Baroclinic 3D ADCIRC from Synthetic Tests to Real NC Storms

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ADCIRC Coordination
Virtual Meeting, 23 Jan 2023

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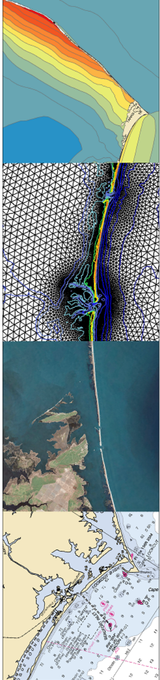
Conclusions and Future Work
Conclusions and Future Work
Thanks for Your Attention!



Updates to Baroclinic 3D ADCIRC

A Fathi[1], JC Dietrich[2], CN Dawson[3],
CA Blain[4], R Cyriac[5], KM Dresback[6], RL Kolar[6], A Samii[7]

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GULF OF MEXICO RESEARCH INITIATIVE

Improvements to BPGs, Stability

In a project after the Deepwater Horizon oil spill, Arash Fathi updated a few aspects of the baroclinic 3D ADCIRC:

1. Interpolation of baroclinic pressures
2. Automated bathymetry smoothing
3. and 4. Biharmonic operators for viscosity/diffusion
5. Adaptive filtering of velocity solution

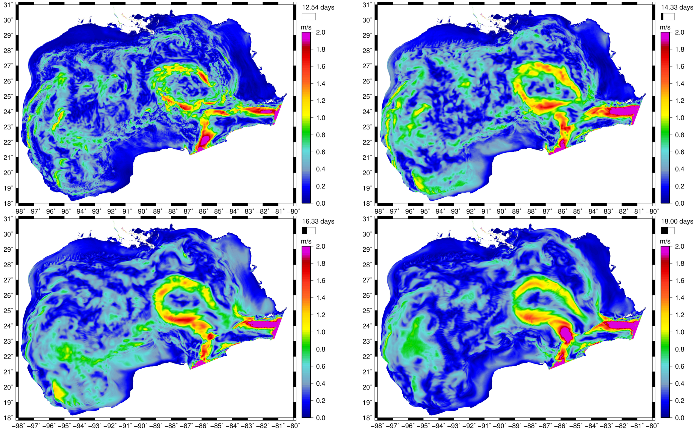
These updates were added to the ADCIRC Github repository a few years ago

- But the 'hooks' were broken to the rest of the code
- I have debugged over the past year, and now everything seems to be working okay

These updates have helped some recent studies with the baroclinic 3D ADCIRC

1.1 Summary of Updates

Example of Baroclinic 3D ADCIRC



Sea surface velocities (m/s) predicted during mid-June 2010 due to a baroclinic 3D ADCIRC simulation. The times are: a) 2010/06/13/1300UTC (12.54 days); b) 2010/06/15/0800UTC (14.33 days); c) 2010/06/17/0800UTC (16.33 days); and d) 2010/06/19/0000UTC (18.00 days).

Changes in temperature and salinity, cause changes in density, cause changes in pressure

- These pressure gradients can drive circulation and transport

These pressure gradients appear as forces in the momentum conservation equations:

- If we are not too picky about the form of the equation, e.g. for the x-direction:

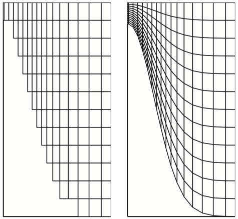
$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} + w\frac{\partial u}{\partial z} - fv = -g\frac{\partial}{\partial x}\left[\zeta + P_s/g\rho_0 - \alpha\eta\right] + \frac{\partial}{\partial z}\left(\frac{\tau_{zx}}{\rho_0}\right) - b_x + m_x$$

where the baroclinic pressure gradients are given by:

$$b_x = \frac{\partial P}{\partial x} = \frac{g}{\rho_0}\frac{\partial}{\partial x}\int_z^{\zeta}(\rho - \rho_0)\ \mathrm{d}z$$

A key challenge is how to compute these baroclinic pressure gradients in 3D

- ADCIRC (and many other models) discretize the water column with σ levels:



(a) (b)

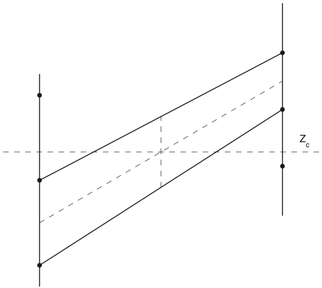
- These levels make it challenging to compute horizontal derivatives:

$$\frac{\partial P}{\partial x} = \frac{\partial P}{\partial x_\sigma} + \frac{\partial P}{\partial \sigma}\frac{\partial \sigma}{\partial x}$$

Figure: Wang *et al.* (2004) *JGR Oceans*

A common approach is to evaluate an untransformed horizontal derivative

- Baroclinic pressures are mapped to a constant z level, and then gradients are computed



- We need to minimize any errors in the interpolation
  - Very small roundoff errors can accumulate and drive significant circulation

