Wind and Plume Driven Circulation and Surface Transport in Estuarine Systems

Ph.D. Research Proposal
October 10, 2017

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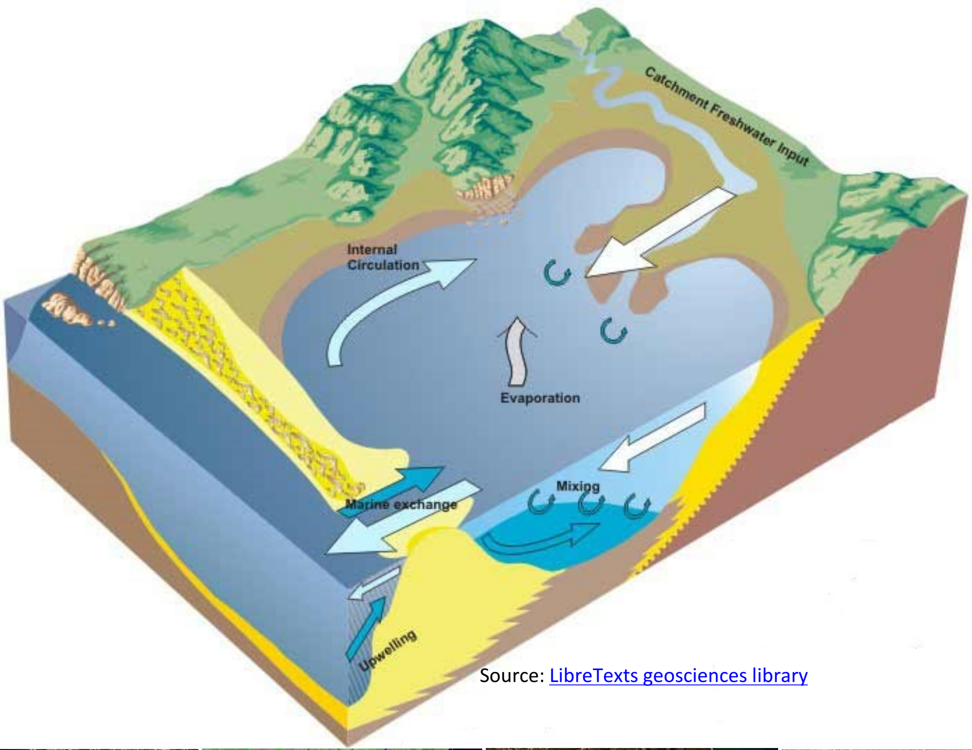
Estuaries

- "Semi-enclosed coastal bodies of water …. within which sea water is measurably diluted with fresh water …..'' (Cameron and Pritchard, 1993)
- Also known as bay, sound or lagoon
- Tides, winds, river inflows and density gradients drive the circulation
- Provides many ecosystem services: source of food, flood protection, nutrient traps, scenic and recreational value



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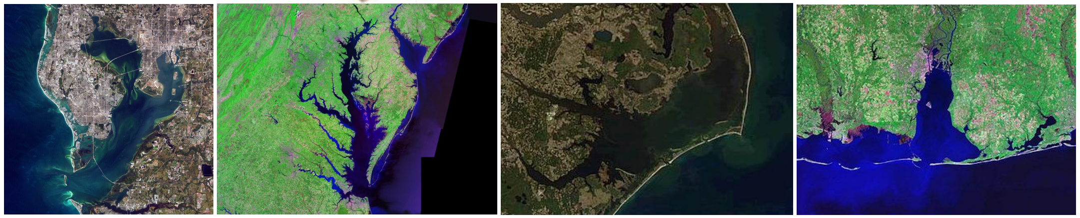
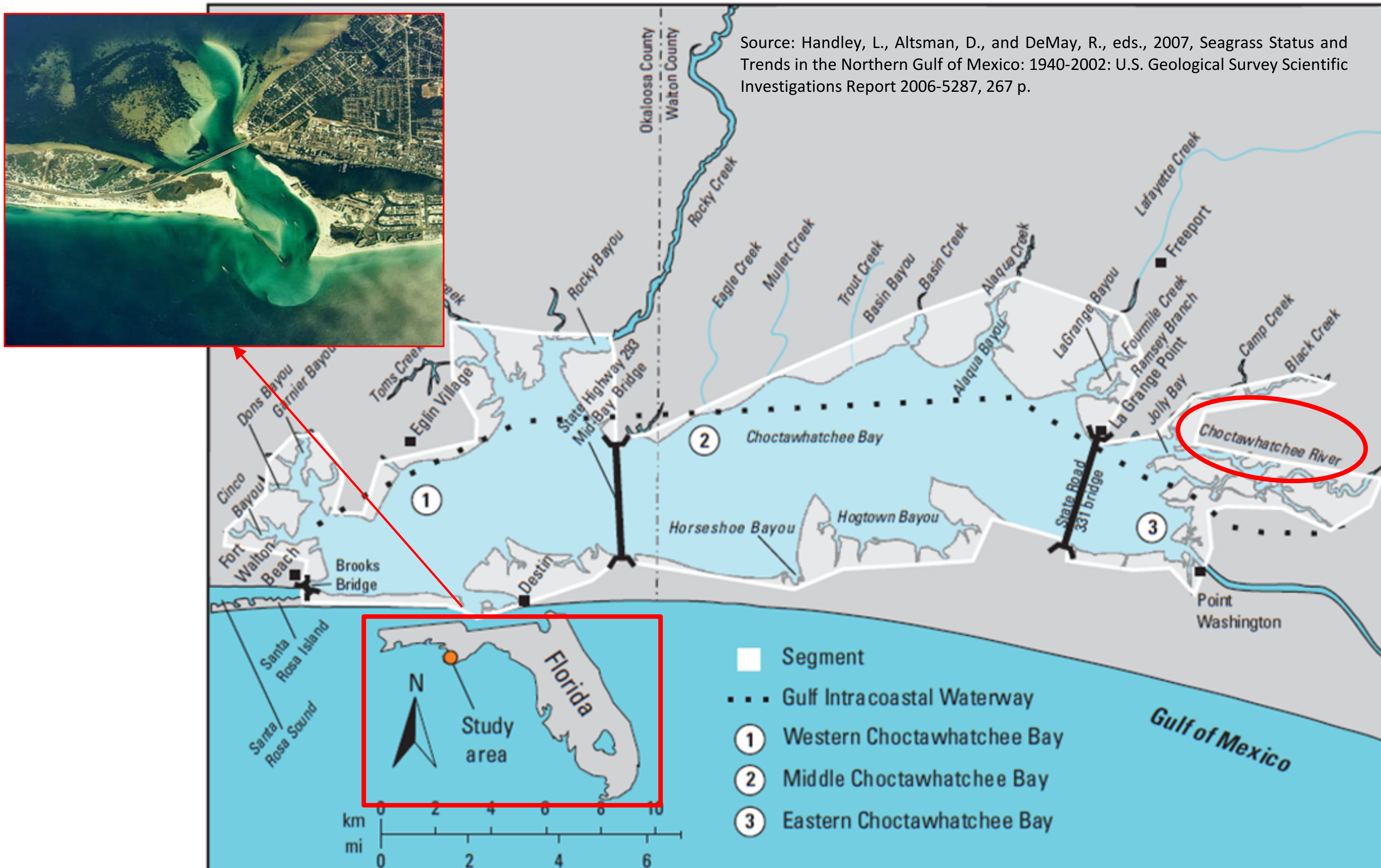


Study Area: Choctawhatchee Bay and Destin Inlet



Surfzone Coastal Oil Pathways Experiment (SCOPE)

- To understand the processes that are important for surface transport, both for oil spills and other pollutants, as well as for natural materials.

- Performed by CARTHE scientists between December 3-17, 2013

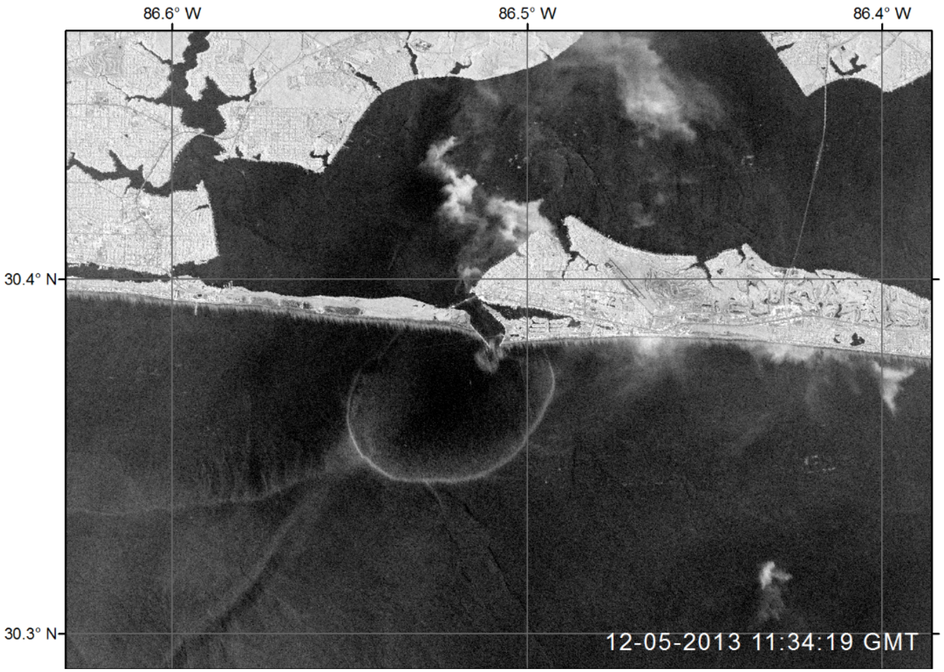
- With the help of:
  - Surface drifters
  - Dye Releases
  - Drones
  - Jetskis
  - Small boats
  - Helicopters
  - ADCPs
  - CTD casts

Source: CARTHE Facebook page

Focus Area #1: Wind and Plume Effects at Destin Inlet

Focus Area #2: Circulation in Choctawhatchee Bay

Focus Area # 1: Wind and Plume Effects at Destin Inlet



Source: COSMO-SkyMedâ¢ Product Â©ASI 2013 processed under license from ASI â Agenzia Spaziale Italiana. All rights reserved. Distributed by e-GEOS. Downlinked and processed by CSTARS.

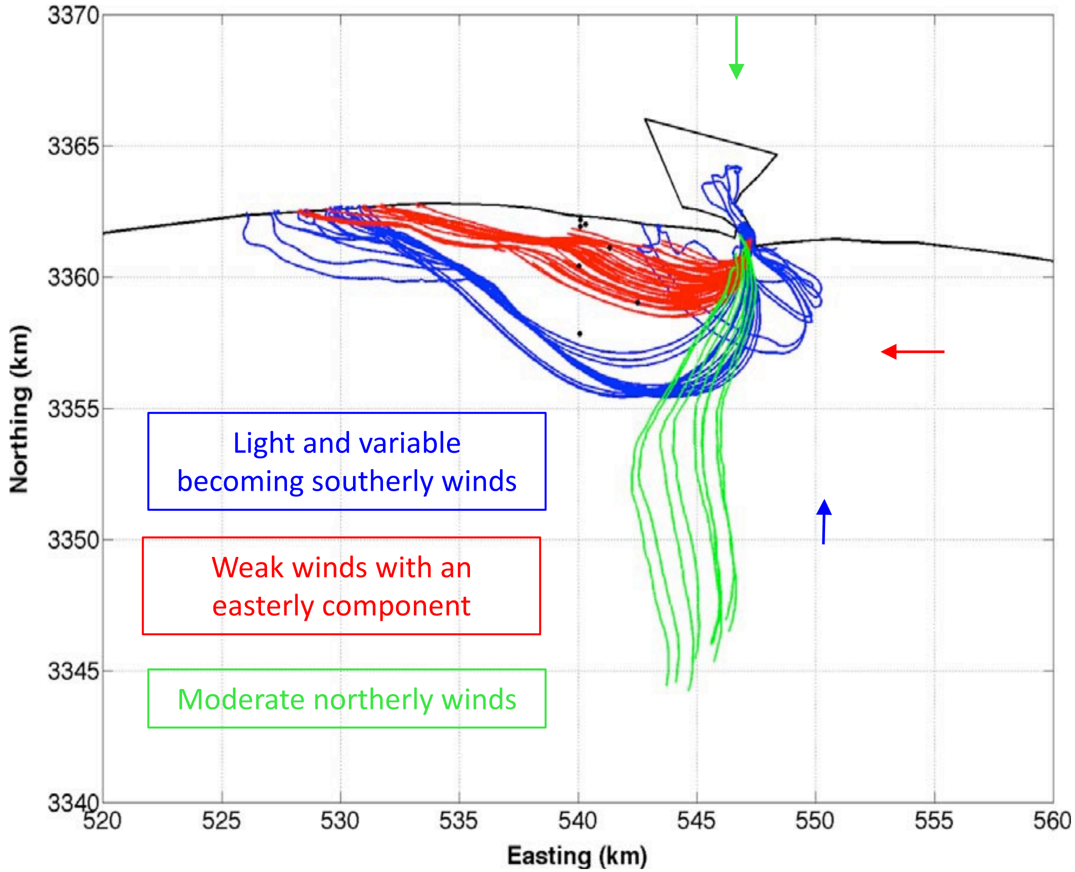
Source: CARTHE Facebook page

- Freshwater river discharge that enters an estuary can flow out into the coastal ocean as brackish, buoyant plumes
- Surface material slows down and converges along the plume edges due to the density differences across the plume front
- SCOPE datasets recorded the presence of a distinct ebb-phase plume at Destin Inlet

