# Using a Multi-Resolution Approach to Improve the Accuracy and Efficiency of Flooding Predictions

Ph.D. Research Proposal

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Ajimon Thomas

Department of Civil, Construction and Environmental Engineering
North Carolina State University

NC STATE UNIVERSITY

COASTAL RESILIENCE CENTER
*A U.S. Department of Homeland Security Center of Excellence*

# Acknowledgements


## Thesis Committee

Dr. Casey Dietrich[1], Dr. John Baugh[1], Dr. Elizabeth Sciaudone[1], Dr. Rick Luettich[2]

[1]Civil, Construction and Environmental Engineering, North Carolina State University, Raleigh, NC
[2]Institute of Marine Sciences, UNC Chapel Hill, Morehead City, NC

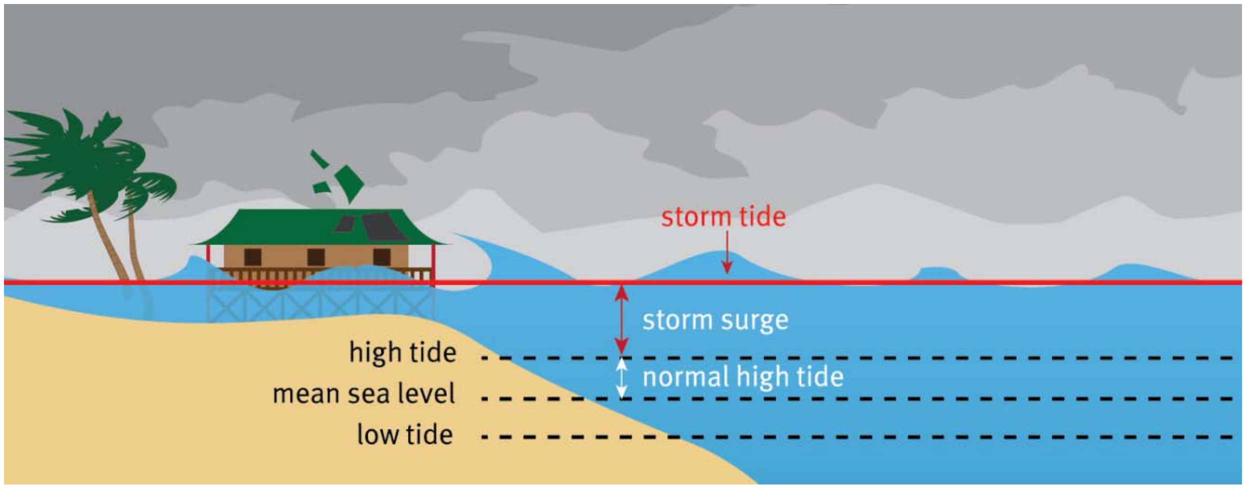
## Other Collaborators

Taylor Asher[1], Dr. Brian Blanton[2], Dr. Clint Dawson[3],
Dr. Jason Fleming[4], Mark Loveland[3]

[1]Institute of Marine Sciences, UNC Chapel Hill, Morehead City, NC
[2]Renissance Computing Institute, Chapel Hill, NC
[3]Institute of Computational Engineering and Sciences, The University of Texas at Austin, Austin, TX
[4]Seahorse Coastal Consulting, Morehead City, NC

# What is Storm Surge ?

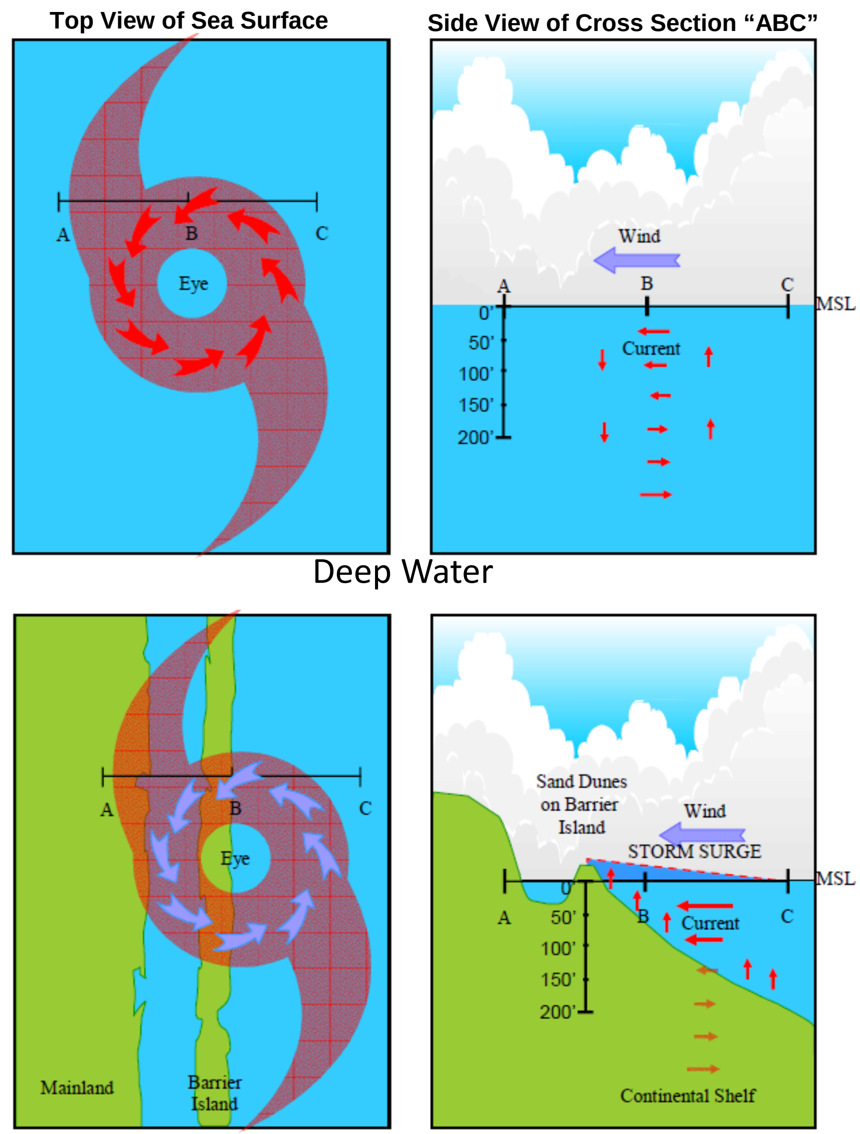
- Height of the water above the normal predicted astronomical tide
- Large-scale features
  - the intensity, size, speed, and path of the storm, the general configuration of the coastline, bottom topography near the coast, the stage of the astronomical tide
- Small-scale features
  - convergence or divergence in bays and estuaries,  local wind-setup, seiching




Source: ivaluesafety.com

# What Causes Storm Surge?

- Strong winds causes piling up of water (more than 85%)
- Wave-setup (5-10%)
- Low pressure at the storm's center causes water to bulge upward (5-10%)



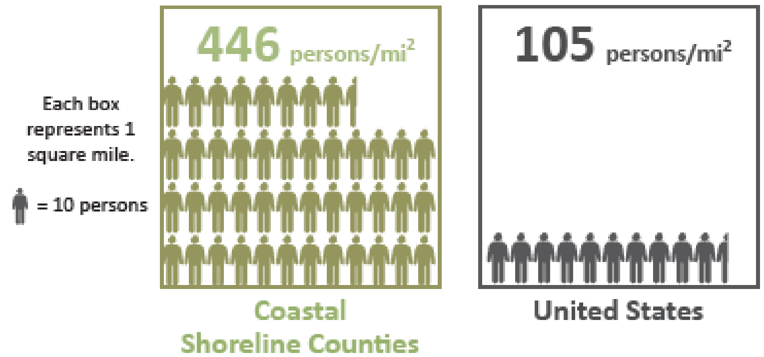

Landfall

Source: SLOSH Display Training, 2003

# Why is Modeling Storm Surge Important?

- 44 % of the worlds population live within 150 km of the coast (UN Atlas of the oceans, 2018)
- In the U.S., > 39 % (123.3 million) of the population lived in coastal shoreline counties in 2010 (NOAA and U.S. Census Bureau, 2013)

Source: NOAA




Source: U.S. Air Force

Source: NOAA

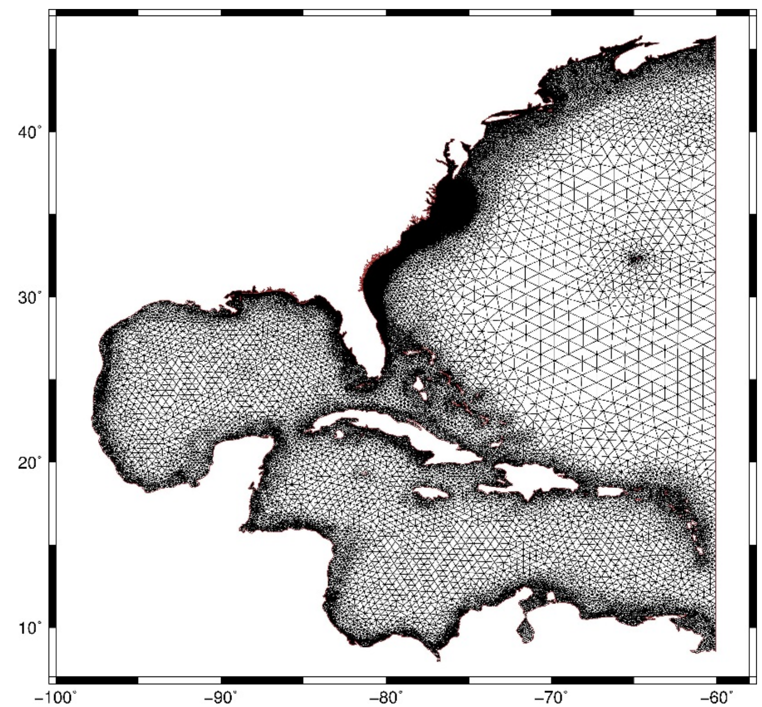
# Numerical Modeling of Storm Surge

- Began as early as 1950s (Hoover, 1957; Conner et al. 1957)
  - used central pressure to compute max surge
- Improvements
  - Tancreto, 1958; Pore, 1964; Chan and Walker; 1979
  - Harris, 1963
- With advance in computing power
  - SPLASH (Jelesnianski, 1972)
    - computed peak surge via nomograms
  - TTSURGE (Dresser et al. , 1985)
    - Developed by FEMA
  - SLOSH (Jelesnianski et al., 1992)
    - developed by NWS to estimate surge heights from historical, hypothetical or predicted storms
    - computationally efficient, small spatial coverage, does not model wave impacts or astronomical tides, use of a structured mesh limits accuracy
  - ADCIRC (Luettich et al., 1992)
    - used by FEMA in the development of flood insurance rate maps, USACE for navigation and storm protection projects and NOAA for tidal calibrations

# Storm Surge Modeling using ADCIRC

## ADvanced CIRCulation

- Finite-element model for oceanic, coastal and estuarine waters
- Unstructured meshes are used to represent relatively small features while maintaining coarser resolution elsewhere in a large domain
- Solves water levels using the Generalized Wave Continuity Equation (GWCE) and the velocities using vertically-integrated momentum equations
- Two-dimensional depth averaged version (2DDI) is commonly used in modeling of storm surge and flooding

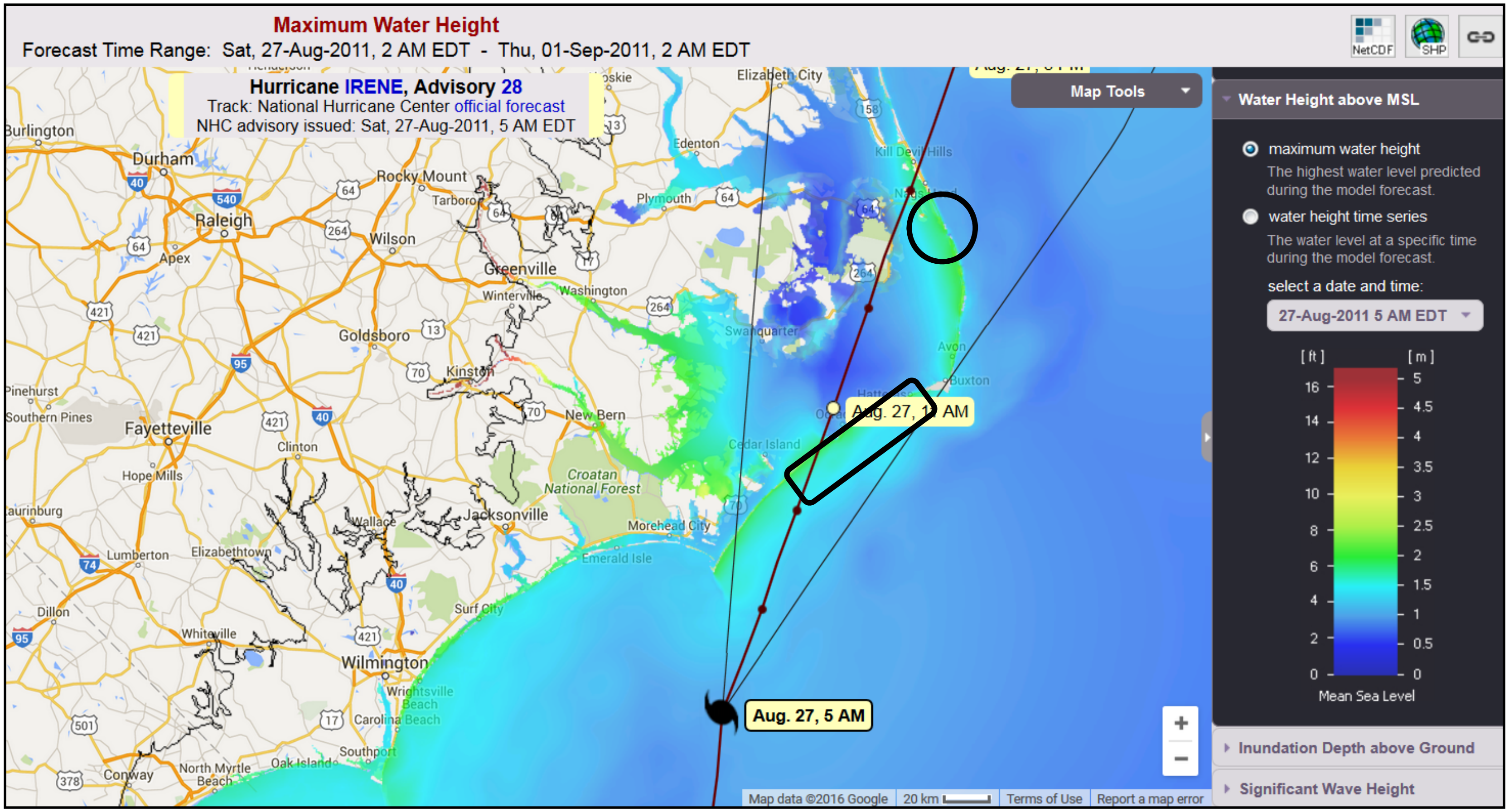


# Storm Surge Forecasting using ADCIRC

- ADCIRC Surge Guidance System (ASGS) provides forecast guidance for winds, waves and storm surge during a hurricane, especially the coastlines of North Carolina, Louisiana, and Texas
- Done by running ADCIRC on high performance super computers
  - Texas Advanced Computing Center (TACC) at University of Texas, LONI Network at Louisiana State University, Renaissance Computing Institute (RENC) at University of North Carolina
- For NC Coast, ADCIRC is run twice daily during normal conditions, and four times daily during severe storms
- Different meshes are used depending on where the storm is at that point in time
- Coastal Emergency Risks Assessment (CERA) (https://cera.coastalrisk.live)
  - an intuitive and interactive visualization tool that integrates modeled results with measured data
  - presentation of results to emergency managers, decision makers, and the scientific community

# Storm Surge Forecasting using ADCIRC

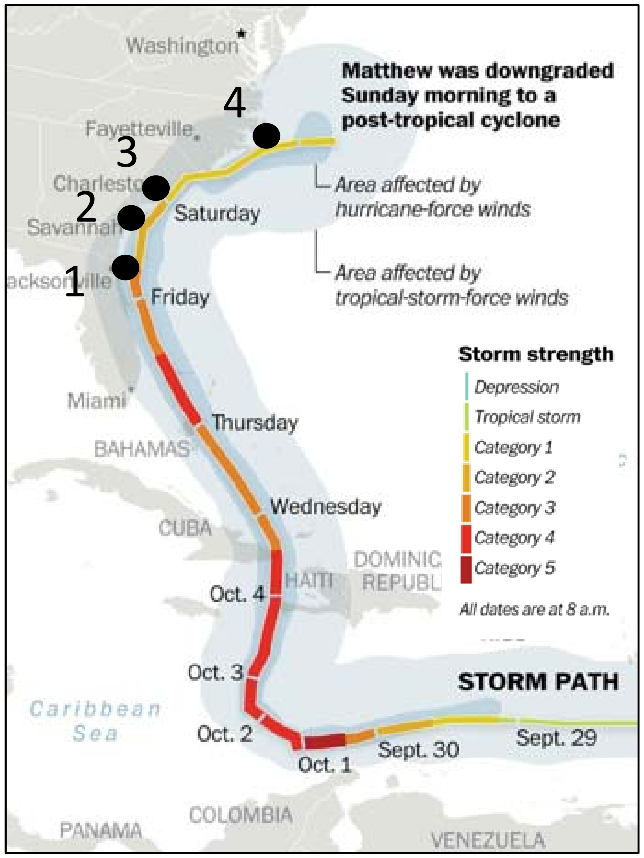
Source: nc-cera.renci.org/



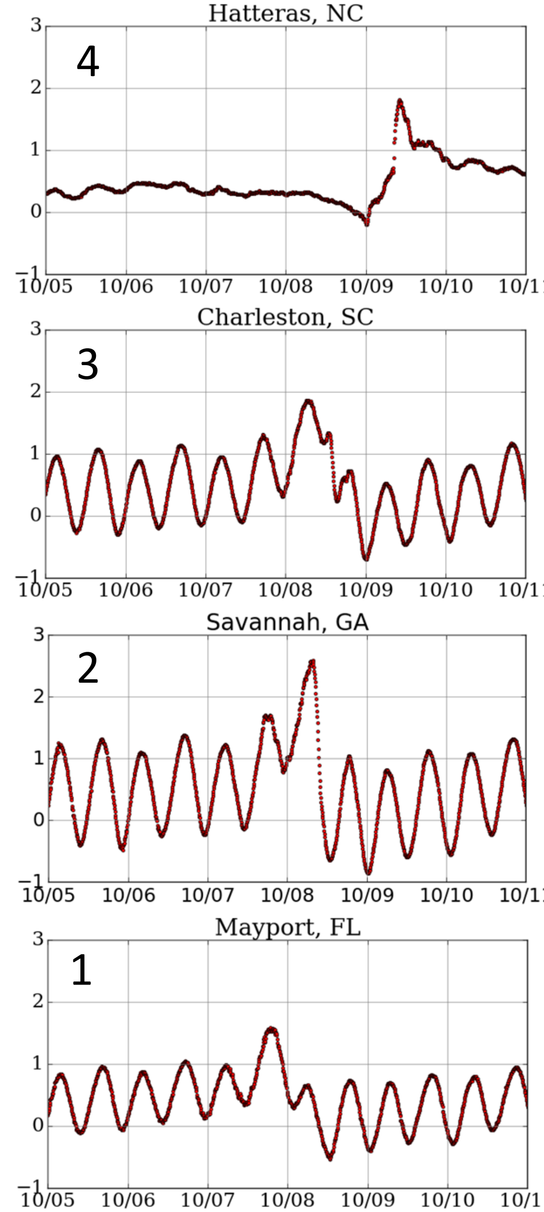

Hurricane Irene, 28th Advisory

# Hurricane Matthew

- Category-5 storm
- Impacted the south-east coast of the U.S. during October 2016
- Caused 34 direct deaths and forced evacuations by 3 million people
- Shore-parallel storm
- Large variations in water levels lasting several days




Source: NOAA

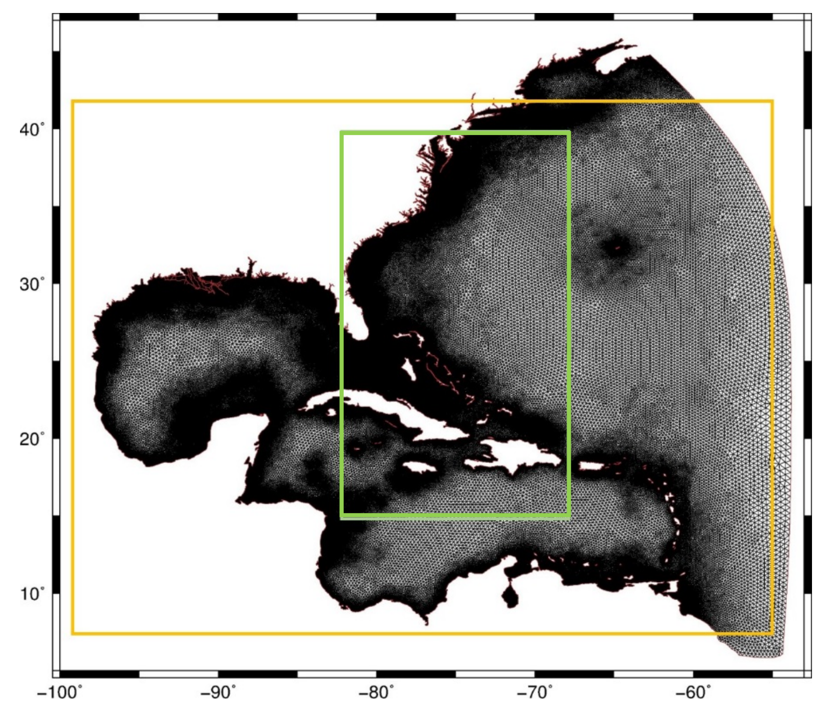



Water Levels in m (NAVD88)

