NC STATE UNIVERSITY

Improving Accuracy of Real-Time Storm Surge Inundation Predictions

M.S. Thesis Defense

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Committee

Advisor – Casey Dietrich

Committee members – Helena Mitasova and Alejandra Ortiz

Special thanks to Kurt Golembesky and Tom Langan at NCEM for their collaboration throughout this project.

THE NATIONAL CONSORTIUM for DATA SCIENCE

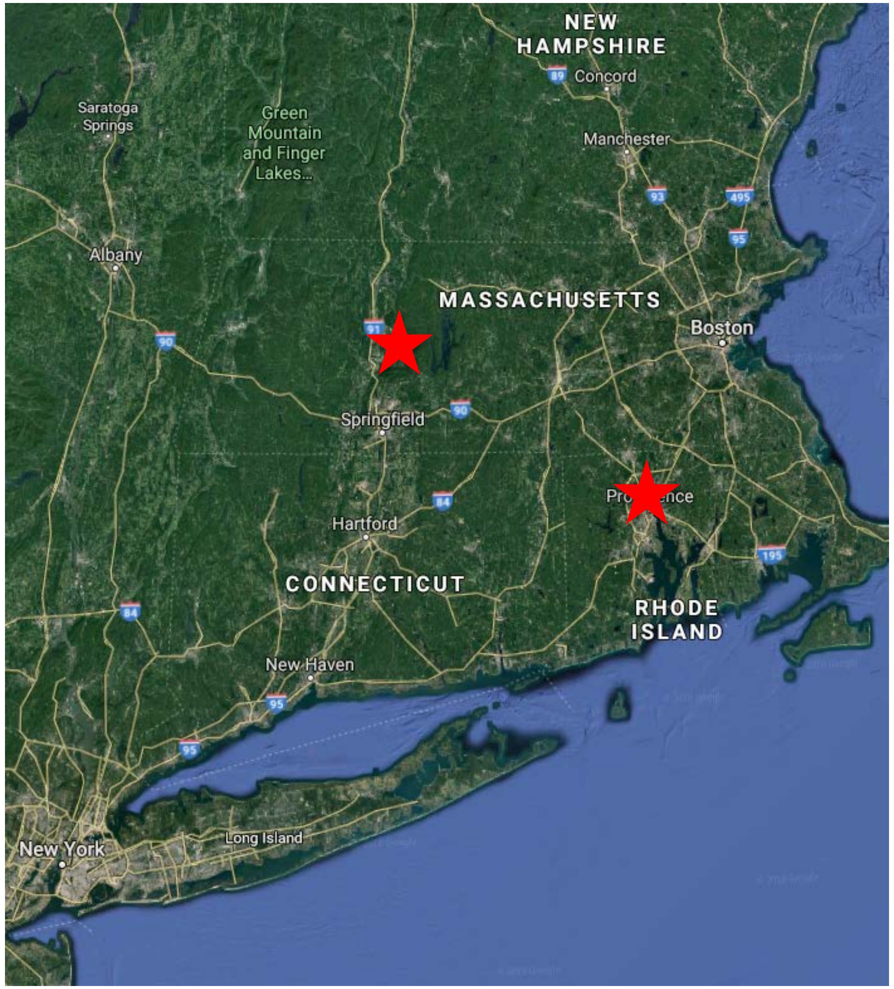
My Background

From Providence, Rhode Island

Attended the University of Massachusetts at Amherst

- Received a B.S. in Civil Engineering in 2016
- Completed a thesis related to groundwater modeling

Came to NCSU to study coastal engineering!



Outline

- Motivation
- Description of Enhanced Resolution Technique
- Evaluation of Accuracy for Hurricane Matthew Flooding Predictions
- Conclusions and Future Work

Importance of Accurate Storm Surge Predictions

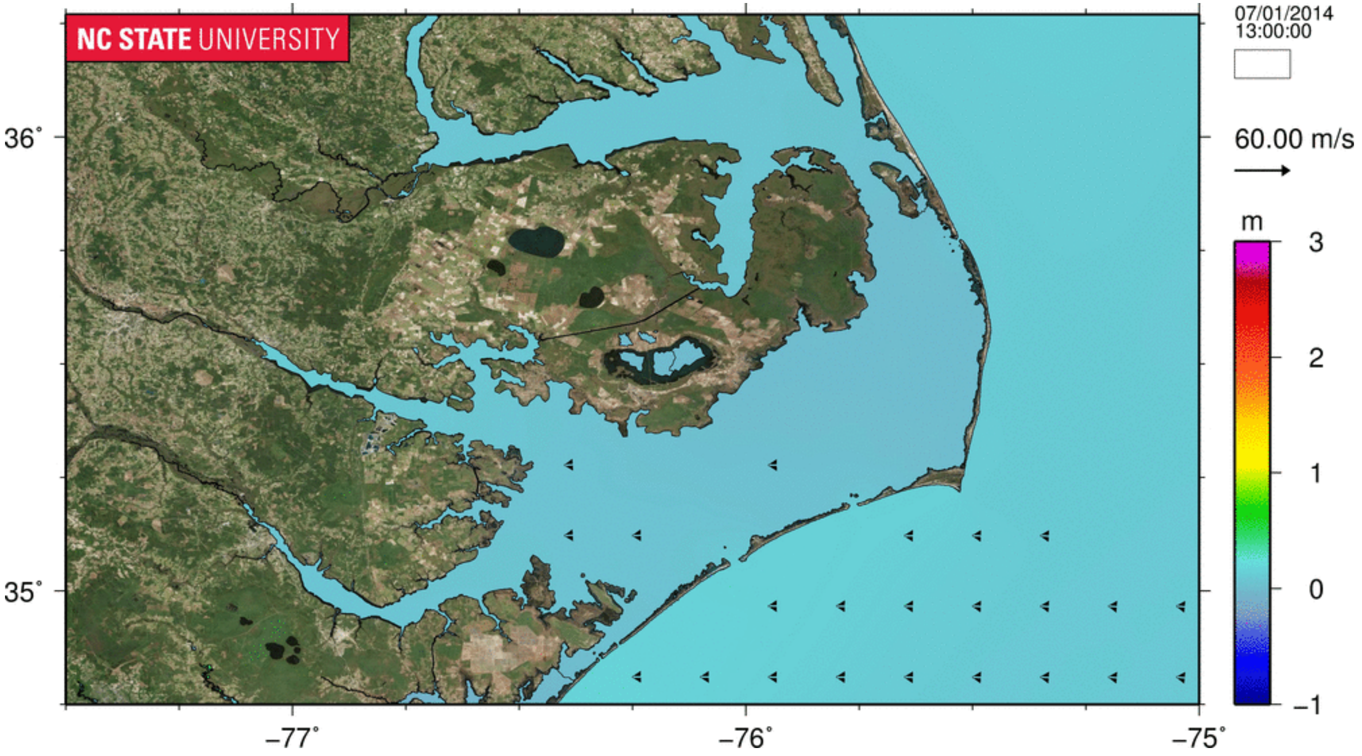
- Hurricane Katrina (2005) resulted in up to 10 m of combined storm tide and wave heights along the MS coast
- Numerous high surge events have impacted the NC coast
- Emergency managers rely on fast and accurate predictions of coastal flooding to make decisions
- How high will water get over land at locations with critical infrastructure?

Storm surge at Kitty Hawk, NC during Hurricane Sandy (2012)

Modeling storm surge with ADCIRC+SWAN

ADvanced CIRCulation + Simulating WAves Nearshore

- Tightly-coupled, finite element model
- Used to predict ocean circulation and overland flooding
- Has been validated and used for a wide range of applications
  - With sufficient resolution, can be accurate to within 25 cm



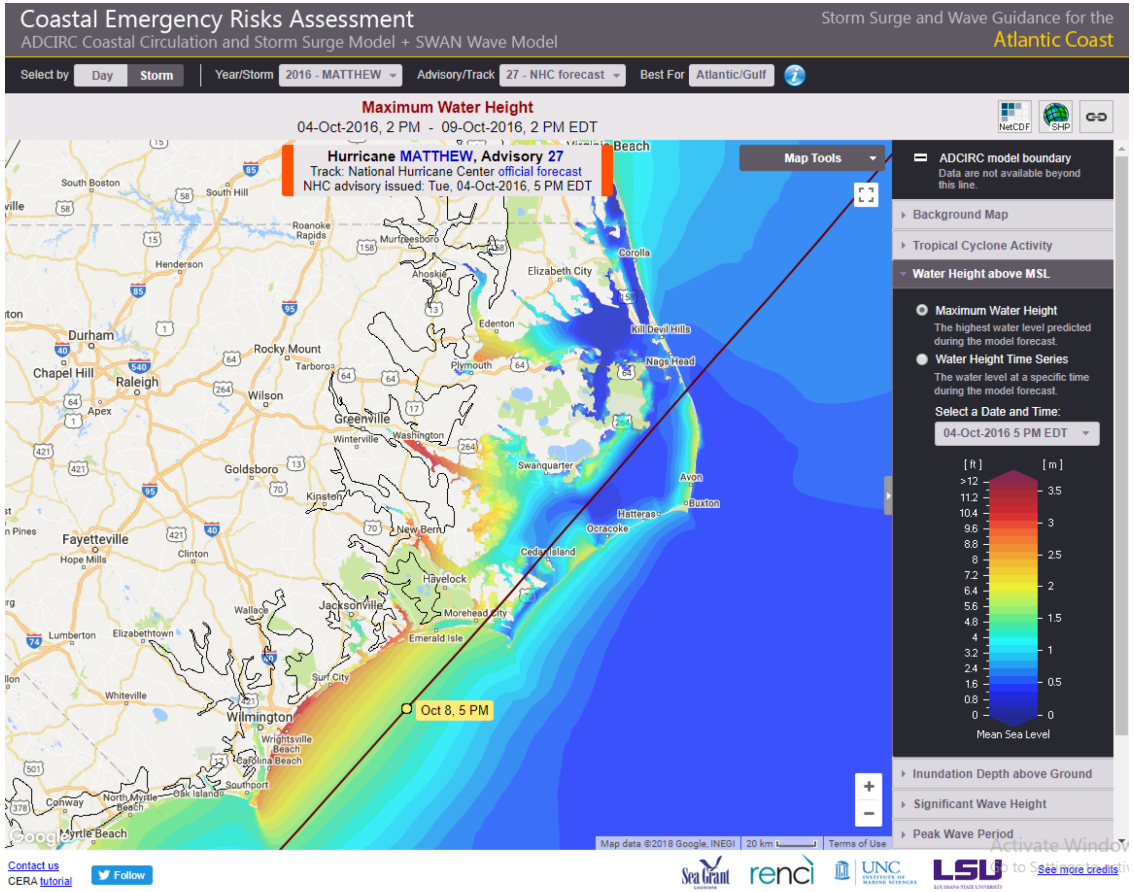
Time-series of water levels during Hurricane Arthur (2014)

Real-Time Forecasting with ADCIRC

General process:

- NHC issues an advisory every 6 hours during a storm
- Several ADCIRC simulations are run directly after each advisory
- Results are visualized in real-time via applications like CERA

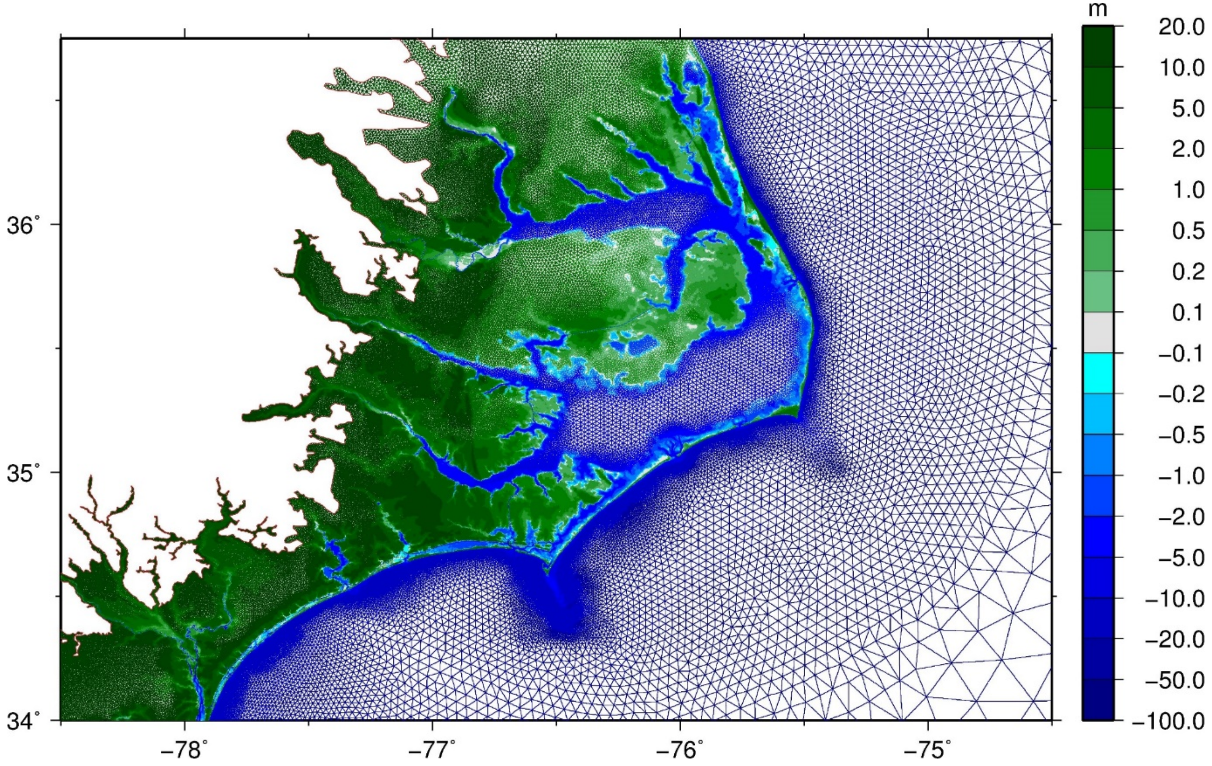
Forecasts should be as fast as possible without sacrificing too much in accuracy



