Impact of storm events on density stratification in the Pamlico and Albemarle Estuarine System

M.S. Thesis Defense

10/28/2021

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Acknowledgements

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About Me

- From Charleston, WV
- Marshall University, WV
  - B.S. in 2019
  - Civil Engineering
- North Carolina State University
  - Spring 2020
- Loves to travel, try new food, and adventures with my family and pets



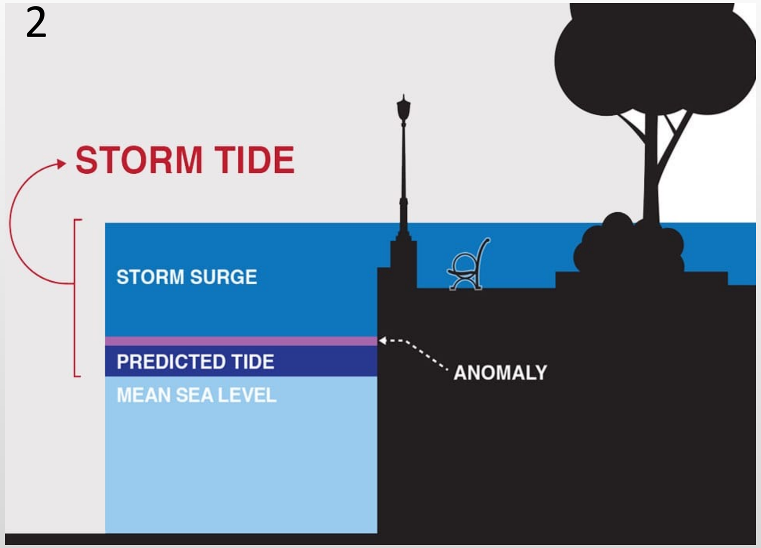
Outline

- Introduction
- Methods
- Results
  - Story of the Storm
  - Specific Areas
- Conclusions & Future Work

Introduction

Tropical Cyclones

- Intense winds, large amounts of rainfall, and flooding
- 1980 – 2020:
  - More damage than any other weather disaster in U.S.
  - More than 6,500 deaths
- Storm surge
  - Rise of ocean waters above the regular tide levels

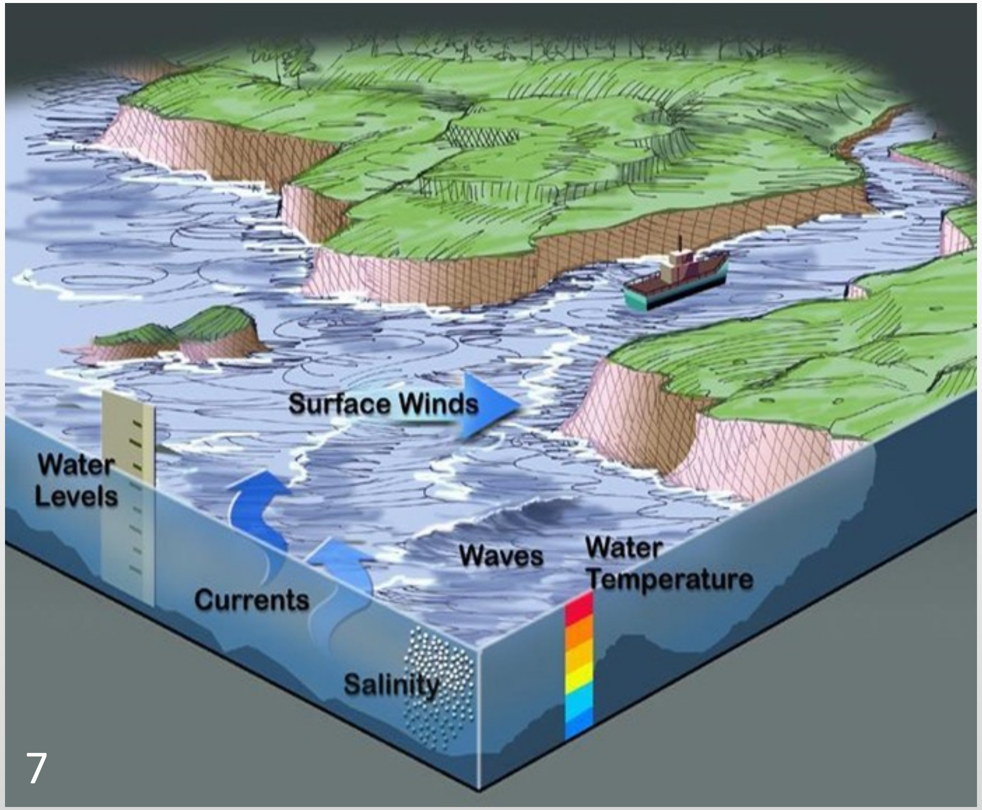


Estuary Impacts

- Nutrient loading/regeneration
- Harmful algal blooms
- Fish mortalities
- Abrupt changes in salinity
- Increases in mixed-layer depth
- Decreases in sea-surface temperature
- Loss of vertical stratification

Coastal Modeling

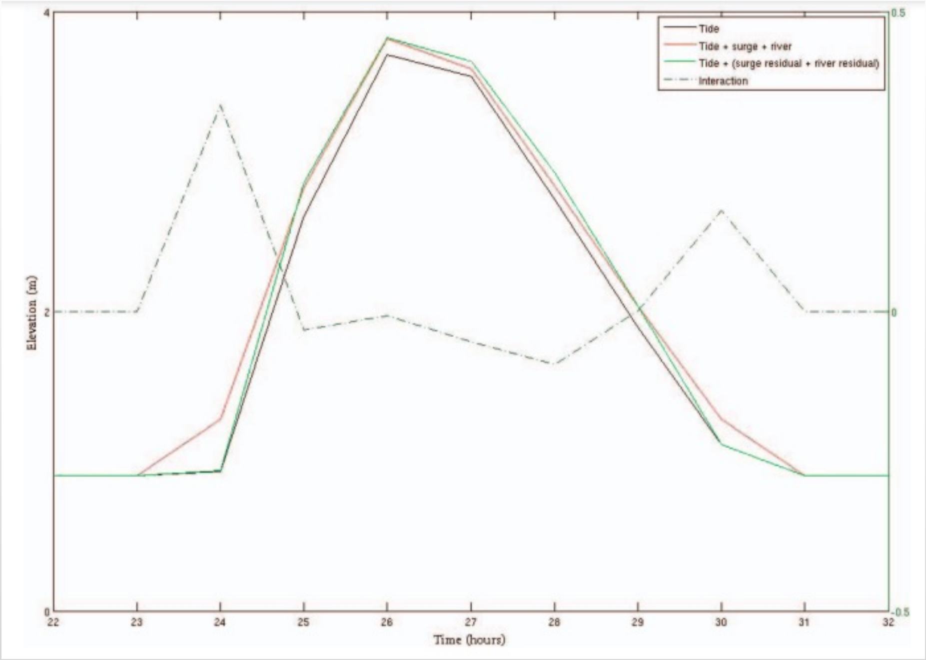
- Numerical models to represent coastal environment
  - Response to tides, rivers, winds, etc.
  - Usually simplified
- Estuaries
  - Storm-driven circulation
  - Density-driven circulation



Storm & Density-Driven Circulation

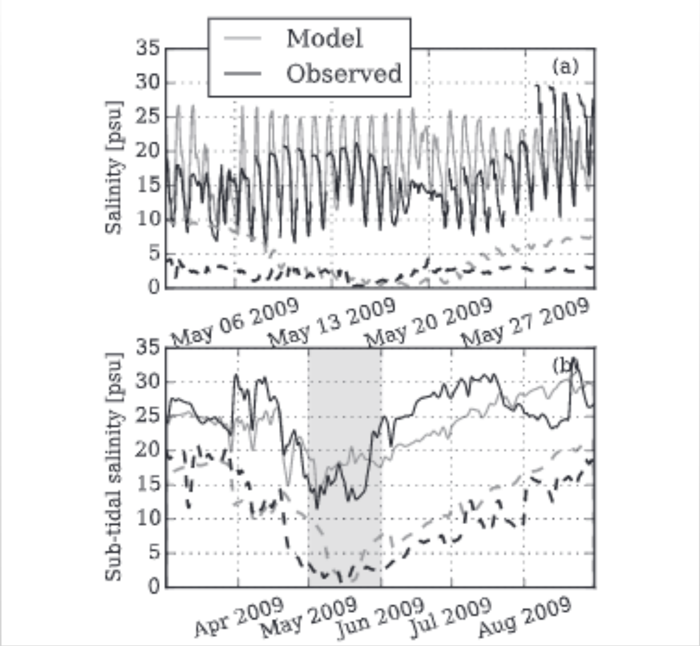
Storm-driven Circulation

- Maskell et al. (2014) used idealized estuary



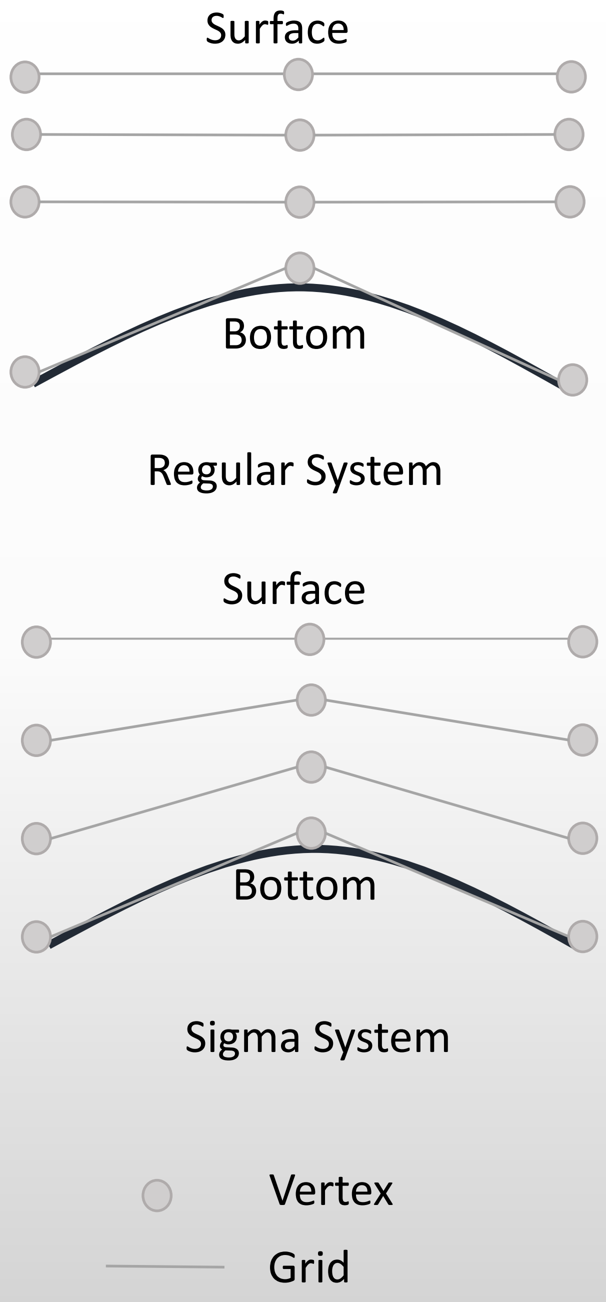
Density-driven Circulation

- Rayson et al. (2015) examined density-driven circulation in Galveston Bay



ADCIRC

- ADvanced CIRCulation
  - (Luettich and Westerink 2004)
- 2D and 3D
  - 2D widely used for storm surge
- Generalized Wave Continuity Equation:
  - Water surface elevations
- Velocities:
  - 2D: vertically-integrated momentum equations
  - 3D: 3D shallow water momentum equations
- Sigma Coordinate System



ADCIRC in Estuaries

- Storm-Driven
  - Yin et al. (2017) investigated the effect of sea level rise and typhoon intensification on storm surge Pearl River Estuary, China
  - Sebastian et al. (2014) investigated maximum water levels and behavior of storm surge in Galveston Bay, Texas
- Density-Driven:
  - Dresback et al. (2010) applied a coupled model to the Northern Gulf of Mexico
  - Cyriac et al. (2020) investigated the tidal, wind, and density-driven circulation at Choctawhatchee Bay, Florida

Combined Circulation

- Liu et al. (2019) investigated impacts on **the circulation and the memory of the system** in response to Irma (2017) at Florida Bay and Charlotte Harbor Estuary
- D'Sa et al. (2019) studied **the response of dissolved and particulate organic carbon** in the Apalachicola Bay, Florida
- Brown et al. (2014) examined the transport of the **dissolved organic carbon** in the Neuse River, North Carolina, during Irene (2011)
- Most of these studies:
    - Coupled to larger models
    - Examined density stratification as additional goal
    - Missing physics

Remaining Questions

- Uncertainty about how the estuary evolves during a storm event.
  - How does the mixing vary through the estuary?
  - How do freshwater discharges due to rainfall affect the mixing?
- Another uncertainty is the restratification
  - How quickly does the system restratify?
  - Do the freshwater discharges interrupt the restratification?

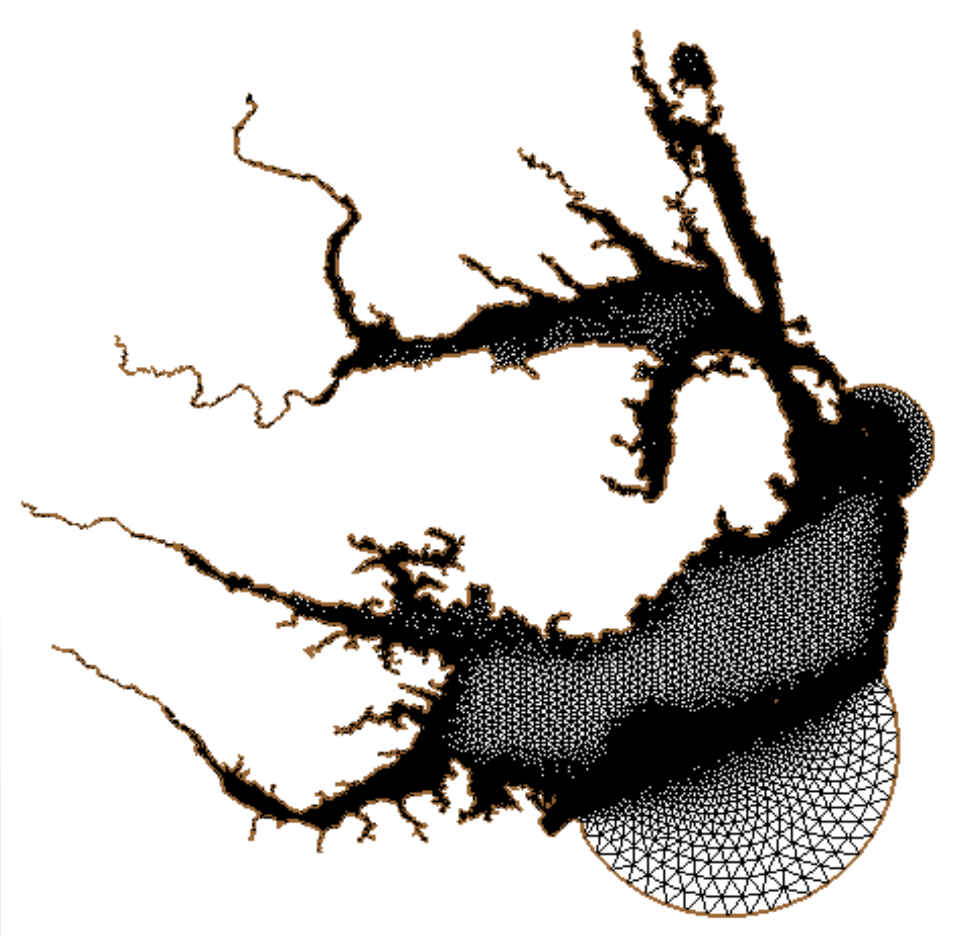
Hypothesis

It is hypothesized that, for a large and shallow estuarine system with minimal connections to the open ocean, the storm forcing will cause large brackish and freshwater intrusions and recoveries that vary through the system.

- Develop a three-dimensional in the Albemarle-Pamlico Estuarine System (APES), NC
  - Include storm and density-driven circulation
  - Irene (2011)

Objectives

1. Develop mesh and initial conditions
   - Tailor to APES
   - August inputs
2. Simulations with and without Irene (2011)
   - Spin up periods
   - One includes winds & increased discharges
3. Quantify the storm effects on density distributions
   - Two methods



Methods

Area of Study

Study Area Major Forcings

- Fresh water from rivers
  - Roanoke River largest flow rate
- Saline water from inlets
  - ~1 m tidal range
- Average distribution
  - Albemarle fresher
    - Currituck ~ 3 ppt average
  - Pamlico brackish
    - ~ 20 ppt average
  - Weak vertical stratification

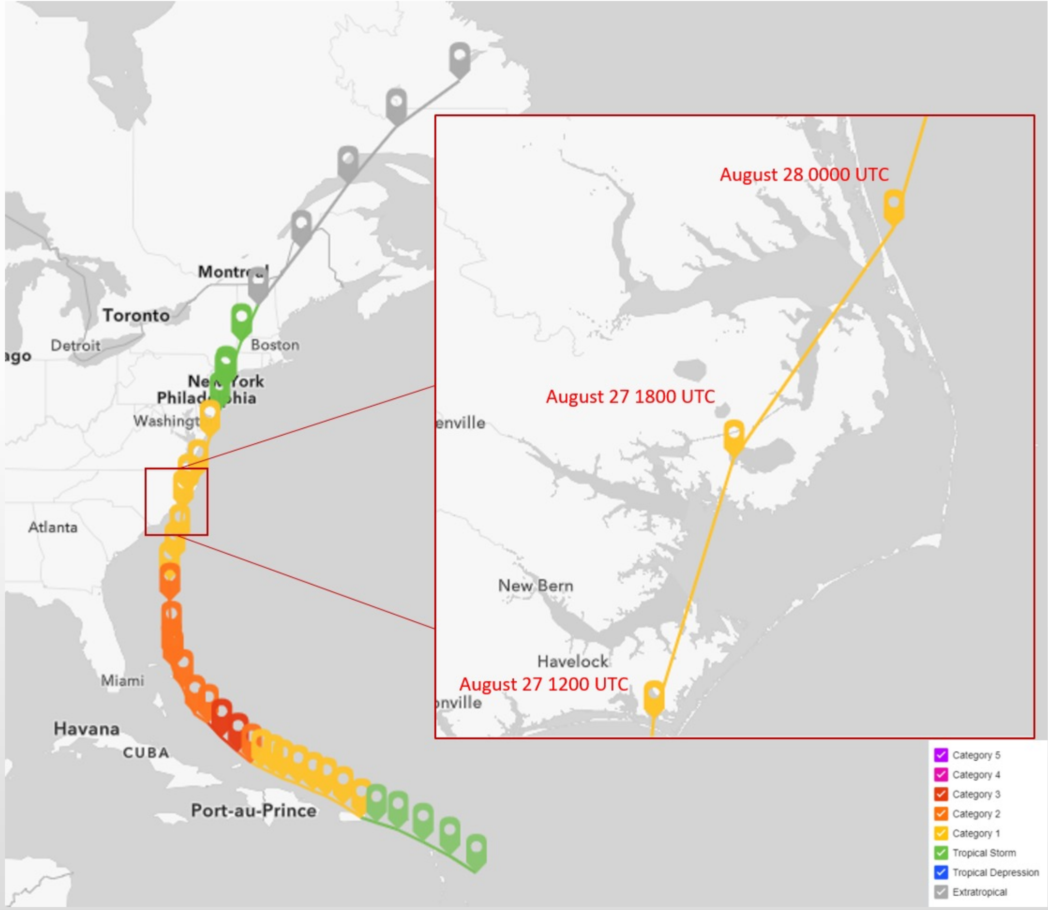
River	Drainage Area km^2	Mean Flow m^3/s	Maximum Flow m^3/s	Date
Chowan	12,000	21.89	320	11 October 2016
Roanoke	25,000	226.68	7,300	18 August 1940
Tar-Pamlico	16,500	70.35	1,000	22 August 1940
Neuse	16,100	117.30	1,600	20 September 1999

ADCIRC in APES

- Luettich et al. (2002) used the barotropic, depth-integrated, two-dimensional version of ADCIRC to investigate a semi-diurnal signal found within the Neuse River
- Dresback et al. (2013) developed a total water forecast system based on ADCIRC
- Haase et al. (2012) used ADCIRC to predict oyster larvae dispersion in APES
- Conclusions:
  - Primary forcing is wind
  - More understanding of density circulation

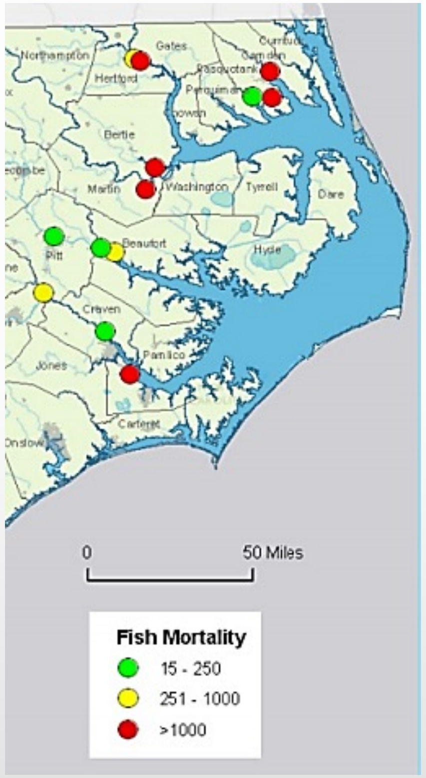
Storm Selection

- Irene (2011)
- August 15 – August 30
- Landfall:
  - Cape Lookout, NC
  - August 27 1200 UTC
  - Wind speed: 38 m/s
  - Category-1
- Progressed over APES

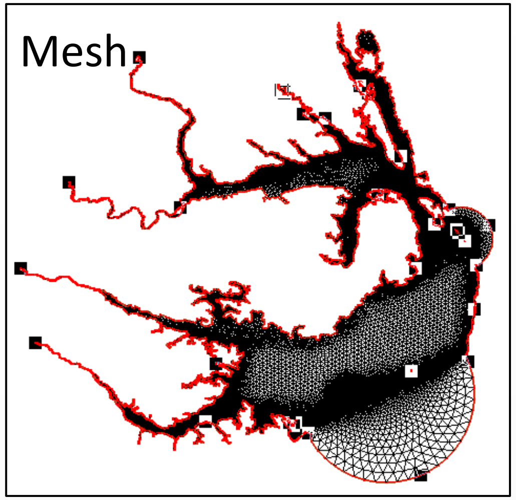


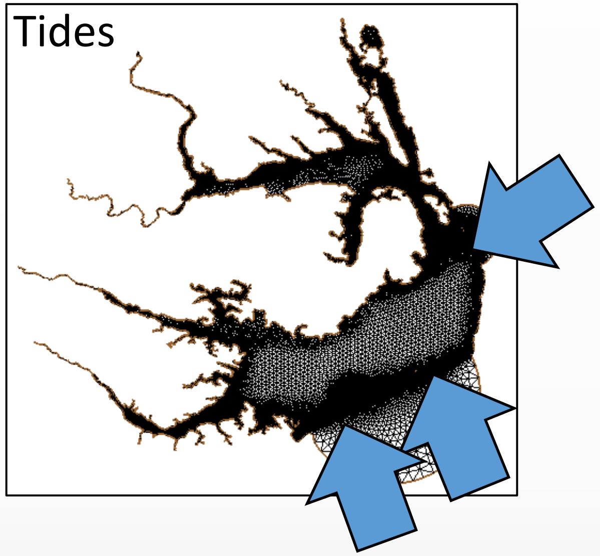
Storm Selection Continued

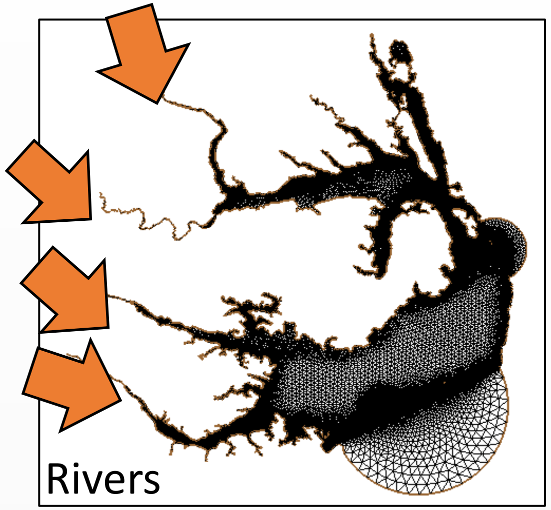
- NCDEQ Fish deaths
- 12 Reports
  - 10 in study area
  - Several in Chowan and Roanoke Rivers
- Last report September 13
  - More than 17 days after storm

