Forecasting and Mapping of Coastal Flooding during Hurricanes

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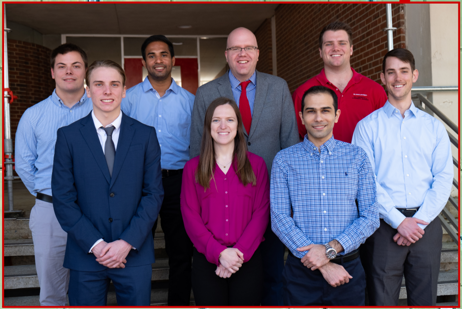
UNCW Department of Earth and Ocean Sciences
Wilmington NC, 1 Nov 2019

NC STATE UNIVERSITY



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

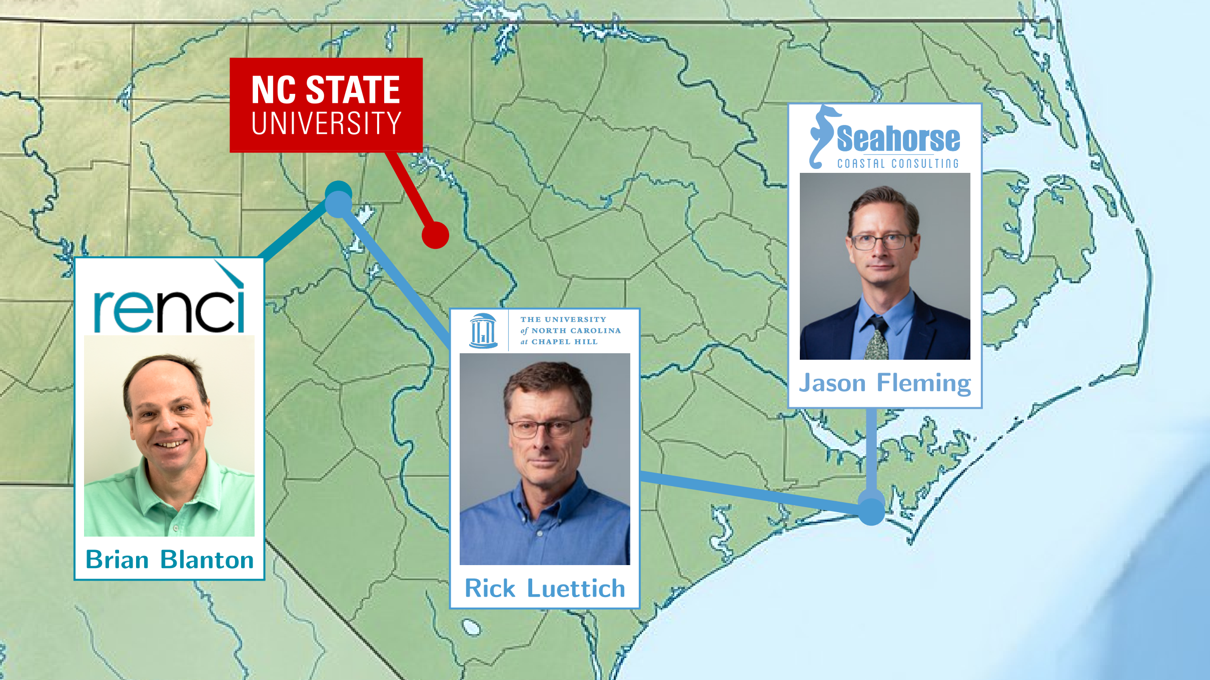
- Institute for Computational Engineering and Sciences
  - Research Associate: 09/2012 to 07/2013
  - Postdoctoral Researcher: 11/2010 to 08/2012

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
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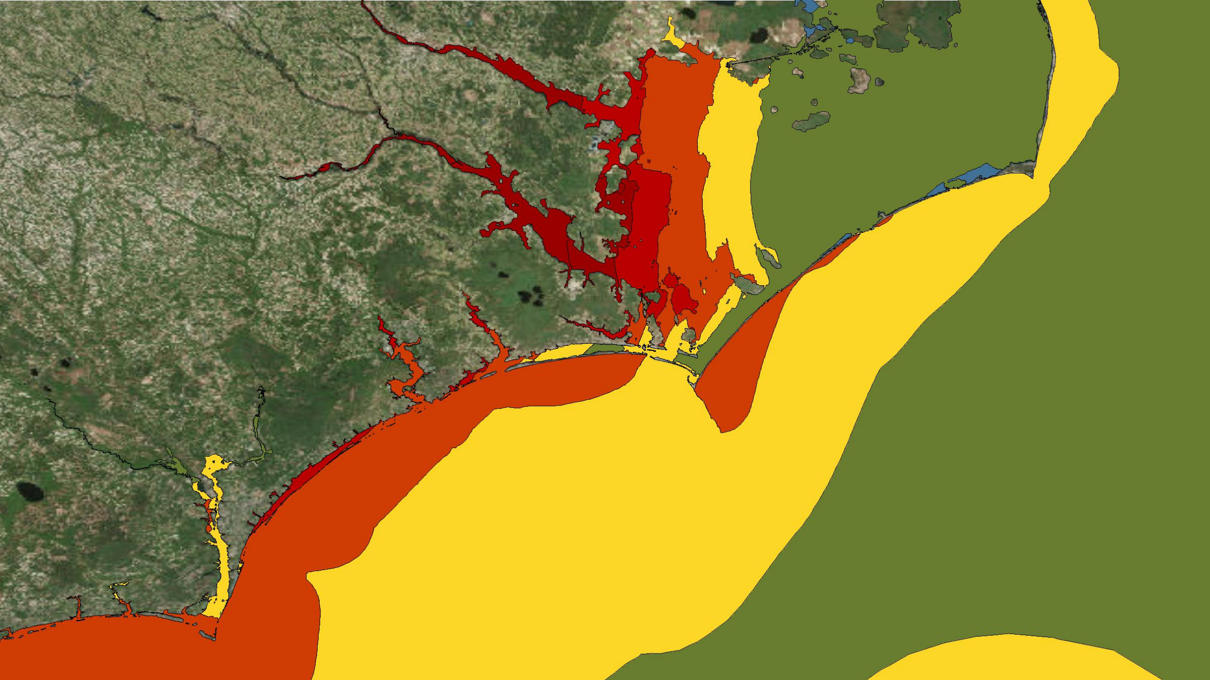
of NORTH CAROLINA
at CHAPEL HILL
Rick Luettich



Forecasting of Coastal Flooding in North Carolina

- Models for Waves and Coastal Circulation
- Real-Time Forecasting
- Florence (2018)

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   - Motivation & Methods
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   - Inlet Creation
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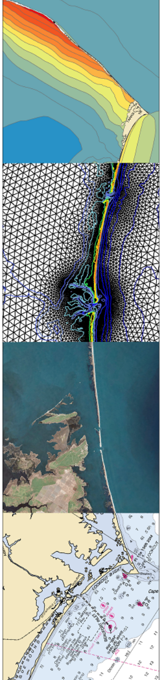
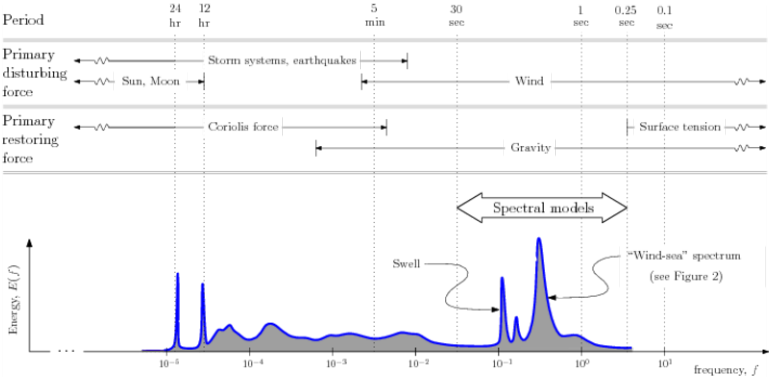
Summary and Future Work



