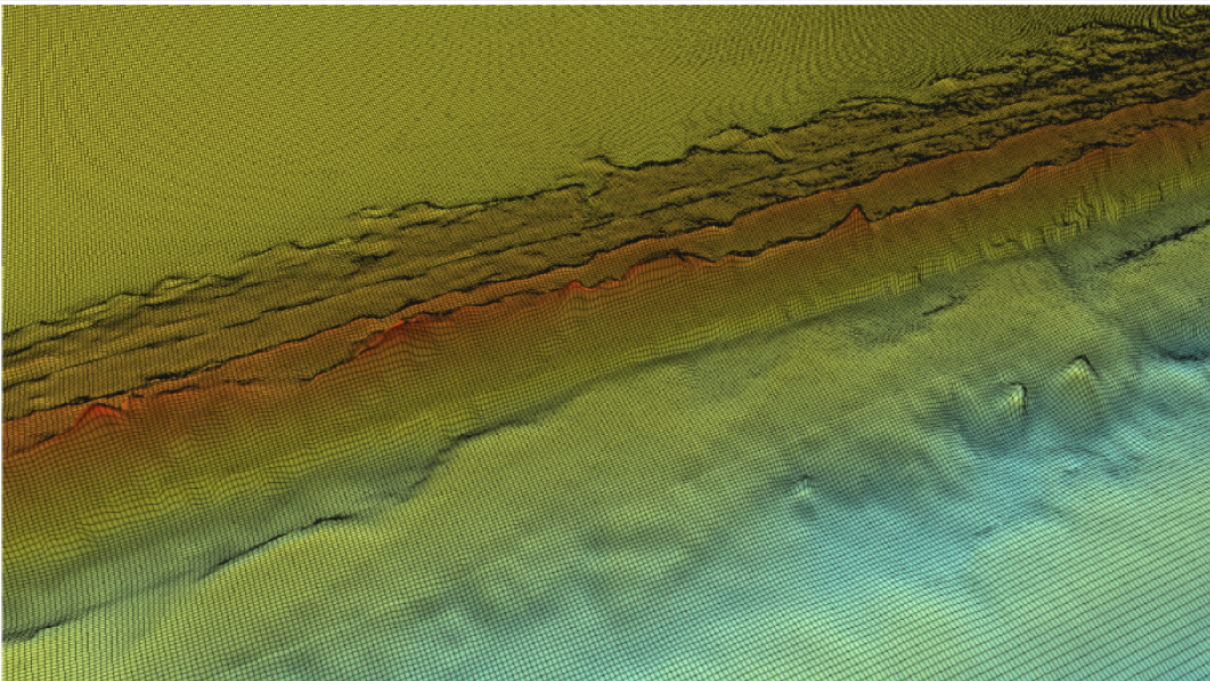
Example for Isabel (2003)



2. Predictions of Coastal Erosion

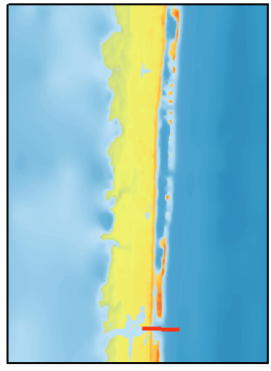
Example for Isabel (2003)

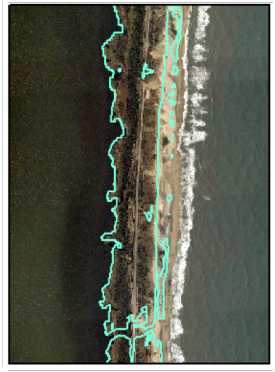


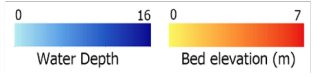


2. Predictions of Coastal Erosion

Example for Isabel (2003)

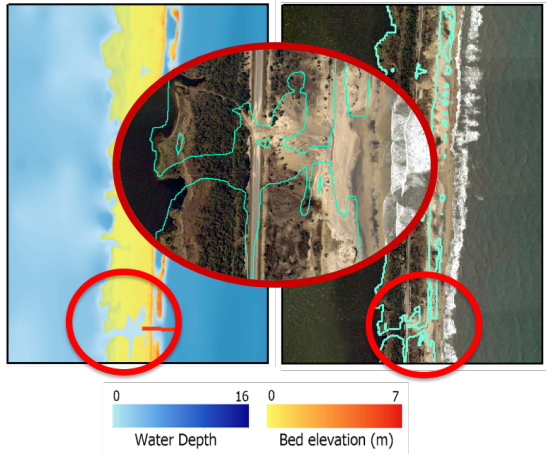






2. Predictions of Coastal Erosion

Example for Isabel (2003)



