Predictive Modeling for Storm Surge and Flooding Risks in North Carolina

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UNC Department of Geological Sciences
Chapel Hill NC, 14 September 2017

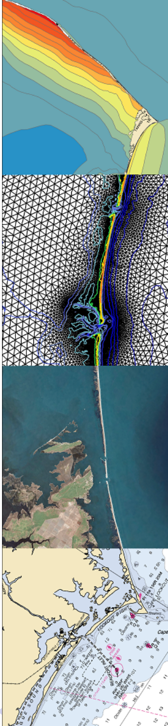
Models for Hurricane Waves and Storm Surge

- Real-Time Forecasting
- Expanding Guidance for End Users
- Downscaling and Extrapolation
- Examples in Carteret County
- Enhanced Guidance for Entire NC Coast

Considering Erosion of Beaches and Dunes

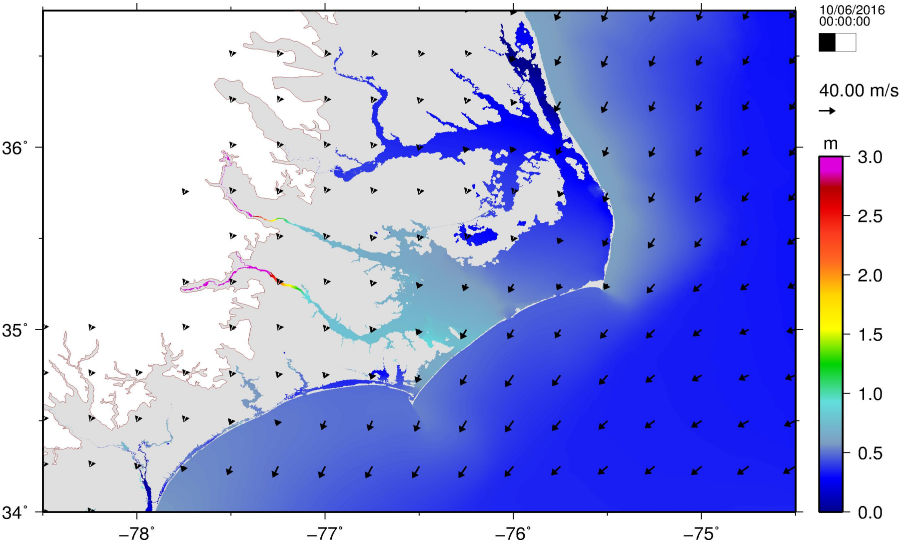
- Exploring Morphodynamics during Isabel (2003)
- Model Setup for XBeach
- Initial Results with XBeach
- Mesh Resolution Sensitivity

Summary and Future Work



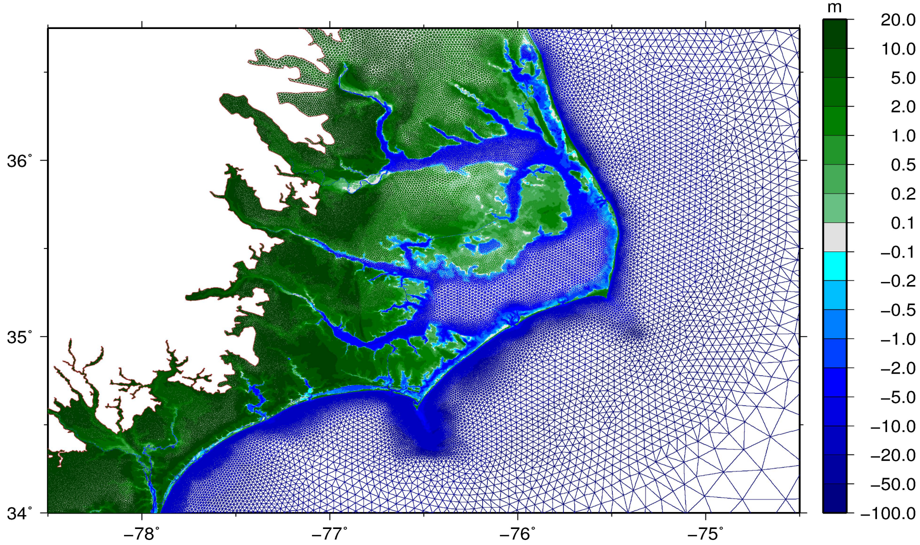
Models for Hurricane Waves and Storm Surge

Hurricane Matthew (2016) – Water Levels in North Carolina



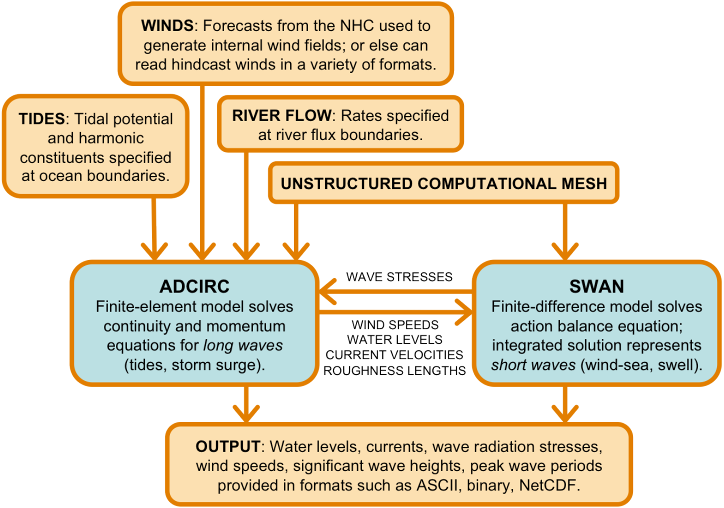
Models for Hurricane Waves and Storm Surge

Finite-Element Mesh for NC Coast



Models for Hurricane Waves and Storm Surge

Tight Coupling of SWAN+ADCIRC



JC Dietrich, et al. (2011). Modeling Hurricane Waves and Storm Surge using Integrally-Coupled, Scalable Computations. *Coastal Engineering*, 58, 45-65, DOI:10.1016/j.coastaleng.2010.08.001.