NC9 Mesh

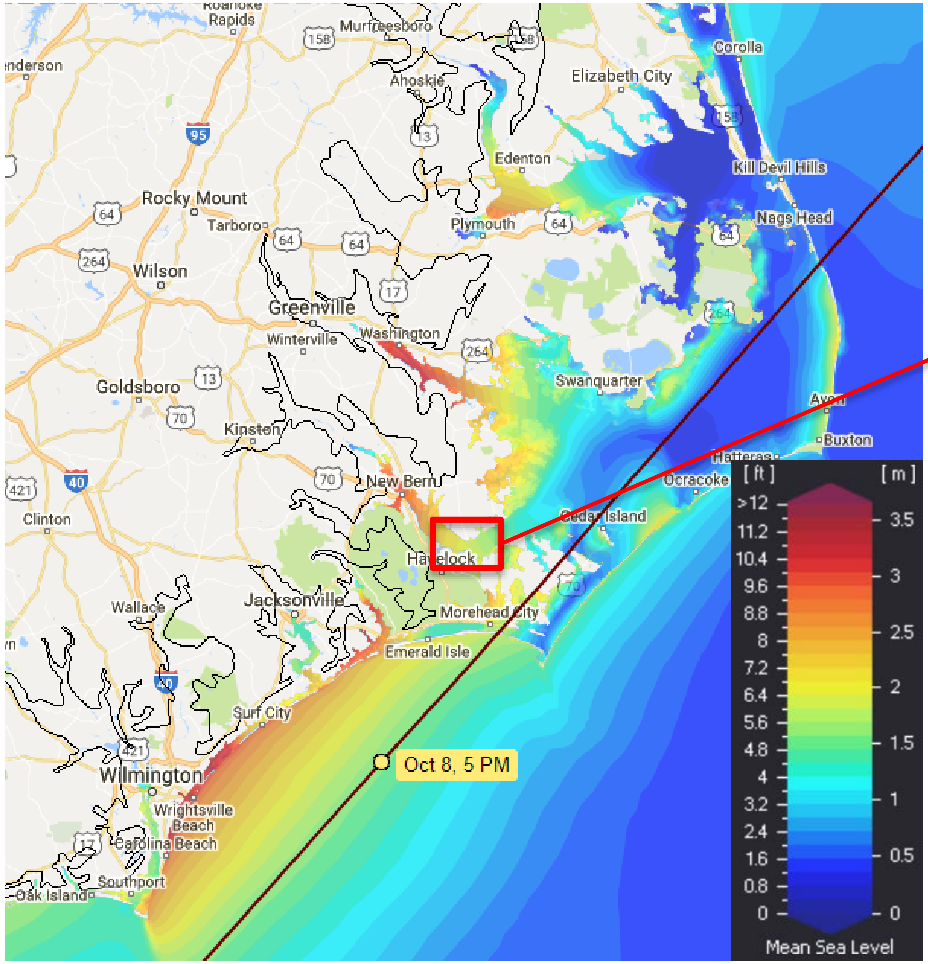
In North Carolina, we often use the NC9 mesh to study storm surge along our coast

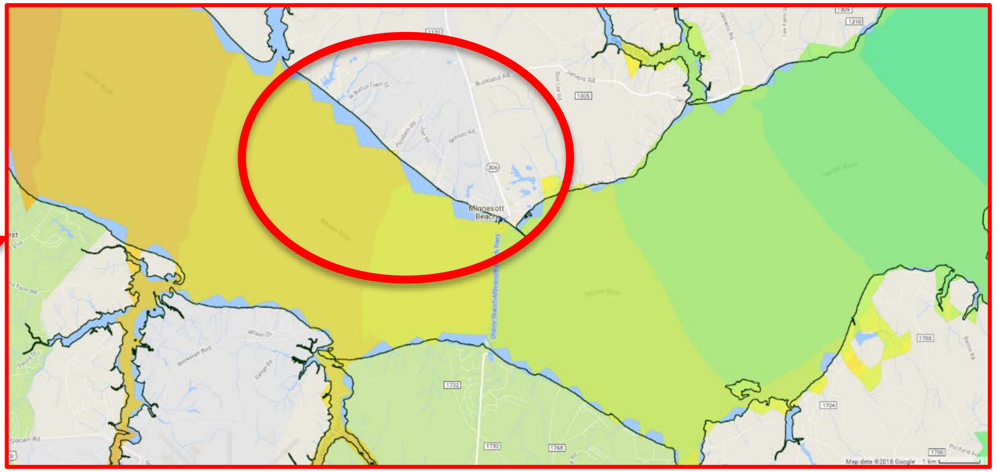
- Contains about 620k vertices
- 90% of resolution is in NC coastal regions
- 56% of resolution represents overland regions
- Typical element sizes:
    - 100-200 m along barrier islands and inlets
    - 300-600 m in most overland regions
- Ideal for forecasting in NC



Elevation of NC9 Mesh bathy/topo

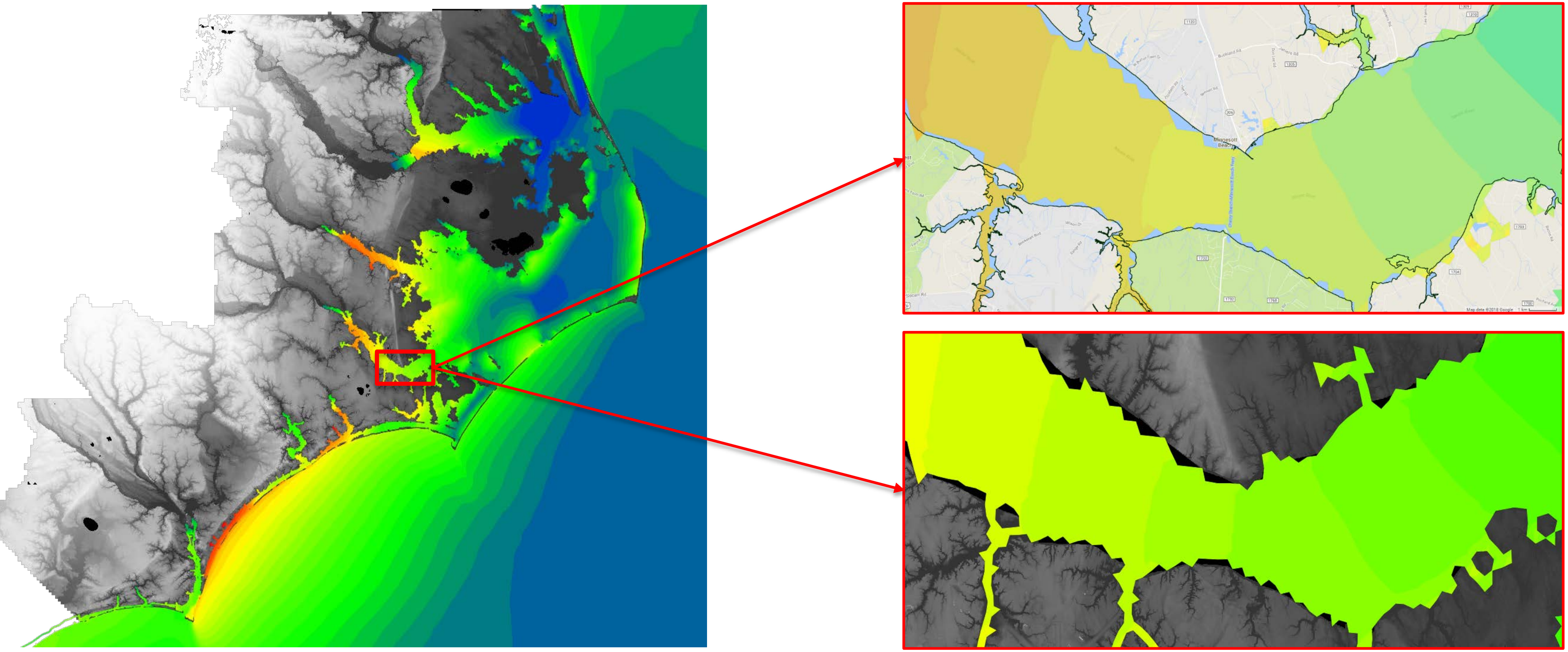
Limitations of ADCIRC





Storm surge in lower Neuse River, increasing from right to left

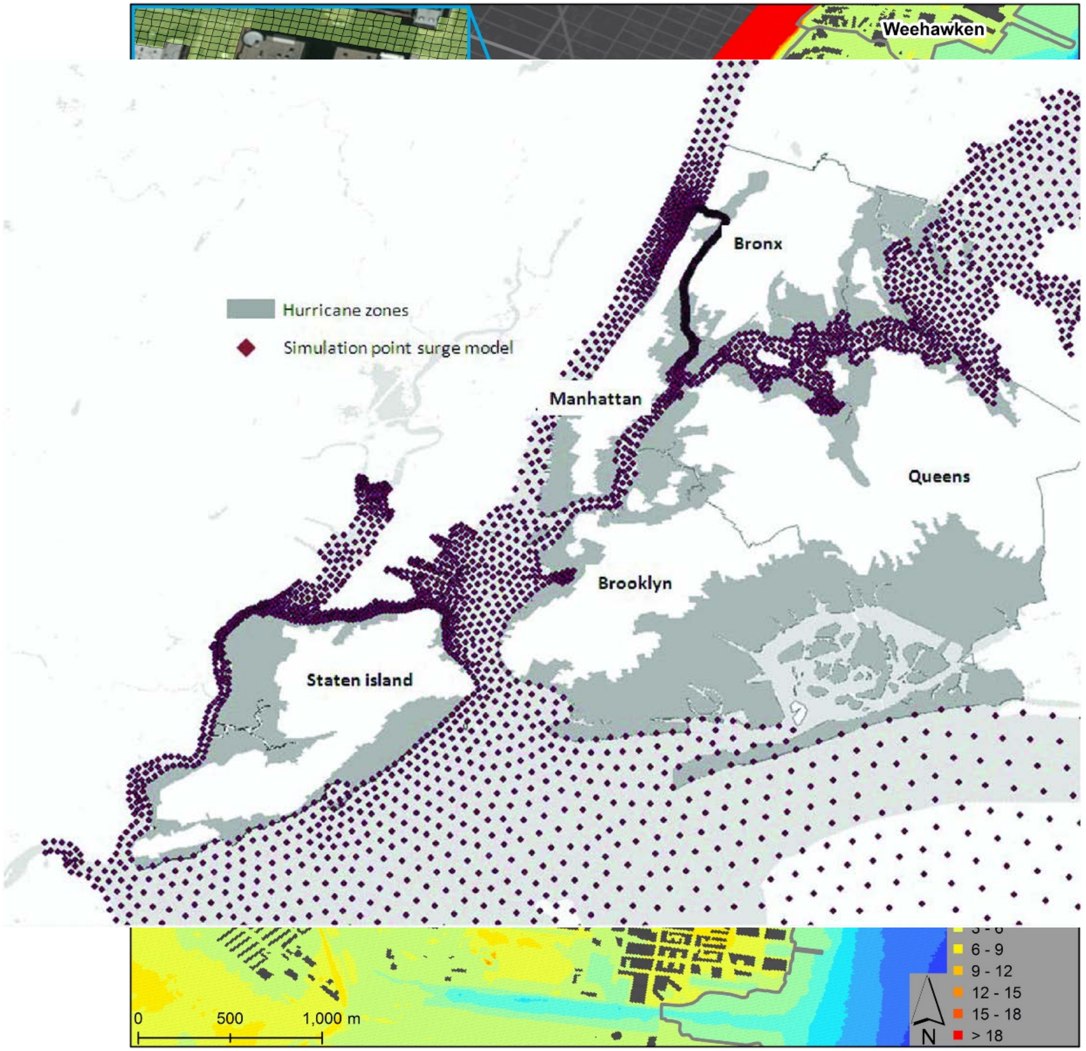
How can we improve smaller-scale flooding predictions?



Previous attempts to model small-scale inundation

High-resolution, multi-scale flood modeling

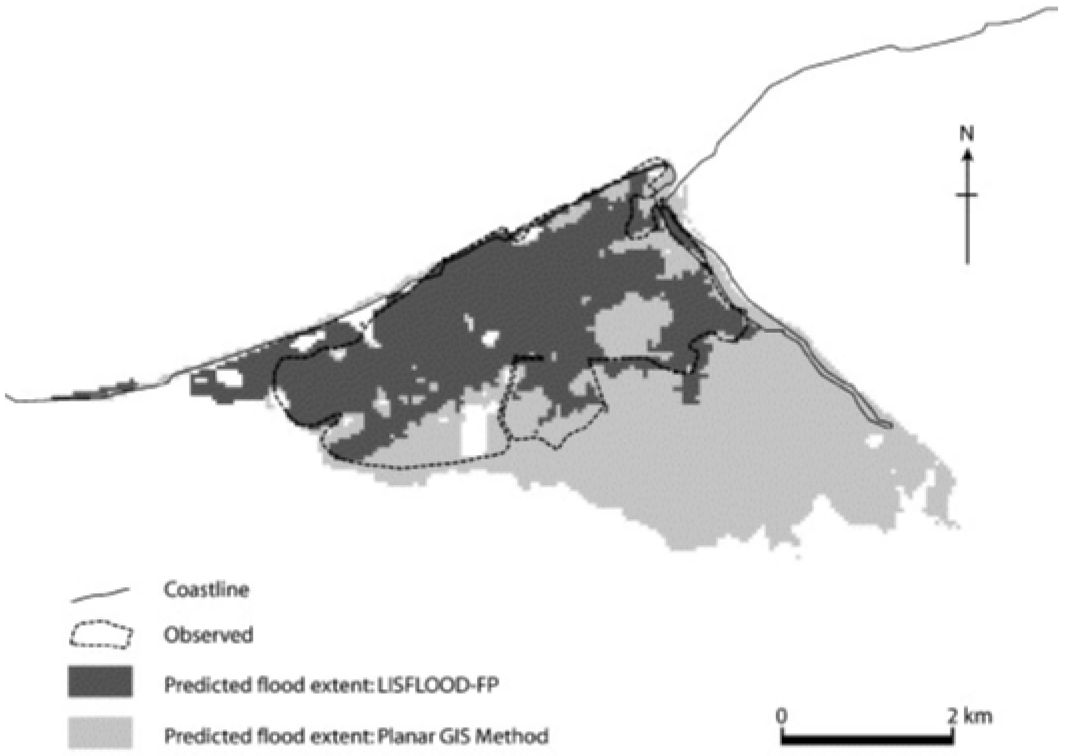
- Wang et al. (2014), Blumberg et al. (2015), Yin et al. (2016)
  - Urban inundation modeling
- Aerts et al. (2013)
  - Extrapolation of ADCIRC water levels into Manhattan as part of a probabilistic storm surge flooding study



Previous attempts to model small-scale inundation

Static vs. dynamic approaches

- Bates & de Roo (2000), Bates et al. (2005), Purvis et al. (2008), Ramirez et al. (2016)
- Static approach is commonly used in flood mapping studies, including from sea-level rise
- Dynamic approach is generally favored, especially when computational time is less important



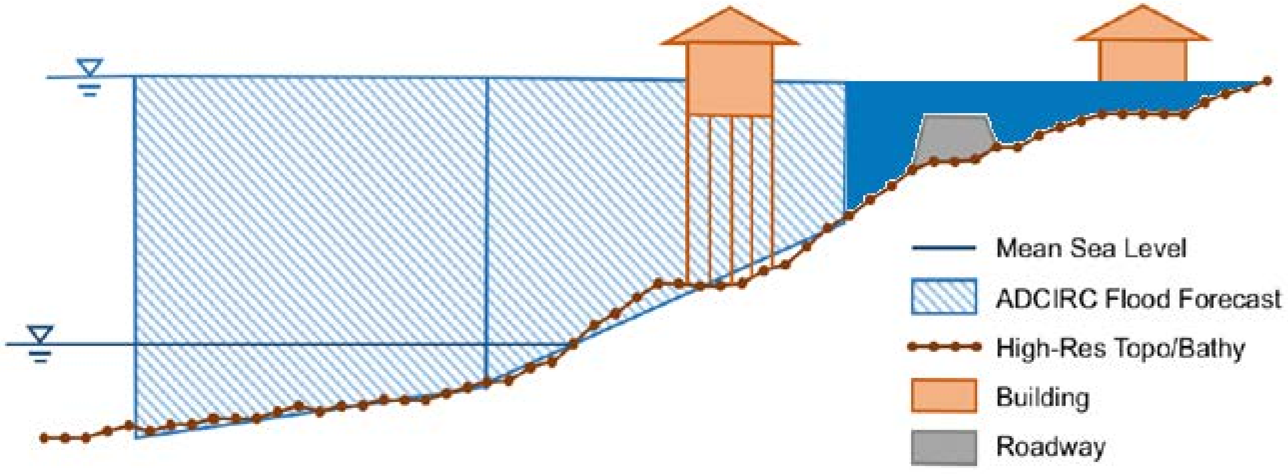
What does this study add to the literature?