Figure: Wang *et al.* (2004) *JGR Oceans*

We made several improvements to the workflow to compute the baroclinic pressures

1. Temperature and salinity are converted to density

$$\rho = \rho\left(T, S\left(, p\right)\right)$$

   - Previous: Density computed at σ levels
   - Now: Density computed at any depth, using cubic interpolation for temperature and salinity

2. Baroclinic pressures are computed by integrating the density

$$P = \frac{g}{\rho_0} \int_z^{\zeta} \left(\rho - \rho_0\right) \,\mathrm{d}z$$

   - Previous: Trapezoidal rule in each layer
   - Now: 2-point Gauss-Legendre quadrature in each layer

We made several improvements to the workflow to compute the baroclinic pressures

3. Gradients are computed on horizontal z levels:

$$b_x = \frac{\partial P}{\partial x}$$

- Previous: Linear interpolation of baroclinic pressures
- Now: Cubic interpolation of baroclinic pressures

Thus, at all stages, we are trying to minimize the roundoff errors as much as possible

– But it is impossible to remove them entirely

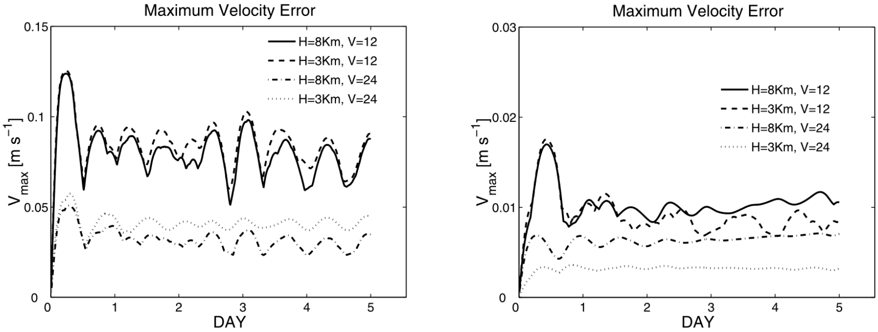
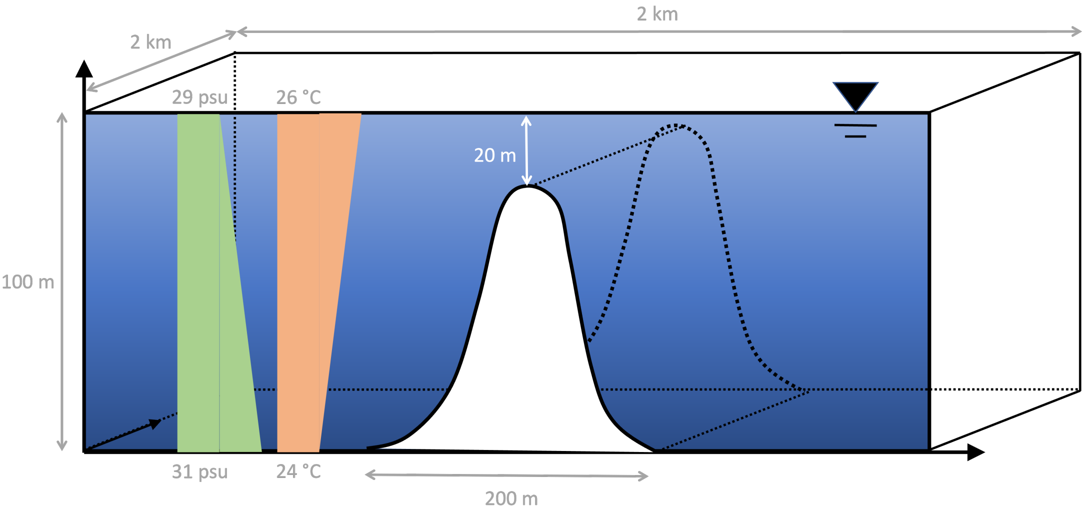


Figure: Wang *et al.* (2004) *JGR Oceans*

1.2 Baroclinic Pressure Gradients

Synthetic Test : Submerged Ridge



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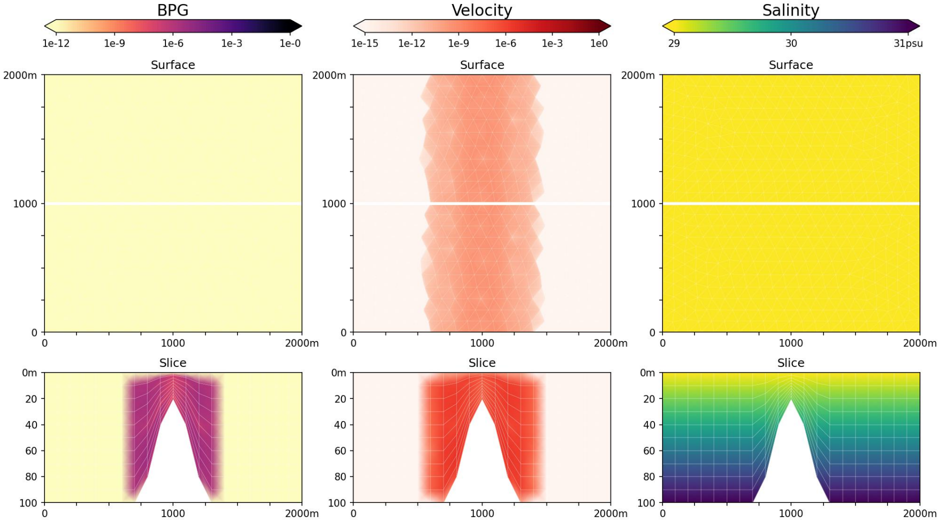