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

Models for Waves and Coastal Circulation

SWAN (Simulating WAves Nearshore)

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:

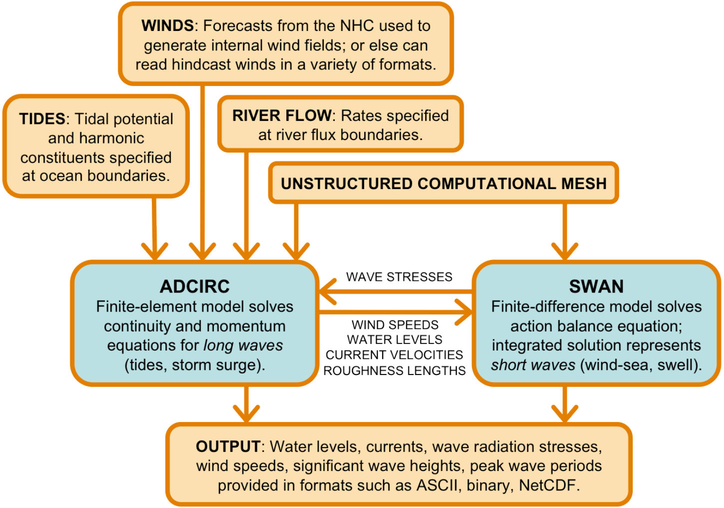
$$\frac{\partial N}{\partial t} + \nabla_{\mathbf{x}} \cdot \left[\left(\mathbf{c}_g + \mathbf{U} \right) N \right] + \frac{\partial c_\theta N}{\partial \theta} + \frac{\partial c_\sigma N}{\partial \sigma} = 0$$

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

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

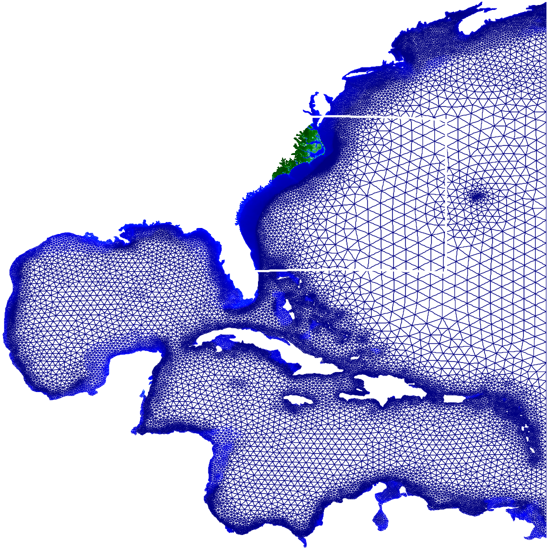
Models for Waves and Coastal Circulation

Tightly-Coupled SWAN+ADCIRC



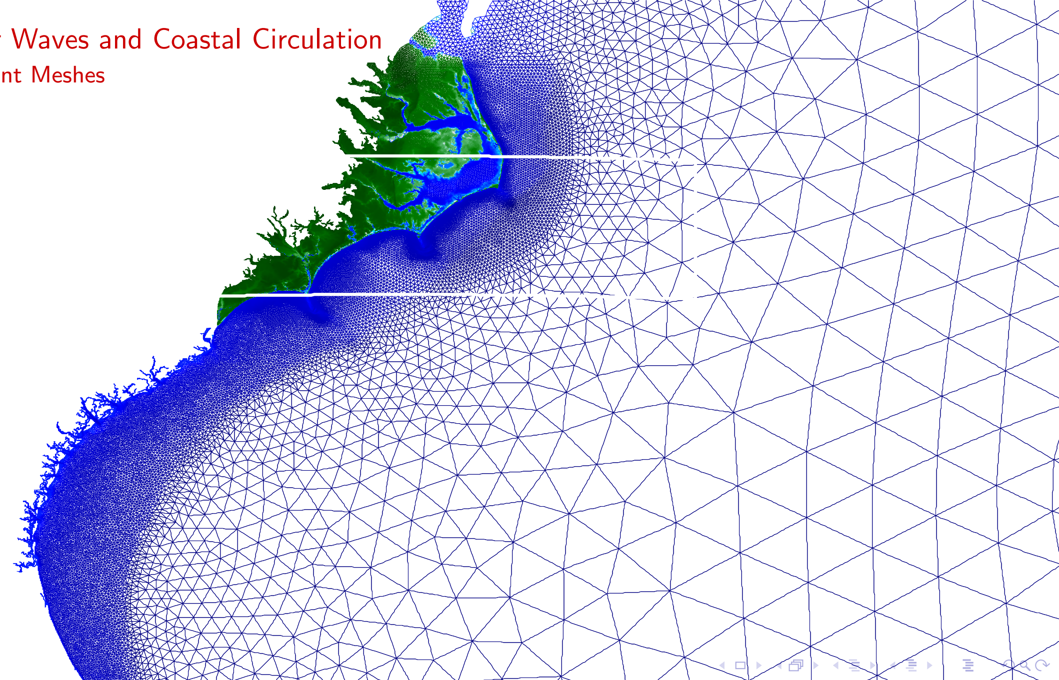
Models for Waves and Coastal Circulation