Focus Area # 1: Wind and Plume Effects at Destin Inlet

Background and Motivation

- SCOPE drifter releases during the ebb phase revealed variability in plume orientation during different wind conditions (Roth et al. 2016)
  - During light and variable winds plume expanded offshore radially
  - During winds with an easterly component plume turned west and formed a coastal jet along the coast

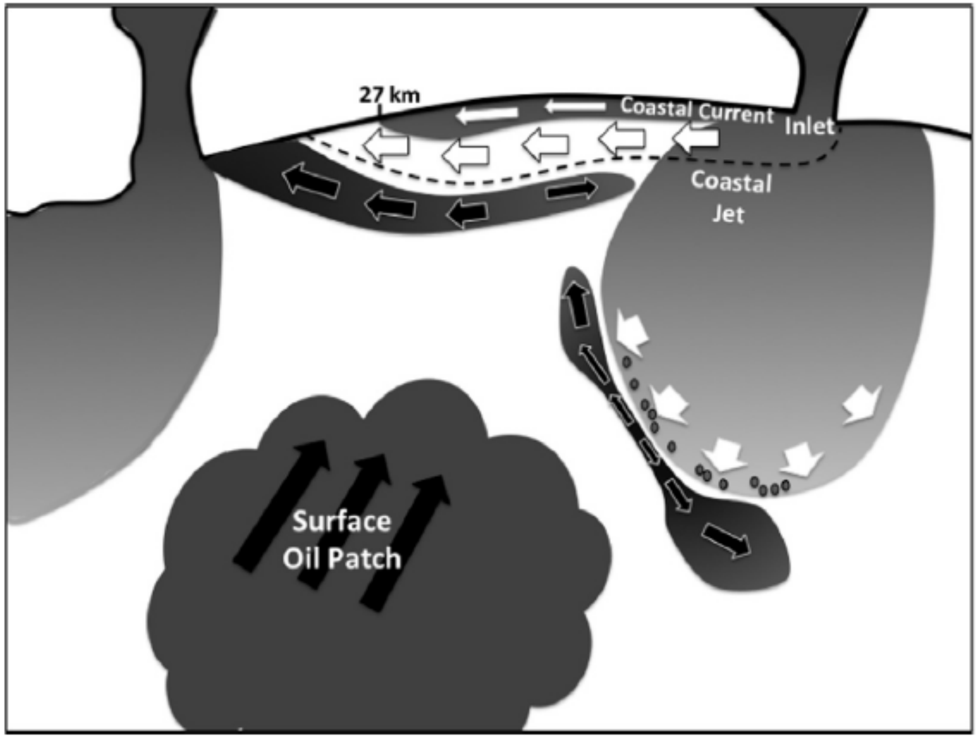


Source: Roth et al. 2016

Focus Area # 1: Wind and Plume Effects at Destin Inlet

Background and Motivation

- Roth et al. 2016 suggested that the plume acts as a **natural barrier that prevents beaching within 27 km west of the inlet** during**:**
    - Winds with an easterly component
    - Light and variable winds
- **Present research aims to explore the effects of plume variability on the surface transport at Destin Tidal Inlet**



Source: Roth et al. 2016

Focus Area # 1: Wind and Plume Effects at Destin Inlet

Research Hypotheses

1. The volume transport and ebb- and flood- phase fronts at Destin Inlet are sensitive to wind effects.

2. The effectiveness of the ebb-phase plume to act as a natural barrier to surface transport at Destin Inlet can vary with wind forcing

Research Objectives

1. Compute volume flow rates at Destin Inlet and examine their sensitivity to wind forcing

2. Quantify variability in the signature of the ebb-phase plume at Destin Inlet during different wind conditions.

3. Perform scenario-based testing with hypothetical drifters to determine surface transport characteristics in the vicinity of the inlet.

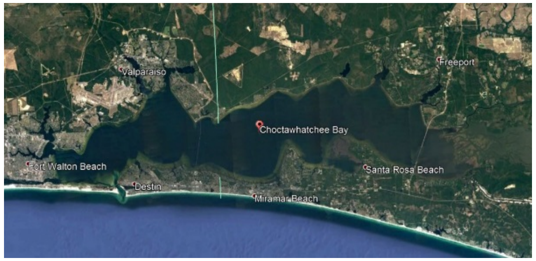
Focus Area #1: Wind and Plume Effects at Destin Inlet

Focus Area #2: Circulation in Choctawhatchee Bay

Focus Area #2: Circulation in Choctawhatchee Bay

Background and Motivation

- The bay supports unique and diverse ecosystems that are of great aesthetic and economic value
- Limited knowledge about hydrodynamic and transport in the bay
  - Last comprehensive studies date back to the 1980's (Livingston, 2010)
  - Stratified conditions with limited flushing (NWFWMD, 2016)
  - Zones of distinct salinity gradients (Hoyer 2010)
- Knowledge of the key features of the bay hydrodynamics and transport is critical for planning management strategies to preserve the bay ecosystems
- Proposed study would be first of its kind for Choctawhatchee Bay



Focus Area #2: Circulation in Choctawhatchee Bay

Research Hypotheses

1. The Choctawhatchee Bay contains distinct zones with varying spatial salinity gradients
2. Wind forcing influences the residence times, flushing rates and the salinity intrusion lengths in the bay.

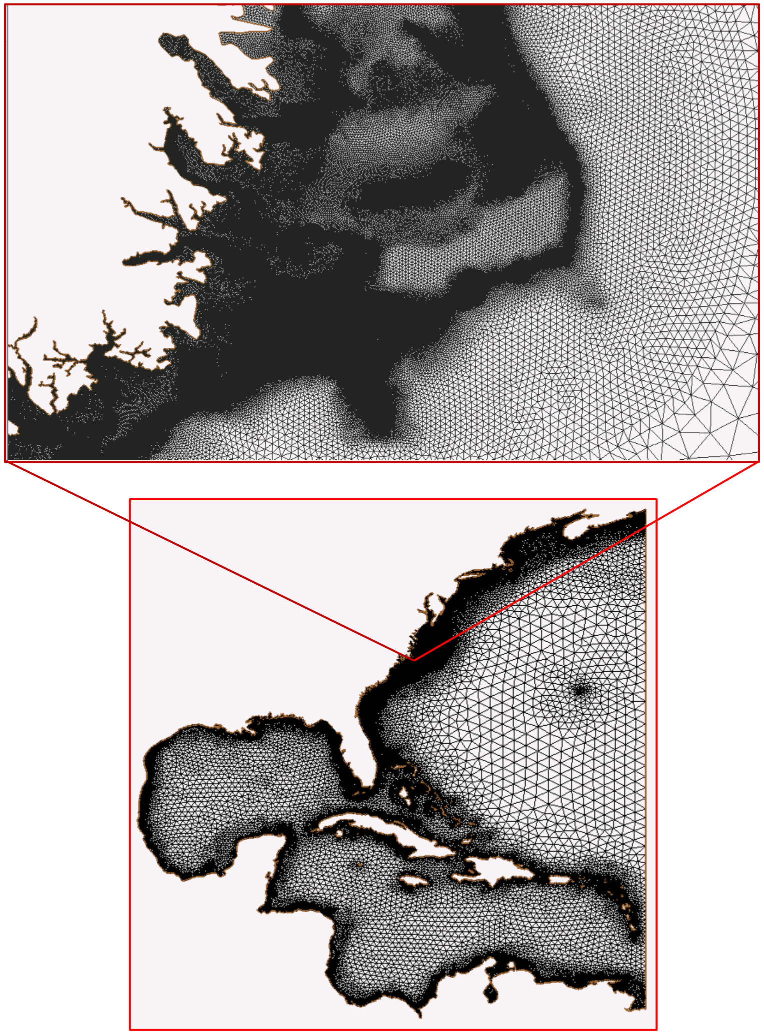
Research Objectives

1. Investigate trends in the daily mean flood- and ebb-phase surface salinities in the eastern, middle and western part of the bay
2. Compute the residence times and flushing rate for Choctawhatchee Bay and check for their sensitivity to wind effects
3. Investigate factors that influence the salinity intrusion length in Choctawhatchee Bay

Research Methods: Numerical Modeling

ADCIRC (Advanced CIRCulation)

- Finite element near-shore ocean circulation model
- Uses large unstructured grids that represents the multiple spatial scales of the open ocean, continental shelf, coastlines and floodplains with triangular elements
- Two-dimensional depth averaged version (2DDI) extensively used for storm surge modeling and predicting the flooding of low lying coastal areas
- Present study is an application of a recently enhanced baroclinic ADCIRC



Research Methods: Numerical Modeling

Part 1: Illustration of 2DDI modeling using ADCIRC to study flooding impacts within estuaries

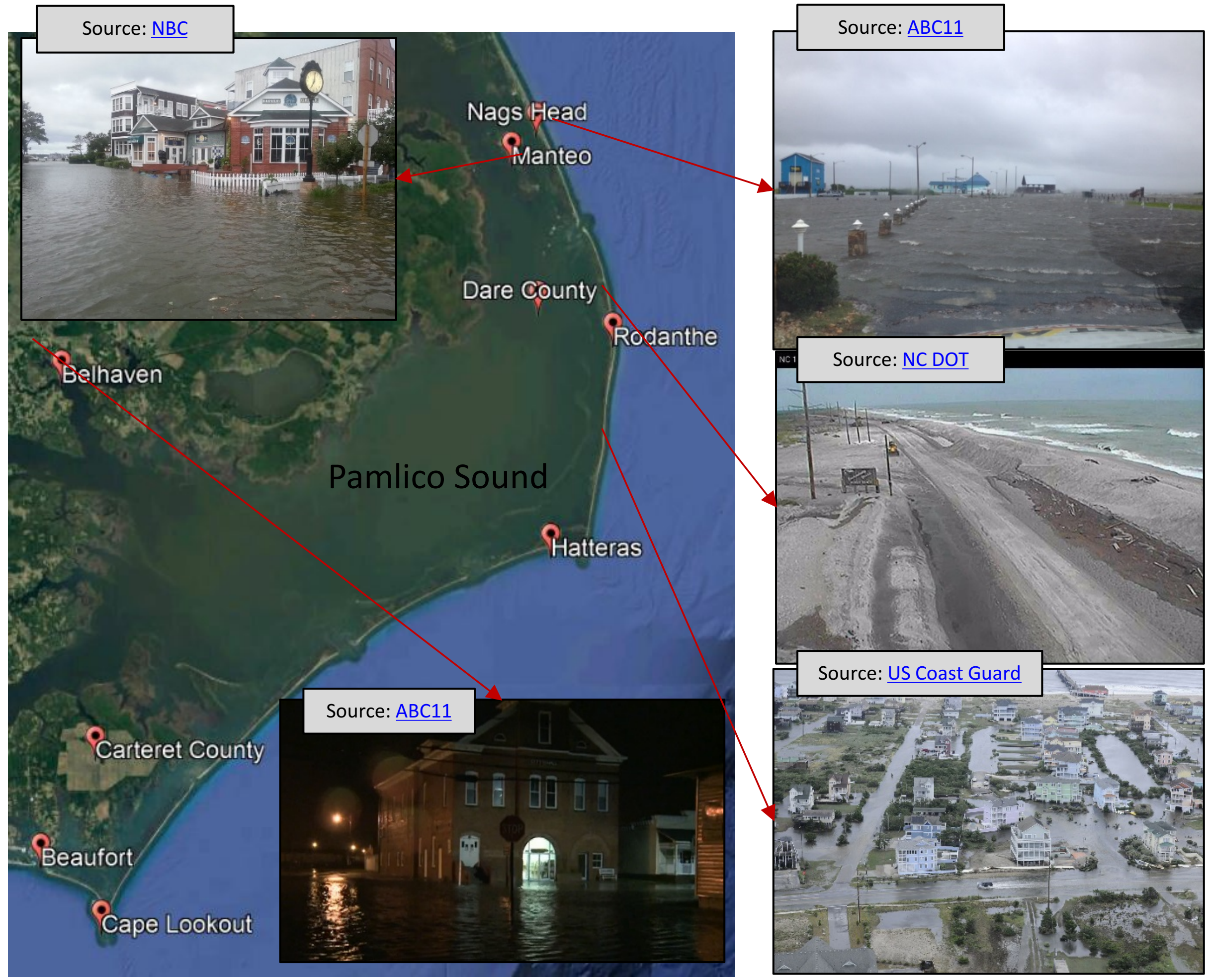
- Case Study: Effects of Hurricane Arthur (2014) in Pamlico Sound, North Carolina