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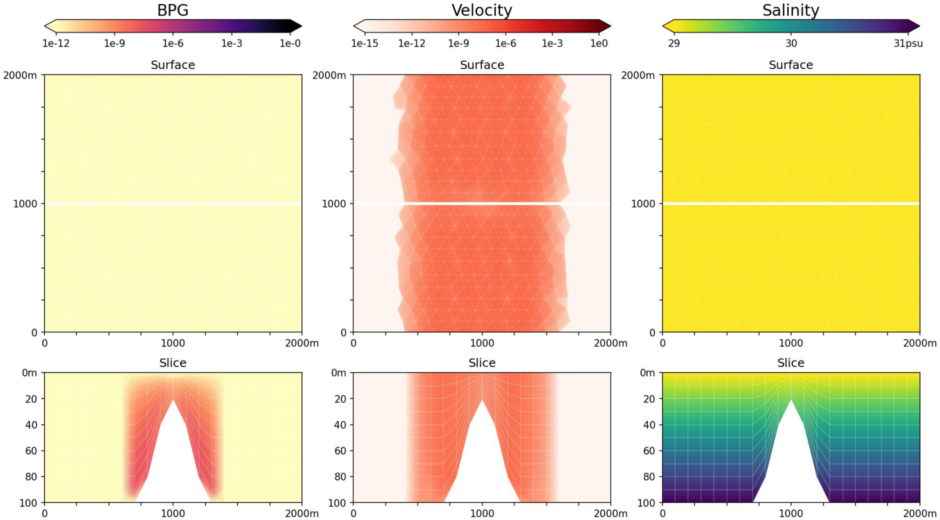

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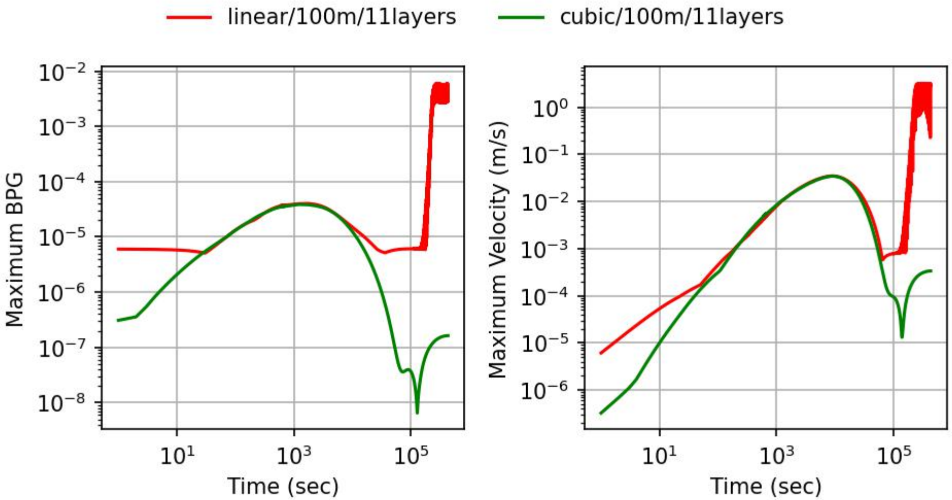

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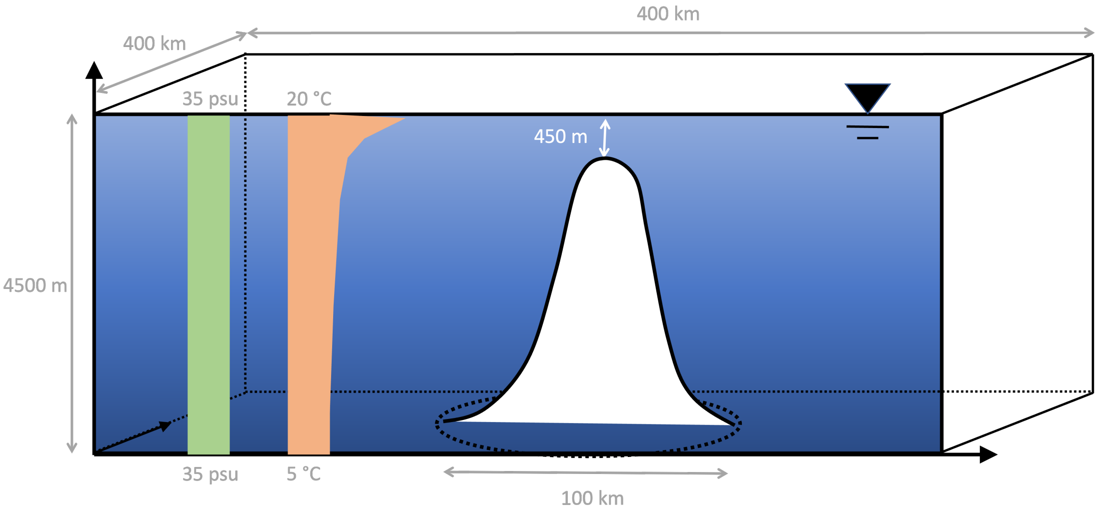
Synthetic Test : Seamount