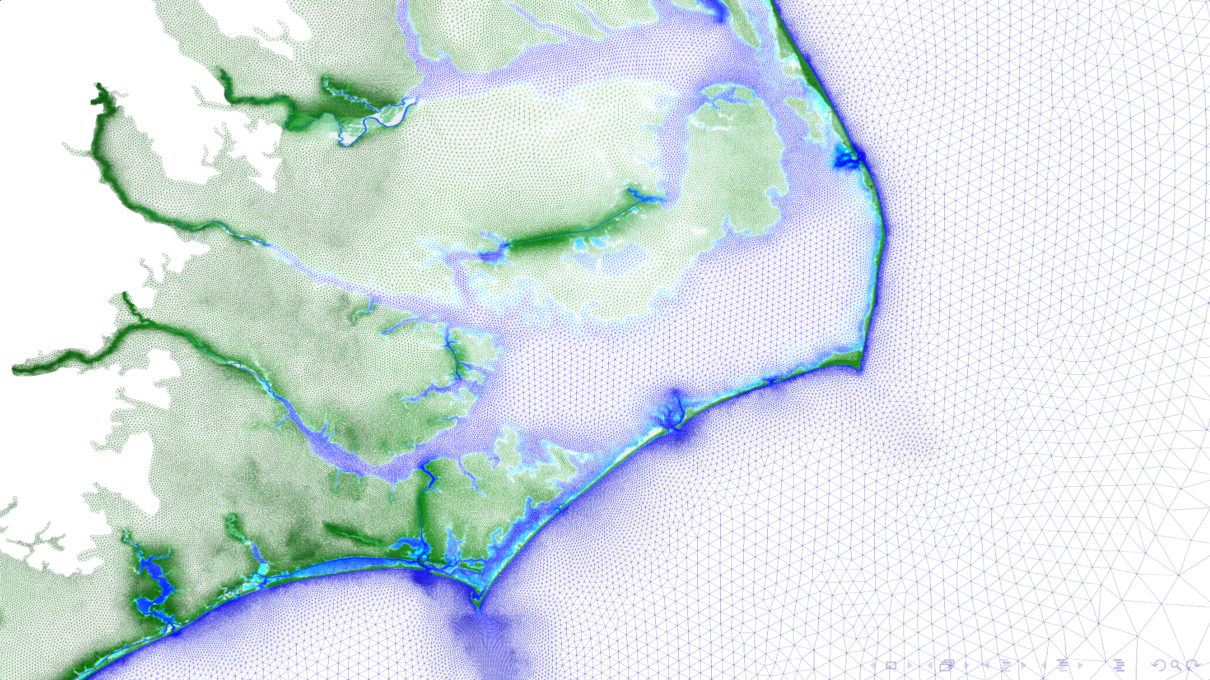
Finite Element Meshes

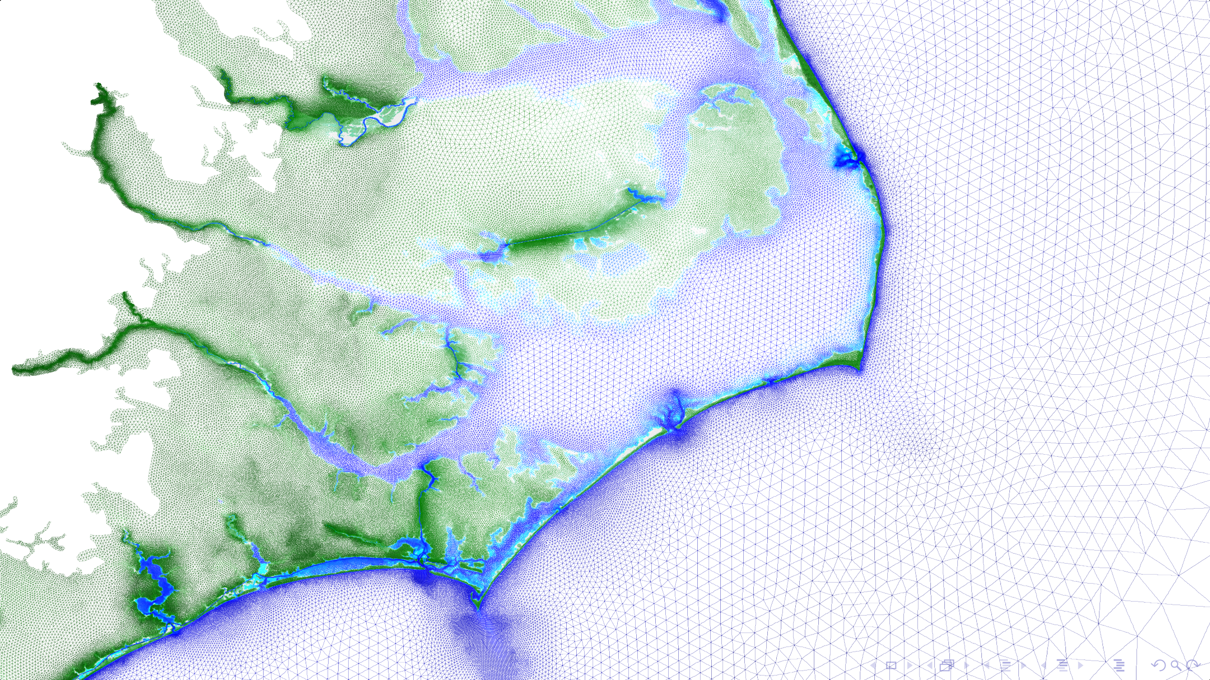


Models for Waves and Coastal Circulation

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`)

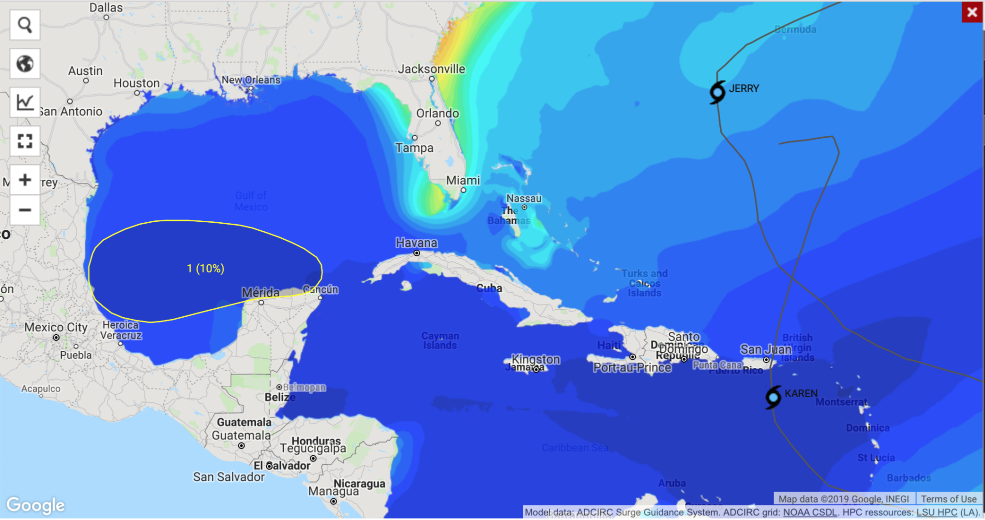
CERA Coastal Emergency Risks Assessment
ADCIRC storm surge and wave guidance

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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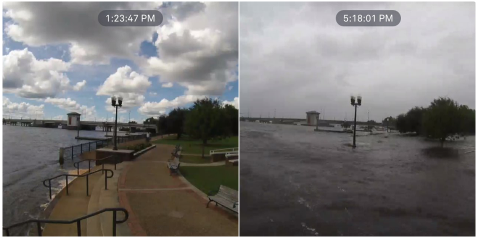
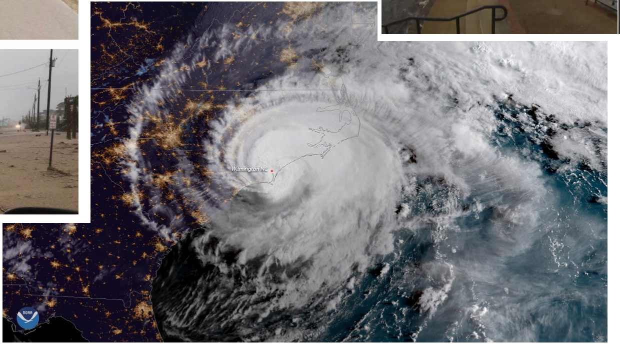
Florence (2018)

Extensive Impacts to Coastal NC

Union Point in New Bern NC (@NWSEastern)



Surf City NC (@AdamWGME)

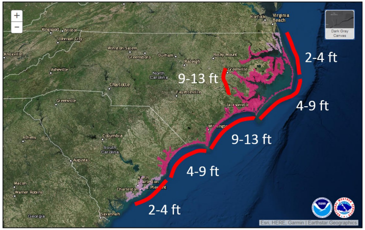


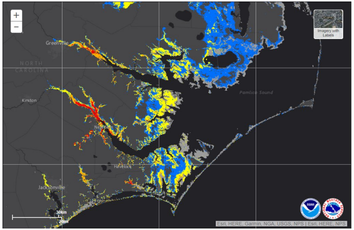
Florence making landfall on Fri Sep 14 (@NOAASatellites)