Part 2: Application of 3D baroclinic ADCIRC to study density driven flows in estuaries

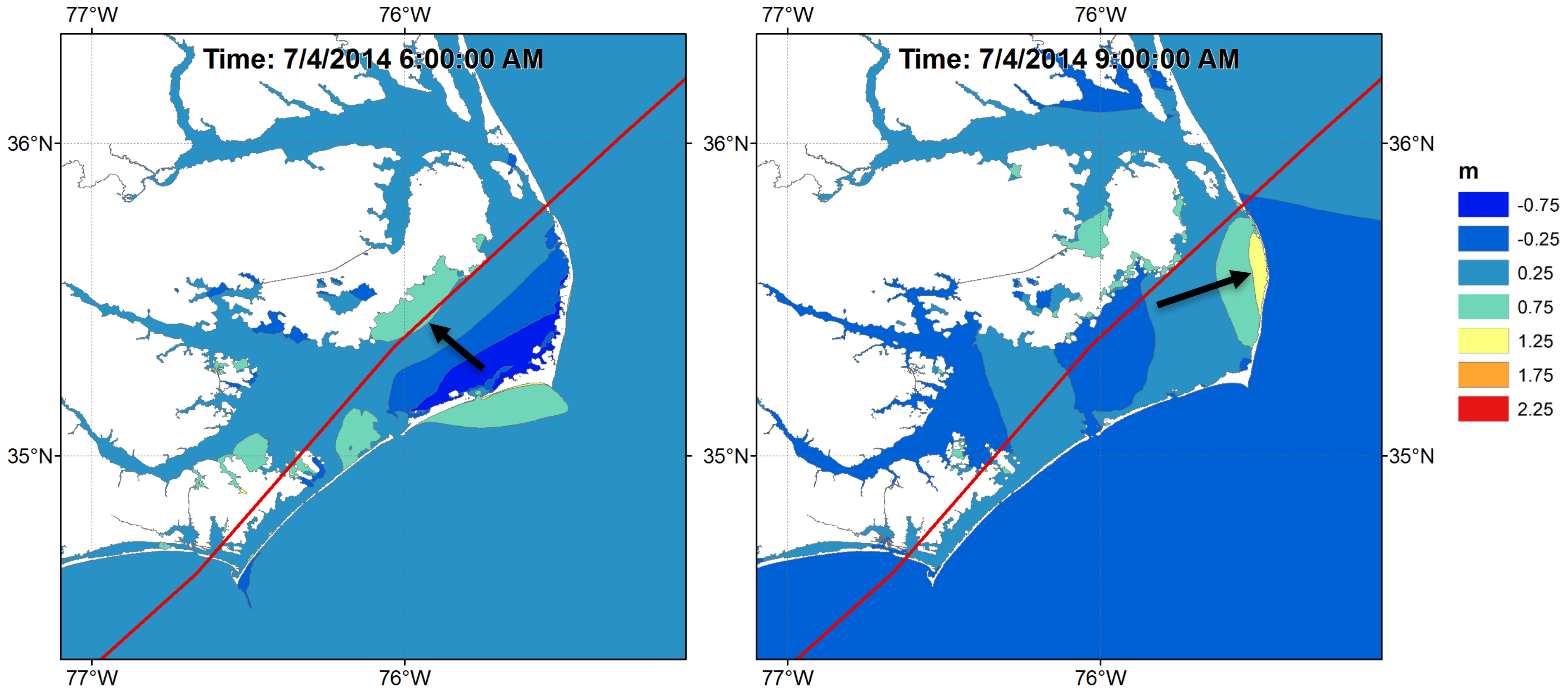
- Model Development for Choctawhatchee Bay and Destin Inlet System

Hurricane Arthur (2014)

- Category 2 Hurricane
- Landfall over Shackleford Banks between Cape Lookout and Beaufort, North Carolina on July 3 2014
- Relatively small and fast moving over NC
- Sound- and ocean-side flooding in Dare and Cartaret Counties
- Storm surge up to 1.5 m



Storm Surge Modeling

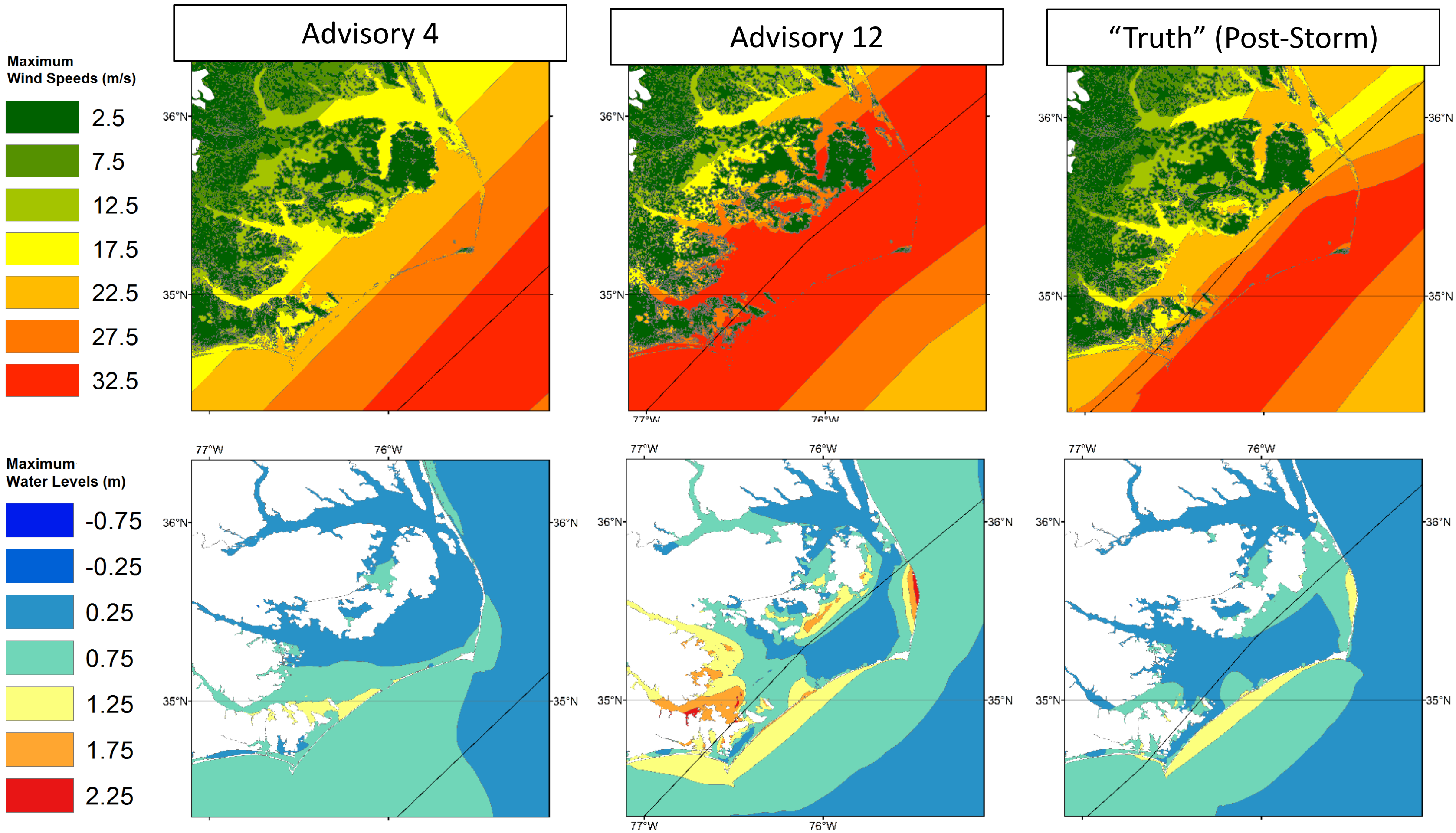


Hindcasts of Wind and Surge Impact in the Pamlico and Albemarle Sounds

- Uses coupled circulation + wave model (ADCIRC+SWAN) on fine unstructured grids
- Based on post-storm wind data
- RMS errors for wind speed = 2.69 m/s, water levels = 0.16 m

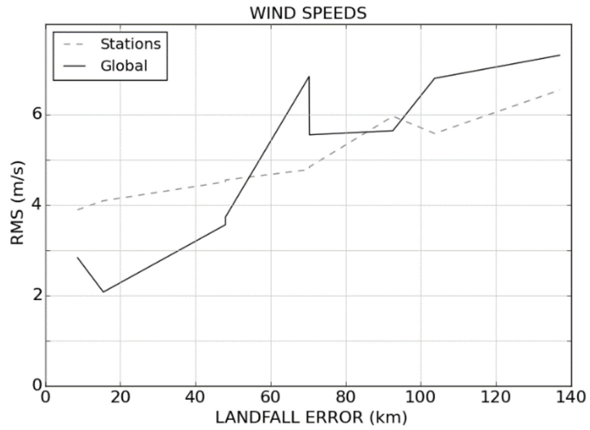
Real-time Surge Forecasting

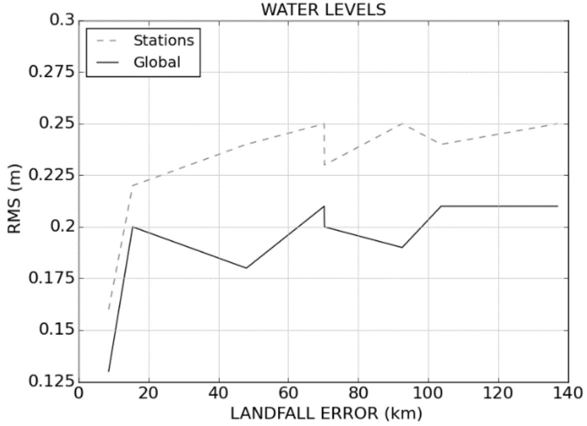
Sensitivity of forecast winds and water levels to errors in forecast storm track and intensity issued by the National Hurricane Center (NHC)



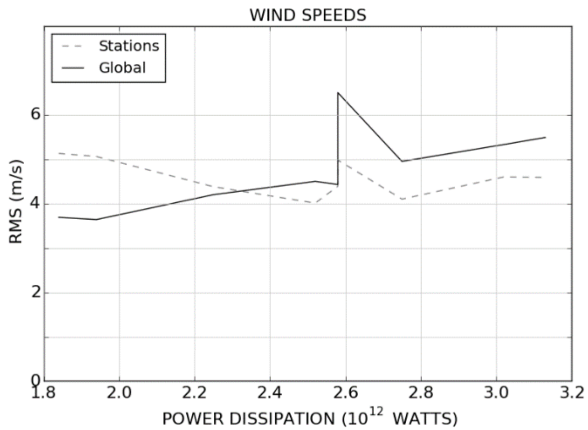
Real-time Surge Forecasting (Cyriac et al. 2017, submitted to *Coastal Engineering*)