There are two novel aspects:

1. We are modeling small-scale coastal flooding in ***real-time***
    - Computational speed is very important
    - Process must be fully-automated
2. We are modeling small-scale coastal flooding on a ***statewide domain***
    - Much larger domain than other high-resolution flood modeling studies
    - High level of variation in potential water levels and topography

Objectives

1. Enhance resolution of real-time storm surge predictions in North Carolina using a static extrapolation
2. Evaluate accuracy of this method by comparing to simulations on a refined ADCIRC mesh



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A Raster Method for Enhancing Resolution

The general steps are:

1. Interpolate ADCIRC points to a raster at 15-meter resolution (same as DEM)
2. Extrapolate water level raster into small-scale channels and floodplains
3. Convert the new, “enhanced” raster to polygon format for easy distribution

GRASS GIS

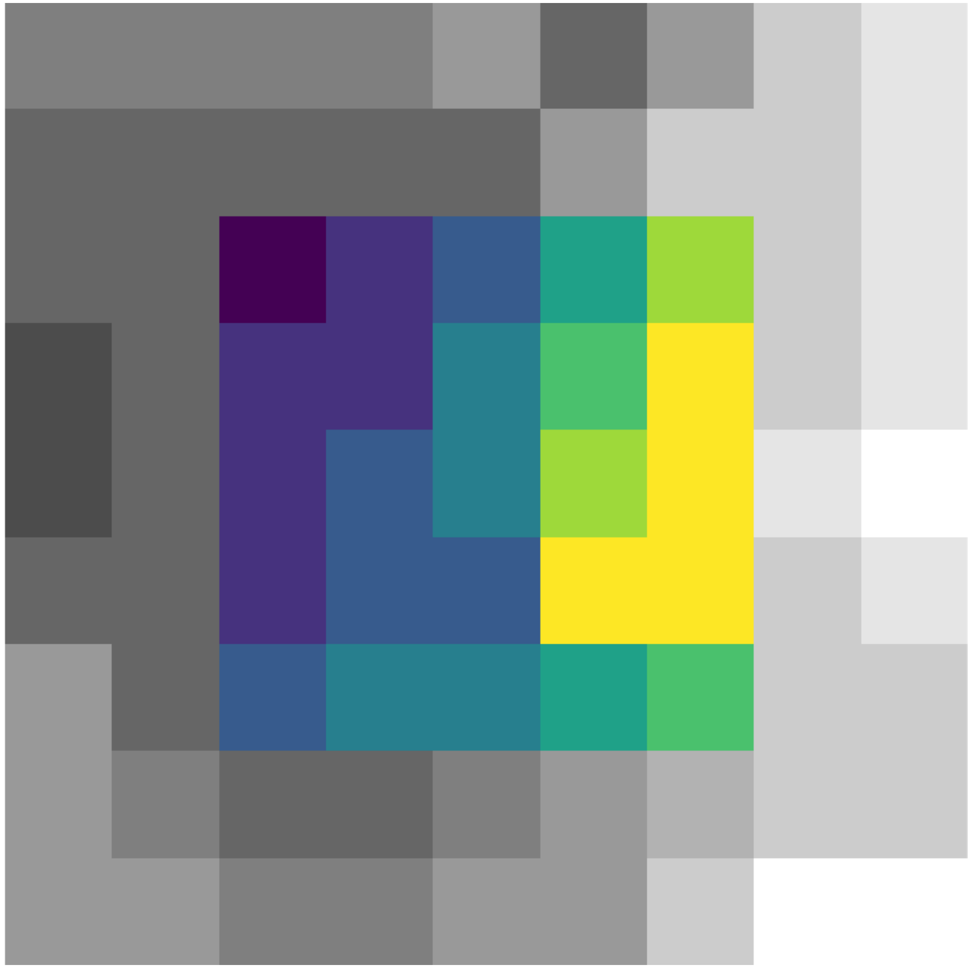
Geographic Resources Analysis Support System (GRASS, grass.osgeo.org)

- Efficient tool for working with large raster datasets
- Easily automated using Python scripts
- Accessible via command line for use in HPC environments
- Open-source – module source code can be modified

GRASS GIS

Bringing advanced geospatial technologies to the world.

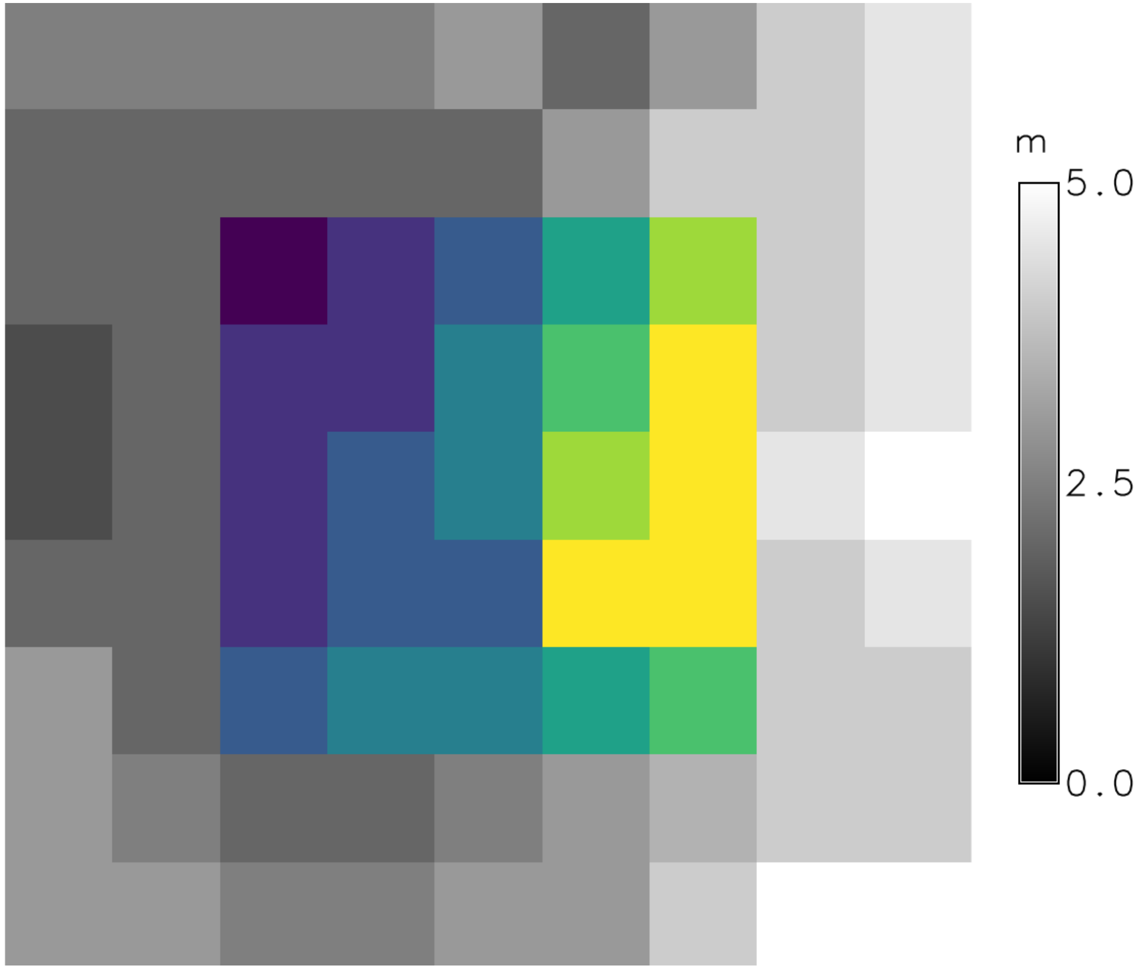
Conceptual Solution

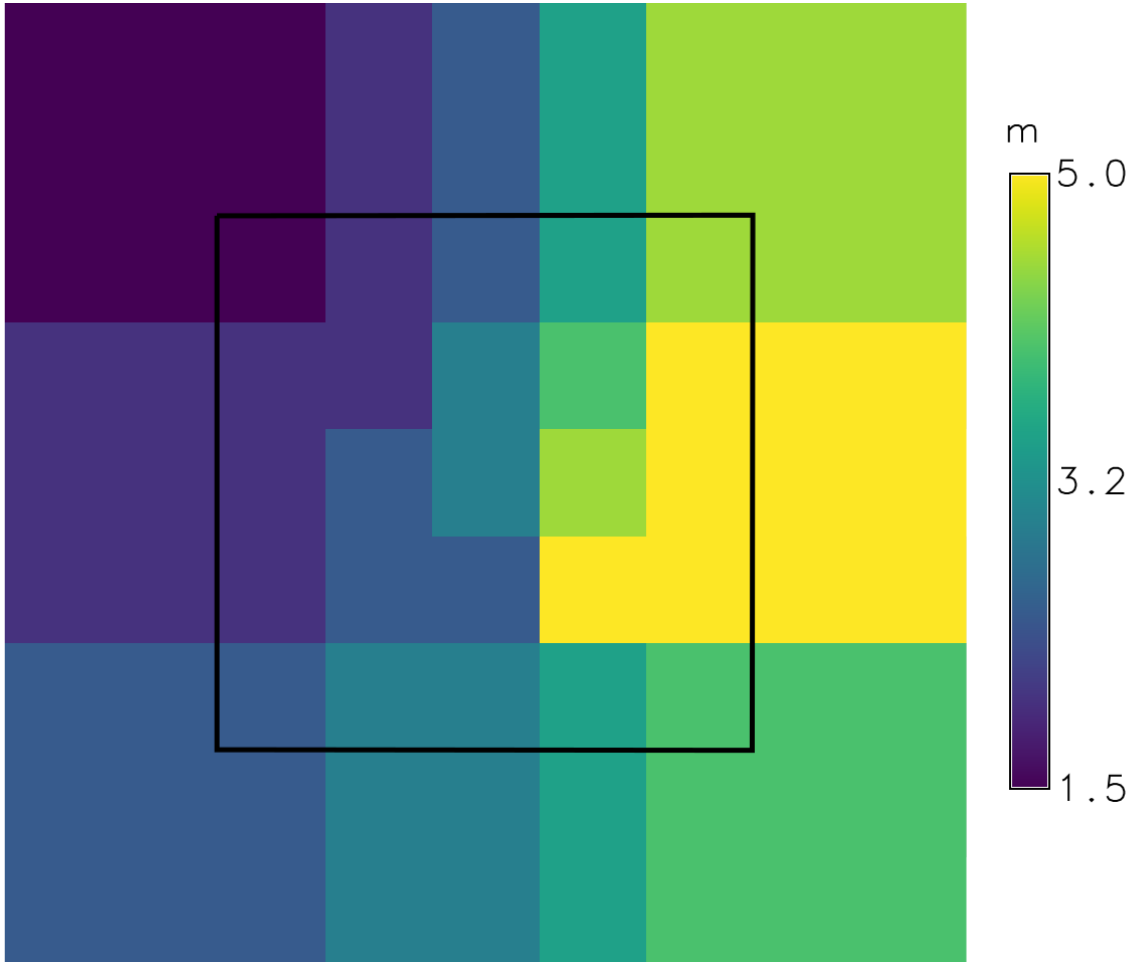


How do we extrapolate water levels?

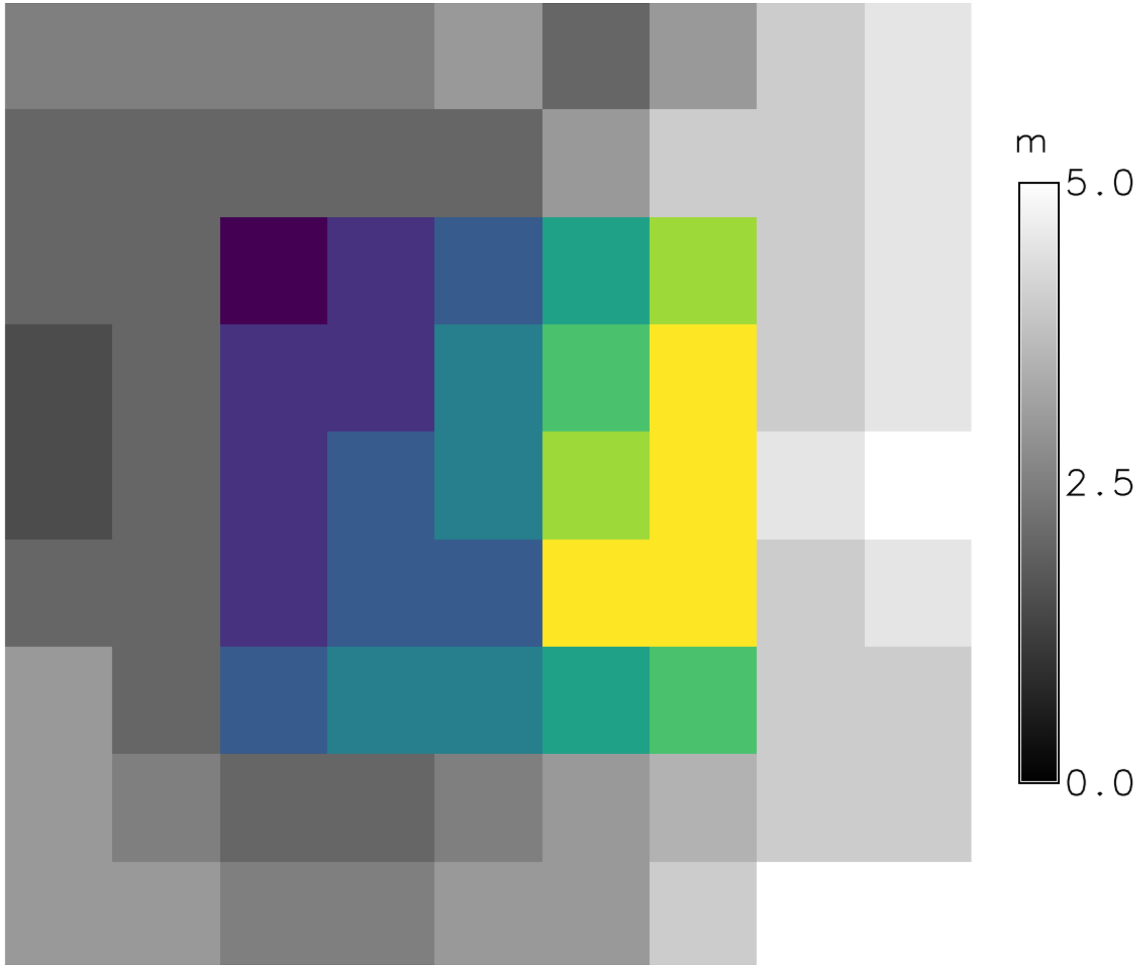
- Use the `r.grow` module in GRASS
  - Expands raster outward into neighboring "null" cells by a specified distance
- Modify `r.grow` to incorporate underlying DEM
- Use `r.clump`, `r.reclass`, `r.mapcalc` to identify and remove new cells isolated from original raster