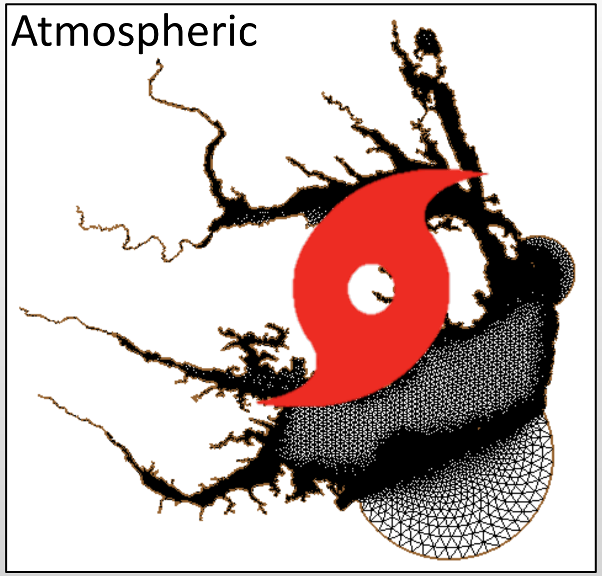


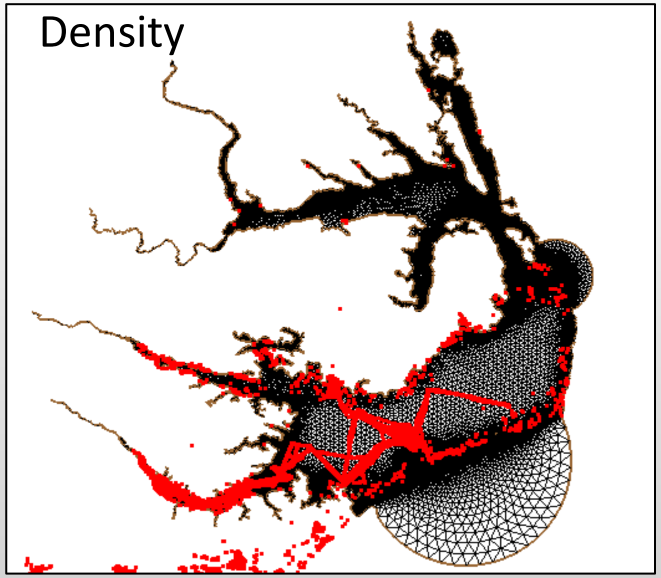
Simulation Development











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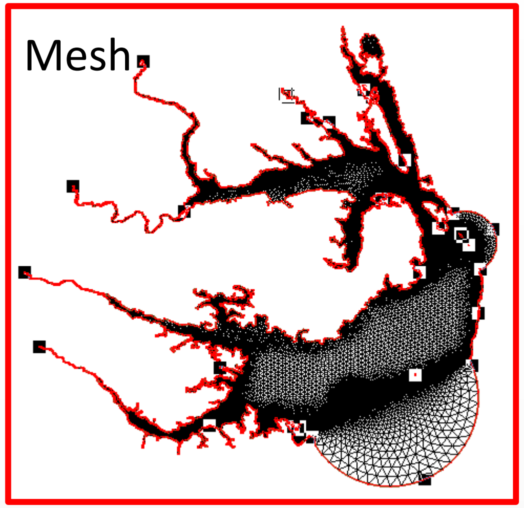
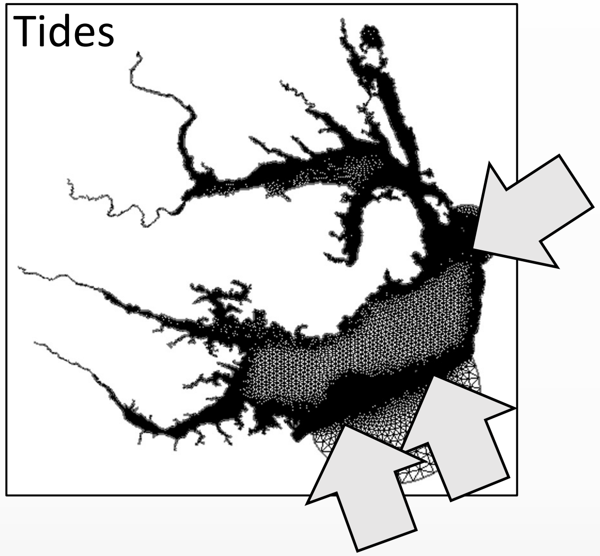
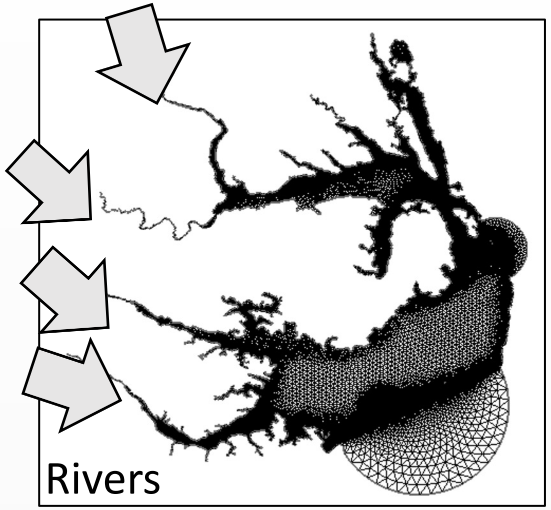
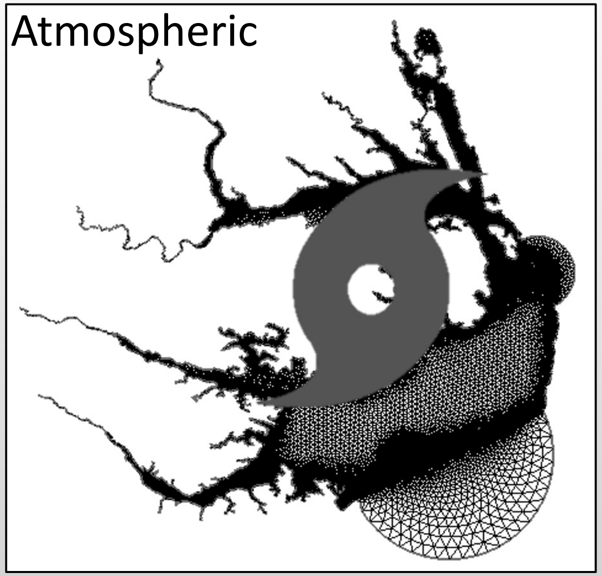
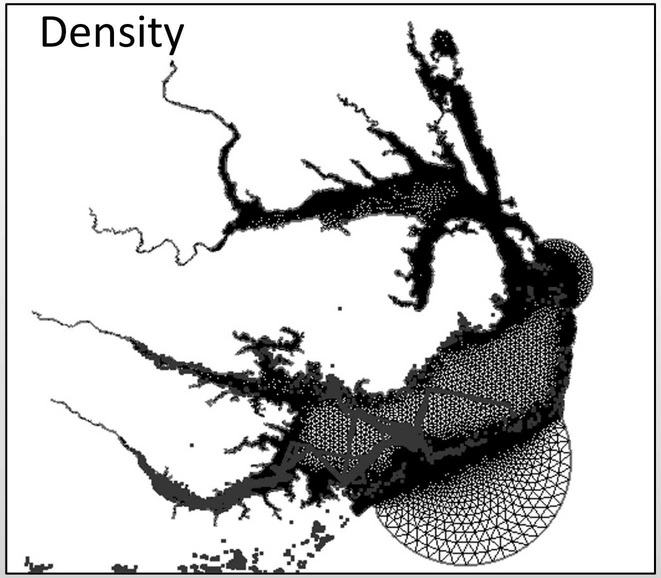
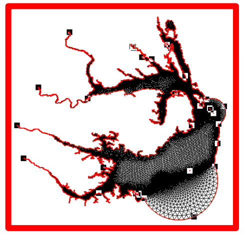






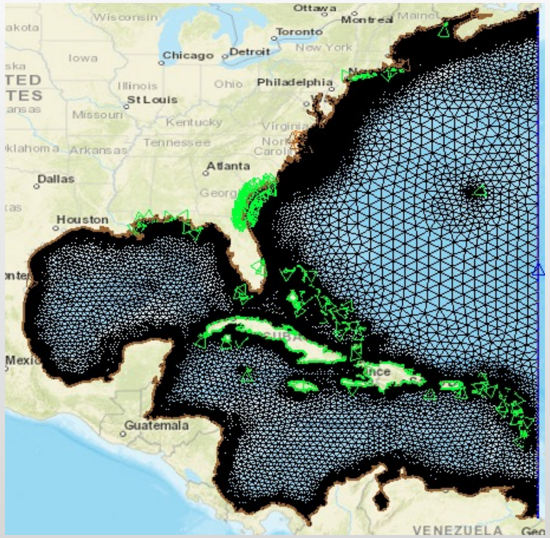


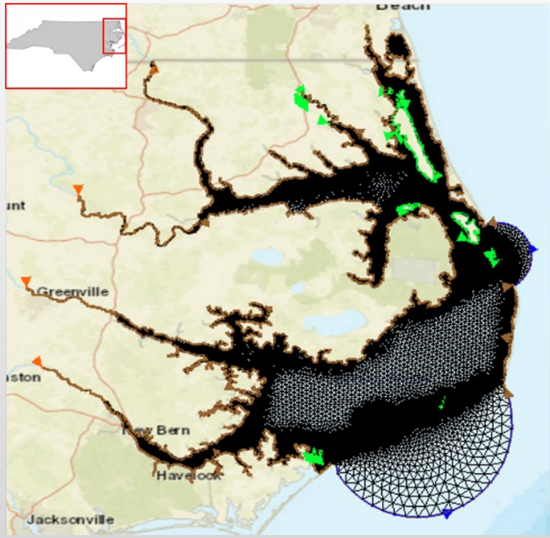


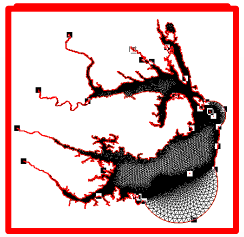


Mesh Development

- NC v9.98 (NC9)
  - 624,782 vertices
- Trimming (NC9-APES)
  - 0 elevation
  - 60330 vertices; 5 km res (ocean) & 50 m res (inlets & rivers)



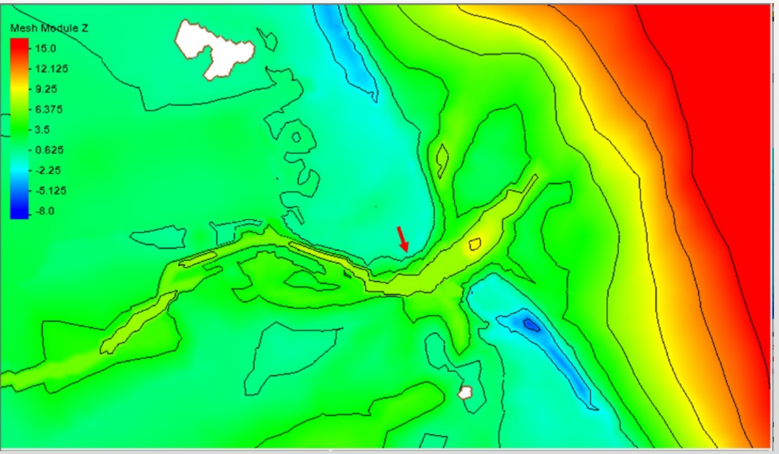




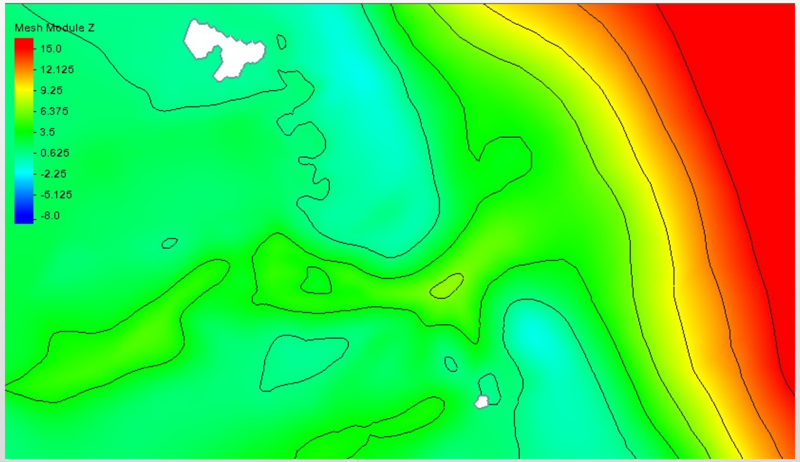
Bathymetry Smoothing

- Steep bathymetry can cause instabilities
- Smoothed based on Cyriac et al. (2020)
- Combined smoothed & original

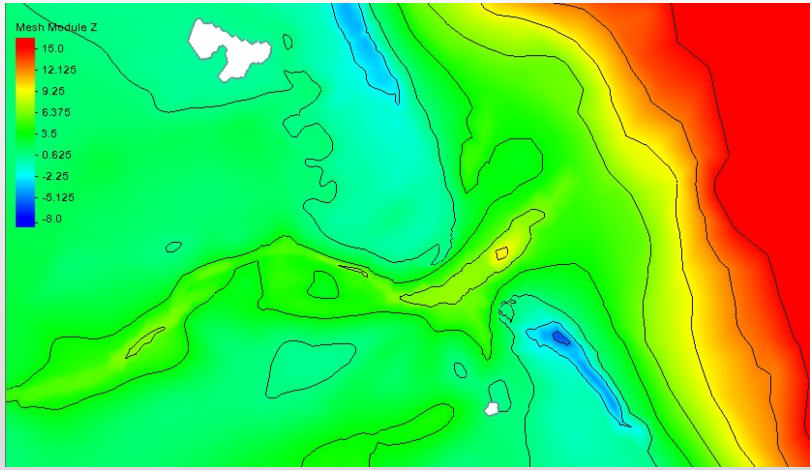
Range (m)	Source for Bathymetry in Combined Mesh
$h > 15$	Original
$5 < h <= 15$	Linear Weighted Combination
$0 < h <= 5$	Smoothed
$-3.5 < h <= 0$	Linear Weighted Combination
$d < -3.5$	Original



Original

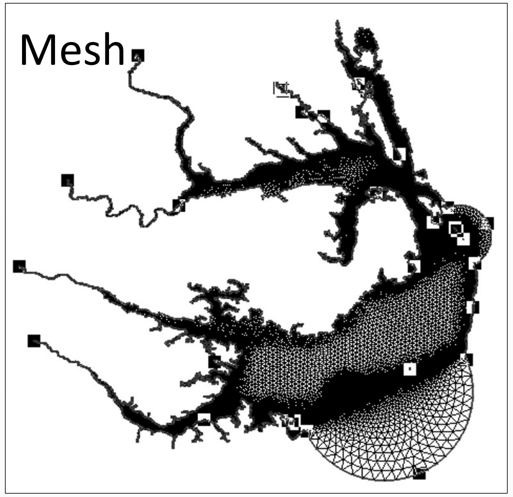


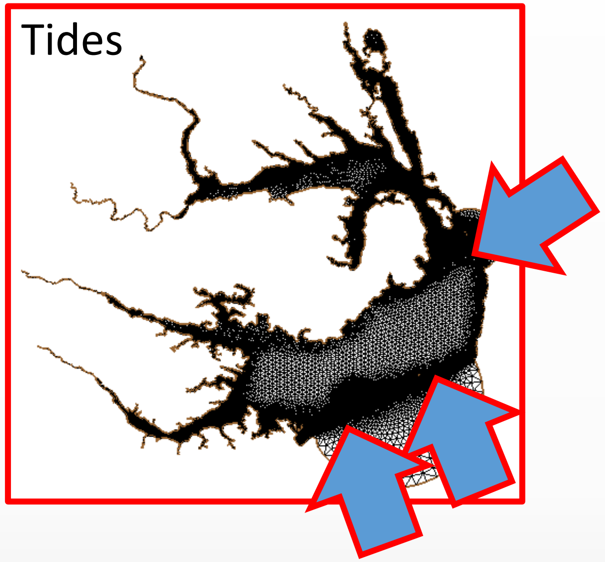
Smoothed

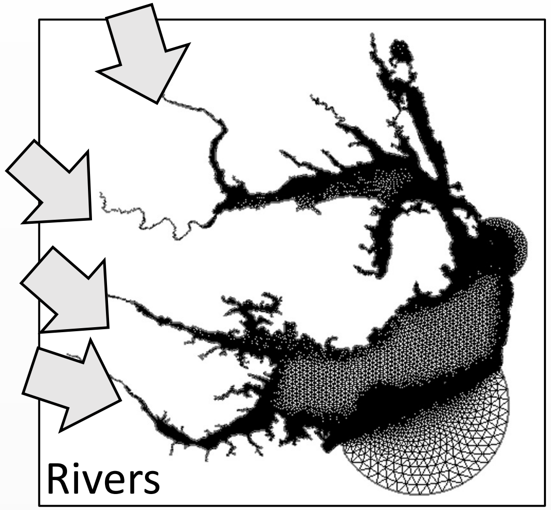


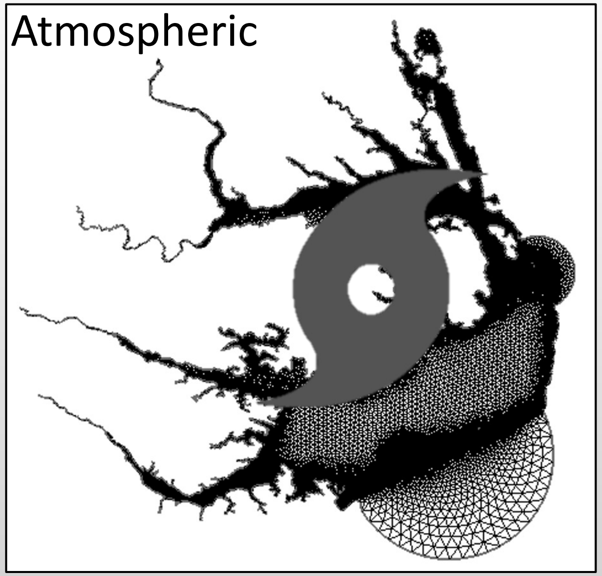
Final

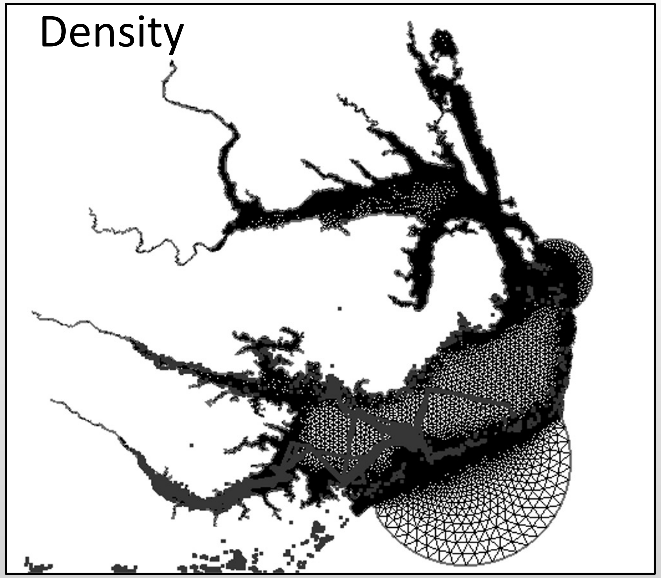
Simulation Development



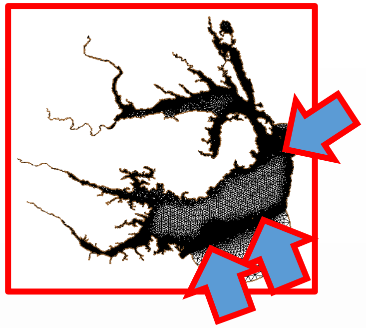






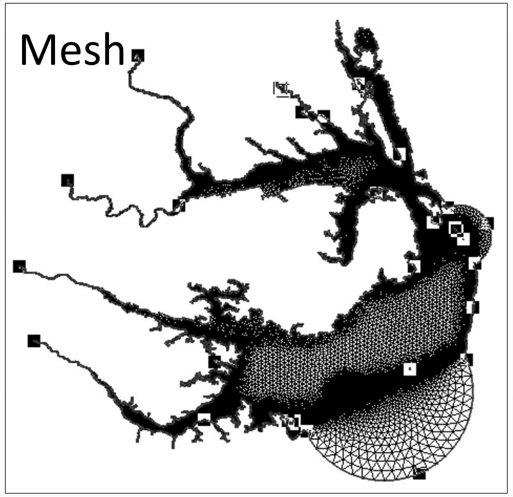


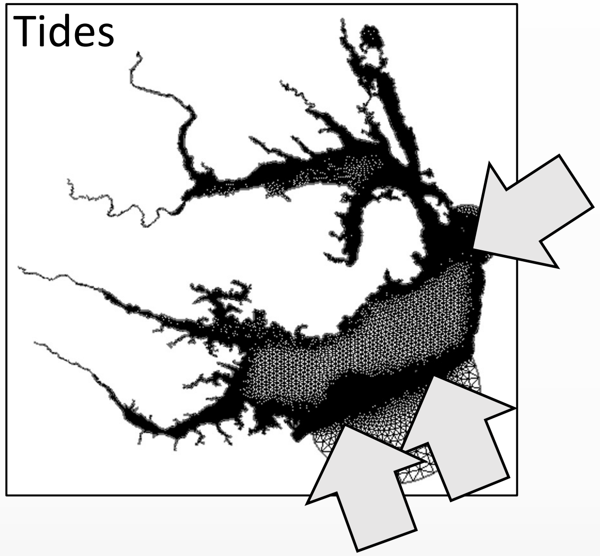
Tides

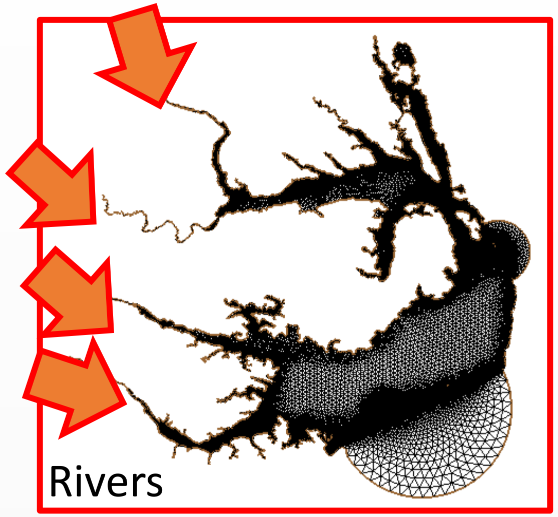


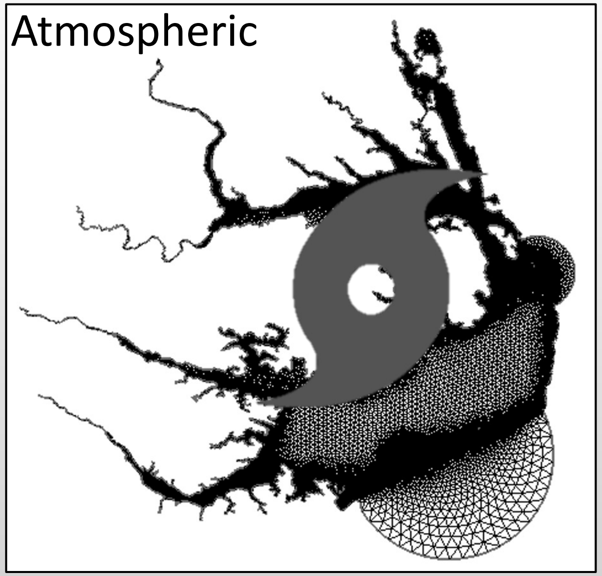
- Applied using tidal constituents
  - 8 Constituents used
- Requires time specific and location specific
  - Location: amplitudes and phases from EC2015 tidal database
  - Time: node factors and equilibrium arguments calculated for time period
- ADCIRC
  - Develops tidal signals
  - Develops tidal potentials

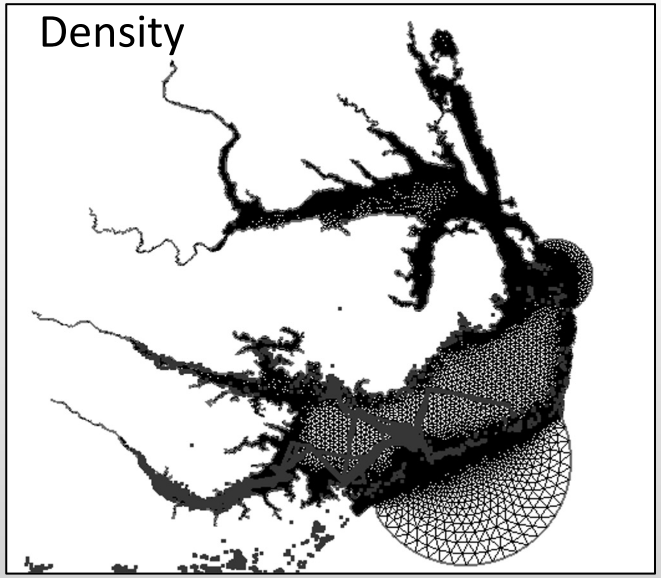
Simulation Development



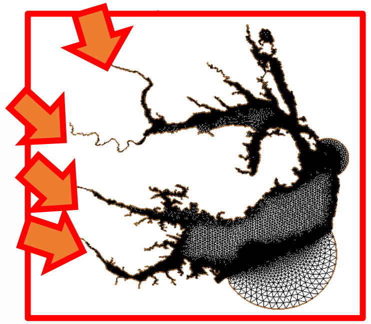








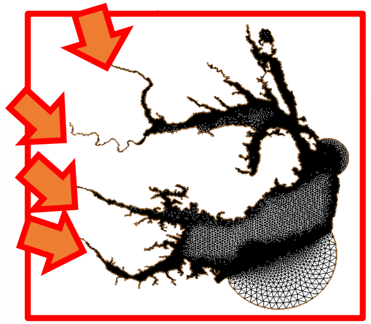
Rivers



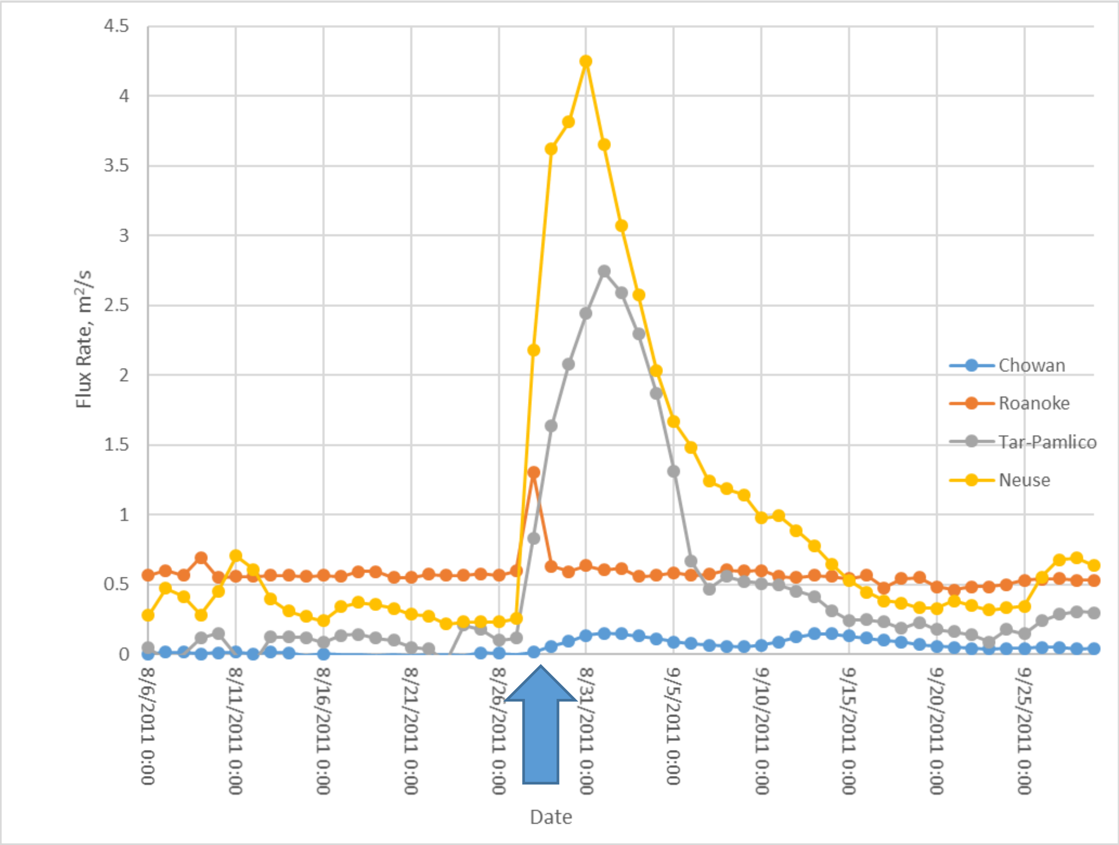
- Two types:
  - Steady
  - Unsteady
- Based off USGS stream gauges
- Flow rates to flux rates
  - Length of boundary
- No-Storm simulation
  - Steady flow rates