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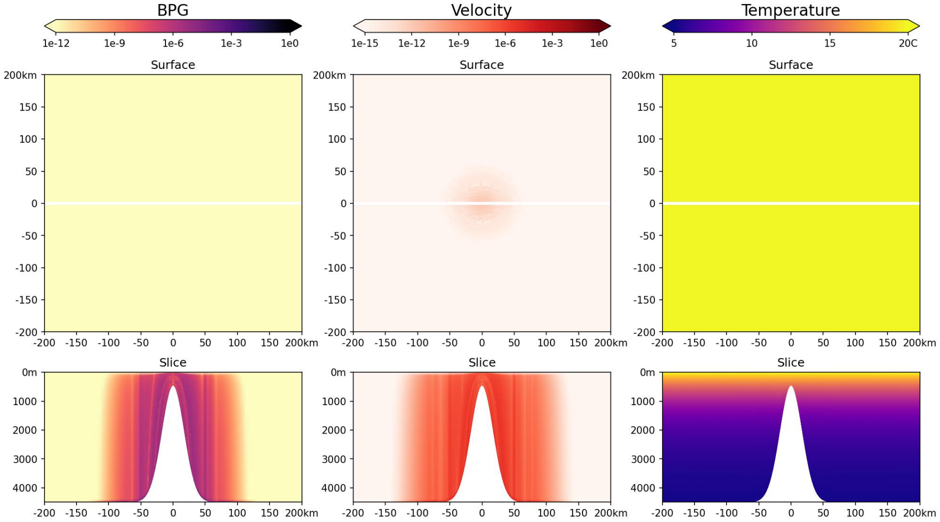

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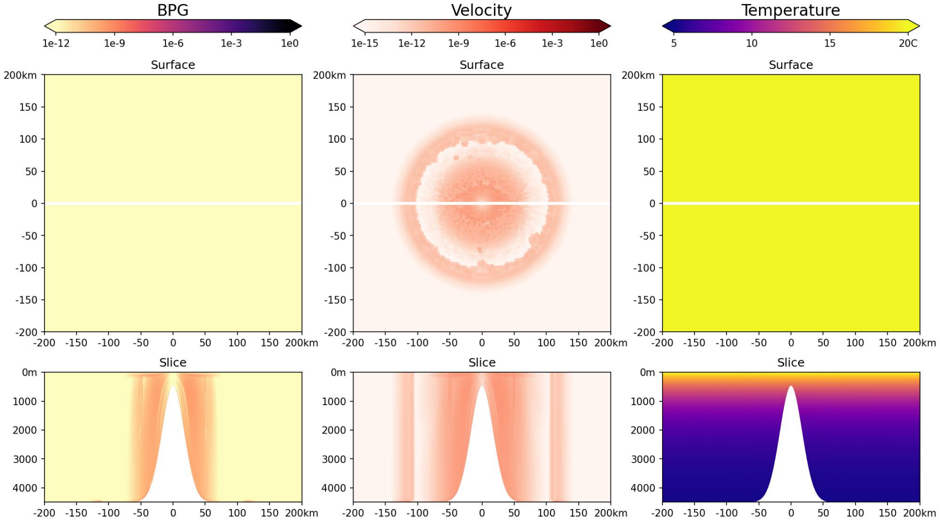