# Methods

## Surface Pressure and Wind Fields

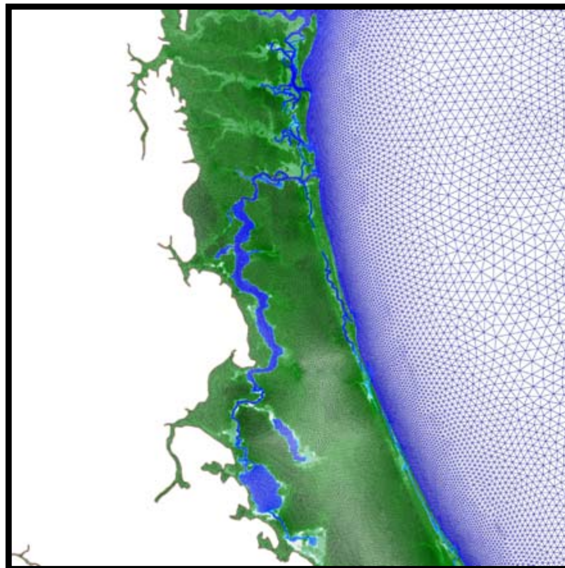
- Generalized Asymmetric Holland Model (GAHM) (Gao et al. 2017)
  - Parametric vortex model
  - Eliminates the assumption of cyclostrophic balance from AHM
  - Makes use of multiple isotachs
- Ocean Weather Inc. (OWI)
  - Based on observations
  - Fields are provided on multiple grids
  - Basin grid at resolution of 1/4°
  - Region grid at resolution of 1/20°
  - 15 min intervals

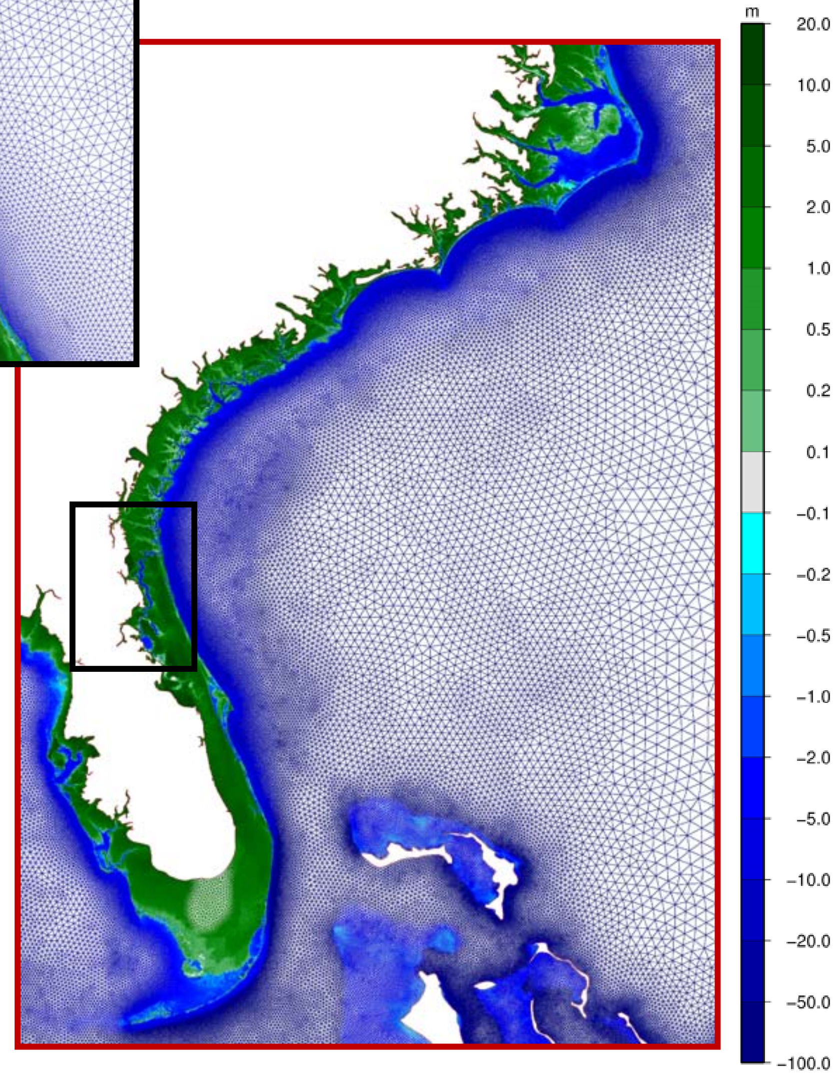


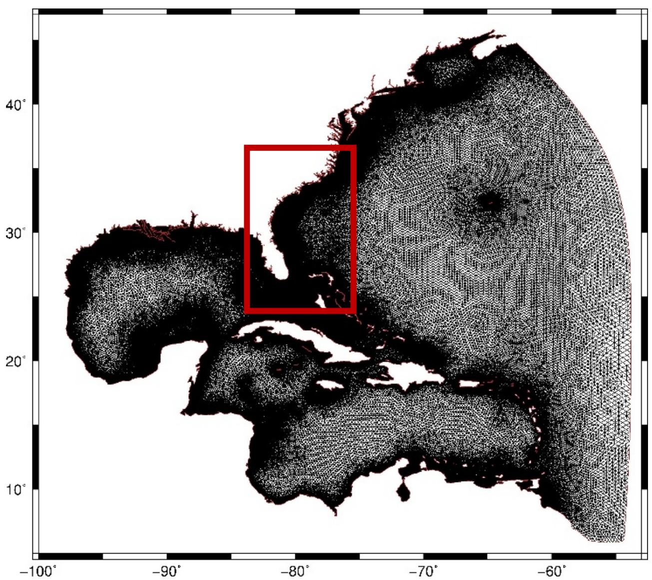
# Methods

## The HSOFS Mesh

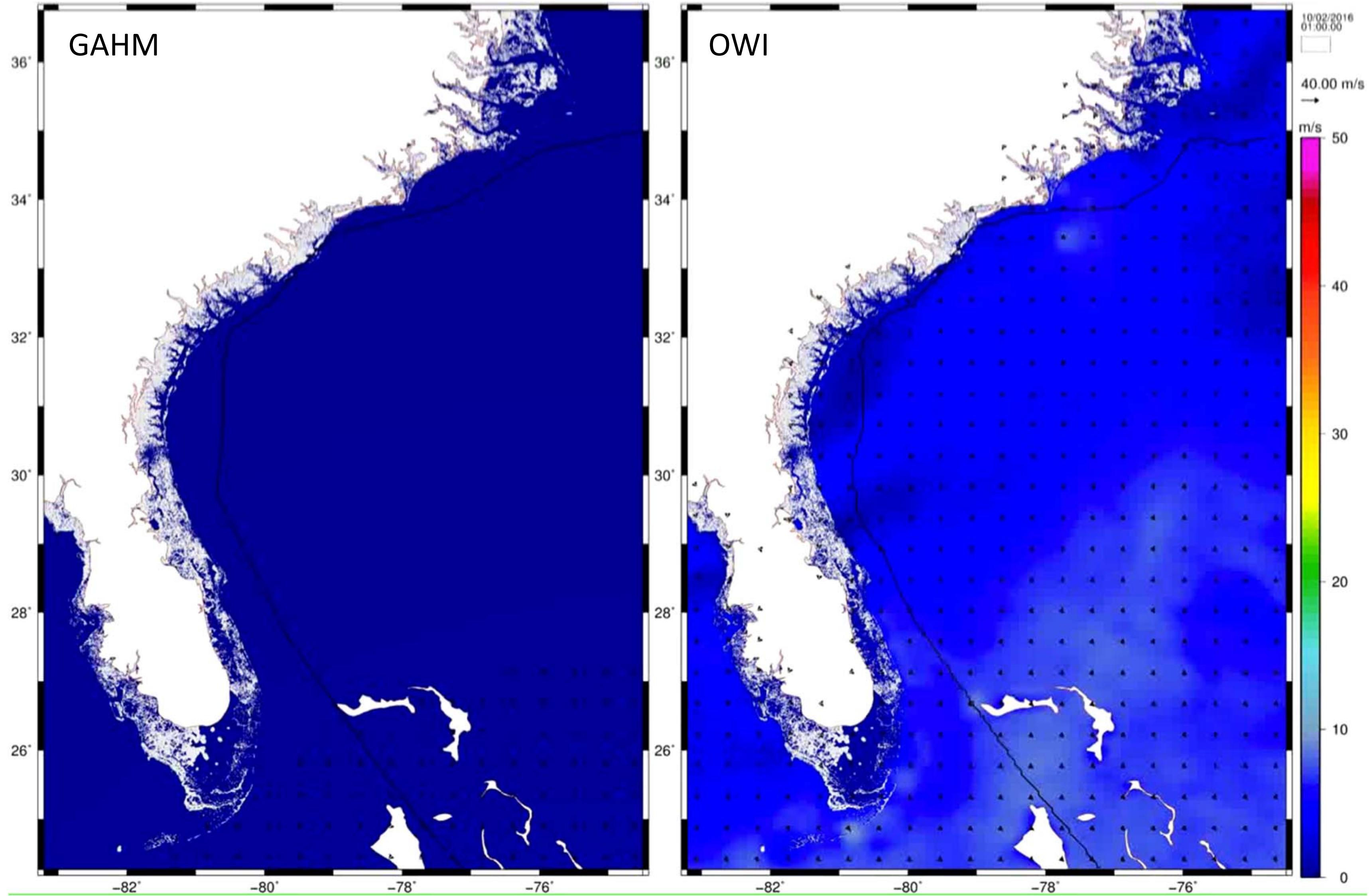
- Riverside, AECOM & NOAA, 2015
- 500 m average coastal resolution
- 1.8 million vertices



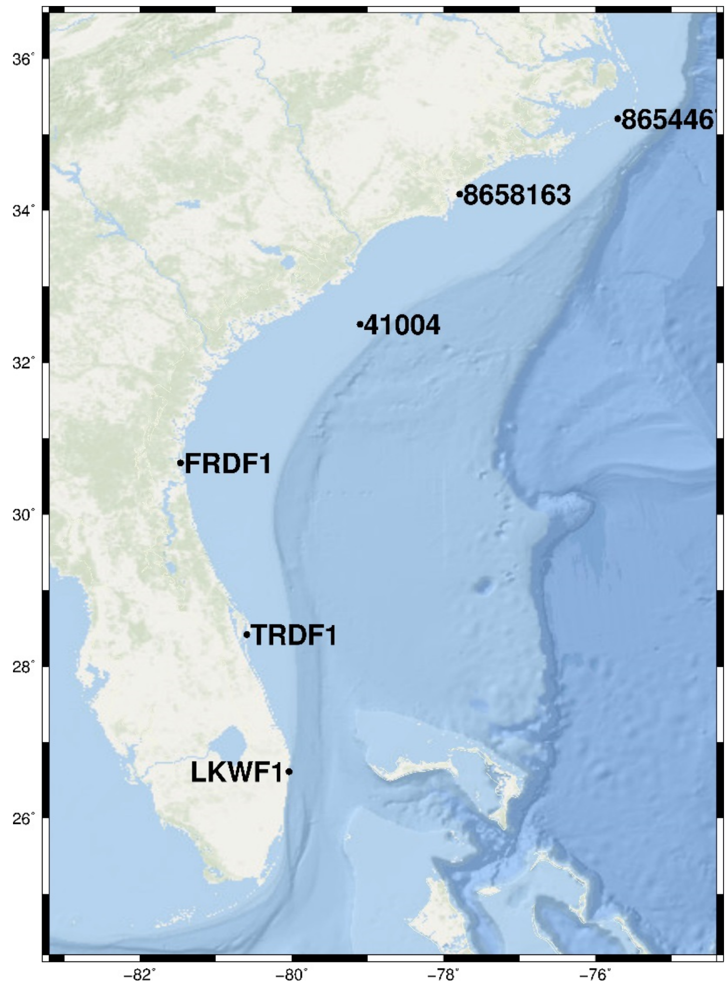


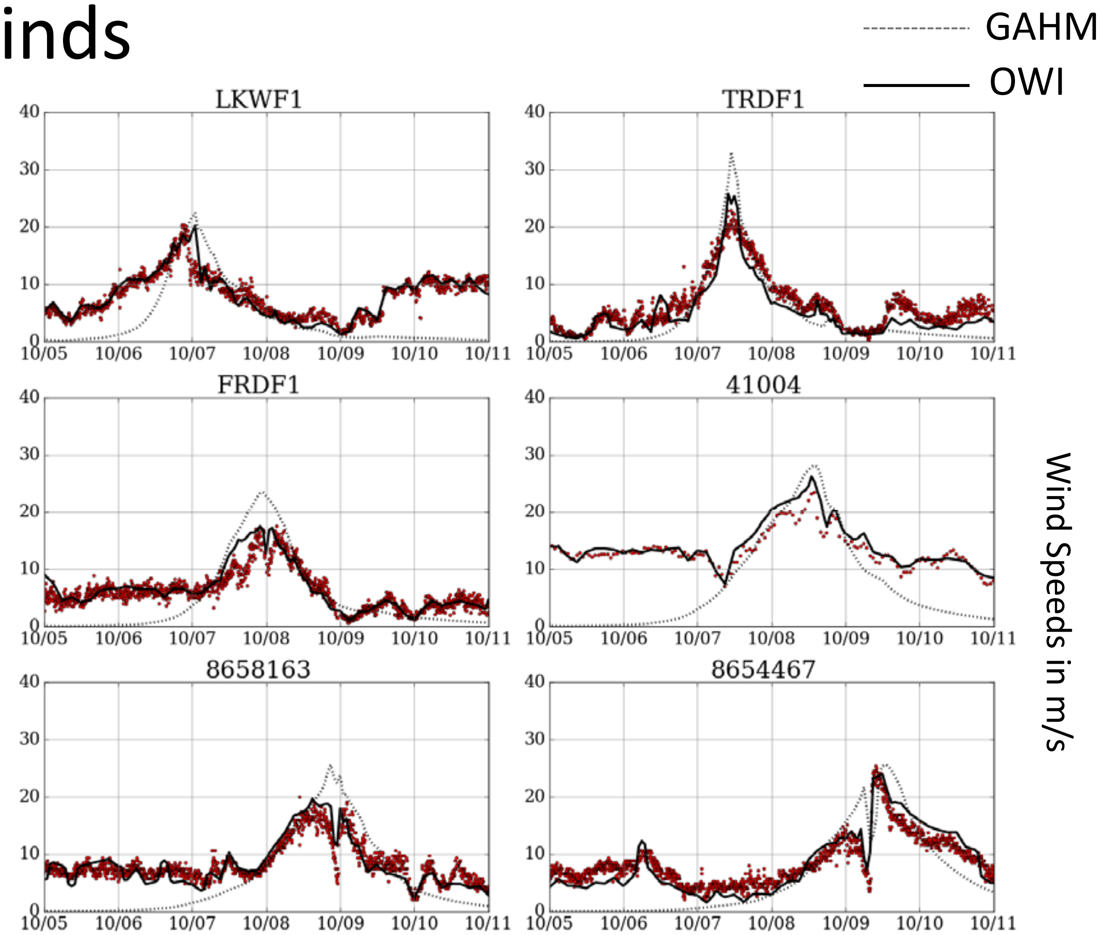



# Model Validation - Winds



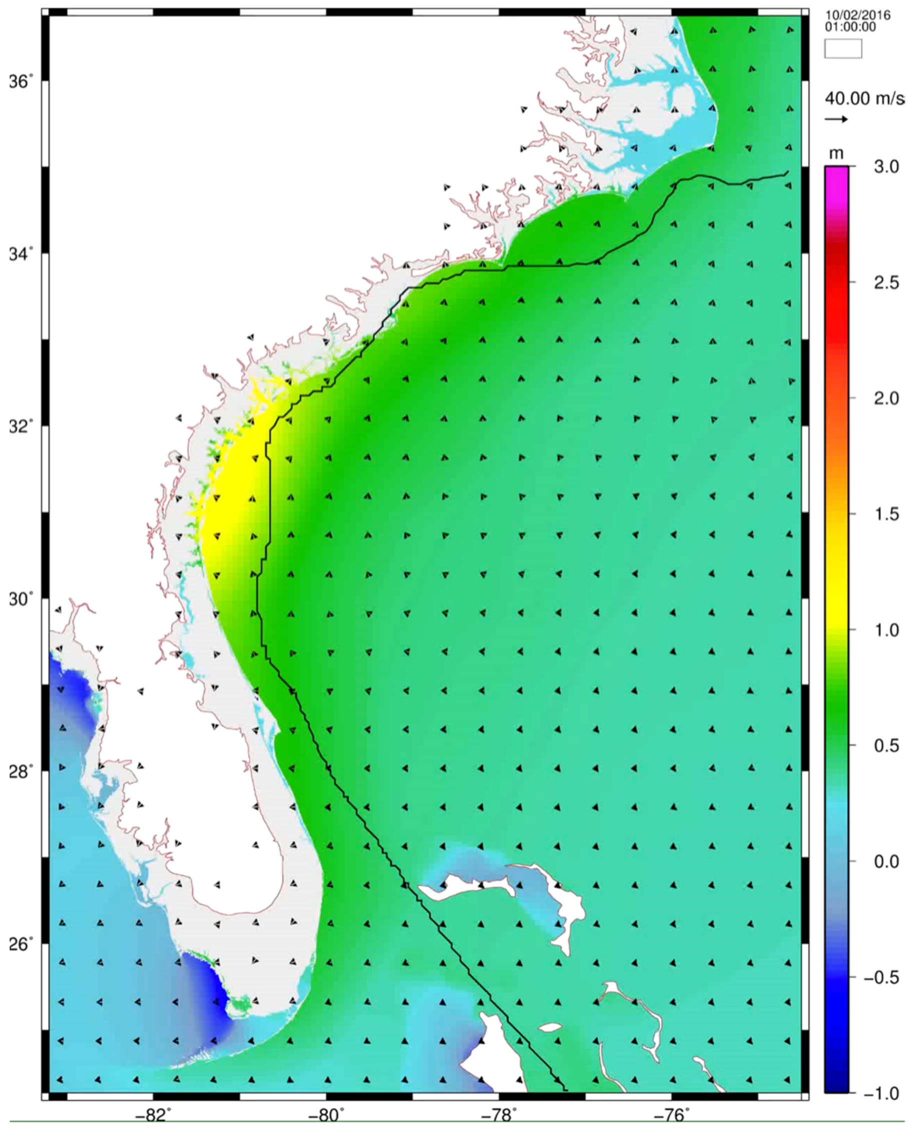
# Model Validation - Winds




| Model | Stations | RMSE (m/s) | Bias |
|---|---|---|---|
| GAHM | 109 | 5.066 | -0.467 |
| OWI | 109 | 1.937 | 0.086 |