River	USGS Gauge	Flow Rate (m^3/s)
Chowan	02050000	49.3
Roanoke	02080500	66.5
Tar-Pamlico	020840000	79.0
Neuse	02091814	112.7

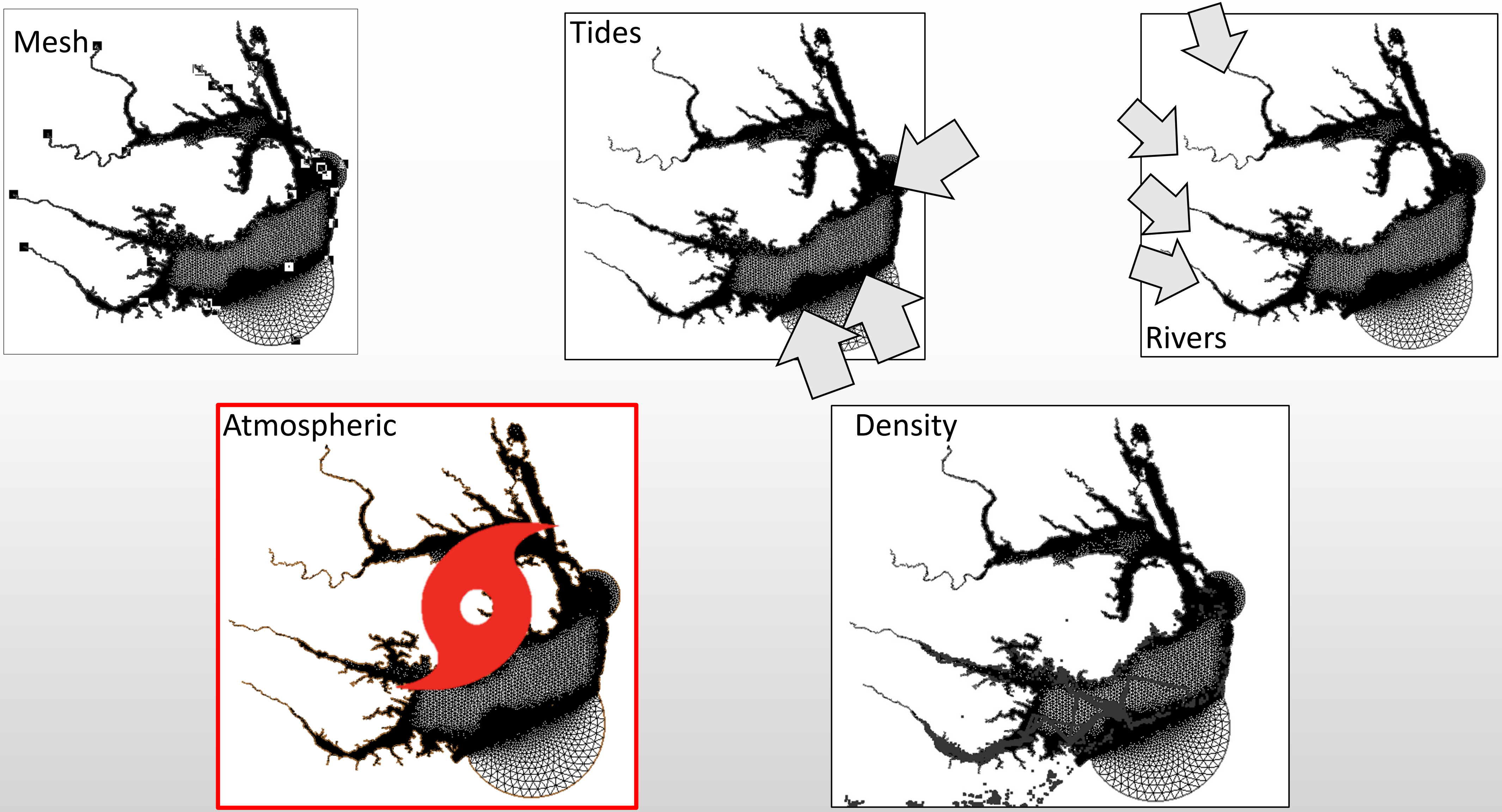
Rivers Continued



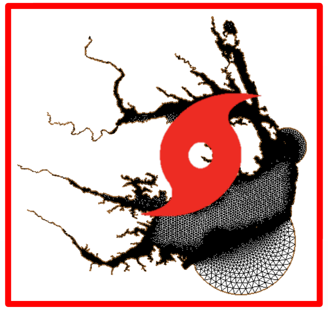
- Storm Simulation
  - Unsteady flow rates
  - Includes larger discharges after storm



Simulation Development

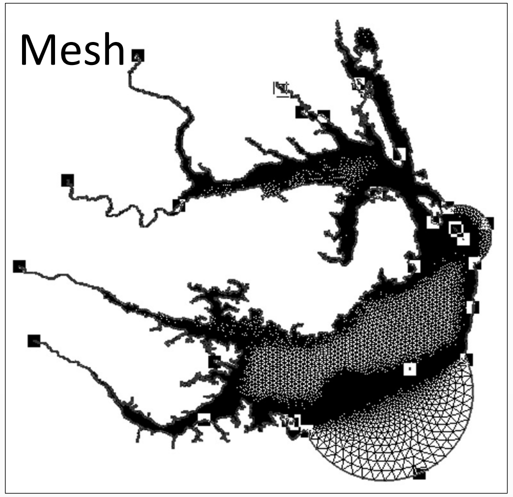


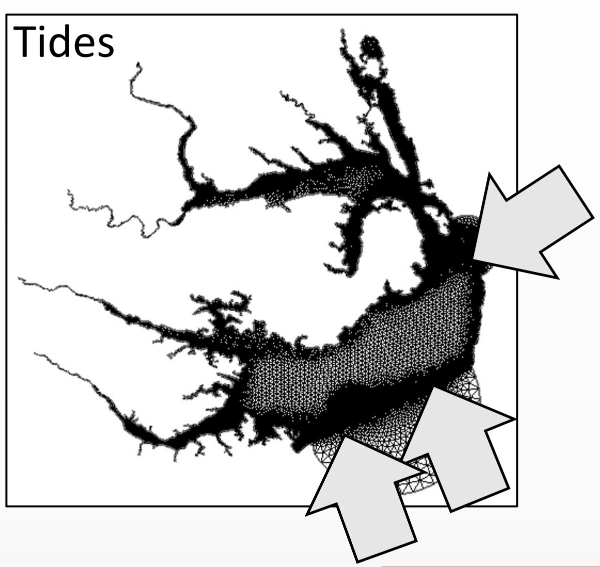
Atmospheric

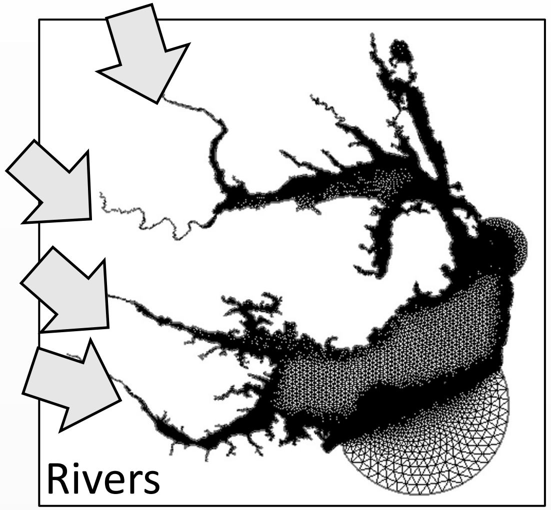


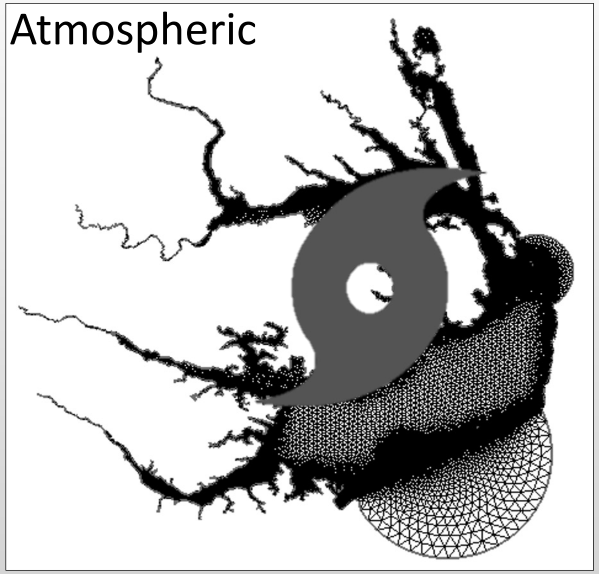
- Generalized Asymmetric Holland Model (GAHM)
  - Develops pressure and wind fields
  - Includes asymmetric wind fields
- Needs storm parameters
  - NOAA Best Track file
  - Pressures, different isotachs for winds, path location, and times of observation
- Irene:
  - Begins 0000 UTC August 21
  - Ends 0000 UTC August 29

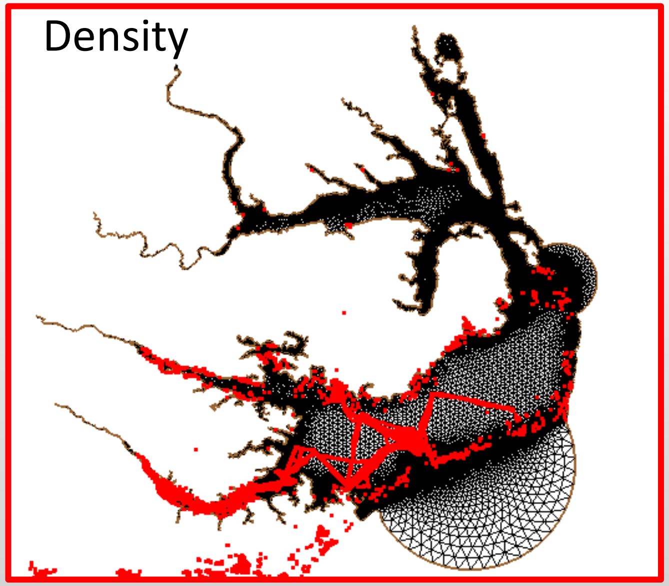
Simulation Development



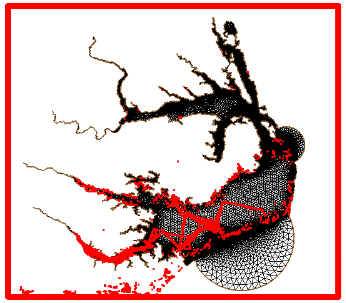








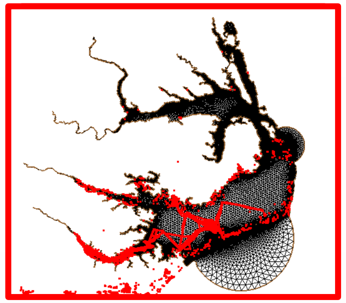
Density - SalWise

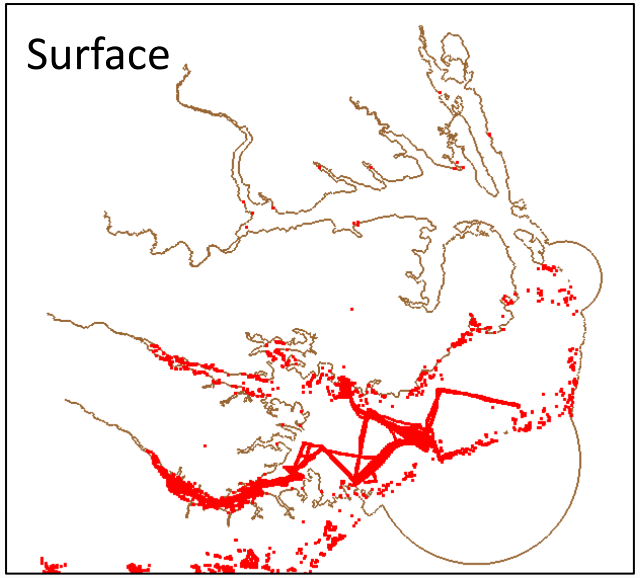


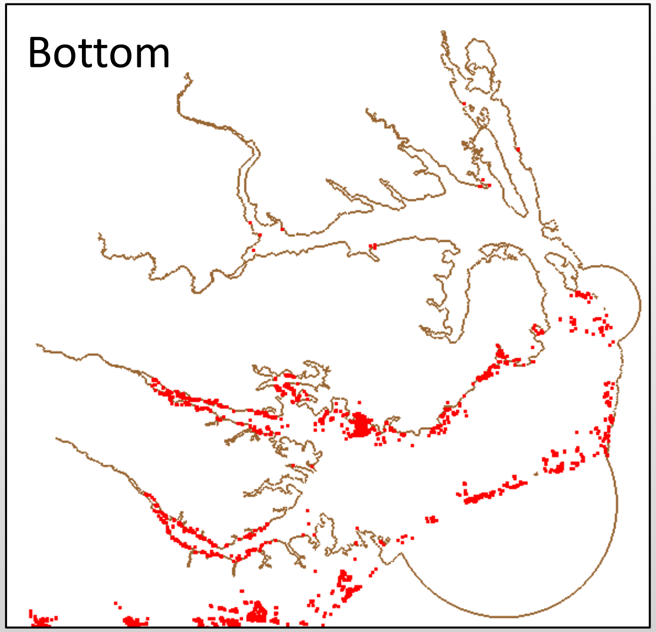
- Database for salinity, temperature, and others
- Developed by Dr. Niels Lindquist (UNC) and Dr. Stephen Fegley (UNC)
  - “Development of a Comprehensive North Carolina Salinity Database to Facilitate Management and Restoration of Critical Fish Habitats”
- Has over 1,980,000 records
- Date ranges from 1945 to 2014
- Parameters come from various NCDMF programs

Density - Forcing

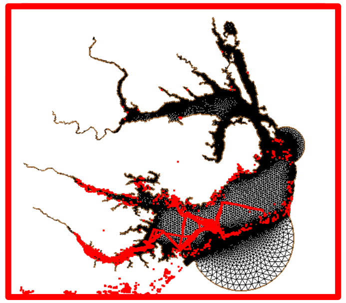
- August 2011
  - Surface: 25,580 points
  - Bottom: 237 points
- Extracted all data for August
  - At least 1 data point from: 1945,1948-1967, 1972-2013
  - Surface: 158,665 points
  - Bottom: 3,789 points



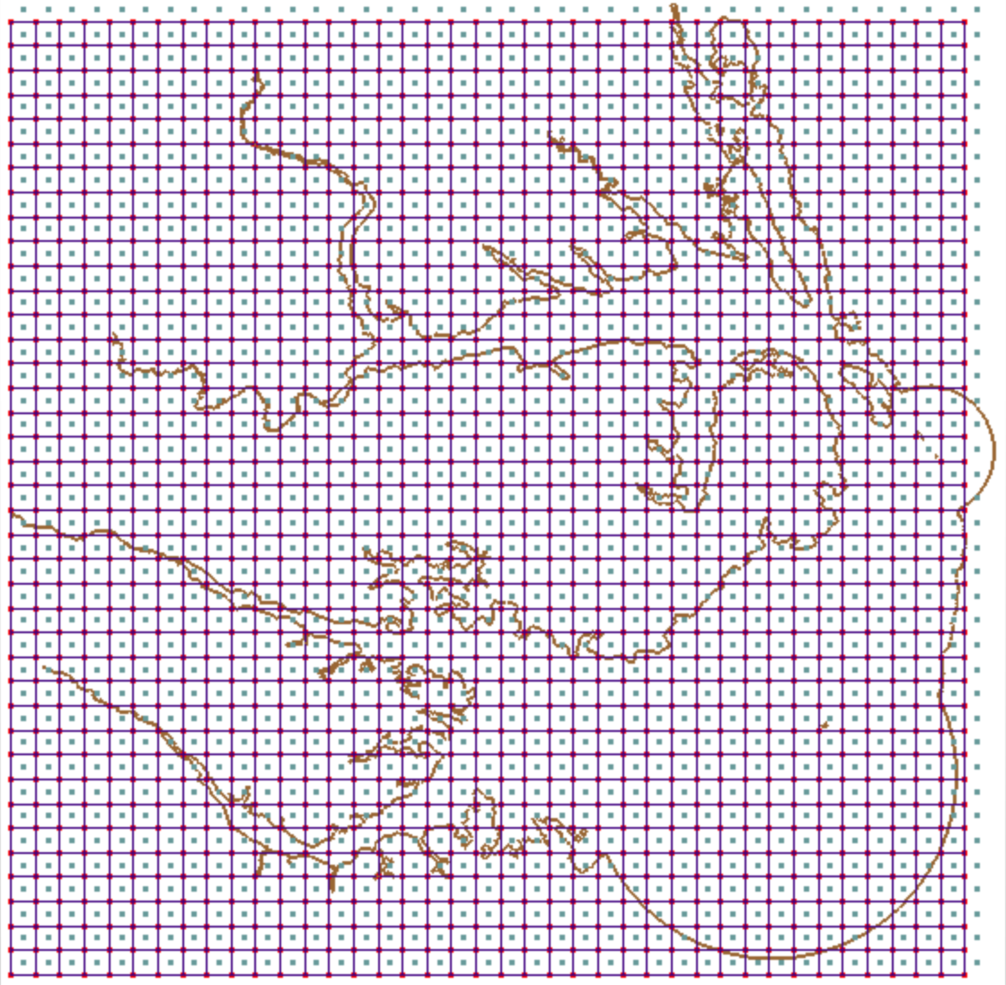




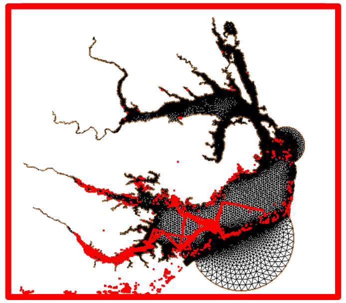
Density – Forcing Continued



- Use binning method
- First, divide up area into equally sized bins
  - Bin size: 0.05 degrees
  - Blue lines bin boundaries
  - Blue dot bin centers

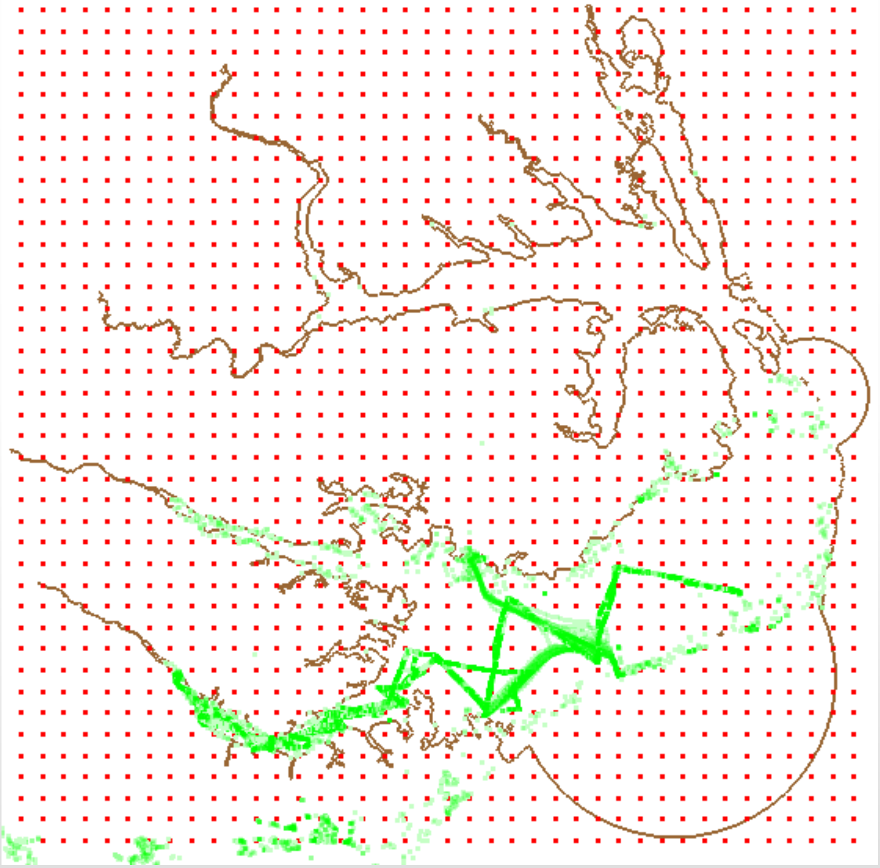


Density – Forcing Continued

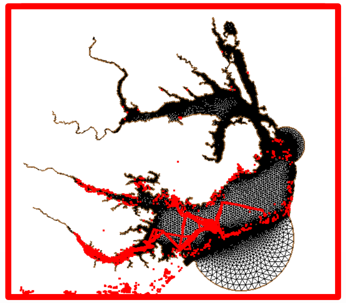


- Sort observational points for each bin
- Calculate metrics for each bin
    - Number of points
    - Max, Min, Median, Mean for salinity and temperature

	Long	Lat	NumPts	Sal_max	Sal_min	Sal_media	Sal_mean	Temp_ma	Temp_mi	Temp_me	Temp_mean
0	-77.95	34.05	9	29.6	13.1	20.2	21.63333	32.7	27.9	30.8	30.7
1	-77.85	34.05	5	34	28.3	28.7	29.7	29.7	25.3	25.9	26.68

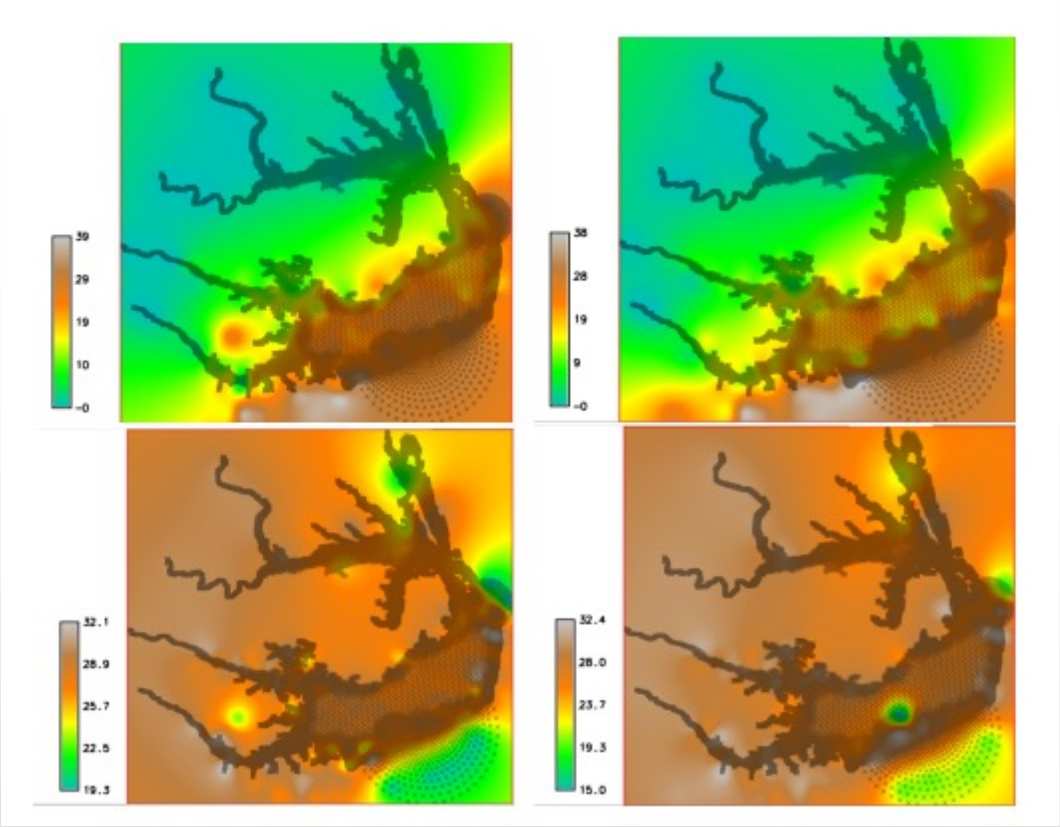


Surface



Density – Forcing Continued

- Develop surface for salinity and temperature
  - GRASS GIS
  - v.surf.rst
- Interpolated onto mesh
  - v.what.rast
- Resulted in ‘average’ August distribution
- Used as input



