Wind and Plume Driven Circulation and Surface Transport in Estuarine Systems

Ph.D. Defense
September 4, 2018

Rosemary Cyriac
Advisor: Dr. Casey Dietrich

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

Acknowledgements

Thesis Committee

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[b]Department of Marine, Earth and Atmospheric Sciences, North Carolina State University, Raleigh, NC
[c]Department of Mathematics, North Carolina State University, Raleigh, NC
[d]Institute of Computational Engineering and Sciences, The University of Texas at Austin, Austin, TX

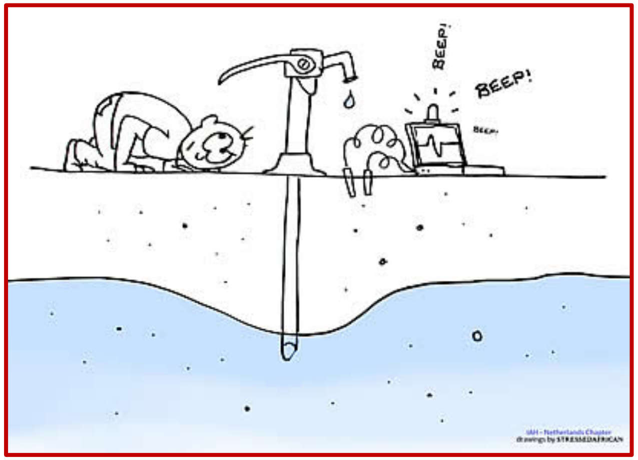
Other Collaborators

Dr. Rick Luettich[a], Dr. Jason Fleming[b], Dr. Brian Blanton[c], Ms. Carola Kaiser[d], Dr. Arash Fathi[e], Dr. Kendra Dresback[f], Dr. Cheryl Ann Blain[g], Dr. Matt Bilskie[h], Dr. Scott Hagen[h], Dr. Hans Graber[i]

[a]Institute of Marine Sciences, UNC Chapel Hill, Morehead City, NC
[b]Seahorse Coastal Consulting, Morehead City, NC
[c]Renaissance Computing Institute, Chapel Hill, NC
[d]School of the Coast and Environment, and Center for Computation and Technology, Louisiana State University, Baton Rouge, LA
[e]Institute of Computational Engineering and Sciences, The University of Texas at Austin, Austin, TX
[f]School of Civil Engineering and Environmental Science, University of Oklahoma, Norman, OK
[g]Oceanography Division, Naval Research Laboratory, Stennis Space Center, MS
[h]Center for Coastal Resiliency, Louisiana State University, Baton Rouge, LA
[i]Rosential School of Marine and Atmospheric Science, University of Miami, Miami, FL

About Me

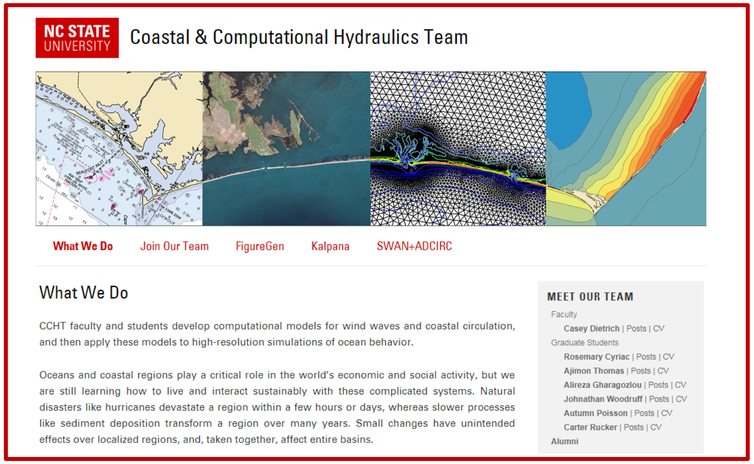
Btech. in Civil Engg., 2007
NIT Calicut



Masters in Water Resources Engg., 2011
IIT Bombay

About Me

Arrived at NC State in Fall 2013


NC STATE UNIVERSITY Coastal & Computational Hydraulics Team

What We Do | Join Our Team | FigureGen | Kalpana | SWAN+ADCIRC

What We Do

CCHT faculty and students develop computational models for wind waves and coastal circulation, and then apply these models to high-resolution simulations of ocean behavior.

Oceans and coastal regions play a critical role in the world's economic and social activity, but we are still learning how to live and interact sustainably with these complicated systems. Natural disasters like hurricanes devastate a region within a few hours or days, whereas slower processes like sediment deposition transform a region over many years. Small changes have unintended effects over localized regions, and, taken together, affect entire basins.

MEET OUR TEAM

Faculty

Casey Dietrich | Posts | CV

Graduate Students

Rosemary Cyriac | Posts | CV

Ajimon Thomas | Posts | CV

Alireza Gharagozlou | Posts | CV

Johnathan Woodruff | Posts | CV

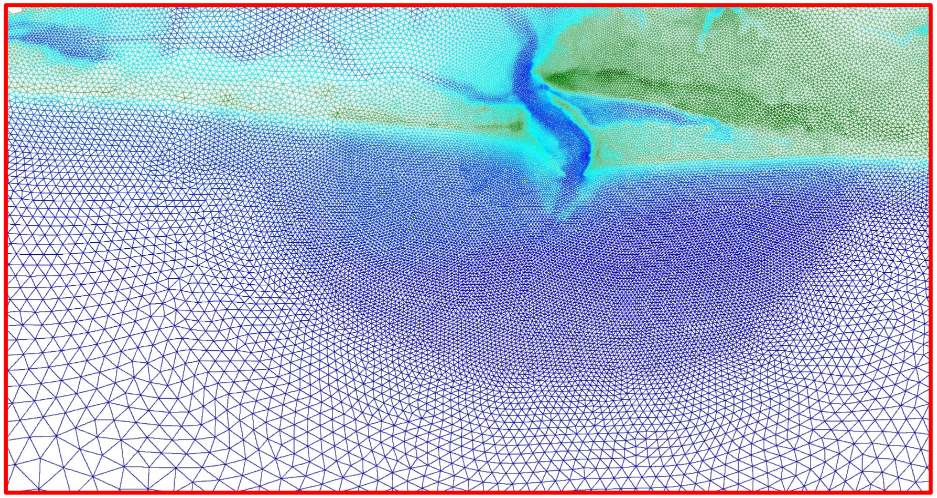
Autumn Poisson | Posts | CV

Carter Rucker | Posts | CV

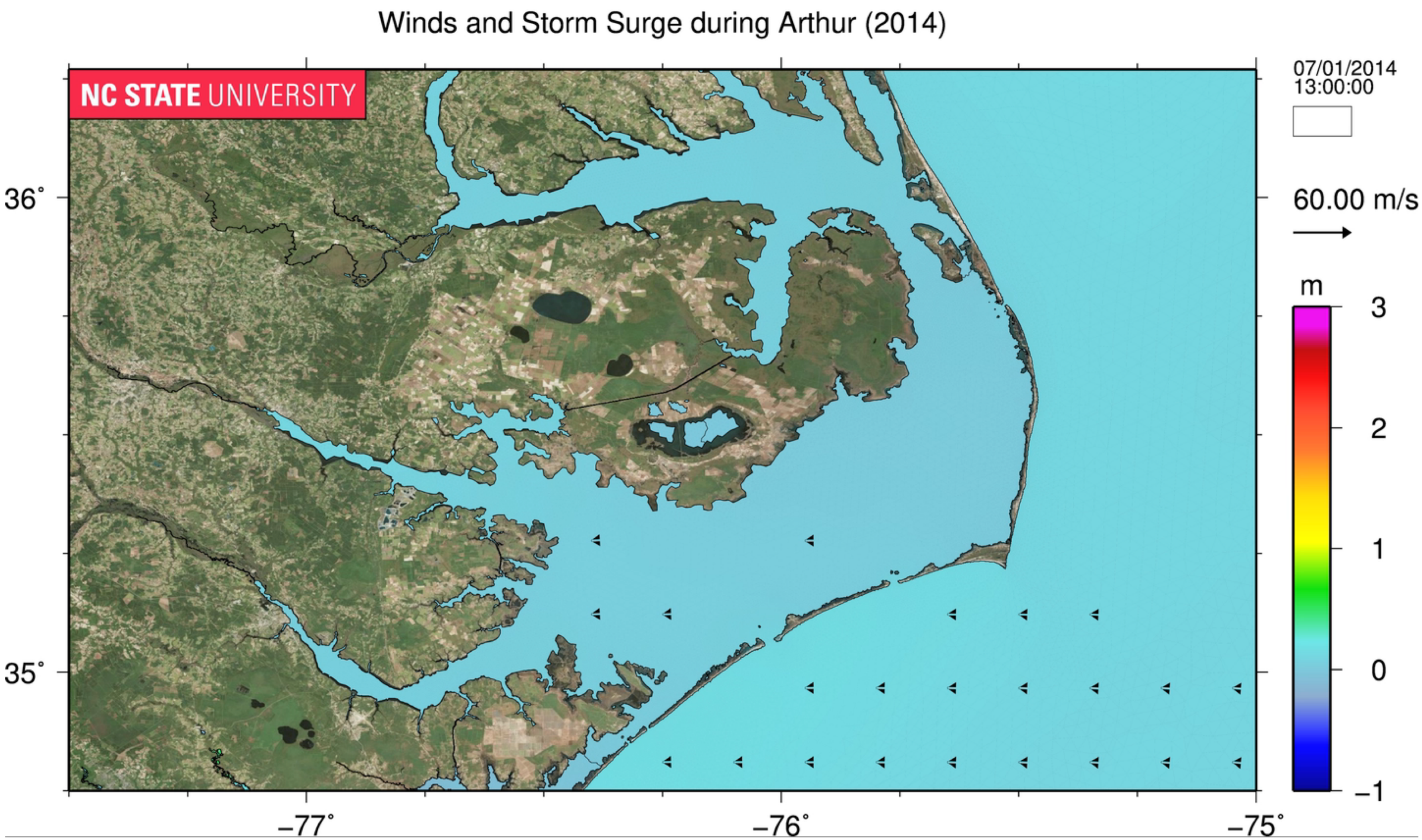
Alumni

Research Interests

- Application of unstructured mesh based numerical models to predict the tide, wind, wave and density driven hydrodynamics in the coastal ocean



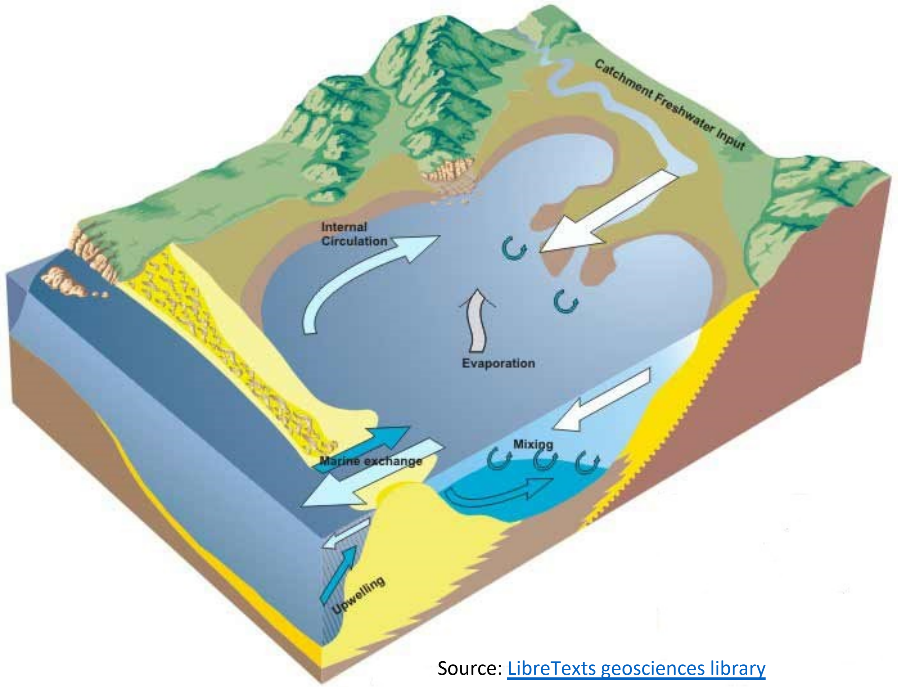
Storm Surge Modeling



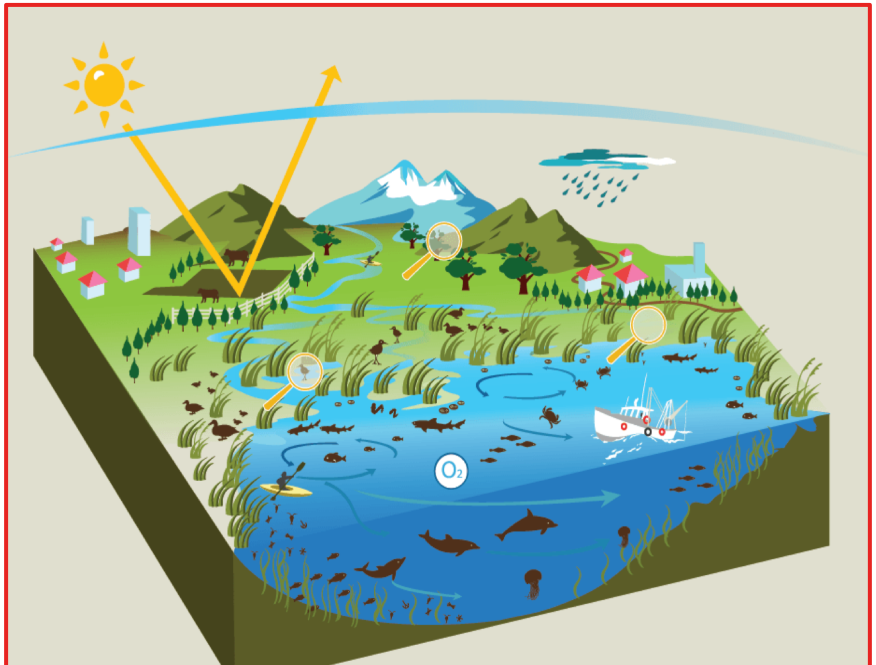
***R. Cyriac** et al., Variability in coastal flooding predictions due to forecast errors during Hurricane Arthur, Coastal Engineering, 137, 59-78, (2018).*

Estuaries

“Semi-enclosed coastal bodies of water …. within which sea water is measurably diluted with fresh water …..” (Cameron and Pritchard, 1993)

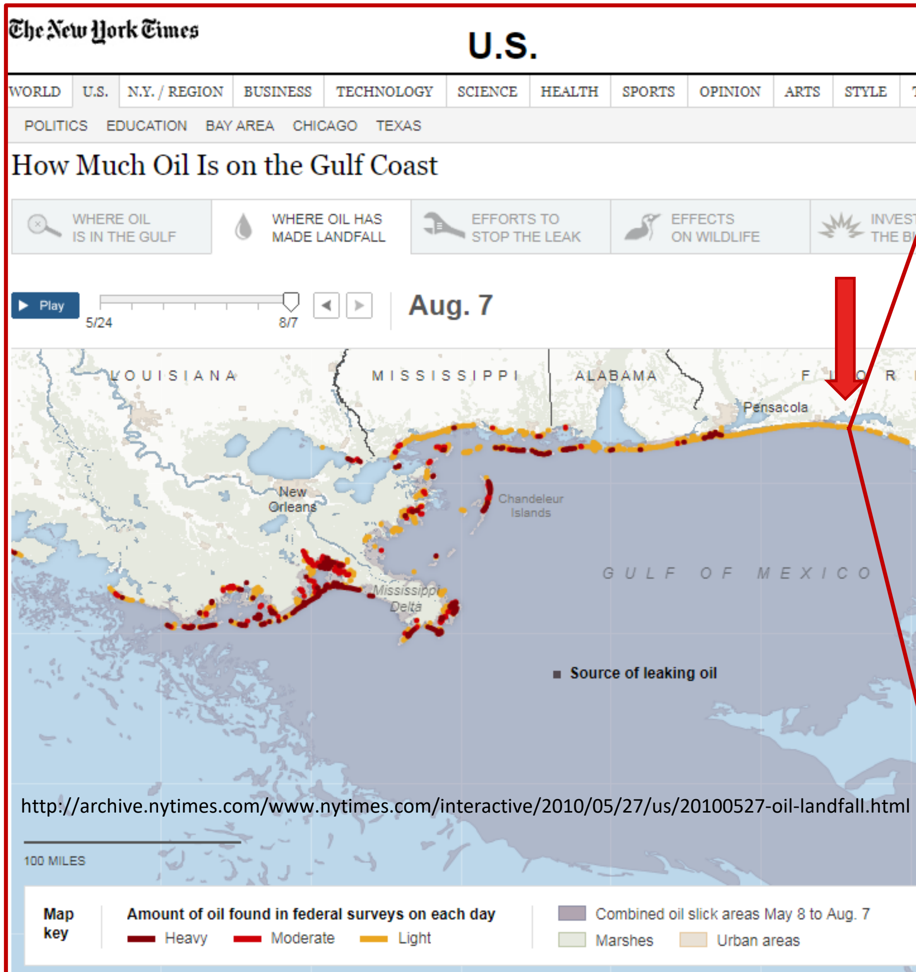


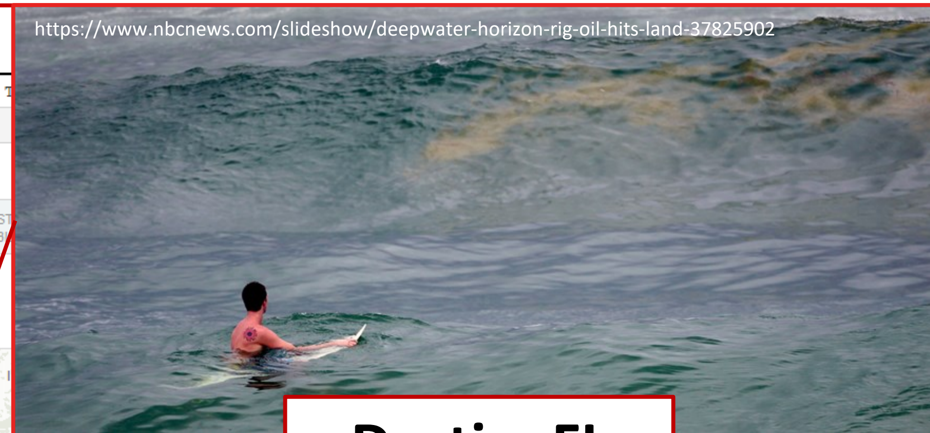
Source: [LibreTexts geosciences library]