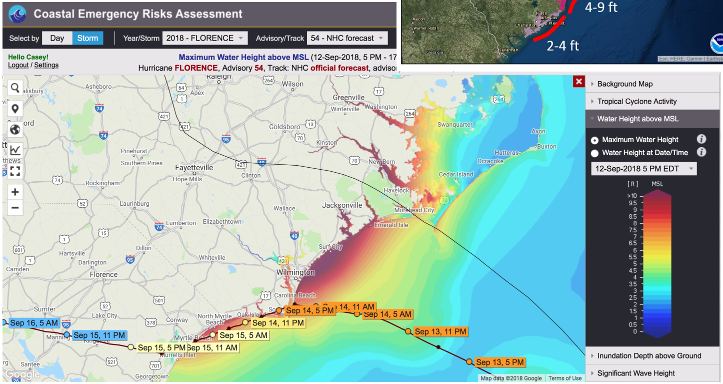
Florence (2018)

Forecasts of Storm Surge

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



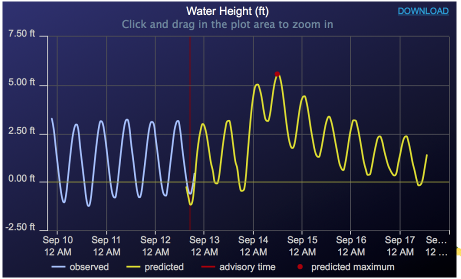


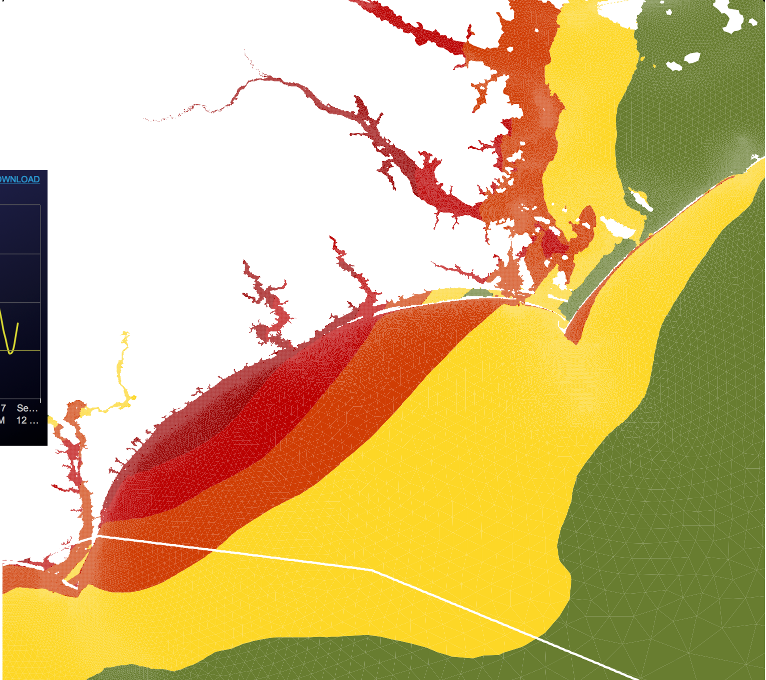


ADCIRC maximum water levels for Advisory 54 (CERA)

Florence (2018)

Adv 54 – Sep 12 Wed 5pm





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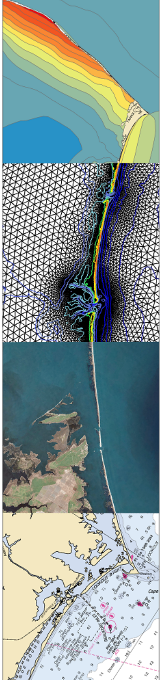
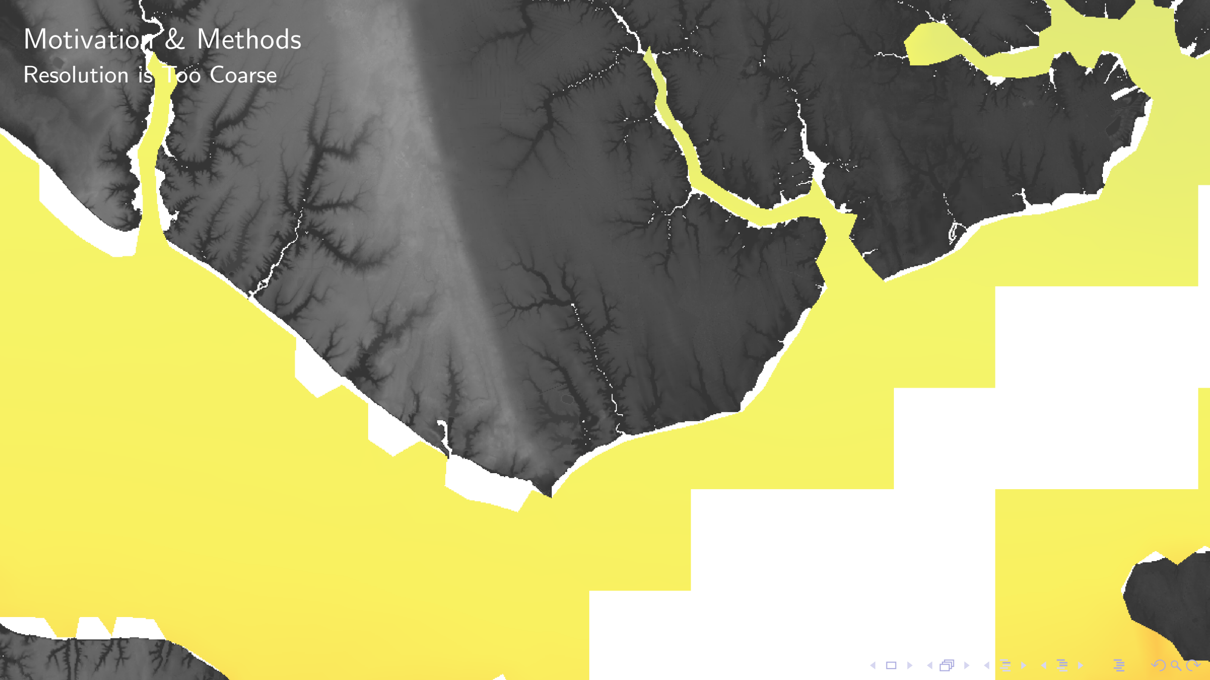


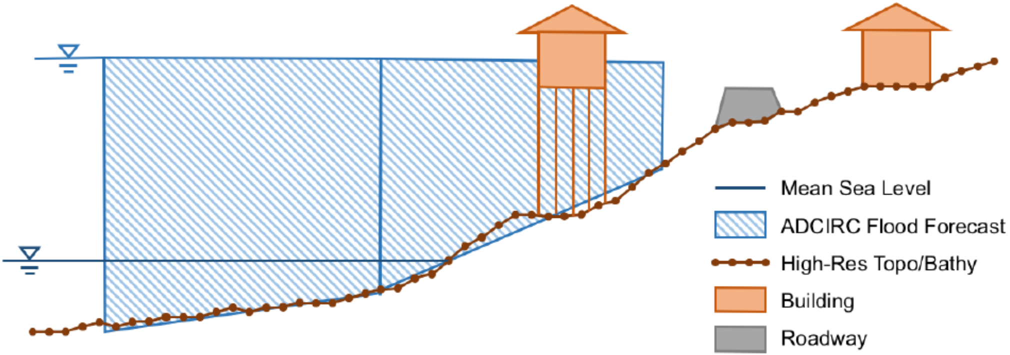
Motivation & Methods

Resolution is Too Coarse



Motivation & Methods

Schematic of Resolution Differences



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

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

Matthew (2016) and Dorian (2019)