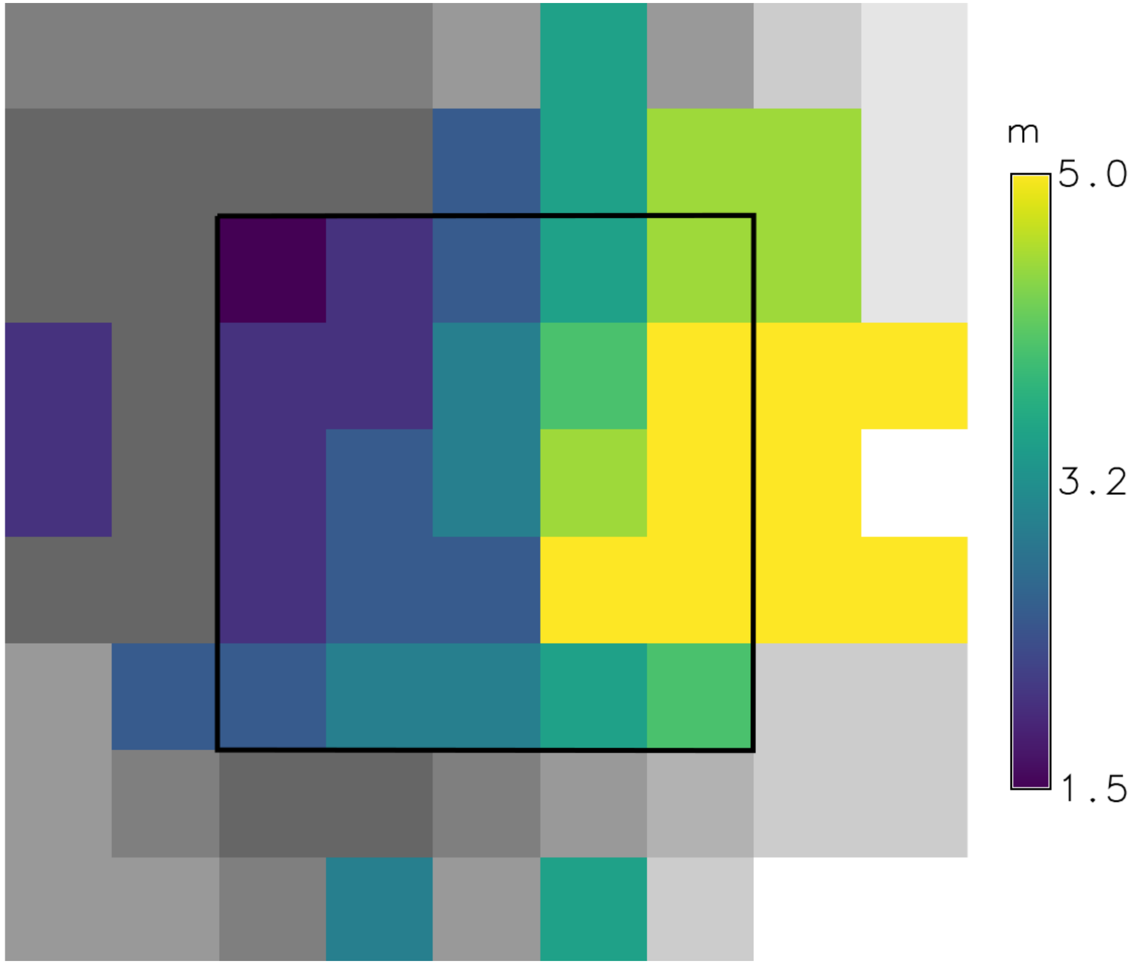
Conceptual Solution – `r.grow`



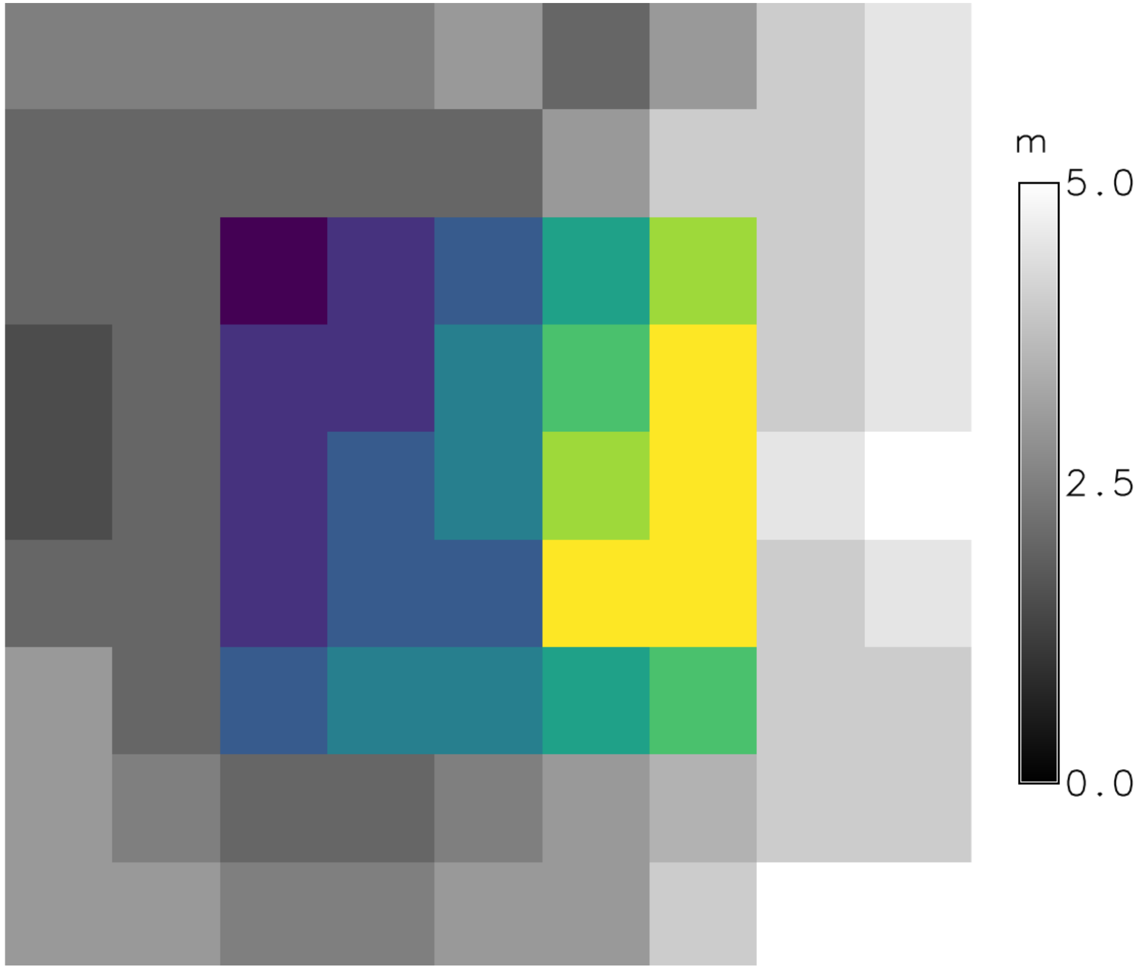


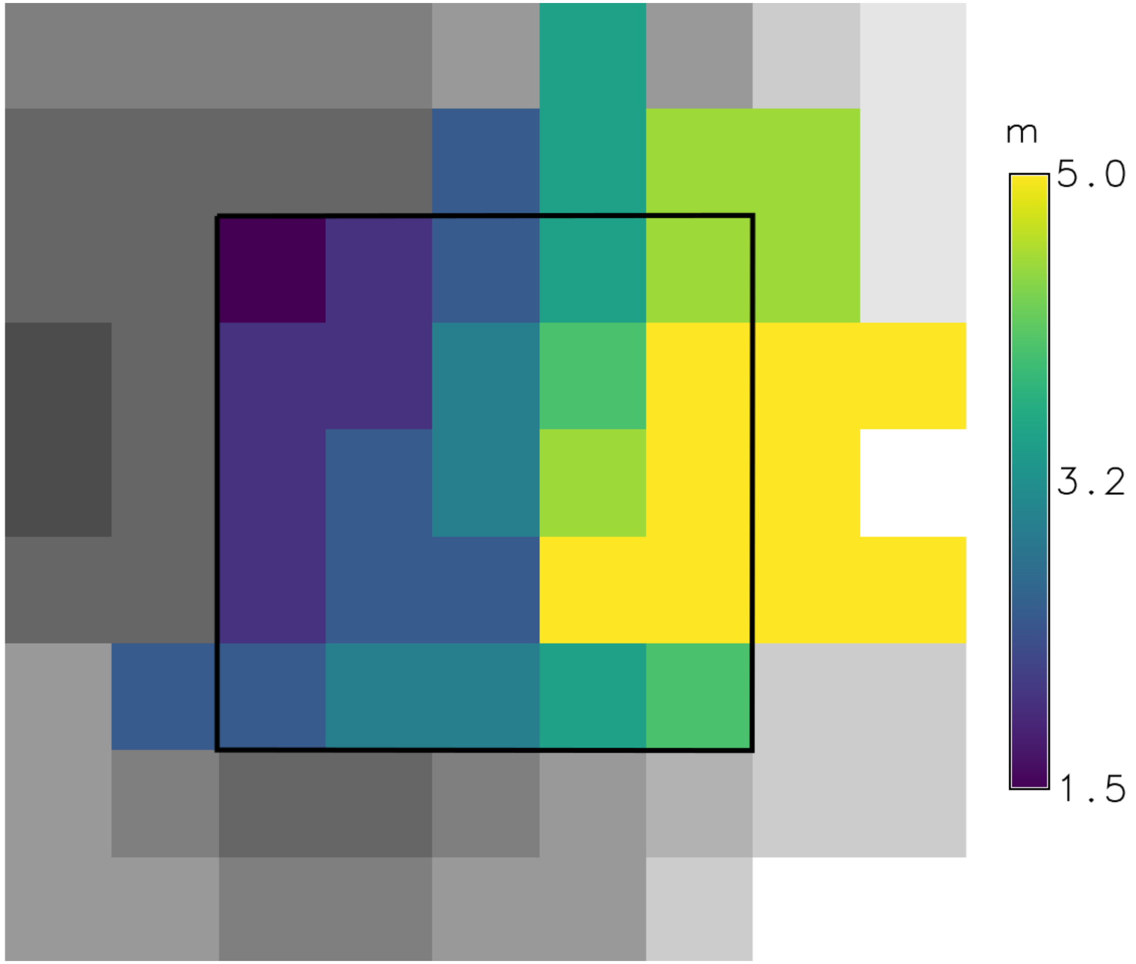
Conceptual Solution – `r.grow` with Elevation Check





Conceptual Solution – Final Raster

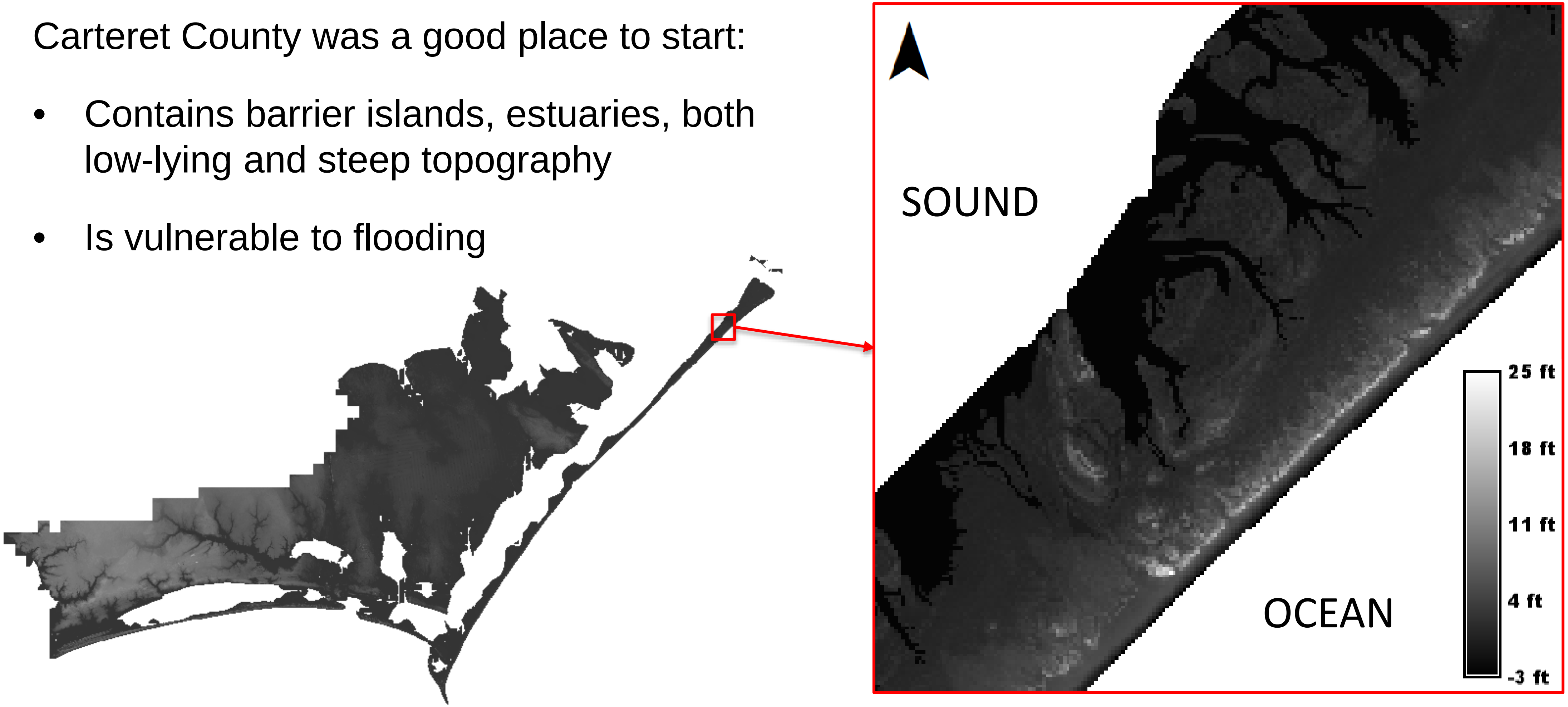




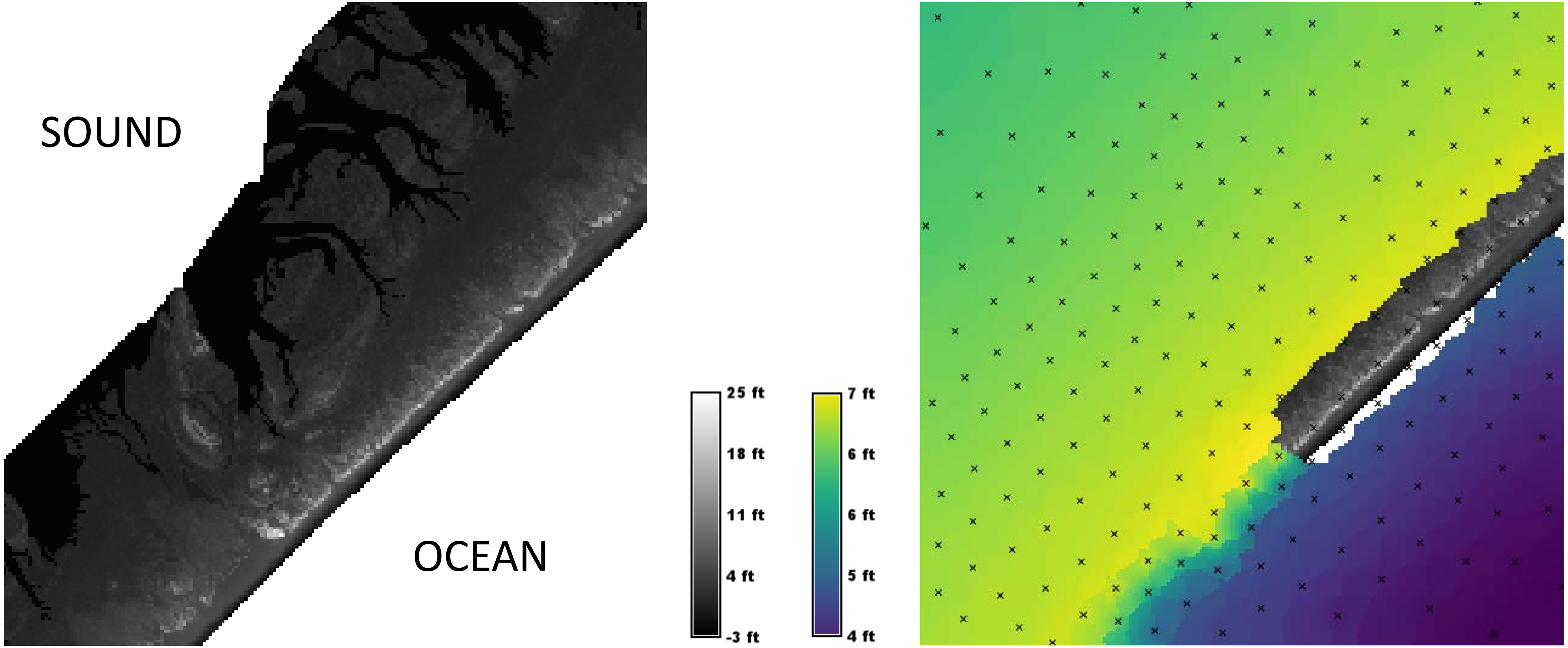
Examples in Carteret County

Carteret County was a good place to start:

- Contains barrier islands, estuaries, both low-lying and steep topography
- Is vulnerable to flooding



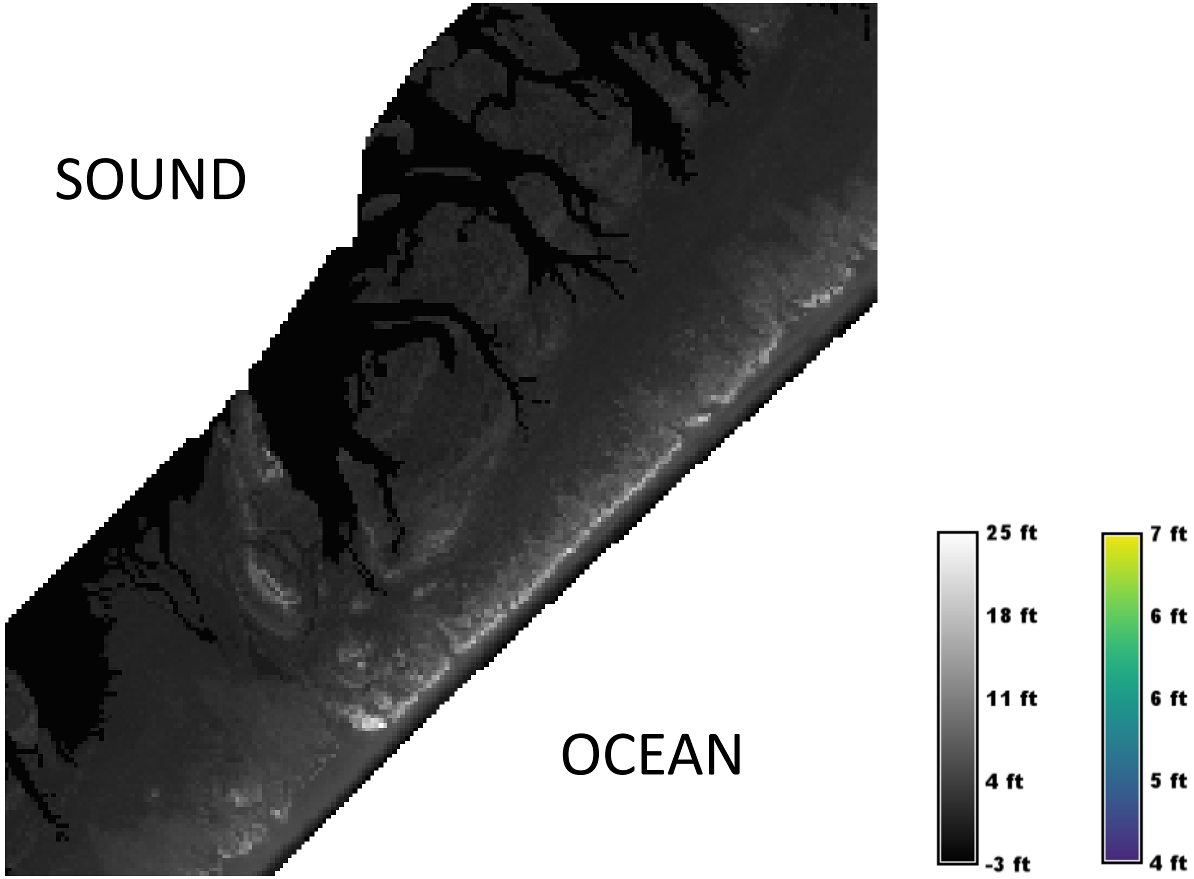
Examples in Carteret County



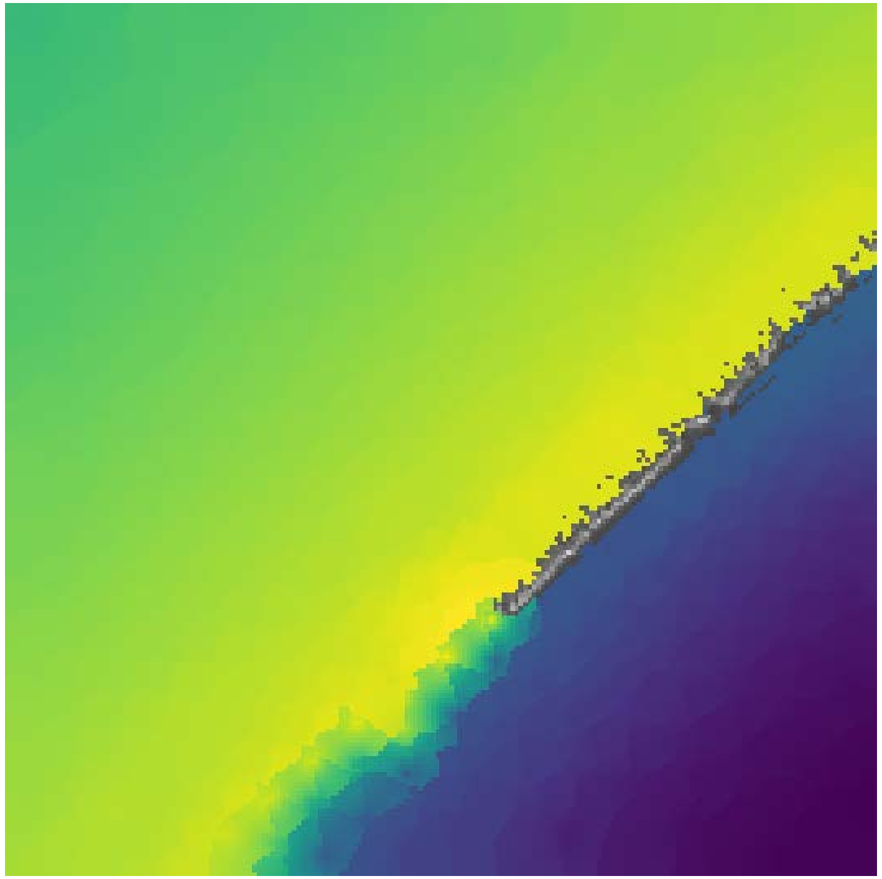
DEM

ADCIRC raster overlying DEM
(mesh vertices shown for scale)

Examples in Carteret County



DEM

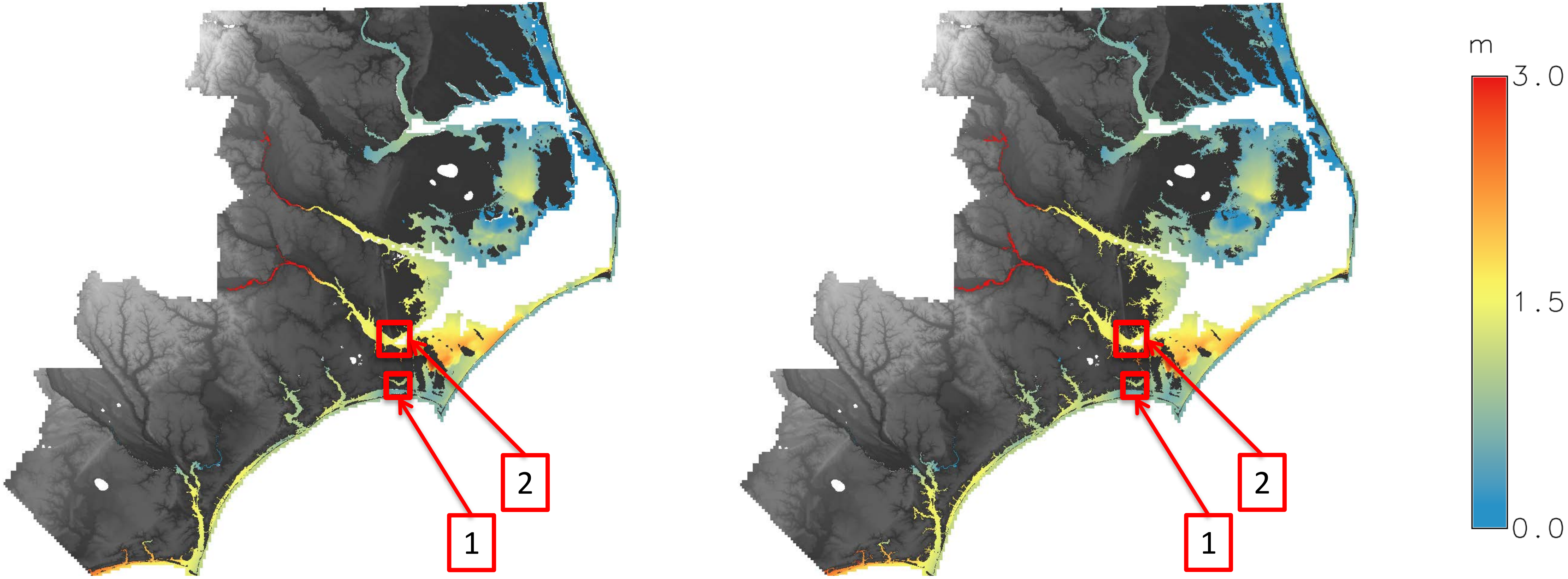


Enhanced ADCIRC raster

How fast is this process for all of NC?

- Interpolation of ADCIRC points is most time-consuming step
  - Inverse-Distance Weights were precomputed, but process was still too slow
- Entire process was taking **40-50 minutes** at first, and clearly needed to be parallelized
  - Scripts were tweaked to allow for parallel processing on up to 16 cores
  - DEM was divided into horizontal strips with overlap of 500 cells
- With parallelization, the entire process now takes **12-15 minutes** to run on the NCSU computing cluster
- Results were shared with NCEM during the 2017 hurricane season via an automated email script