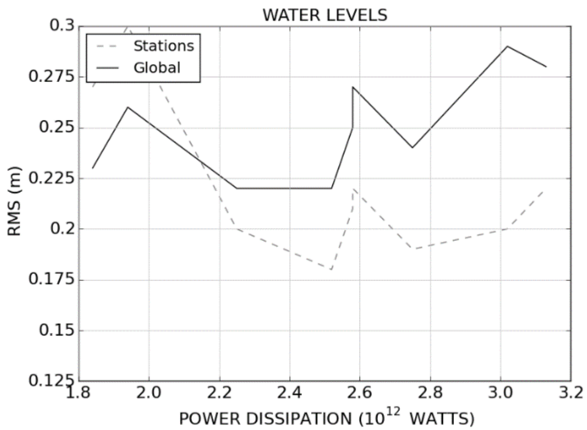
Constant Storm Variable Track Analysis





Variable Storm Constant Track Analysis





Research Methods: Numerical Modeling

Part 1: Illustration of 2DDI modeling using ADCIRC to study flooding impacts within estuaries

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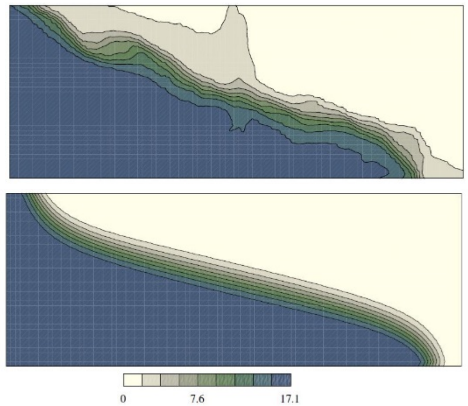
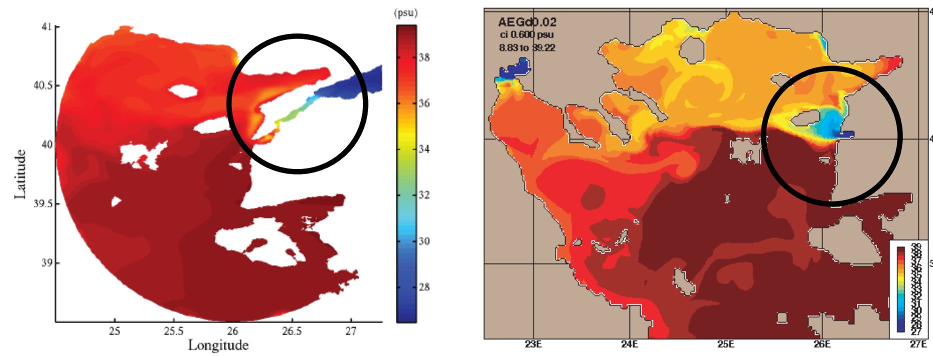
Introduction to 3D baroclinic ADCIRC

Idealized lock exchange test



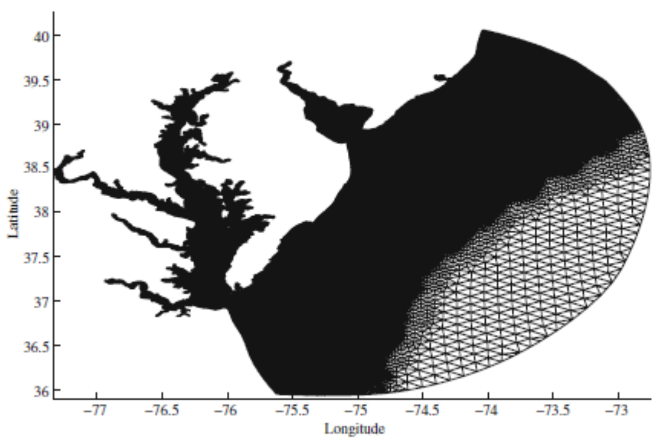
Source: Kolar et al. 2009

Stratified outflows from Dardanelles Strait



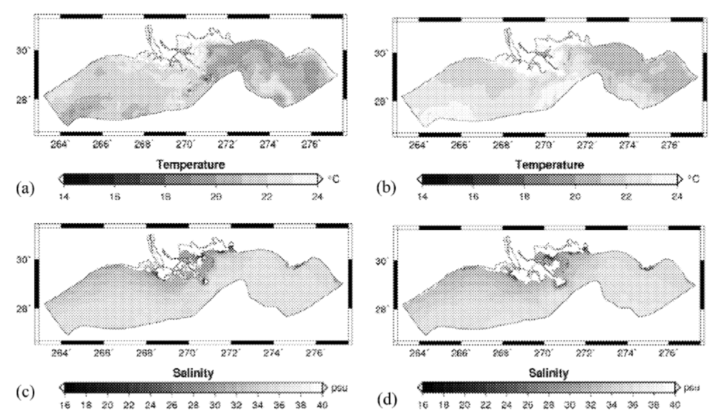
Source: Blain et al. 2009

Coastal forecast system for Chesapeake Bay



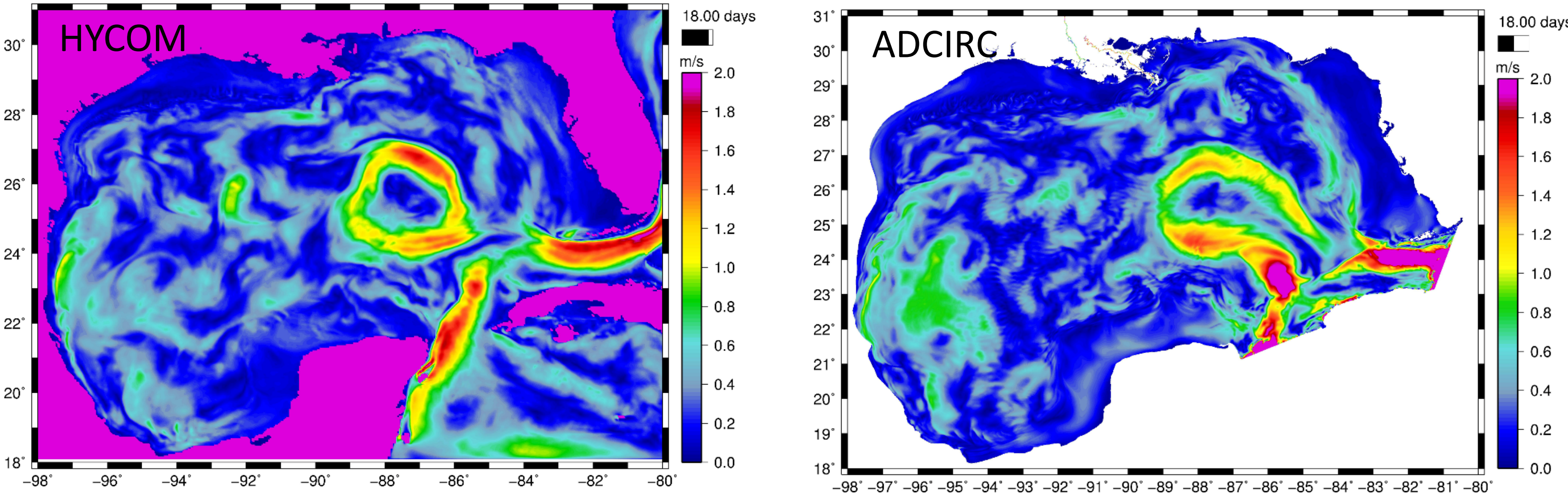
Source: Blain et al. 2012

Models for Northern Gulf of Mexico



Source: Dresback et al. 2010

Recent enhancements to ADCIRC 3D (Fathi et.al. 2017)

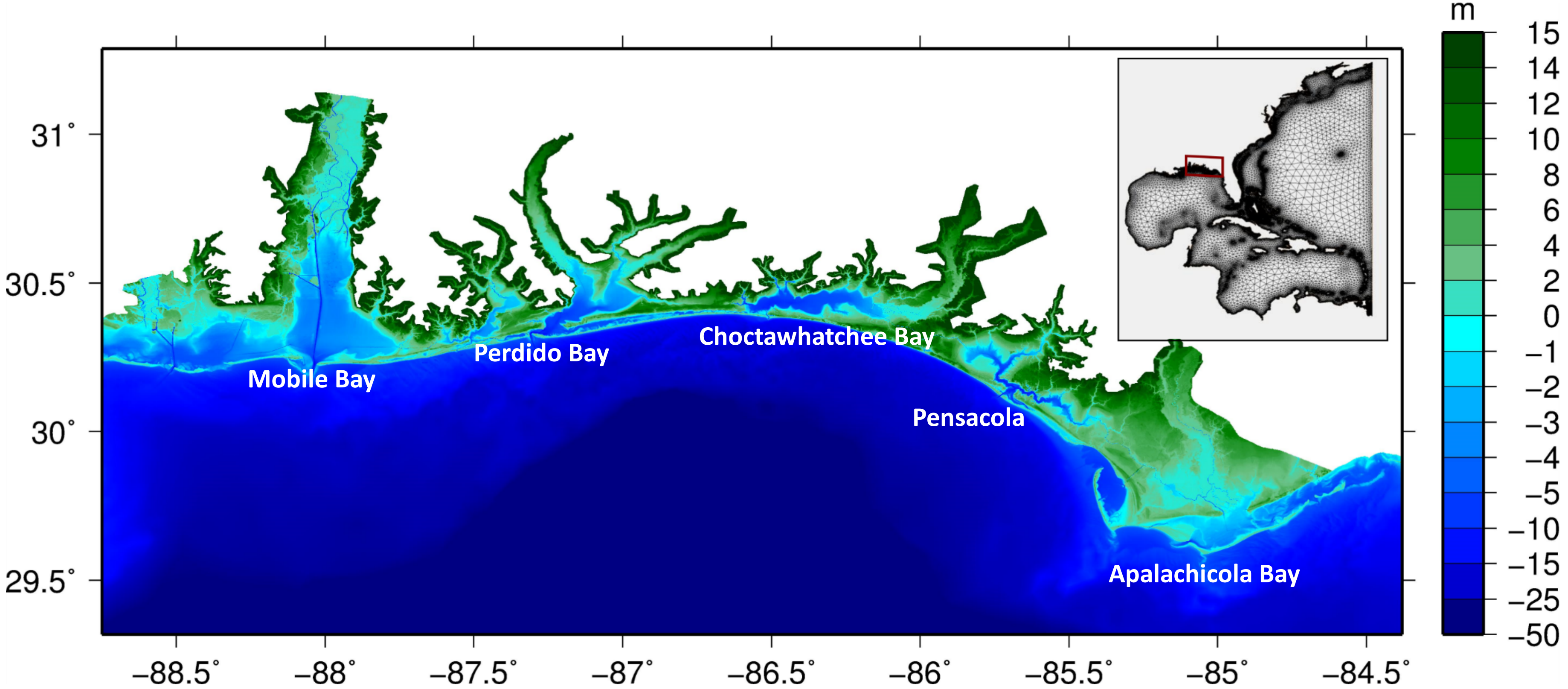


Source: A Fathi, J. C. Dietrich, C. N. Dawson, K. M. Dresback, A. Samii, R. Cyriac, C. A. Blain, R. Kolar. Prediction of surface oil transport in the Northern Gulf of Mexico by using a three-dimensional high-resolution unstructured-grid baroclinic circulation model. Ocean Modelling, 2017. In Revision