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:

- 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)

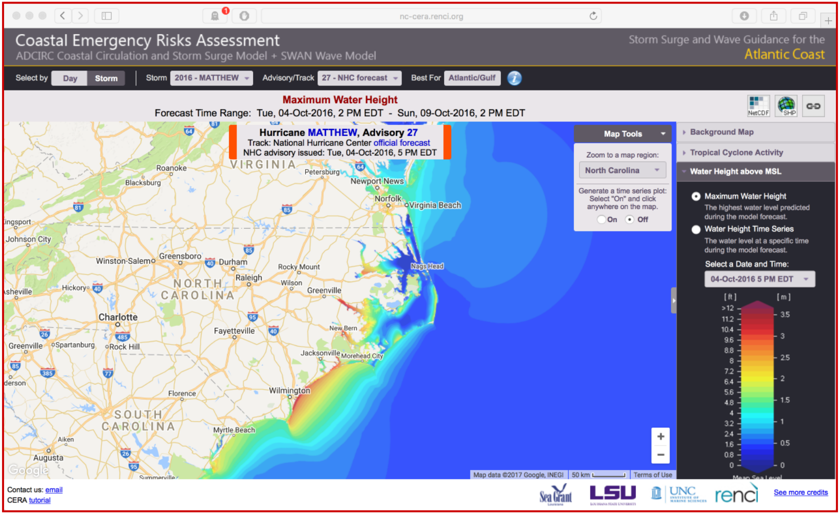
Guidance can be shared in multiple formats:

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

Real-Time Forecasting

Coastal Emergency Risks Assessment (CERA, `http://www.adcirc.org`)

Hurricane Matthew (2016) Advisory 27 - Consensus



Real-Time Forecasting

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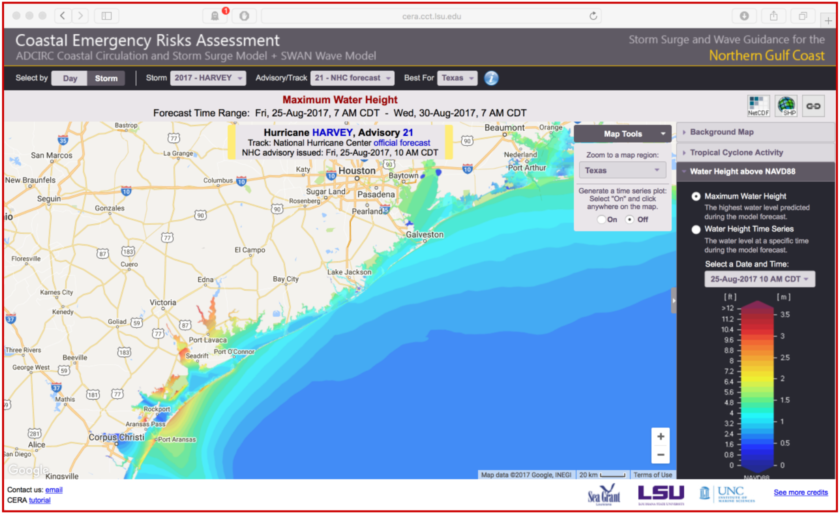
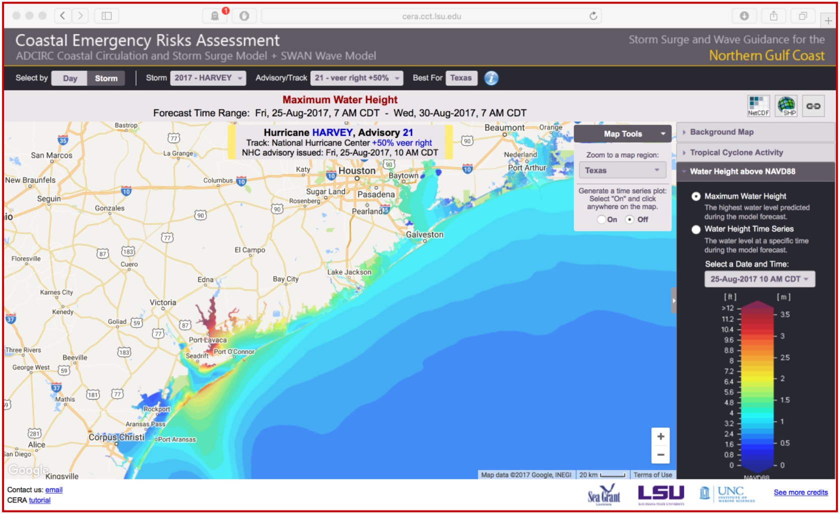
Hurricane Harvey (2017) Advisory 21 - Consensus



Real-Time Forecasting

Coastal Emergency Risks Assessment (CERA, `http://www.adcirc.org`)

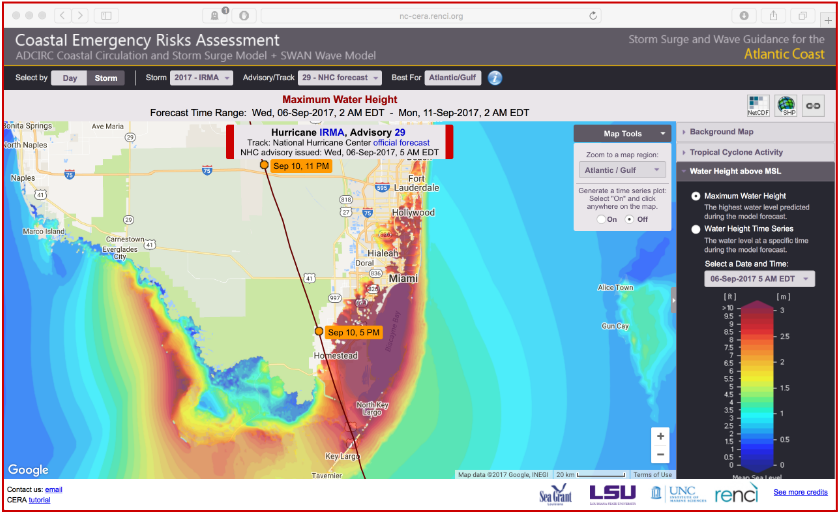
Hurricane Harvey (2017) Advisory 21 - Veer Right 50%