Enhanced Guidance for Entire NC Coast

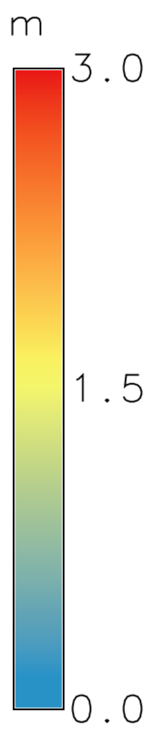


Before **After**

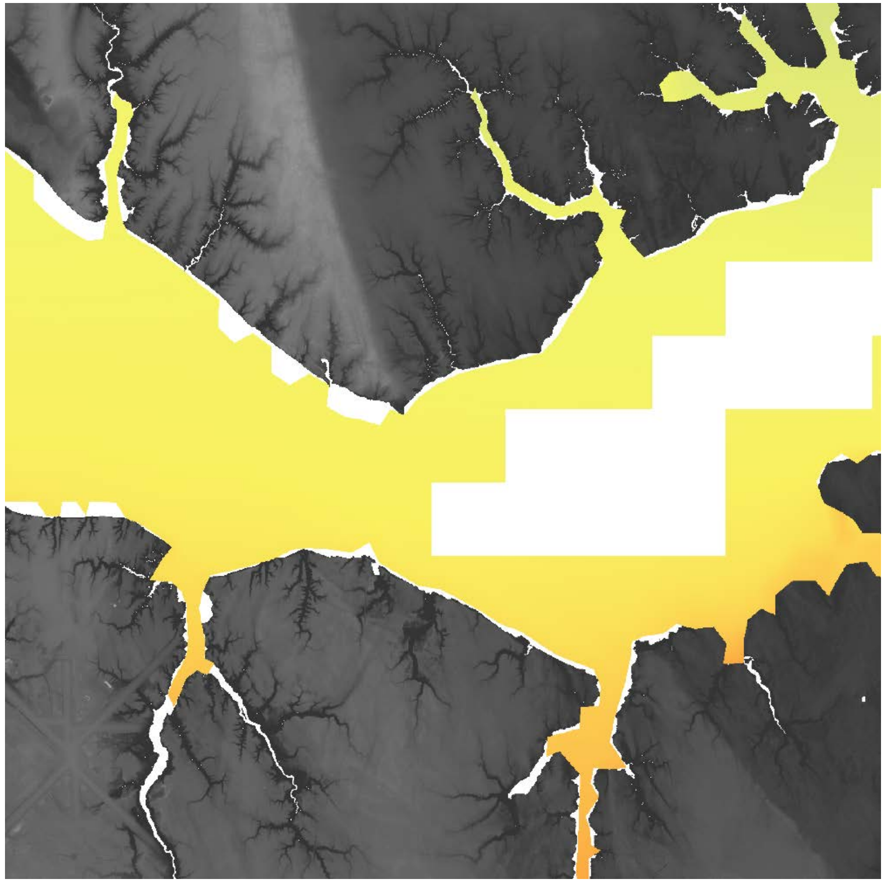
Enhanced Guidance for Entire NC Coast

Before

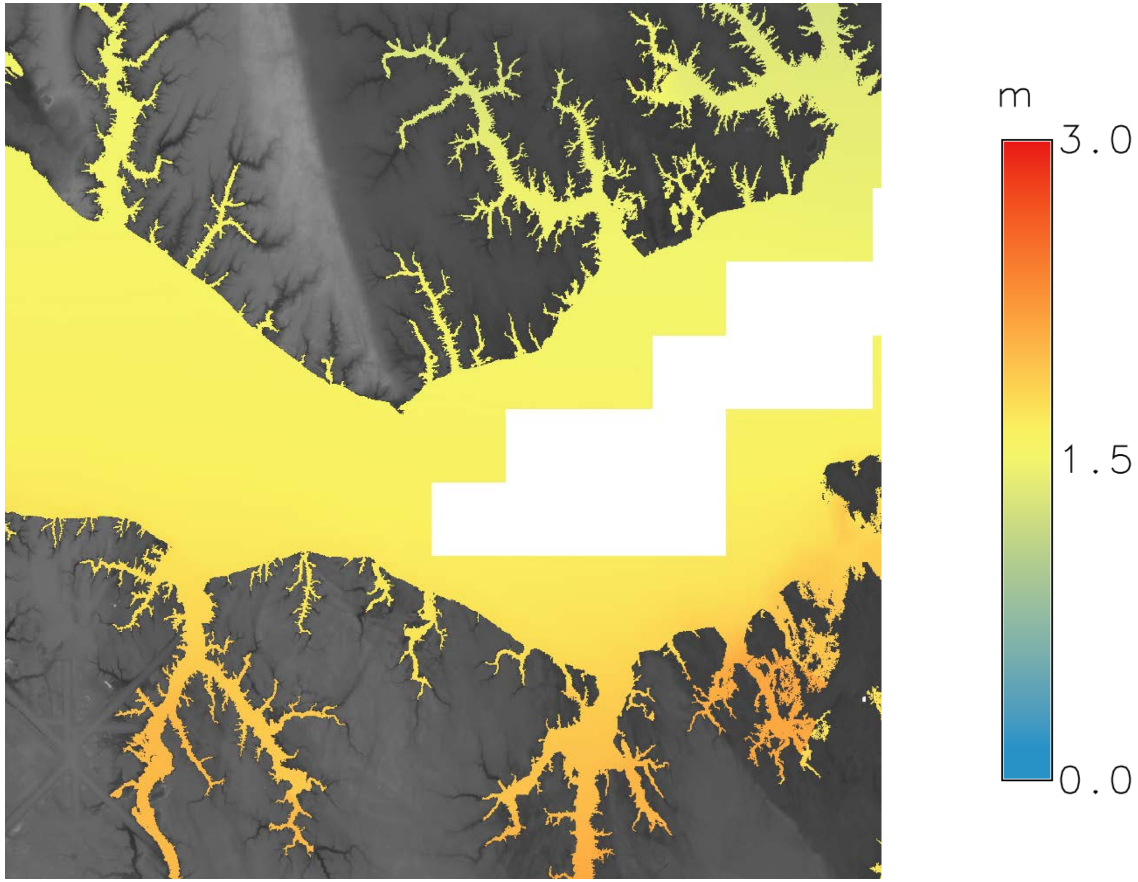
After



Enhanced Guidance for Entire NC Coast



Before



After

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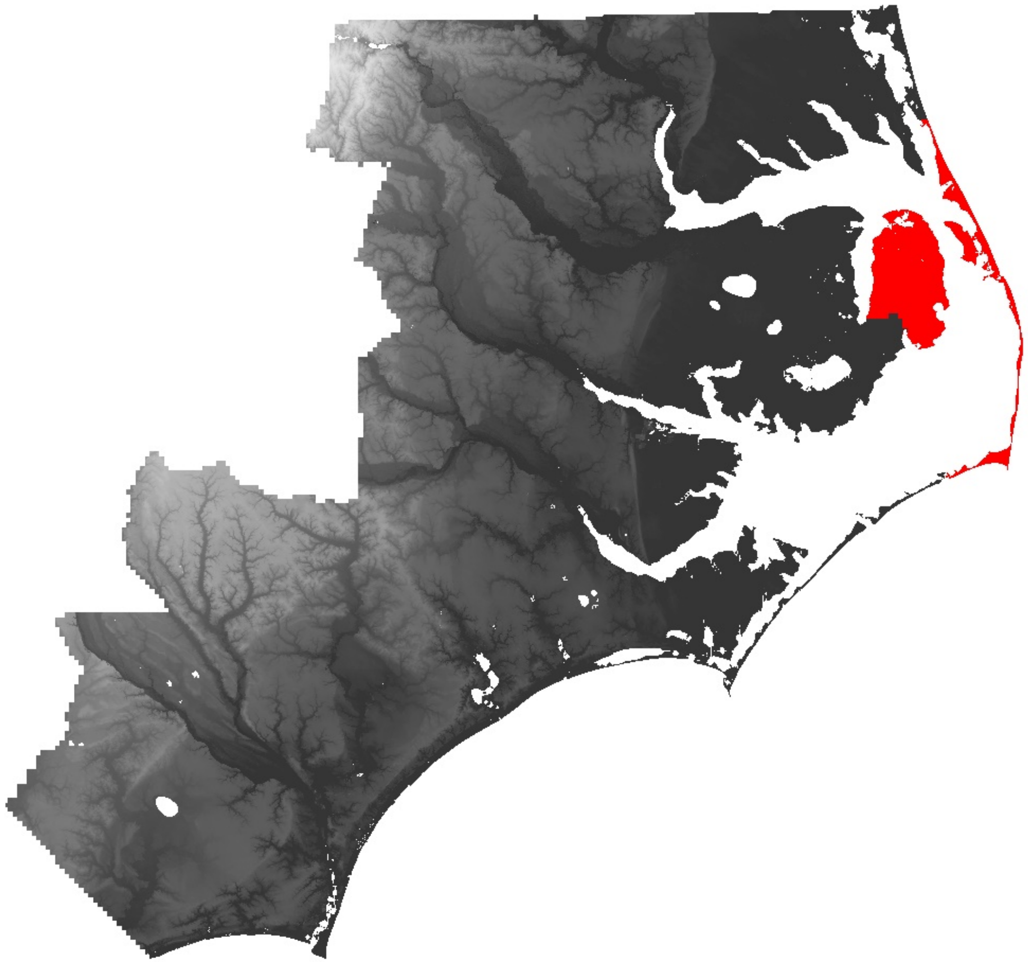
Evaluating Accuracy using a Refined Mesh

Our process does not incorporate physics.

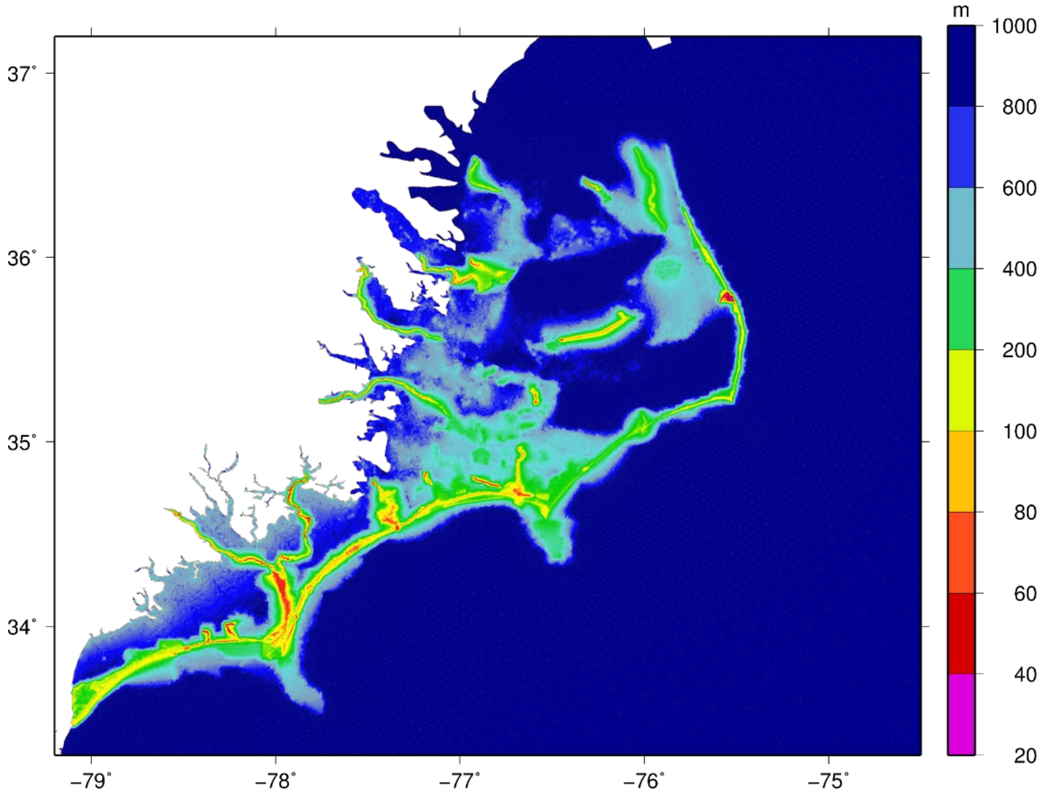
If we could run ADCIRC at a similar 15-m resolution, how would the results compare?

To answer this, we developed a refined mesh for Dare County, NC:

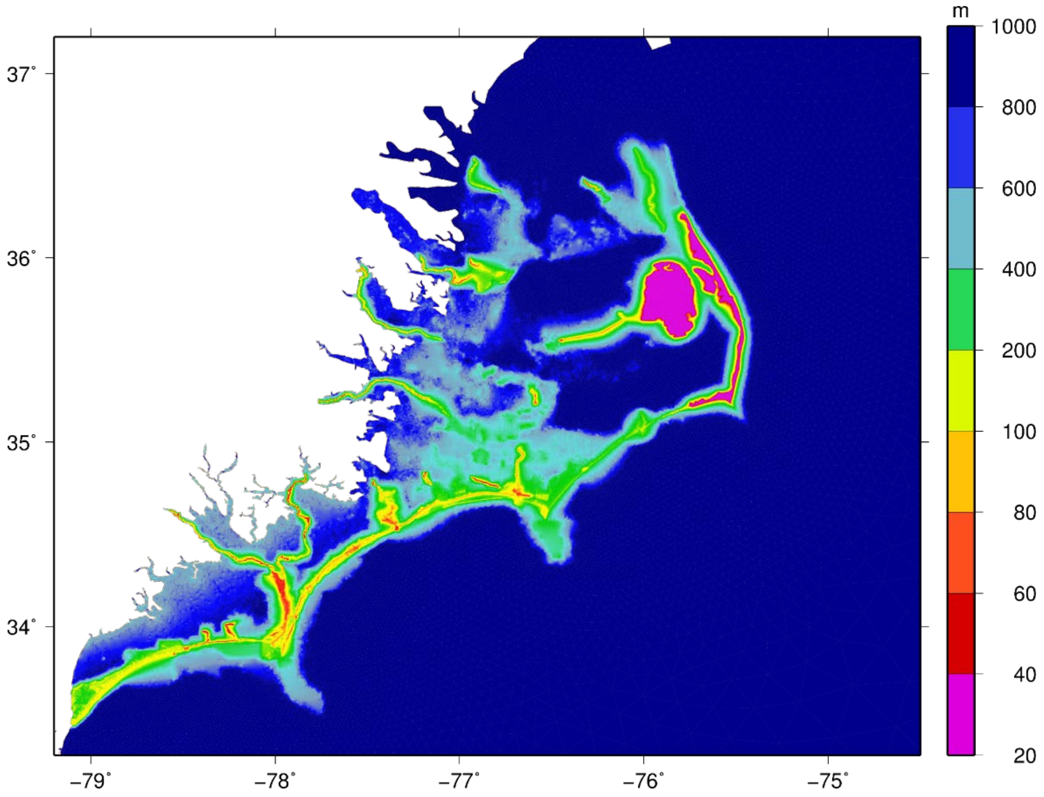
- Modified from the NC9
- Overland vertices in Dare correspond exactly to DEM cells via a 1-to-1 conversion
- Contains 5.7 million total vertices



Mesh Comparison in Dare County

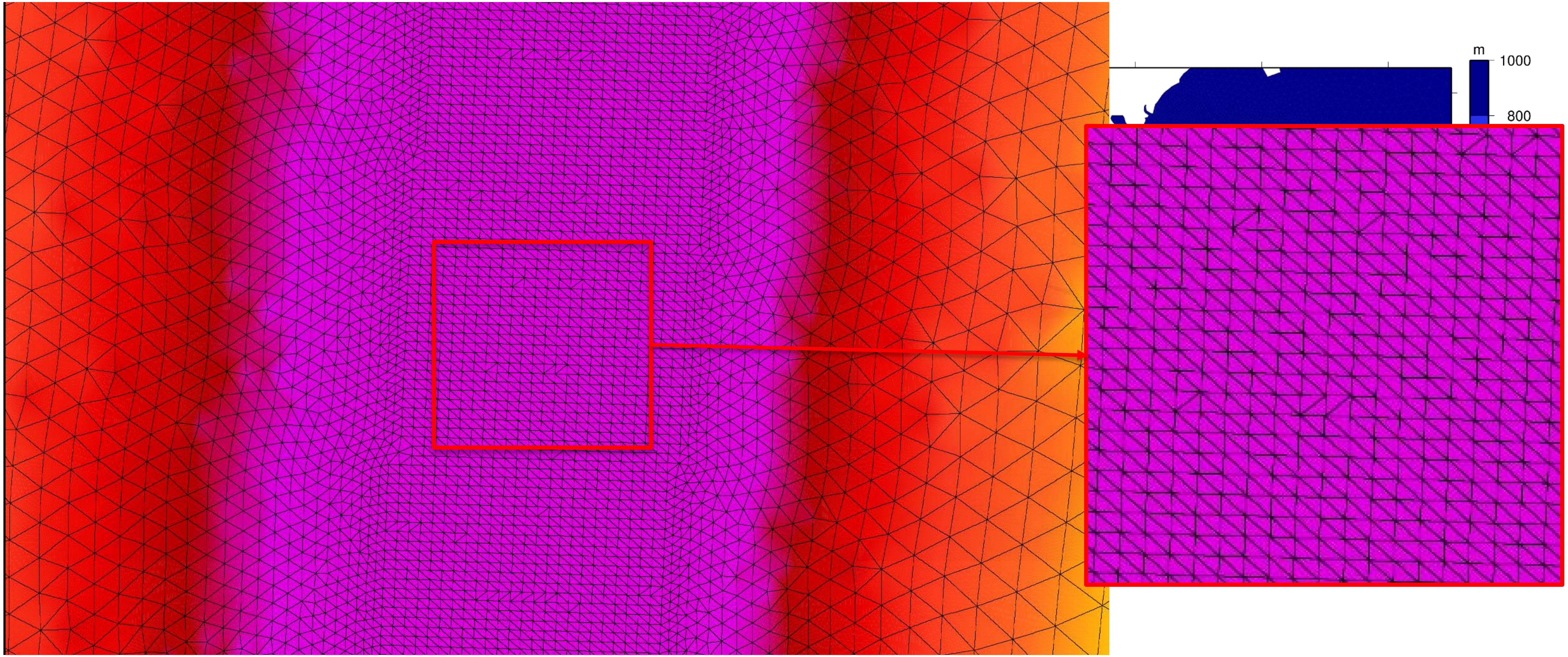


NC9 Mesh Resolution



Refined Dare Mesh Resolution

Mesh Comparison in Dare County



Refined Dare Mesh Resolution – Zoomed

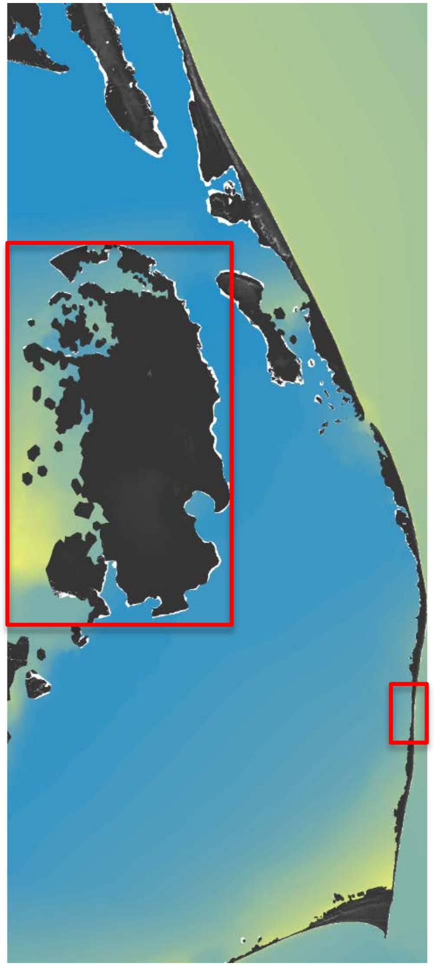
Defining some Abbreviations

Base – Maximum water levels from ADCIRC best-track Matthew simulation using NC9 mesh