Improvements by Dr. Fathi

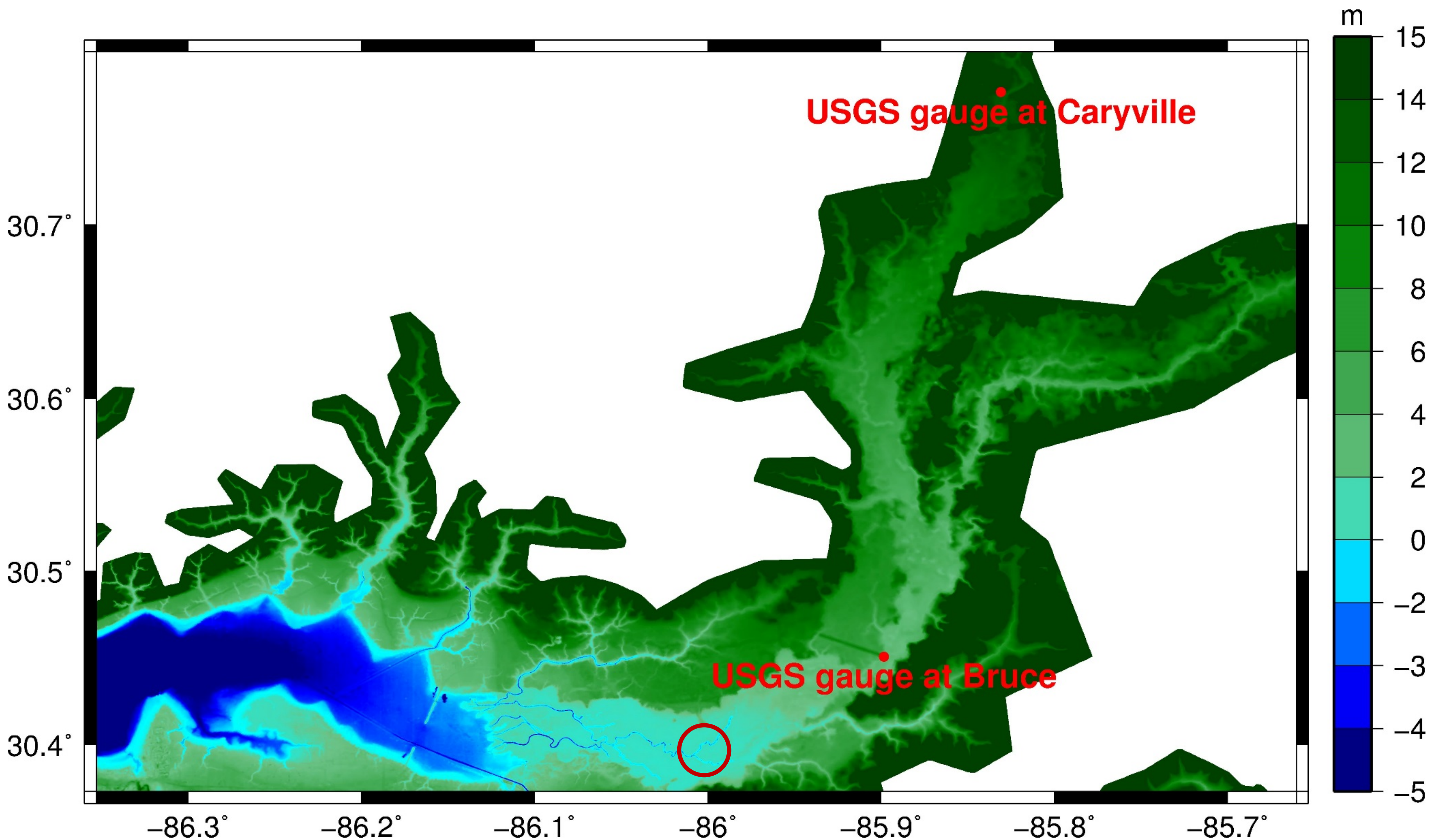
- Accurate computation of the baroclinic pressure gradient term
- Implementation of a biharmonic horizontal viscosity/diffusion operator
- Scale adaptive filtering of the viscosity field
- Bathymetry Smoothing

Mesh Development

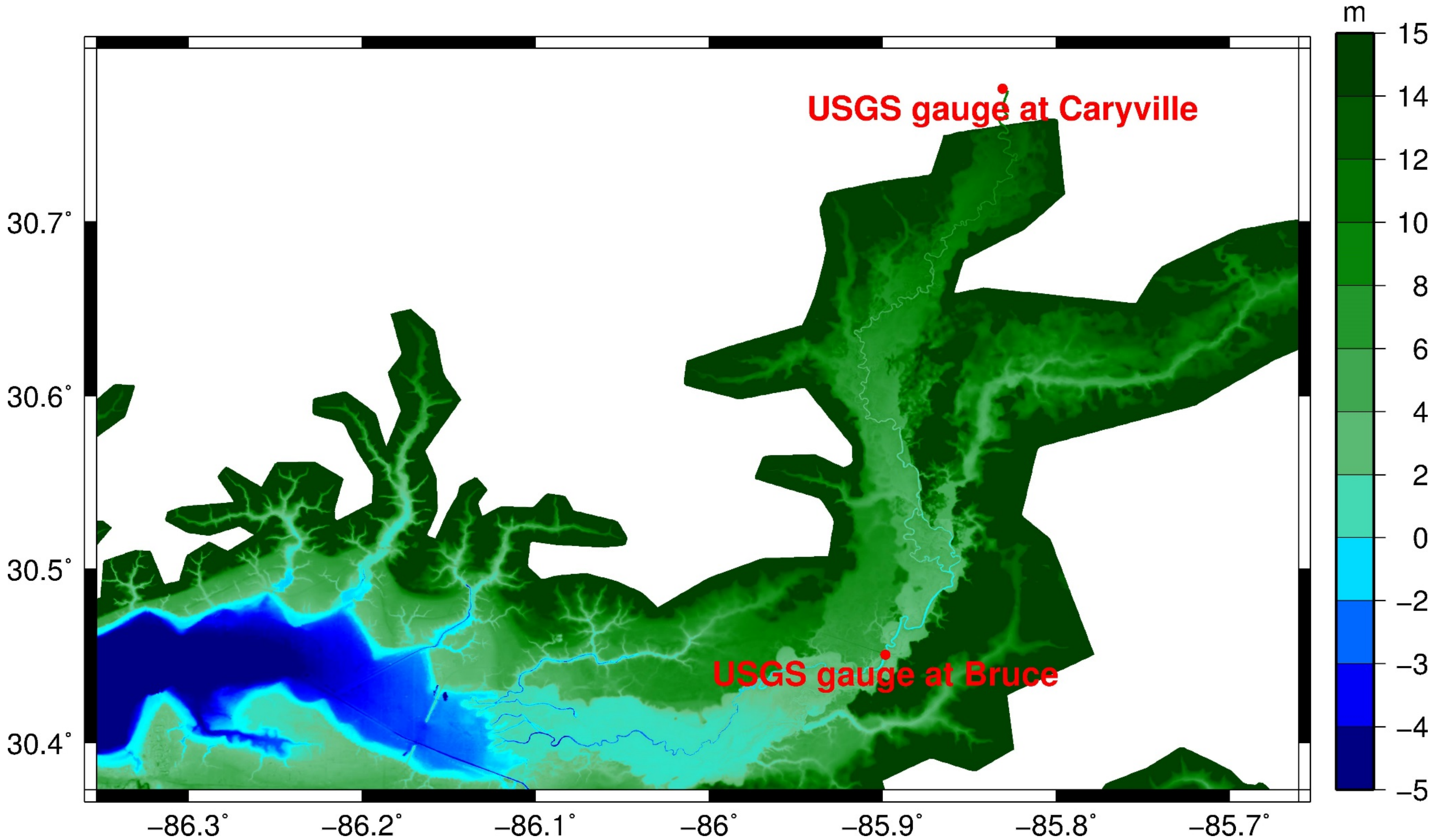


Source : S. Hagen , A. Daranpob, P. Bacopoulos, S. Medeiros, M. Bilskie, D. Coggin, M. Salisbury, J. Atkinson and H. Roberts. Storm Surge Modeling for FEMA Flood Map Modernization for the Northwest Florida and Alabama Coast, Digital Elevation Model and Finite Element Mesh Development. Prepared for the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

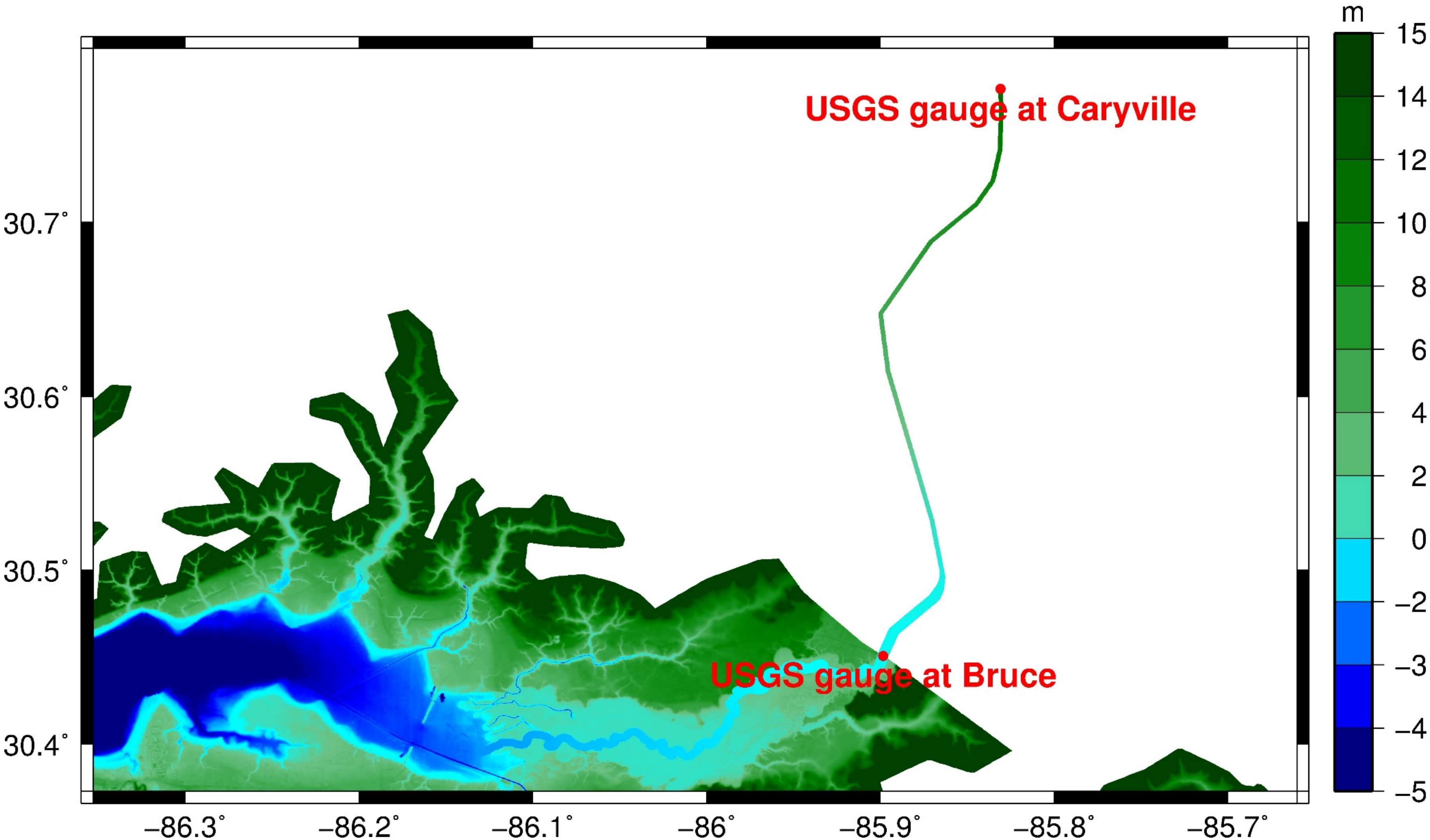
Resolving Choctawhatchee River



Resolving Choctawhatchee River



Resolving Choctawhatchee River



Model Set-up

Simulation Period

- Coincides with timing of SCOPE experiment
  - Diagnostic phase : November 1-5
  - Prognostic phase : November 5 – December 15

Open Ocean Boundary Conditions

- Tides
  - K_1, O_1, Q_1, M_2, S_2, N_2 and K_2 constituents

- Vertical Salinities and Temperatures
  - Interpolated from publicly archived HYCOM data (HYCOM + NCODA Southeast United States 1/25 Degree Analysis/GOMl0.04/expt_31.0/2013)

Other Forcings

- Upstream River Boundary is forced with a discharge of 200 m^3/s
  - Annual Mean Discharge of Choctawhatchee Bay is 248 m^3/s (Ruth and Handley, 2008)
- Surface Heat Flux over model domain
  - Derived from HYCOM model output