Real-Time Forecasting

Coastal Emergency Risks Assessment (CERA, `http://www.adcirc.org`)

Hurricane Irma (2017) Advisory 29 - Consensus



Expanding Guidance for End Users

Conversion of Output Products to Other Formats

Some partners prefer guidance in other formats:

- Polygon-based formats:
  - Shapefiles and ancillary files for GIS
  - KML files for Google Earth
- These files can be overlaid with information from other sources

We developed Python-based scripts to convert SWAN+ADCIRC output

- Based on scripts from BO Blanton, RA Luettich
- Expanded to consider time series information, KML formats

Now sharing guidance in these formats with partners at North Carolina Emergency Management (NCEM), NWS offices, state and local emergency management teams

- **Guidance products are generated and shared automatically**

Expanding Guidance for End Users

Differences in Horizontal Resolution

We want to enhance the flooding guidance we provide to NCEM

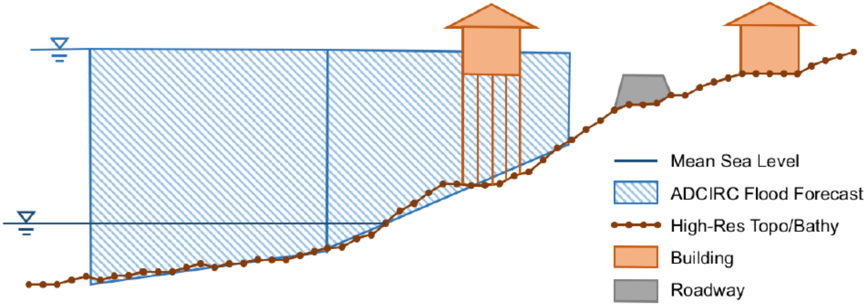
- Now we provide water levels at our model resolution
  - Use an unstructured *mesh* with unequal spacings
  - More than 600K points
  - Minimum spacing of about 50 to 100 m
- NCEM wants to combine with other datasets
  - Use a structured *raster* with equal spacing
  - More than 400M cells
  - High-resolution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

Need to do two things:

1. *Downscale* – Increase resolution to match their high-resolution topography datasets
2. *Extrapolate* – Extend our flooding guidance into small-scale coastal regions that cannot be represented by our model

Expanding Guidance for End Users

Downscaling and Extrapolating the Coastal Flood Forecasts



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

- Available as open-source software (`https://grass.osgeo.org`)
- Developed partly by Prof. Mitasova and others in the NCSU 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 ADCIRC water levels are greater than the ground surface
  - Remove isolated (not hydraulically-connected) cells
- Convert the new "grown" raster to polygon format for distribution

Examples in Carteret County

Testing in a Realistic Setting

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

Examples in Carteret County

Zoom of Cape Lookout National Seashore

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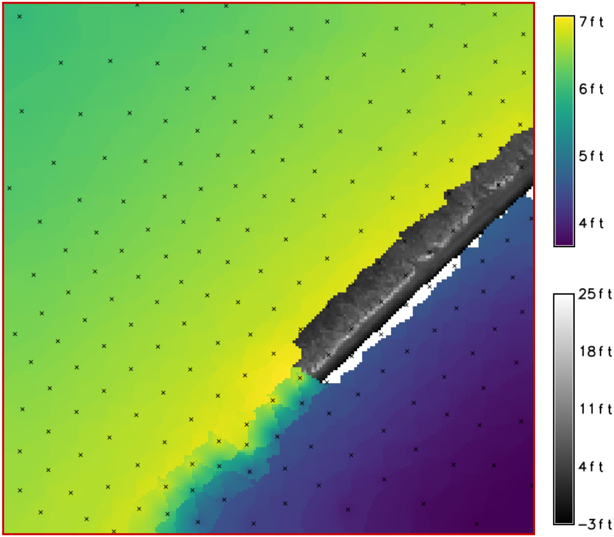
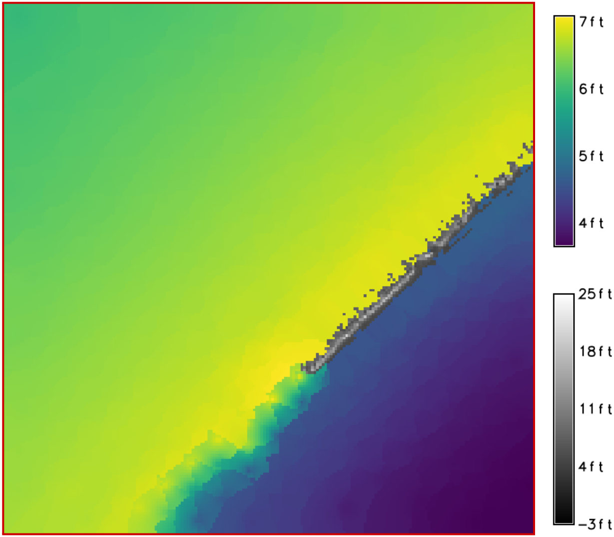