# Model Validation – Water Levels



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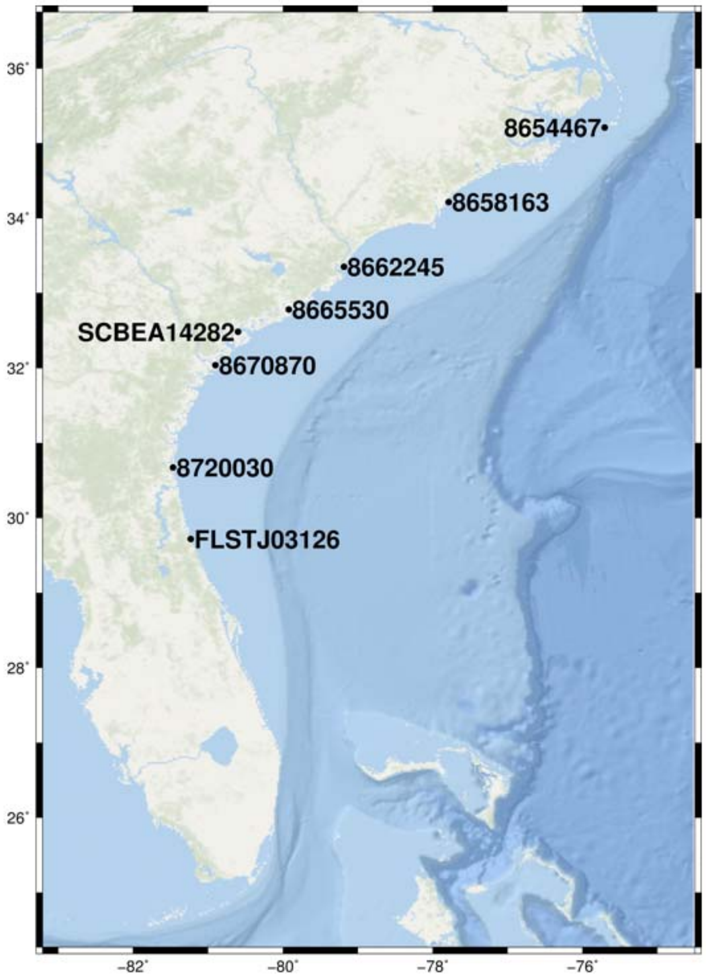
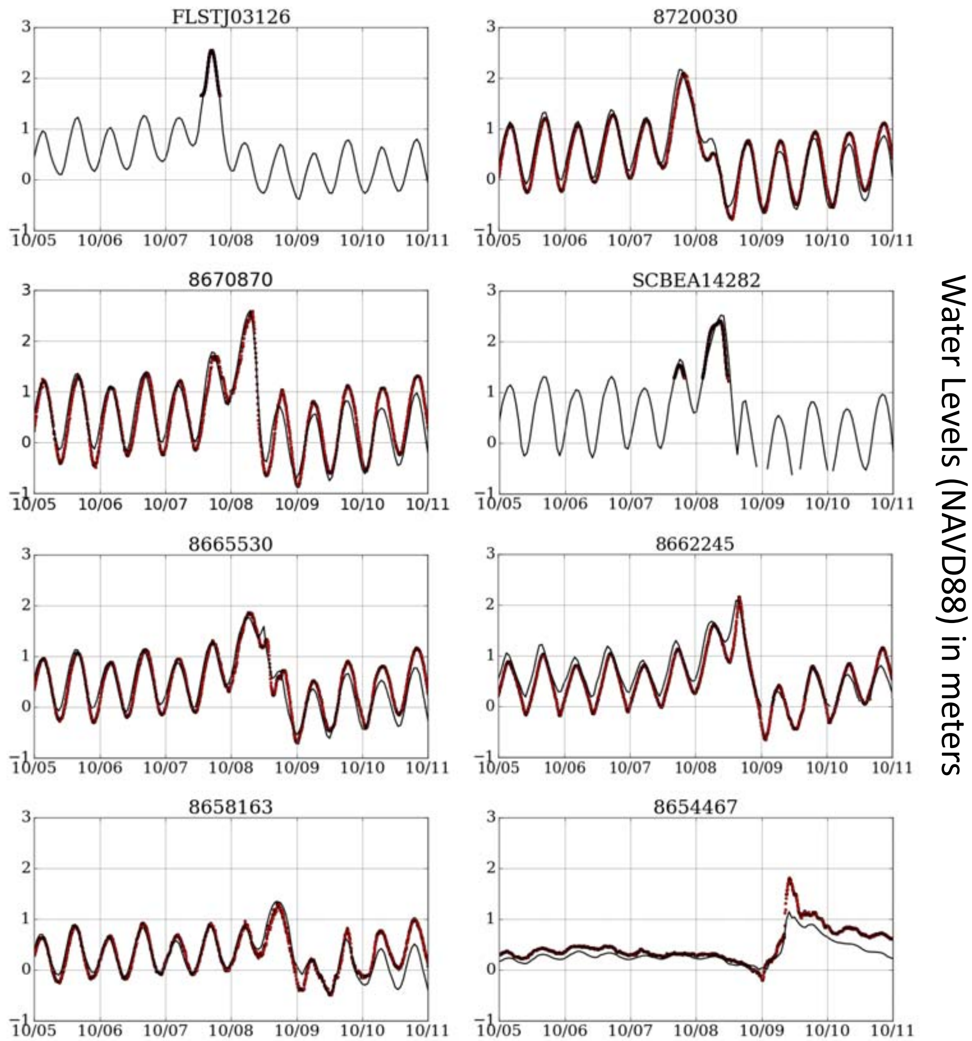
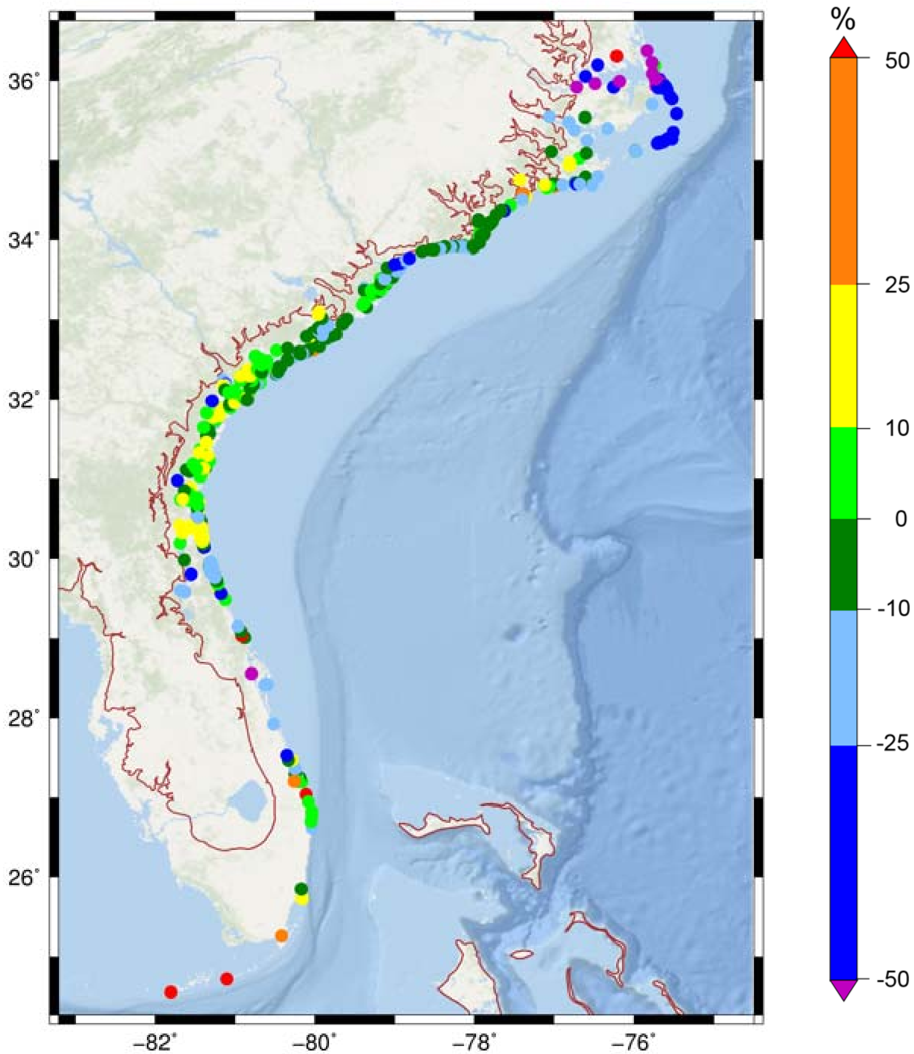
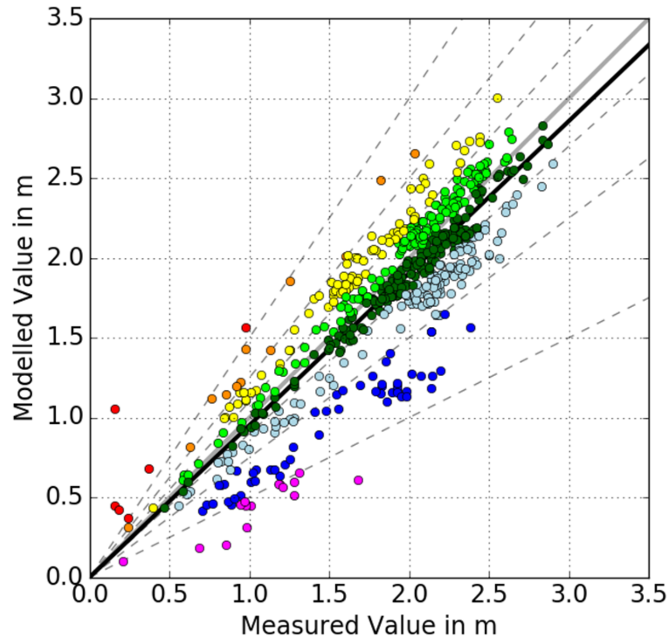



241 stations, RMSE of 0.28m, Bias of 0.04

# Model Validation – High Water Marks

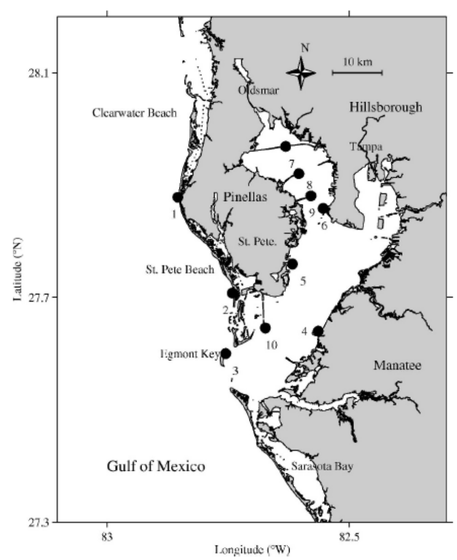


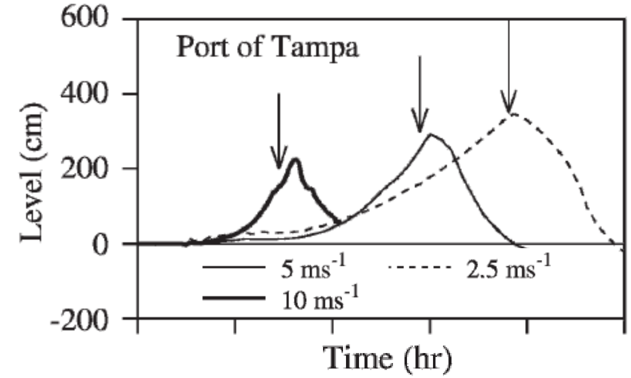




622 peaks
$R^2 = 0.78$
RMSE = 0.28m
Bias = -0.04
Best fit slope = 0.95

# Influence of Storm Timing and Forward Speed on Surge

- Several studies – Weisburg and Zheng, 2006; Irish et al. 2008; Rego and Li, 2009; Berg, 2013; Sebastian et al., 2014
- Example – Weisburg and Zheng, 2006 studied storm surge response to forward speed in Tampa Bay, FL

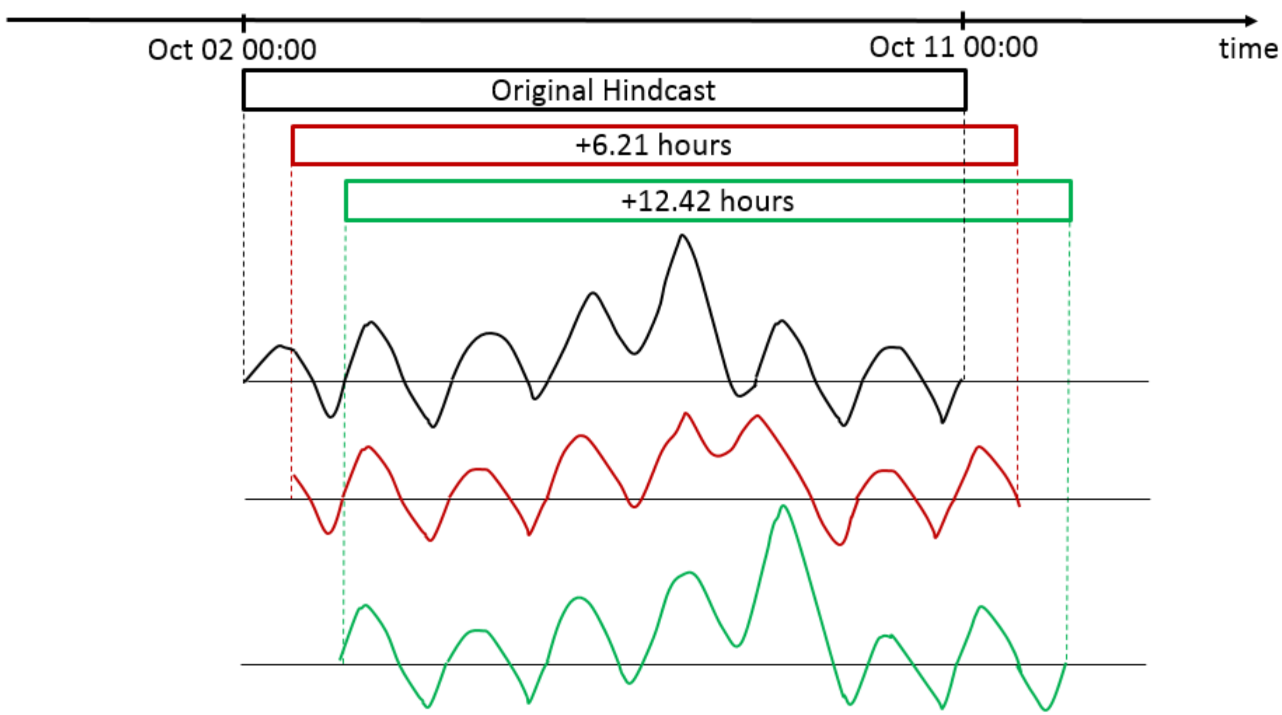


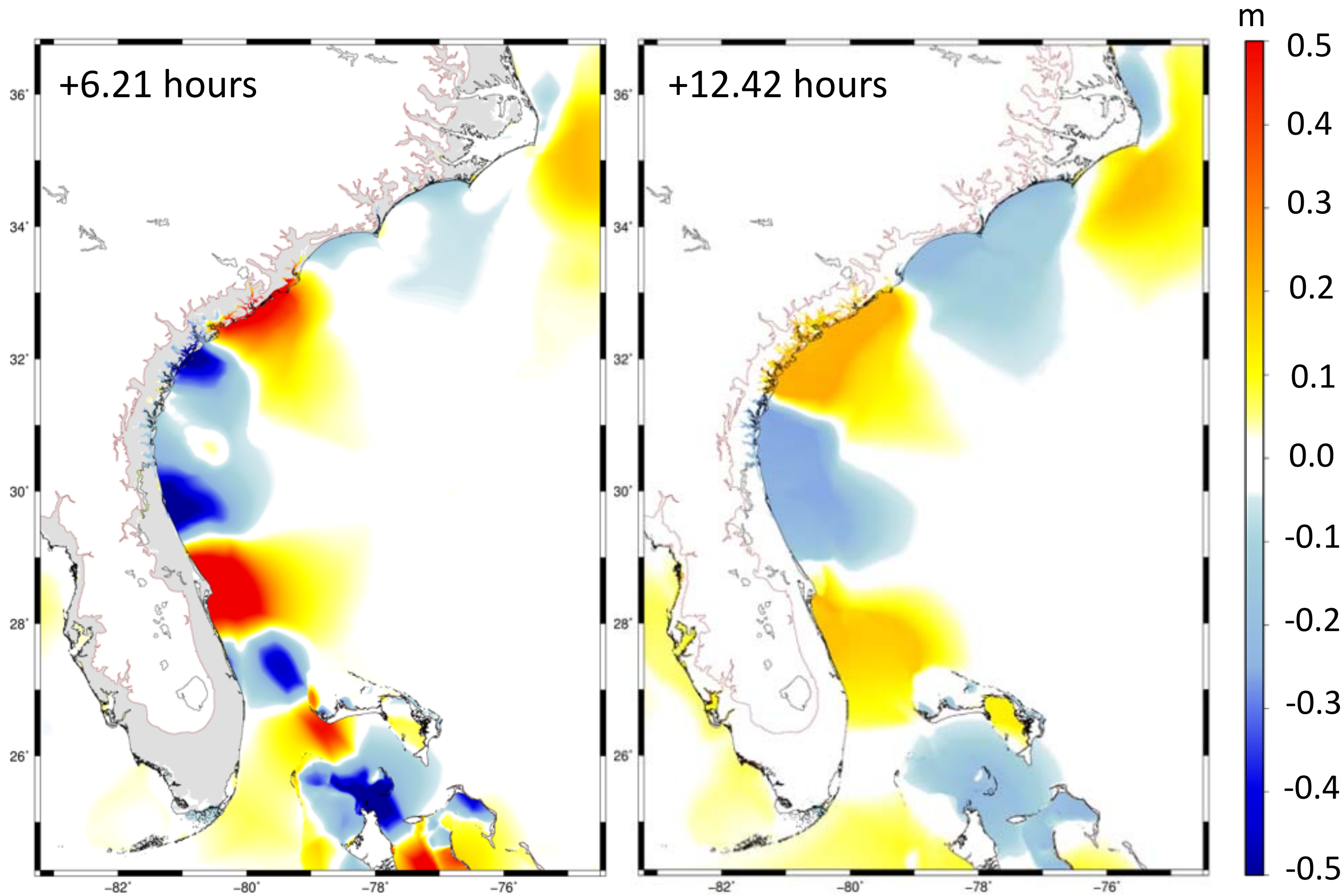

- Common Limitation – modifying storm track and wind fields, shore-normal storms, small/idealized coastlines
- Remaining Question – What is the effect of storm parameters like timing and speed on surge during a shore-parallel storm and on a large complex coastline?

# Influence of Storm Timing

- Changing storm's timing but keeping the speed constant
- ±6.21 hours and ±12.421 hours → advancing and delaying the storm by one-half and full M2 tidal constituent period



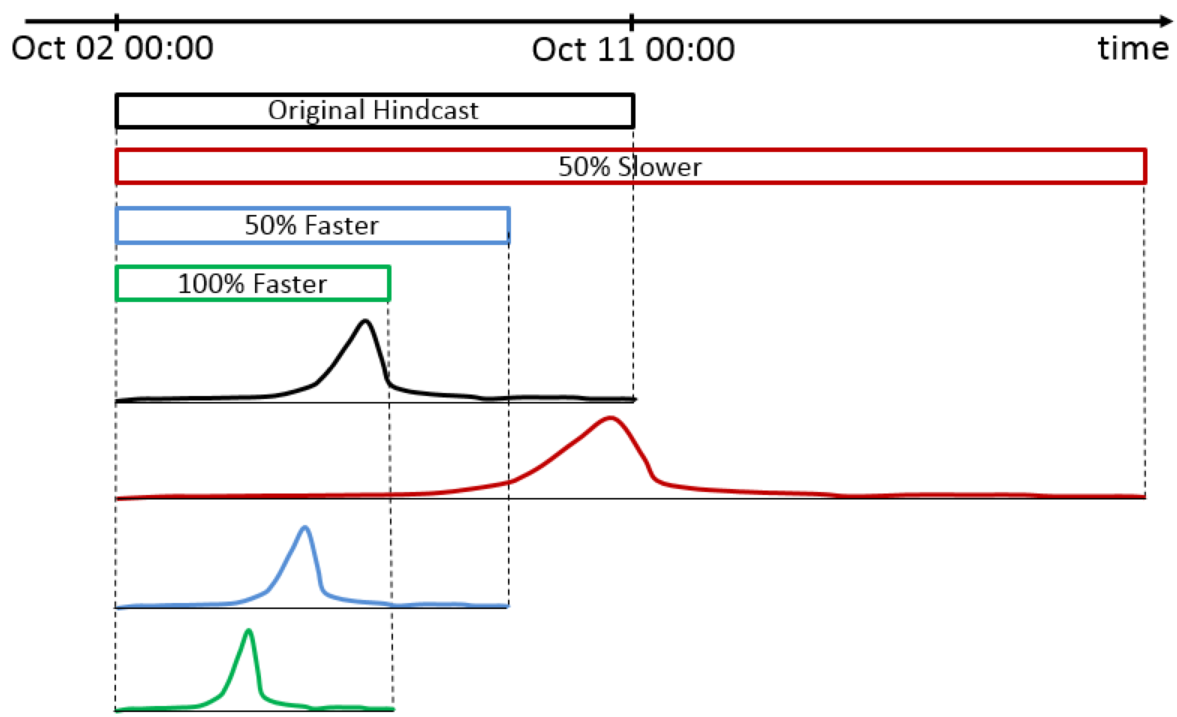
# Influence of Storm Timing



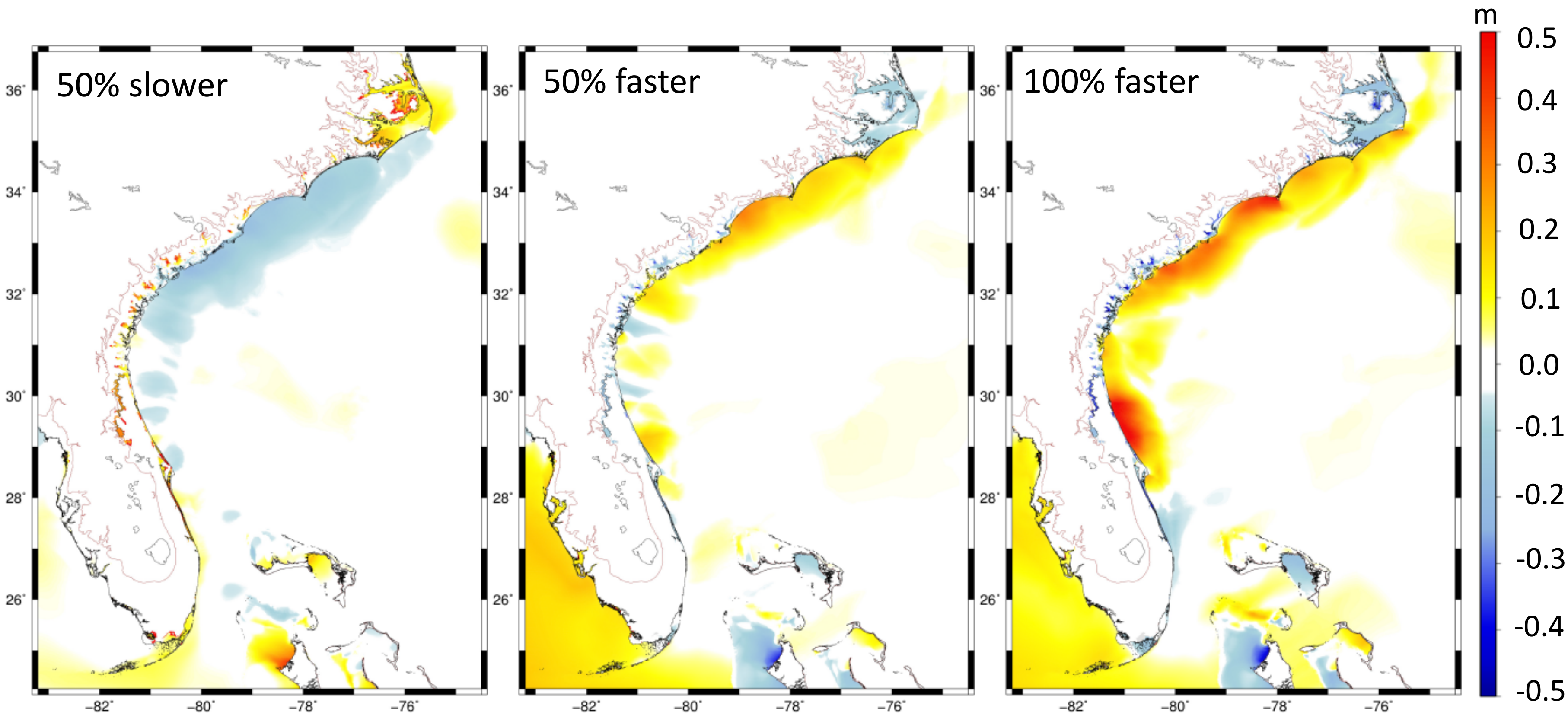

Change in maximum water levels (adjusted – base)