Model Set-up

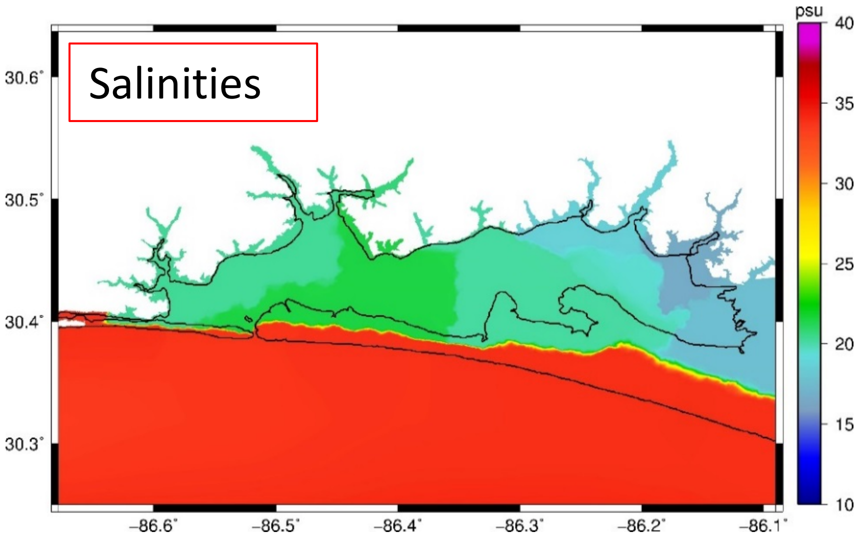
Others

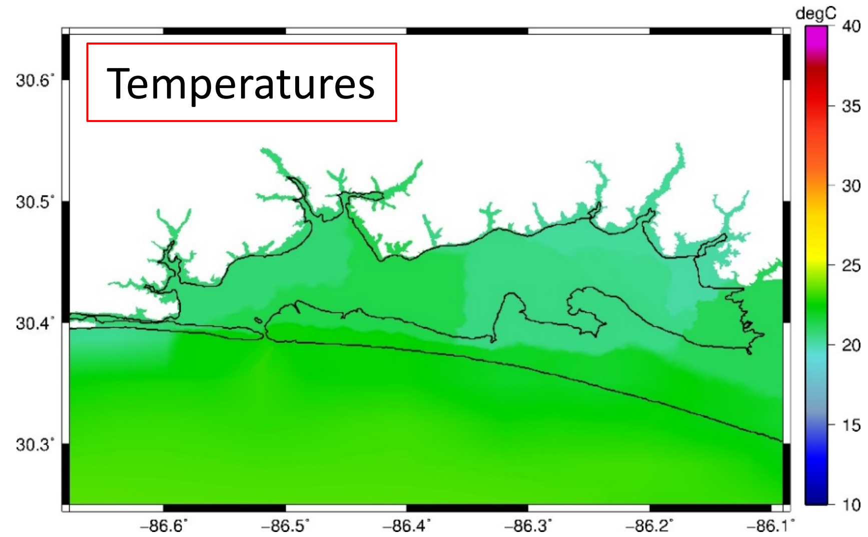
- 11 uniform vertical layers
- Biharmonic horizontal diffusion scheme
- Mellor-Yamada level 2.5 turbulence closure scheme for vertical diffusion

Computational Time

- Time step = 0.5 s
- Total simulation time is roughly 10 days on 3840 cores at the Texas Advanced Computing Center's Stampede 2 systems

Initial Conditions





Sources

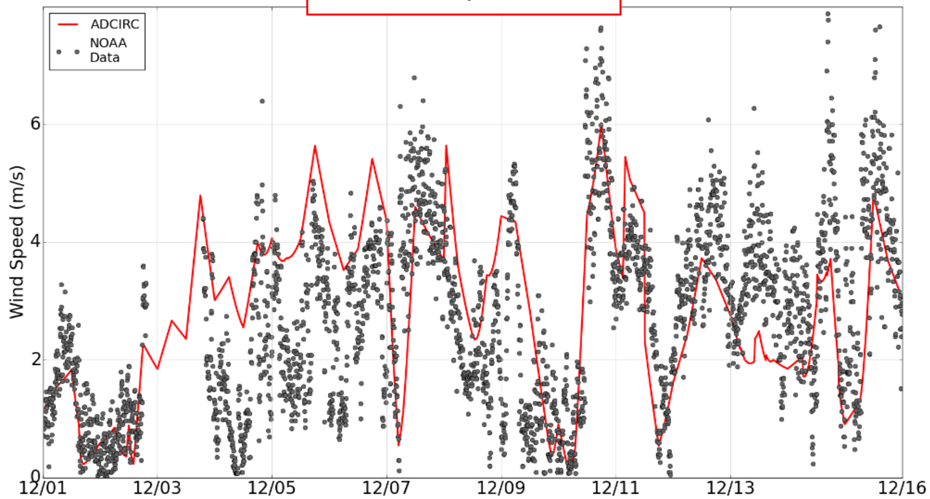
- Gulf of Mexico HYCOM output
- Monthly measurements within the bay (from Choctawhatchee Basin Alliance)

Developing initial salinities and temperatures

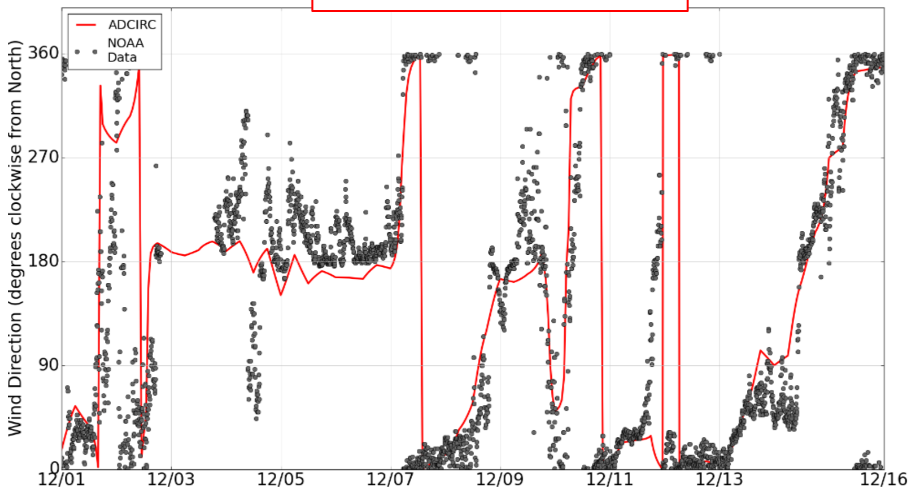
- Offshore salinities and temperatures interpolated from publicly available Gulf of Mexico HYCOM model results
- Combination of extrapolation of HYCOM output and interpolation from measurements within the bay were used to derive initial conditions within the bay

Wind Forcing

Wind Speeds



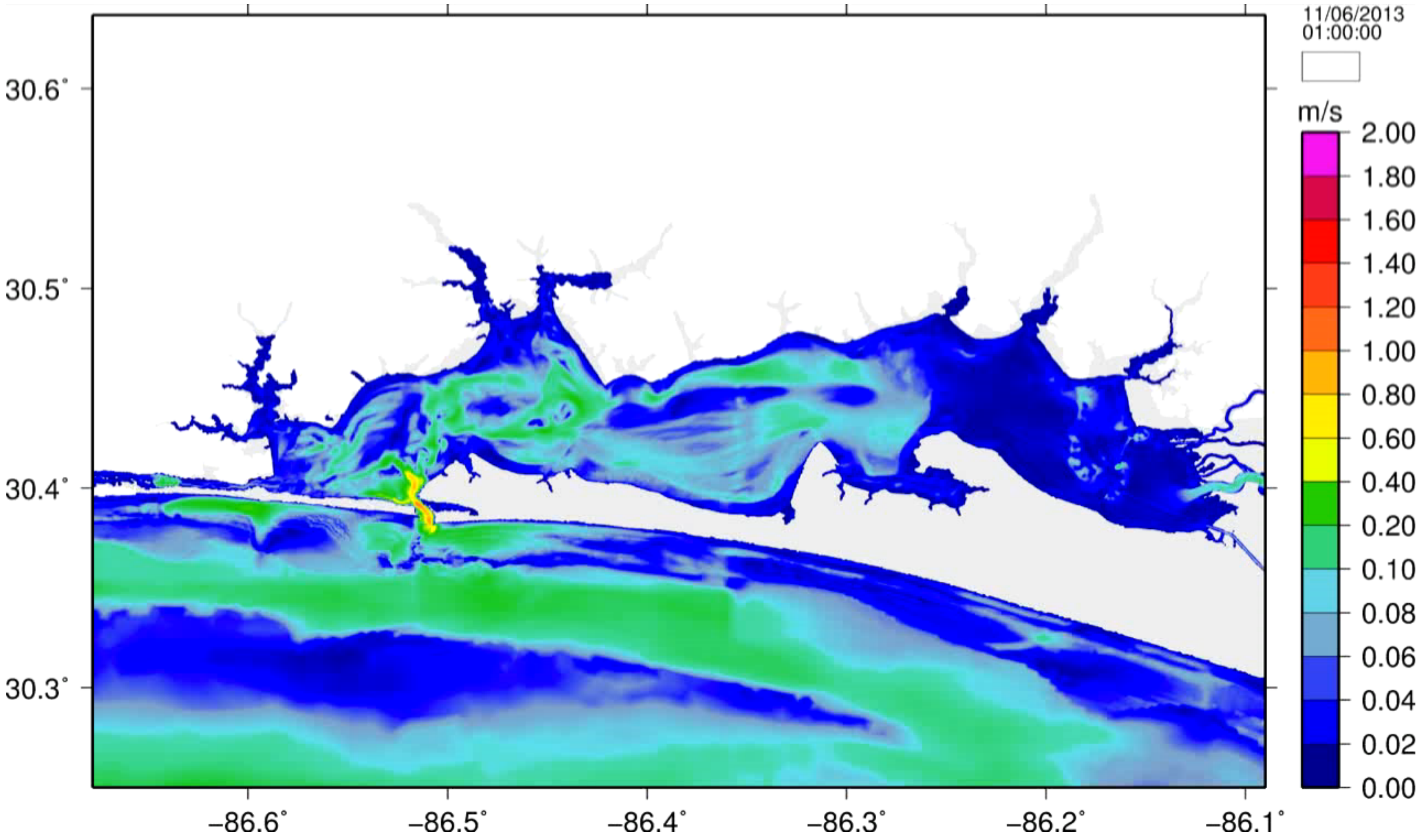
Wind Directions



Wind Forcing

- Applied winds are from the North American Mesoscale (NAM) model, which is run by the National Center for Environmental Prediction
- NAM winds (available at 6 hr intervals) interpolated to ADCIRC mesh vertices
- Model winds show good agreement in general at NOAA station at Pensacola

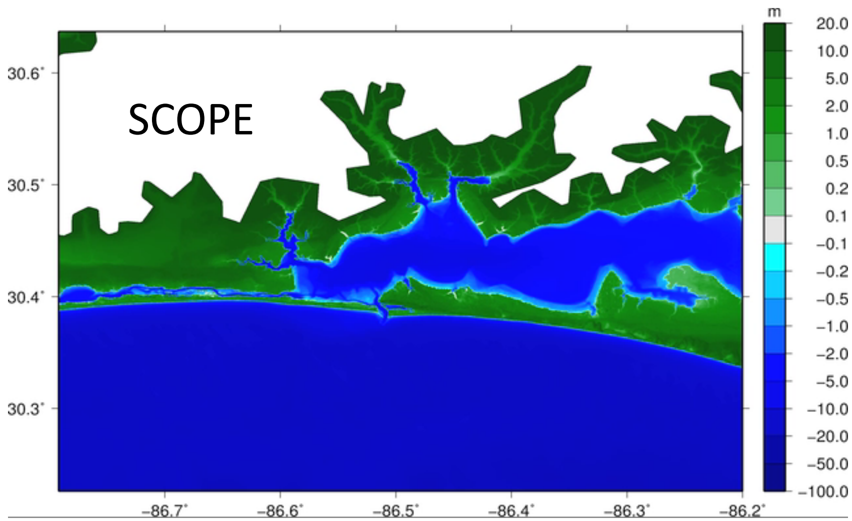
Preliminary Results – Surface Currents in the Bay