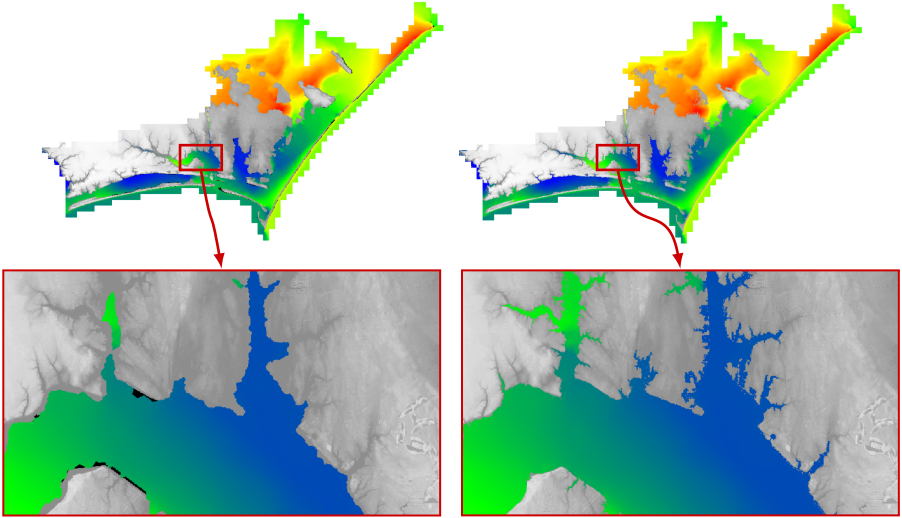
Examples in Carteret County

Zoom of Cape Lookout National Seashore

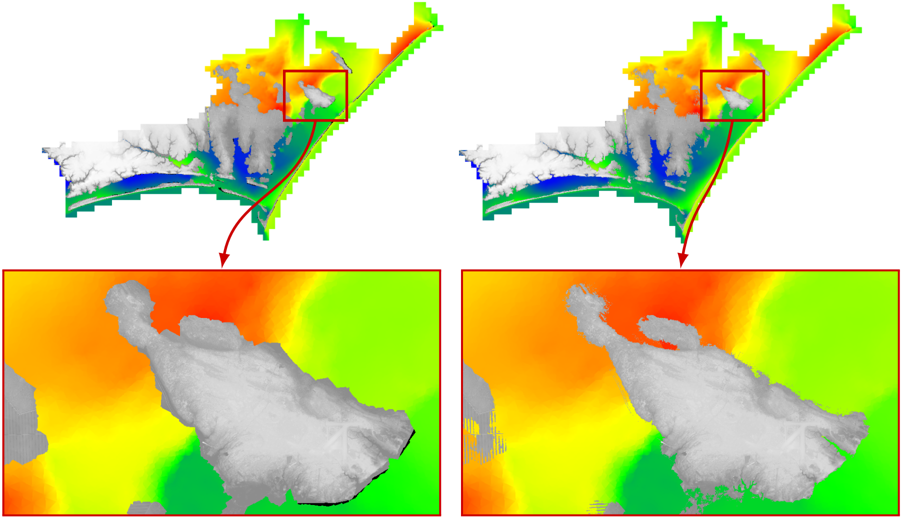


Examples in Carteret County

Newport River



Examples in Carteret County
Cedar Island



Examples in Carteret County
Analysis of Impacted Buildings

We can intersect the flooding guidance with known buildings

- NCEM has compiled a database of infrastructure in every NC county
- Building footprint, first floor elevation, etc.
- Used for their planning during and after storm events

We can analyze the number of buildings covered by our flooding prediction for a Hurricane Matthew hindcast

- Before enhancement: **2,435 buildings**
- After enhancement: **3,886 buildings**
- This is an increase of 60 percent

This is not a perfect comparison

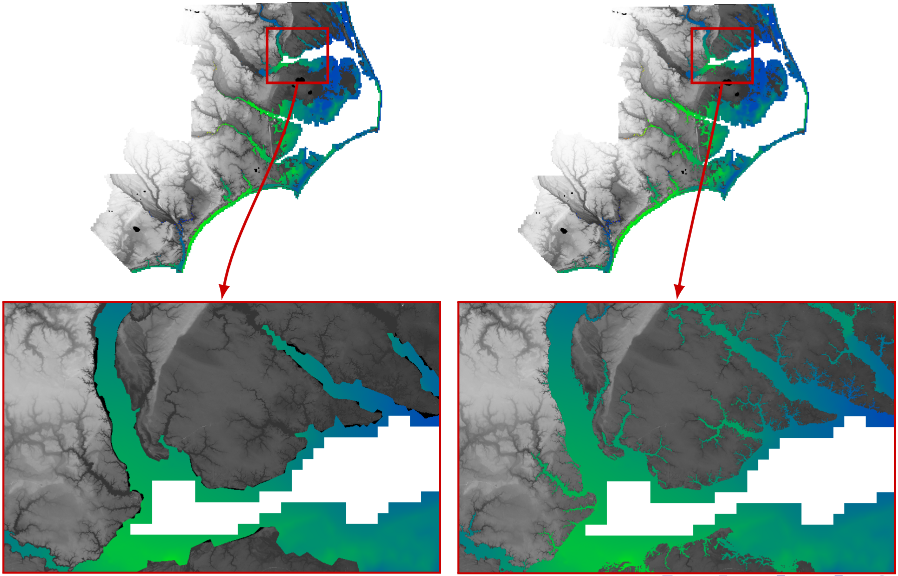
- Future work – compare with flood insurance claims

We need the method to be *fast*:

- Interpolation of ADCIRC points to raster format is most time-consuming part of process, even with precomputed weights
- Entire process was taking **30-40 minutes** at first, and clearly needed to be parallelized:
  - Scripts were tweaked to allow for parallel processing on up to 16 CPUs
  - DEM was divided into horizontal strips with overlap of 500 cells
- Some aspects cannot be parallelized
  - Final conversion into 0.5-ft polygons
- With parallelization, the entire process now takes **12-15 minutes** to run on the NCSU computing cluster