Source: https://coast.noaa.gov/estuaries/curriculum/climate-extension.html

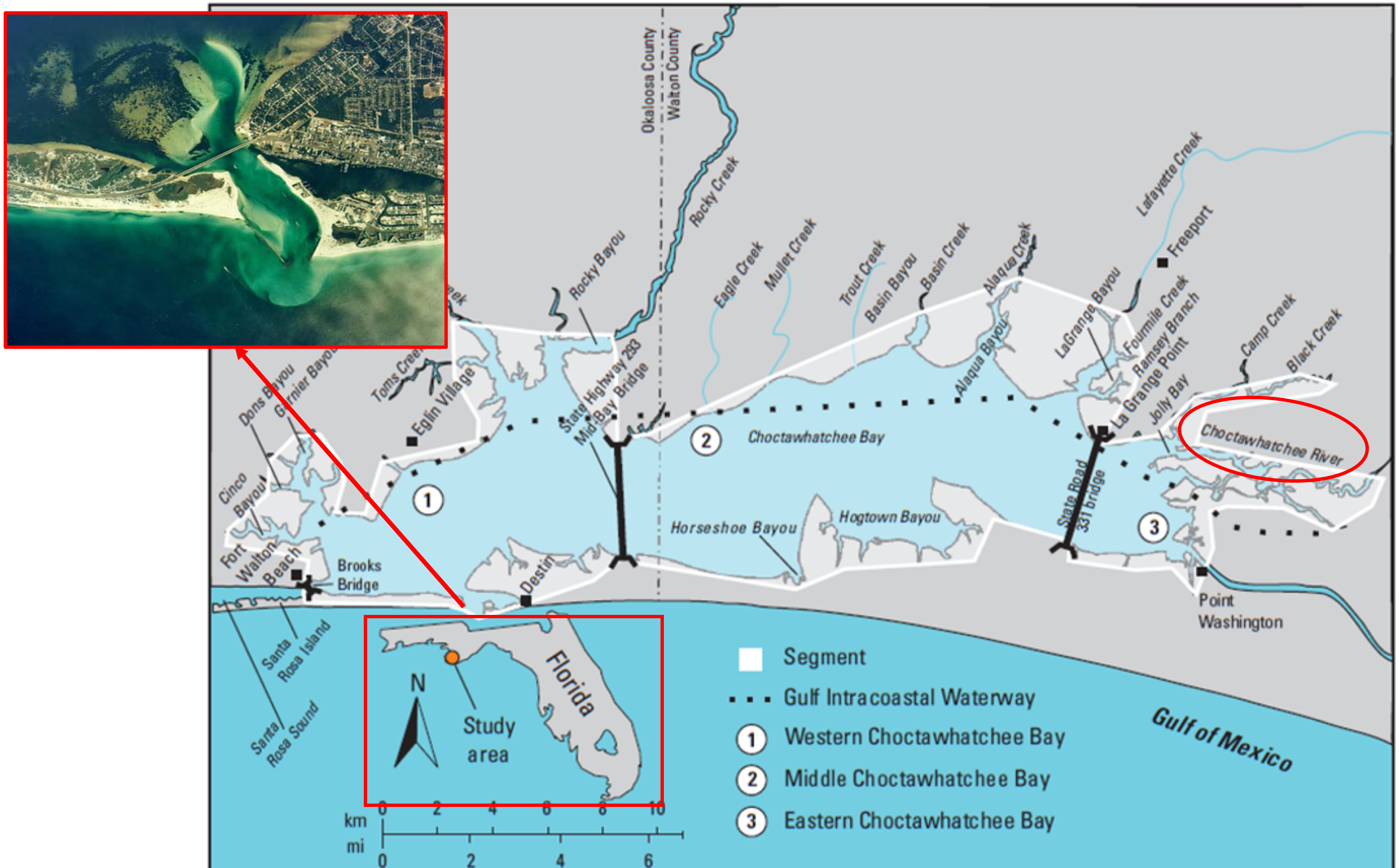
Oil Spill Effects Along the Coast





Destin, FL

Choctawhatchee Bay and Destin Inlet

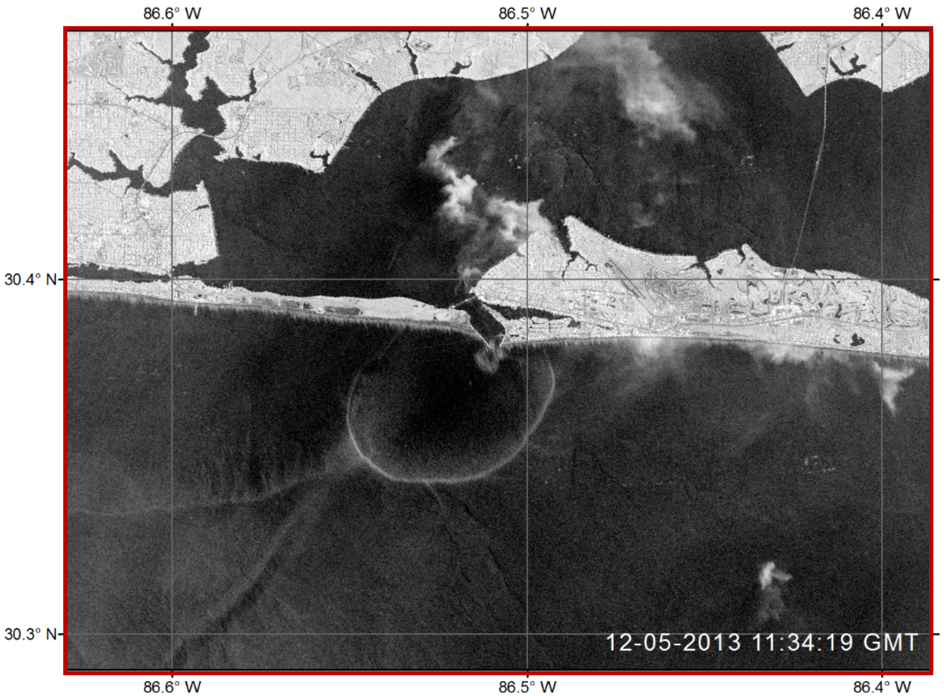


Surfzone Coastal Oil Pathways Experiment (SCOPE)

Field experiment performed by CARTHE scientists in December 2013

- To study factors that influence the near-shore surface transport
- Including drifter releases, CTD casts, aerial surveys etc.

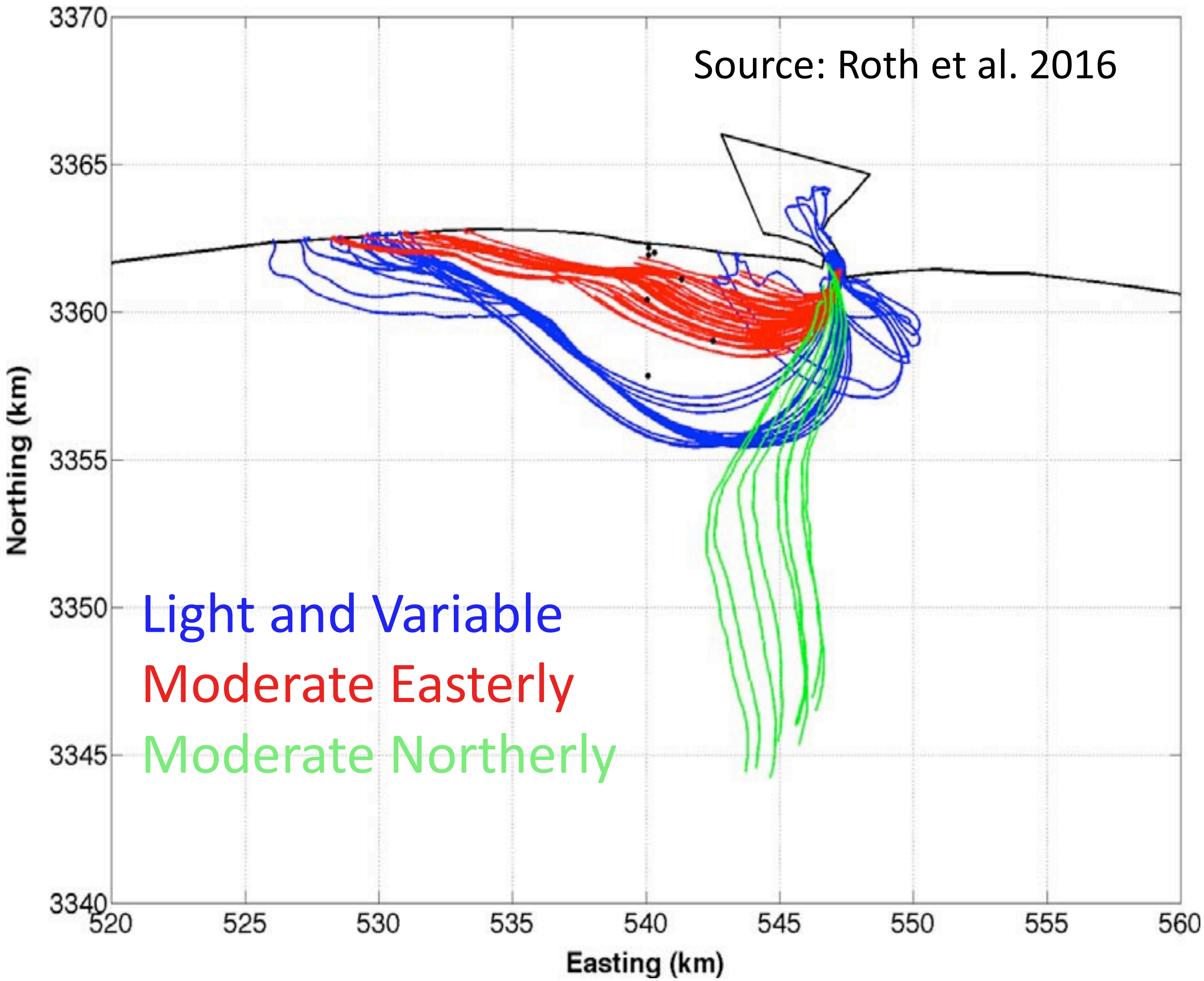
Plume Dynamics at Destin Inlet



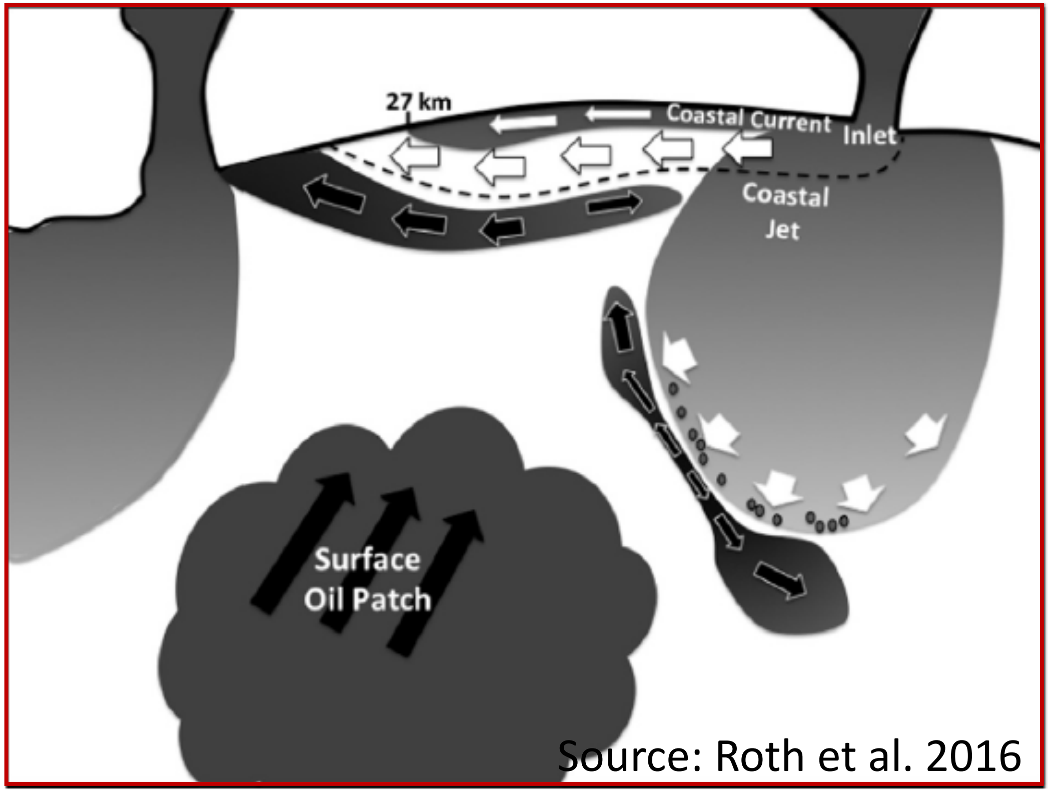
Source: CARTHE Facebook page

- SCOPE satellite SAR imagery shows visible plume at Destin Inlet
- Plume dynamics influence surface transport pathways in the shelf

Insights from SCOPE : Ebb-Phase Drifter Movement



Insights from SCOPE : Plume as natural barriers



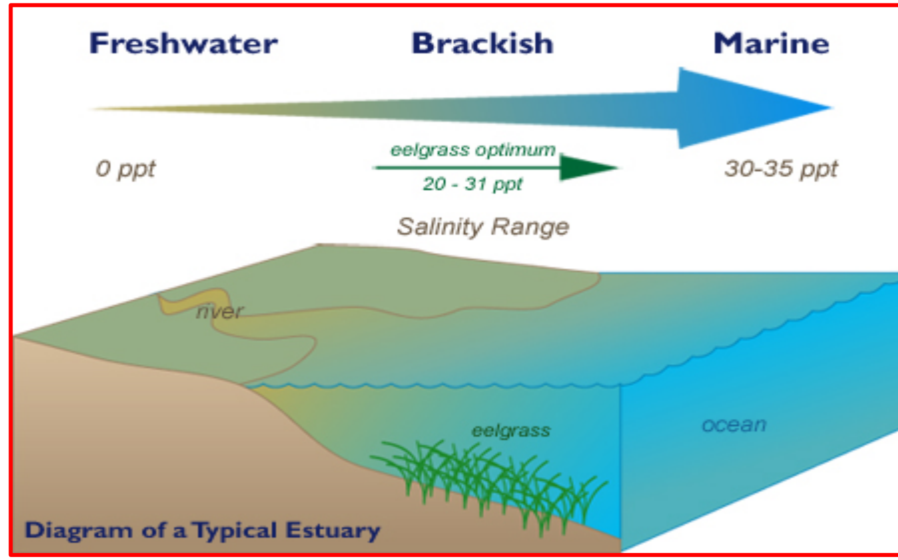
Source: Roth et al. 2016

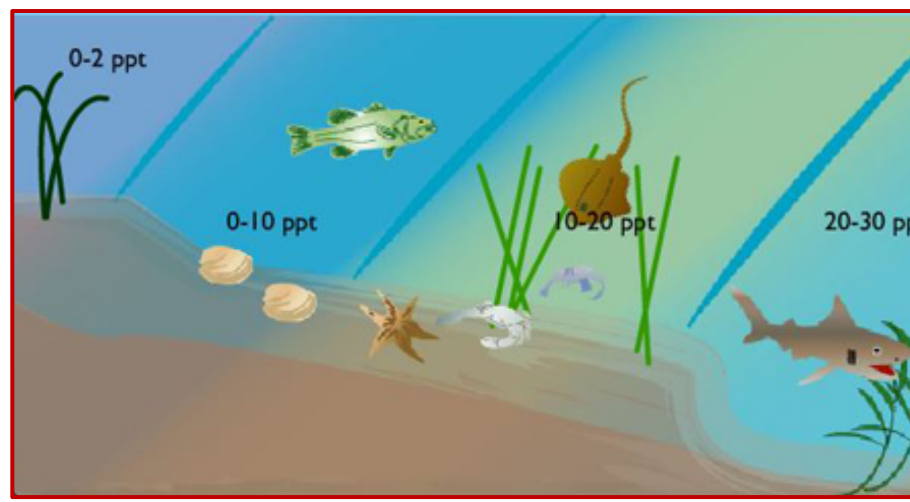
- Plume dynamics influence the transport and eventual fate of surface material
- Knowledge of plume behavior useful for oil response operations, fisheries management etc.

Salinity Transport within Choctawhatchee Bay

- Most estuarine species thrive within limited ranges of estuarine salinities
  - Knowledge of estuarine salinities critical for resource management

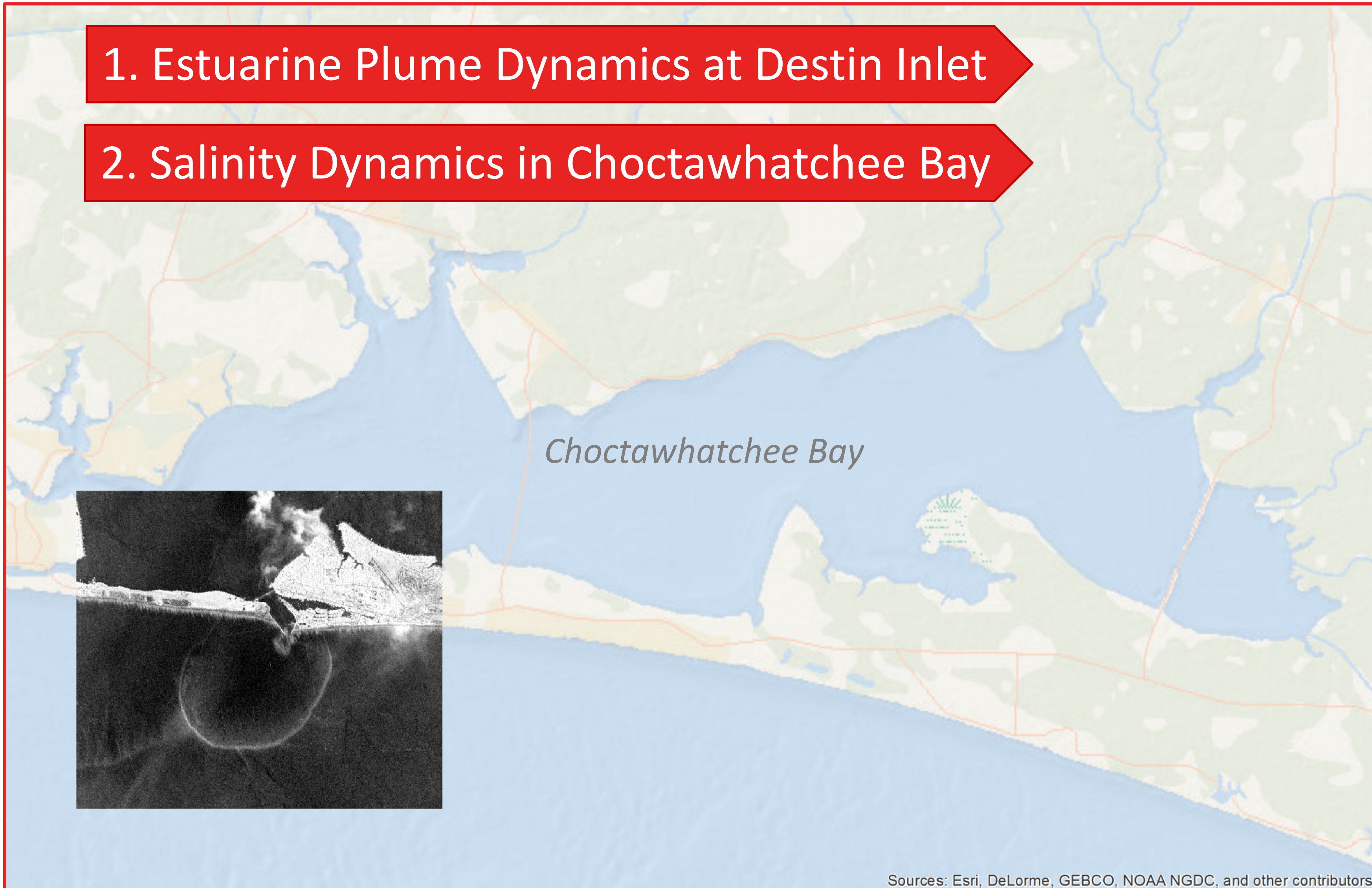
- Limited knowledge about salinities within Choctawhatchee Bay
  - Stratified conditions with limited flushing (Livingston, 1986)
  - Zones of distinct salinity gradients (Hoyer 2010)





Research Focus

1. Estuarine Plume Dynamics at Destin Inlet
2. Salinity Dynamics in Choctawhatchee Bay



Research Gaps and Hypotheses

Plume Dynamics

How does the plume geometry change in response to passing winter cold fronts and neap to spring variability in tides?

- Moderately strong and variable winds cause substantial differences in the plume geometry on consecutive days
- Larger plume when tides change from neap to spring

Estuarine Salinity Dynamics

What are the key features of salinity transport within Choctawhatchee Bay during a period of low river flows?