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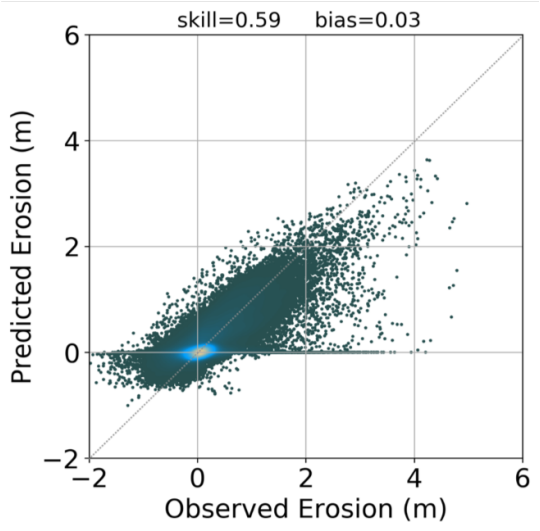

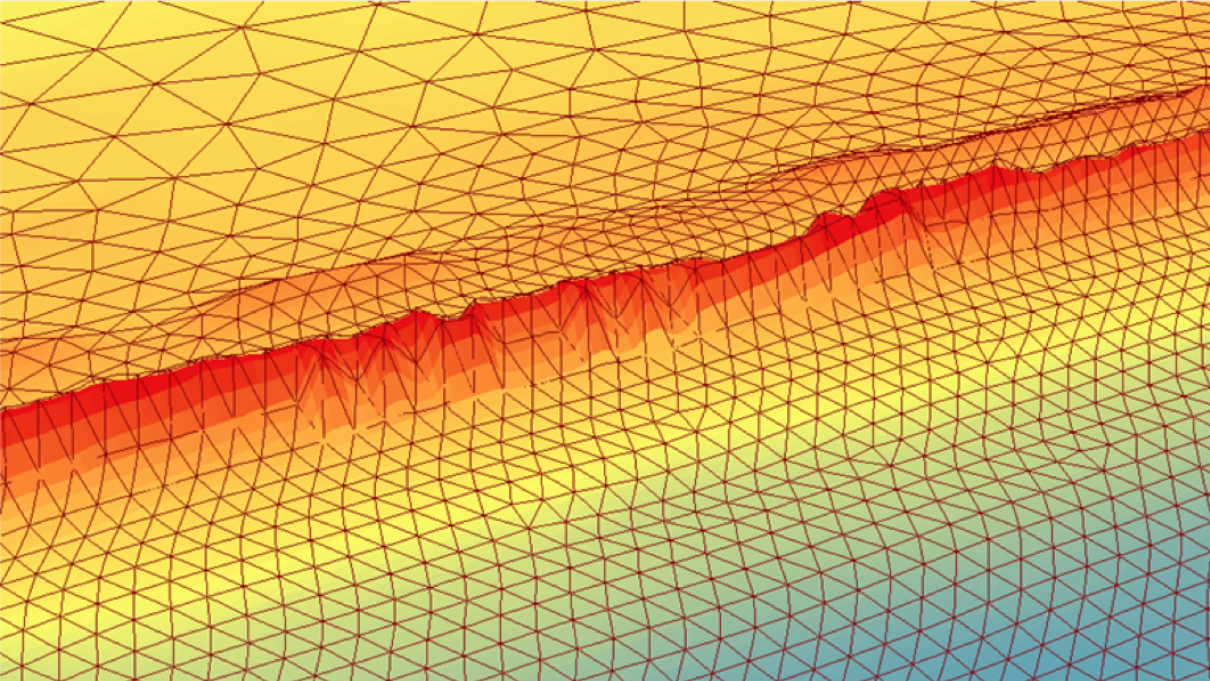

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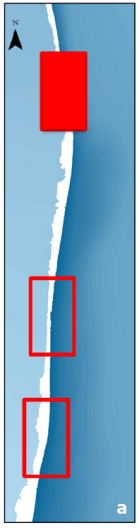
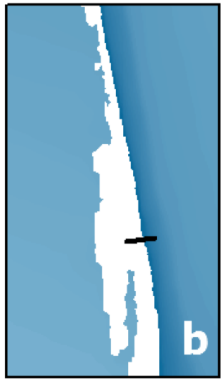
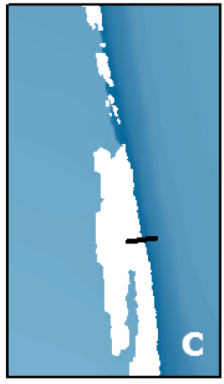
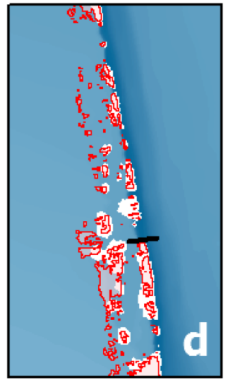


ADCIRC Simulations with Static Topography from ...