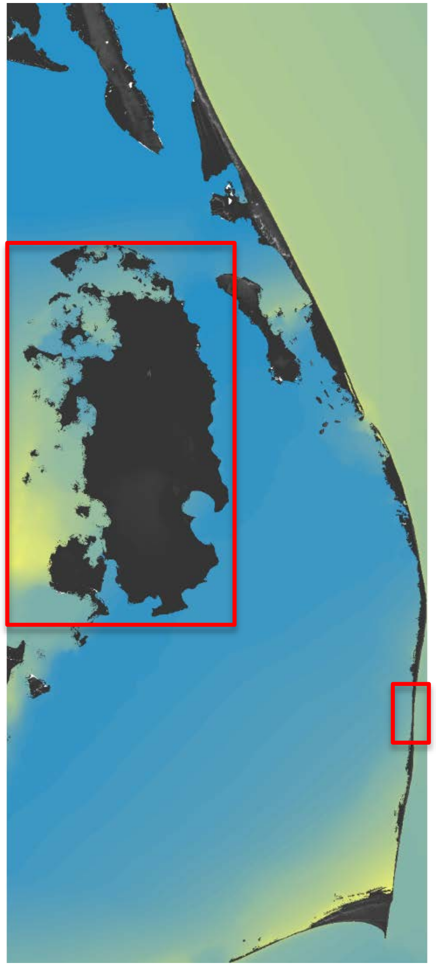
Enhanced(30) – Results from Base, enhanced using `r.grow` with a radius of 30 cells

Refined – Maximum water levels from ADCIRC best-track Matthew simulation using the refined Dare County mesh

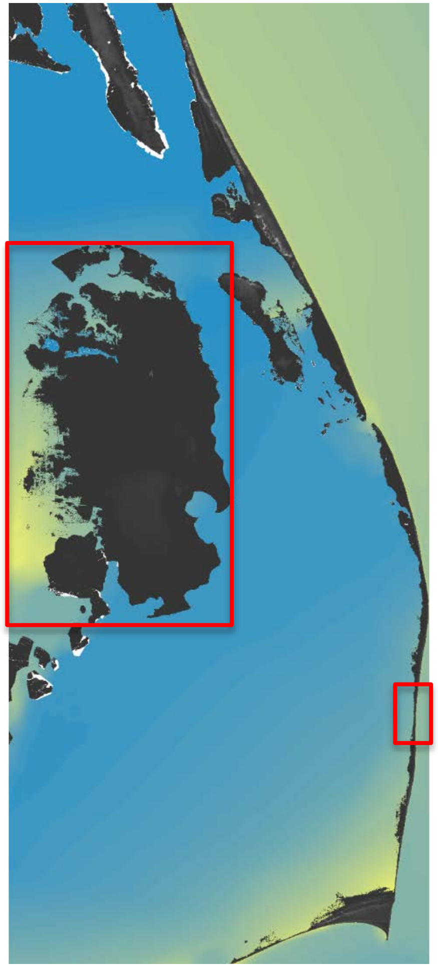
Comparing Enhanced Res. with Refined ADCIRC



Base



Enhanced(30)

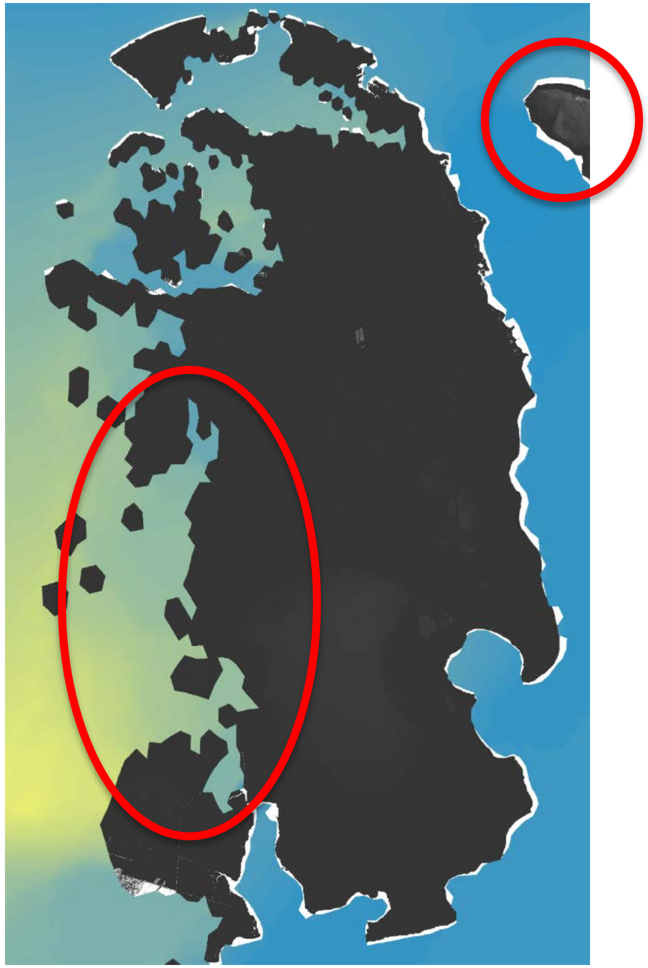


Refined

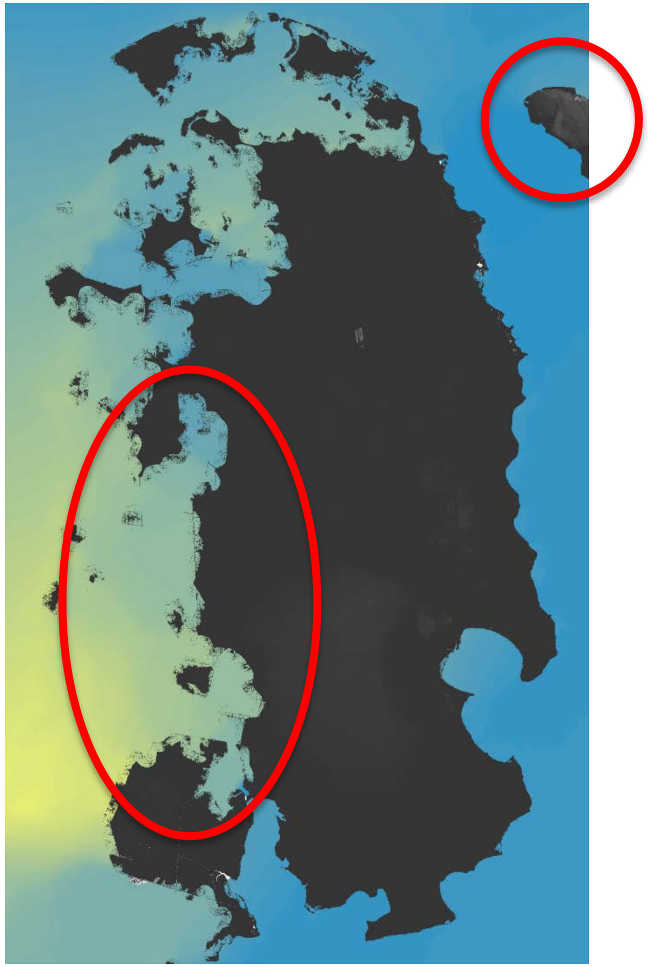
Flooding Comparison in Dare (total numbers)

	Statistic (% of total in Dare)	
Simulation	Bldgs.	Area (km^2)
Base	1,940 (4.8)	185 (18.6)
Enhanced(30)	3,742 (9.3)	291 (29.2)
Refined	1,674 (4.1)	133 (13.4)

Inland Dare Comparison



Base



Enhanced(30)

Refined

Barrier Island Comparison

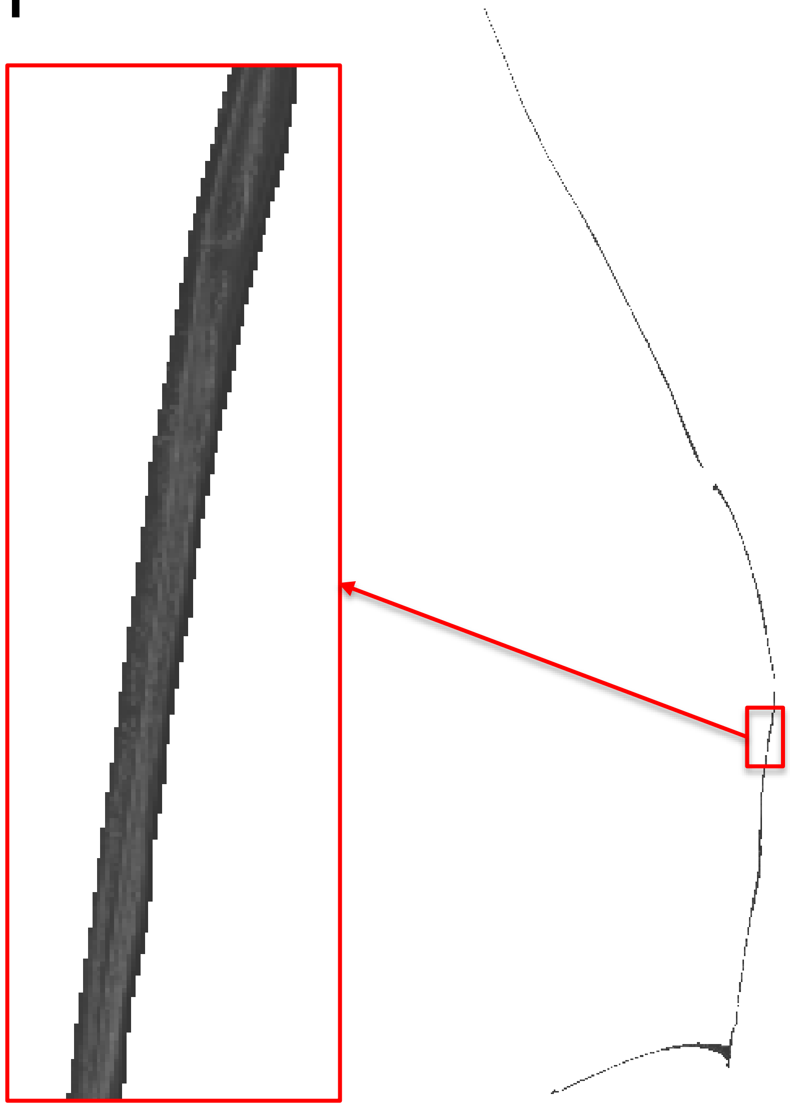
Base

Enhanced(30)

Refined

Barrier Island Dune-Area Comparison

	Statistic (% of total)	
Simulation	Bldgs.	Area (km^2)
Base	4 (0.1)	0.6 (2.2)
Enhanced(30)	19 (0.5)	3.8 (14.4)
Refined	10 (0.3)	3.0 (11.5)



Conclusions

- NCEM is very happy with this guidance
  - They have said the enhanced guidance is a much better match to the flooding they observed during Matthew
- The enhanced resolution may work better in some areas than in others
  - May be a better predictor in steeper regions where ADCIRC is more likely to under-predict
- This is a tool for *forecasting*, better methods are available for hindcasting (e.g., high-resolution ADCIRC meshes or subdomain inundation modeling)

Future Work

This is not a rigid process; some methods can change depending on needs of end-users

- Radius (30 or 500 cells)
- Subtraction of over-predicted water levels
- Raster interpolation method

Can we include physics?

- Incorporate land-type raster and use a friction factor
- Use a rule-based method to vary `r.grow` radius

Can we apply this to other coasts?

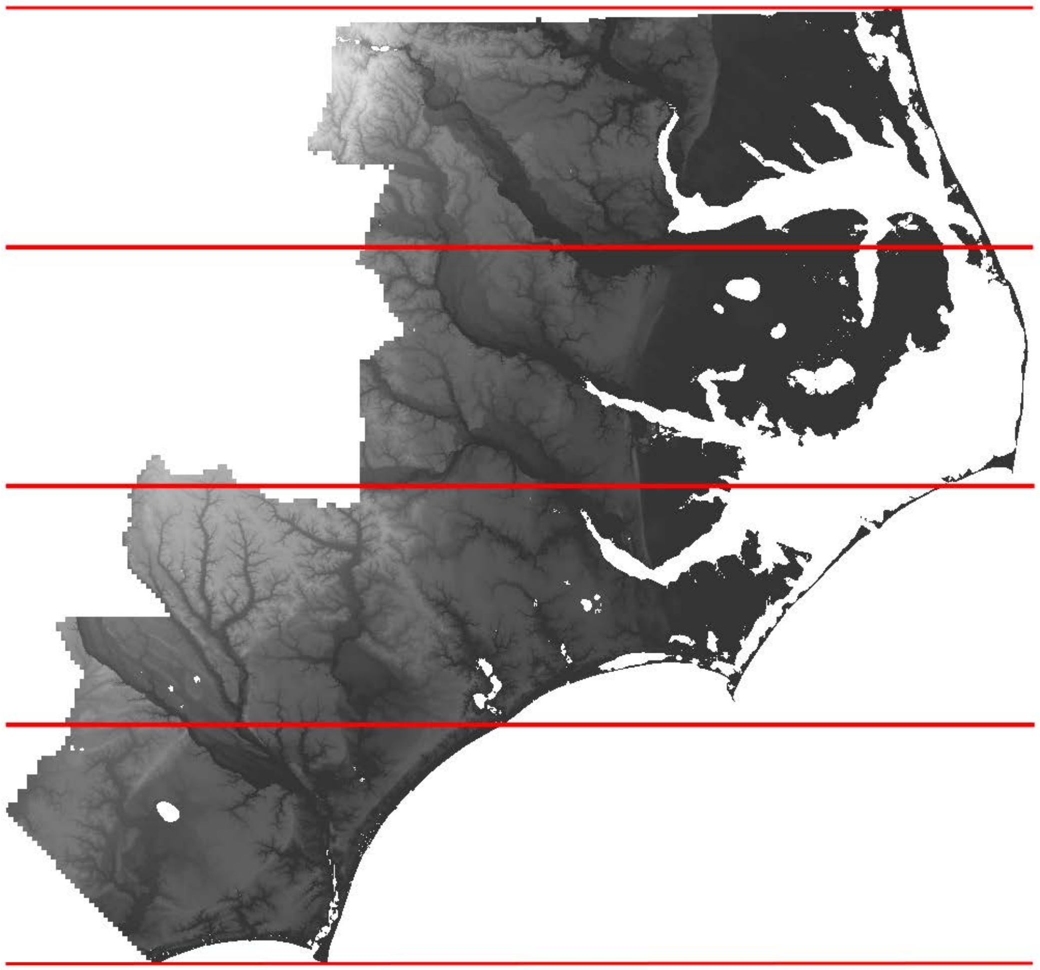
Thank you. Questions?