# Influence of Storm Speed

- The forward speed of the storm was varied, keeping the tides off
- 2.9 m/s, 7.2 m/s and 10.5 m/s (Blanton and Vickery, 2008)
    - Represent 50% slower, 50% faster and 100% faster simulations



# Influence of Storm Speed




Change in maximum water levels (no tides) (adjusted – base)

# Summary

- Observation-based wind fields like OWI provide better meteorological forcing for hindcasting, as compared to parametric models like GAHM
- The model results showed good agreement to observations for water levels and HWMs
- A change in timing can cause the storm to interact with different periods in the tidal cycle at different locations
- A slower storm produces lesser flooding on the open coast but pushes more water into the estuaries and bays
- A faster storm causes an increase in peak water levels along the coast especially along straight coastlines

# Motivation

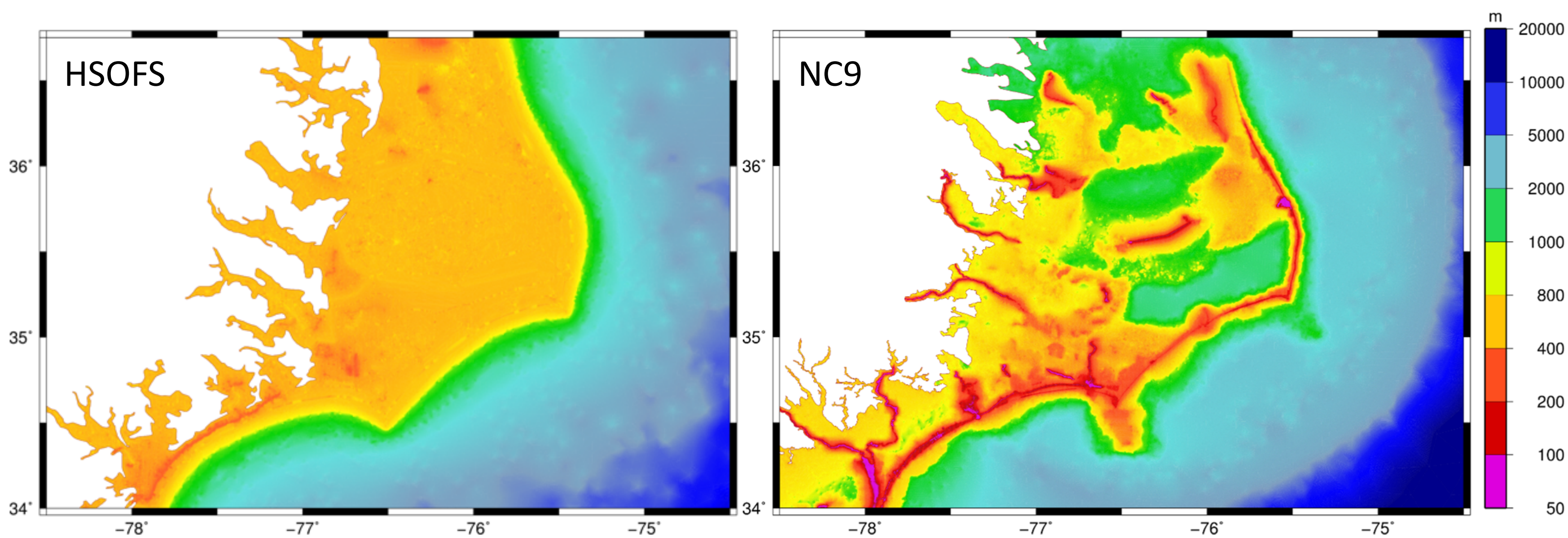
## #1 Need for Higher Resolution

## #2 Need for Faster Forecasts

# Motivation

## Need for Higher Resolution

1. Experience from hindcasts of Hurricane Matthew

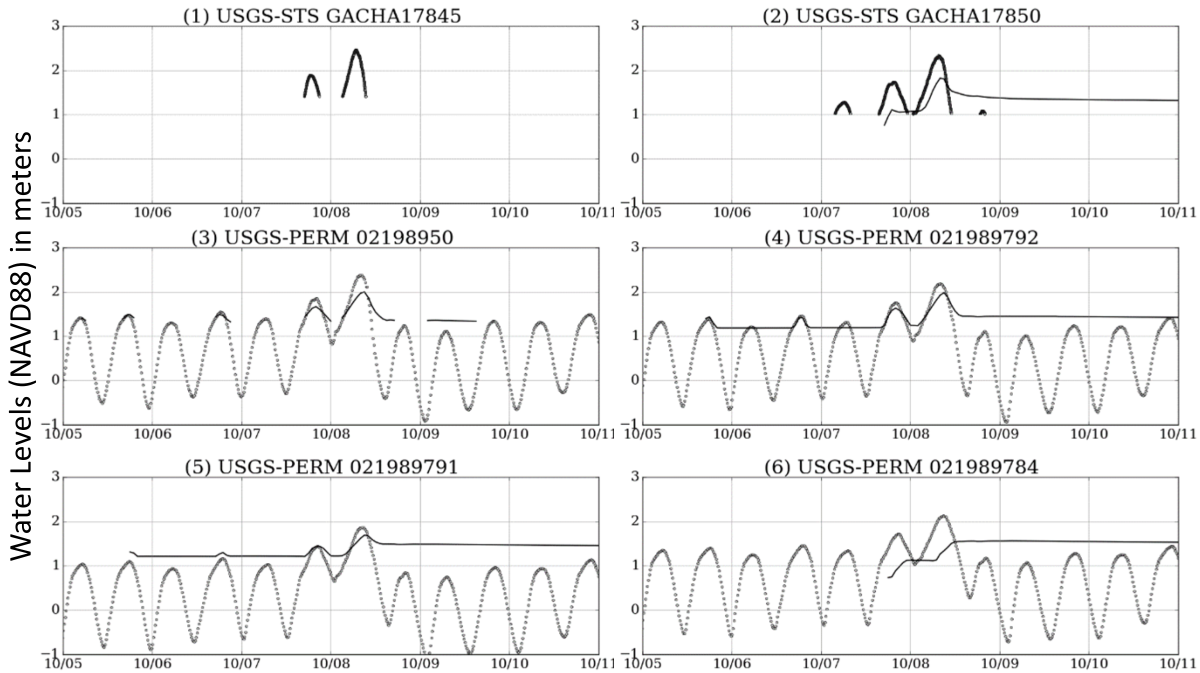



Resolution

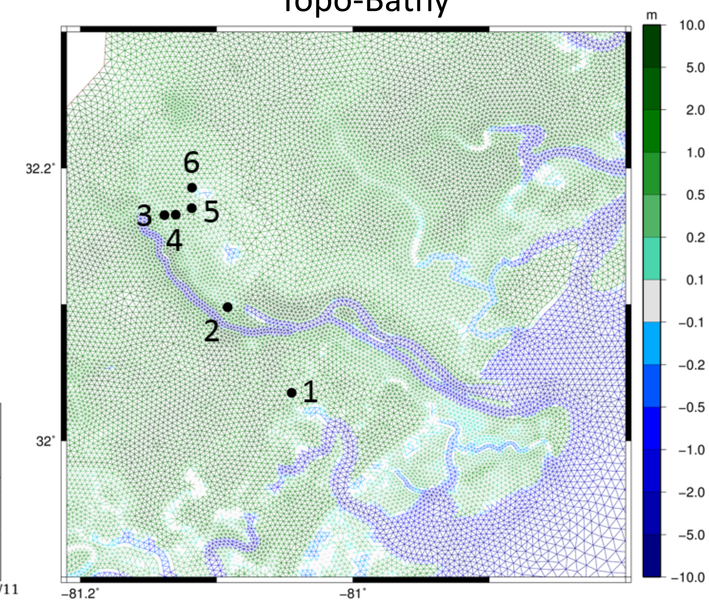
# Motivation

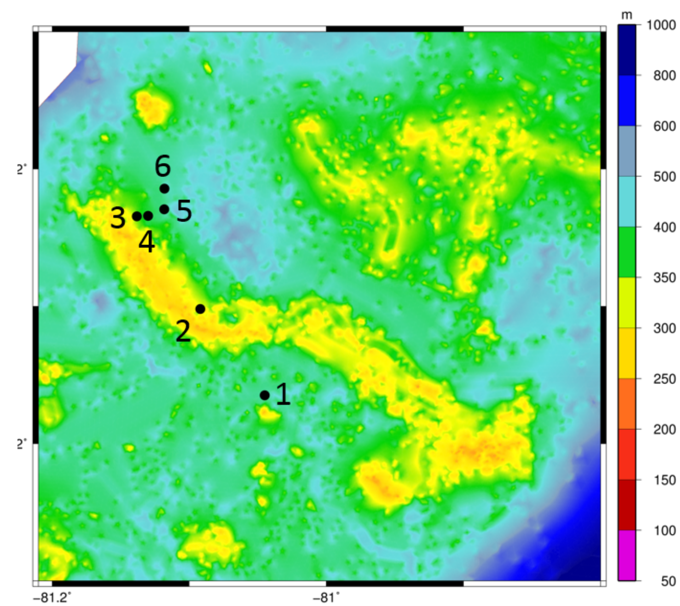
## Need for Higher Resolution

### 1. Experience from hindcasts of Hurricane Matthew




Topo-Bathy



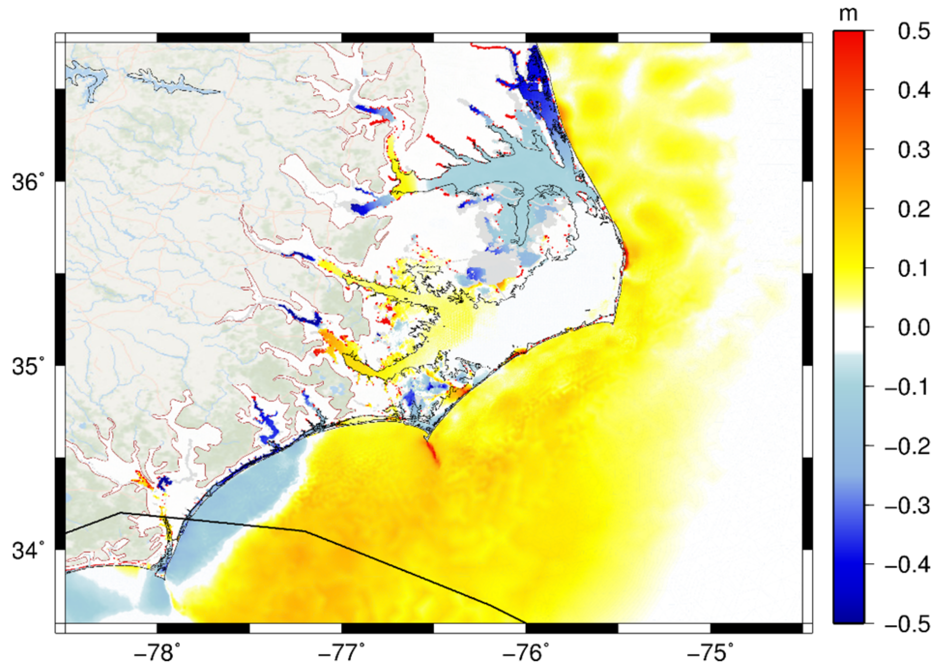

Resolution

# Motivation

## Need for Higher Resolution

2. Forecasting during Hurricane Florence (2018)

- HSOFS mesh was used when the storm was far away (up till Advisory 41)
- As the storm approached the NC coast, NC9 mesh was employed  (starting from Advisory 42)

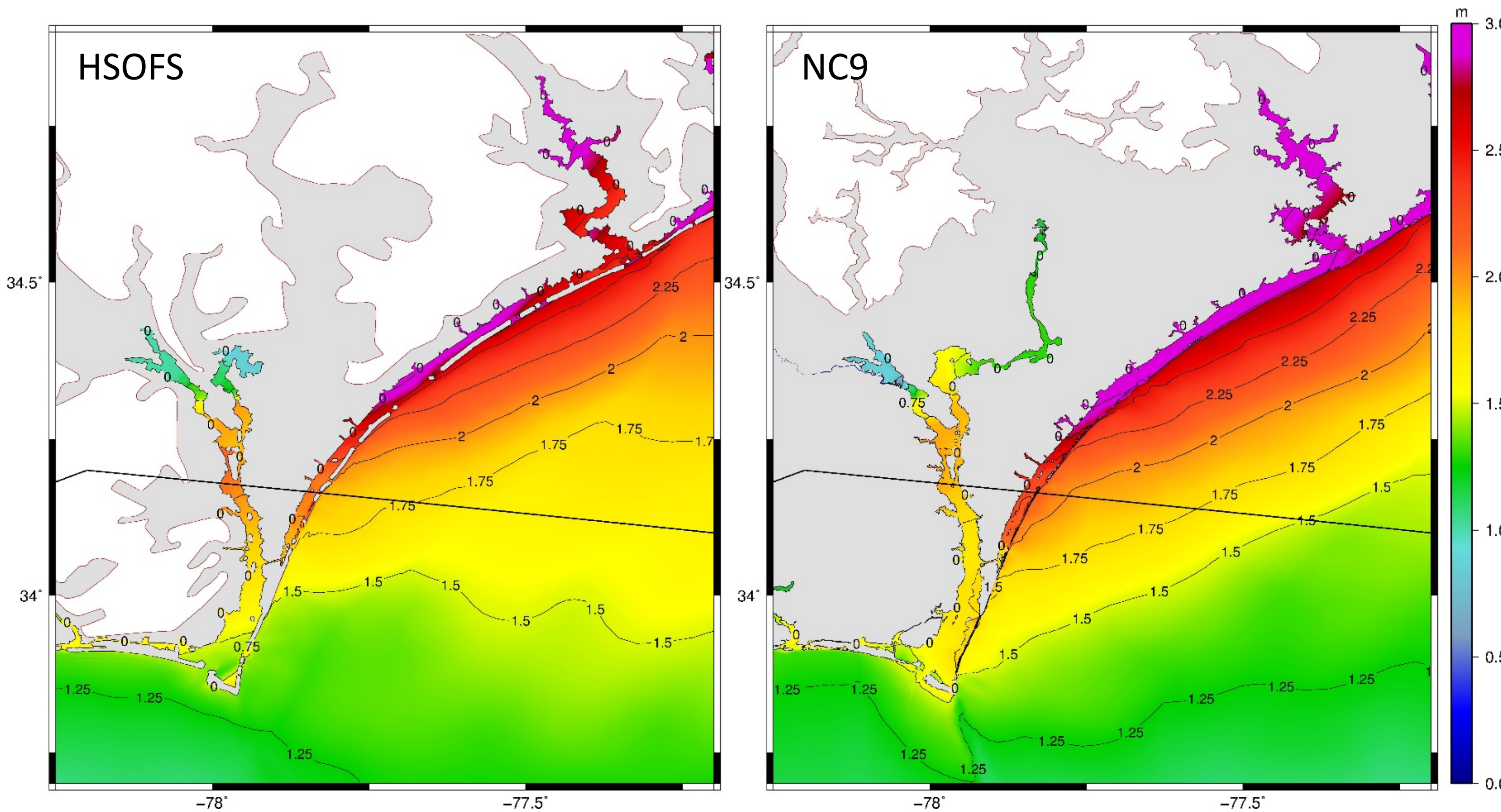



Difference in the HSOFS and NC9 maximum water levels corresponding to Advisory 58

# Motivation

## Need for Higher Resolution

### 2. Forecasting during Hurricane Florence (2018)




Maximum water levels corresponding to Advisory 58

# Motivation

## #1 Need for Higher Resolution

## #2 Need for Faster Forecasts

# Motivation

## Need for Faster Forecasts

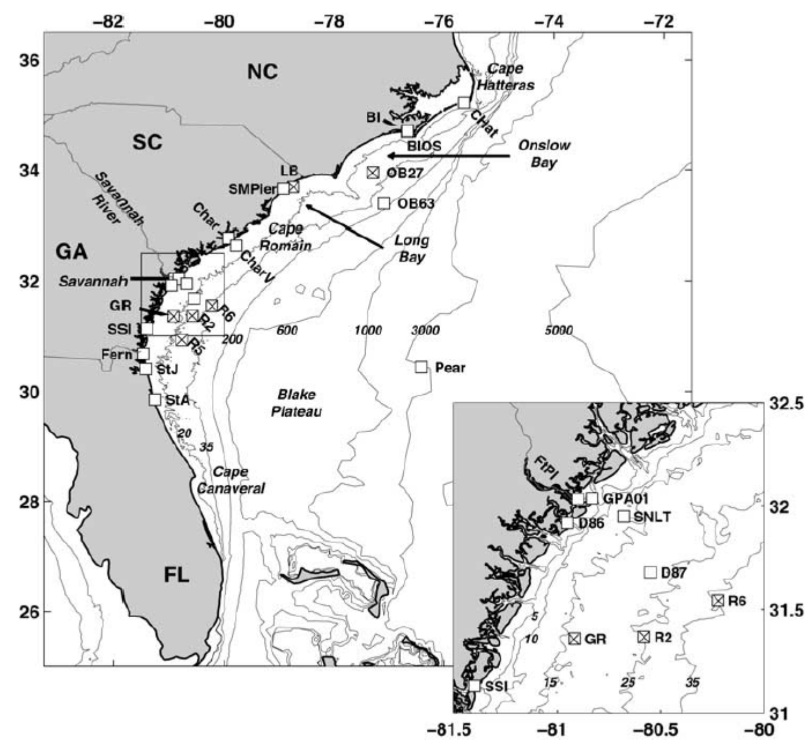
1. Ensemble Possibilities
   - For each advisory, there is uncertainty in the storm parameters , which translates directly into uncertainty in the predicted surge
   - SLOSH computes Probabilistic Storm Surge (P-surge) in real-time
     - Includes uncertainty in track/landfall location, forward speed, intensity, and historical errors
     - Results are approximately 30 minutes after full advisory release time
   - ASGS runs only a few variations (eg. veer-left, veer-right)
   - Faster simulations will allow for more scenario-testing, which can help in reducing uncertainties in the forecast results (Leutbecher and Palmer, 2008)

2. Hurricane Bill (2015)
   - Made landfall in southeast Texas
   - When the storm was in Gulf, high-res mesh (6.7 million elements) for Texas was used
   - Tidal spin-up on this mesh even on 1120 cores at TACC, took 18 hours
   - By this time, the storm had already moved inland

# Literature Review

## Benefits of Resolution

- Required to represent
  - steep gradients in bathymetry like the continental shelf break (Westerink et al., 1992; Luettich and Westerink, 1995; Blain et al., 1998; Hagen et al., 2000)
  - wave propagation in shallow water regions (Hagen et al., 2001)
  - complex topography in overland regions (Westerink et al., 2008)
  - estuaries and inter-tidal zones that can modify tidal propagation (Blanton et al., 2004; Bacopoulos and Hagen, 2017)
- Example – Blanton et al. (2004), studied the influence of the estuary/tidal inlet complex on barotropic tides in the South Atlantic Bight