- Surface salinities within the bay are relatively constant
- Highly stratified conditions with limited flushing (residence time of the order of weeks or months)

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Outline

Model Development

- Introduction to ADCIRC
- Mesh Development and Model Setup
- Model Validation

Plume Dynamics

- Variability in Winds
- Plume Response to changing winds
- Plume Response to neap-spring variability in tides

Estuarine Salinity Dynamics

- Inlet Salinities
- Surface Salinities
- Vertical Stratification
- Residence Time

Summary and Conclusions

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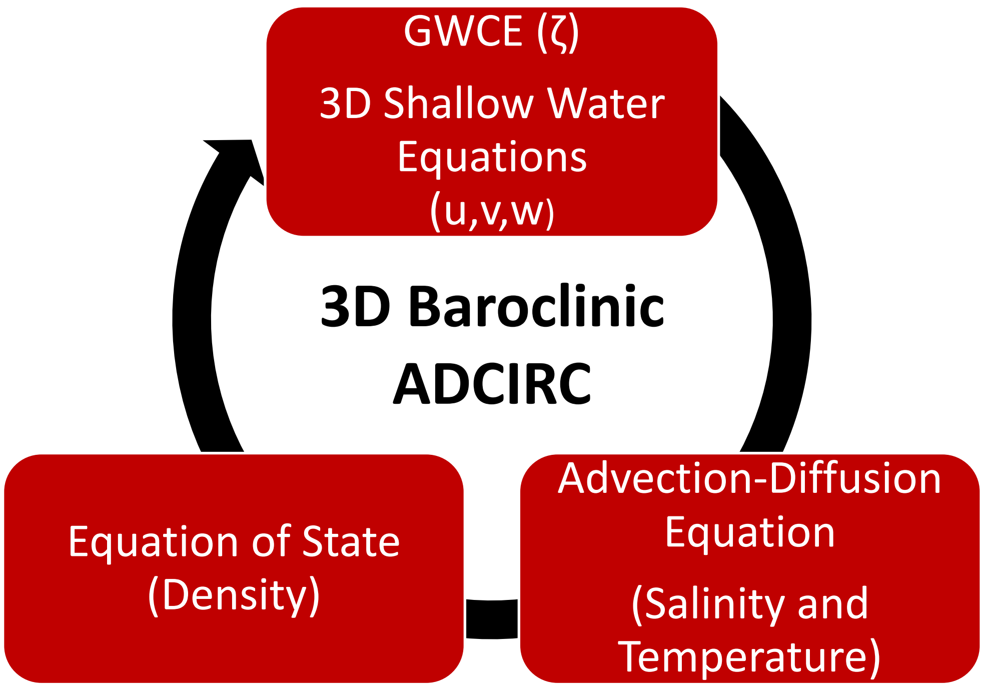
- Residence Time

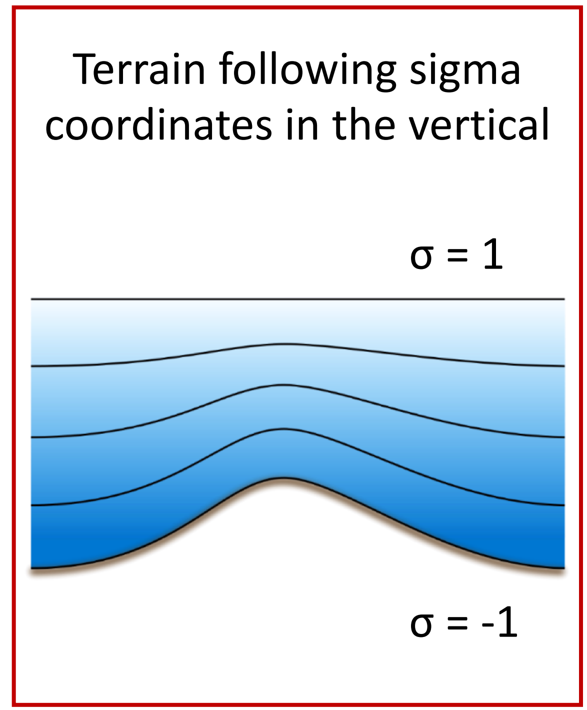
Summary and Conclusions

Methods: Numerical Modeling

ADvanced CIRCulation (ADCIRC)

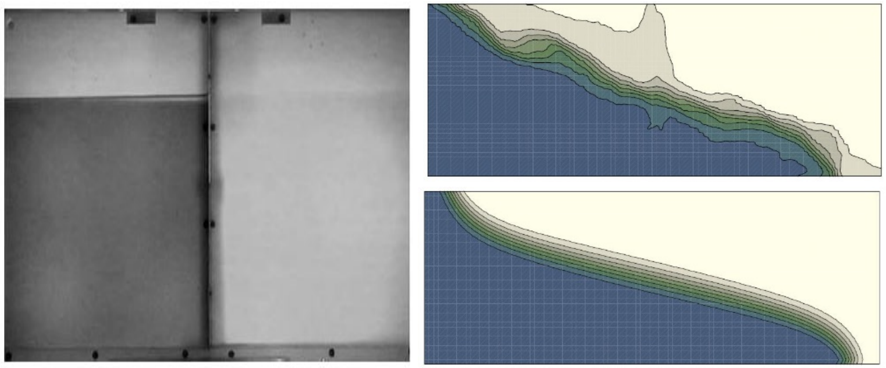
- Unstructured finite element model used widely for tide & storm surge studies
- 3D baroclinic version has only undergone limited testing





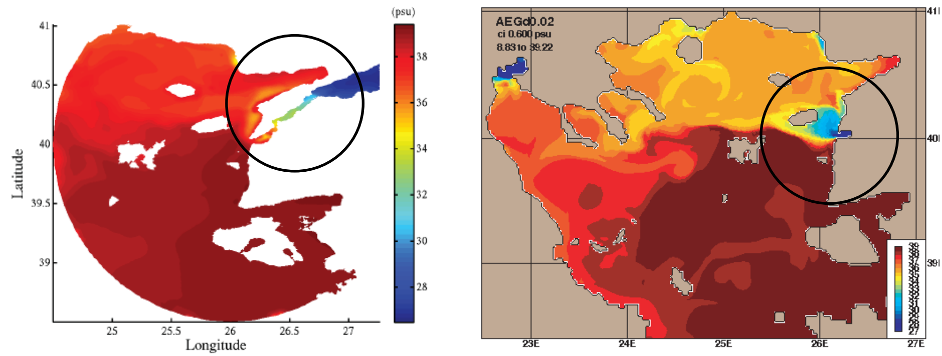
Introduction to 3D baroclinic ADCIRC

Idealized lock exchange test



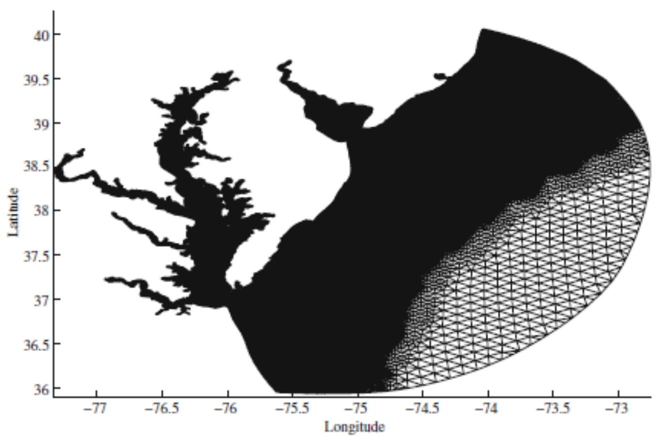
Kolar et al. 2009

Stratified outflows from Dardanelles Strait



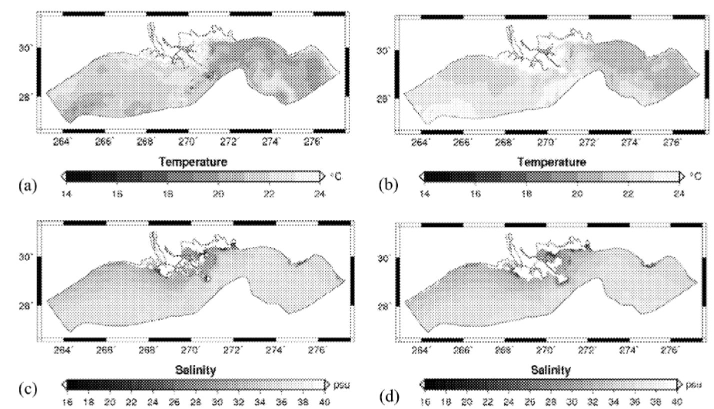
Blain et al. 2009

Coastal forecast system for Chesapeake Bay



Blain et al. 2012

Models for Northern Gulf of Mexico



Dresback et al. 2010

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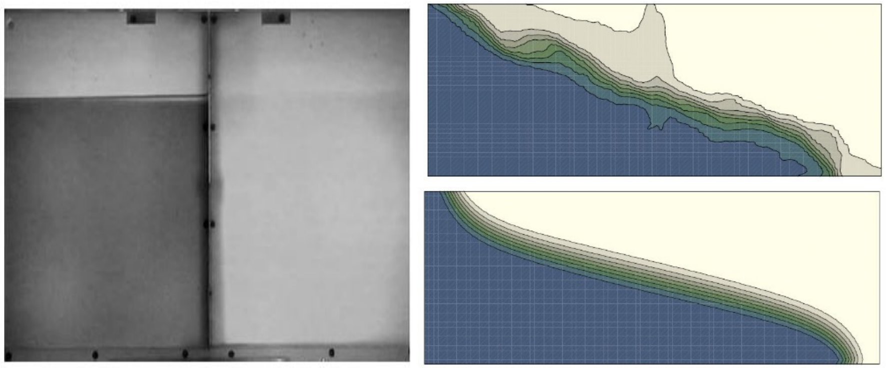

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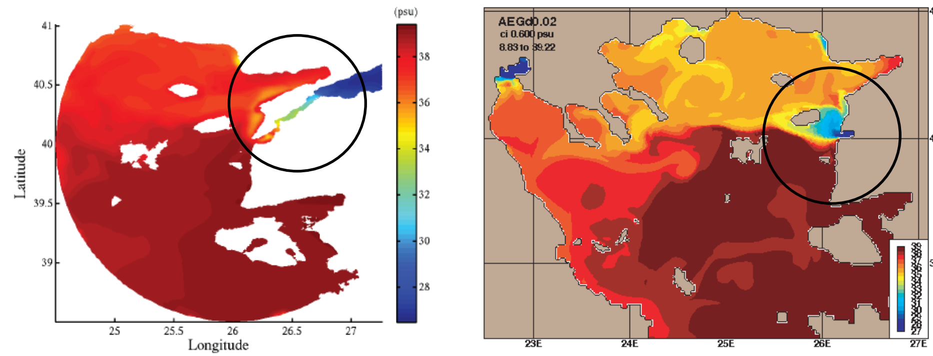

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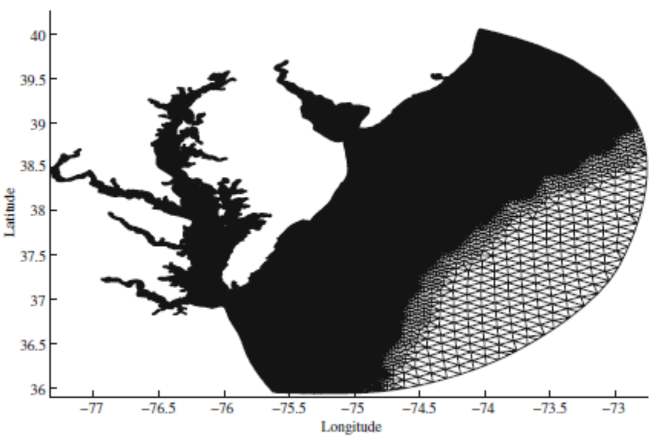

Blain et al. 2012

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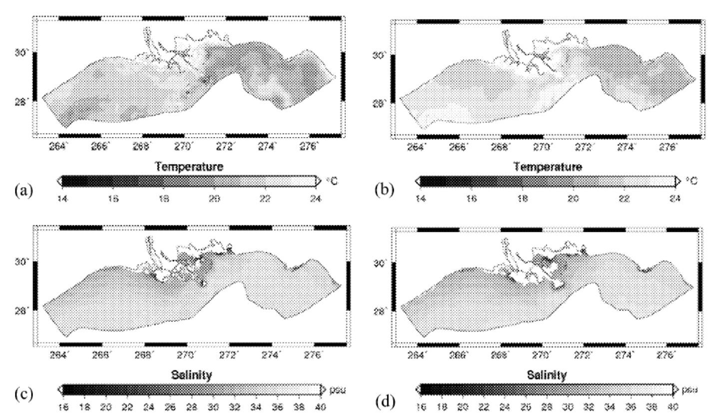

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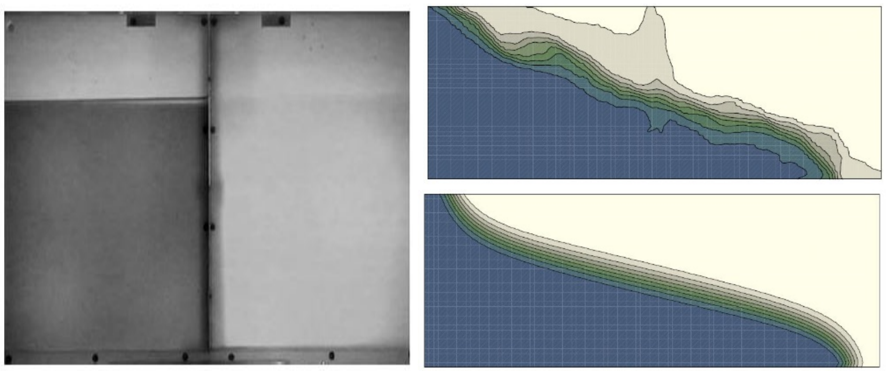

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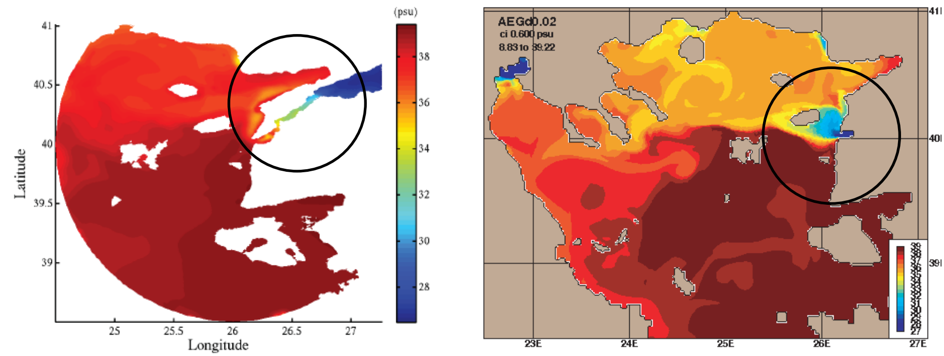

Blain et al. 2009

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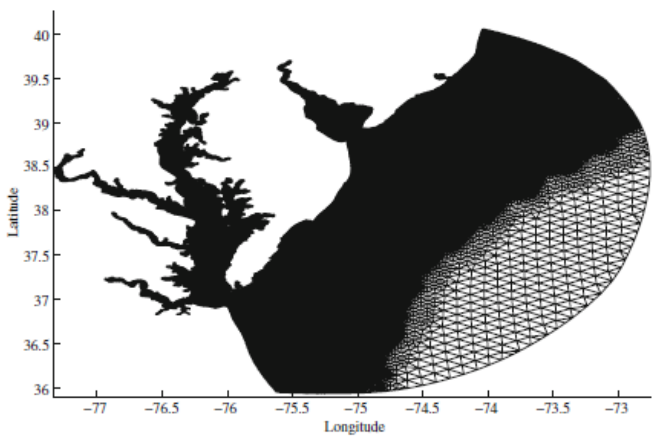
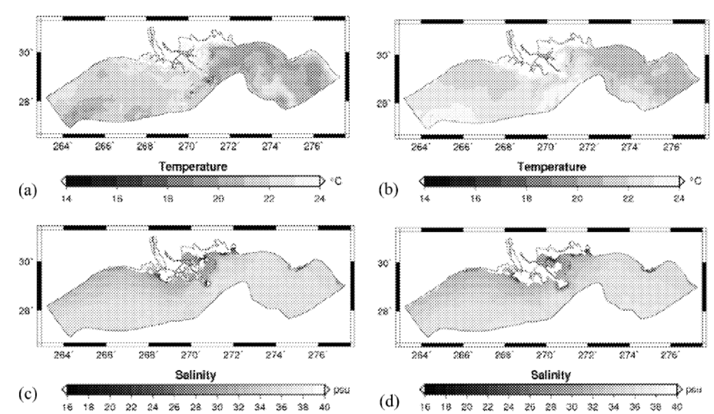


Blain et al. 2012

Models for Northern Gulf of Mexico



Dresback et al. 2010

Introduction to 3D baroclinic ADCIRC

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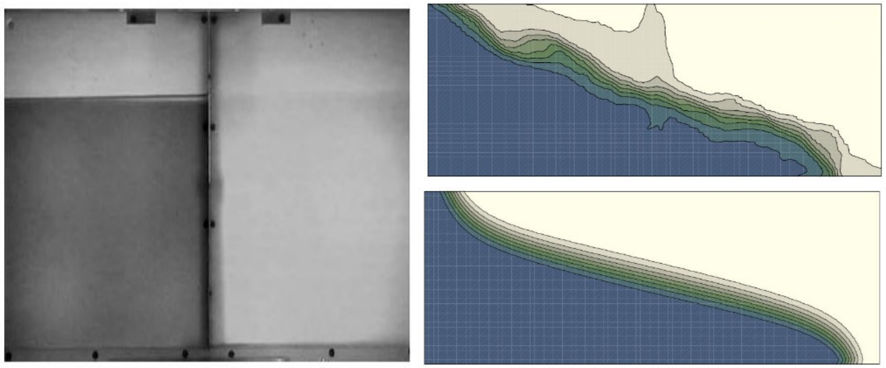

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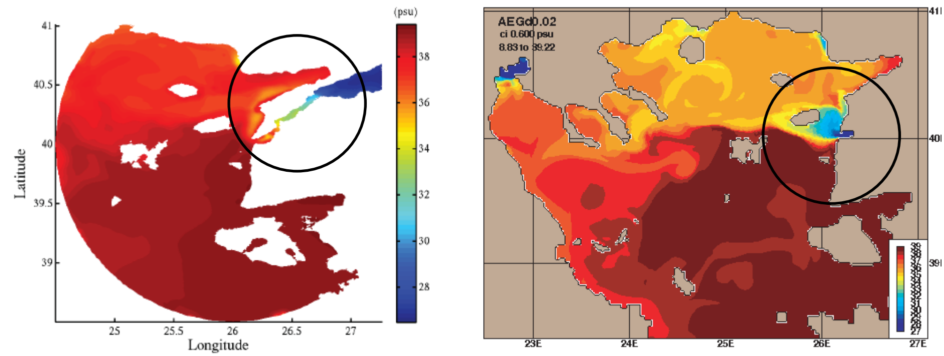

Blain et al. 2009

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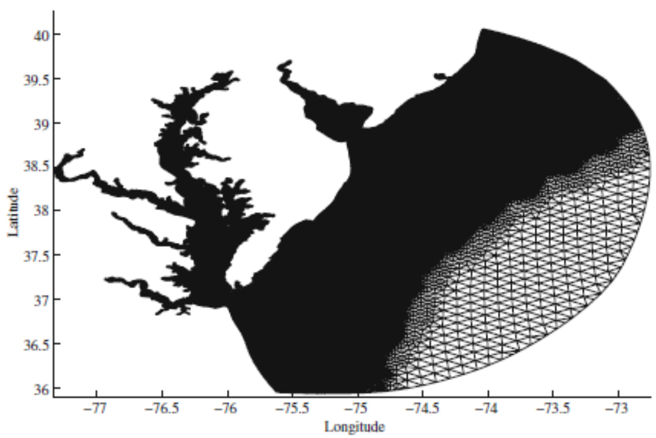

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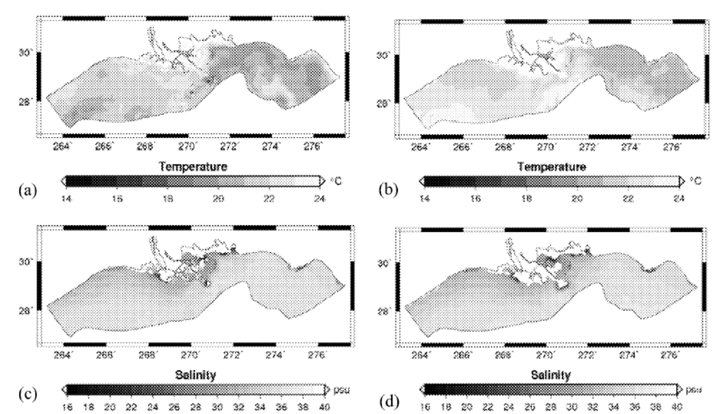
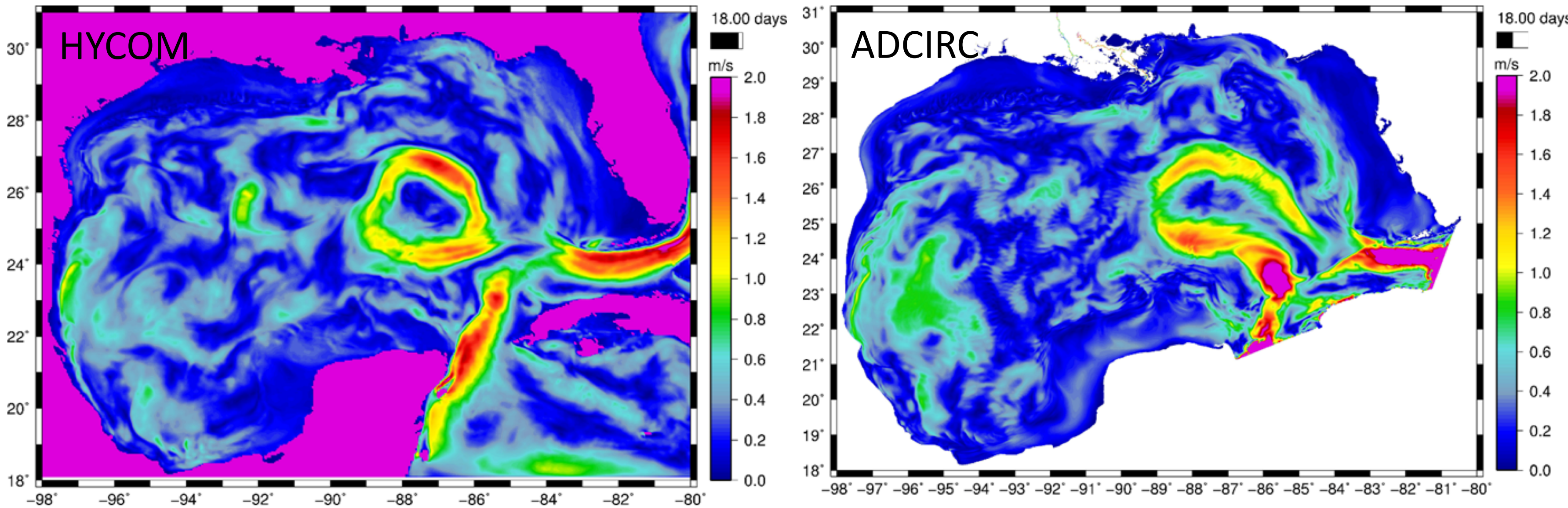
Models for Northern Gulf of Mexico