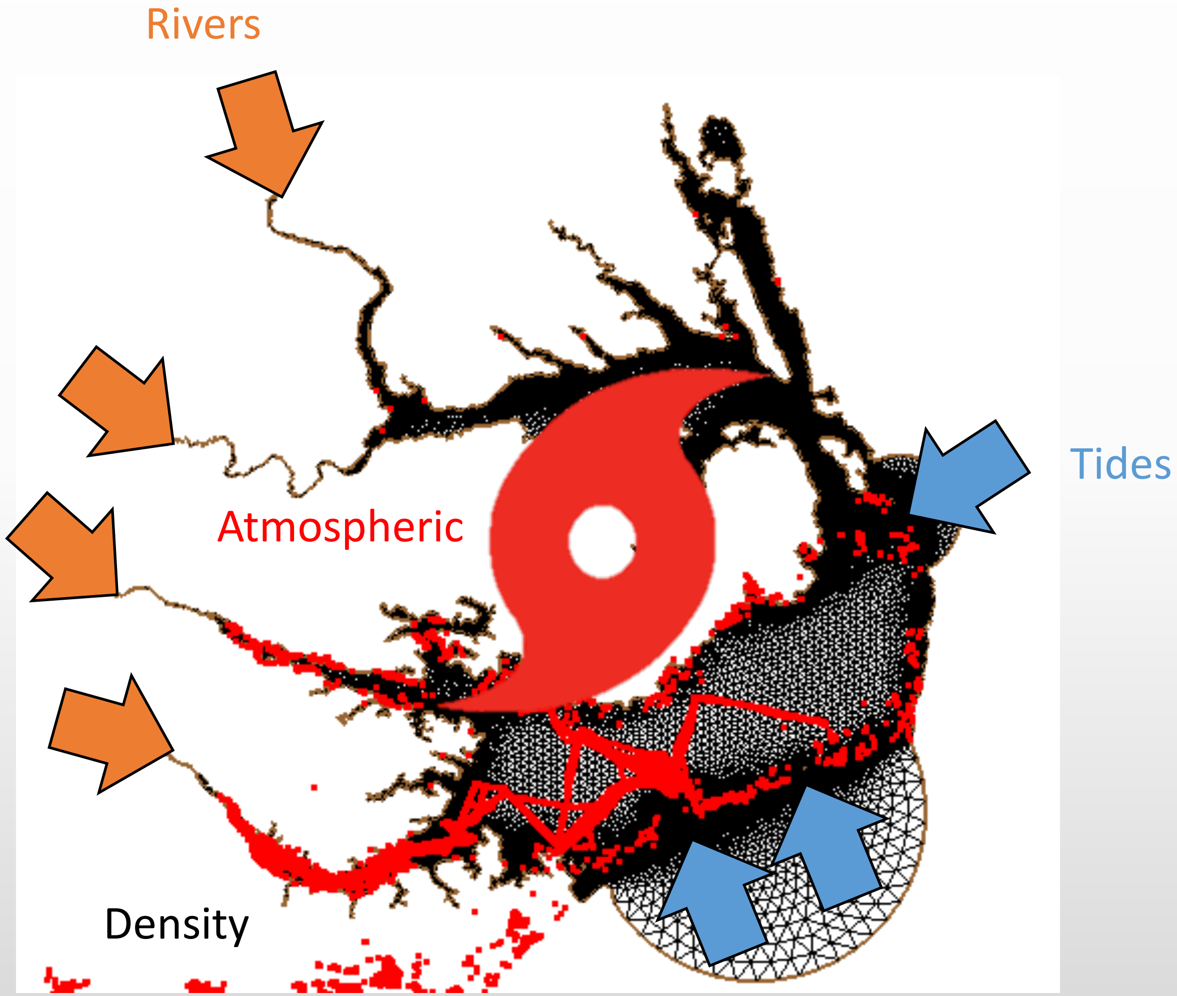
Salinities

Temperatures

Surface

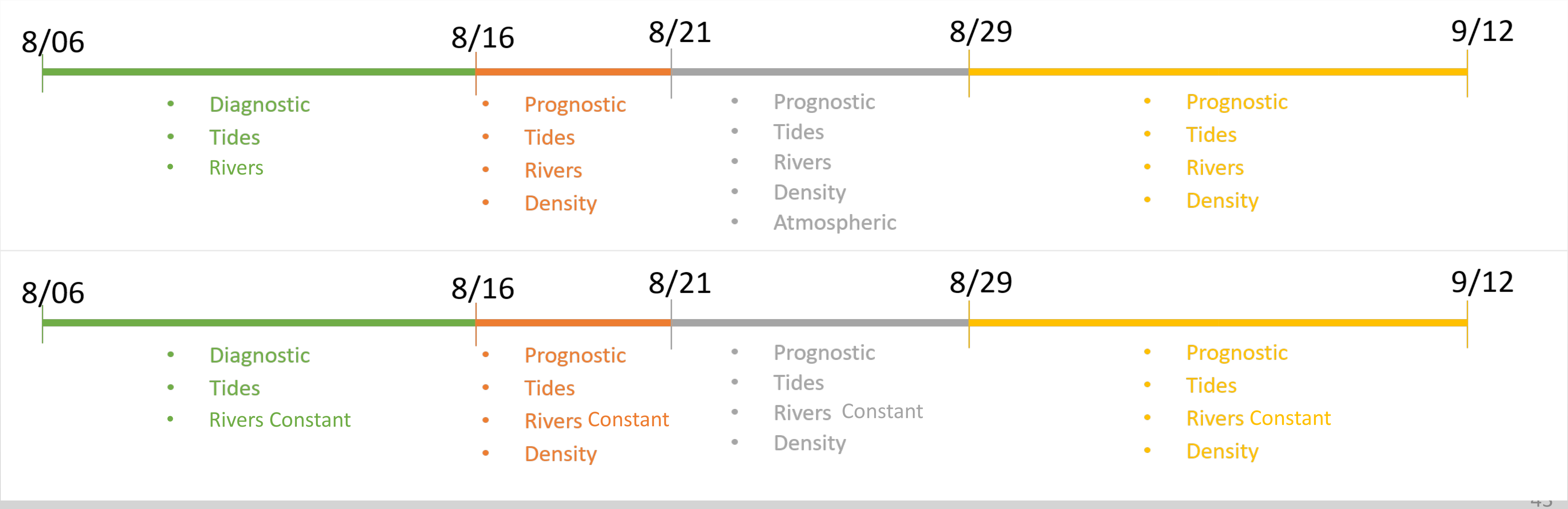
Bottom

Full Forcing



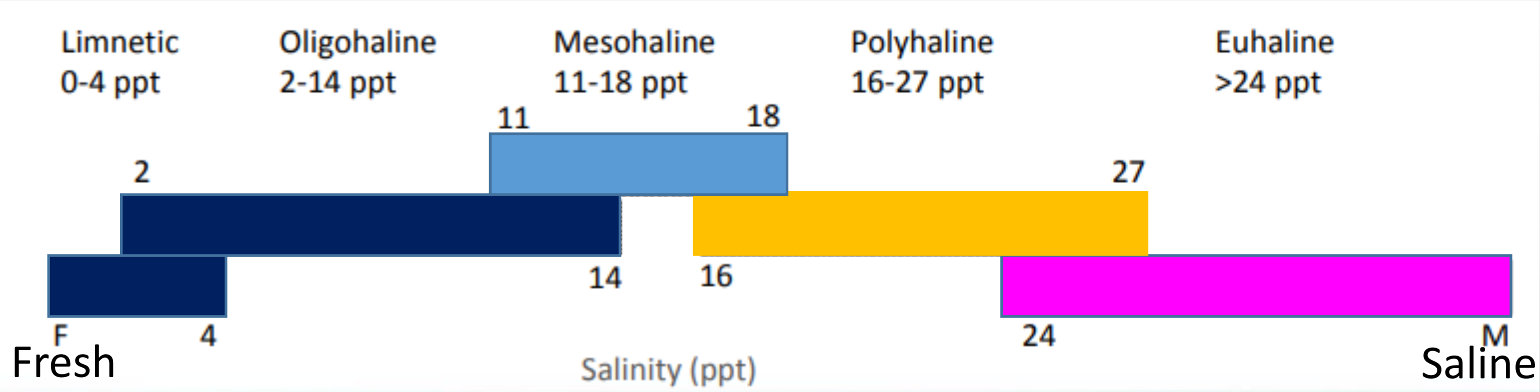
Simulation Details

- Two simulations
  - With storm forcing – atmospheric forcing and changing river discharges
  - Without storm forcing – no atmospheric forcing and constant river discharges



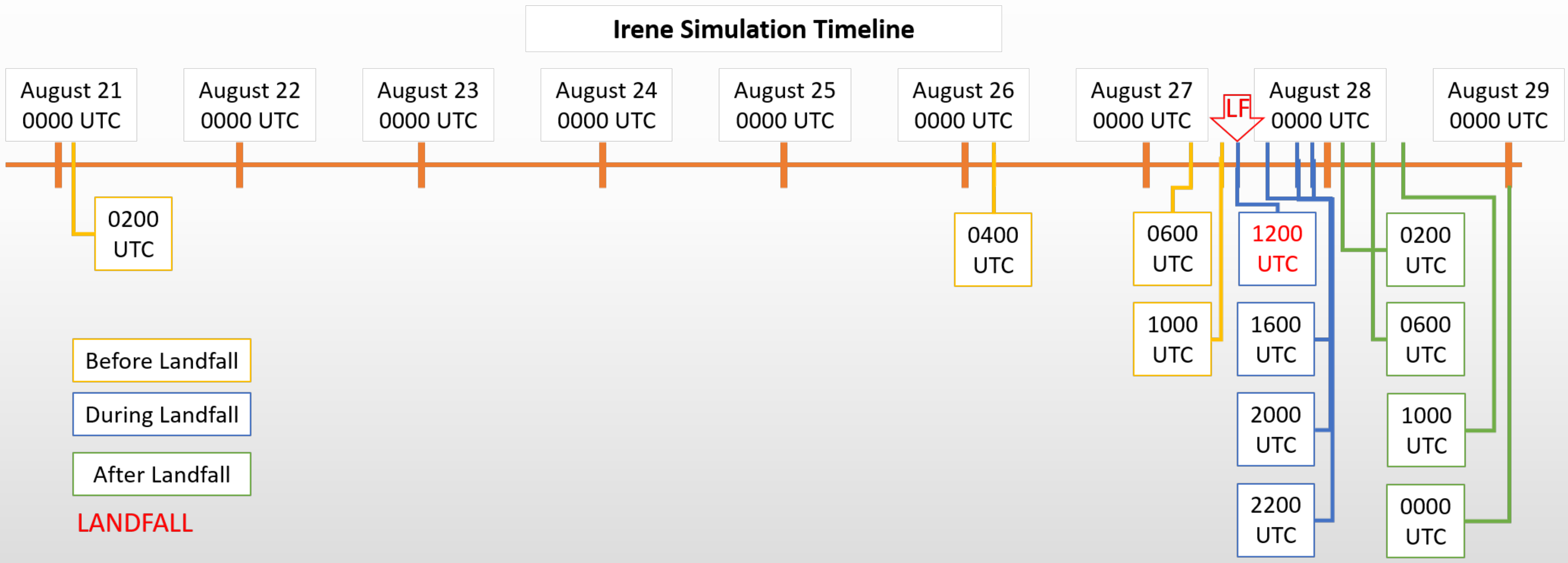
Analysis Methods

- Biologically-based salinity zones
  - Developed for the Mid-Atlantic region, based off over 300 species
- Focus on mesohaline, polyhaline, euhaline zones
  - Optimal living conditions for blue crabs (polyhaline/euhaline) and oysters (mesohaline/polyhaline/euhaline)
  - Highest commercial revenue for 2019



Results

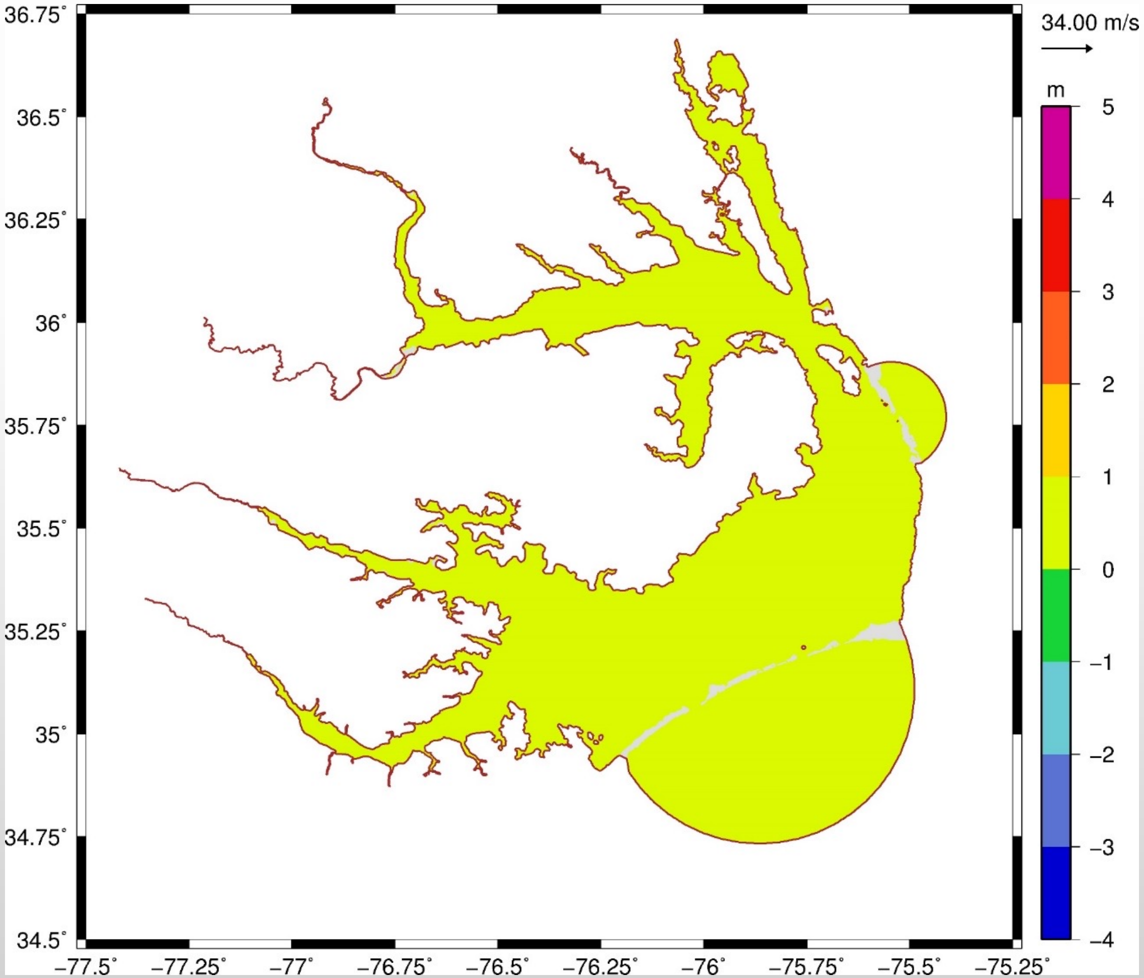
Story of the Storm



Results – Story of the Storm

8/21 8/22 8/23 8/24 8/25 8/26 8/27 8/28 8/29

0200 UTC



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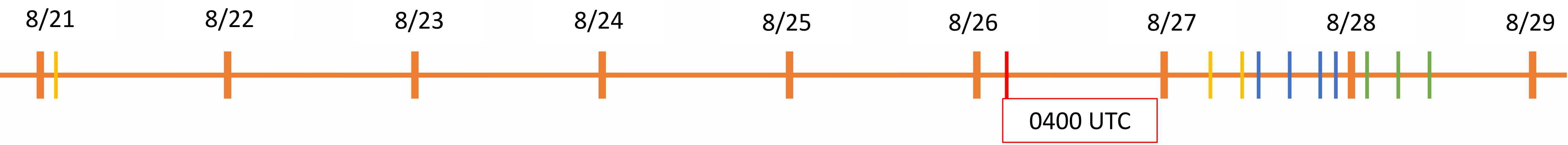
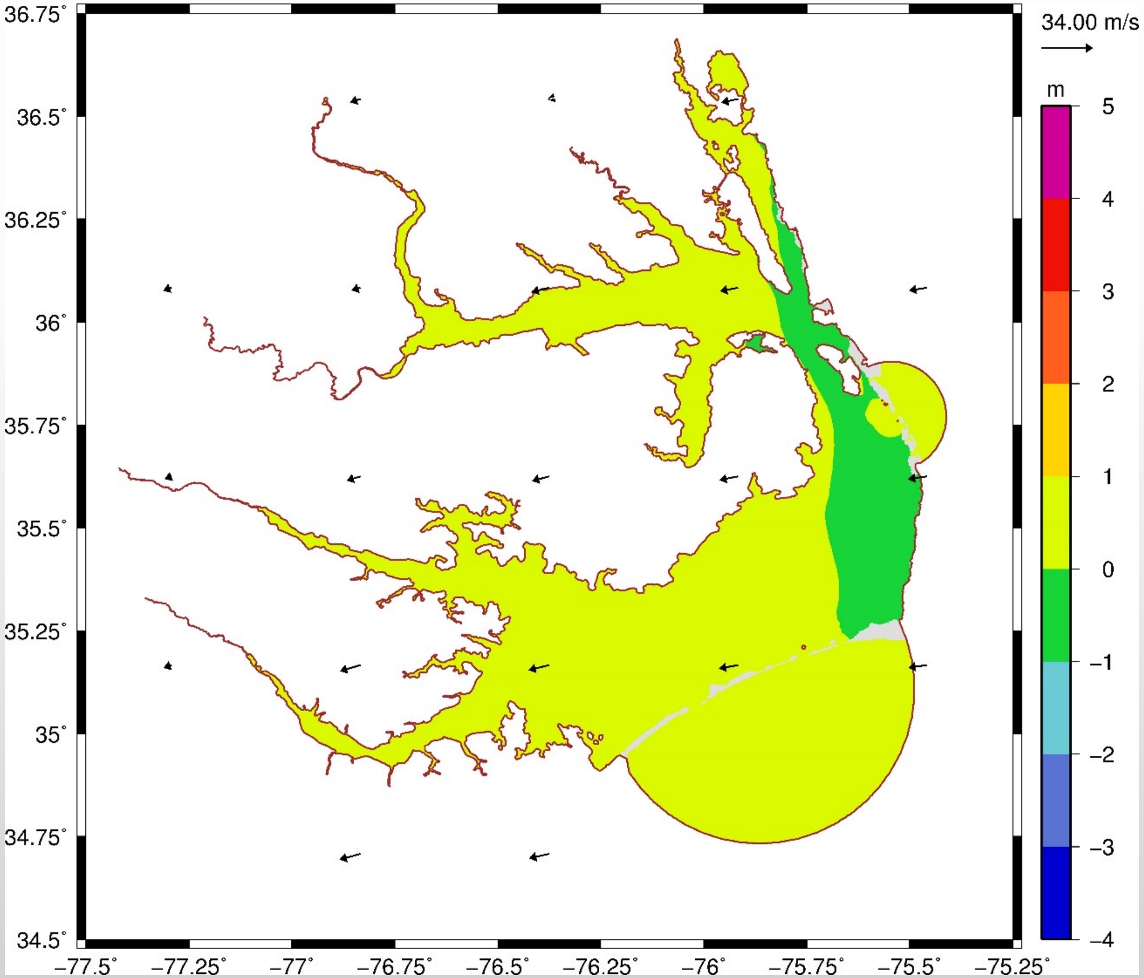
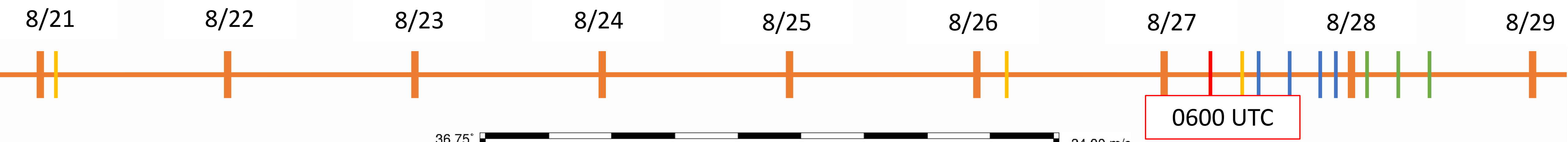
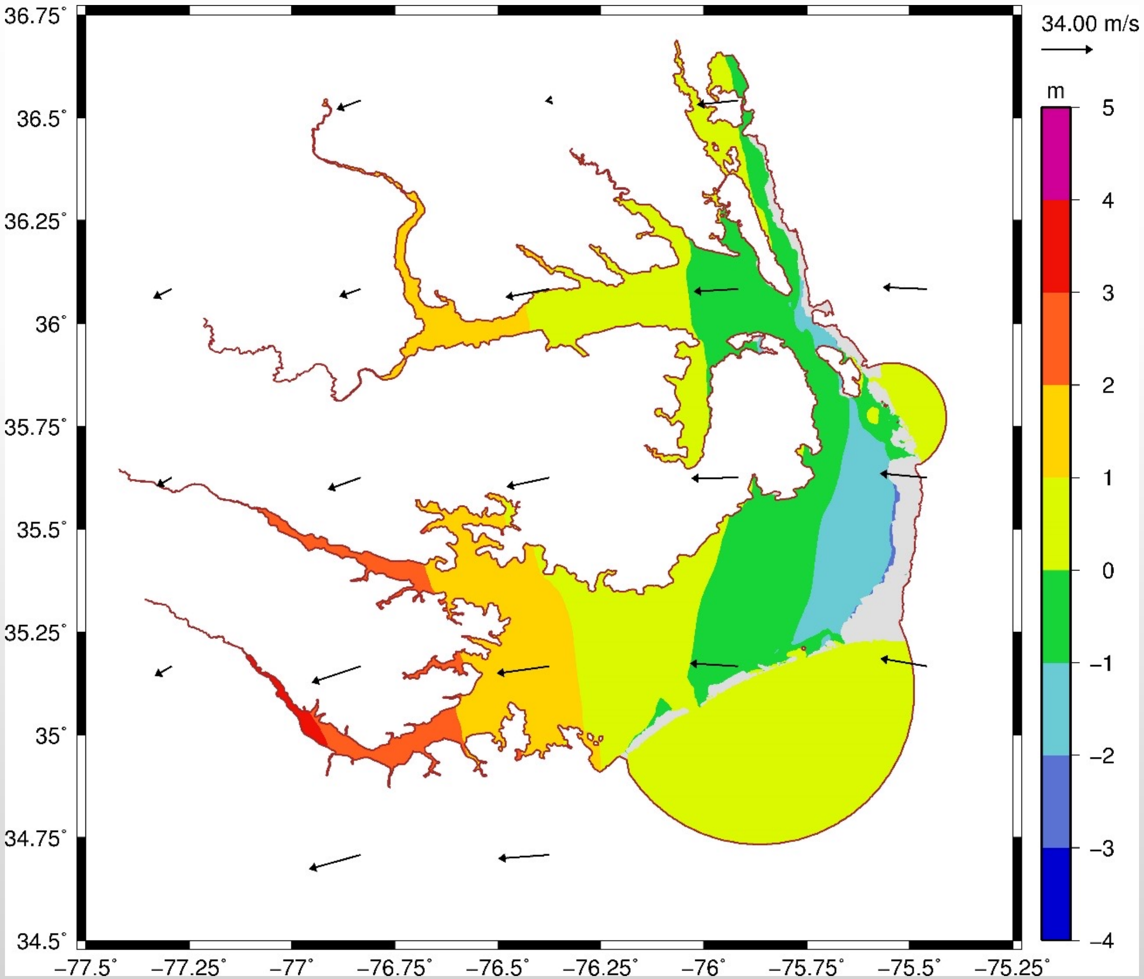




Story of the Storm





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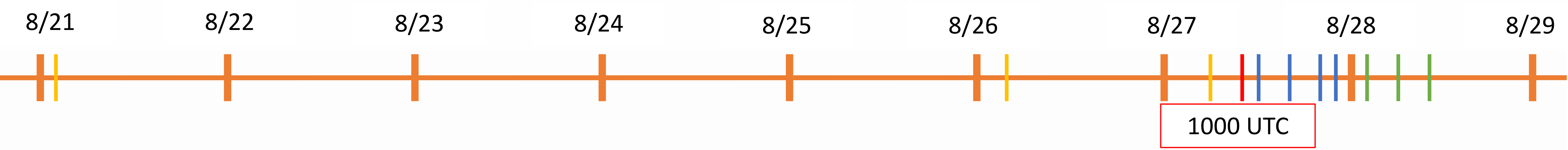