# Literature Review

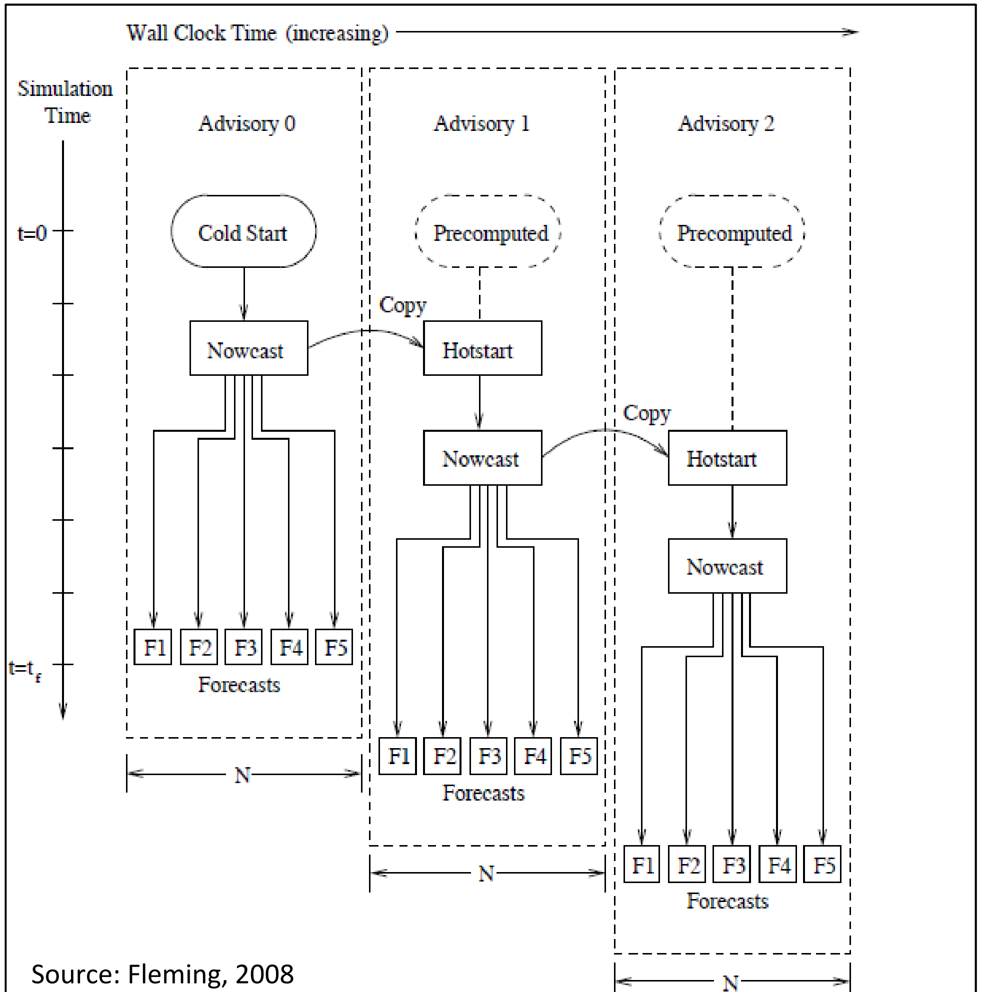
## Ways to Provide Increased Resolution in models

- Adaptive Mesh Refinement – use algorithms that dynamically refine the grids spatially, temporally or both, to obtain fine scale solutions in the areas of interest
    1. Use multiple overlapping grids (Nested approach)
        - Moving grids - high-resolution grids to move with storms within larger domains with lower resolution (Harrison, 1973; Kurihara et al. 1979; Tolman and Alves, 2005, etc.)
    2. Split elements of the mesh into finer elements on the same mesh
        - h (grid size) and/or p (polynomial order) refinement (Kubatko et al. 2006), Dynamic h- and/or p-adaptive techniques (Kubatko et al. 2009)
    - Storm surge modelling (Mandli and Dawson, 2014)
        - Implemented in the GEOCLAW framework (Berger et. al, 2011) for simulating Ike
- Subdomain Modeling in ADCIRC
    - assess local changes without requiring separate full-scale simulations (Baugh et al. 2015; Altuntas and Baugh, 2017)

# The Multi-Resolution Approach

## Current Forecasting Technique

- Save the state of the simulation right at the nowcast point (end of the hindcast)
- Reload this saved state during the next advisory cycle to avoid having to start the simulation from the beginning
- The system thus always builds on previous results
- The hot-starts have to be always done on the same mesh
- This prevents use of high resolution meshes-without having to run tidal spin-up that take several hours of computational time




Source: Fleming, 2008

# The Multi-Resolution Approach

## Steps

- Use a relatively coarse resolution when the storm is far
- As the storm approaches the coastline, switch to a fine-resolution mesh without doing a cold-start
- Map results from the coarse to the fine mesh and continue the simulation on the fine mesh

## Main Objectives

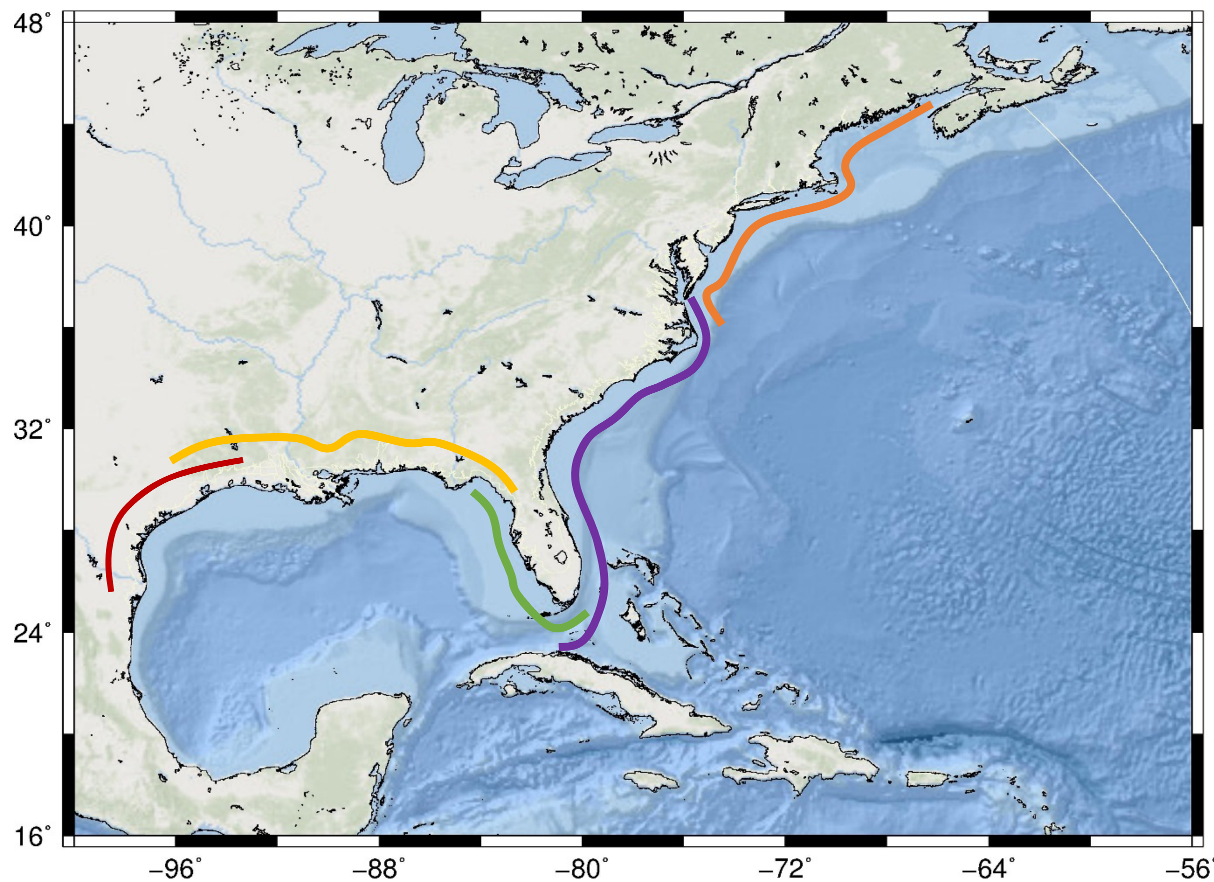
- Reduce the computational load by using a coarser resolution mesh when the storm track is uncertain
- Increase the accuracy of predictions by using a higher resolution mesh as the storm approaches landfall
- Increase the simulation possibilities including ensemble generation during operational forecasting

# The Multi-Resolution Approach

## Methods

- Coarse Resolution Mesh
  - HSOFS (1.8 million vertices)
- Fine Resolution Meshes for the U.S. Gulf and Atlantic coasts
  - Each 3-4 million vertices

1. Western Gulf
2. Northern Gulf
3. Eastern Gulf
4. South and Central Atlantic
5. Northern Atlantic



# The Multi-Resolution Approach

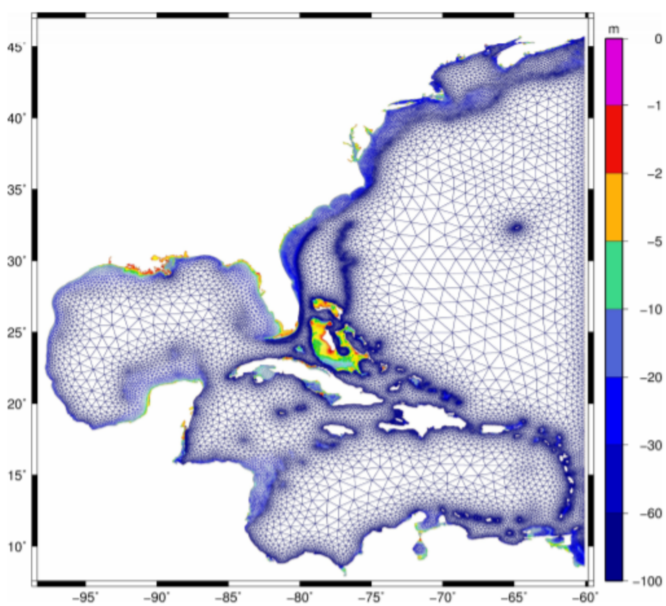
## Methods

- Adcirpolate
  - A toolset for interpolating between meshes
  - Developed by our collaborators at U.T. Austin
  - Implemented via the Earth System Modeling Framework (ESMF)
    - Allows for parallel interpolation between unstructured meshes
  - Interpolation is done bilinearly in region destination points
  - Extrapolation is done for the remaining points with nearest source to destination
  - Proper checks to take care of wetting/drying state of elements
  - Convert the hot-start file from the coarse mesh simulation to a hot-start file for the fine mesh simulation

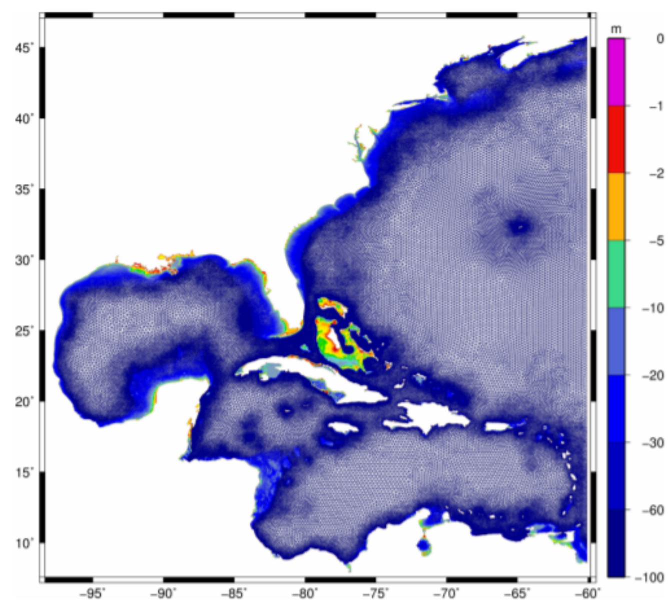
# Initial Results – from presentation at the DHS CRC Meeting

## Hurricane Ike (2008)

- Run the simulation on the coarse/source mesh for the first 6 days
- Use the interpolation module to maps the coarse/source data onto the fine/destination mesh
- Continue the simulation on the fine/destination mesh through the 10th day




Source: 52,774 vertices

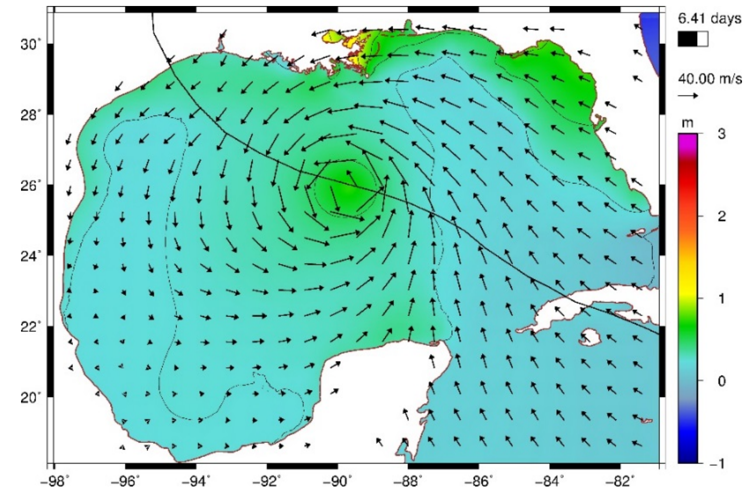


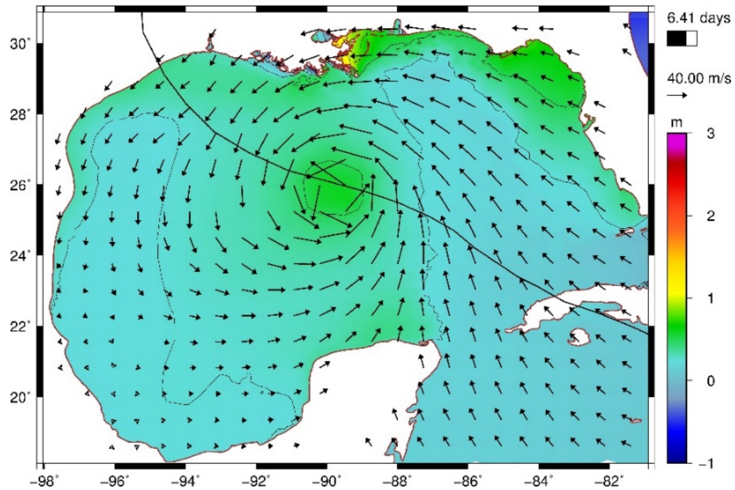

Destination: 254,565 vertices

# Initial Results

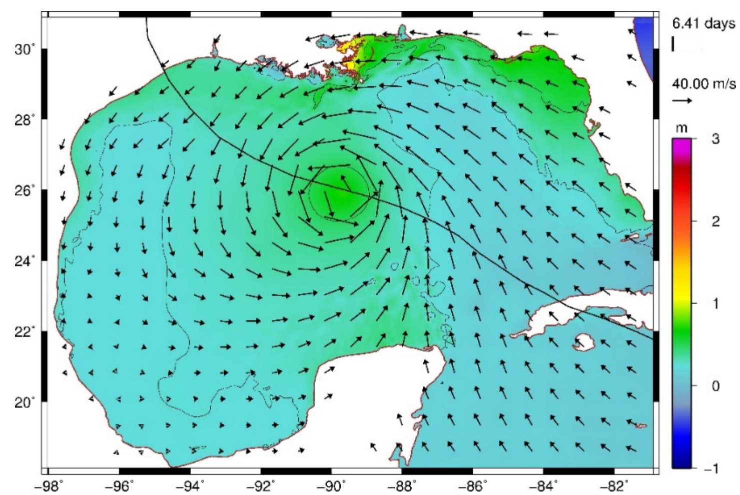
## Hurricane Ike (2008)

Fine



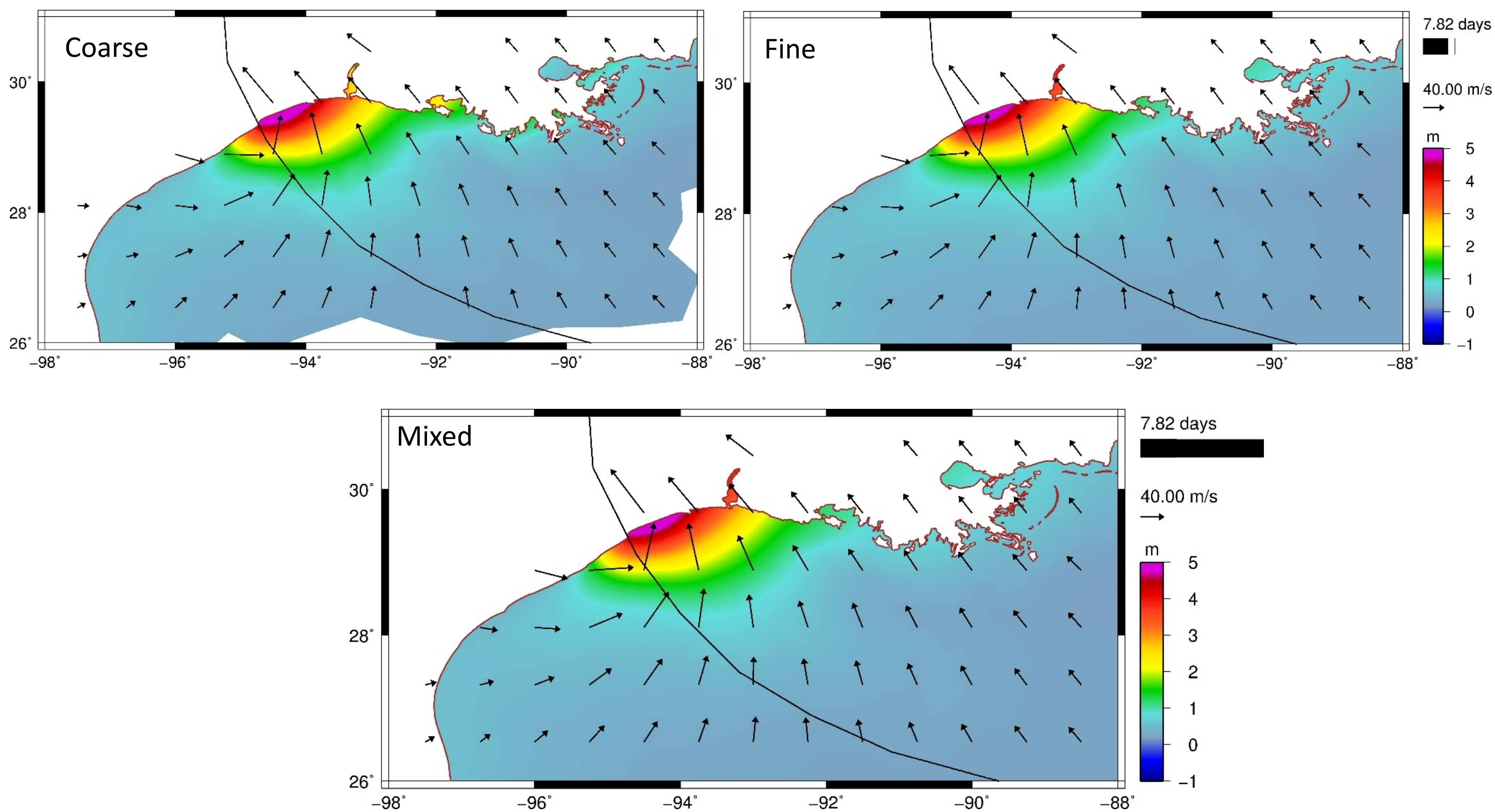

Coarse



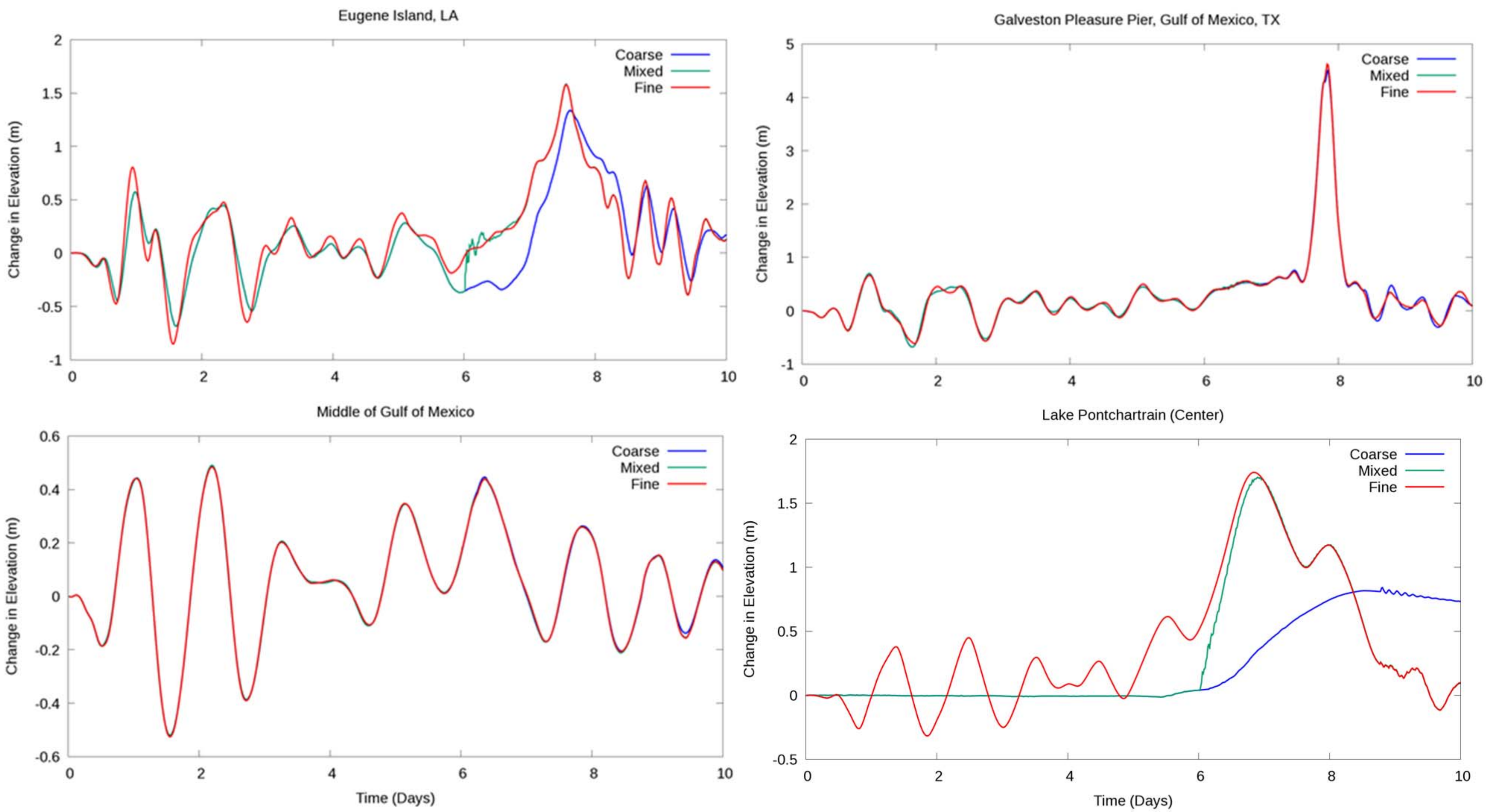

Mixed

# Initial Results

At landfall



# Initial Results




- Average time savings of 40%
- Results are close to a ‘true’ solution of all 10 days on the fine mesh