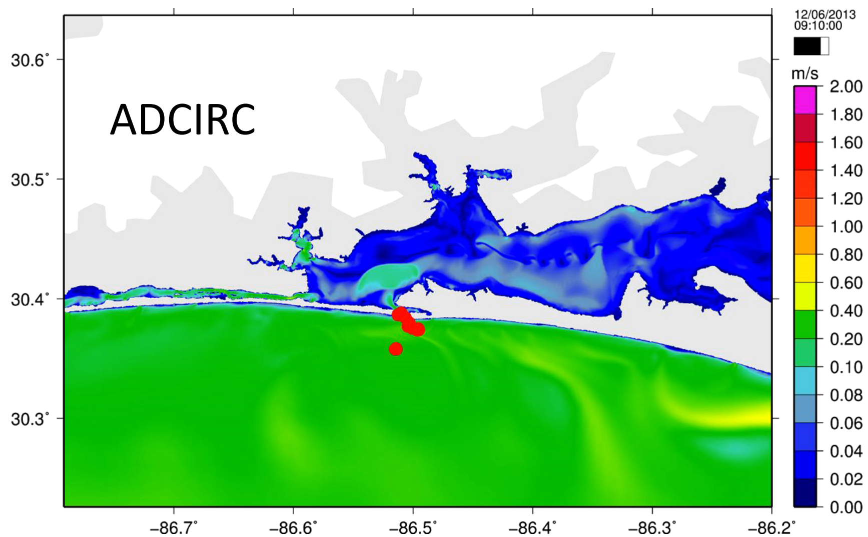


Model Validation for Surface Currents

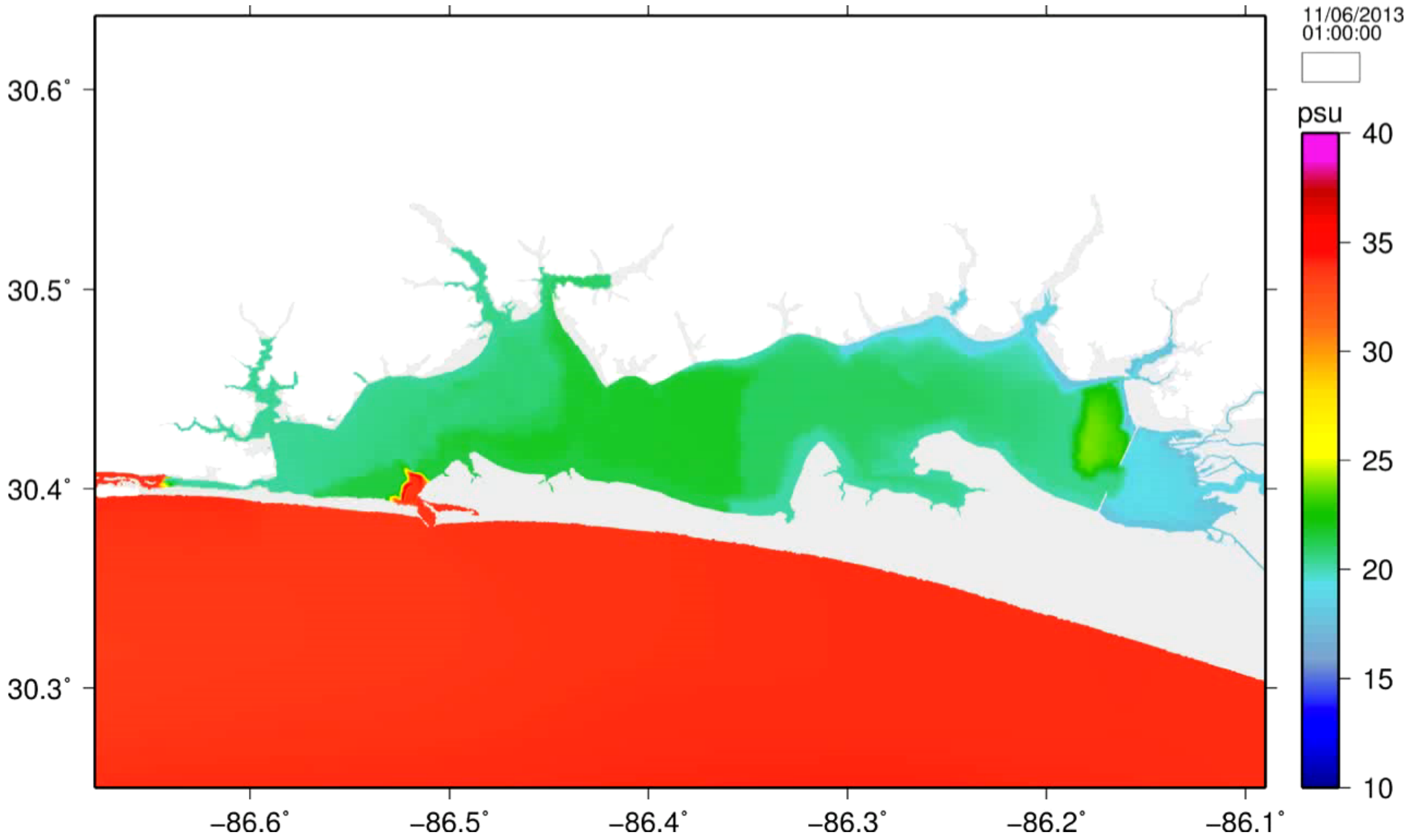
Model results will be validated against the SCOPE measurements:

- Surface current measurements at Destin Inlet and in the inner shelf
- Observed drifter movements
  - Particle transport model with ADCIRC surface currents

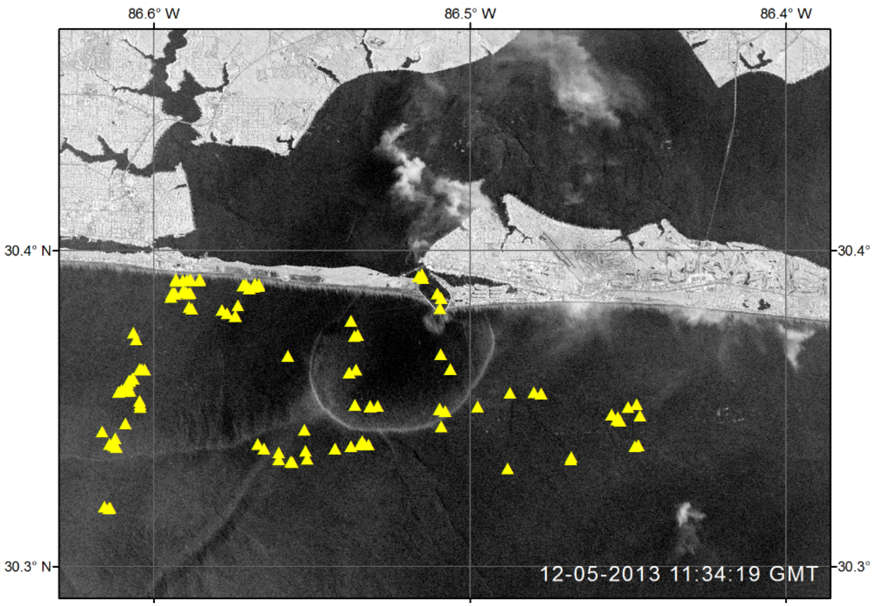


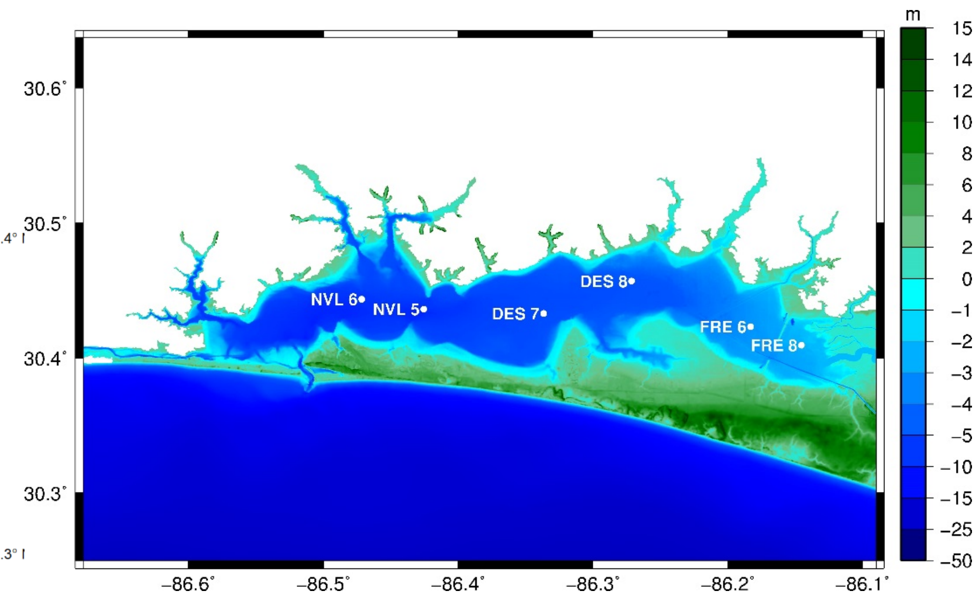


Preliminary Results – Surface Salinities in the Bay



Model Validation for Surface Salinities





SCOPE datasets

- Satellite Imagery
- CTD casts near Destin Inlet

Choctawhatchee Basin Alliance

- Measurements within the bay
- Monthly salinity measurements

Future Work: Proposed Tasks

Focus Area #1: Wind and Plume Effects at Destin Inlet

- Plume signature
- Surface transport

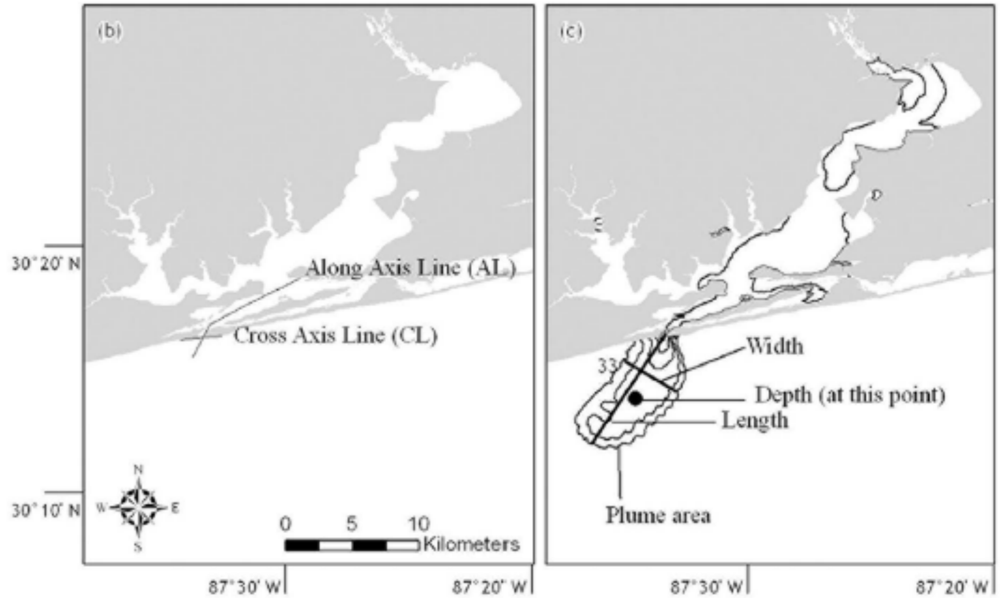
Focus Area #2: Circulation within Choctawhatchee Bay

- Longitudinal salinity gradients
- Estuarine timescales

Focus Area #1: Proposed Tasks

Variability in plume signature with different wind conditions

- Validate model predictions of plume signature by comparisons with satellite imagery
  - Quantify length, width and plume area of the plume signature using GIS tool
- Apply validated model to analyze plume signature during the different wind conditions associated with the simulation period