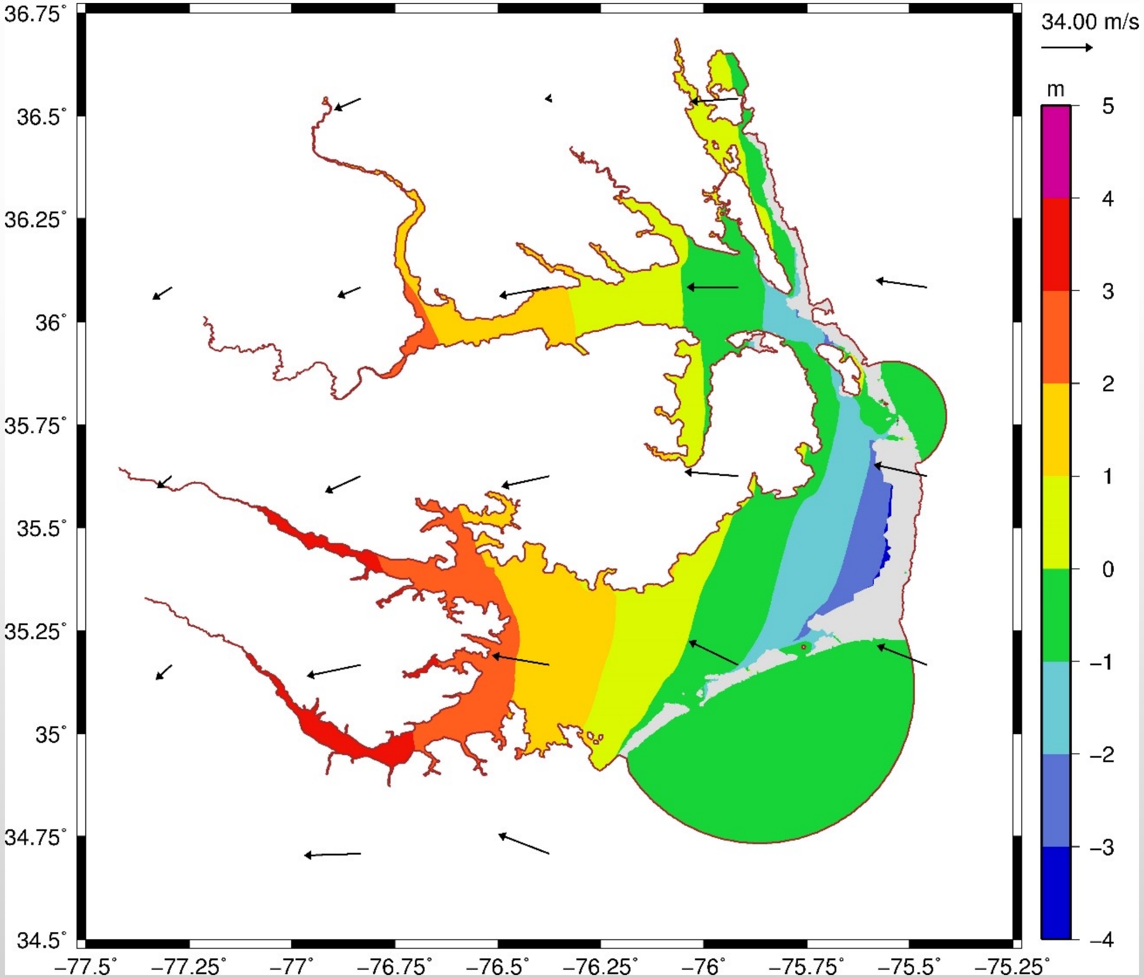

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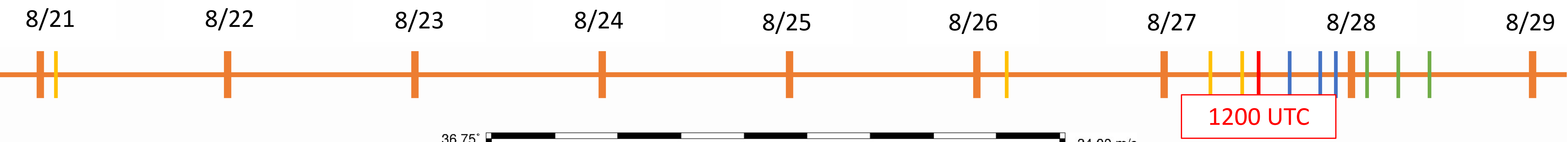

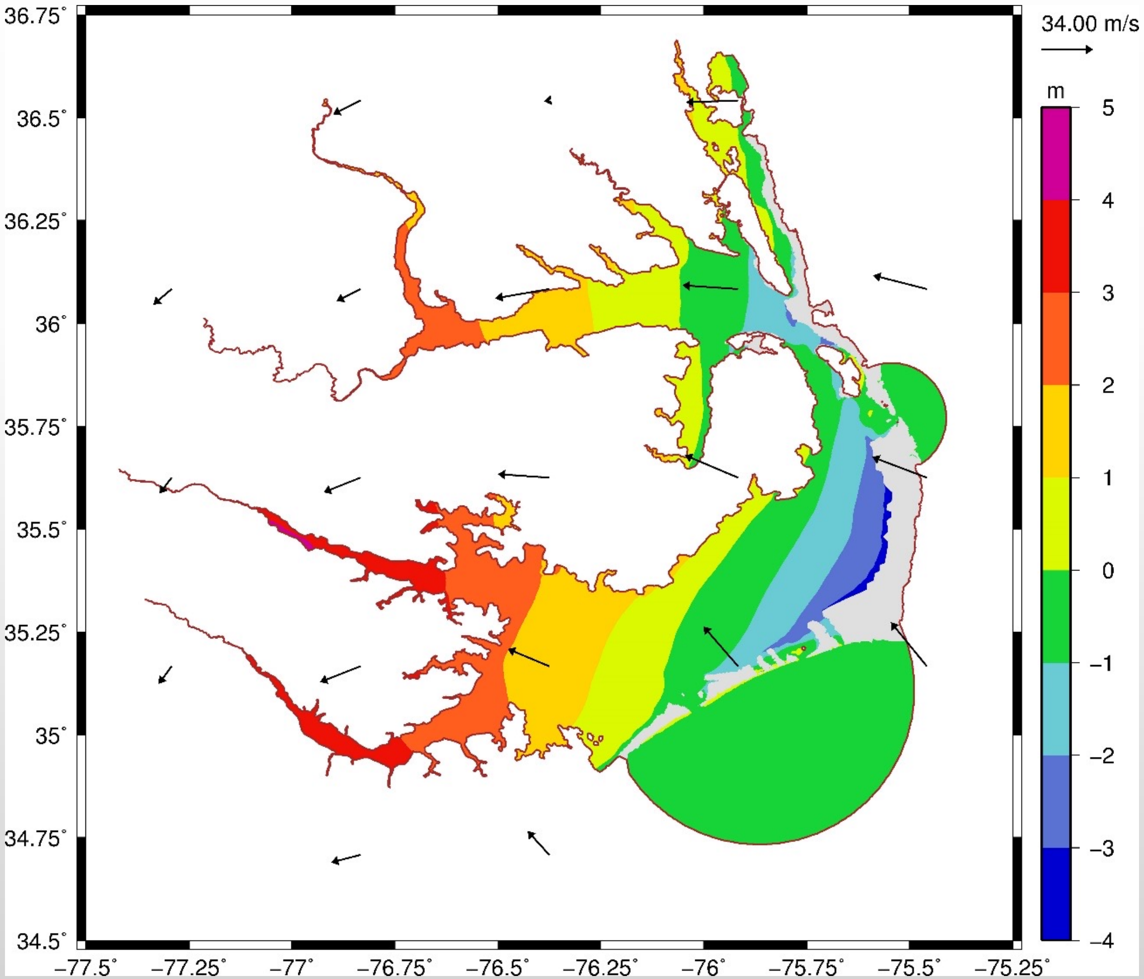

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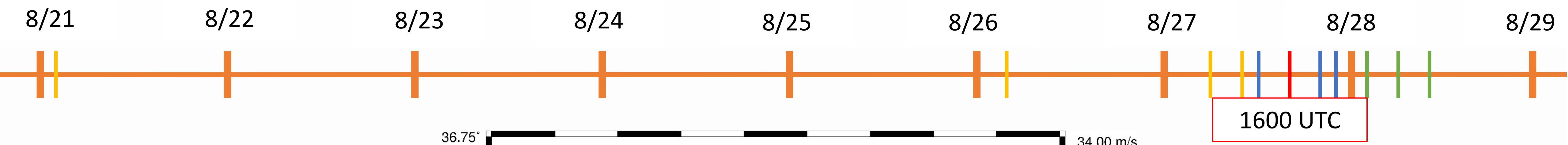
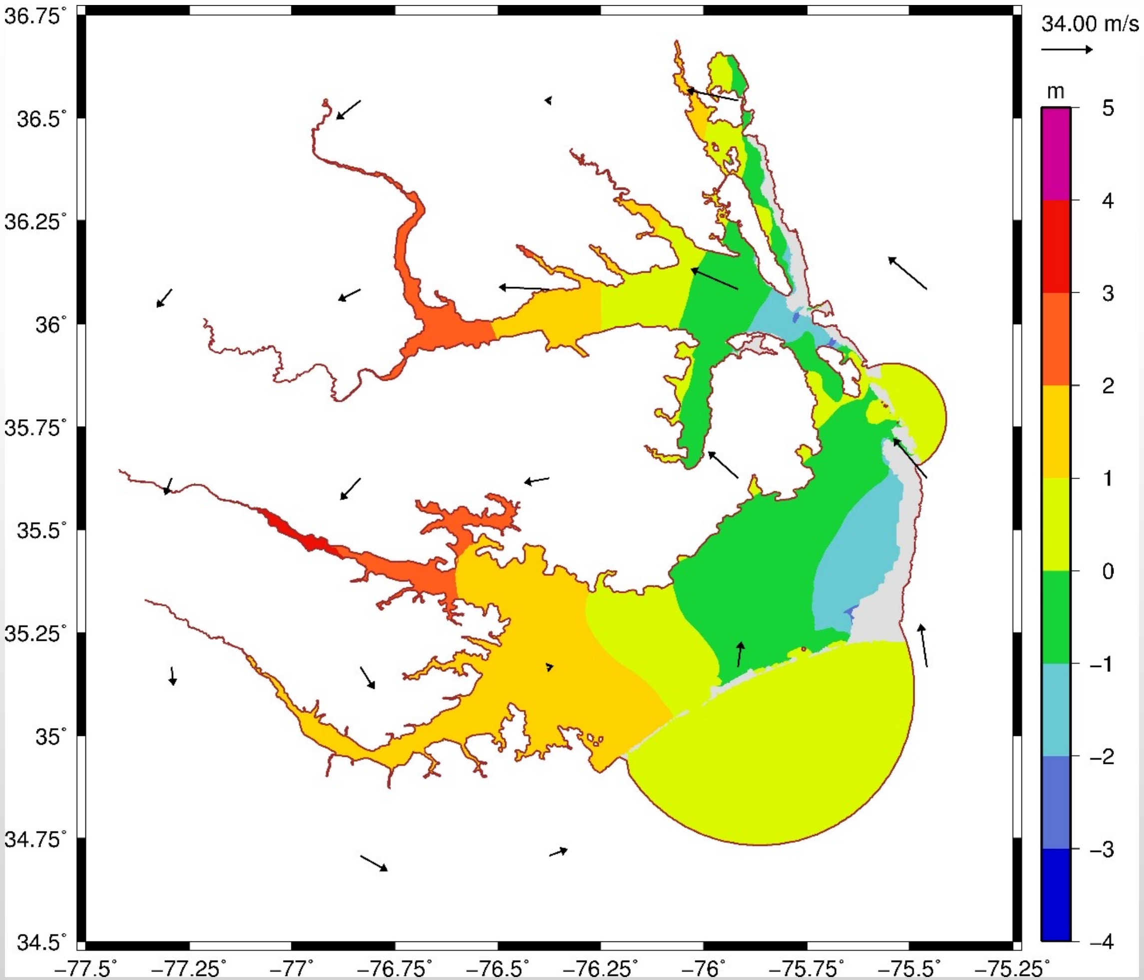
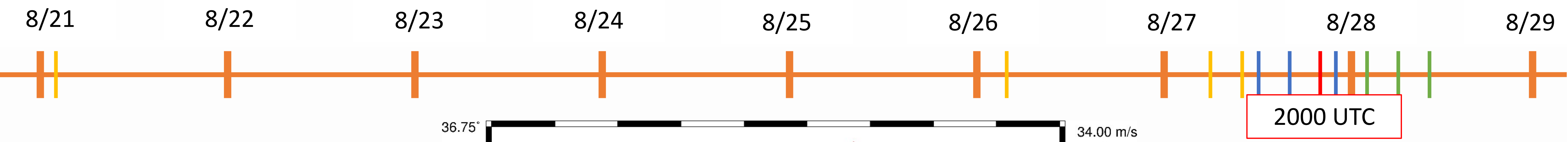
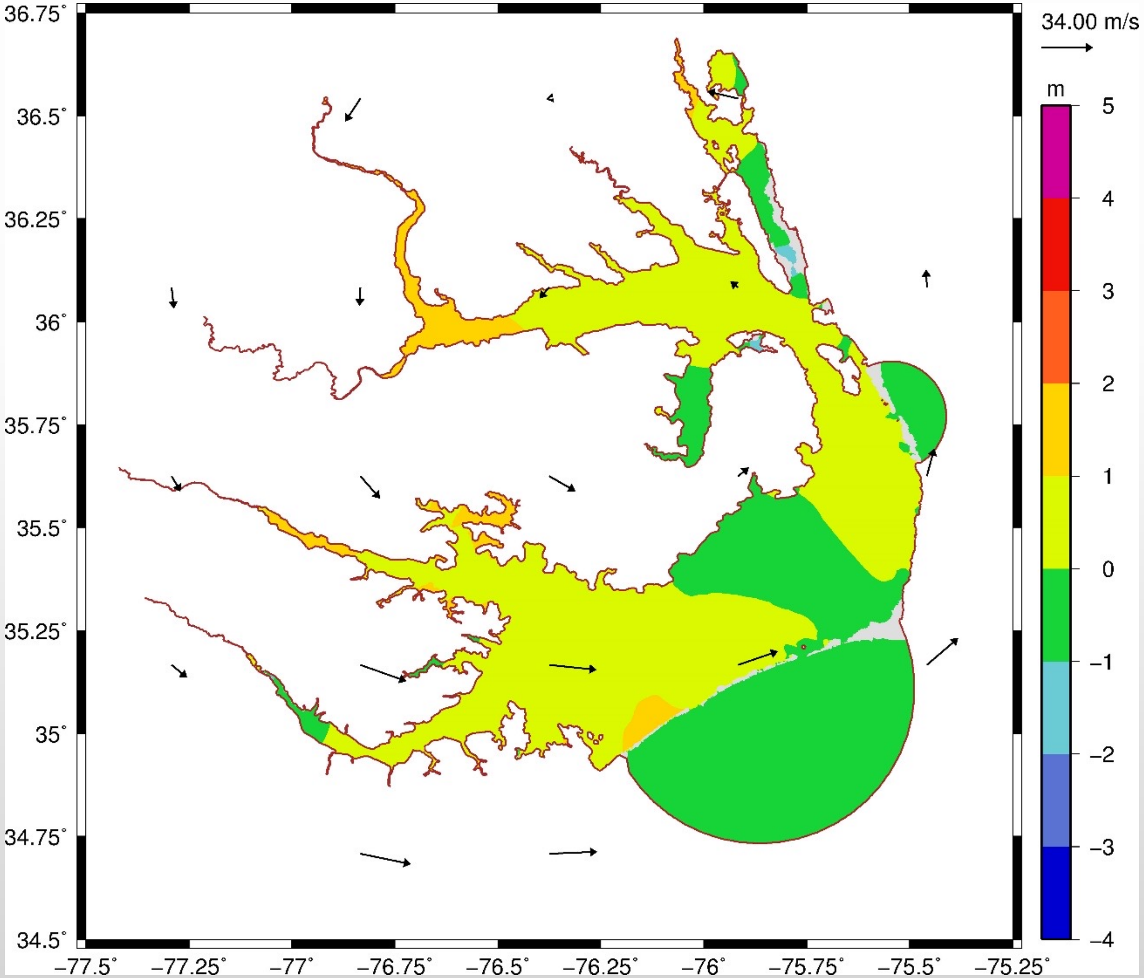