Enhanced Guidance for Entire NC Coast

Albemarle Sound



We are now providing the enhanced guidance to NCEM

- For the current hurricane season, we use an automated email script that is running on our cluster at NCSU
- This script:
  - Detects when ADCIRC results are posted to the archive
  - Downloads the maximum water levels
  - Runs the enhanced-resolution process
- We produced results for Hurricane Harvey, and are beginning to produce results for Hurricane Irma
- We will be working to incorporate this script into the ADCIRC Surge Guidance System (ASGS)

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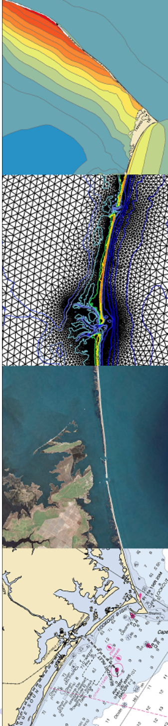


Considering Erosion of Beaches and Dunes

eXtreme Beach (XBeach): `xbeach.org`

Our forecast system is limited:

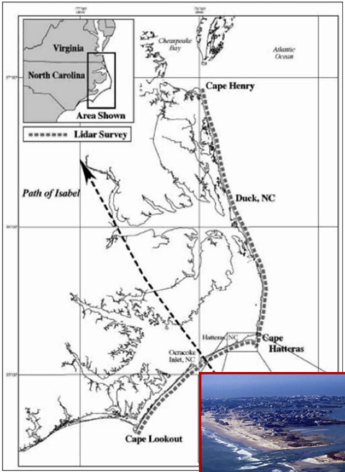
- Bathymetry and topography are fixed / constant
- No consideration of beach erosion, dune breaching, etc.
- Flooding impacts are limited behind the dunes

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

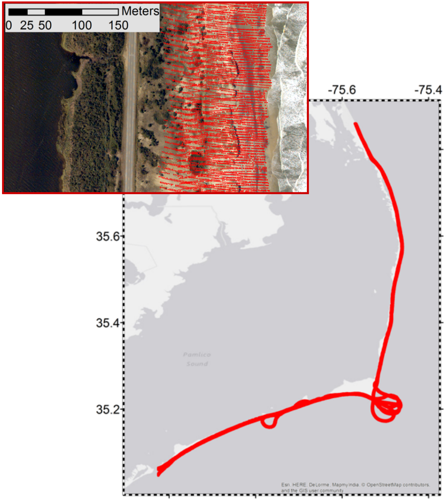
- Most powerful hurricane in 2003
- Made landfall on the Outer Banks on 18 Sep as Category 2 hurricane
- Caused overwash, dune breaching, and infrastructure destruction
- NC-12 closed at identified hotspots
- Major breaching occurred northeast of Hatteras Inlet

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

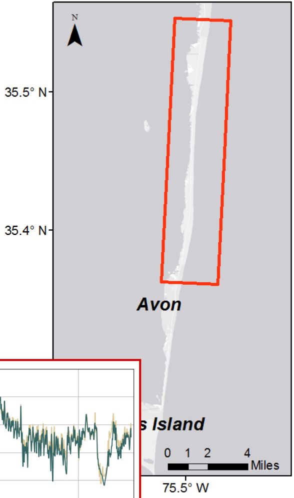


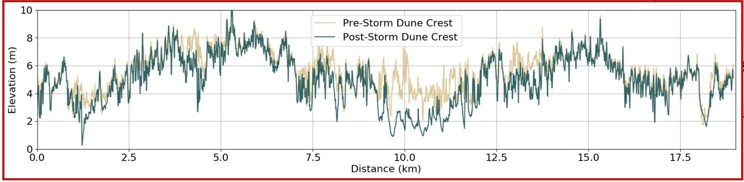
Exploring Morphodynamics during Isabel (2003)

Storm Impacts in Study Area

Alongshore crest elevation change:

- Study area between Avon and Salvo
  - Distance of about 18 km
- Elevation changes at pre-storm crest line
  - Average = 1 m
  - Maximum = 5.6 m
- Total of 20 major dune erosion events
  - All wider than 15 m





Model Setup for XBeach
Generating Mesh for XBeach Simulations

Combining data sets:

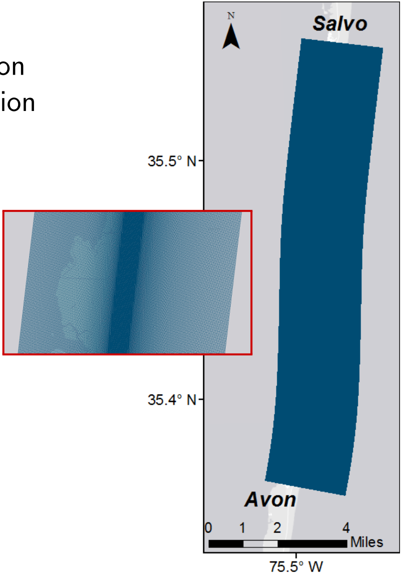
- Pre-storm LiDAR with 1 m resolution
- NC coastal DEM with 10 m resolution

Converting to computational mesh:

- Total of 1400×560 cells
- Cell widths:
  - Alongshore = 15 m
  - Cross-shore:
    - At offshore boundary = 15 m
    - At shoreline = 3 m

Need boundary and initial conditions:

- Waves and water levels
- Sediment properties



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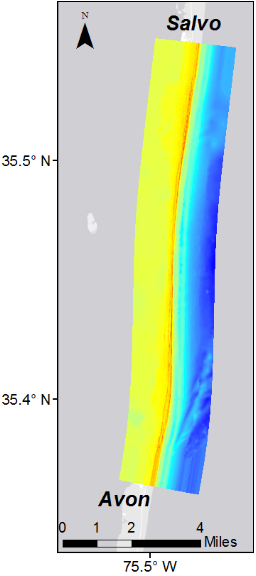
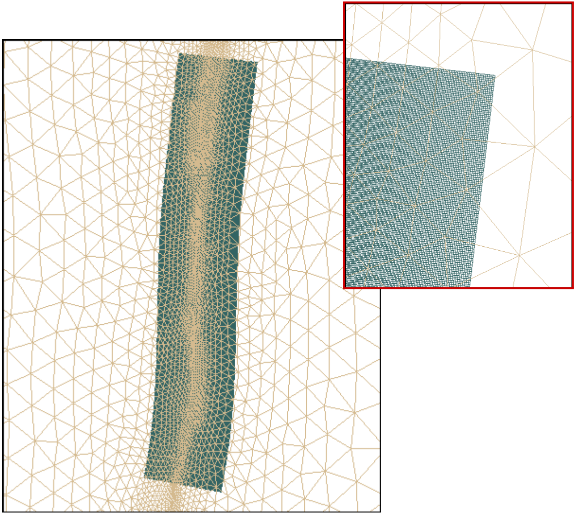


Model Setup for XBeach

Wave and Surge Boundary Conditions from SWAN+ADCIRC



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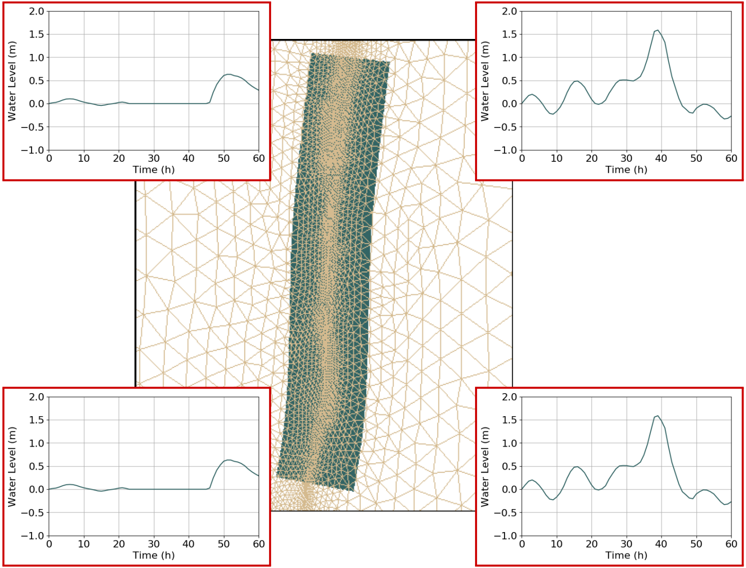

Model Setup for XBeach

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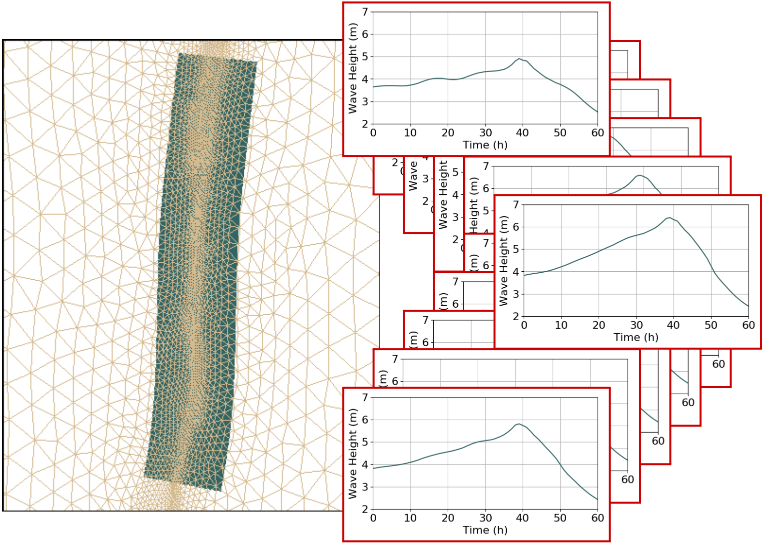


Model Setup for XBeach
Sediment Properties

Sediment size:

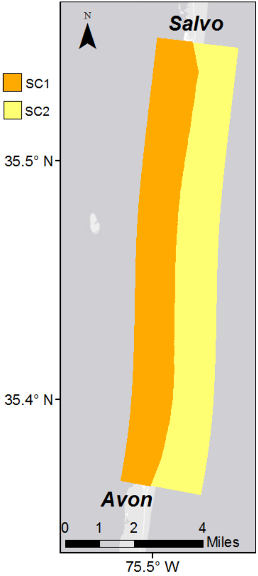
- $D_{50} = 0.0003$ m, $D_{90} = 0.0005$ m

Early model results:

- Too much erosion on the beach
- Too little erosion on the dune

Define two sediment classes:

- Use XBeach parameter `SedCal`
- Sediment transport calibration coefficient
- Landward of dune toe:
  - `SedCal` $= 0.2$
- Shoreward of dune toe:
  - `SedCal` $= 0.1$

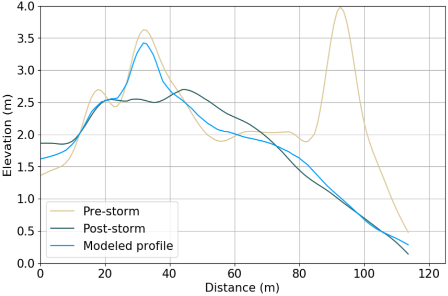


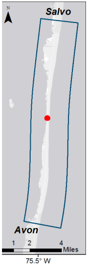
Initial Results with XBeach

XBeach Profiles at Major Dune Erosion Events

Dune Erosion Event #1:

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

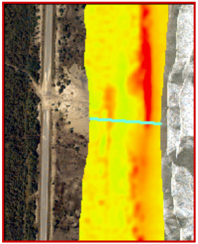




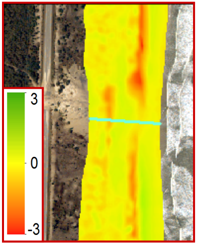
Pre-storm Orthophoto

Post-storm Orthophoto

LiDAR Post – Pre



LiDAR Post – Model

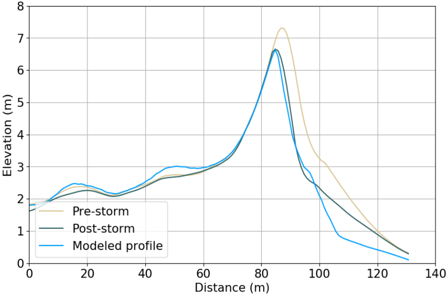


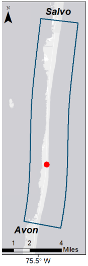
Initial Results with XBeach

XBeach Profiles at Major Dune Erosion Events

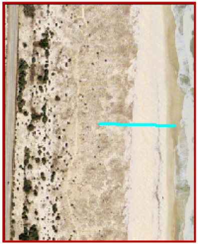
Dune Erosion Event #2:

- Dune crest elevation change modeled well
- Over erosion on the beach

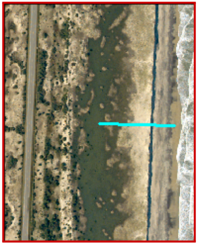




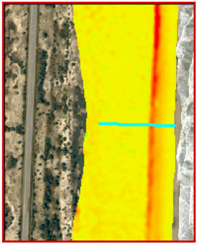
Pre-storm Orthophoto



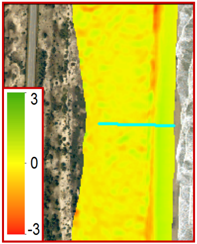
Post-storm Orthophoto



LiDAR Post – Pre



LiDAR Post – Model

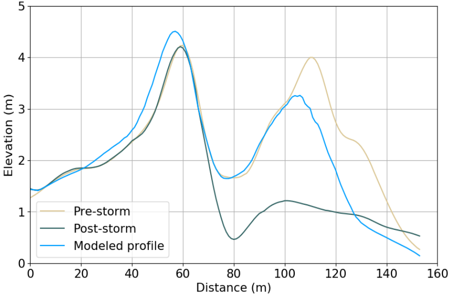


Initial Results with XBeach

XBeach Profiles at Major Dune Erosion Events

Dune Erosion Event #3:

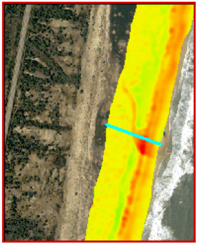
- No changes to profile behind first dune



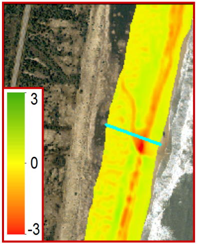
Pre-storm Orthophoto

Post-storm Orthophoto

LiDAR Post – Pre

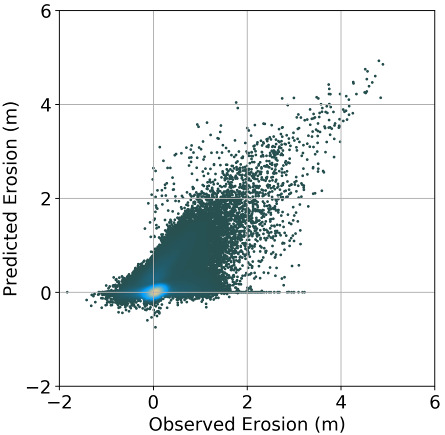


LiDAR Post – Model



Initial Results with XBeach

Model Accuracy – Skill Score



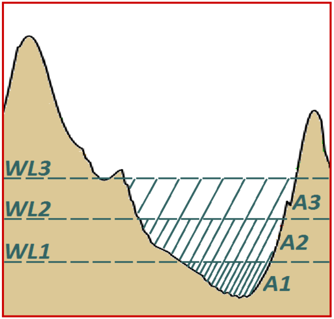
$$\text{Skill} = 1 - \frac{\sum_{i=1}^{N} \left(dz_{LiDAR,i} - dz_{XBeach,i}\right)^2}{\sum_{i=1}^{N} \left(dz_{LiDAR,i}\right)^2} = 0.51$$

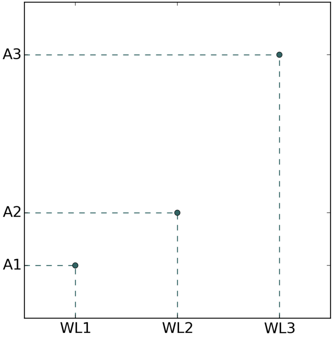
Initial Results with XBeach

Model Accuracy – Water Overpassing Area (WOA)

Water Overpassing Area (WOA):

- Represents the amount of water that overpasses the dune crest
- Area between the dune crest and water level





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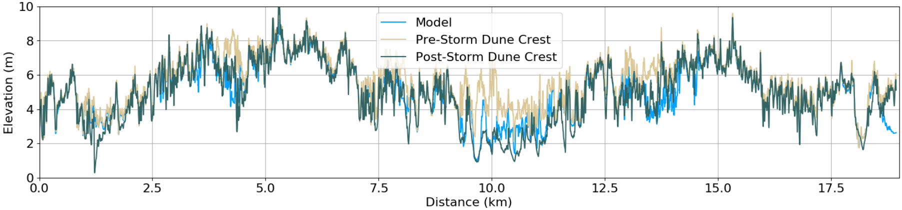