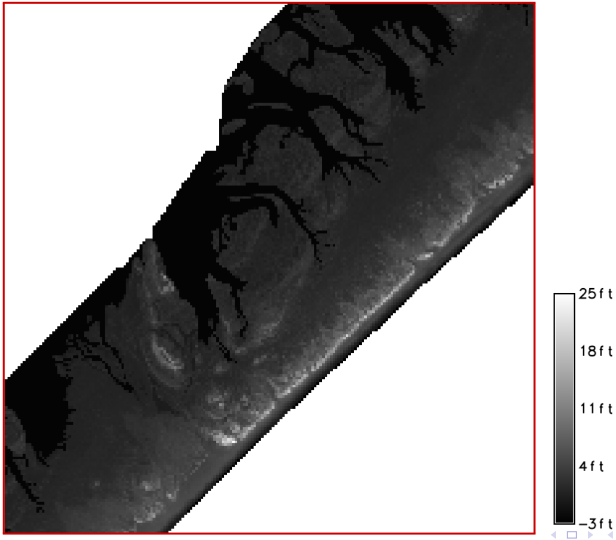
Carteret County

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

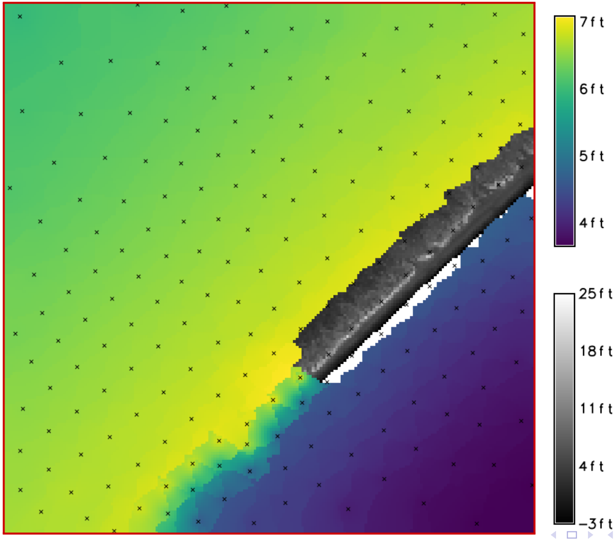
Matthew (2016) and Dorian (2019)

Process to Enhance Resolution



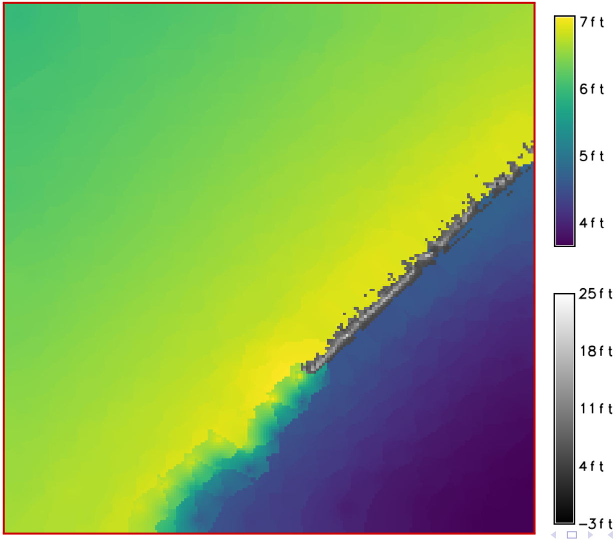
Matthew (2016) and Dorian (2019)

Process to Enhance Resolution



Matthew (2016) and Dorian (2019)

Process to Enhance Resolution



Matthew (2016) and Dorian (2019)
Real-Time Forecast Products

We are now providing the enhanced guidance to our partners

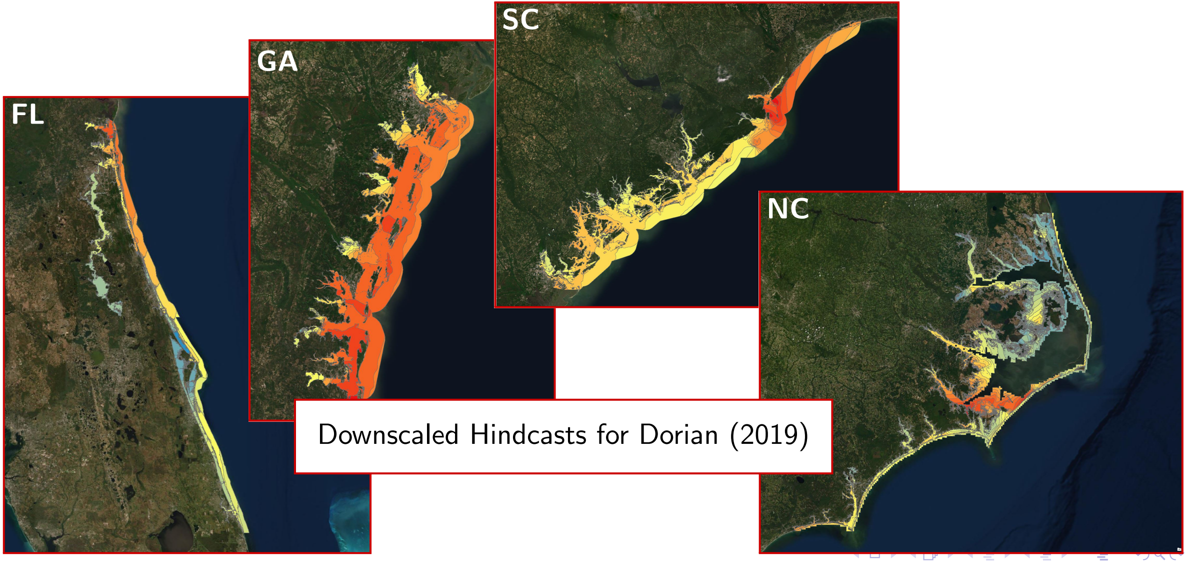
- During hurricane season, we use an automated script on our cluster at NCSU:
  - Detects when ADCIRC results are posted to the archive
  - Downloads the maximum water levels
  - Runs the enhanced-resolution process
- Recent storms:
  - 2017 – Harvey & Irma
  - 2018 – Florence & Michael
  - 2019 – Dorian

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`)

Matthew (2016) and Dorian (2019)

Enhanced Products for Dorian



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

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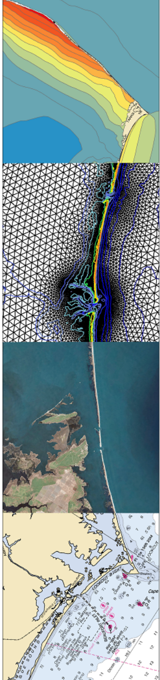