Observed Pre-Storm | Observed Post-Storm | XBeach Prediction



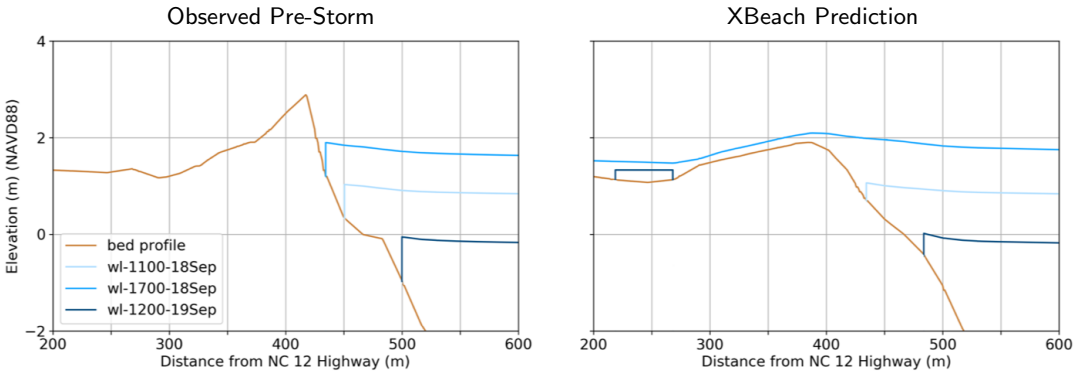


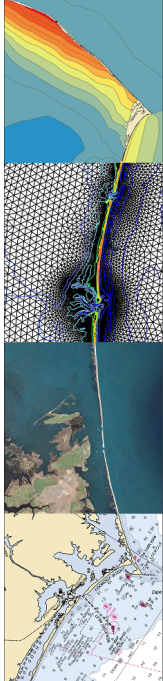


2. Predictions of Coastal Erosion

Example for Isabel (2003)

ADCIRC Simulations with Static Topography from ...





Summary and Future Work

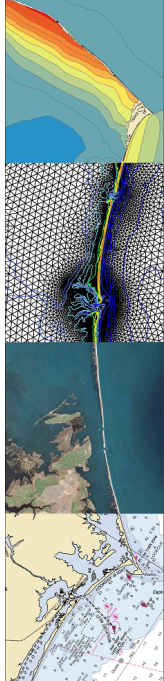
Forecasting and Mapping of Coastal Flooding during Hurricanes

Forecasting of Coastal Flooding in North Carolina:

- Available at: `www.adcirc.org`
- Providing guidance for recent storms:
  - Matthew, Harvey & Irma, Florence & Michael, Dorian

1. Downscaling of Flooding Guidance for Decision Support
   - Downscale our model results to DEM
   - Extrapolate into small-scale channels and floodplains
   - Provide automatically as GIS shapefiles

2. Predictions of Coastal Erosion
   - Preliminary results for Isabel (2003) are encouraging
   - Working to predict breaches of barrier islands



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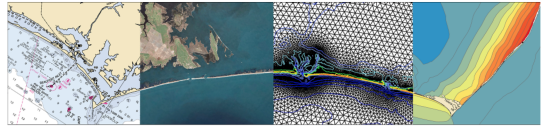
Latest ADCIRC Prediction System results for the US East and Gulf Coasts via the CERA web portal

ADCIRC is a system of computer programs for solving time dependent, free surface circulation and transport problems in two and three dimensions. These programs utilize the finite element method in space allowing the use of highly flexible, unstructured grids. Typical ADCIRC applications have included:

- prediction of storm surge and flooding
- modeling tides and wind driven circulation
- larval transport studies
- near shore marine operations
- dredging feasibility and material disposal studies

ccht.ccee.ncsu.edu

NC STATE UNIVERSITY Coastal & Computational Hydraulics Team



What We Do | Join Our Team | FigureGen | Kalpana | SWAN+ADCIRC

Welcome to the CCHT! We develop computational models for wind waves and coastal circulation, and then apply these models to high-resolution simulations of ocean behavior. Our goals are to understand how coastlines are threatened during storms, how materials are transported in the coastal environment, and how to communicate these hazard risks for use in decision support. Our research spans the disciplines of coastal engineering, numerical methods, computational mathematics, and high-performance computing.

MEET OUR TEAM

Faculty

Casey Dietrich | Posts | CV

Post-Doctoral Researchers

Dylan Anderson | Posts | CV

Graduate Students

Ajimon Thomas | Posts | CV

Alireza Gharagozlou | Posts | CV

Johnathan Woodruff | Posts | CV

Autumn Poisson | Posts | CV

Carter Rucker | Posts | CV

Undergraduate Students

Chloe Stokes

Carter Howe