Dresback et al. 2010

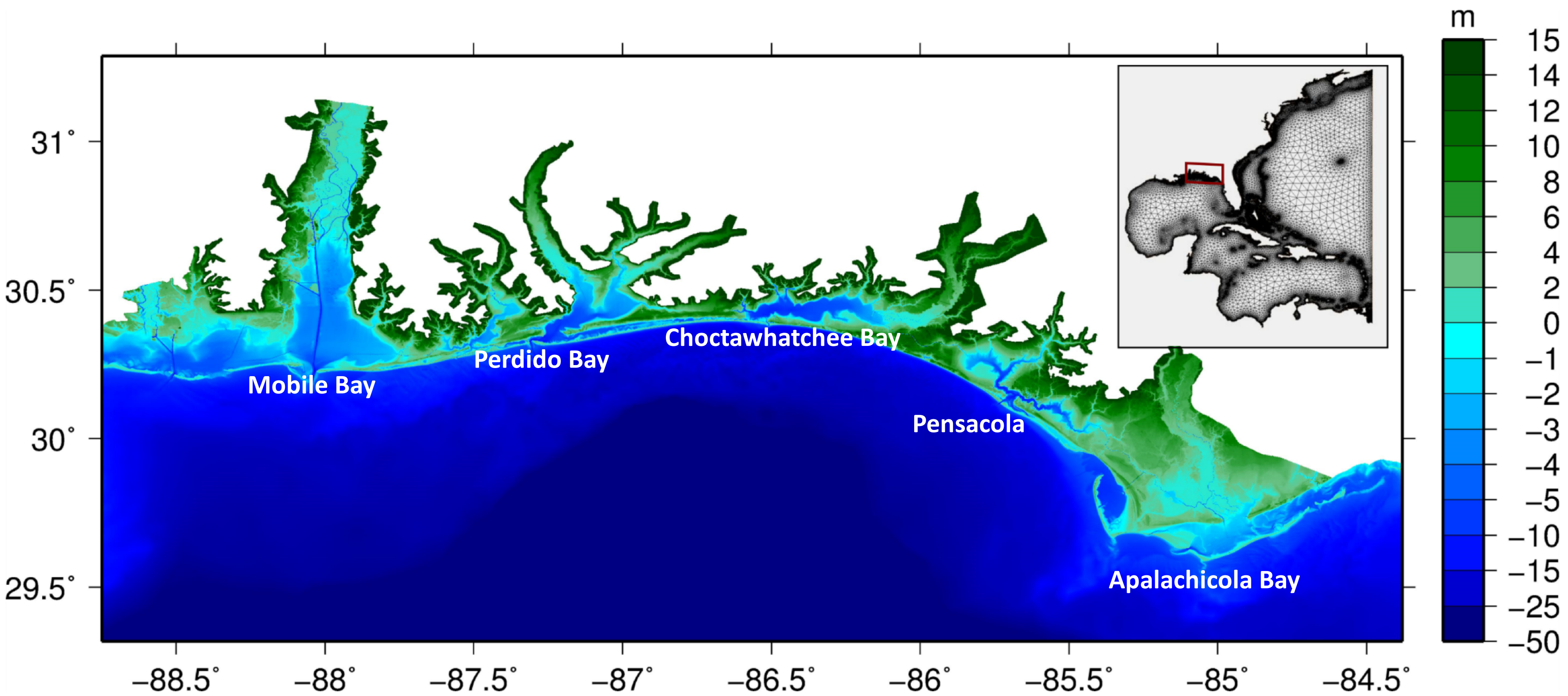
Recent Improvements to 3D ADCIRC (**Dr. Arash Fathi)**

Sea surface velocities in the Gulf of Mexico



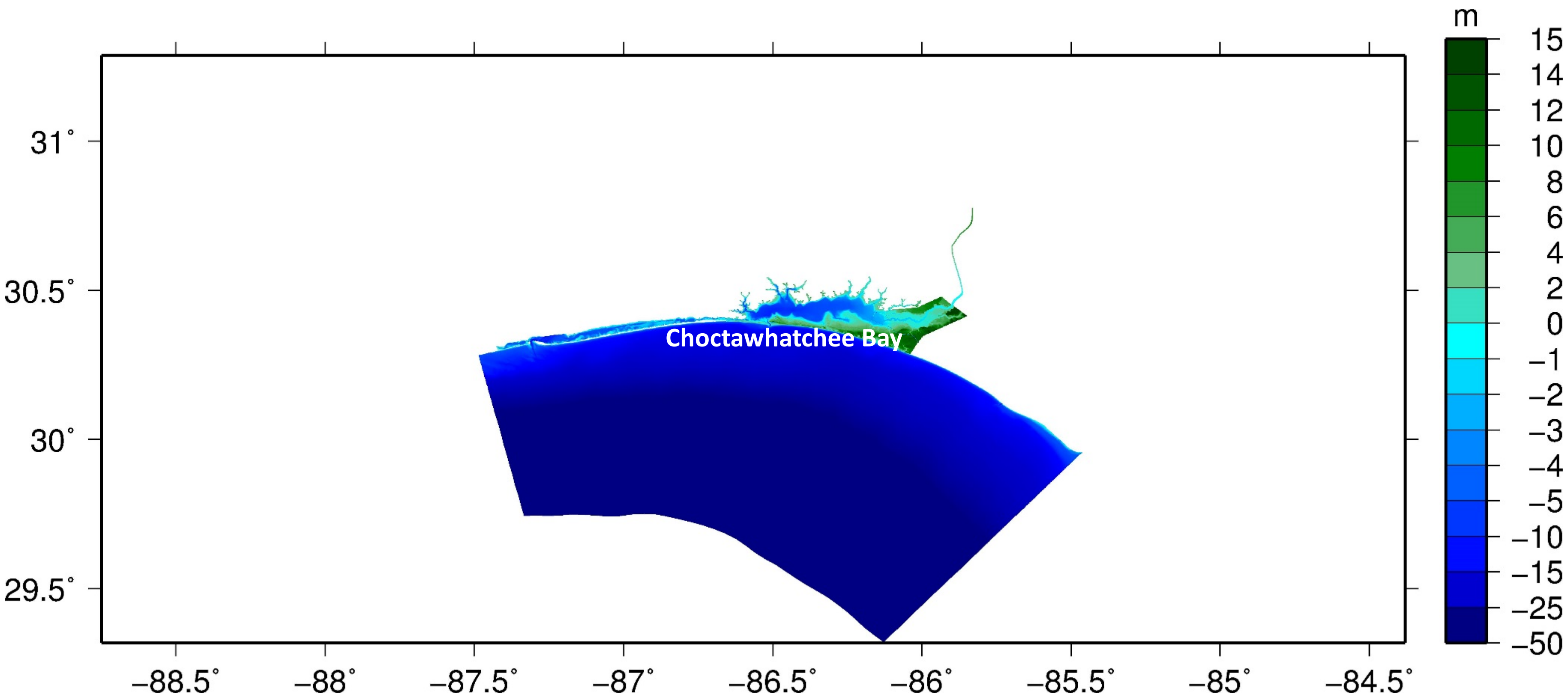
Improvements were made to apply this updated code for shelf- and estuarine-scale modeling in the present study

Mesh Development



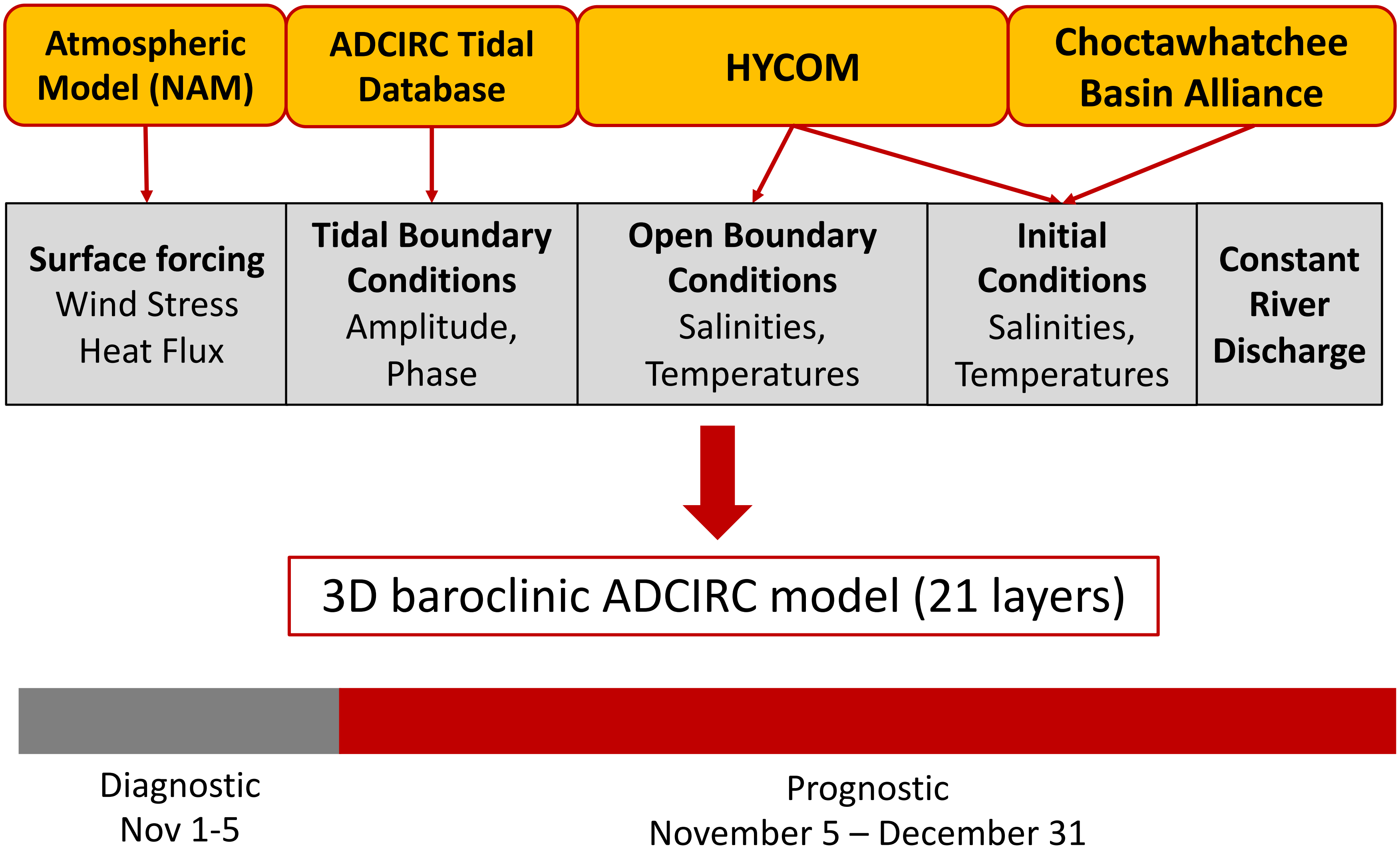
Source : S. Hagen , A. Daranpob, P. Bacopoulos, S. Medeiros, M. Bilskie, D. Coggin, M. Salisbury, J. Atkinson and H. Roberts. Storm Surge Modeling for FEMA Flood Map Modernization for the Northwest Florida and Alabama Coast, Digital Elevation Model and Finite Element Mesh Development. Prepared for the Northwest Florida Water Management District and the FEMA, 2011.

Mesh Development

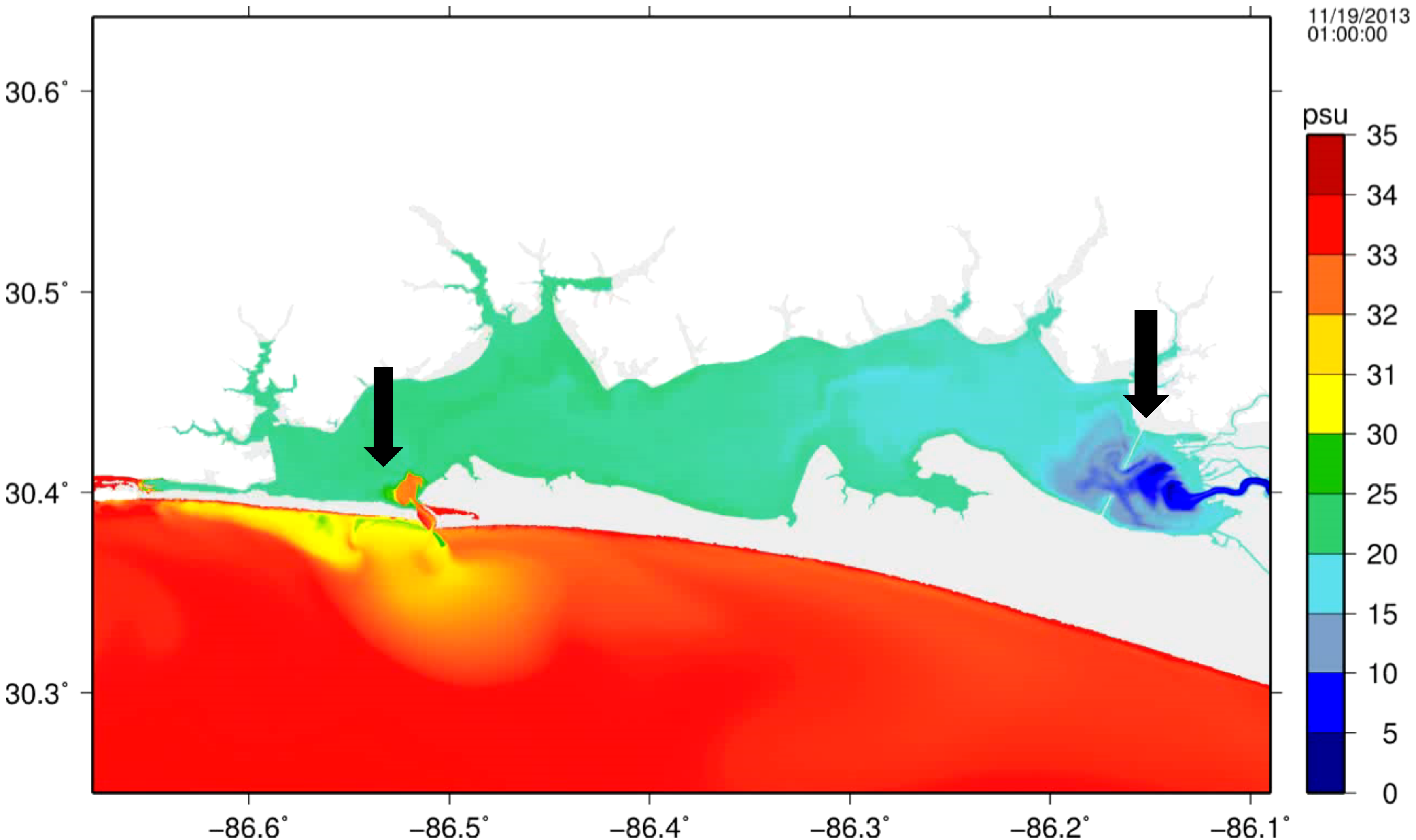


- Resolving Choctawhatchee River
- Bathymetry Smoothing above 15m
- Increasing offshore resolution
- Inlet Refinement
- Shelf-scale mesh
    - Ocean boundary at 200m contour

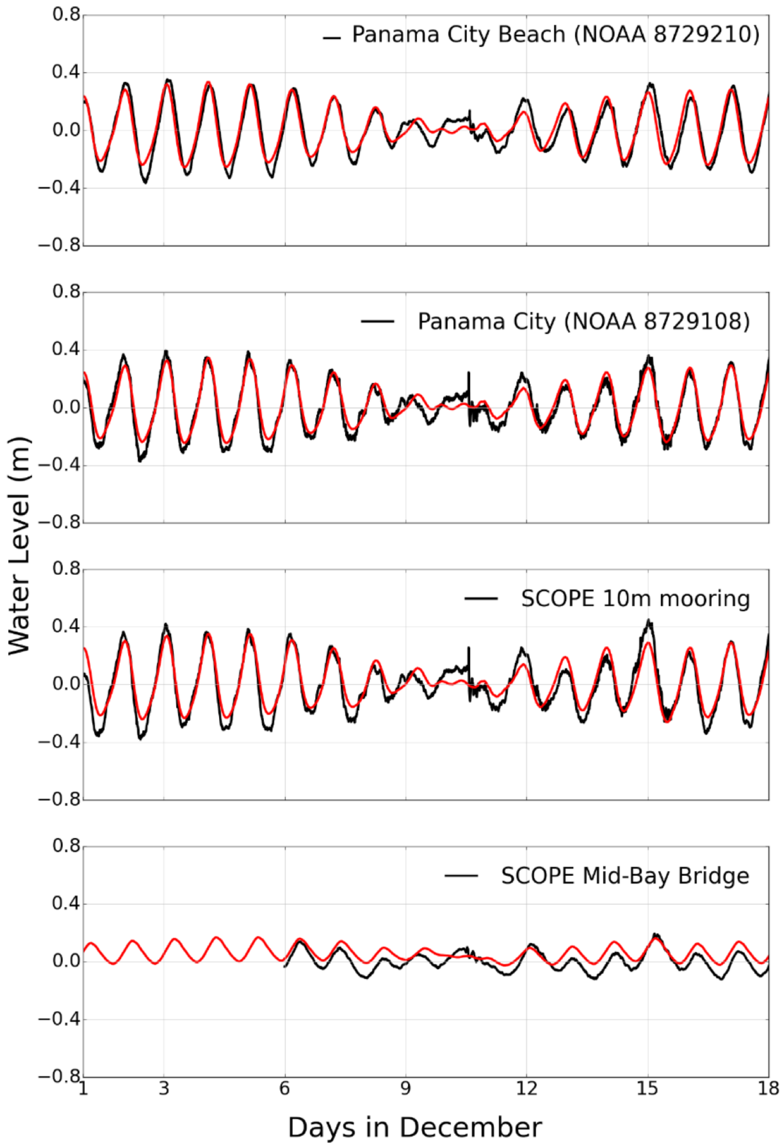
Model Setup

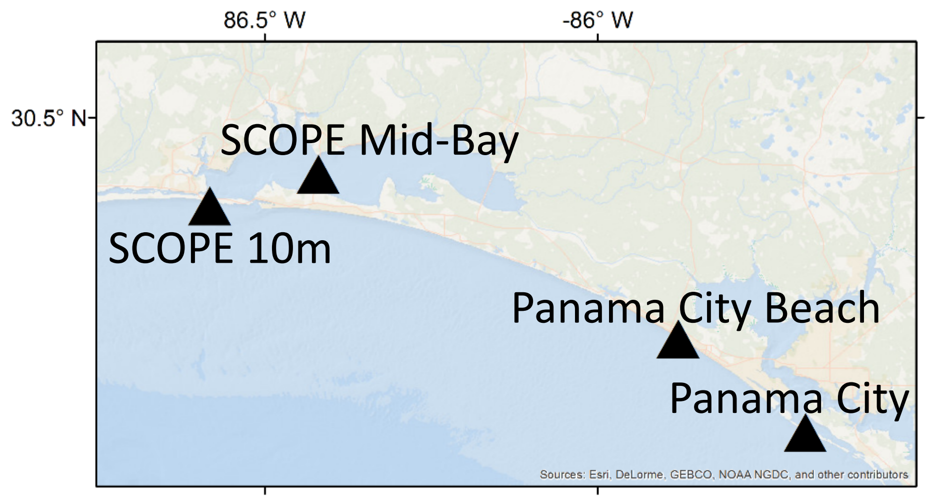

Atmospheric Model (NAM)
ADCIRC Tidal Database
HYCOM
Choctawhatchee Basin Alliance
Surface forcing
Wind Stress
Heat Flux
Tidal Boundary Conditions
Amplitude, Phase
Open Boundary Conditions
Salinities, Temperatures
Initial Conditions
Salinities, Temperatures
Constant River Discharge
3D baroclinic ADCIRC model (21 layers)
Diagnostic
Nov 1-5
Prognostic
November 5 – December 31