Appendix

Limitations

- This study did not have access to aerial flooding observations or flooded building data
- Using total area and total number of flooding buildings as basis for comparison is not ideal
- The refined Dare County mesh has not been validated
- Hurricane Matthew is only one storm, and did not produce high surge levels
- Dare County does not have all of the topographic complexity of Carteret County
- This does not account for changes in morphology during storms

Domain Decomposition Scheme



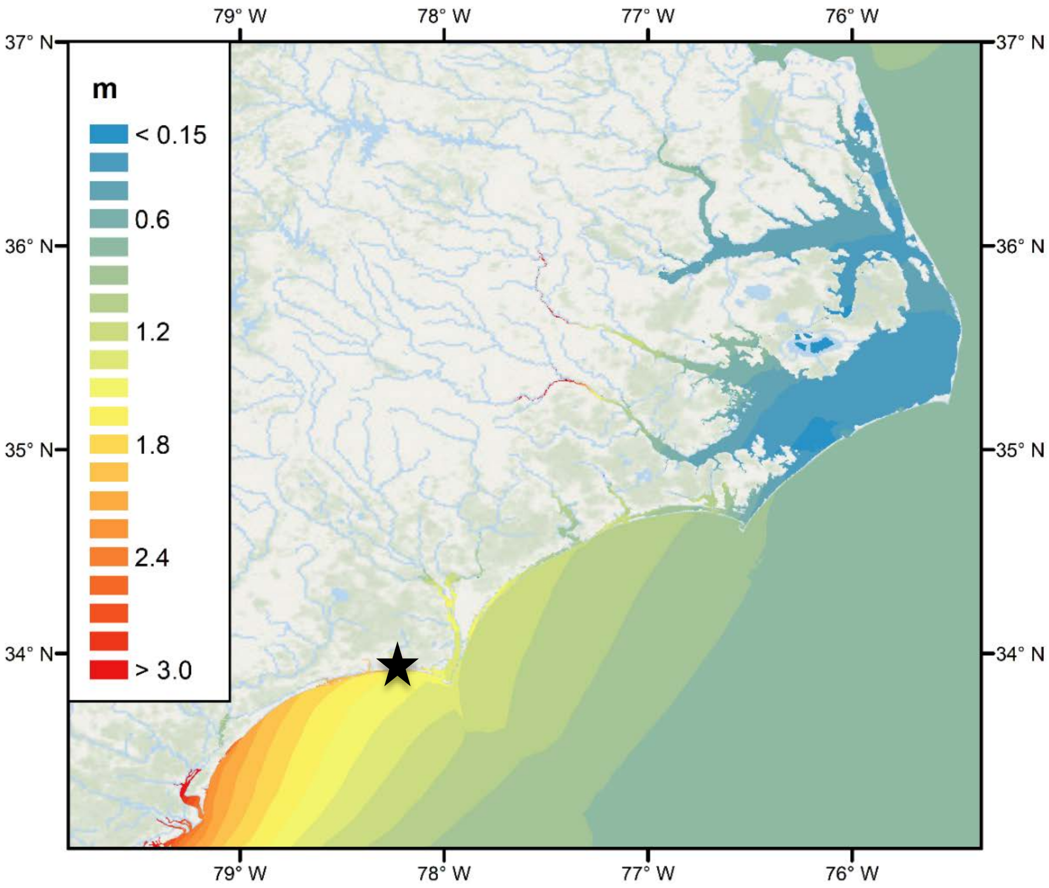
Comparing Effect of Radius – Matthew Best-Track

			`r.grow` radius (cells)	
Region	Statistic	None	30 (% change)	500 (% change)
Carteret County	Bldgs.	2,353	3,298 (40.2)	3,344 (42.1)
	Area (km^2)	489	547 (11.8)	568 (16.1)
Dare County	Bldgs.	4,711	5,754 (22.1)	6,028 (28.0)
	Area (km^2)	249	284 (13.9)	332 (33.3)
North Carolina	Bldgs.	28,018	37,146 (32.6)	39,534 (41.1)
	Area (km^2)	2,791	3,333 (19.4)	3,849 (37.9)

Comparing Effect of Radius – Matthew Advisory 27

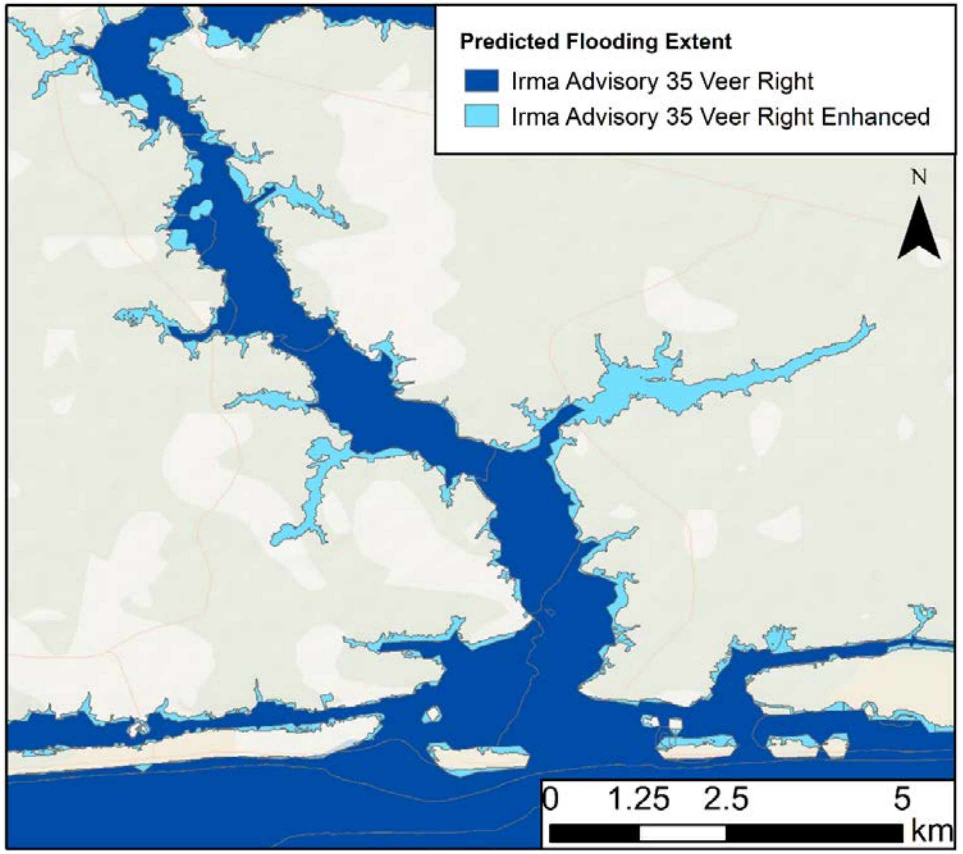
			`r.grow` radius (cells)	
Region	Statistic	None	30 (% change)	500 (% change)
Carteret County	Bldgs.	9,198	12,494 (35.8)	12,635 (37.4)
	Area (km^2)	610	674 (10.5)	688 (12.7)
Dare County	Bldgs.	8,320	10,394 (24.9)	10,491 (26.1)
	Area (km^2)	427	490 (14.6)	563 (31.9)
North Carolina	Bldgs.	71,742	87,992 (22.7)	92,706 (29.2)
	Area (km^2)	4,091	4,694 (14.7)	5,274 (28.9)

Real-Time Guidance during 2017 Hurricane Season



Prediction of maximum water levels for Hurricane Irma Advisory 35 “veer right” ensemble

Real-Time Guidance during 2017 Hurricane Season

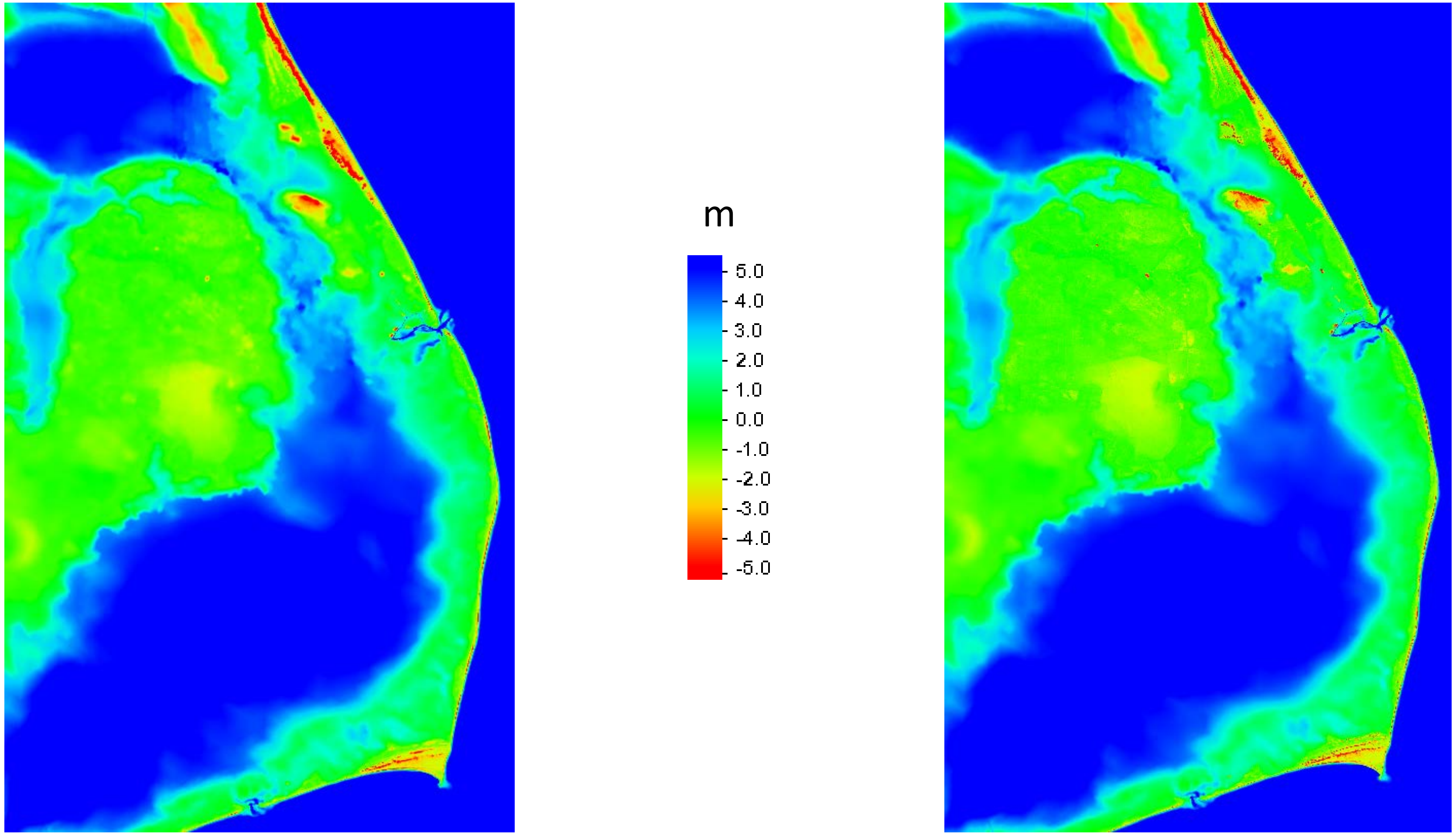


Change in predicted flooding extent, before (dark blue) and after (light blue) enhancing resolution

Inland Dare Comparison

	Statistic (% of total)	
Simulation	Bldgs.	Area (km^2)
Base	156 (11.0)	160 (21.9)
Enhanced(30)	191 (13.5)	228 (31.1)
Refined	42 (3.0)	104 (14.1)

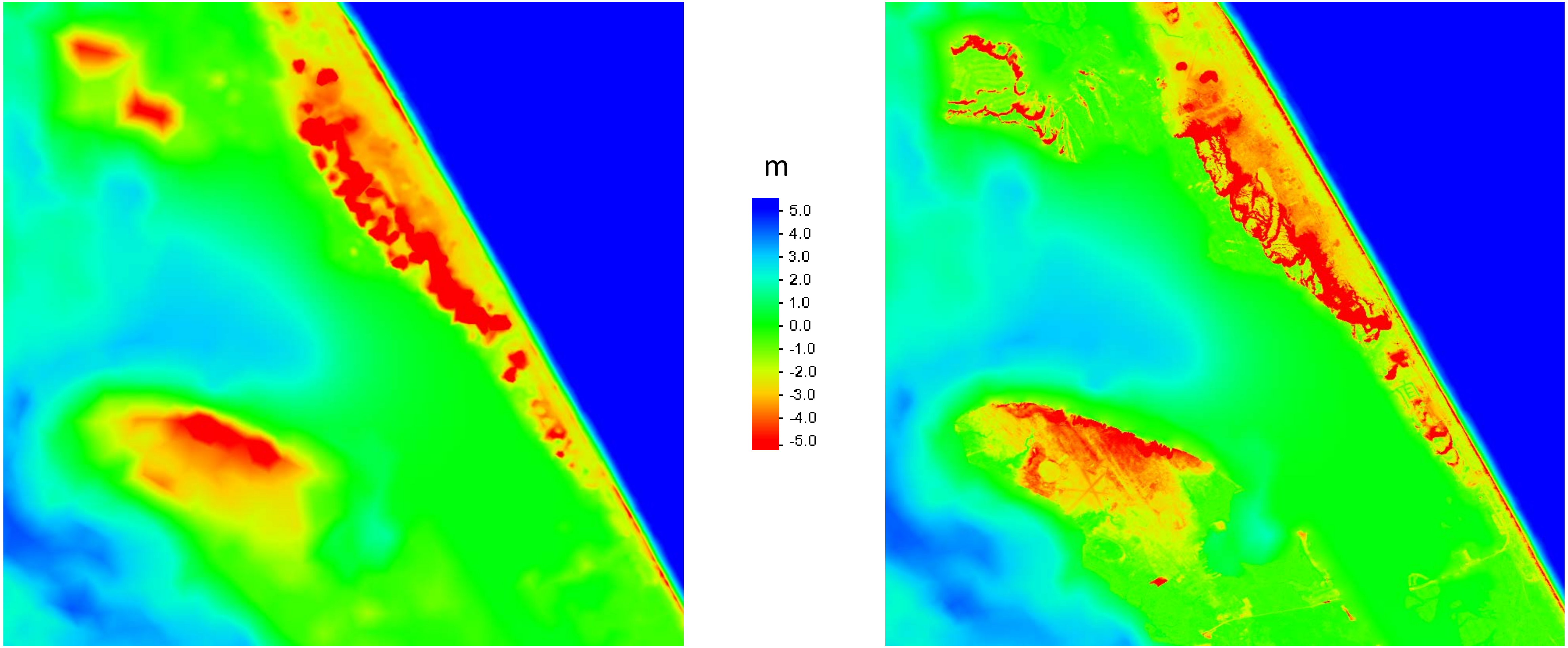
Bathy/Topo Comparison



Base

Refined

Bathy/Topo Comparison



Base *Refined*