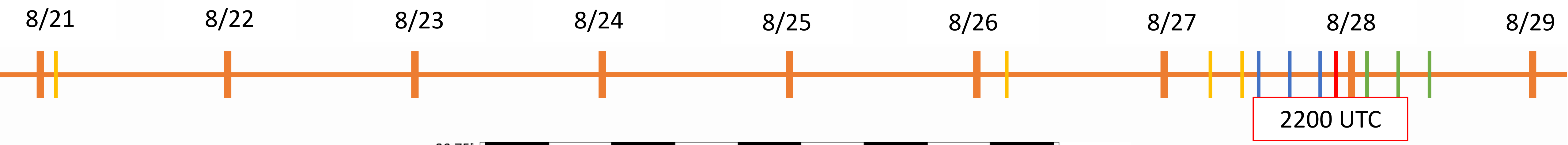


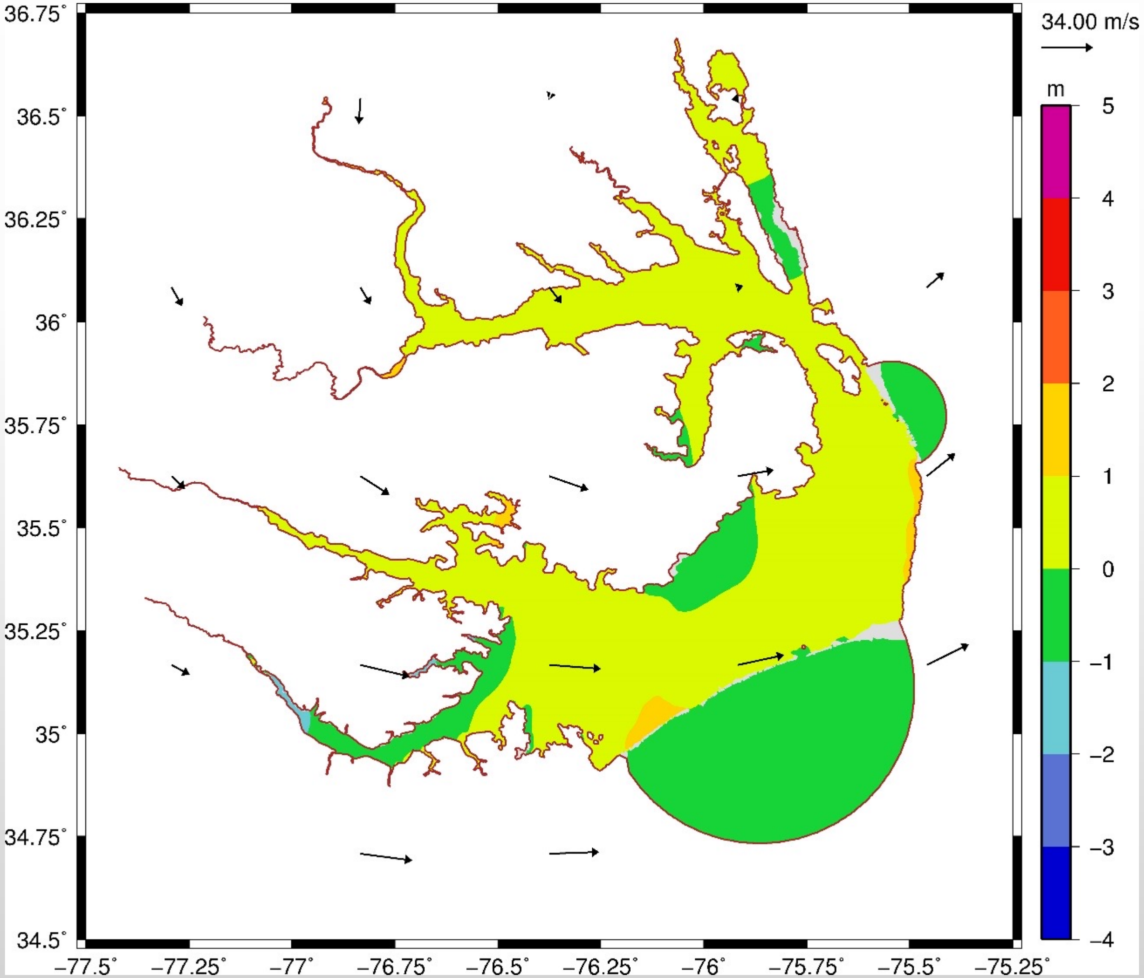
Story of the Storm



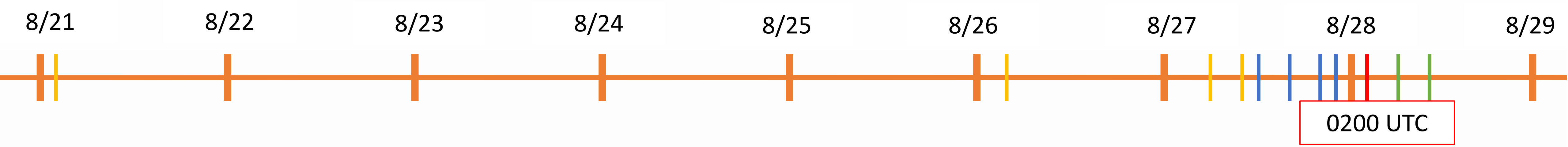


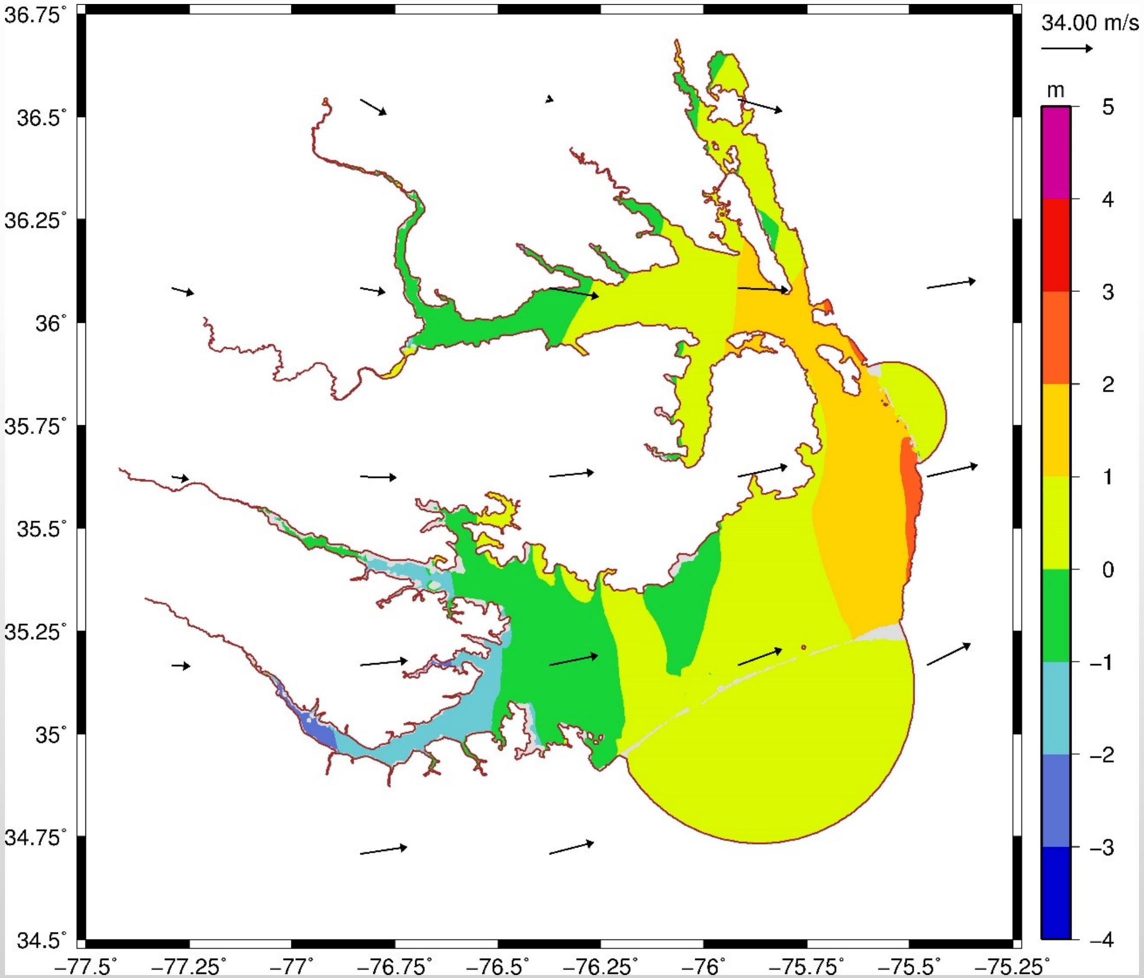
Results – Story of the Storm





Story of the Storm

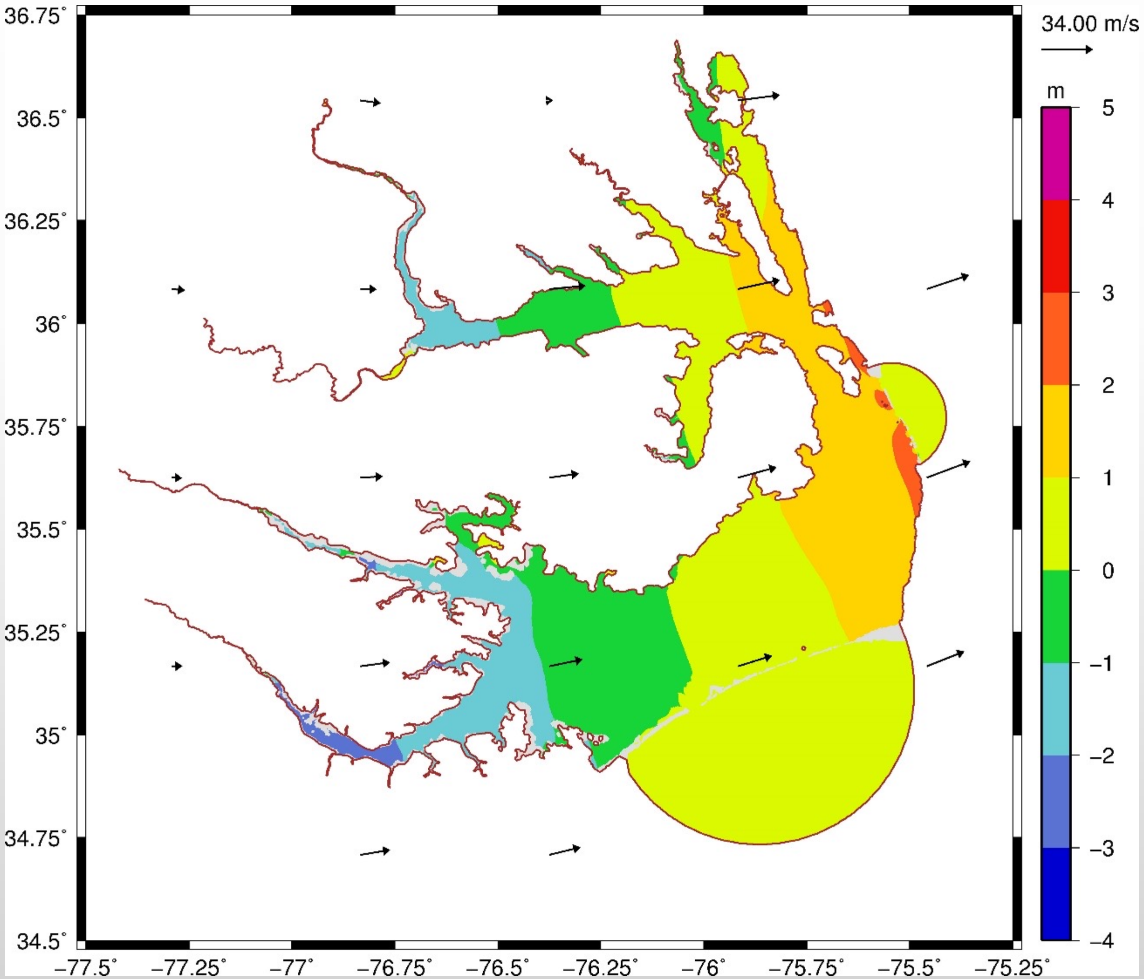




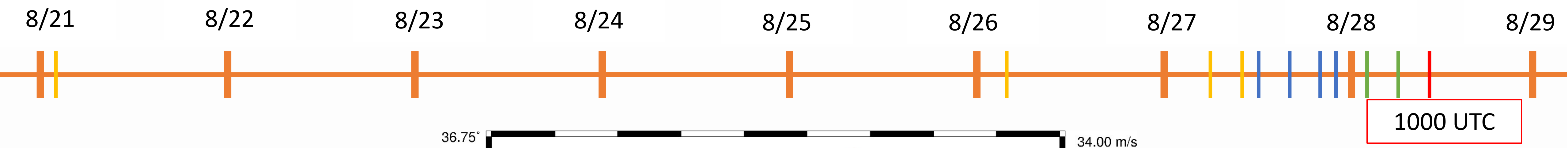
Story of the Storm

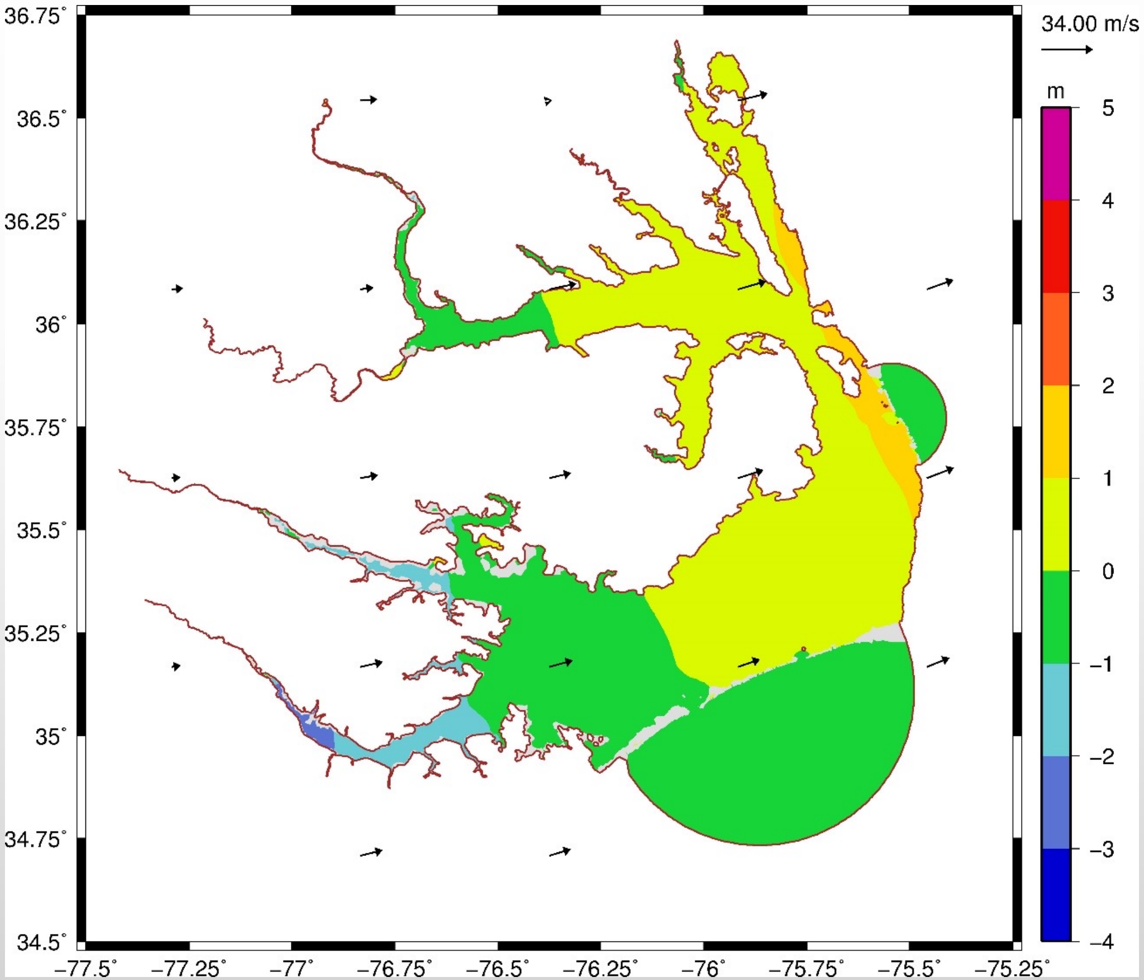
8/21 8/22 8/23 8/24 8/25 8/26 8/27 8/28 8/29

0600 UTC



Story of the Storm

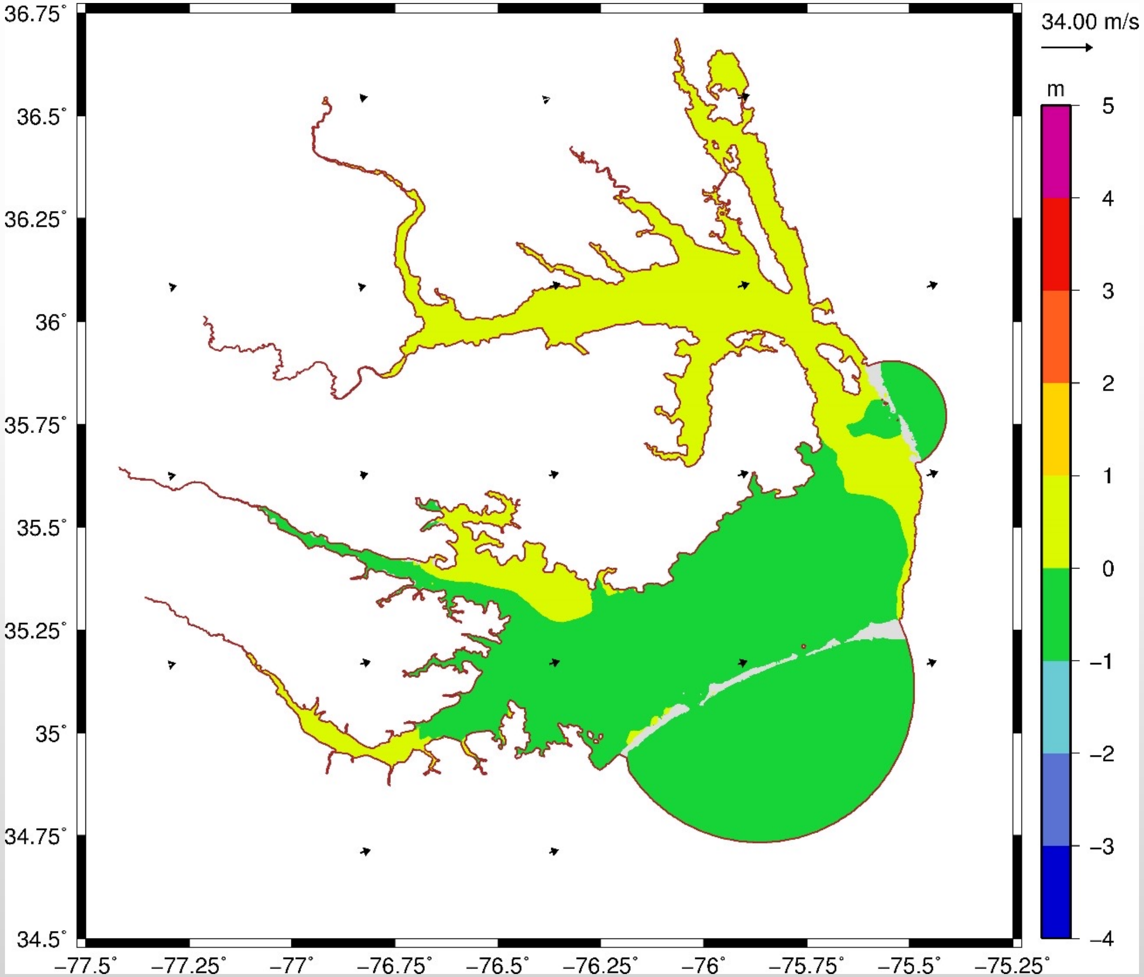




Story of the Storm

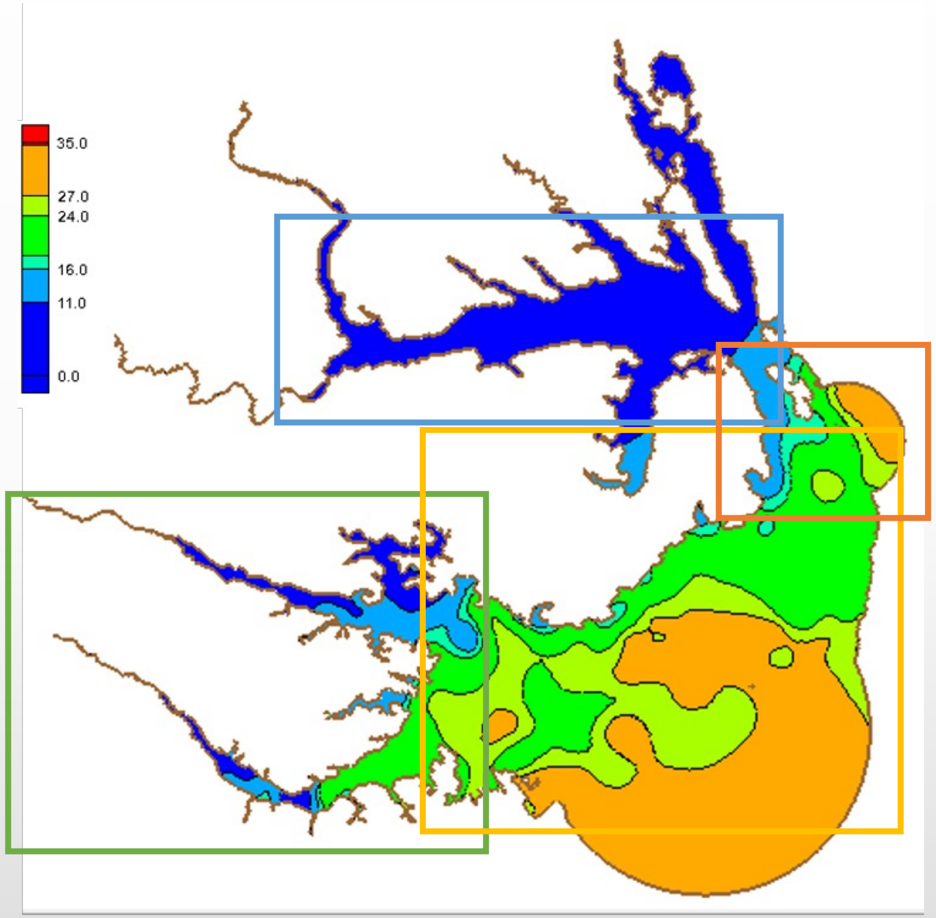
8/21 8/22 8/23 8/24 8/25 8/26 8/27 8/28 8/29

0000 UTC

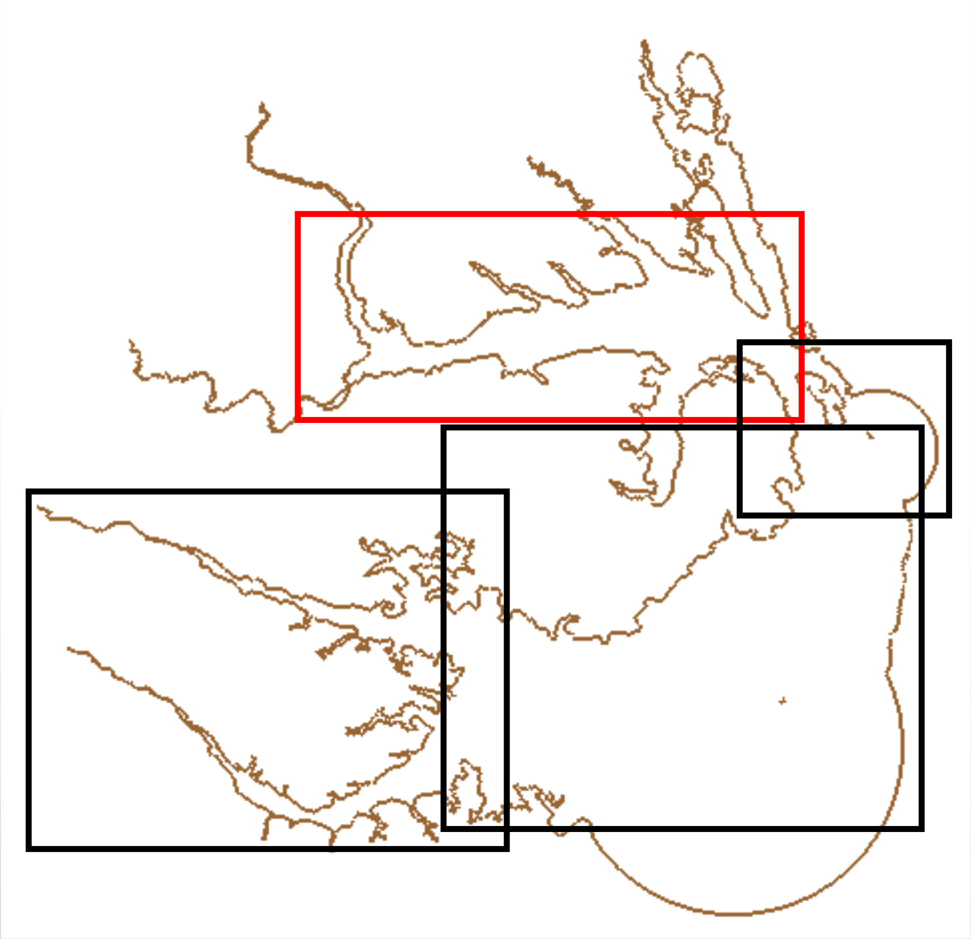


Sub-regions

- Average August Distribution
- Divide into 4 sub-regions
  - Albemarle Sound
  - Pamlico Sound, Hatteras & Ocracoke Inlets
  - Roanoke Island & Oregon Inlet
  - Tar-Pamlico & Neuse Rivers