Surface Salinities



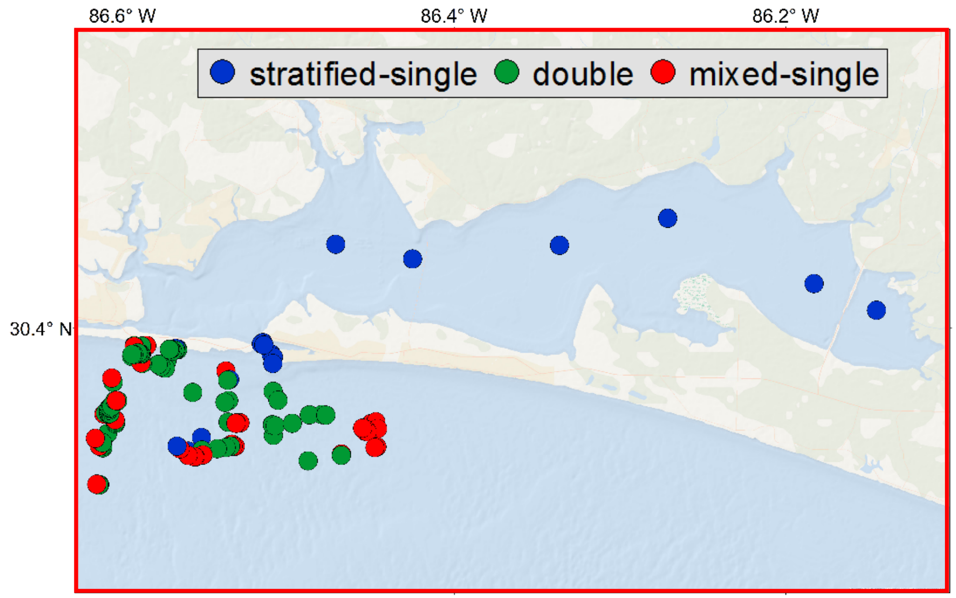
Water Levels

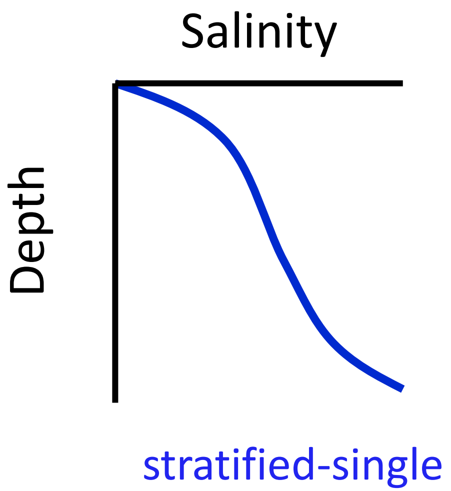


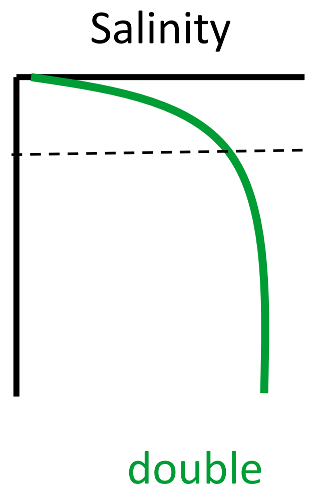


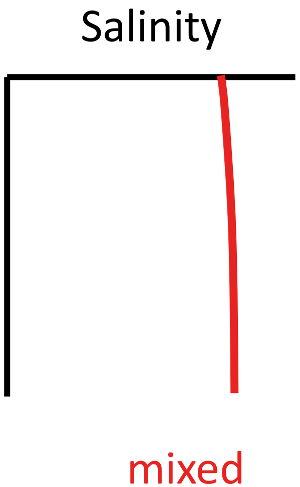
ADCIRC
Observed

Vertical Salinities

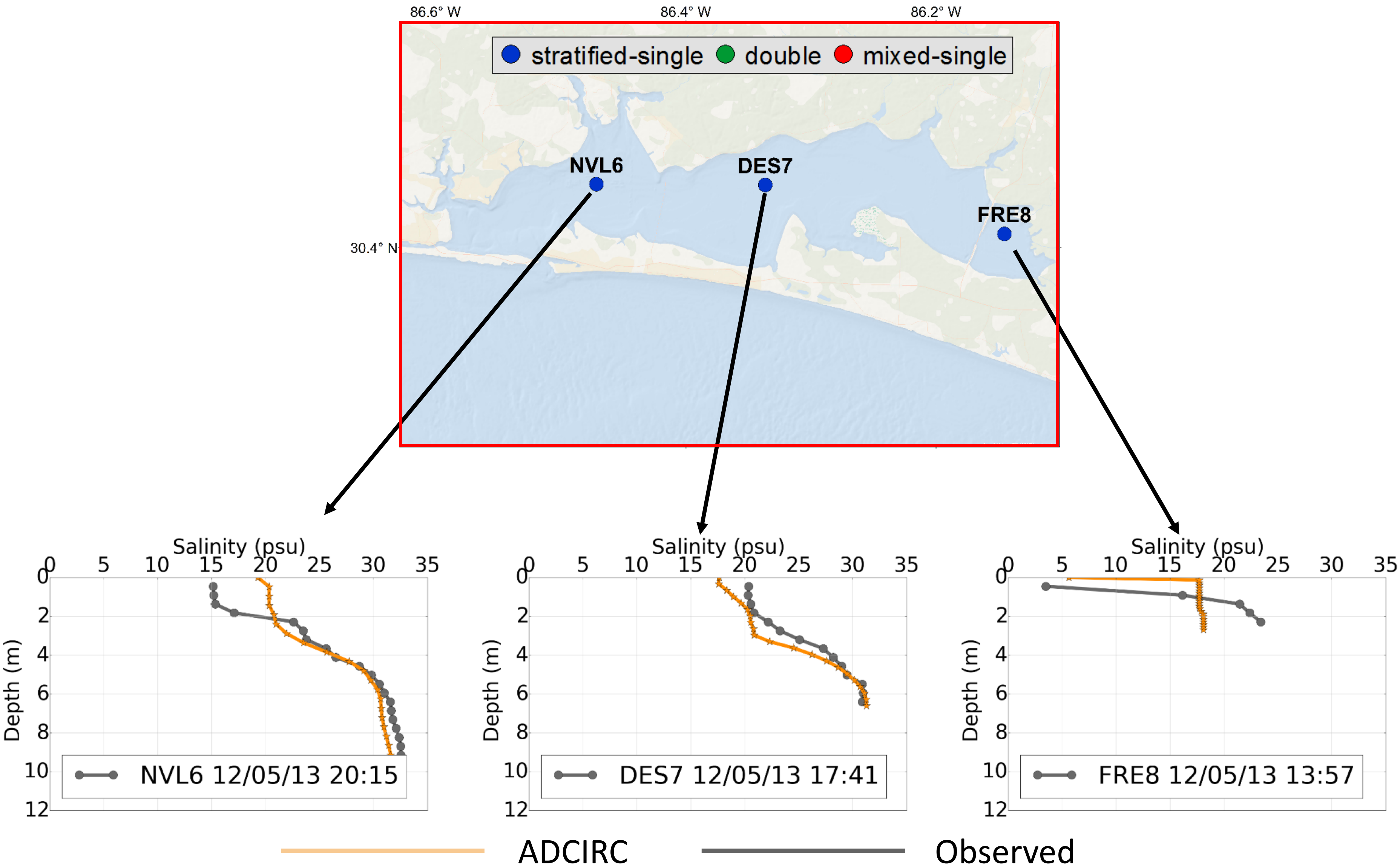








Model Validation: Vertical Salinities



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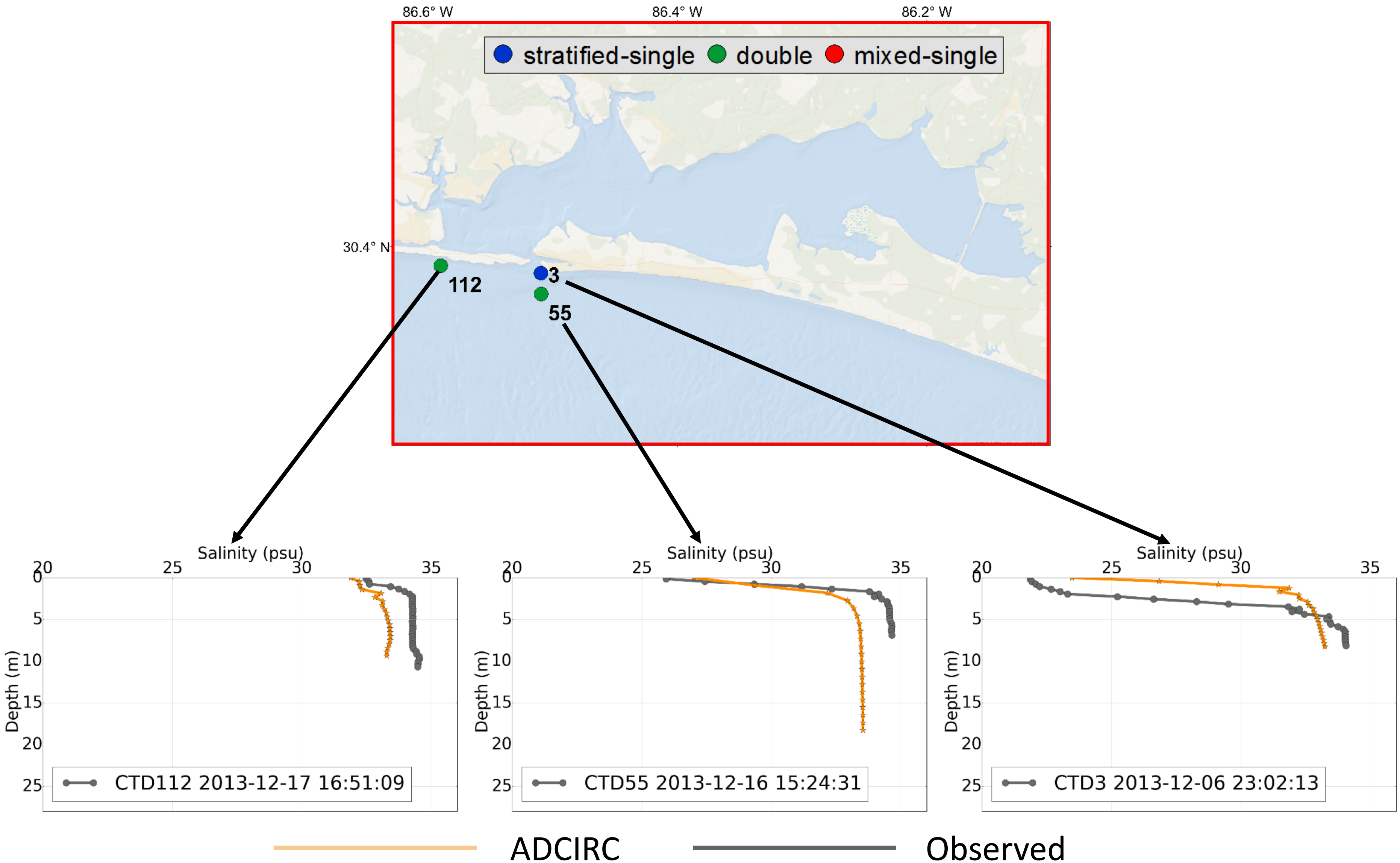

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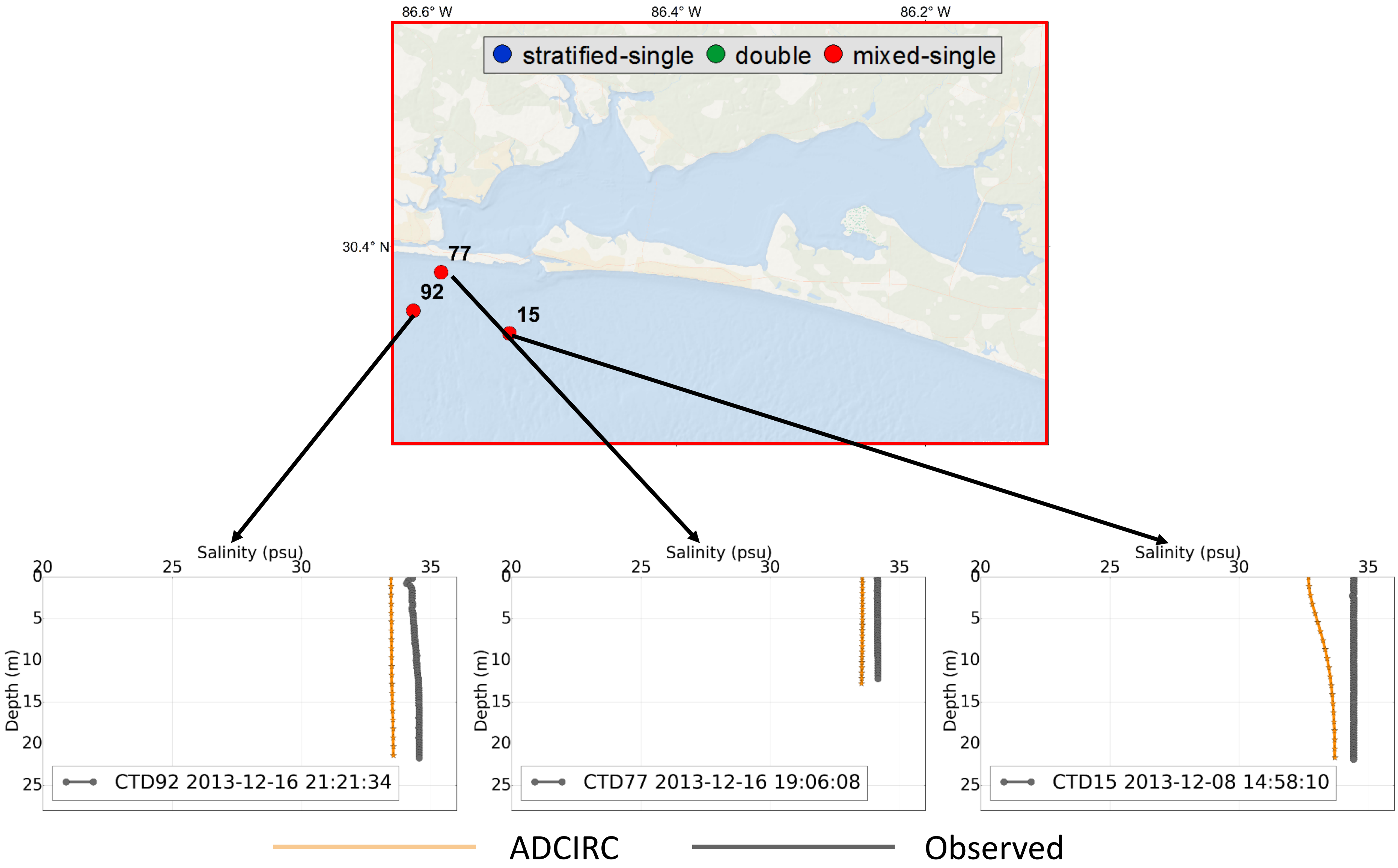
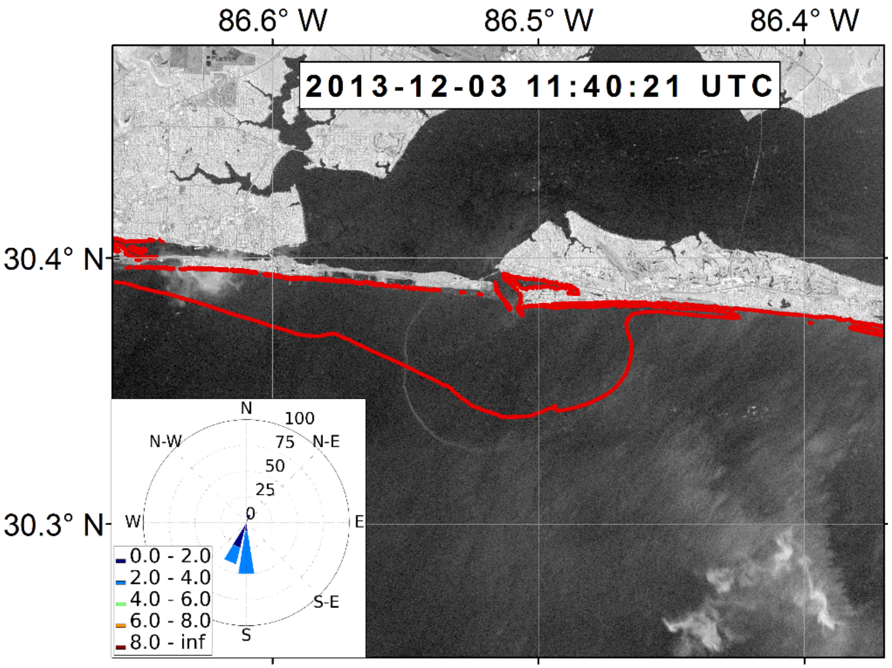
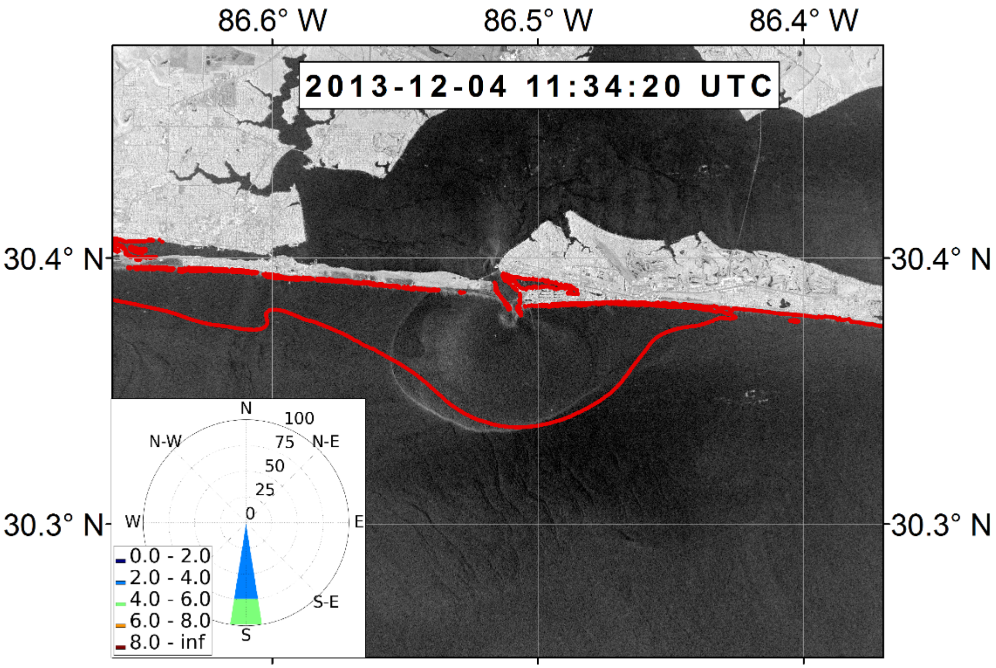


Plume Geometry via Satellite Imagery





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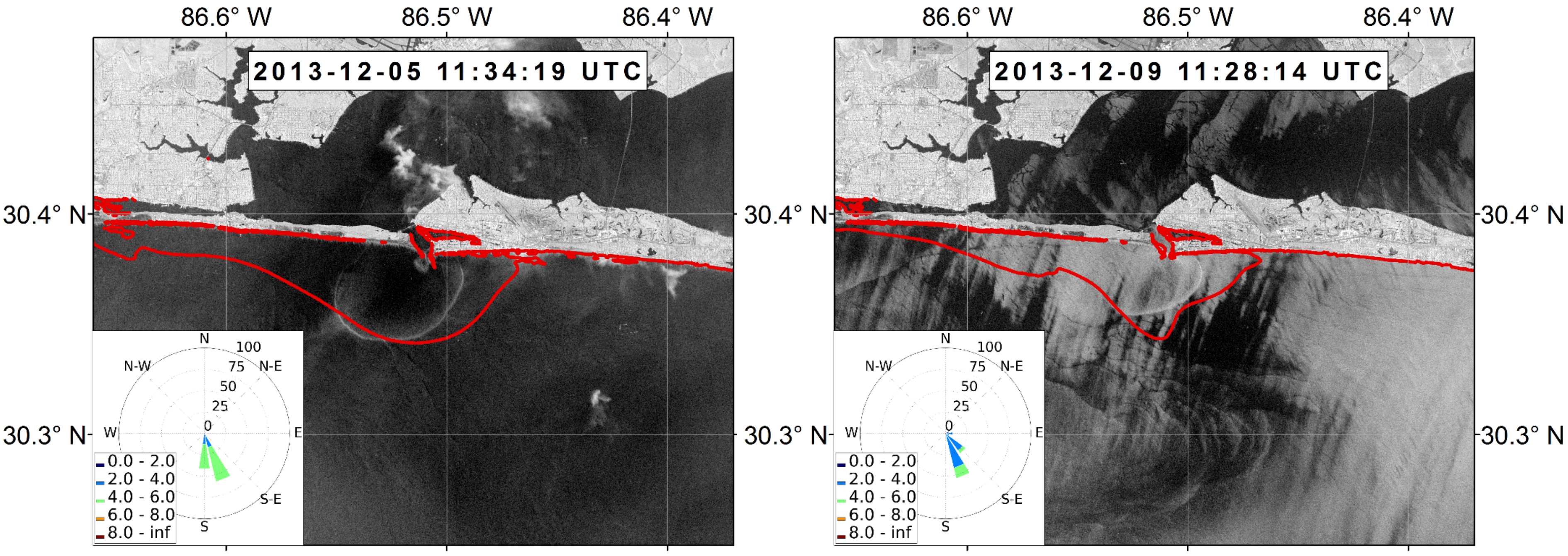