Inlet Creation

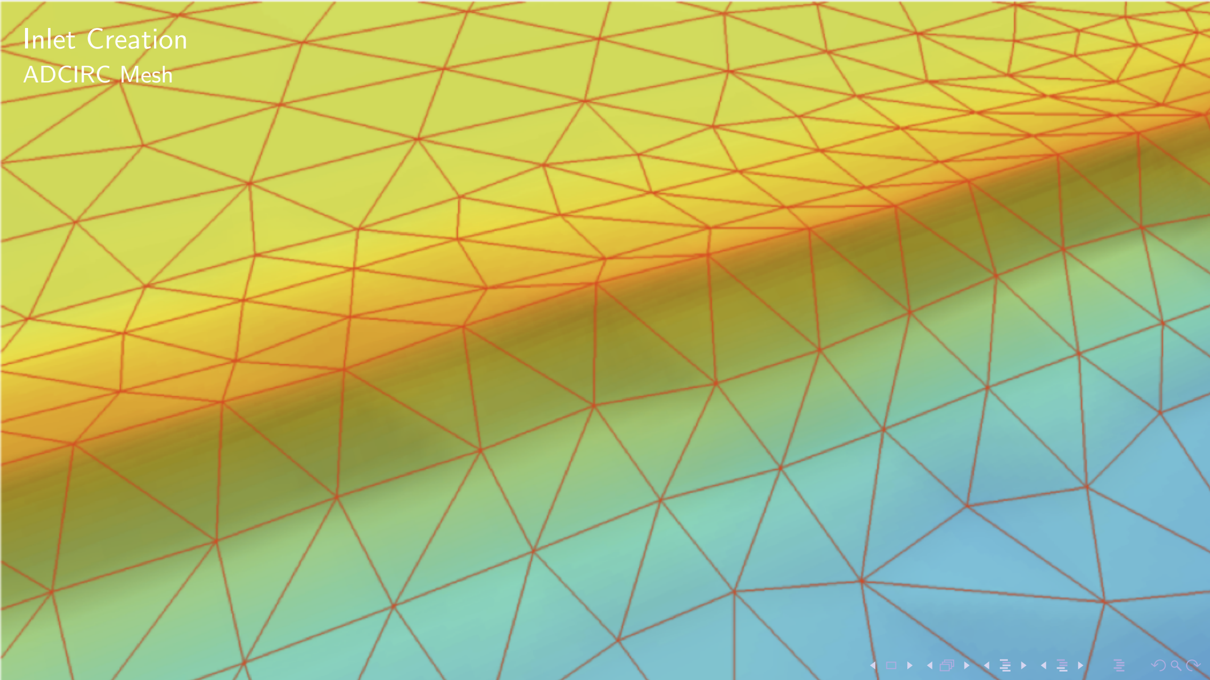
Isabel Inlet (2003)

Inlet Creation

Aerial Photo of Hatteras Island

Inlet Creation

ADCIRC Mesh



Inlet Creation

Motivation

Our forecast system is limited:

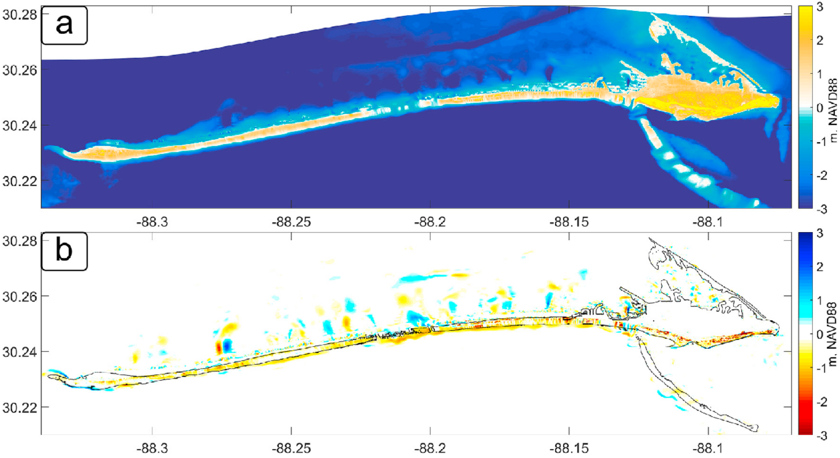
- Bathymetry and topography are fixed / constant
- No consideration of beach erosion, dune breaching, etc.
- Flooding impacts are limited behind the dunes

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)

Inlet Creation

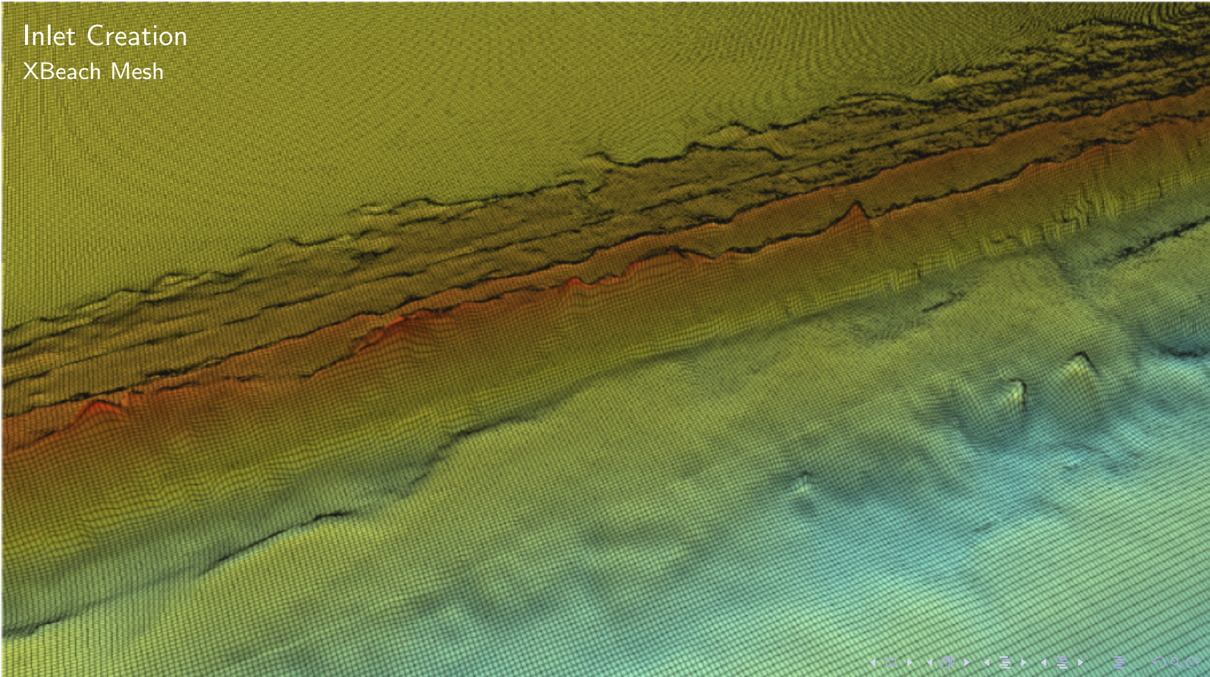
eXtreme Beach (XBeach)



Passeri et al. (2018)

Inlet Creation

XBeach Mesh



Goals:

1. Better understand the storm-induced erosion of barrier islands
2. Develop ways to represent that erosion in predictive models on large domains

Objectives:

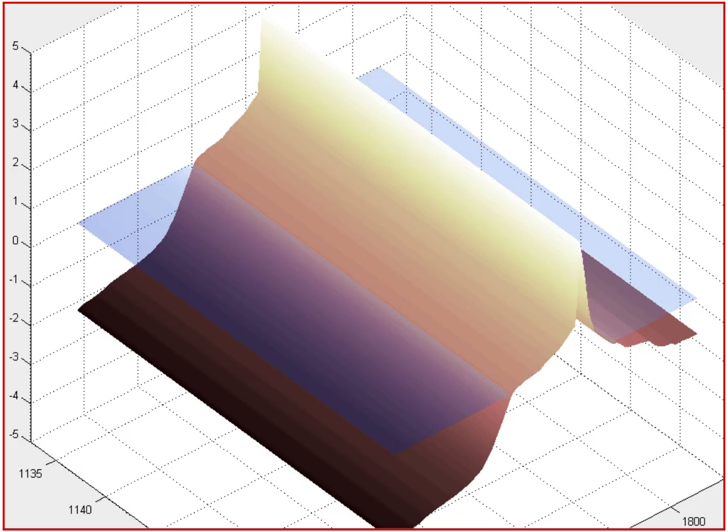
1. Develop a high-resolution hindcast of inlet creation in a barrier island system
2. Explore the sensitivity of erosion predictions to the quality of input data
3. Implement a two-way coupling of small-scale erosion to larger-scale flooding

We used a combination of XBeach and ADCIRC modeling:

- **Idealized Domain** – Uniform geometry, smooth hydrodynamic forcing
  - XBeach:
    - Can we initiate the inlet formation?
    - Can we control the location of the inlet?
- **Isabel Inlet** – Real geometry, real hydrodynamic and atmospheric forcing
  - XBeach:
    - How much of a ‘seed’ is necessary?
    - Instead of calibration factors, can we use bed friction?
  - ADCIRC:
    - Can we use the erosion timing from XBeach to inform the variation of the bathymetry in ADCIRC?

Idealized Domain

Barrier Island with Uniform Cross-Section



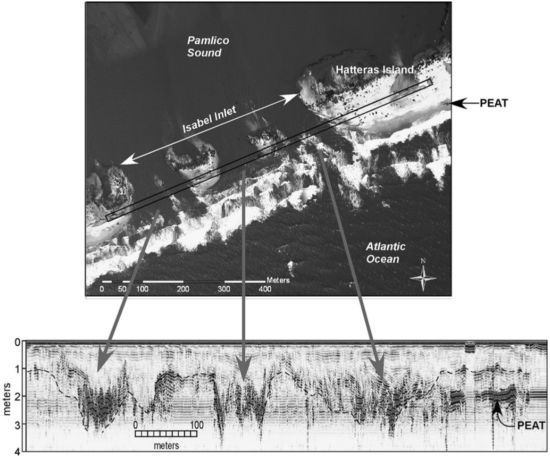
We explored sensitivity of:

- Grid resolution
- Waves and water-level forcing
- XBeach input parameters
- Presence of an initial cut or channel

Findings:

- XBeach has a tendency to widen a breach, but not deepen it
- How can we initiate the formation of a true inlet?
- How can we utilize sub-surface geologic information?

Idealized Domain
Sub-Surface Geology



Mallinson et al. (2010)

Idealized Domain

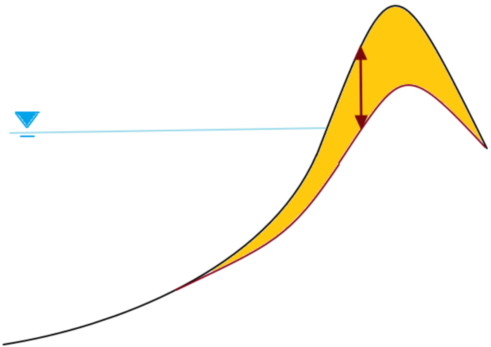
Use of Non-Erodible Layer

So we added a non-erodible layer:

- Specified as a second ground surface as input to XBeach
- Erosion is computed until the ground surface is lowered to the non-erodible layer
- Then erosion is stopped

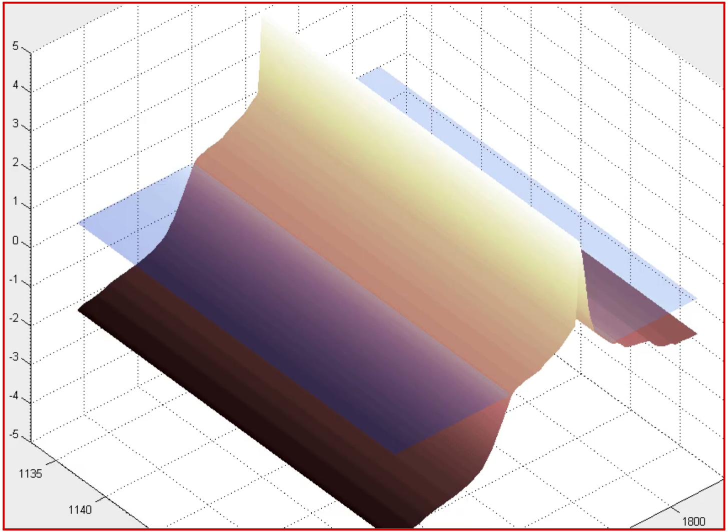
Used first on the idealized domain:

- Allowed erosion in the channel
- Prevent erosion in the beaches and dunes



Idealized Domain

Inlet is Created

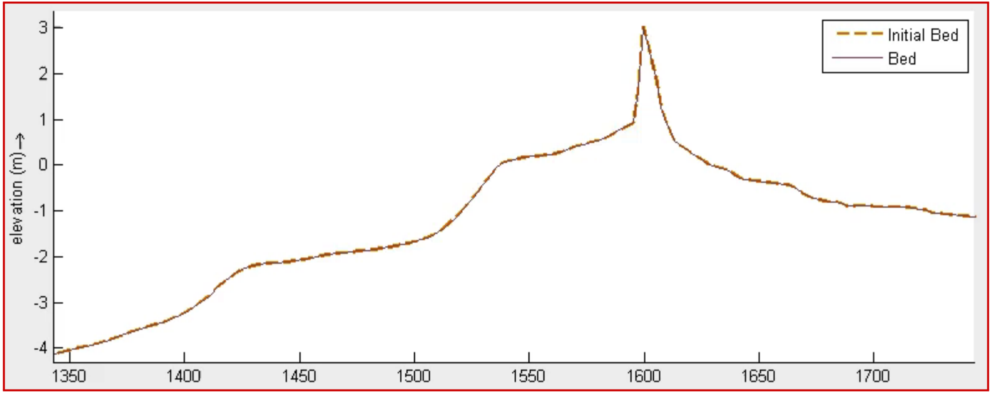


Idealized Domain

Success of Inlet Creation

Now we can erode a full channel:

- Without any initial seed, the full beach and dune are removed
- Animation of ground surface at centerline of channel:



Isabel (2003)

Pre-Storm Ground Surface

Isabel (2003)

Post-Storm Ground Surface

Isabel (2003)

XBeach Grid

Domain Size:

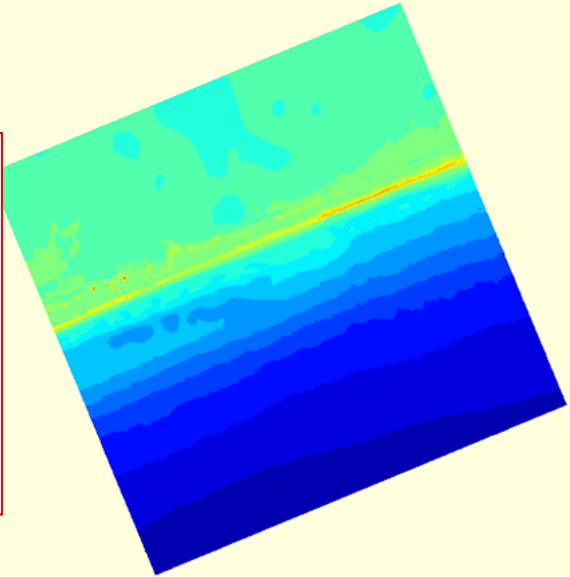
- 2.2 km $\times$ 2.2 km

Resolution:

- Alongshore: 2 to 5 m
- Cross-shore: 2 to 15 m

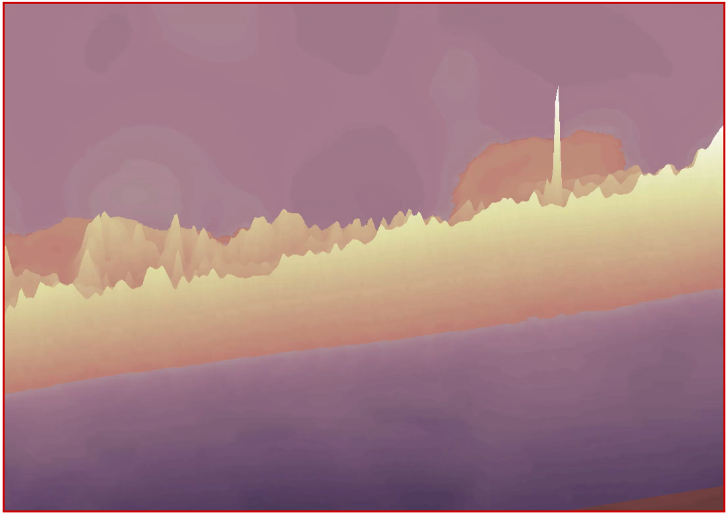
Layers:

- Pre-storm: bathy/topo
- Post-storm: non-erodible



Isabel (2003)

XBeach Hindcast of Inlet Creation



Isabel (2003)

Coupling from XBeach to ADCIRC

Remaining questions:

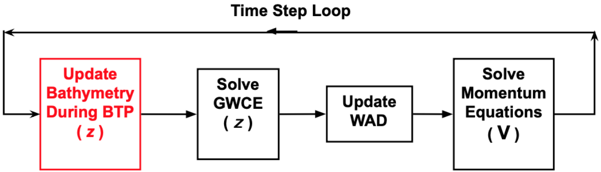
- Is it possible for XBeach to predict this inlet creation, without the erodible layer?
  - Exploring ways to slow the erosion by adjusting the maximum Shields parameter
  - Exploring ways to control location via variable bed friction
- How to connect to ADCIRC?
  - Can we use the erosion predictions to inform the flooding predictions?

Isabel (2003)

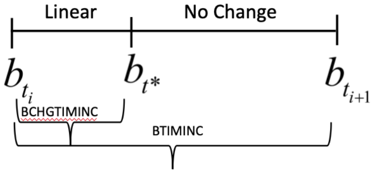
Use of Time-Varying Bathymetry

USACE's Dr. Chris Massey added capability for time-varying bathymetry:

- Occurs at start of time step:



- Control over timing during simulation:



We created ADCIRC input files with the erosion

- Changes in ground surface, specified at only the vertices near the breach

Location and magnitude of erosion is coming from the post-storm survey

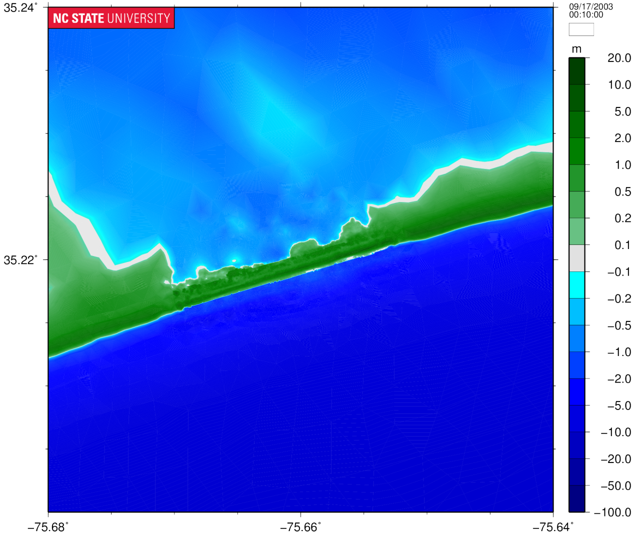
- Similar to the non-erodible layer in XBeach
- Need more work with XBeach to gain predictions of inlet creation

Timing of erosion is coming from XBeach

- Controlling the erosion over 1 day, during the landfall of the storm
- Incremental variations:
  - Changes over 1 hour
  - Static over 2 hours
- Repeat over 1 day

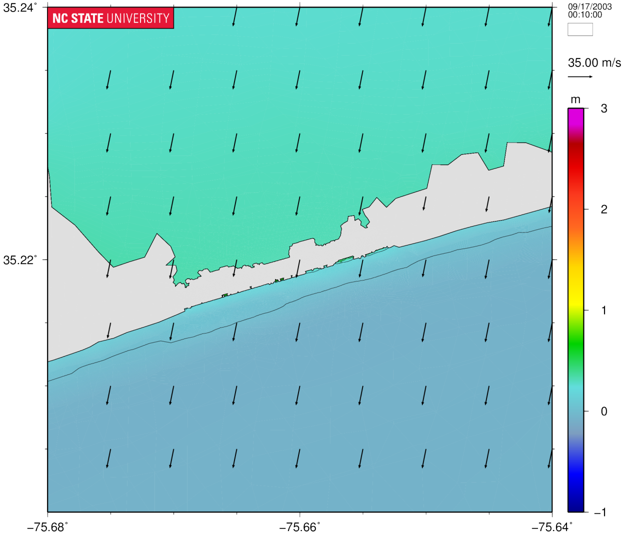
Isabel (2003)

Erosion over 1 Day



Isabel (2003)

Erosion over 1 Day



Forecasting of Coastal Flooding in North Carolina

- Models for Waves and Coastal Circulation
- Real-Time Forecasting
- Florence (2018)

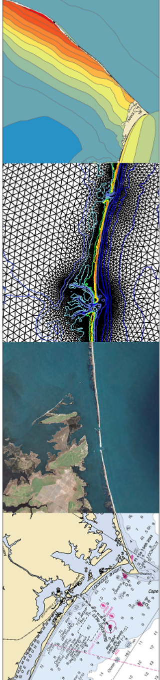
1. Downscaling of Flooding Guidance for Decision Support

- Motivation & Methods
- Matthew (2016) and Dorian (2019)

2. Predictions of Coastal Erosion

- Inlet Creation
- Idealized Domain
- Isabel (2003)

Summary and Future Work



Summary and Future Work

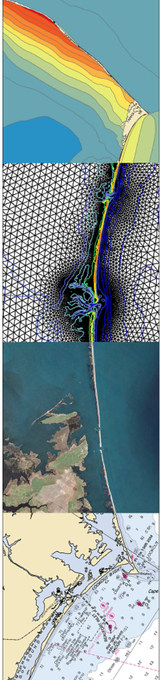
Forecasting and Mapping of Coastal Flooding during Hurricanes

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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