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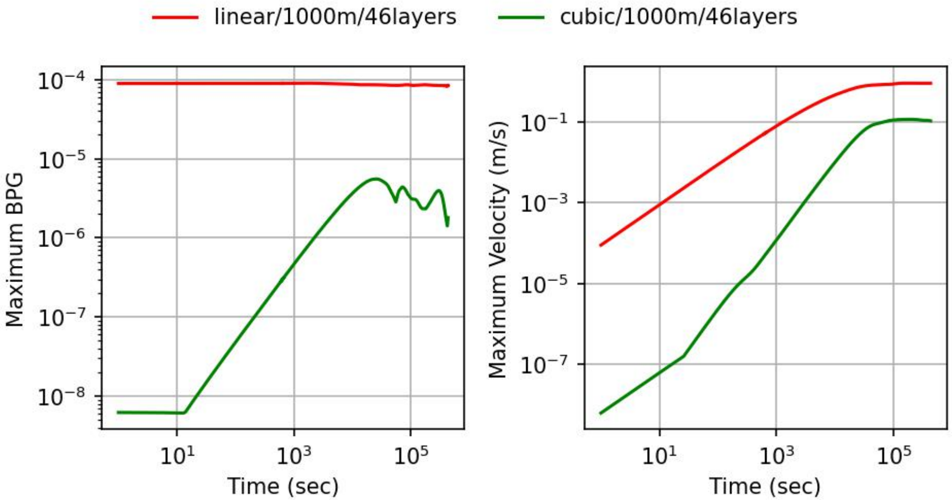
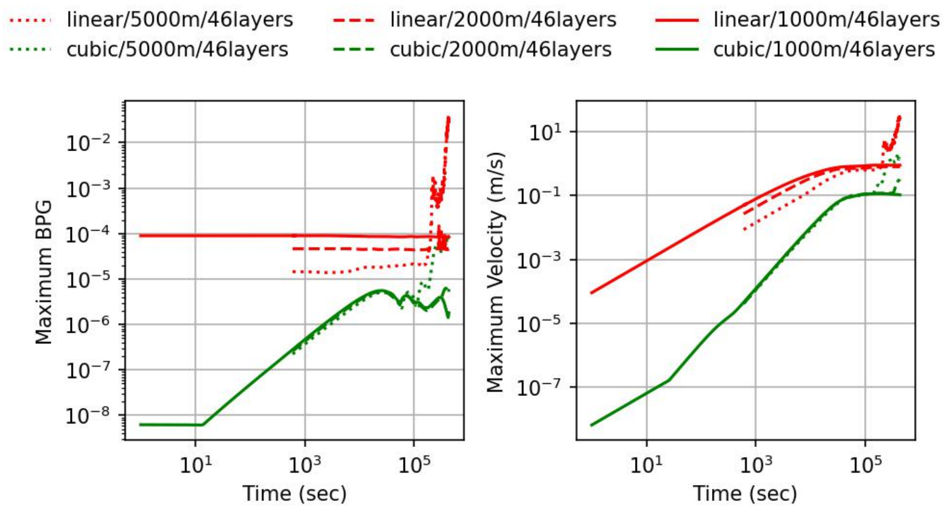


1.3 Resolution Sensitivity and Bathymetry Smoothing

Results are Sensitive to Horizontal and Vertical Resolution



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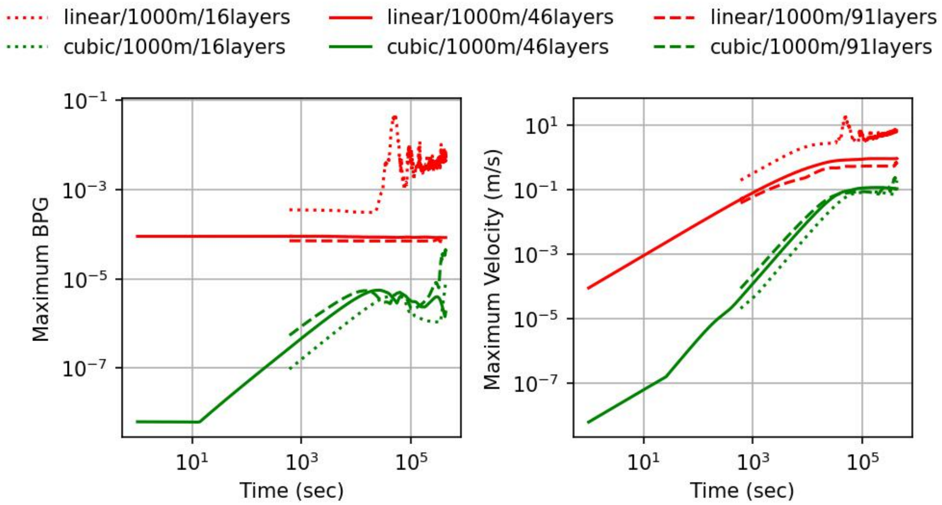


There are common metrics for the mesh resolution

- For the horizontal resolution:

$$rx_0 = \frac{|h_i - h_j|}{h_i + h_j}$$

  where i and j are neighboring vertices

- As $\Delta x \to 0$, this metric $rx_0 \to 0$ ... horizontal resolution helps!
- For the vertical resolution (Haney number):

$$rx_1 = \frac{|h_i^k - h_j^k + h_i^{k-1} - h_j^{k-1}|}{h_i^k + h_j^k - h_i^{k-1} - h_j^{k-1}}$$

  where k and $k-1$ are neighboring layers

- As $\Delta z \to 0$, this metric $rx_1 \to \infty$ ... vertical resolution may not help on its own!

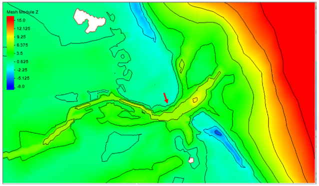
Update #2 : Automated Bathymetry Smoothing

Arash wrote a code to smooth the bathymetry in an ADCIRC mesh to minimize rx_0 and rx_1

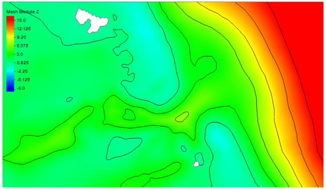
- Loop over all element/layer edges, adjust depths
- Iterate to an acceptable results

This smoothing can be applied selectively:

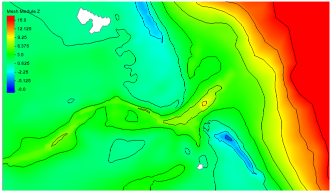
- In Cyriac (2020), smoothing was applied to all depths larger than 15 m
- In Rumbaugh (2021), smoothing was applied to depths between 0 and 5 m



Original



Smoothed



Final

In ADCIRC's momentum equations, another forcing is the lateral stress gradient

- Represented in the equations as:

$$m_x = E_h \nabla^2 u \qquad m_y = E_h \nabla^2 v$$

  in which E_h is a lateral eddy viscosity
- This Laplacian operator can be over-diffusive, especially in problems with a wide range of spatial scales
- Need a way to tie the viscosity to the local mesh size

Update #3 : Biharmonic Operator for Viscosity

Arash implemented a biharmonic operator for the lateral stress gradient

- Given by:

$$m_x = E_h \nabla^2 \nabla^2 u \qquad m_y = E_h \nabla^2 \nabla^2 v$$

  in which the eddy viscosity uses a modified Leith formula:

$$E_h = \frac{L^5}{8\pi^3} \sqrt{\Lambda^6 |\nabla \omega|^2 + \Lambda_d^6 |\nabla \nabla \cdot u_h|^2}, \tag{1}$$

  in which the quantities $\nabla \omega$ and $\nabla \nabla \cdot u_h$ are functions of the horizontal velocities u and v, and Λ can be related to the local mesh size L:

$$\Lambda = 1.4 + \frac{2.5 - 1.4}{6000 - 100} \, (L - 100), \quad 1.4 \leq \Lambda \leq 2.5. \tag{2}$$

- This implementation allows the horizontal eddy viscosity to vary with the local resolution

Update #4 : Biharmonic Operator for Diffusivity

Similarly, in the transport equation, there is a horizontal diffusion operator

- Given by:

$$\mathcal{D}_h\left(c, N_h\right) = N_h \nabla^2 c$$

  in which c is a transported species (S or T), and N_h is a diffusivity coefficient

- Arash implemented a biharmonic operator:

$$\mathcal{D}_h\left(c, N_h\right) = N_h \nabla^2 c$$

  with:

$$N_h = E_h$$

- Thus the horizontal diffusion can also vary with the local resolution

Update #5 : Adaptive Filtering of Velocity Solution

The last update is a new adaptive scheme that filters the velocity field

- Similar to filters in SELFE and MITgcm

Based on a weighted average of the velocities at its neighbor vertices

- Weights are locally adjusted, based on the local velocity field, local grid spacing, and local viscosity magnitude
- Based on a quantity similar to that of the local element Péclet number

Should be adaptive to flow conditions:

- Minimal when the flow is well-resolved, i.e. in regions with high resolution and low velocity magnitudes
- Significant when mesh resolution is coarse and velocity field has large magnitudes

1.4 Biharmonic Viscosity/Diffusion and Adaptive Filtering

Example of Instability

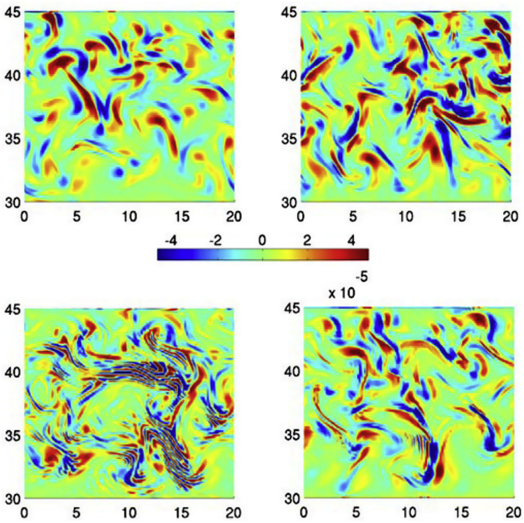


Figure: Danilov *et al.* (2012) *Ocean Modelling*

1.4 Biharmonic Viscosity/Diffusion and Adaptive Filtering

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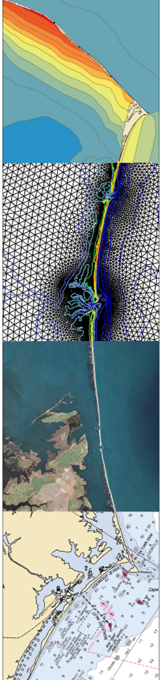

Storm Effects on Salinities in NC Estuaries

BA Rumbaugh[1], JC Dietrich[2],
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[1]Environmental Resources Management, Raleigh NC
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[7]ExxonMobil Upstream Research Company, Houston TX

Sea Grant North Carolina

ADCIRC Studies of Estuarine Circulation

ADCIRC has been applied to understand estuarine circulation **due to storms** ...