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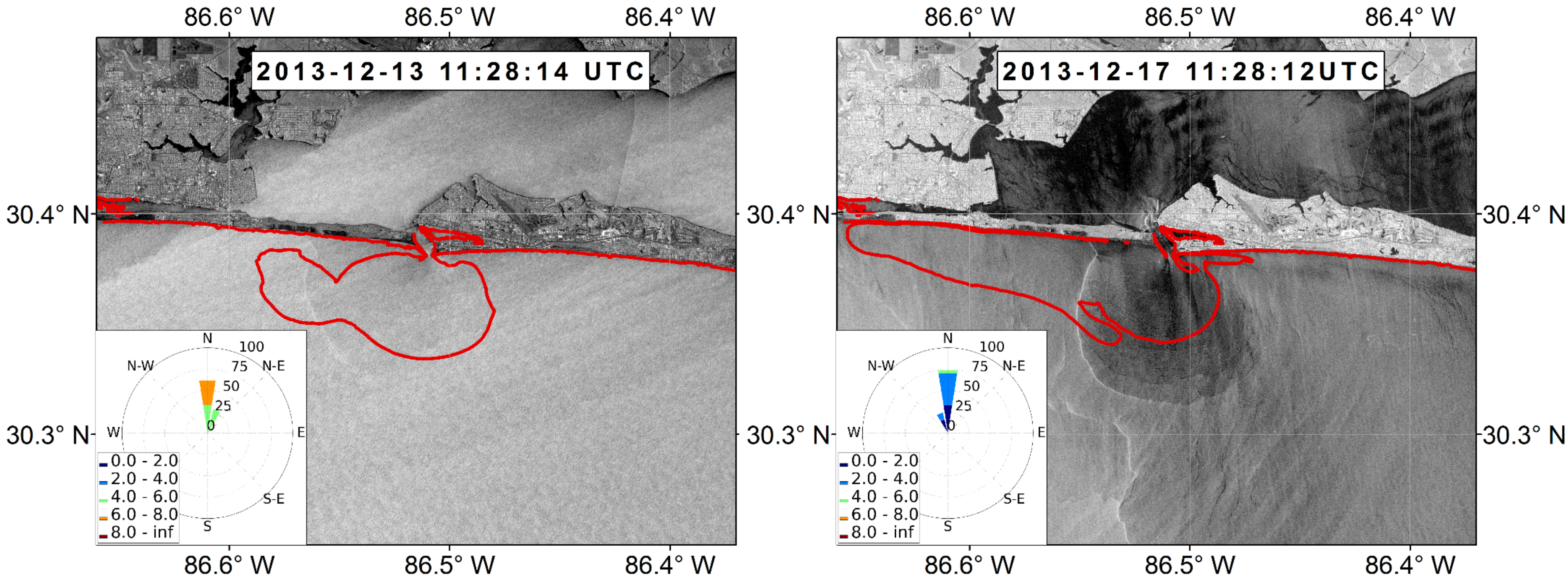
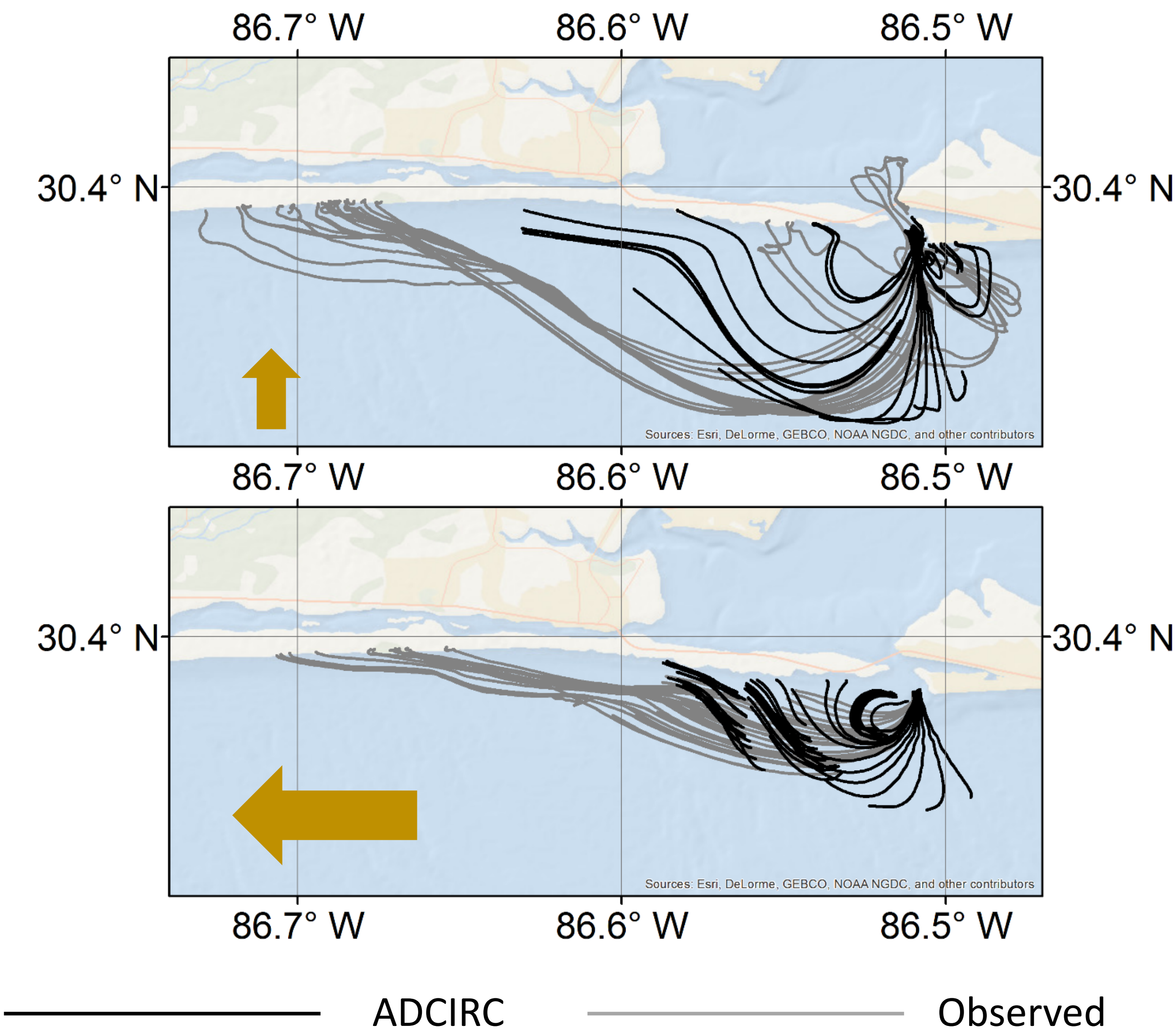
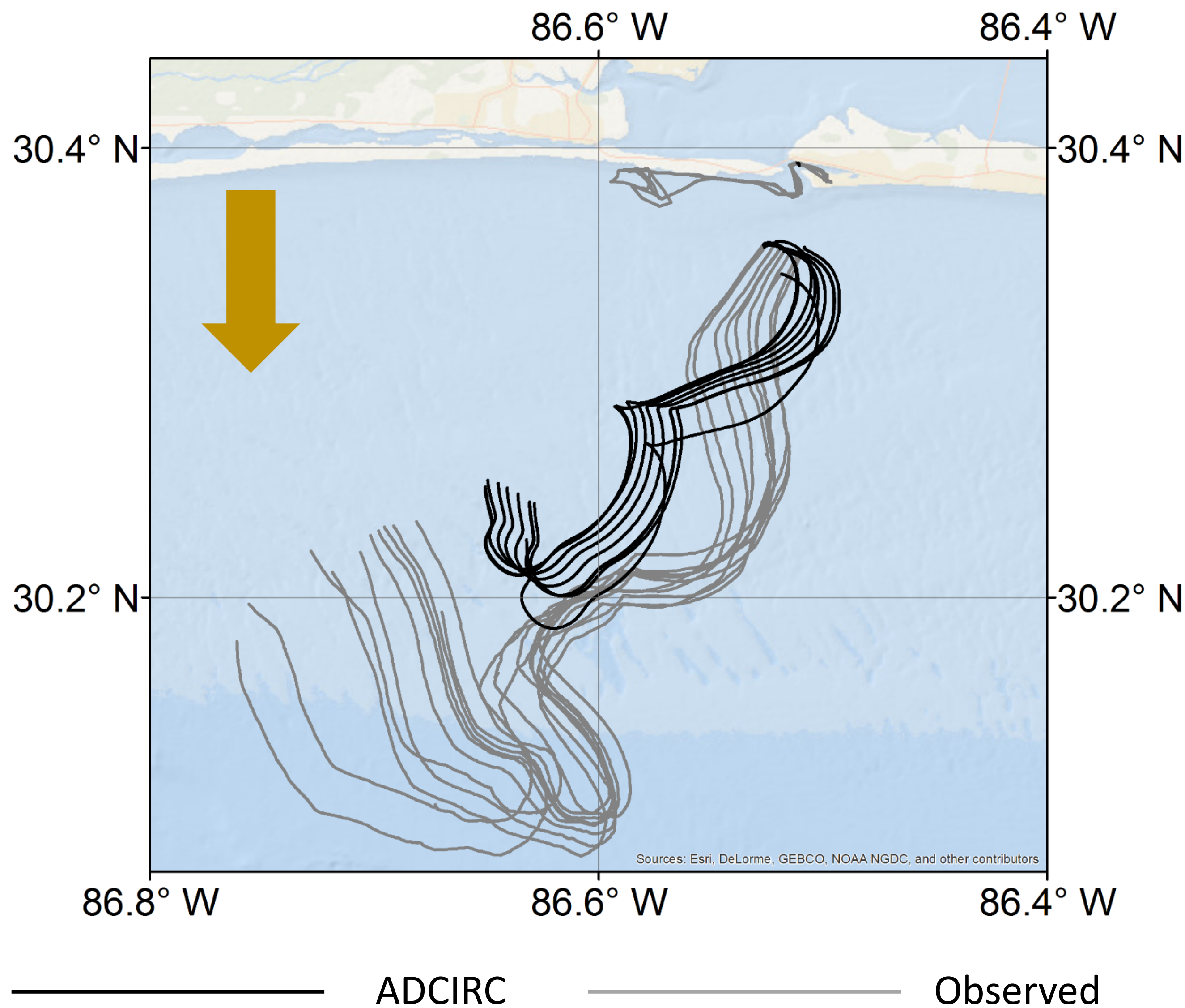


Drifter Movement



Model Validation: Drifter Movement



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Plume Dynamics

- Variability in Winds
- Plume Response to changing winds
- Plume Response to neap-spring variability in tides

Estuarine Salinity Dynamics

- Inlet Salinities
- Surface Salinities
- Vertical Stratification
- Residence Time

Summary and Conclusions

Focus Area #1: Plume Dynamics

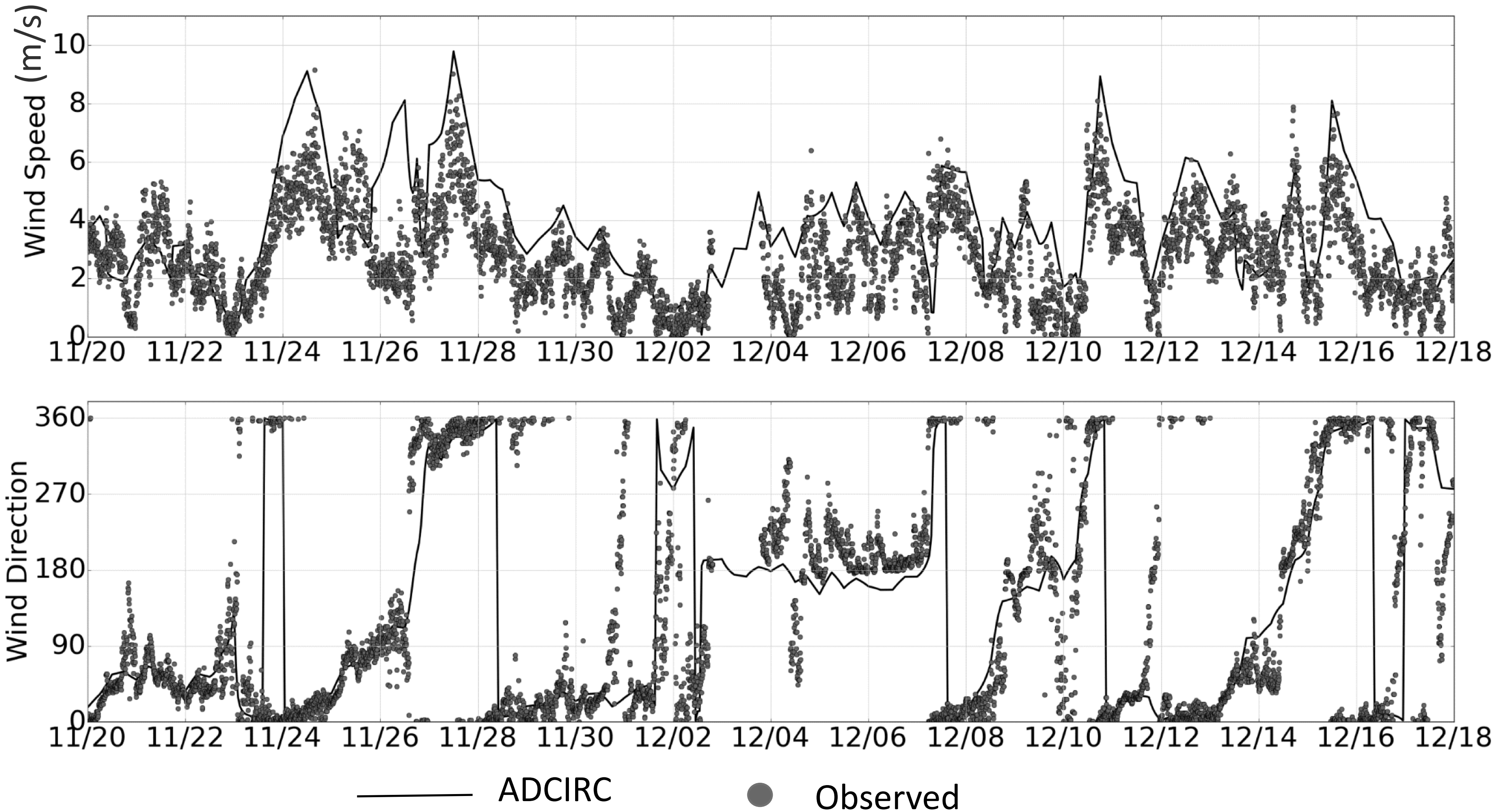
Research Objectives

How does the plume geometry change in response to passing winter cold fronts and neap to spring variability in tides?

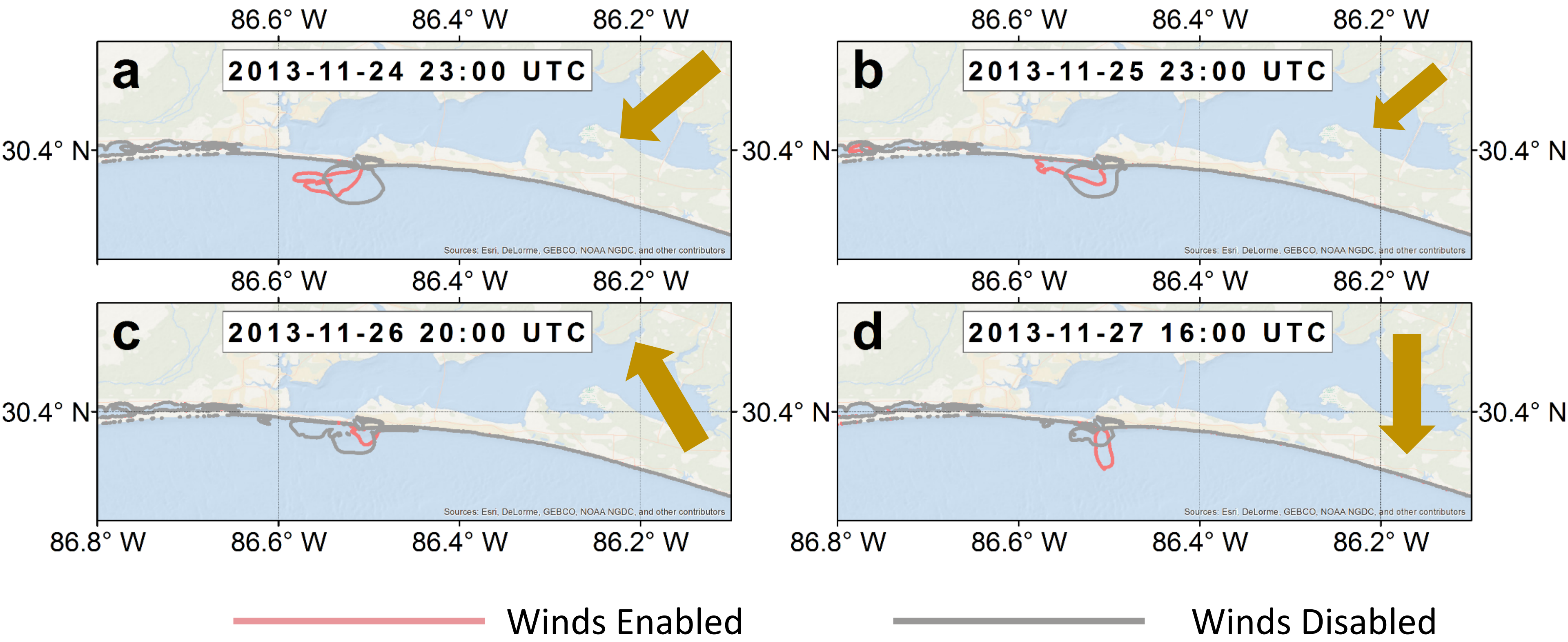
1. Investigate the response of the ebb-phase plume at Destin Inlet on consecutive days of near-constant tides and variable wind forcing

2. Investigate the response of the ebb-phase plume at Destin Inlet on consecutive days of near-constant winds and neap to spring variability in tides

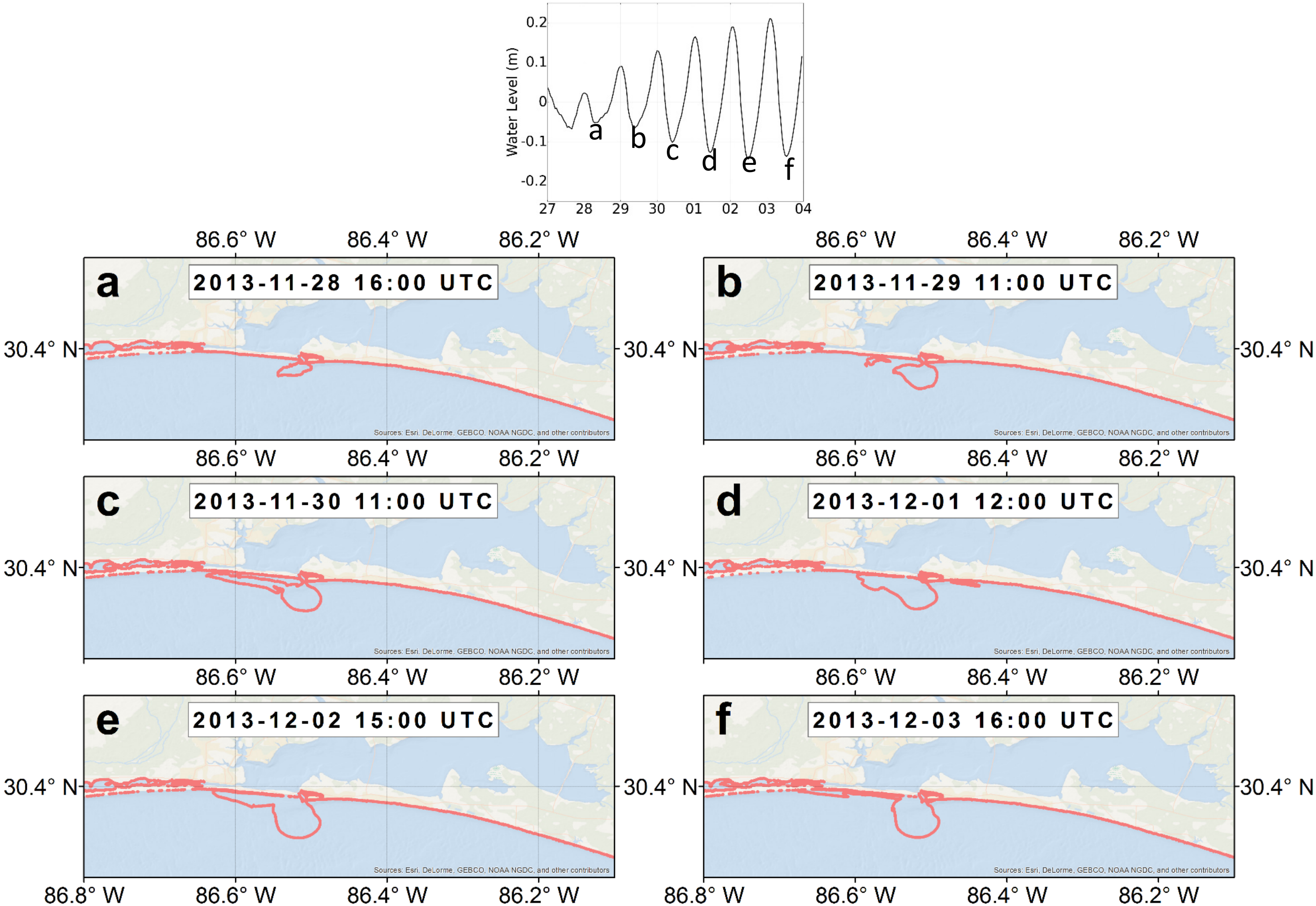
Variability in Wind Forcing



Period of near-constant tides and changing winds



Period of near-constant winds and changing tides



Outline

Model Development

- Introduction to ADCIRC
- Mesh Development and Model Setup
- Model Validation

Plume Dynamics

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Estuarine Salinity Dynamics

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Summary and Conclusions

Focus Area #2: Estuarine Salinity Dynamics

Research Objectives

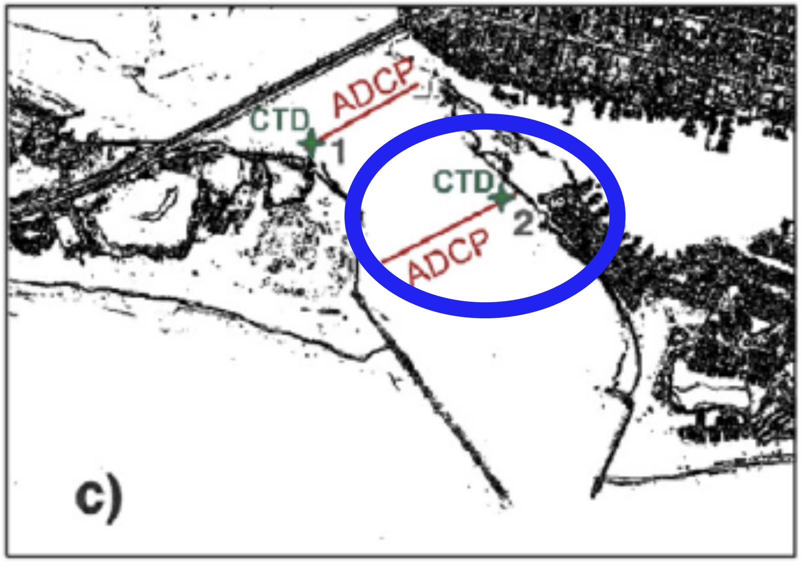
What are the key features of salinity transport within Choctawhatchee Bay during a period of low river flows?