# Proposed Tasks

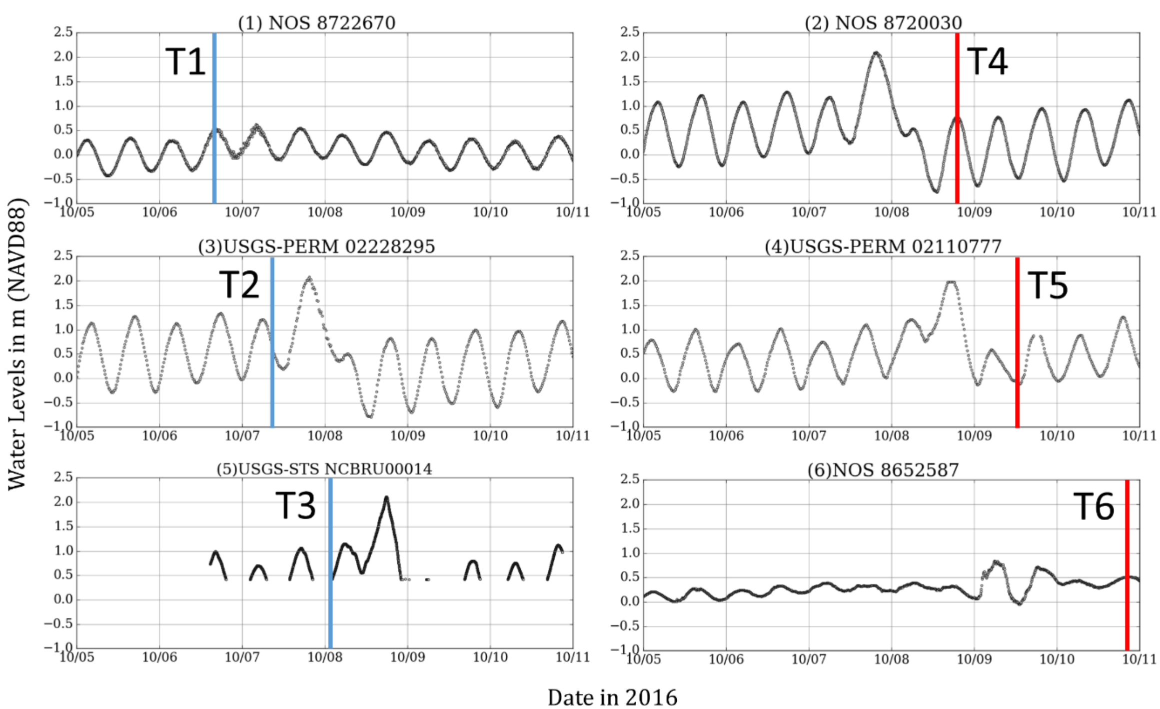
Focus Area #1: Optimization of the multi-resolution approach through hindcasts of recent storms to hit the U.S. south east coast

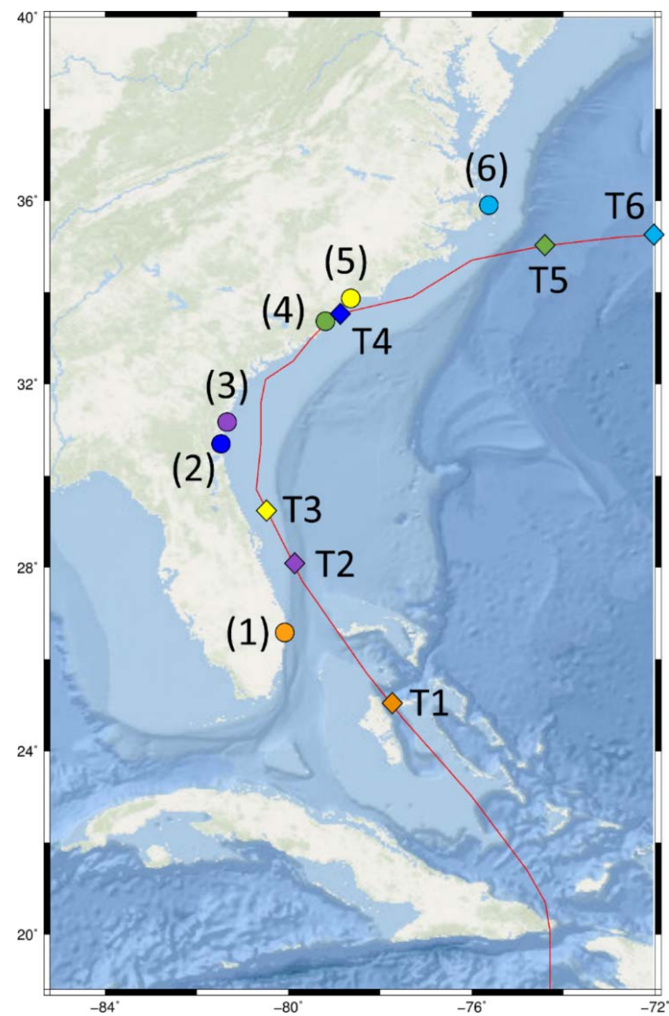
Focus Area #2: Application of the multi-resolution approach during forecasting

# Focus Area #1

## Matthew

- Shore-parallel storm moved from south-to-north
- But it did not impact this entire region at the same time

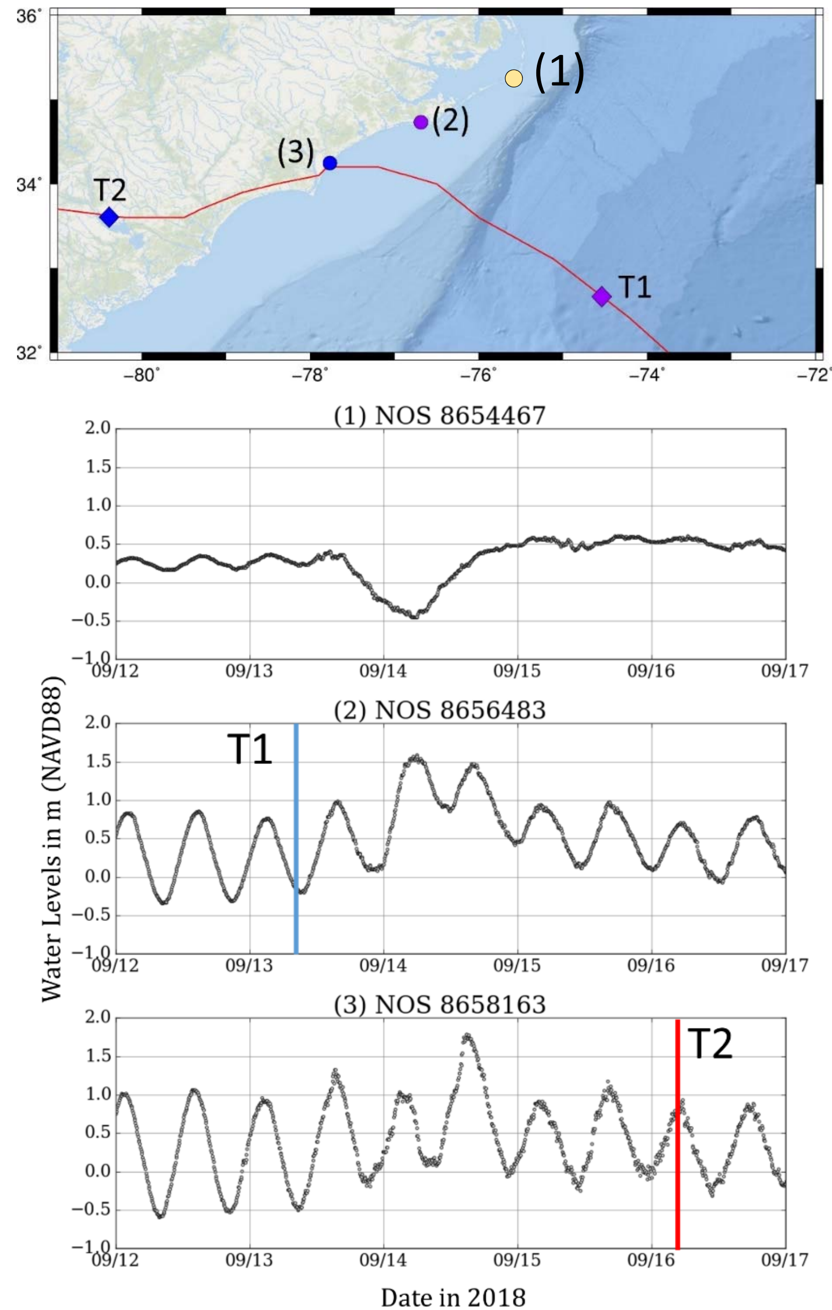


# Focus Area #1

## Florence

- Shore-normal storm causing elevated water levels along the NC coast
- Impacted a small geographic area
- These storms will be a good test of the multi-resolution approach, as we will want to apply the highest spatial resolution only in regions as they are impacted by the storm



# Focus Area #1

- Research Hypothesis
  - By applying different high-resolution meshes that describe specific regions of the U.S. southeast coast as they are affected by these storms, the predictions can be improved in both accuracy and efficiency
  - By using information available during the storm, the optimal times for switching meshes can be identified
- Research Objectives
  - Identify the optimal number of segments along the southeast U.S. Atlantic coast, to represent the variation in water levels during these storms without excessive switching between meshes
  - Evaluate the storm information available during the storm, including both storm parameters (track, size, intensity, etc.) and ocean response (waves and water levels at real-time gauges), as possible triggers for switching between meshes
  - Quantify the benefits in accuracy of the multi-resolution approach, via comparisons with single simulations on coarse- and fine-resolution meshes
  - Quantify the benefits in efficiency of the multi-resolution approach, via comparisons with single simulations on coarse- and fine-resolution meshes

# Research Methods

## Objective #1

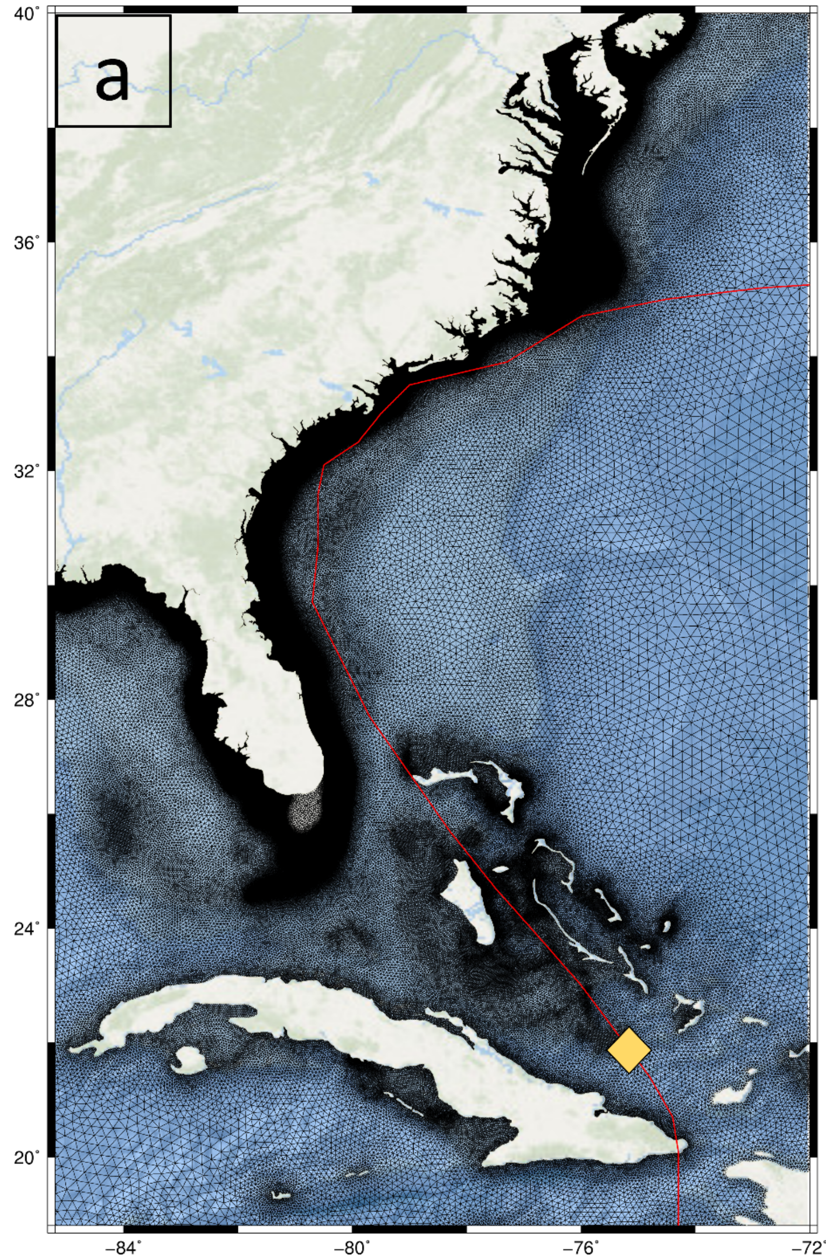
Identify the optimal number of segments along the southeast U.S. Atlantic coast, to represent the variation in water levels during these storms without excessive switching between meshes

- Different regions along the coast are impacted by the storm at different times
- Once we have high-resolution meshes for the entire coastline, we can we can create different segments to test the approach during Matthew and Florence
- One way is to cut along state boundaries