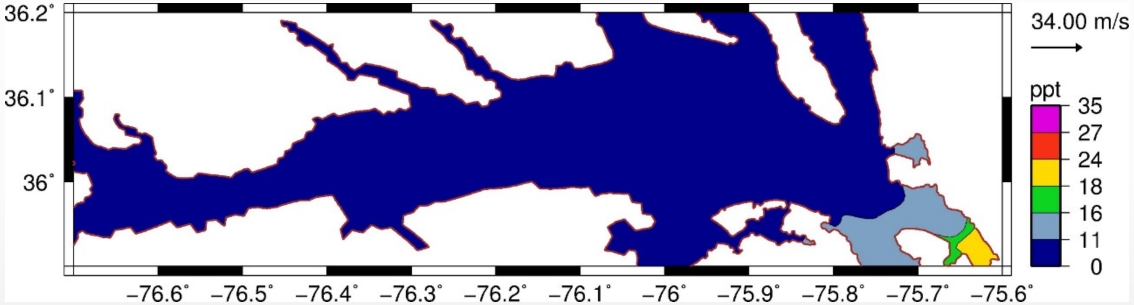


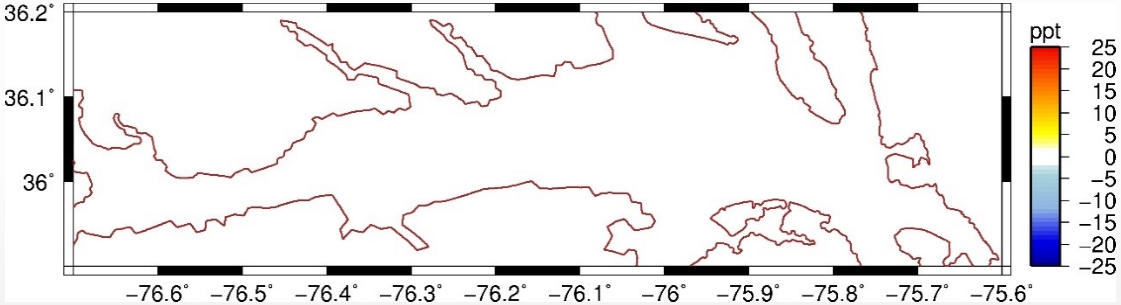
Sub-regions



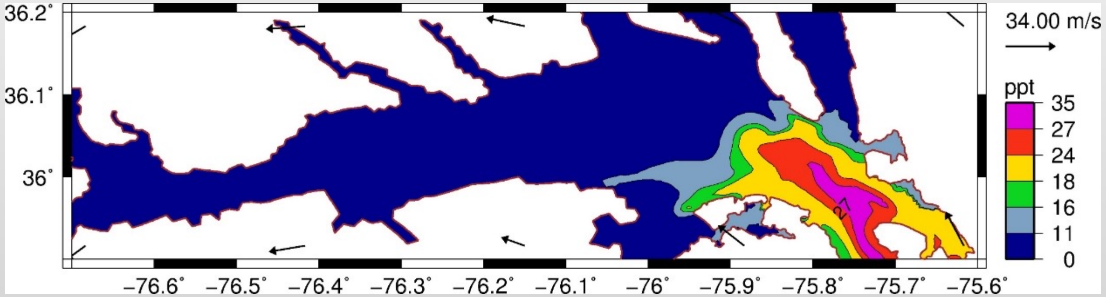
Albemarle Sound

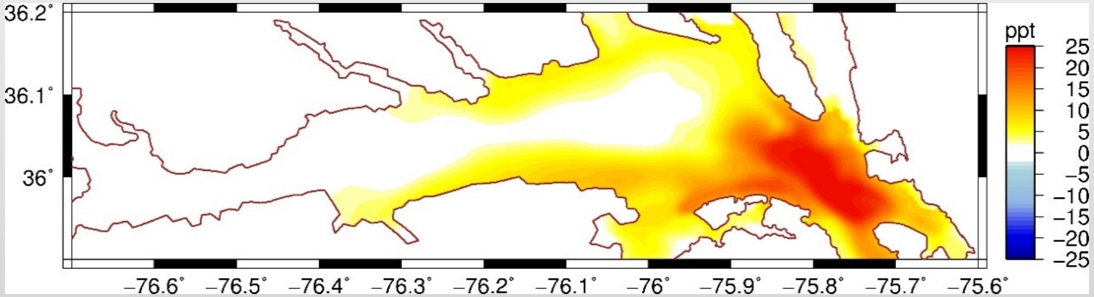
0200 UTC 21 August



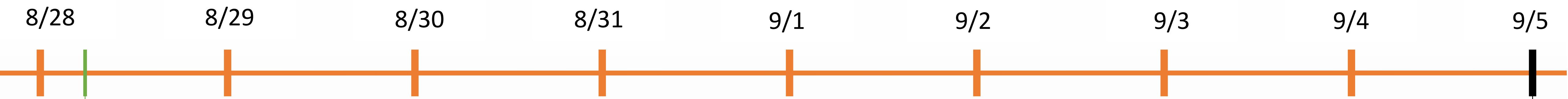


1800 UTC 27 August

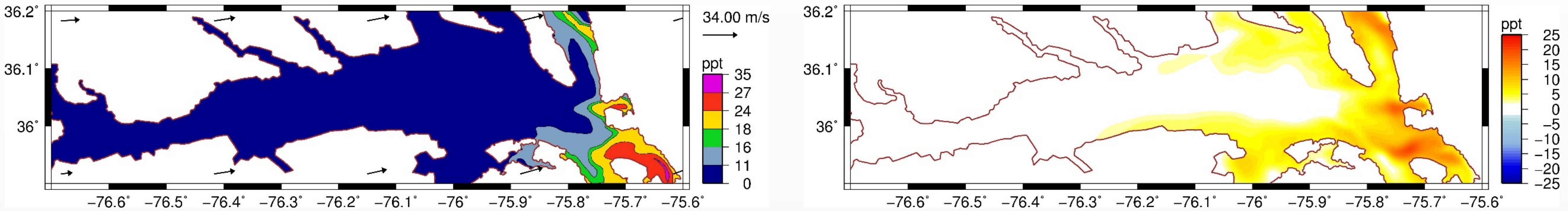




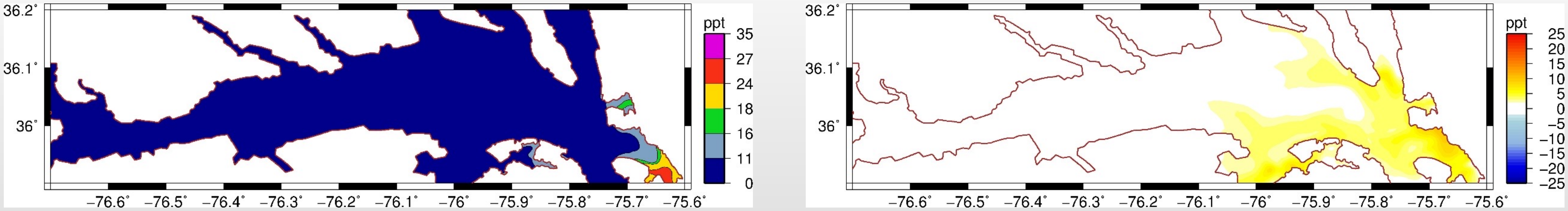
Albemarle Sound



0800 UTC 28 August

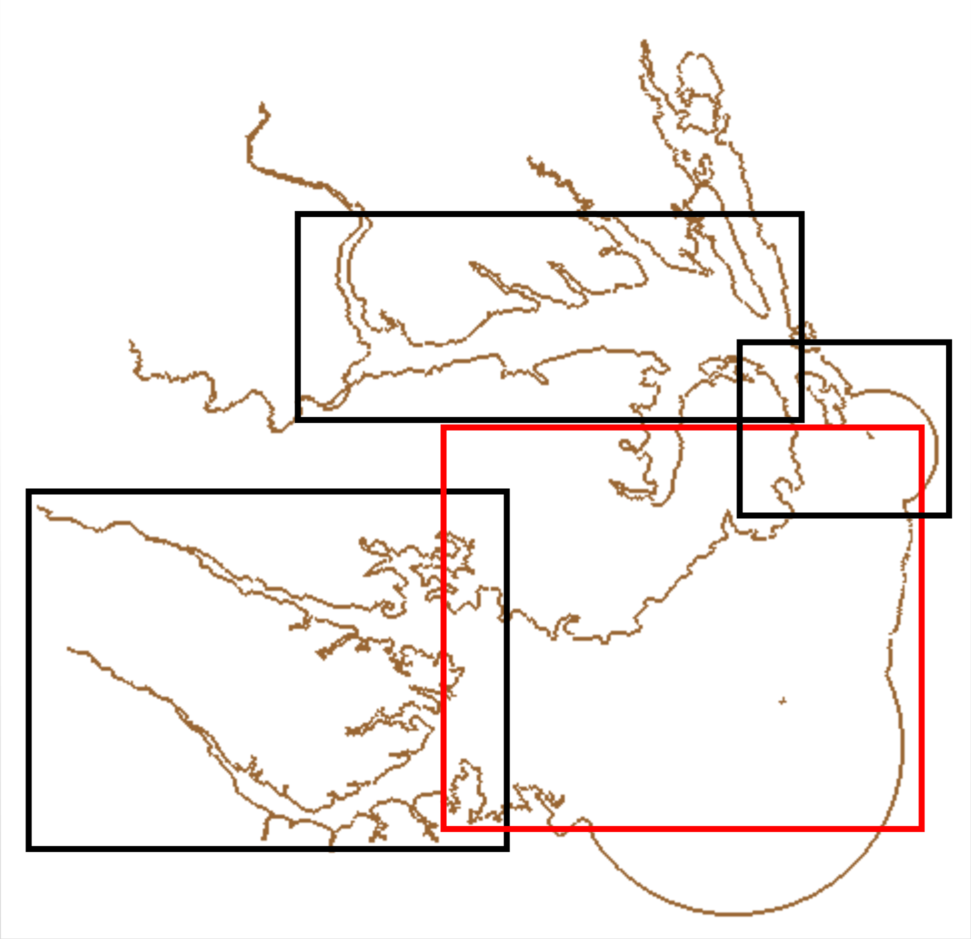


0000 UTC 5 September

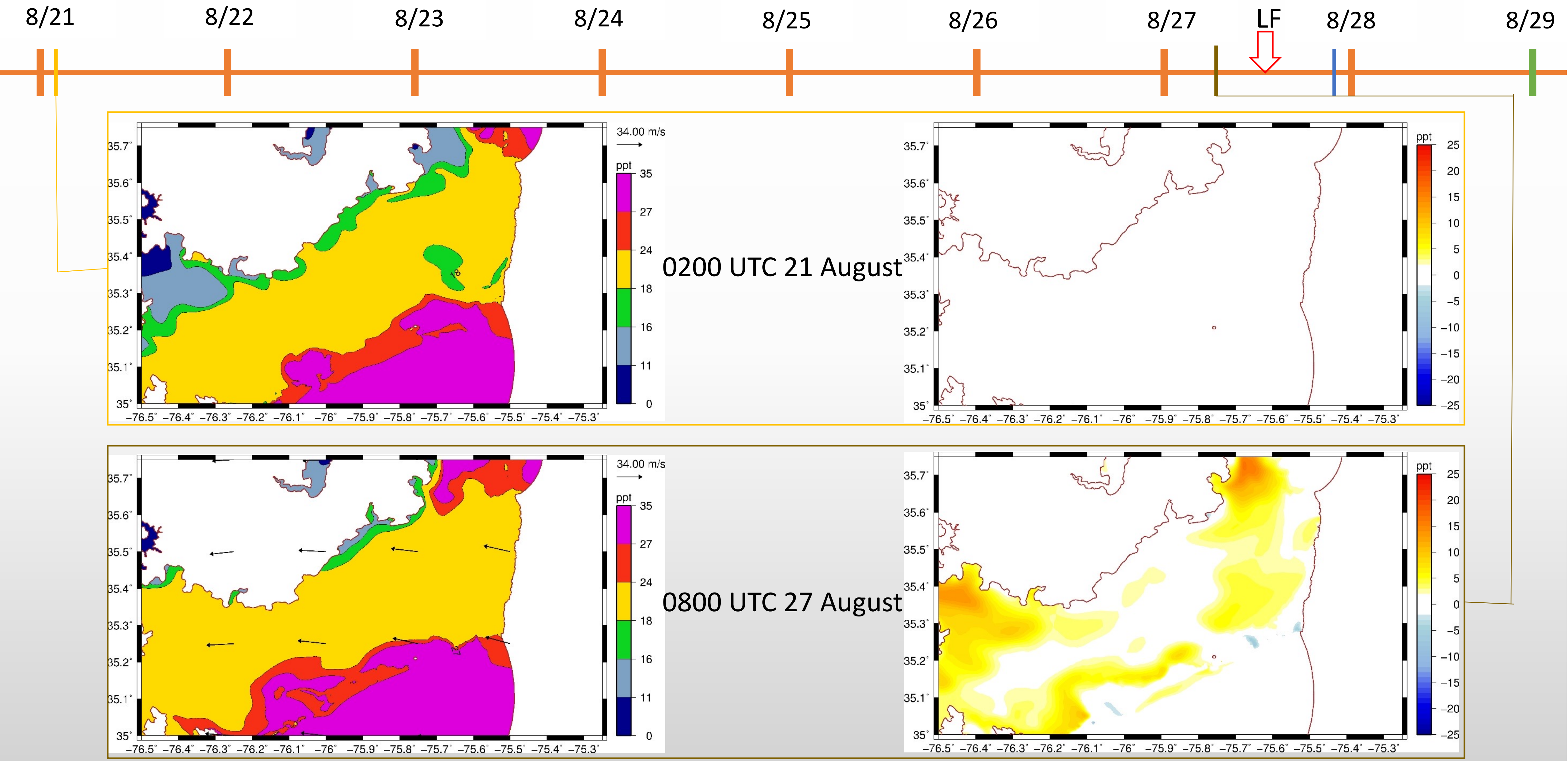


- Eastern experienced up to 24 ppt range of salinities
- Western experienced differences less than 1.89 ppt