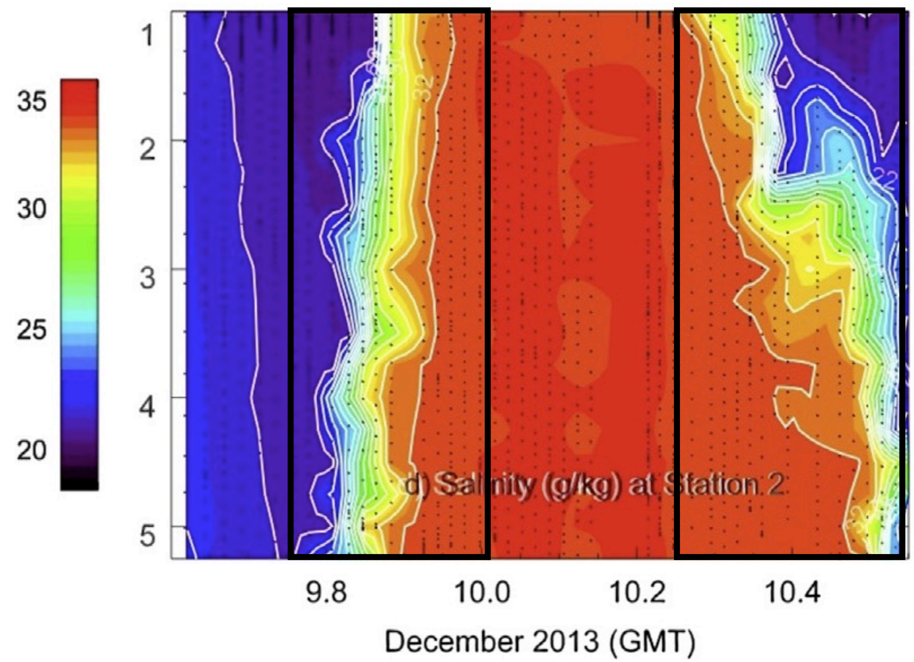
1. Behavior of the ebb- and flood-phase salinity at Destin Inlet

2. Identify trends in estuarine surface and bottom salinities from observed data and model predictions

3. Compute residence times within Choctawhatchee Bay using a lagrangian particle tracking model forced by surface currents from the validated model

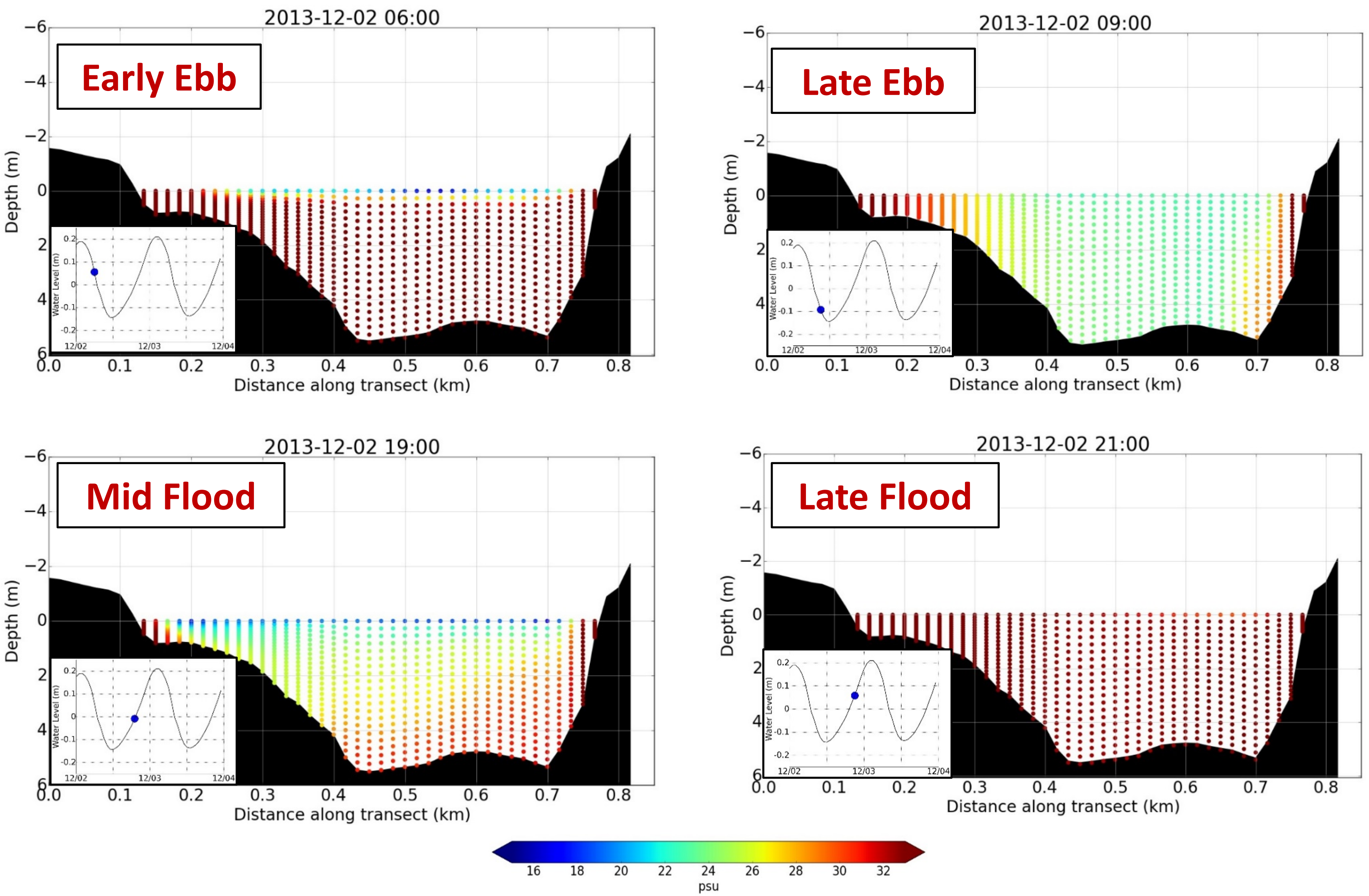
Inlet Salinities: Observed Trends (Valle-Levinson et al. 2015)



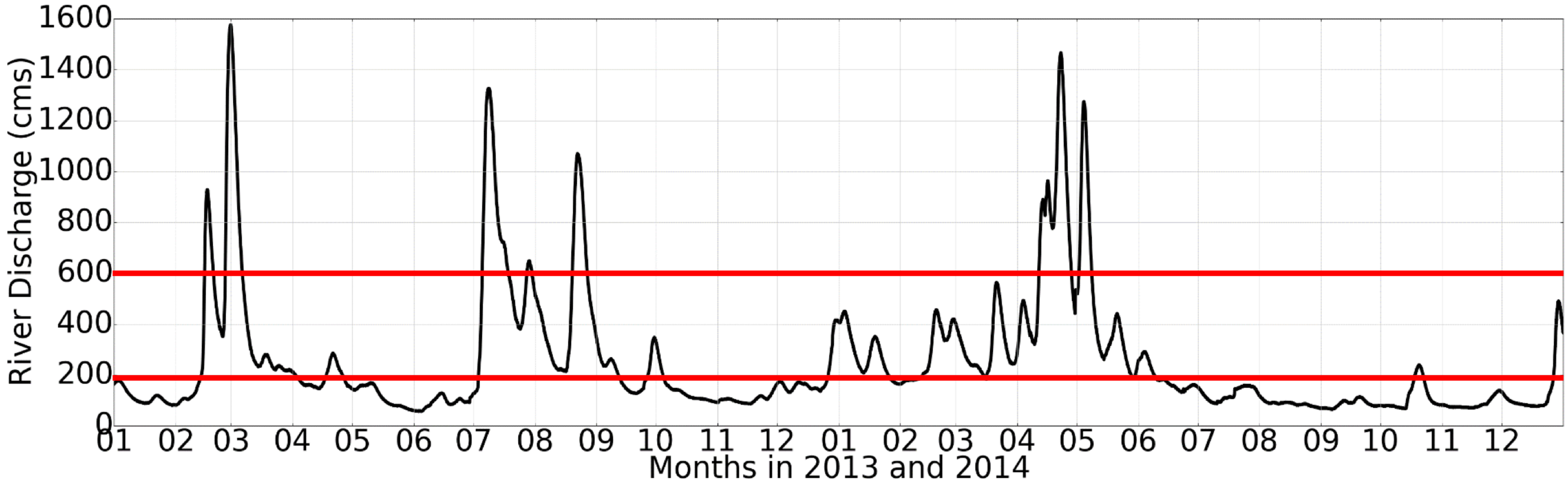


- Nearly depth-independent tidal intrusion front
  - Salinities change from 20 to 33 psu in 2 hours
- Depth dependent ebb-phase front
  - Surface changes lead bottom changes by 3.6 hours

Inlet Salinities: Model Predictions



Trends in River Discharge

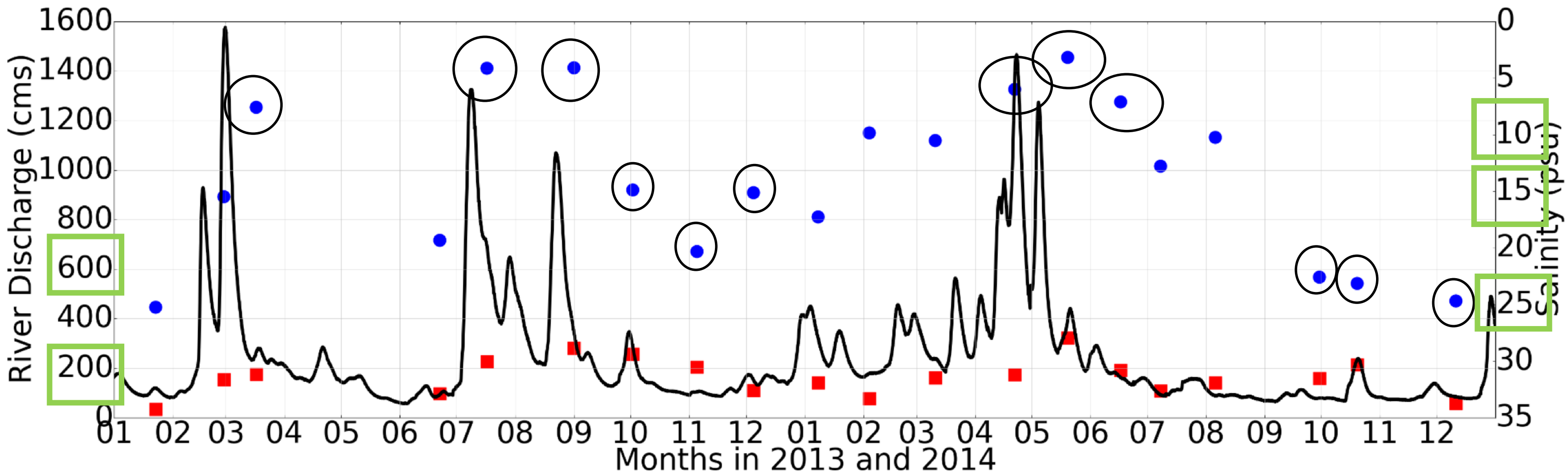


- River discharge has large seasonal variations

- Periods of high river flows (> 600 m^3/s)
  - Eg. Feb-March 2013, July-Sept 2013, and April-June 2014

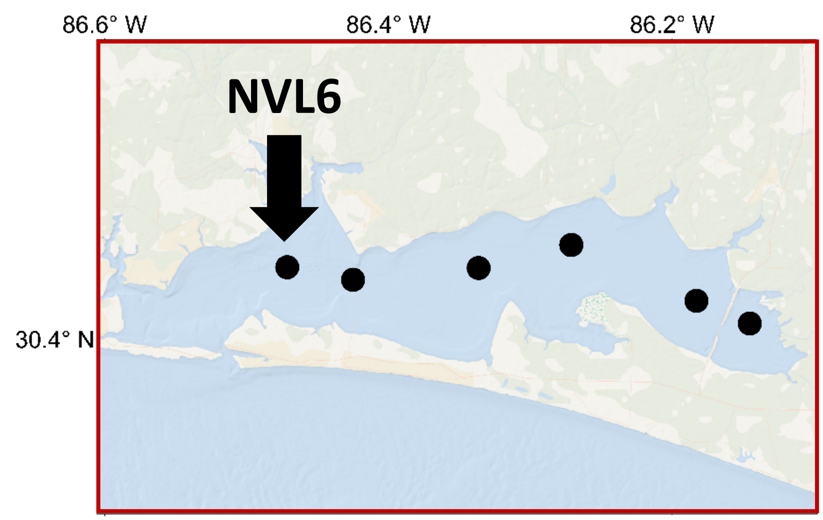
- Periods of low river flows (< 200 m^3/s)
  - Eg. Oct-Nov 2013, July-Sept 2014, and Aug-Dec 2014

Trends in Bay Salinities from Observed Data (West Bay)

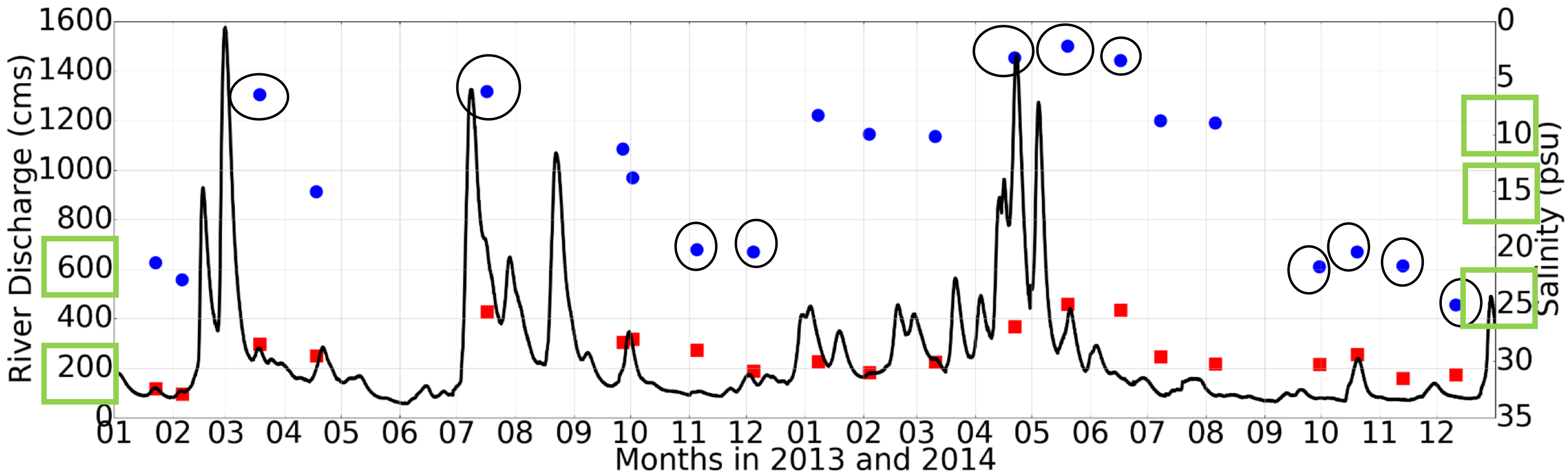


Surface Salinities

Bottom Salinities

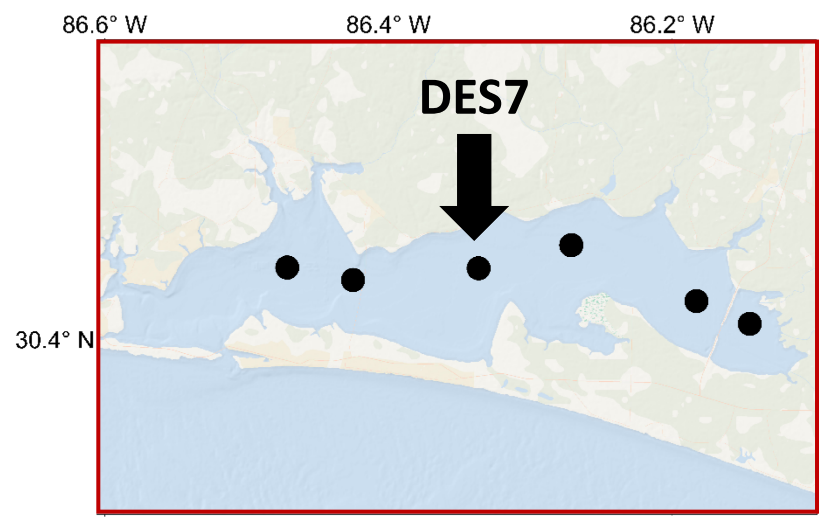


Trends in Bay Salinities from Observed Data (Mid Bay)