Quantifying plume geometry at Perdido Bay. Source: Xie et al. 2011

Focus Area #1: Proposed Tasks

Variability in plume signature with different wind conditions

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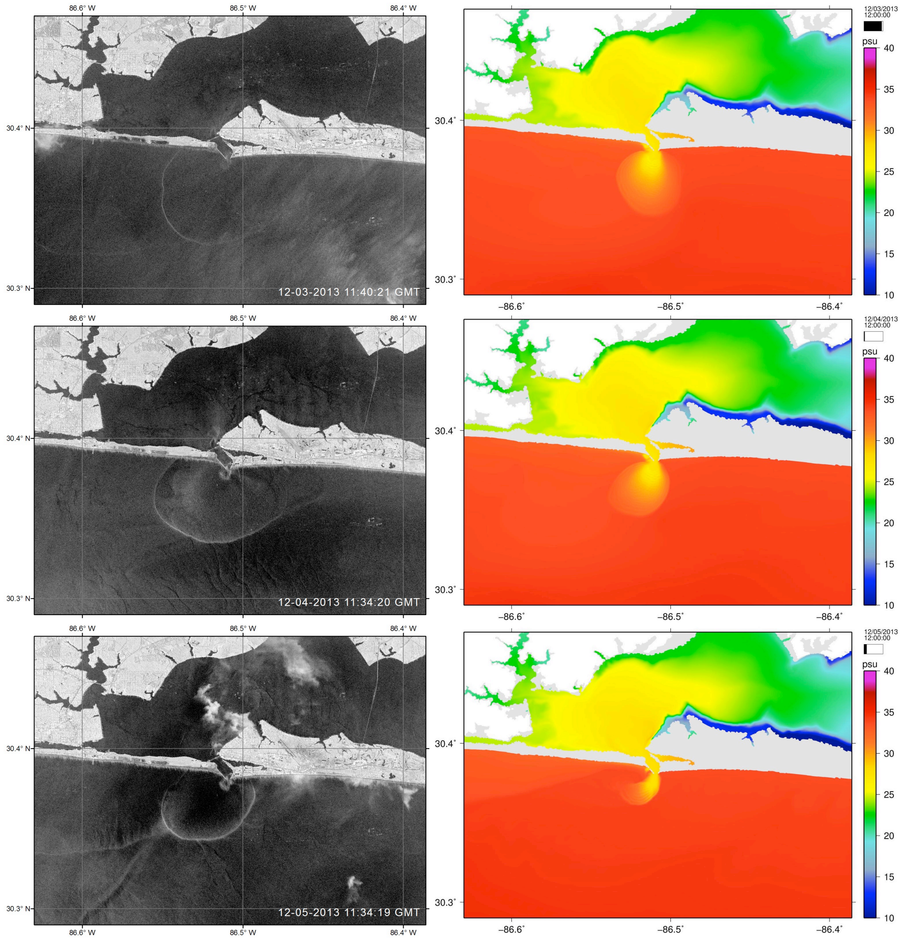
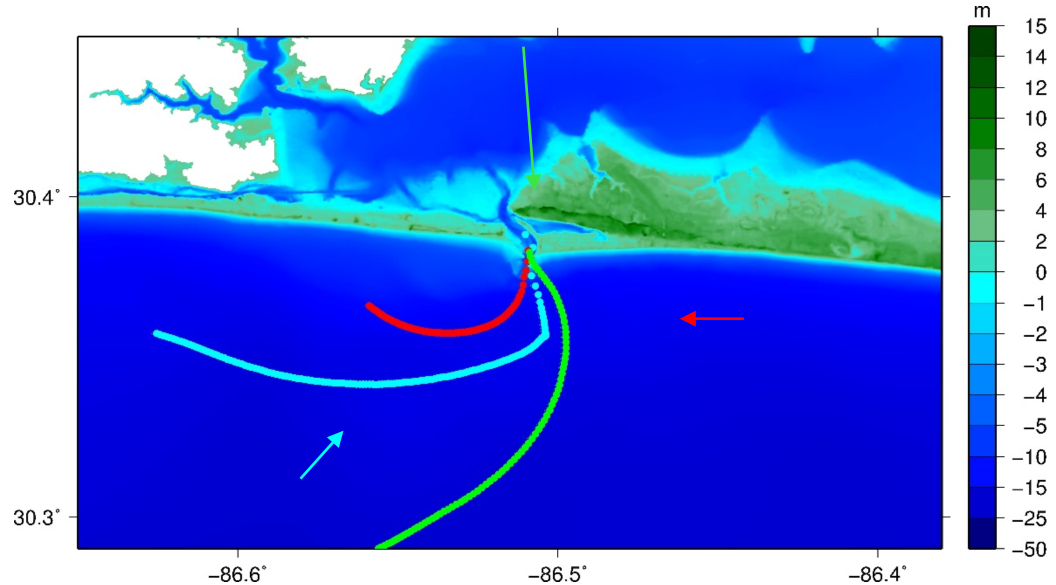


Comparison of plume signature from satellite imagery and ADCIRC salinities.

Focus Area #1: Proposed Tasks

Variability of surface transport at Destin

- Compare model predictions for drifter movements with observed paths
  - Use a particle tracking code in which particles will be advected by ADCIRC surface currents
- Hypothetical particle releases at inlet during northerly, easterly and southerly winds
  - Design suitable particle release scenarios
  - Are certain conditions more conducive for particle transport into inlet?



Drifter transport predicted by ADCIRC surface currents

Future Work: Proposed Tasks

Focus Area #1: Wind and Plume Effects at Destin Inlet

- Plume signature
- Surface transport

Focus Area #2: Circulation within Choctawhatchee Bay

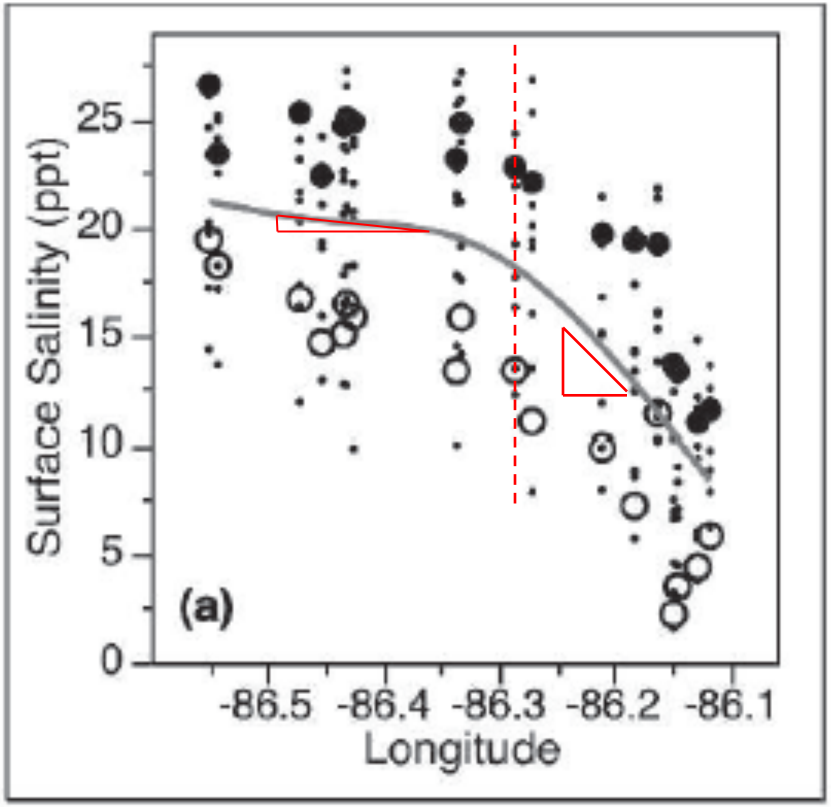
- Longitudinal salinity gradients
- Estuarine timescales

Focus Area #2: Proposed Tasks

Longitudinal salinity trends within the bay

- Mean monthly salinities from 2001-2011 show differences in salinity gradients at different parts of the bay

- Model salinities within the bay will be analyzed to answer these questions:
    - Do the surface salinities in the bay exhibit similar trends over timescales of a few hours to days?
    - Are there noticeable wind effects on the longitudinal salinity gradients in the bay?

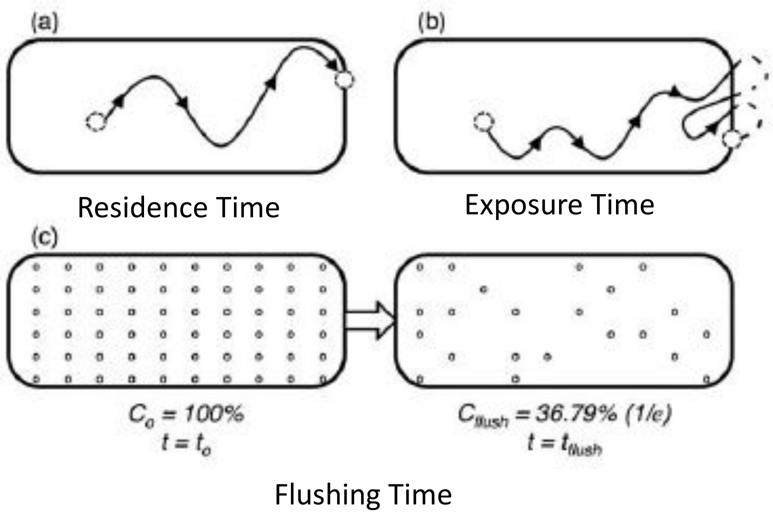


Mean monthly salinities in the bay between 2001-2011 (Hoyer et al. 2008)

Focus Area #2: Proposed Tasks

Estuarine Timescales (Residence Times and Flushing Rates)

- Residence time is "the time required for a fluid parcel starting at a specific location, to leave a discrete region through one of its defined boundaries"
- Exposure time is defined as "the accumulated time spent by water parcels in a specified region"
- Flushing time is calculated as "the amount of time required to reduce some initial concentration to 1/e (e = 2.71828; 1/e ~ 0.37) of its initial value"

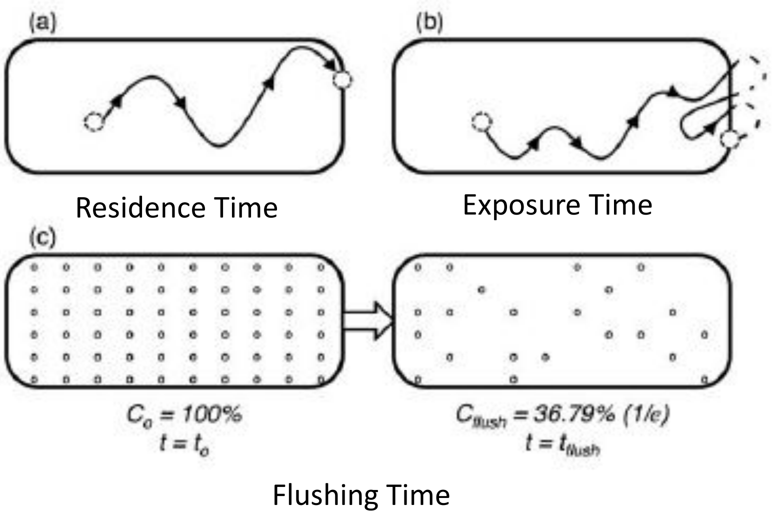


Source: Webb and Marr 2016

Focus Area #2: Proposed Tasks

Estuarine Timescales (Residence Times and Flushing Rates)

- ADCIRC output will be combined with particle tracking code to examine spatial and temporal variability of residence times
    - Residence times can vary from O(hours) to O(weeks) depending on particle initial locations, river discharge and winds (Allen et al. 2011, Safak et al. 2015 ,Webb and Marr 2016)



Source: Webb and Marr 2016

Significance of Proposed Research

- Provide insights into the features and variability of surface transport at tidal inlets
- Unique (first of its kind) study for the Choctawhatchee Bay that quantifies:
  - Signature of the Choctawhatchee Bay plume
  - Features of spatial surface salinity distribution in the bay
  - Spatial and temporal variability of estuarine time scales
- Application of baroclinic ADCIRC to model density driven flows in estuaries
  - Supports future model development for predicting impacts of hurricane-force winds on the hydrodynamics and transport within estuaries

Summary

Research Hypotheses and Objectives

- Wind and Plume Effects at Destin Inlet
  - Effect of winds on plume variability and surface transport near Destin
- Circulation in the Choctawhatchee Bay
  - Investigation of wind effects on salinity gradients and estuarine timescales

Research Methods: Numerical modeling using ADCIRC

- Coastal flooding impacts using 2DDI ADCIRC
  - Case Study: Hurricane Arthur (2014)

- Density driven flows in Choctawhatchee Bay using 3D baroclinic ADCIRC
  - Preliminary results from the ADCIRC baroclinic flow model are encouraging
  - Efforts to validate the model are ongoing

Future Research Tasks

- Quantifying signature of the Choctawhatchee Bay plume
- Particle release scenarios to investigate surface transport near Destin Inlet
- Computation of salinity gradients, residence times and flushing rates within the bay