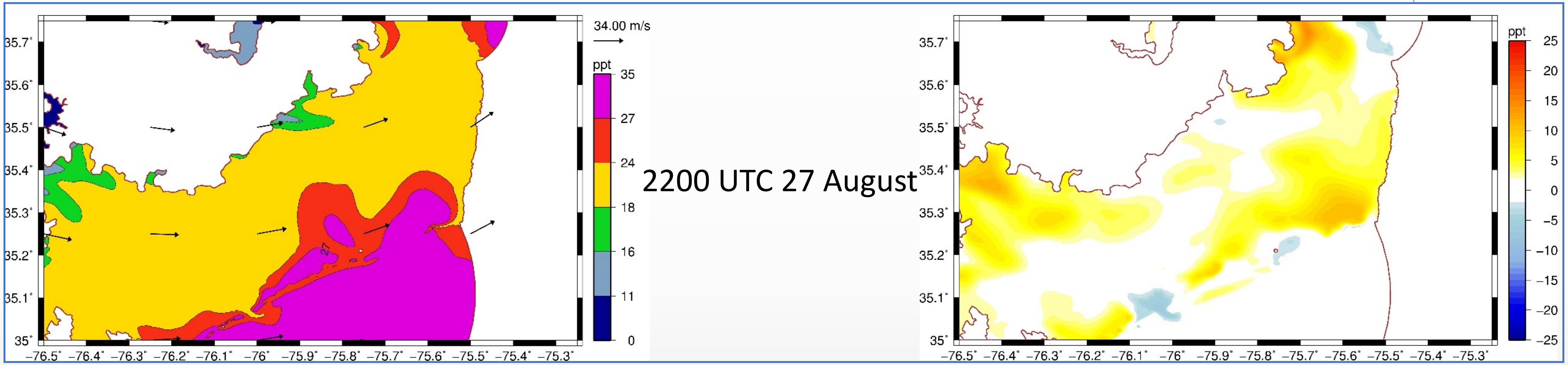
Sub-regions

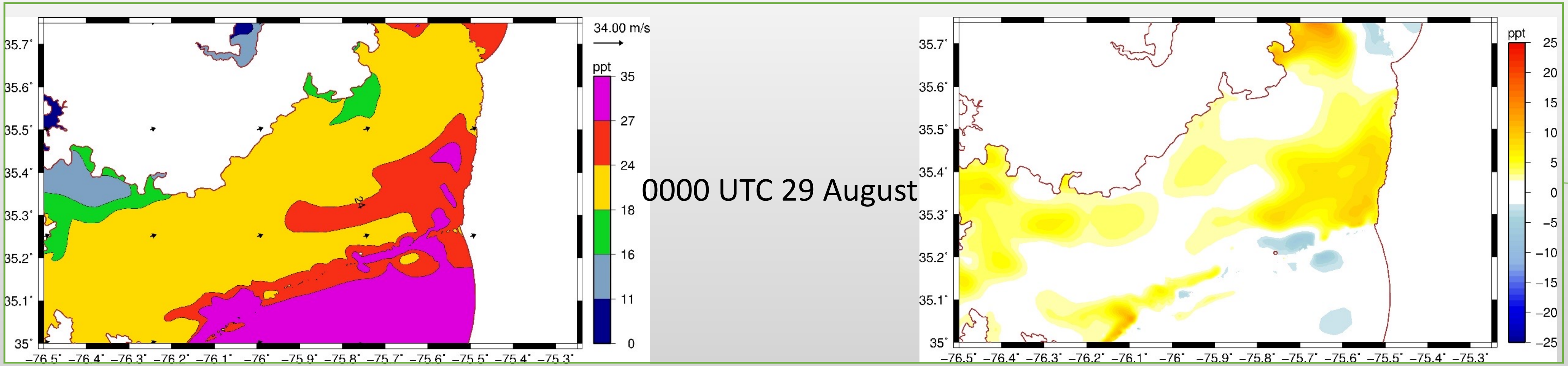


Pamlico Sound, Hatteras & Ocracoke Inlets

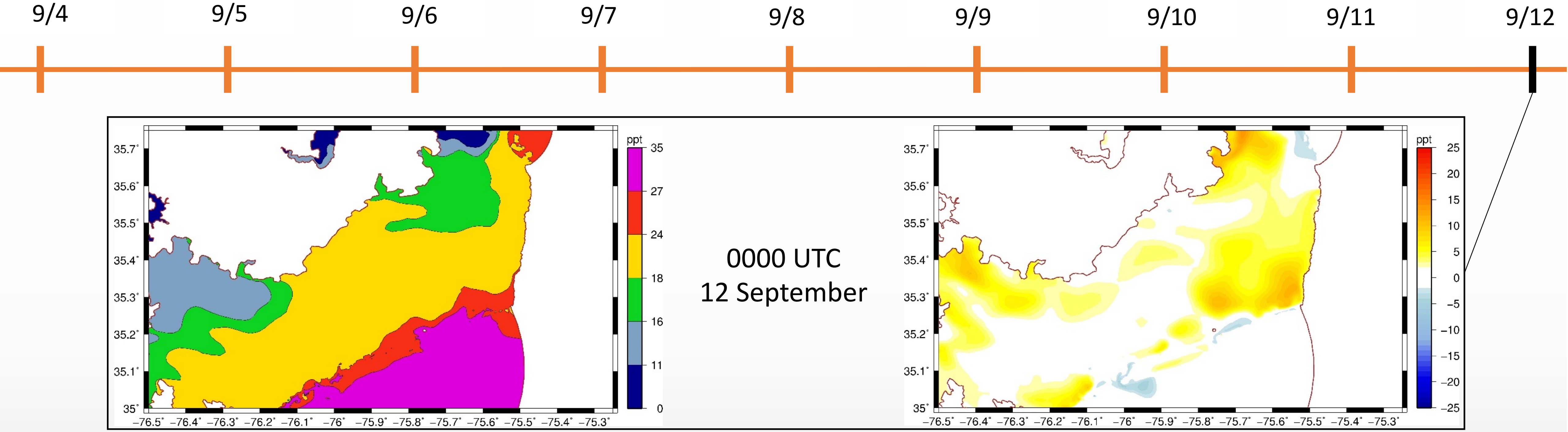


Pamlico Sound, Hatteras & Ocracoke Inlets



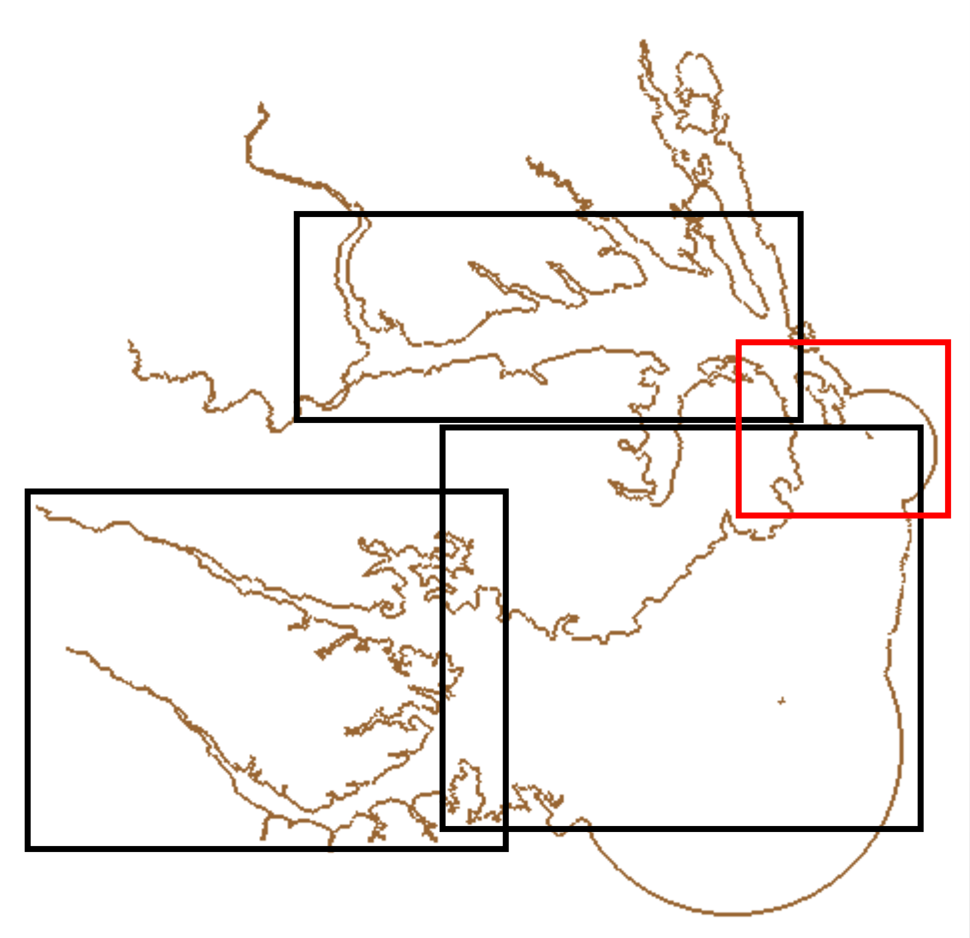


Pamlico Sound, Hatteras & Ocracoke Inlets

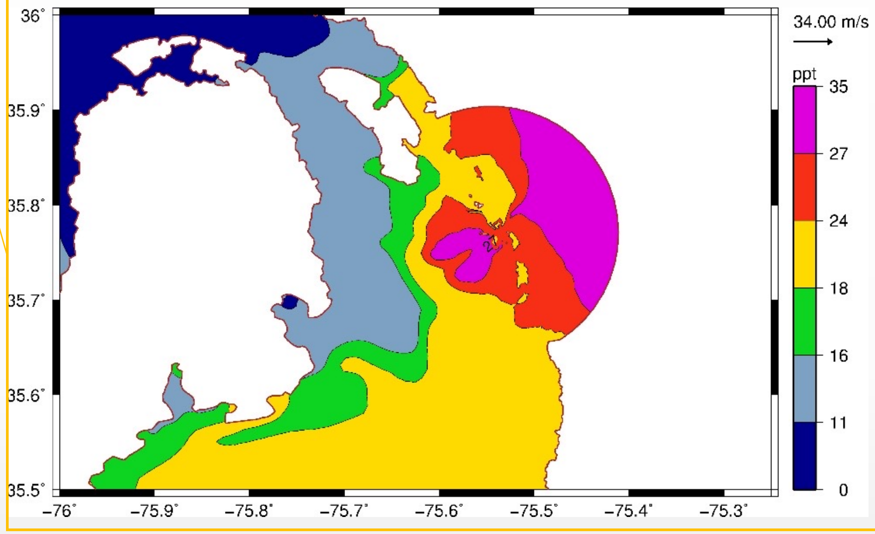


- Experienced differences less than 7 ppt in center of sound

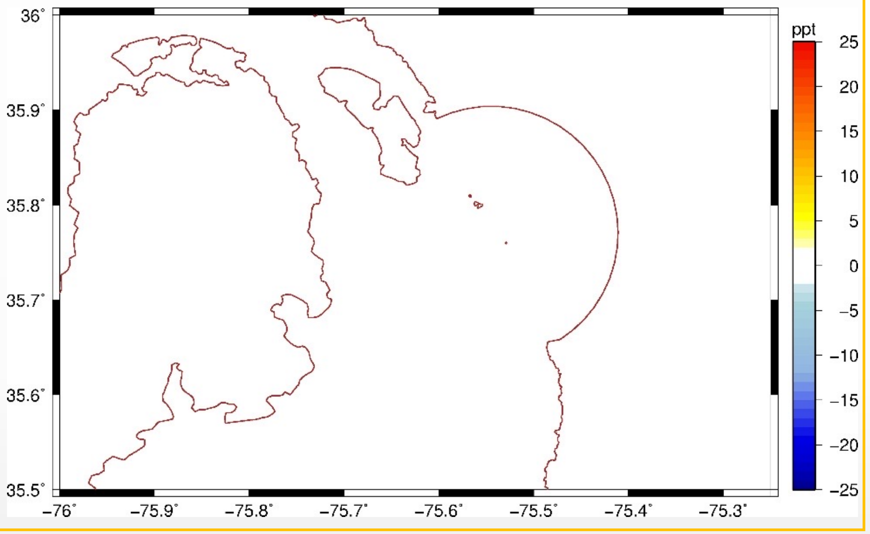
Sub-regions

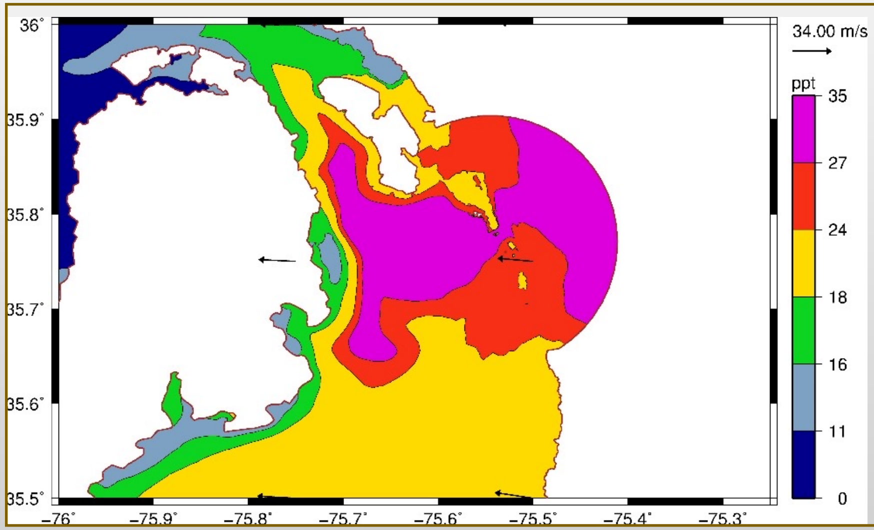


Roanoke Island & Oregon Inlet

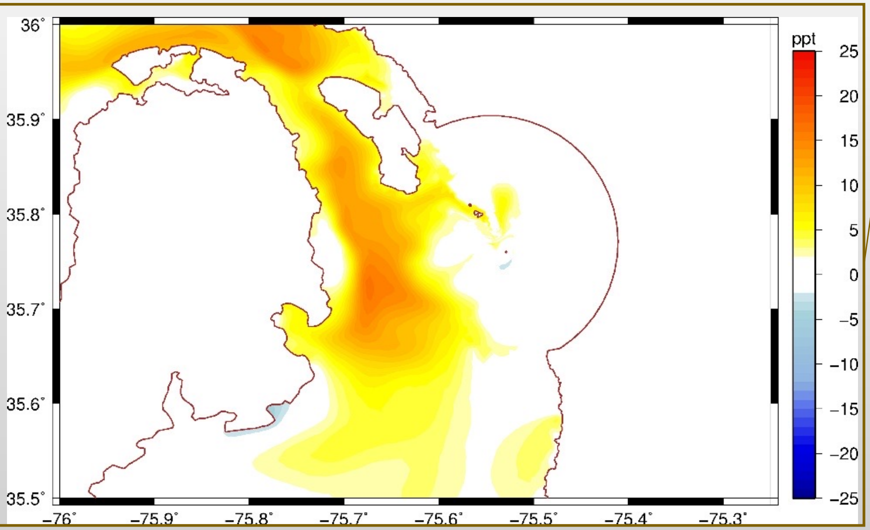


0200 UTC
21 August

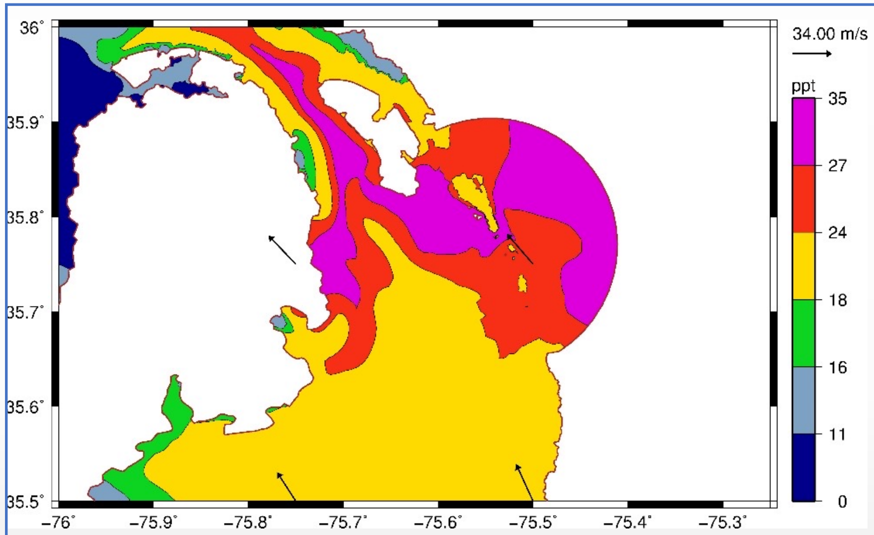




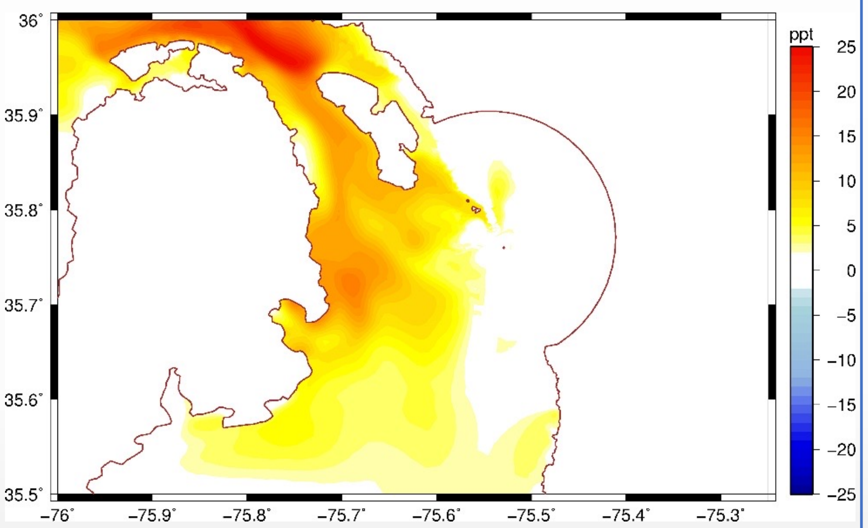
0600 UTC
27 August

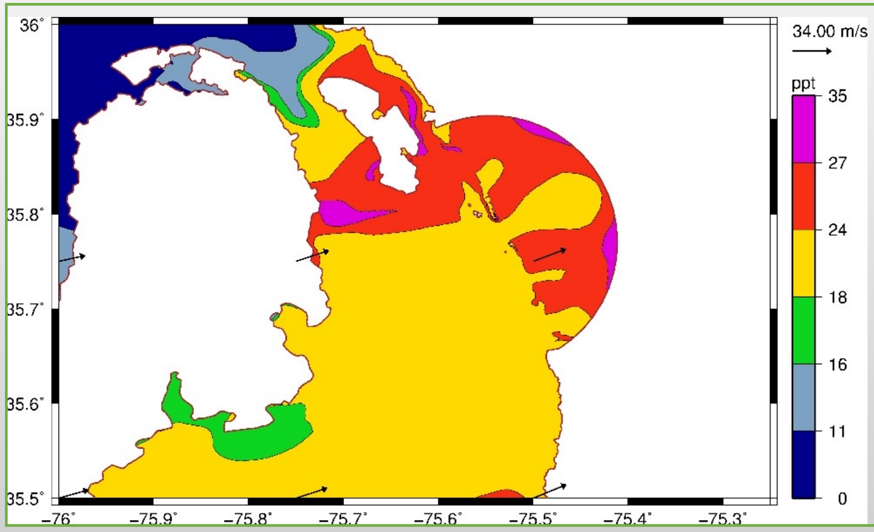


Roanoke Island & Oregon Inlet



1600 UTC
27 August





0600 UTC
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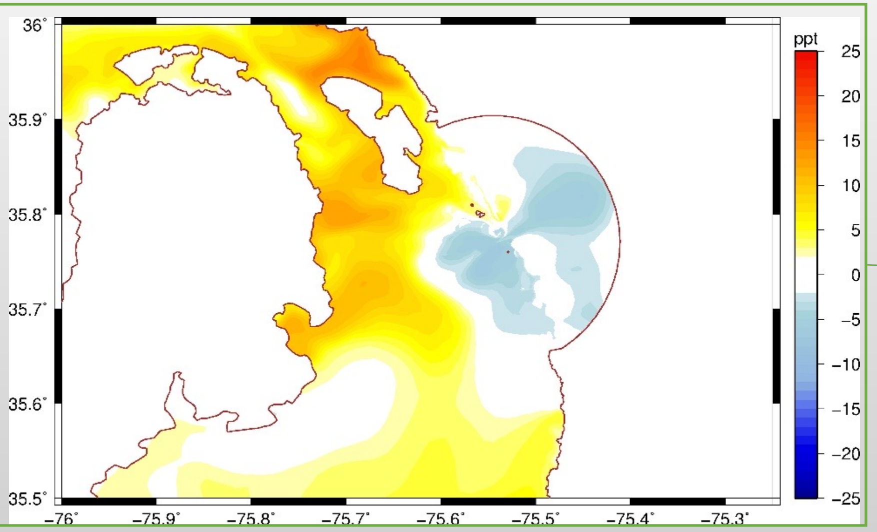
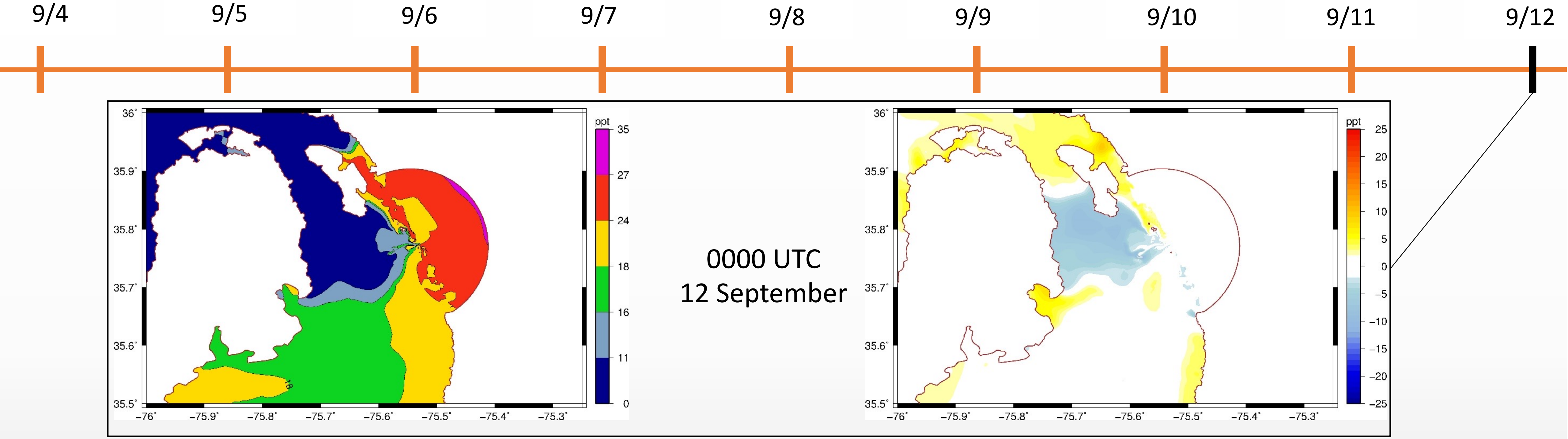
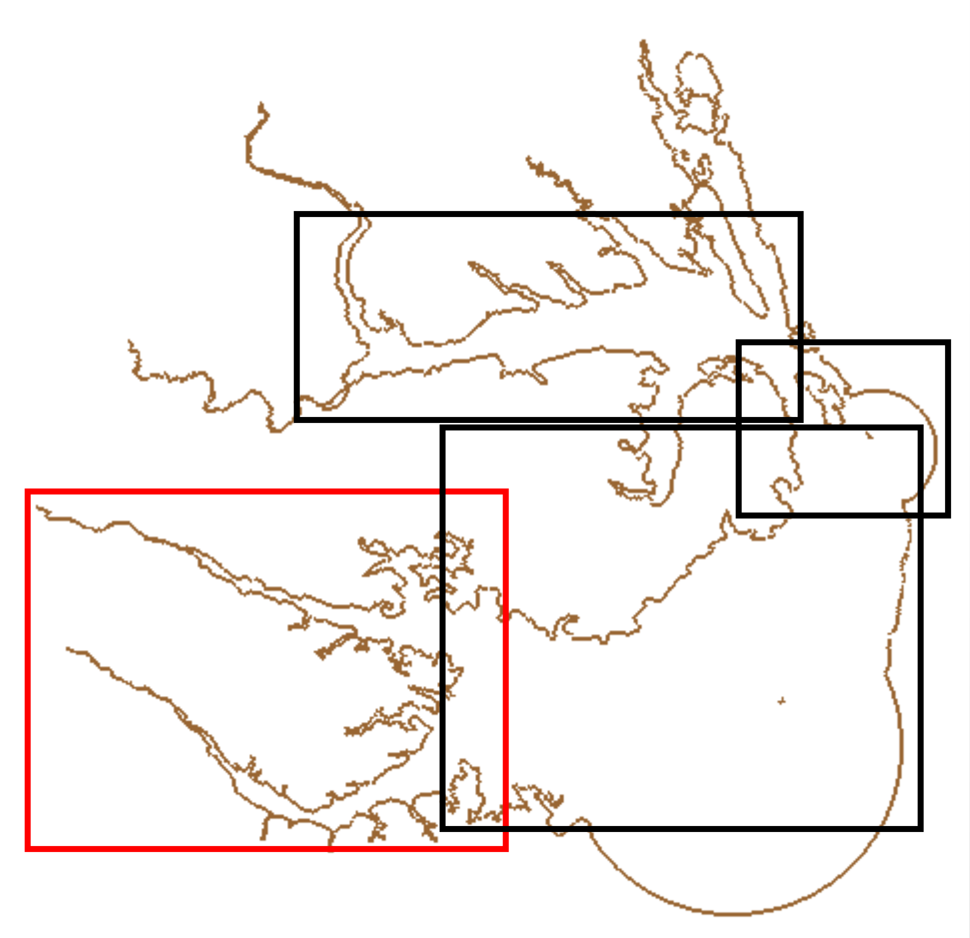


Roanoke Island & Oregon Inlet

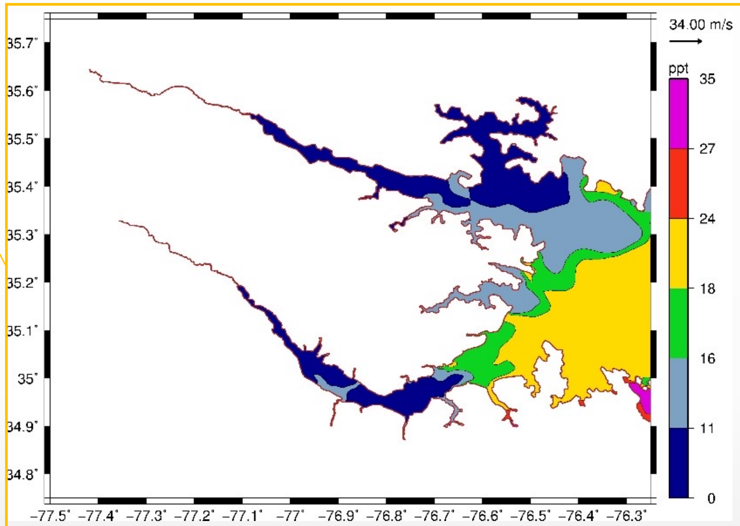


- Northern end: ranges of 20.8 ppt
- Southern end: ranges of 19.56 ppt
- Western side: ranges of 22.34 ppt
- Eastern side: ranges of 8.76 ppt

Sub-regions



Tar-Pamlico & Neuse Rivers



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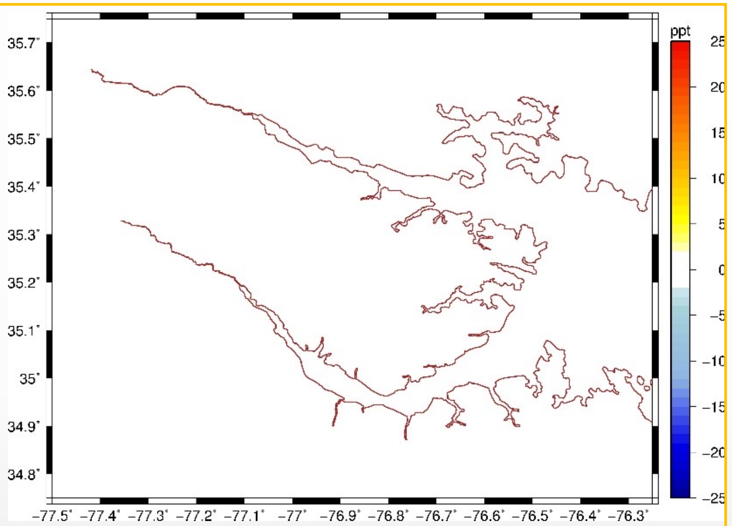
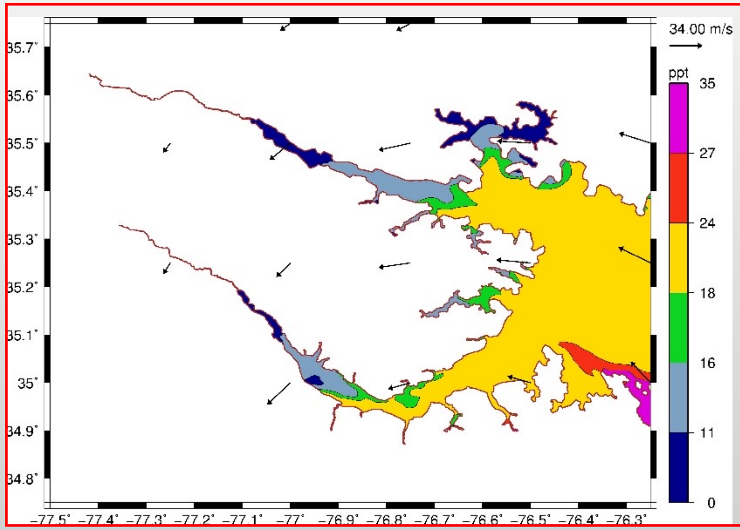
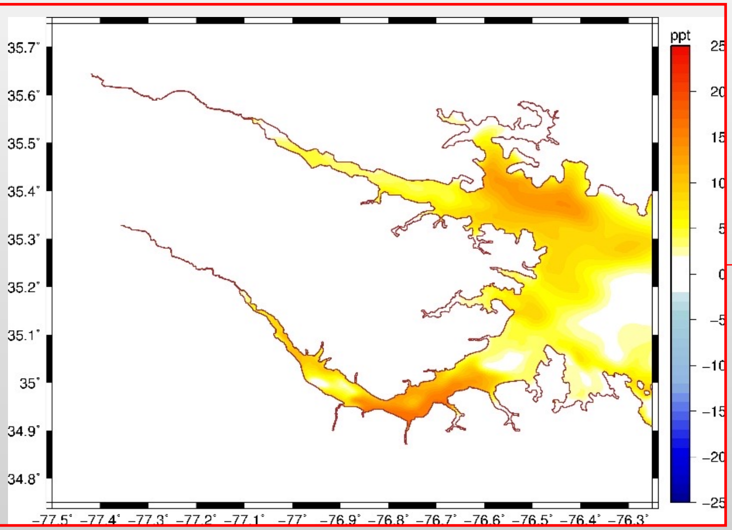
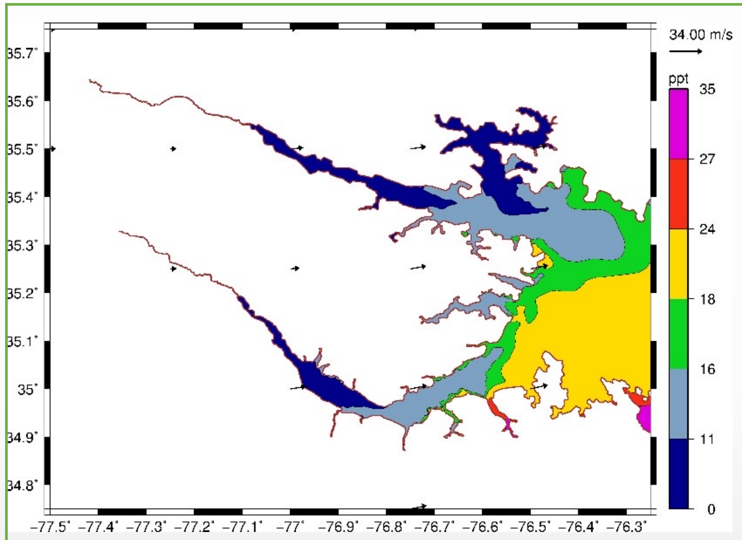




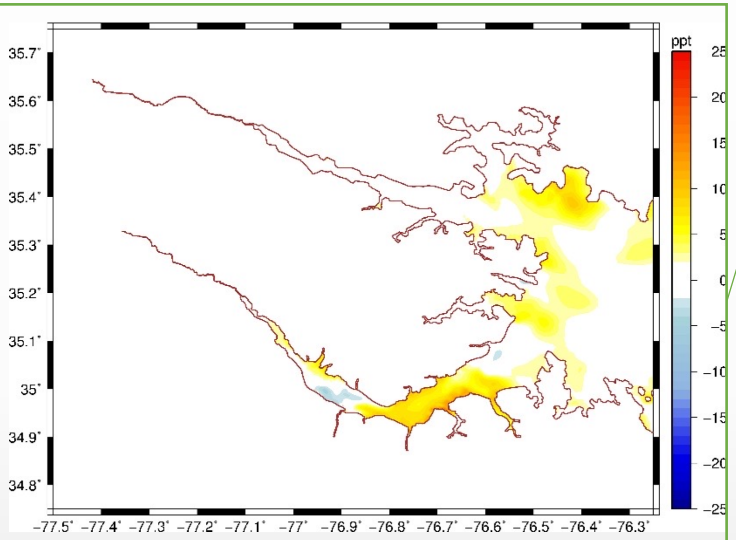
1200 UTC
27 August

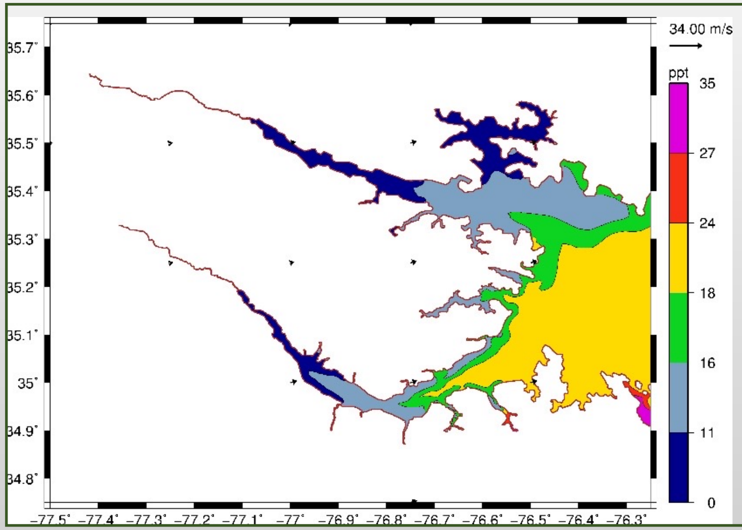


Tar-Pamlico & Neuse Rivers

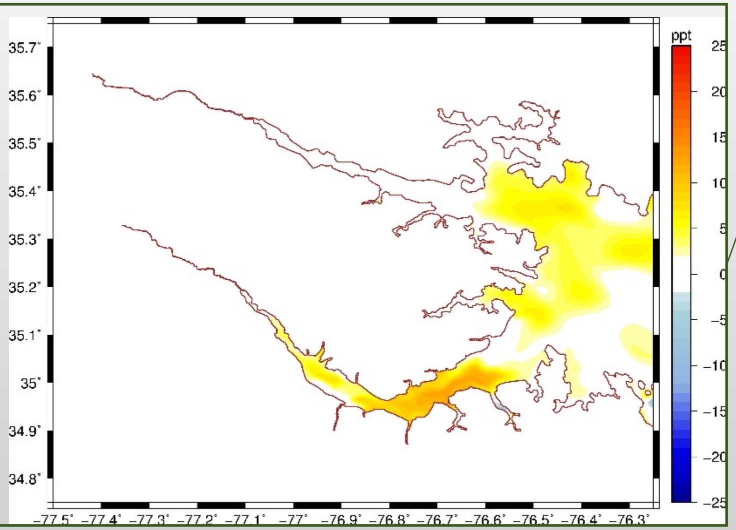


0800 UTC
28 August



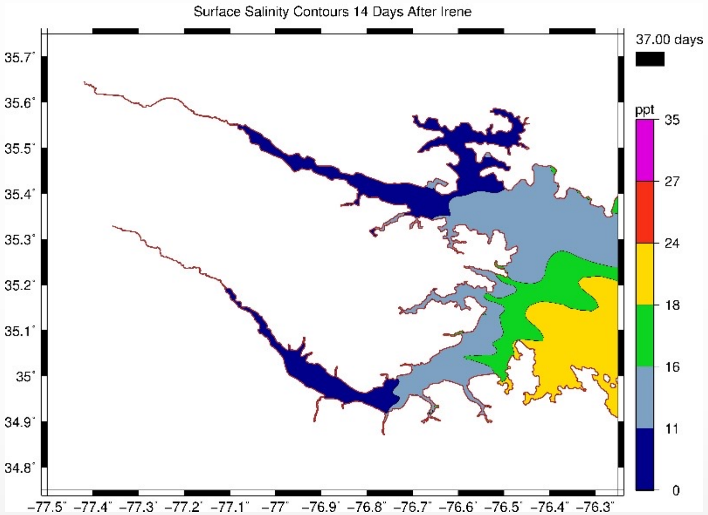


0000 UTC
29 August

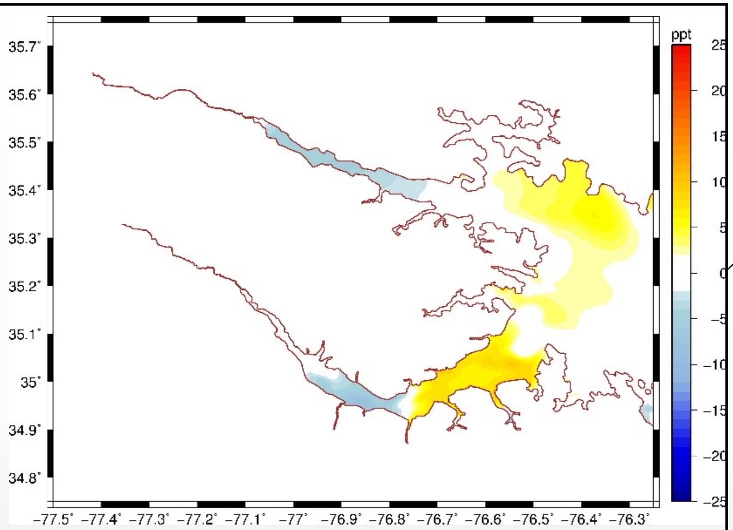


Tar-Pamlico & Neuse Rivers

9/4 9/5 9/6 9/7 9/8 9/9 9/10 9/11 9/12



0000 UTC
12 September

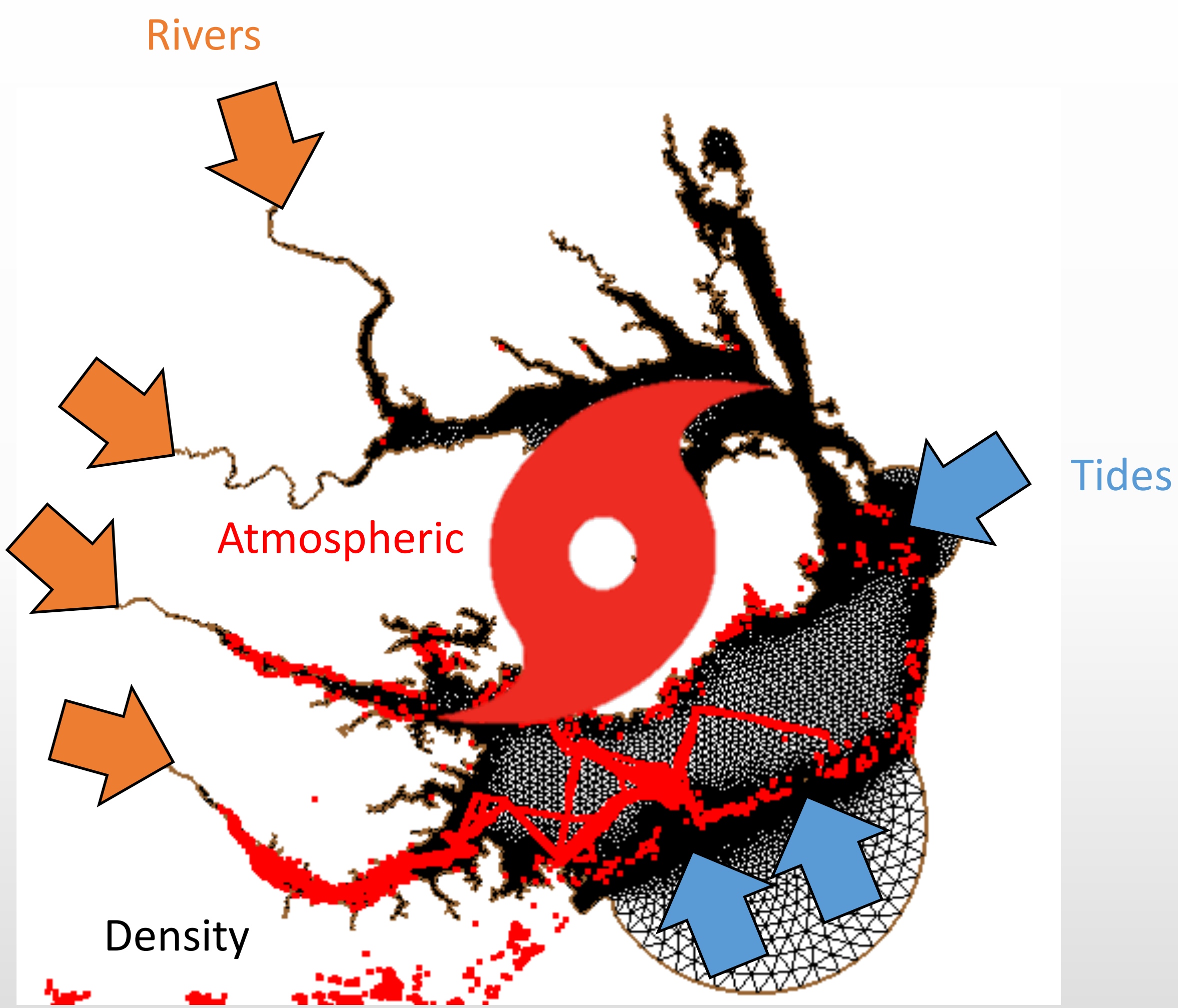


- From Greenville, NC: fresher zone extended about 76 km
- From New Bern, NC: fresher zone extended about 36 km

Conclusions & Future Work

Simulation

- 3D ADCIRC model of APES
  - Tides
  - Rivers
  - Atmospheric
  - Density



Main Take-Aways

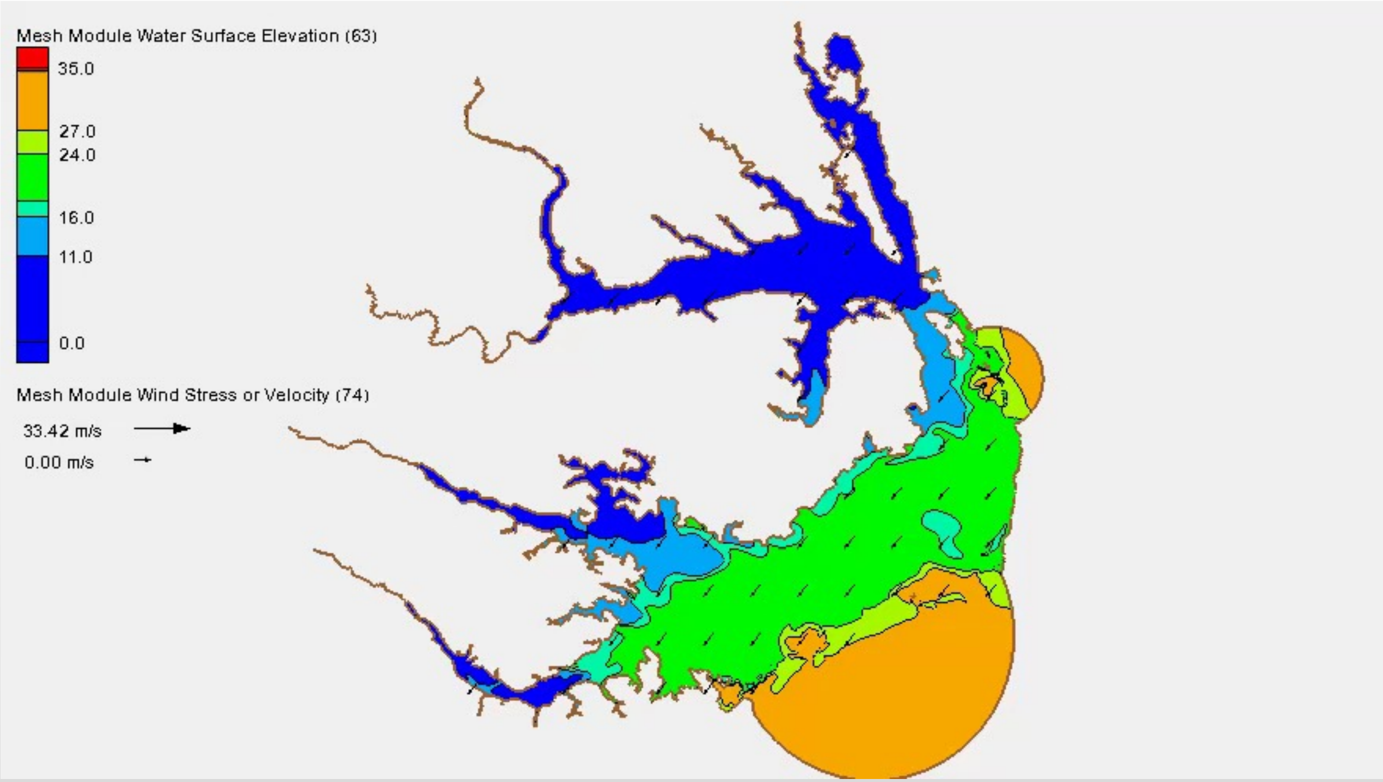
- In the eastern Albemarle Sound, surface salinities can increase by as much as three zones.
- Most of Pamlico Sound stayed within the polyhaline zone throughout Irene
- Waters near Roanoke Island saw the largest changes in salinity
- The Neuse and Tar-Pamlico Rivers experienced saline intrusions during the storm and fresh extrusions after the storm.
- If the fresh water intrusions stay for extended period of time, detrimental to ecosystem

Future Work

- Investigate the return to pre-storm conditions
- Effects on distribution of different types of storms
  - Shore perpendicular
  - Heavy rainfall
- Focus more on temperature changes
  - Inclusion of heat flux

Thank You

- Questions?



Sources of Images

1. https://www.weather.gov/mhx/Aug272011EventReview
2. https://oceanservice.noaa.gov/facts/stormsurge-stormtide.html
3. https://coastalreview.org/2018/09/research-hurricanes-effects-on-estuaries/
4. https://nypost.com/2018/09/26/waste-from-hurricane-florence-starts-to-flow-into-atlantic-ocean/
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