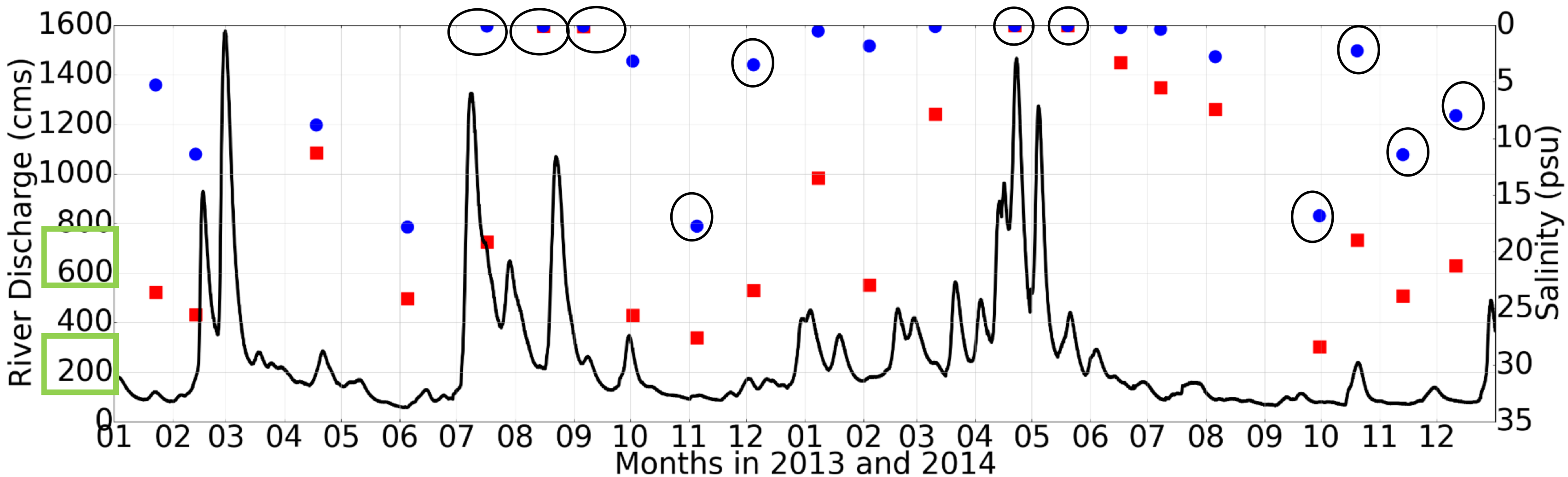


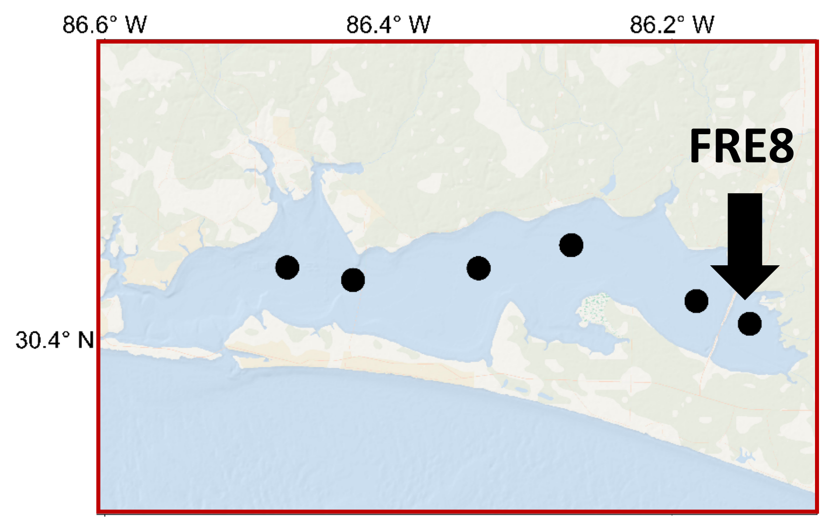
Surface Salinities

Bottom Salinities



Trends in Bay Salinities from Observed Data (East Bay)



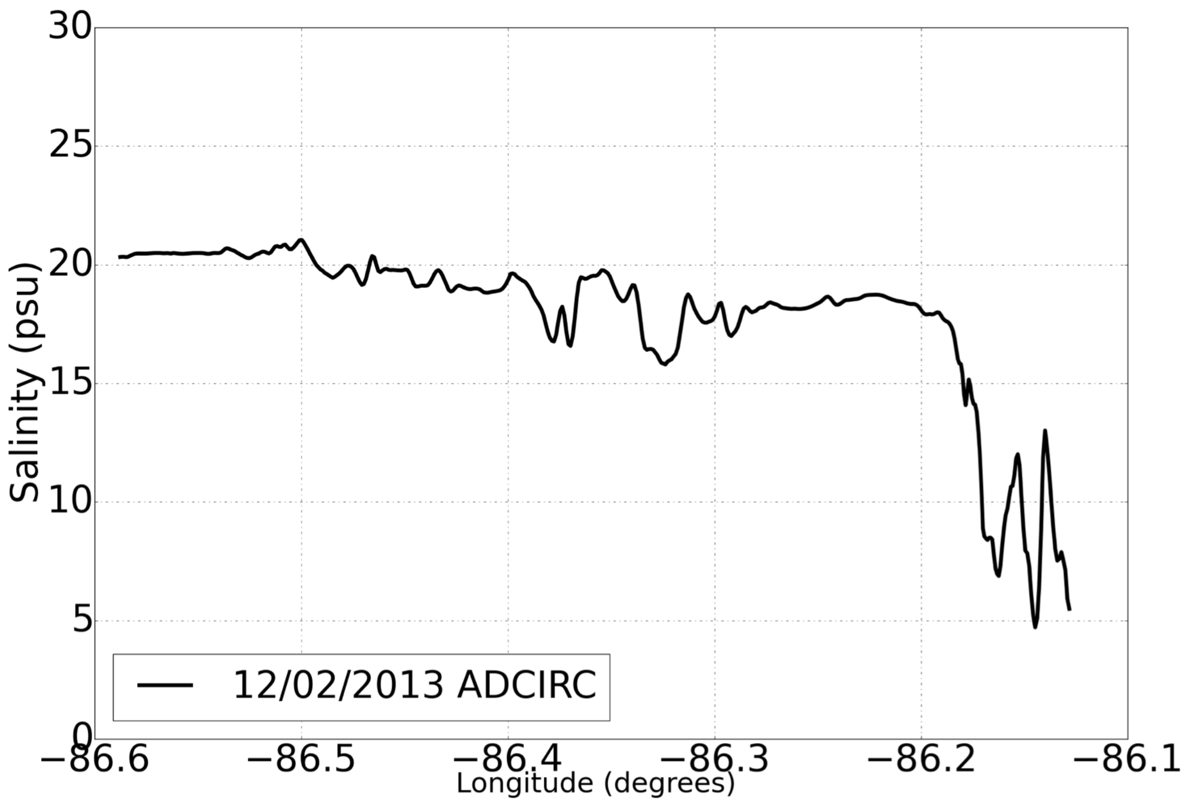


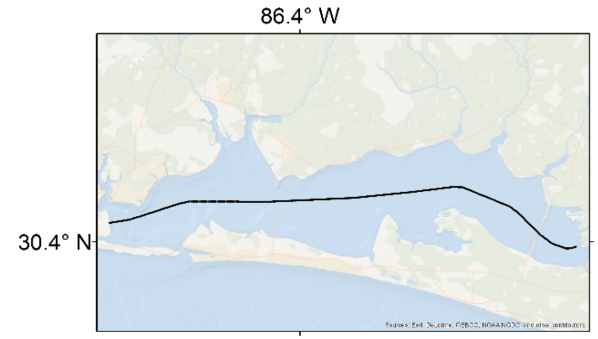
Trends in Bay Salinities from Observed Data (Summary)

- During high river flows:
    - Surface layer is fresh throughout the bay
    - Water column is fresh and well-mixed near the river mouth
    - Highly stratified conditions in mid- and west-bay

- During low river flows:
    - Surface salinities range between 15-25 psu throughout the bay with fresher conditions near the river mouth
    - Bay is highly stratified with a difference of 10 psu between surface and bottom salinities

Surface Salinities

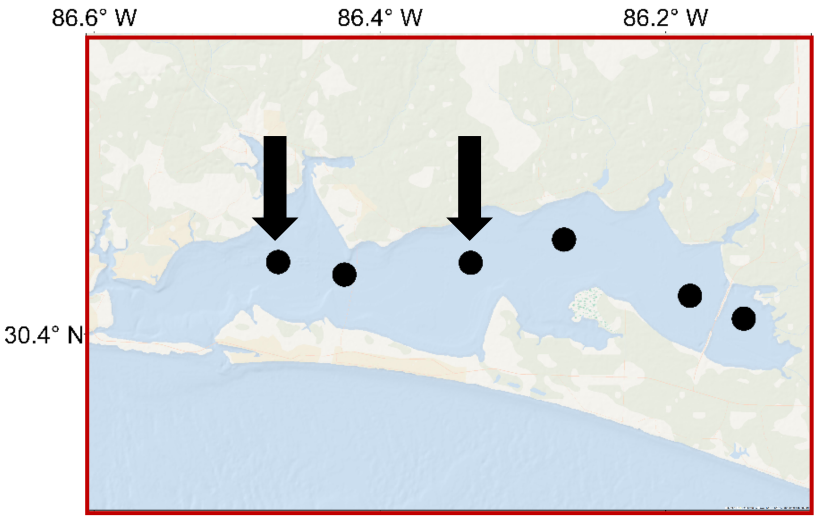


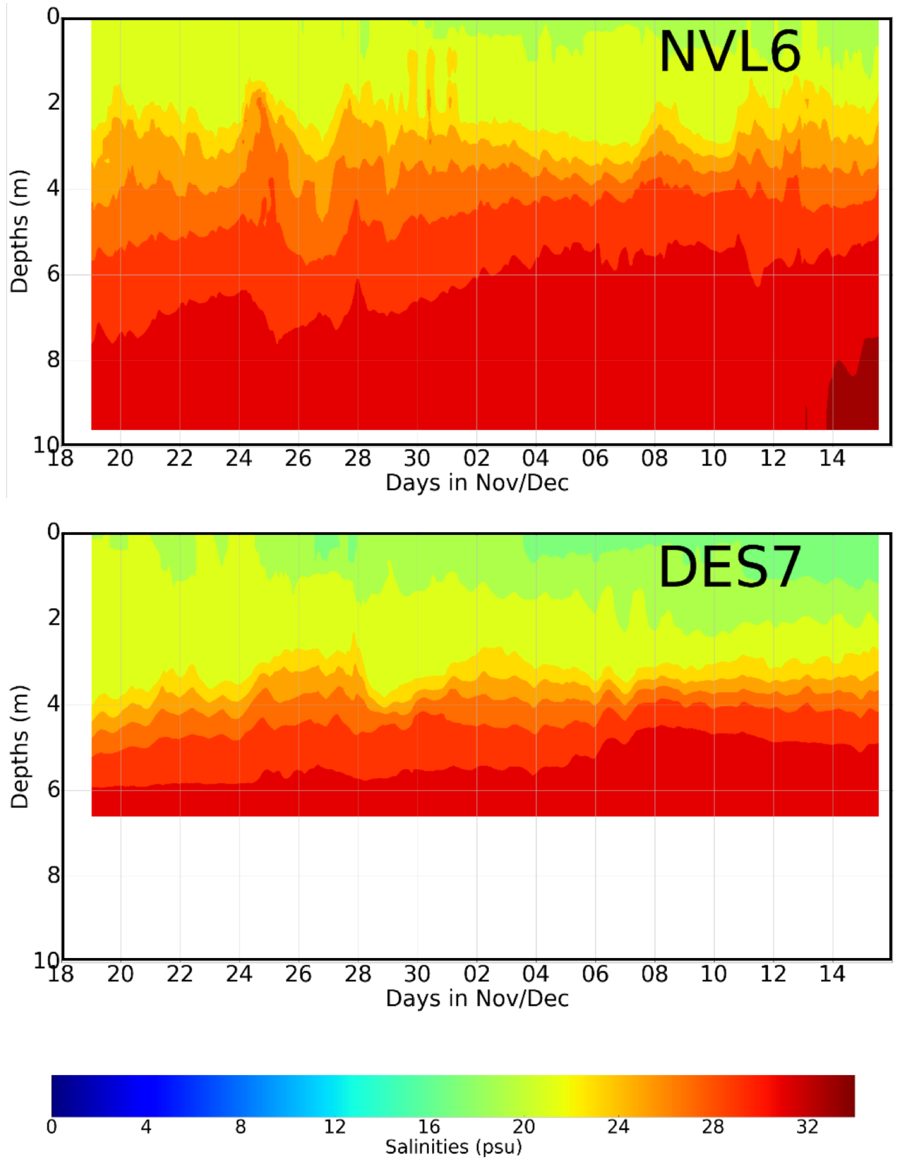


In December 2013 (river discharge equal to 150 m^3/s)

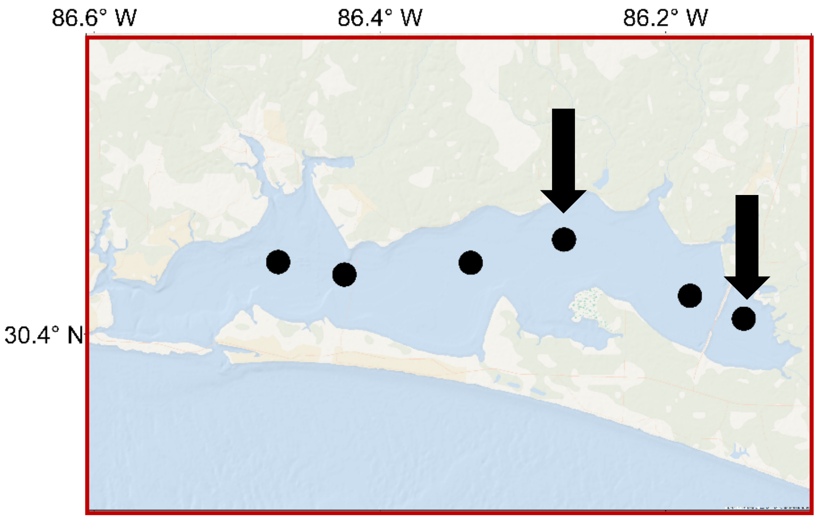
- Surface salinities are relatively constant at around 20 psu
- Freshwater conditions near river mouth

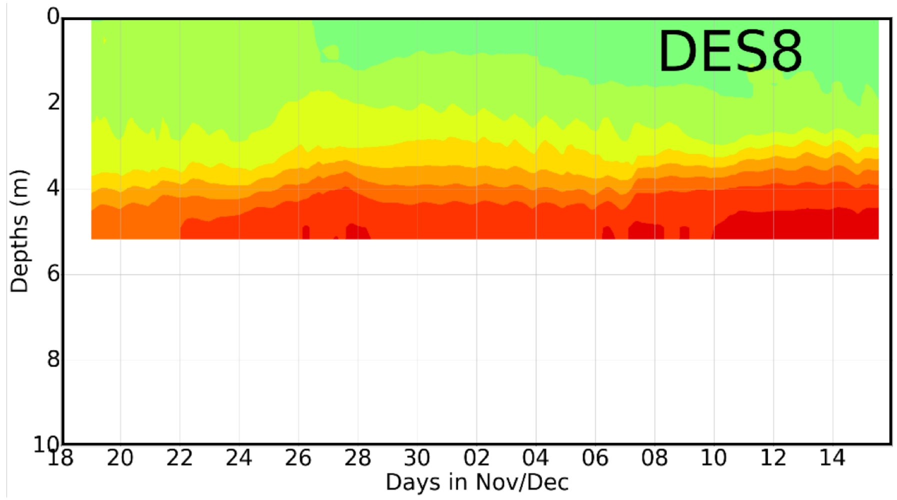
Vertical Stratification (West and Mid Bay)

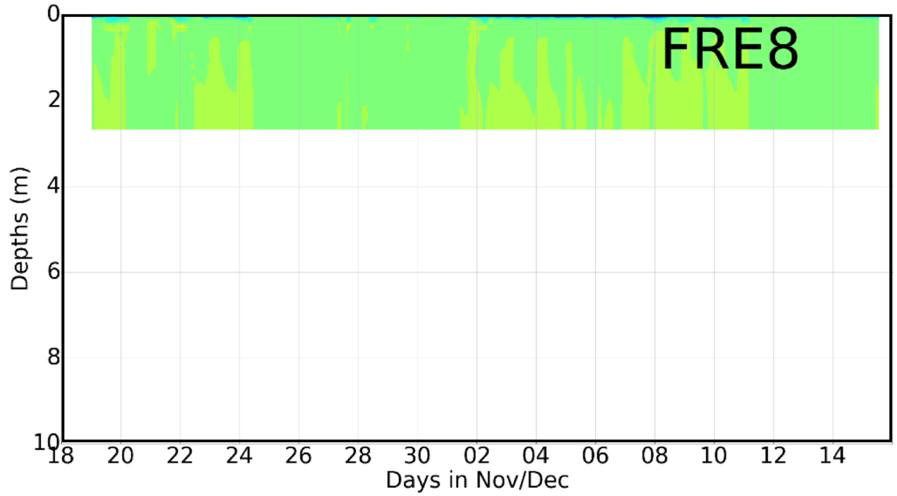


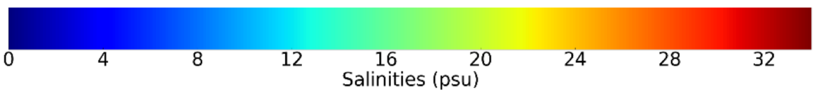


Vertical Stratification (West and Mid Bay)

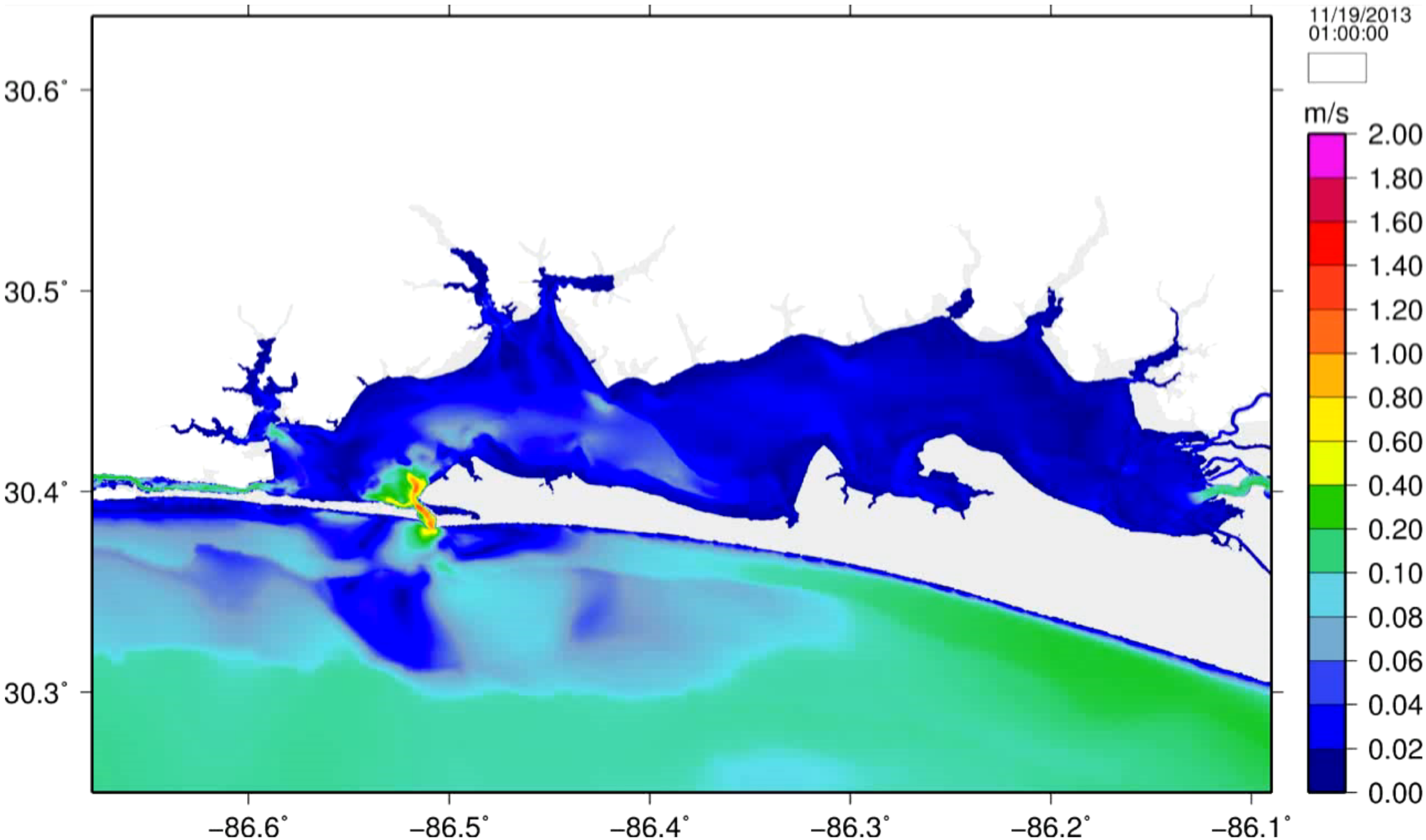








Residence Time



It takes about 36 days for a particle released at the river mouth to exit the inlet.

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Model Development and Validation

- Recently enhanced baroclinic ADCIRC model applied with improvements to represent the shelf-estuarine circulation in the vicinity of Choctawhatchee Bay
- Model validation efforts demonstrate model's ability to represent key features of the circulation and salinity transport

Plume Dynamics

- Plume geometry on consecutive days is different due to changes in wind & tidal forcing
  - Northerly winds enhance offshore expansion whereas southerly winds confine plume near the coastline
  - Plume expands west along the coastline under prevailing easterly winds
  - When wind forcing is disabled the plume expands out radially near the inlet

Summary and Conclusions

Estuarine Salinity Dynamics

- During a period of low river flows
  - Surface salinities stay constant throughout the bay except near the river
  - At Destin, the ebb-phase plume is surface advected whereas the flood-phase plume is bottom advected
  - Highly stratified conditions inside the bay
  - Residence times within the bay are of the order of 1 month

Future Work

- Incorporate more realistic representation of Choctawhatchee River

- Apply a range of different river discharges and investigate bay salinities

Thank You!