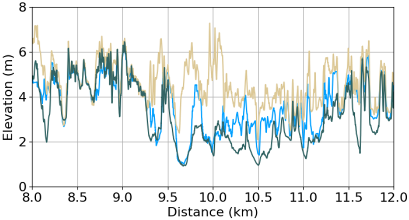

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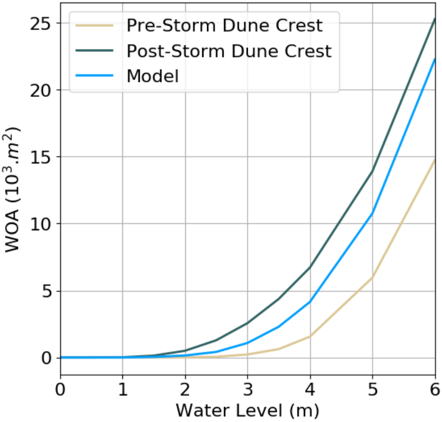


Mesh Resolution Sensitivity

4-km Model Domain

We want to couple with ADCIRC:

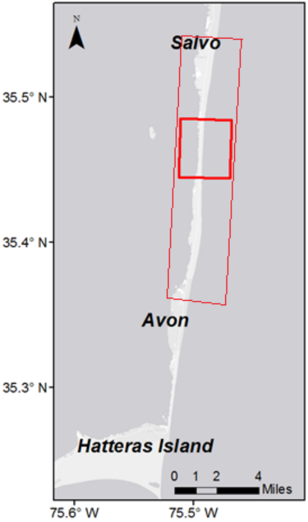
- Pass updated topo/bathy on the island
- Allow waves and surge to push farther

But ADCIRC uses a larger spatial resolution

- Does the larger-scale flooding need to see the exact erosion on Hatteras Island?
- Can we get away with a coarser mesh resolution in XBeach?

Sensitivity tests:

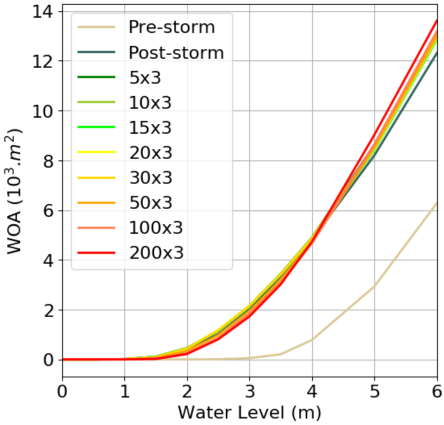
- Changing to 4-km subdomain
- Varying the mesh spacing:
  - Alongshore direction
  - Cross-shore direction



Mesh Resolution Sensitivity

Variation in Cross-Shore Spacing

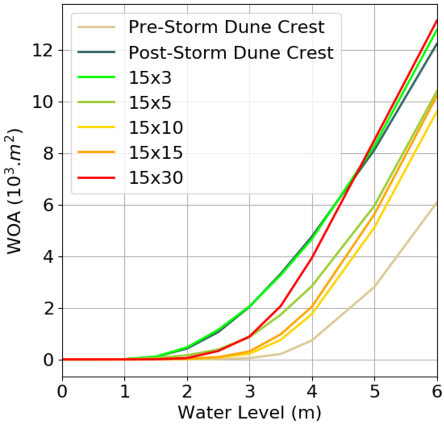
Mesh	Skill	Bias
5m	0.63	0.13
10m	0.61	0.12
15m	0.61	0.12
20m	0.61	0.12
30m	0.62	0.12
50m	0.62	0.12
100m	0.64	0.12
200m	0.60	0.11



Mesh Resolution Sensitivity

Variation in Alongshore Spacing

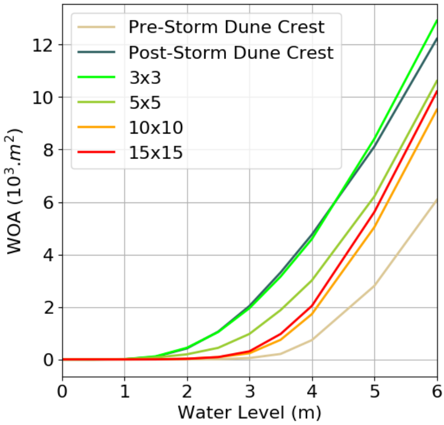
Mesh	Skill	Bias
3m	0.61	0.12
5m	0.52	0.05
10m	0.28	-0.03
15m	0.12	-0.07
30m	0.00	-0.06

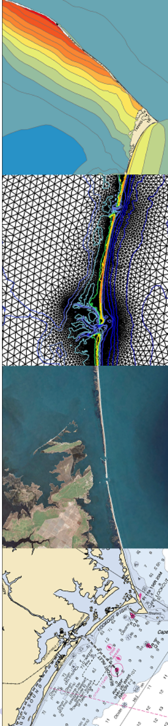


Mesh Resolution Sensitivity

Variation in Cross-Shore and Alongshore Spacing

Mesh	Skill	Bias
3m	0.63	0.08
5m	0.57	0.05
10m	0.27	-0.03
15m	0.12	-0.07





Real-time forecasting for coastal North Carolina:

- Available at: `www.adcirc.org`
- Hurricanes Matthew (2016), Harvey and Irma (2017)
  - Providing guidance for multiple states
  - Every advisory and perturbations
- Working with NCEM to add to their workflow
  - Extrapolate into small-scale channels and floodplains

Working with XBeach to simulate beach and dune erosion:

- Results are encouraging for Hatteras Island
  - "Excellent" skill score and promising WOA
  - Improving accuracy for complex erosion patterns
- Sensitivity to mesh resolution
  - Can we get away with a coarse representation of cross-shore erosion?