# Research Methods

## Objective #1

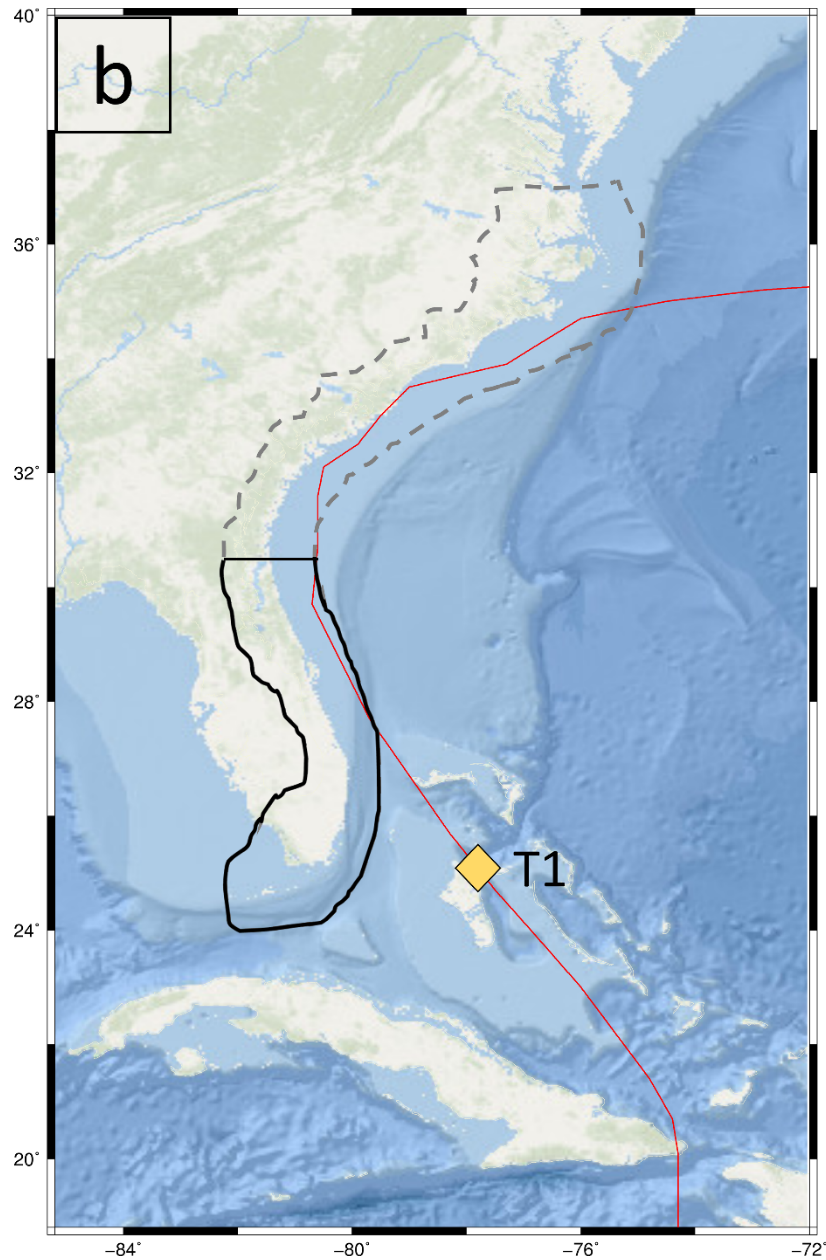
- Application during Matthew
  - Step 1



# Research Methods

## Objective #1

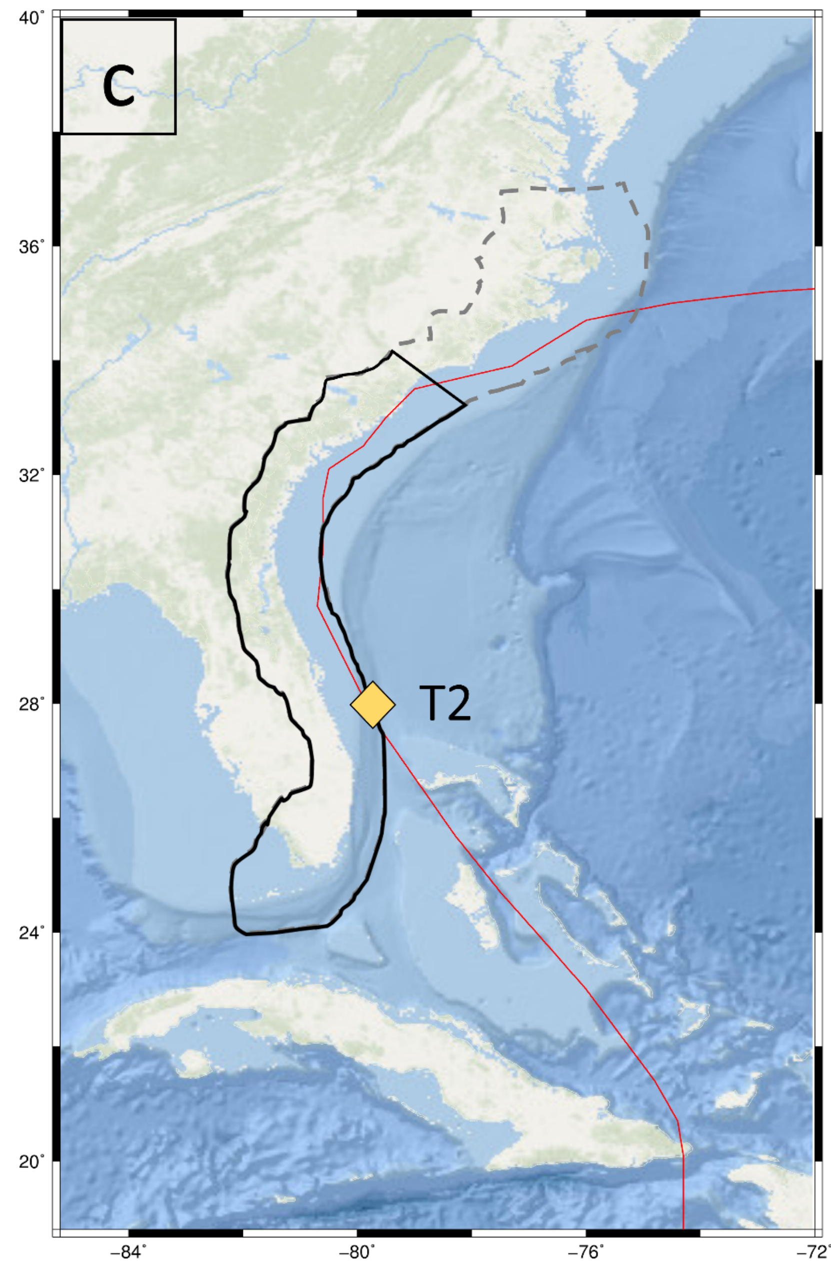
- Application during Matthew
  - Step 2



# Research Methods

## Objective #1

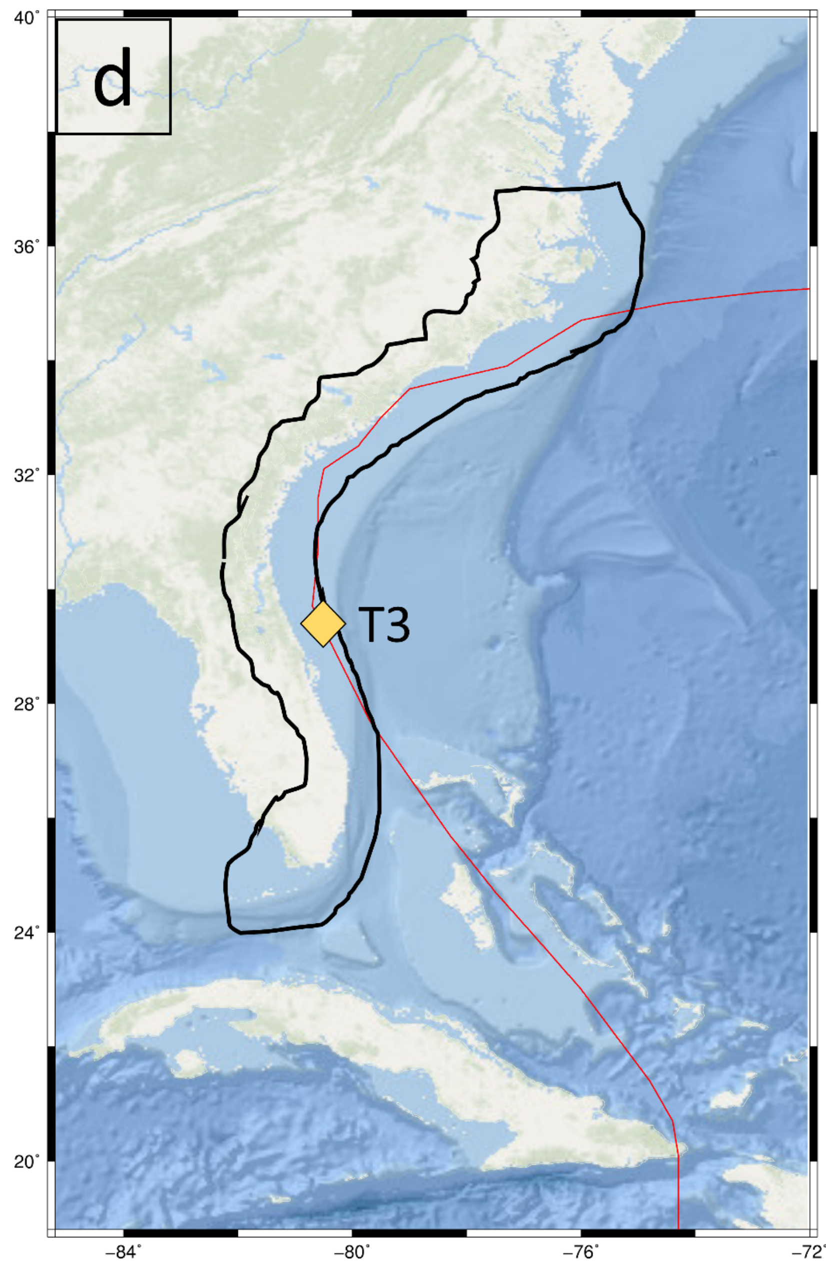
- Application during Matthew
  - Step 3



# Research Methods

## Objective #1

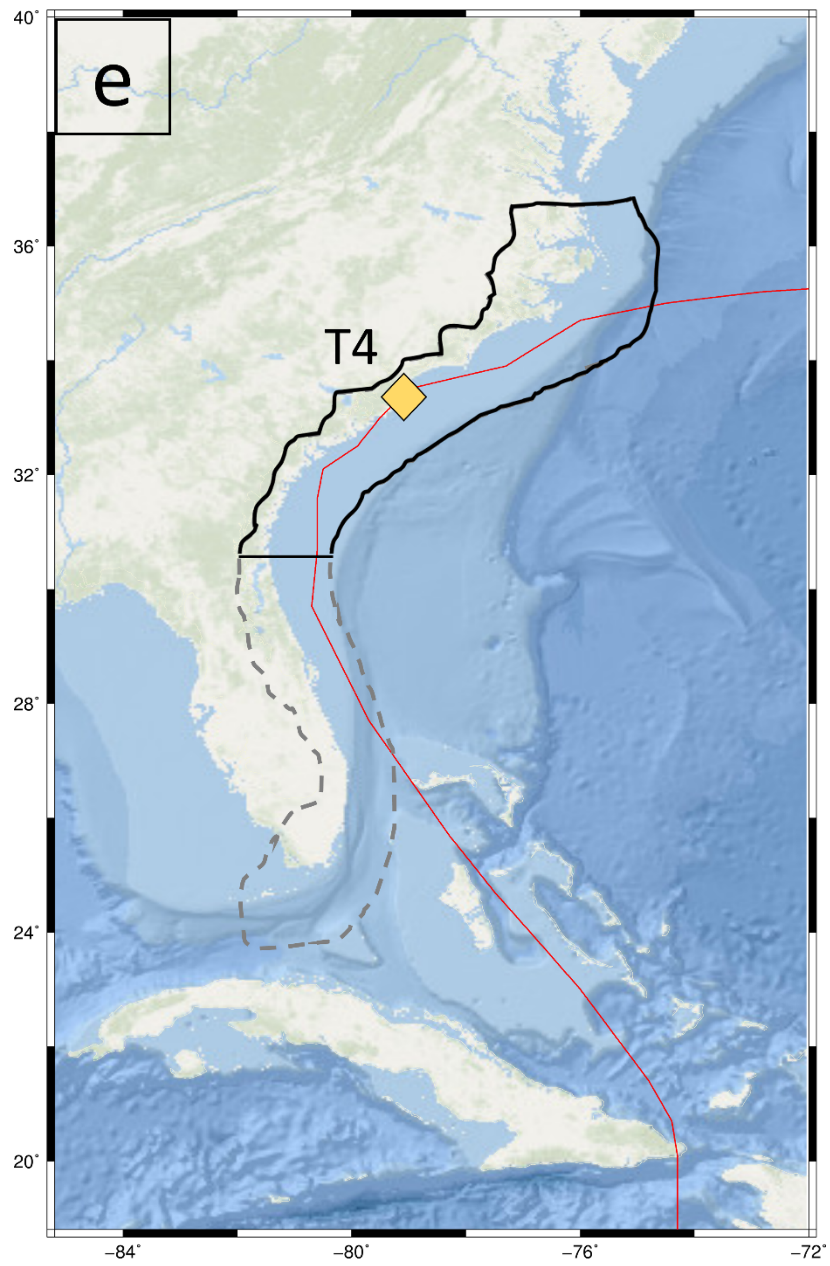
- Application during Matthew
  - Step 4



# Research Methods

## Objective #1

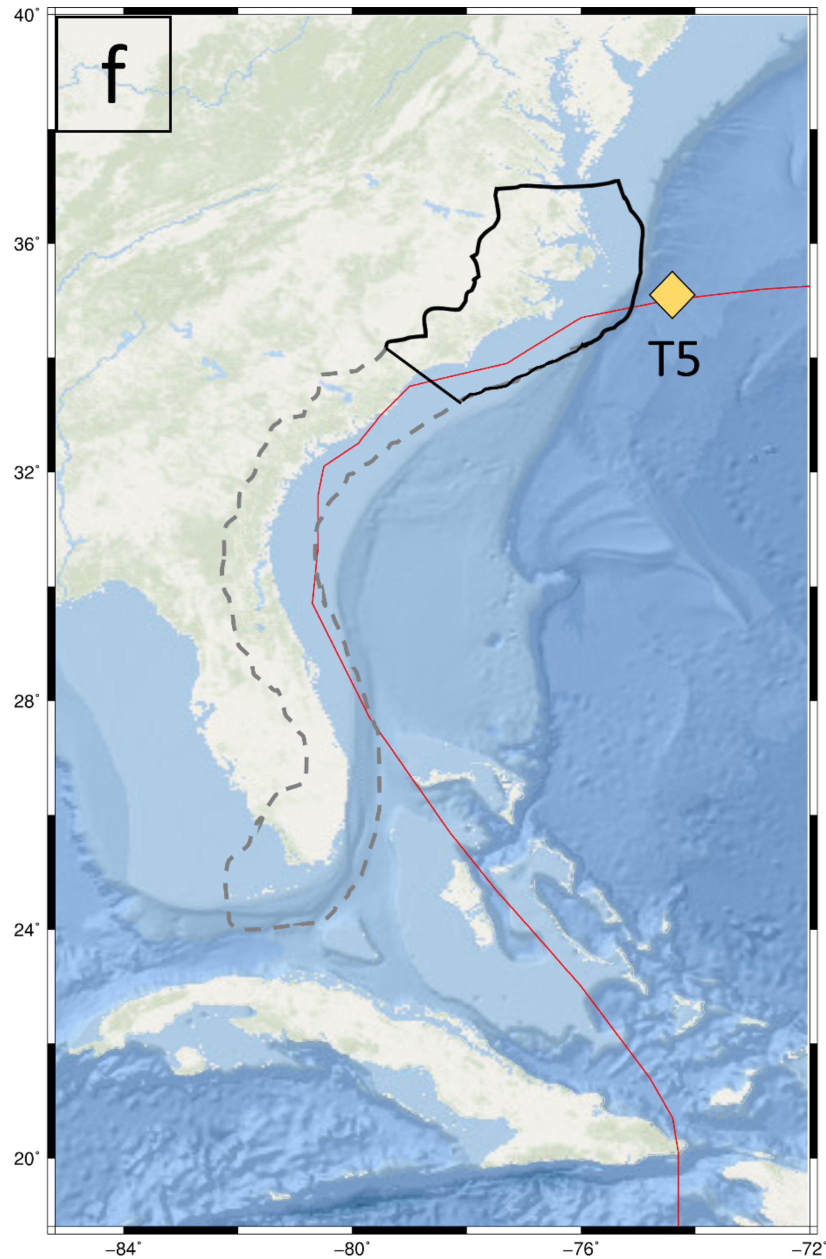
- Application during Matthew
    - Step 5



# Research Methods

## Objective #1

- Application during Matthew
  - Step 6



# Research Methods

## Objective #2

Evaluate information available during the storm as possible triggers for switching

- Water levels at NOAA gauges, Wave Heights at NDBC buoys, Storm Parameters

## Objective #3

Quantify the benefits in accuracy

- Comparisons to single simulations on HSOFS and high-resolution mesh
- RMSE, Bias

## Objective #4

Quantify the benefits in efficiency

- HSOFS mesh takes about 6.5 hours to run a 15-day tides on 160 cores
- With more complexity, this time is increased
- Compare total time to run the proposed approach (including interpolation) to that for a simulation using a single high-resolution mesh for the entire storm duration

# Proposed Tasks

Focus Area #1: Optimization of the multi-resolution approach through hindcasts of recent storms to hit the U.S. south east coast

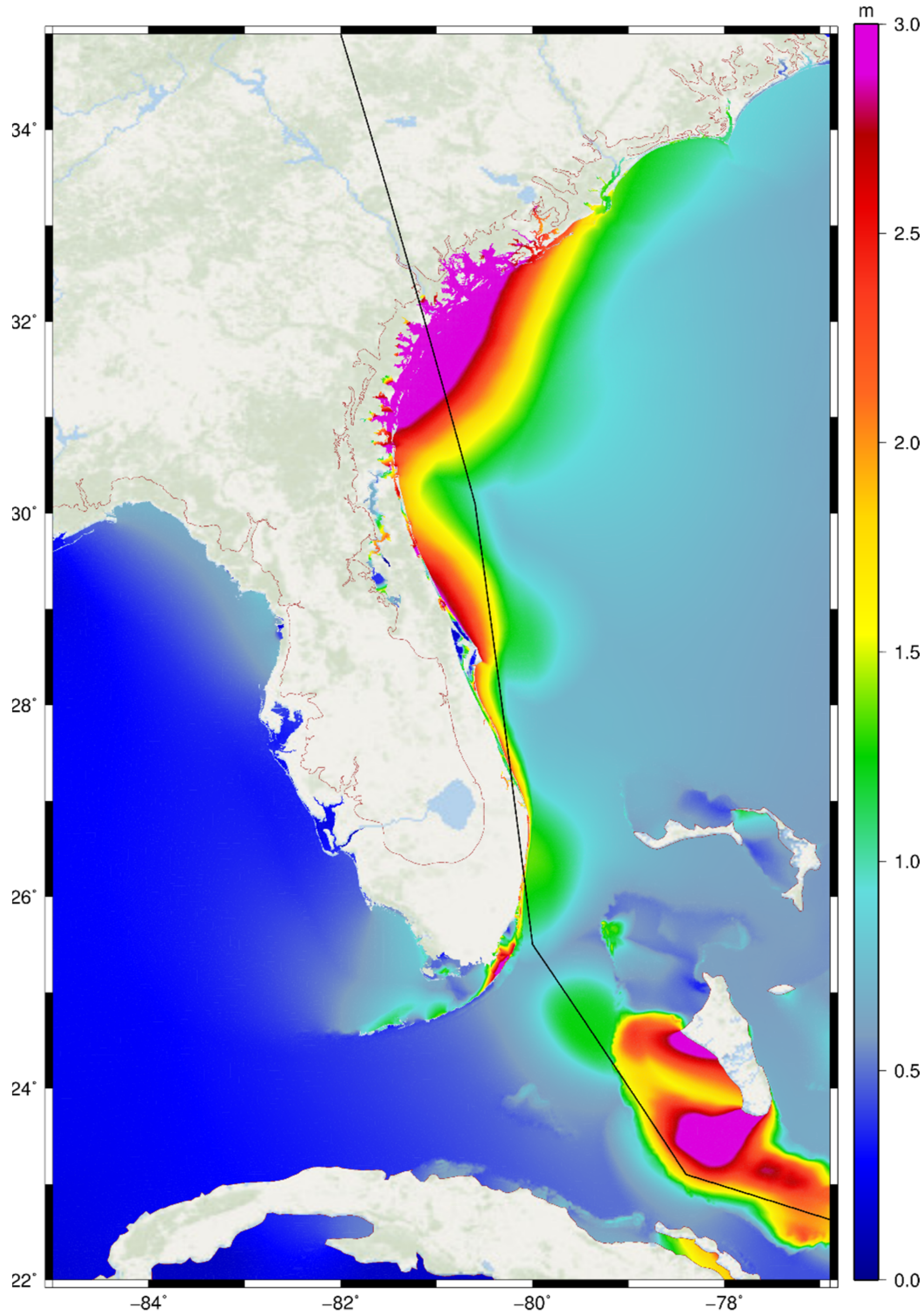
Focus Area #2: Application of the multi-resolution approach during forecasting

# Focus Area #2

- Compared to hindcasting, forecasting of storm surge is more challenging
  - Time constraints
  - Uncertainty in storm parameters in each advisory
- The storm surge is highly sensitive to parameters like storm size, forward speed, track, angle relative to coast (Peng et al., 2004, 2006; Zhong et al., 2010; Irish et al., 2008)
- During Arthur (2014), the later surge predictions were shown to be a progressively-worse representation of the storm's impact in coastal NC (Cyriac et al., 2018)
- Irma (2017)
  - Category-5 hurricane that impacted the Florida Gulf coast during September 2017
  - Large variability in advisories issued by the NHC

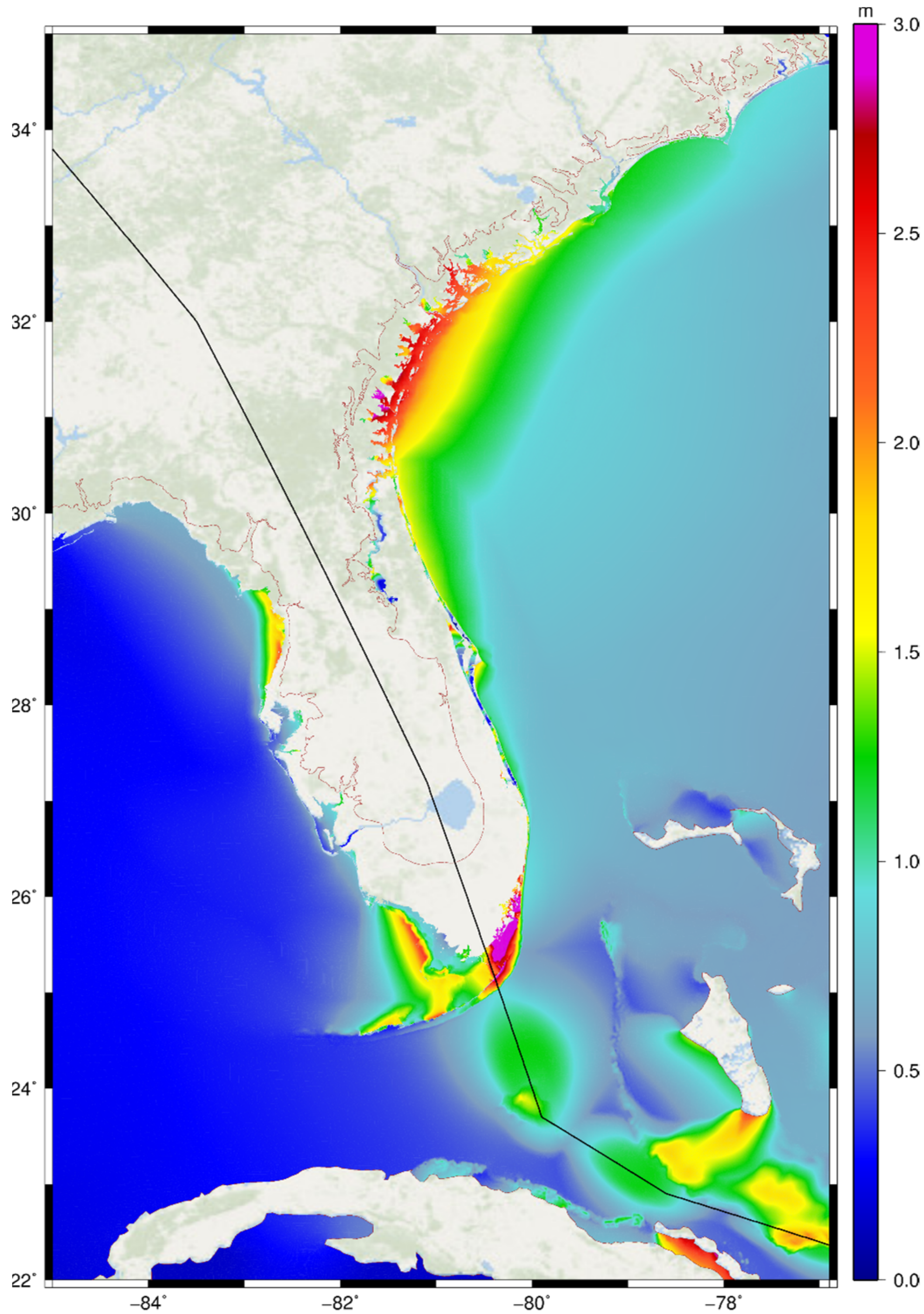
# Focus Area #2

Advisory 34
Sept 7, 15:00 UTC
66 hours before landfall



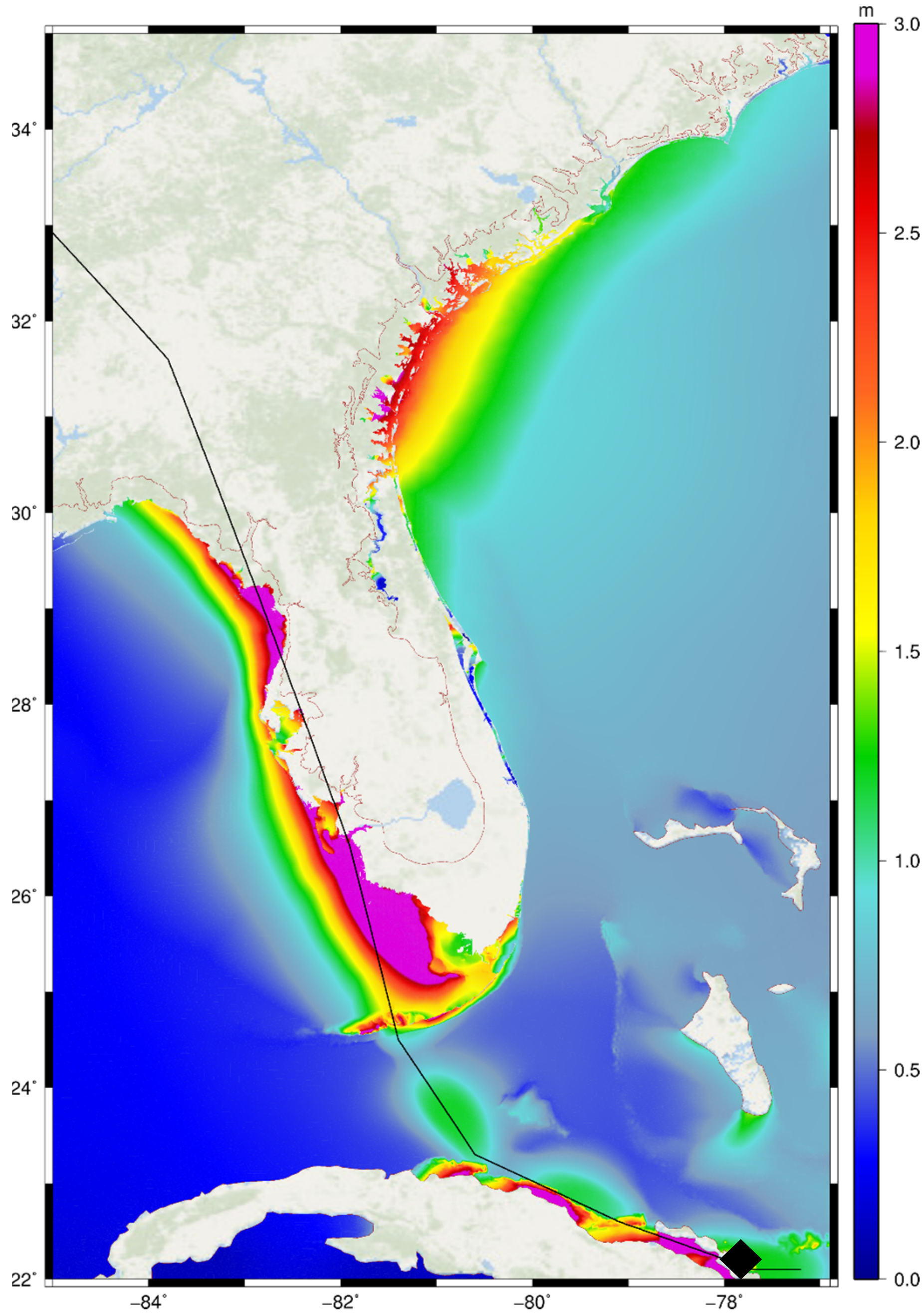
# Focus Area #2

Advisory 36
Sept 8, 03:00 UTC
54 hours before landfall



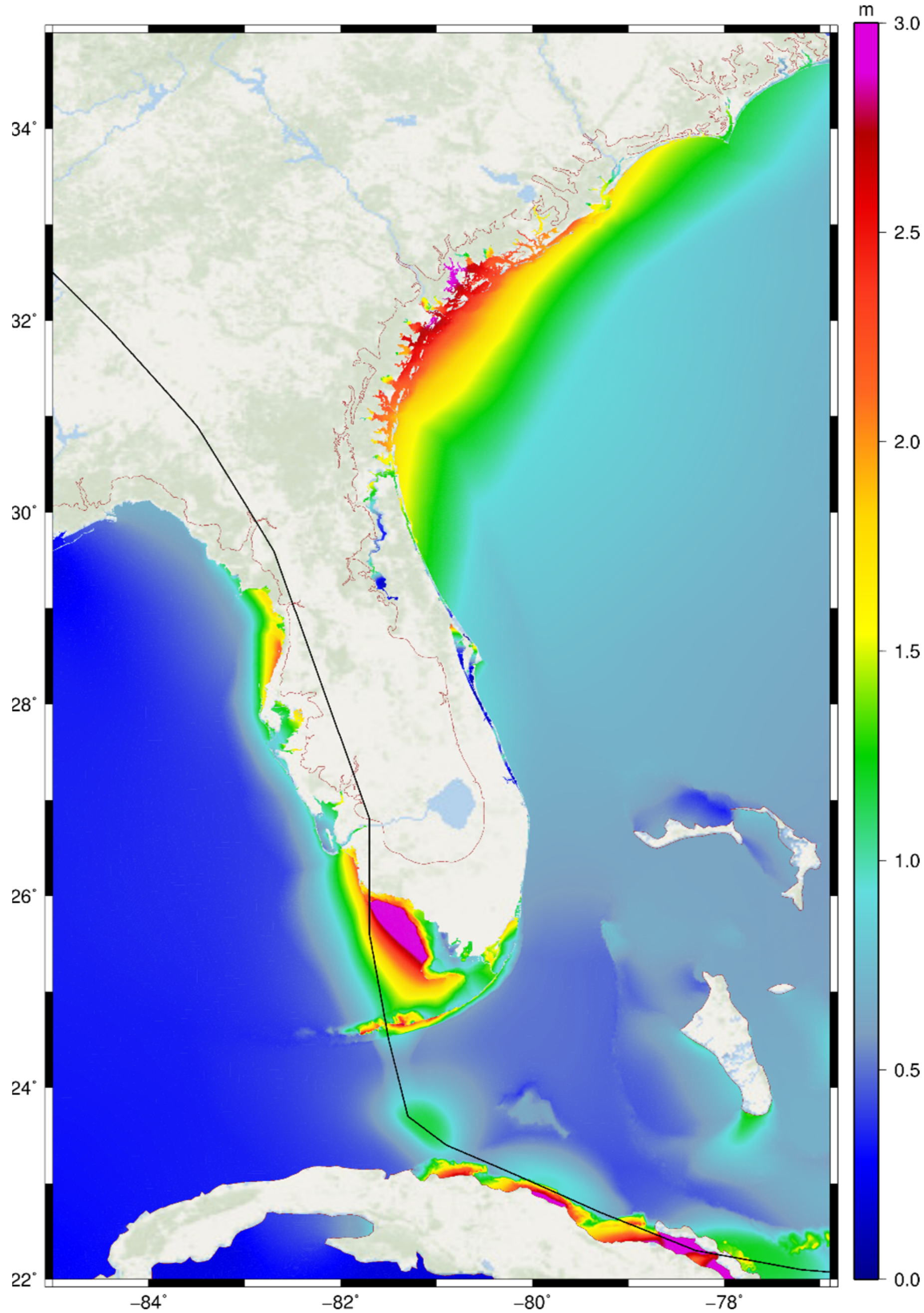
# Focus Area #2

Advisory 40
Sept 9, 03:00 UTC
30 hours before landfall



# Focus Area #2

Best Track



# Focus Area #2

- Research Hypothesis
  - By using a combination of coarse- and fine-resolution meshes, more perturbations can be done for each advisory
  - By developing our own "advisories" where the storm parameters based on a given NHC advisory is varied largely, possible meshes that needs to be used in the proposed approach can be identified
- Research Objectives
  - Perform scenario-based testing on a given advisory, by varying multiple storm parameters
  - Quantify computational gains from using the proposed approach, via comparisons with a simulation using the same high-resolution mesh for different scenarios

# Research Methods

## Objective #1

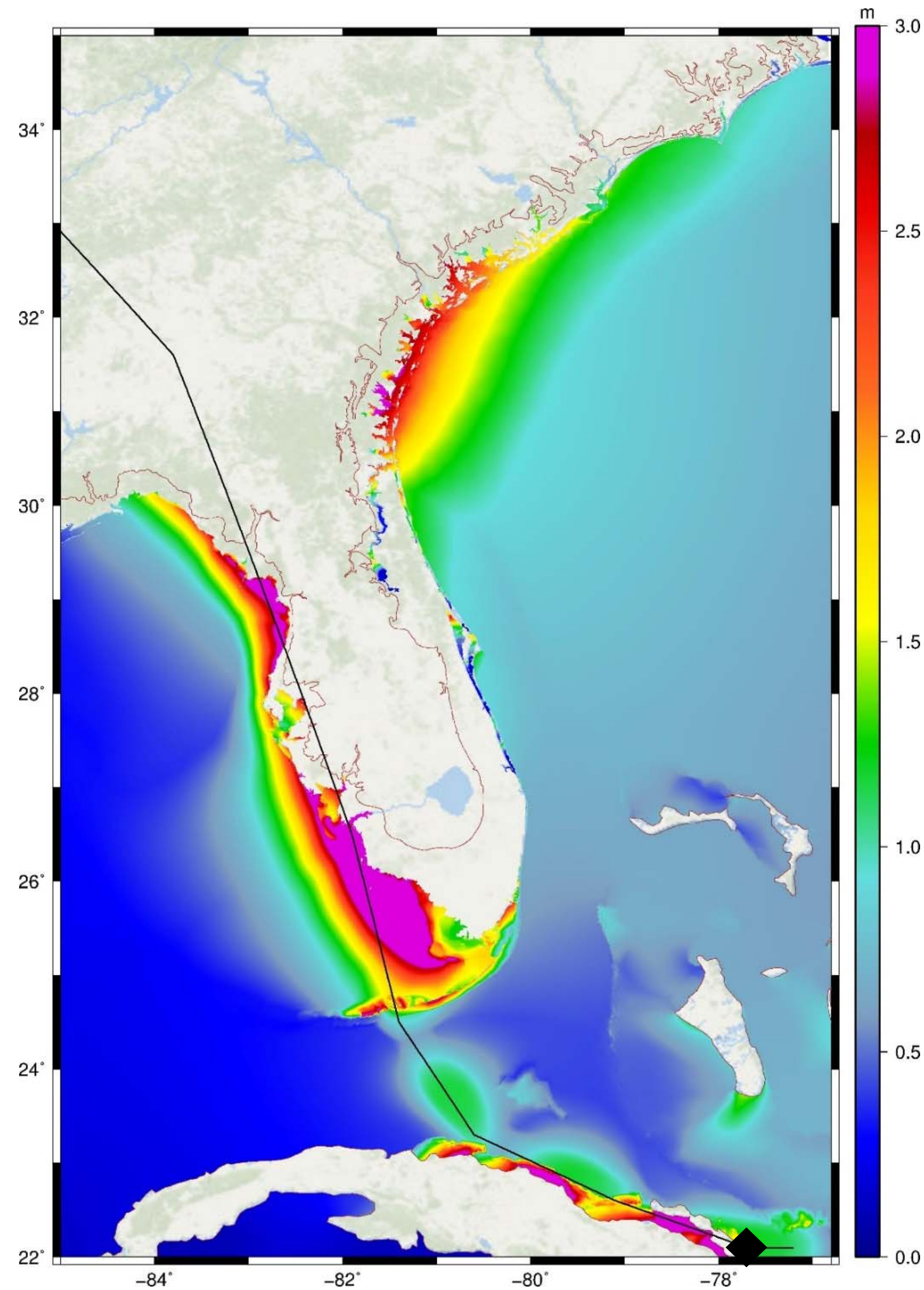
Perform scenario-based testing on a given advisory, by varying multiple storm parameters

- The aim here is to understand, if given a perturbation, how can be optimize the proposed approach through multiple scenarios
- Take an advisory, vary storm parameters like track, intensity, size to create multiple scenarios that represent possible outcomes
- Different high-resolution different meshes will have to be used to run the proposed method for these scenarios
- Optimize the method based on how many cuts needs to be made, what is the correct time to do the switching, etc.

# Research Methods

## Objective #1

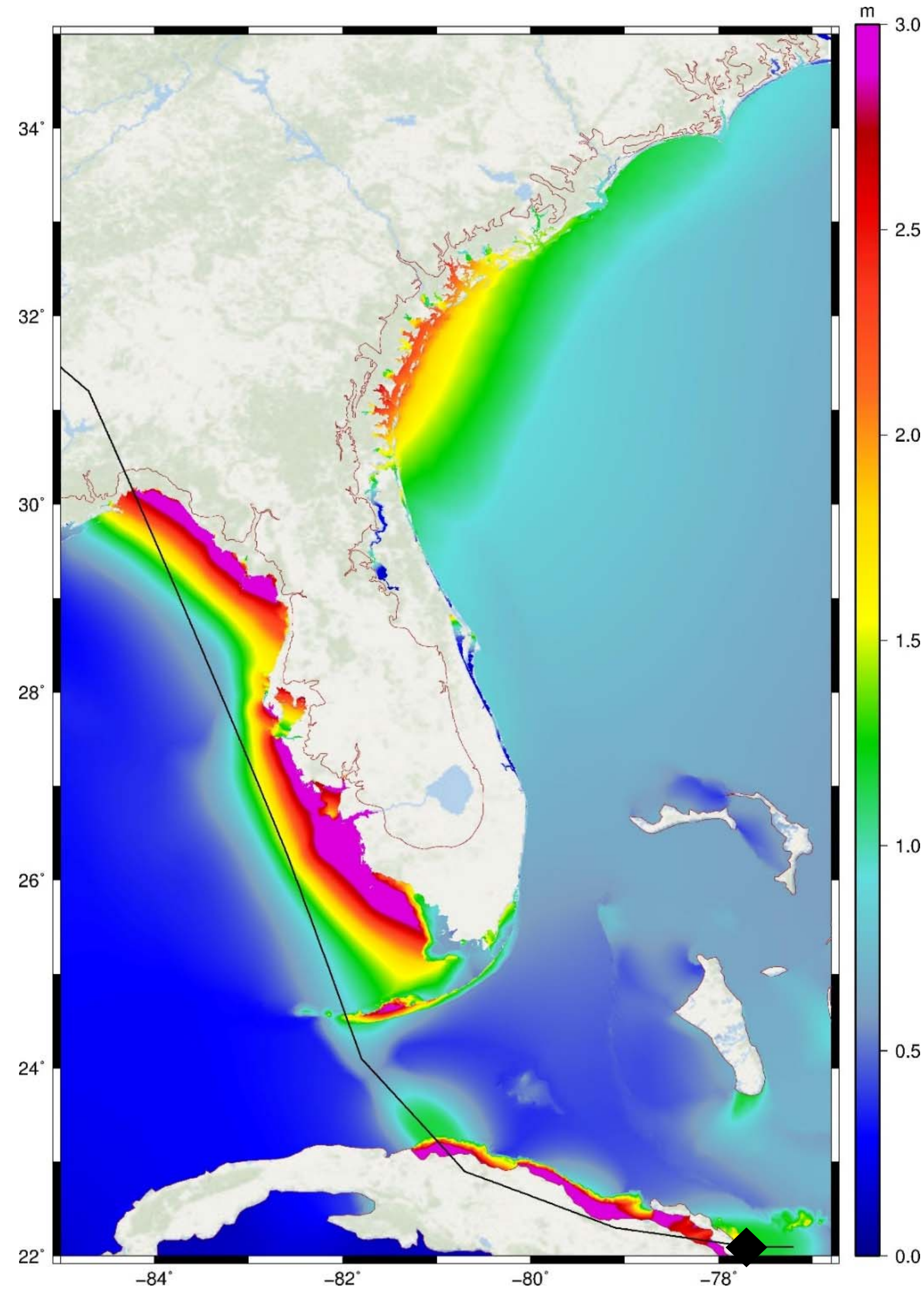
- Irma Advisory 40
  - best-track run at LONI, and RENCI



# Research Methods

## Objective #1

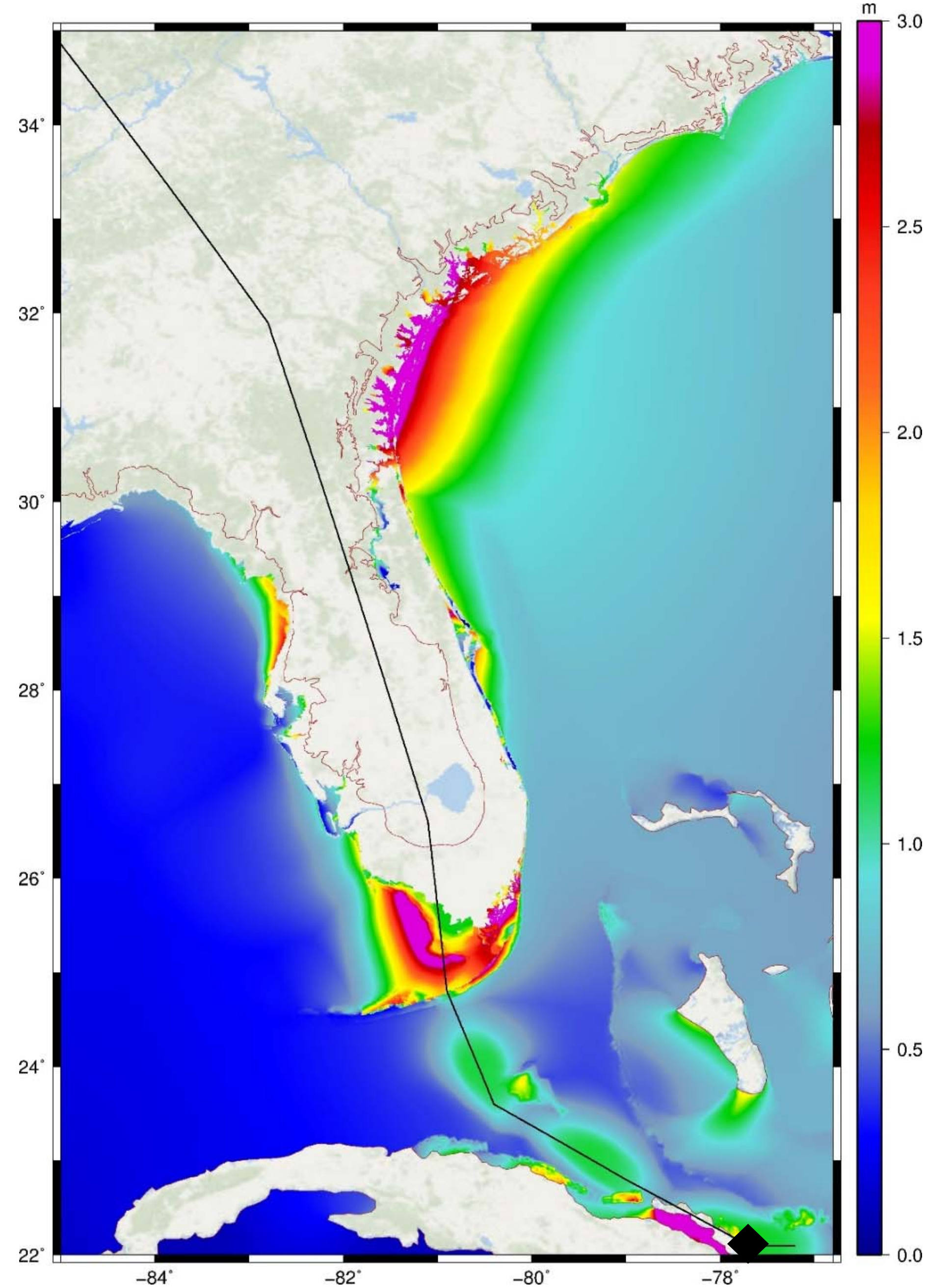
- Irma Advisory 40
  - veerLeft50 run at LONI



# Research Methods

## Objective #1

- Irma Advisory 40
    - veerRight50 run at TACC



# Research Methods

## Objective #2

Quantify computational gains from using the proposed approach, via comparisons with a simulation using the same high-resolution mesh for different scenarios

- HSOFS mesh is used for all of the few perturbations run by ASGS
- Instead, a possible combination of fine- and coarse-resolution meshes can be used
- This way, more simulations can be performed for each advisory, thus reducing uncertainty in the storms forecast
- Example
  - 3 perturbations are run in 2 hours using a single high-resolution mesh for all the runs
  - 6 simulations in the same time using a combination of meshes that vary in resolution
  - Indicates the proposed method is 100% more efficient

# Significance of the Proposed Research

- Improve efficiency of the ADCIRC model, which is used by a lot of agencies including USACE, DHS, FEMA, NOAA, etc.
  - Increase the accuracy of flood risk products used in building design and the establishment of flood insurance rates, and thus lessen the impact of a disaster
  - Improve the communication and understanding of potential hazards to individuals, community officials, the insurance industry, and government agencies
- Forecasting
  - Ensemble capabilities
  - More accurate and faster forecasts, thus providing a more reliable and timelier guidance for decision support

# Timeline

**TIMELINE FOR THE PROPOSED WORK**

| Topics | | | 2017 - June 2018 | 2018 | | 2019 | | | | | | | | | | | | 2020 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | July - Nov | Dec | Jan | Feb | Mar | Apr | May | June | July | Aug | Sept | Oct | Nov | Dec | Jan | Feb |
| Objective 1 | Perform high-resolution storm surge hindcasts of Hurricane Matthew (2016) | 1. Obtain HSOFS mesh, Wind files and collect observations | | | | | | | | | | | | | | | | | |
| | | 2. Offset Surface, Running hindcasts with GAHM and OWI | | | | | | | | | | | | | | | | | |
| | | 3. Detailed validation and computing error metrics for surface pressures, wind speeds, wave heights and water levels | | | | | | | | | | | | | | | | | |
| | | 4. Writing and publication in Ocean Modeling | | | | | | | | | | | | | | | | | |
| Objective 2 | Optimizing the proposed multi-resolution approach through hindcasts of Matthew and Florence (2018) | 1. Create an open-water mesh; testing and validating for various storms on the US coast | | | | | | | | | | | | | | | | | |
| | | 2. Obtain high resolution meshes representing the entire U.S. southeast coast; testing | | | | | | | | | | | | | | | | | |
| | | 3. Obtain source files; install ESMF libraries; compiling adcirpolate; testing the approach | | | | | | | | | | | | | | | | | |
| | | 4. Testing the approach using different combinations of fine- and coarse-resolution meshes for both storms | | | | | | | | | | | | | | | | | |
| | | 5. Analyze benefits | | | | | | | | | | | | | | | | | |
| | | 6. Submission of results to journal | | | | | | | | | | | | | | | | | |
| Objective 3 | Applying the approach during forecasting | 1. Obtain high-res meshes for the region depending on the selected storm; testing | | | | | | | | | | | | | | | | | |
| | | 2. Testing the approach using a few advisories and different combinations of fine- and coarse-resolution meshes | | | | | | | | | | | | | | | | | |
| | | 3. Collect observations for validation | | | | | | | | | | | | | | | | | |
| | | 4. Analyze benefits | | | | | | | | | | | | | | | | | |
| Writing | | | | | | | | | | | | | | | | | | | |
| Final Defense | | | | | | | | | | | | | | | | | | | |

| Color | % Complete |
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# Thank you!