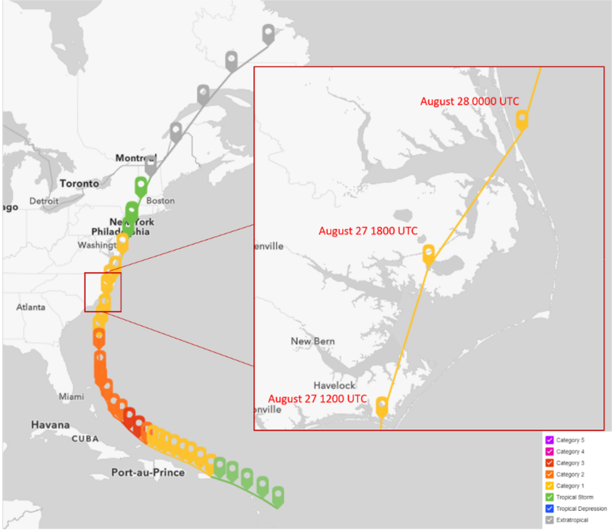
- Sebastian *et al.* (2014) investigated maximum water levels and behavior of storm surge for Ike (2008) in Galveston Bay, Texas
- Yin *et al.* (2017) investigated the effect of sea level rise and typhoon intensification on storm surge in the Pearl River Estuary, China

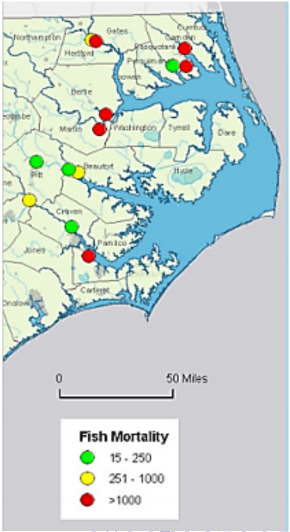
... or **due to density differences**:

- 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

Albemarle and Pamlico Estuarine System (APES)

Irene (2011) Tracked Over APES and Caused Fish Kills





Questions about how estuaries respond to storms:

- How does the density stratification (horizontally and vertically) change during the storm?
- How quickly does it restratify after the event?

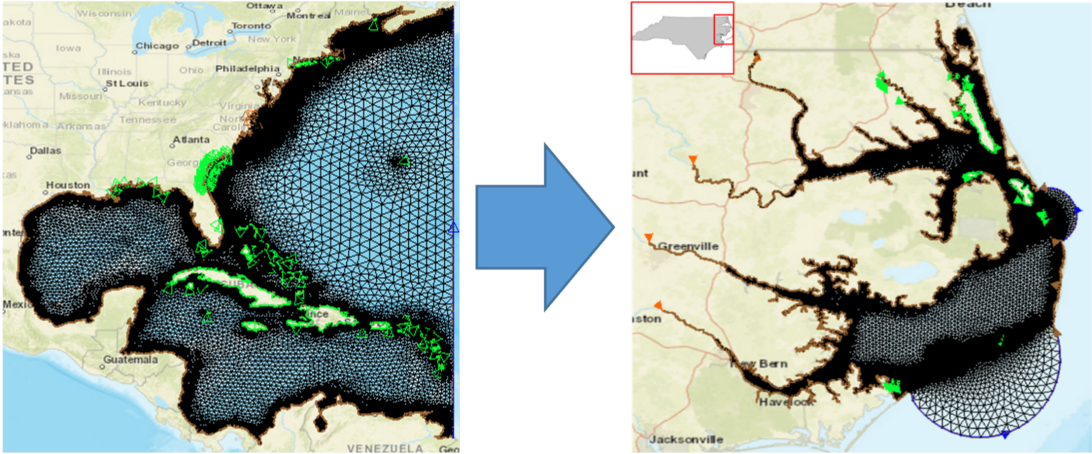
Our goal was to understand how salinities and temperatures in the Albemarle-Pamlico Estuarine System (APES) are disturbed during and recover after a storm

Our objectives were:

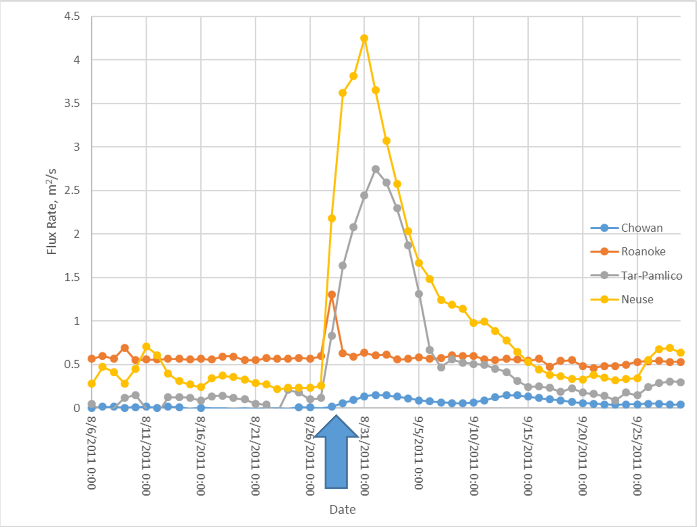
- Develop a baroclinic 3D ADCIRC model for circulation and transport in this system
- Apply all forcings to simulate Irene (2011)
- Quantify the storm effects on density distributions

Cut APES From the NC9 Mesh

Trimmed mesh has 60,330 vertices, resolution from 5 km to 50 m



2.2 Methods
Apply River Fluxes from USGS



Tide and Atmospheric Forcing

We applied tides at the two ocean boundaries:

- Interpolated from the EC2015 tidal database
- Eight leading constituents

We applied atmospheric forcing with a parametric vortex model:

- Generalized Asymmetric Holland model (GAHM)
- Best-track parameters from the NHC
- Covers 0000 UTC August 21 to 0000 UTC August 29

Initial Conditions for Density

ADCIRC needs initial conditions for temperature and density

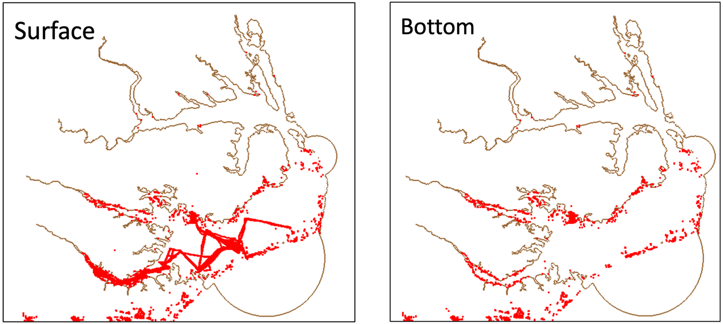
- Could start from a basic distribution and allow ADCIRC to develop a realistic stratification
- But APES residence times are on the order of months
- Better to start with something realistic

SalWise

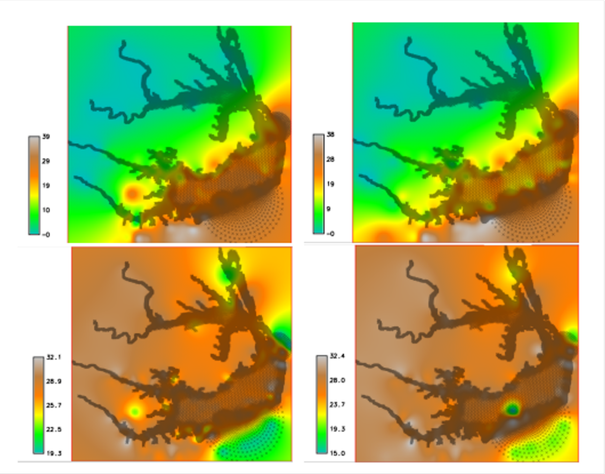
- Database for salinity, temperature, and other water quality parameters
- Developed by Dr. Niels Lindquist (UNC) and Dr. Stephen Fegley (UNC)
    - "Development of a Comprehensive North Carolina Salinity Database to Facilitate Management and Restoration of Critical Fish Habitats"
- Has more than 1,980,000 records
- Dates range from 1945 to 2014

However, it is challenging to develop fields from SalWise

- Limited data points and coverage in APES
- August 2011 had 25,580 points at surface, 237 points at bottom
- All Augusts (any year) had 158,665 points at surface, 3,789 points at bottom



Fields for Initial Salinity, Temperature

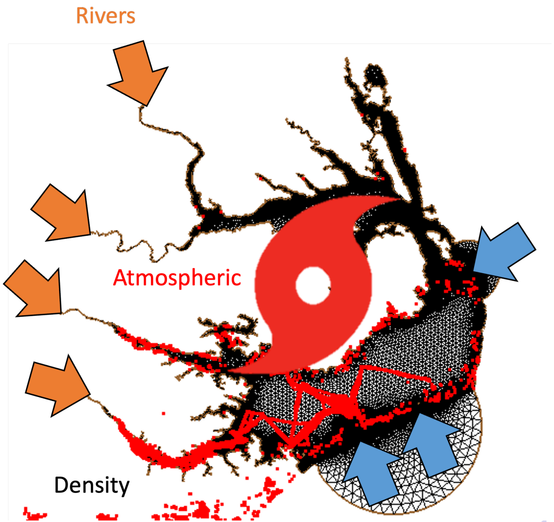


Salinity

Temperature

Surface   Bottom

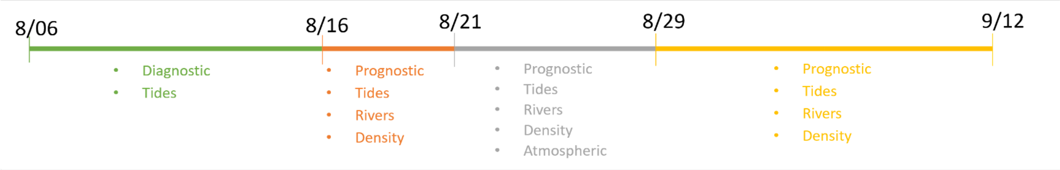
We Cannot Get Any More Complicated Than This



2.2 Methods

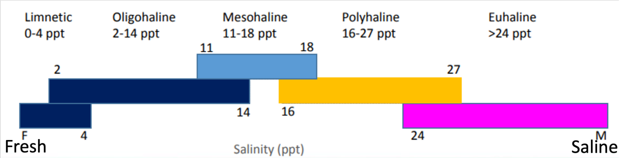
Simulations and Analysis Zones

Series of simulations to build up to the storm and then examine behavior afterward



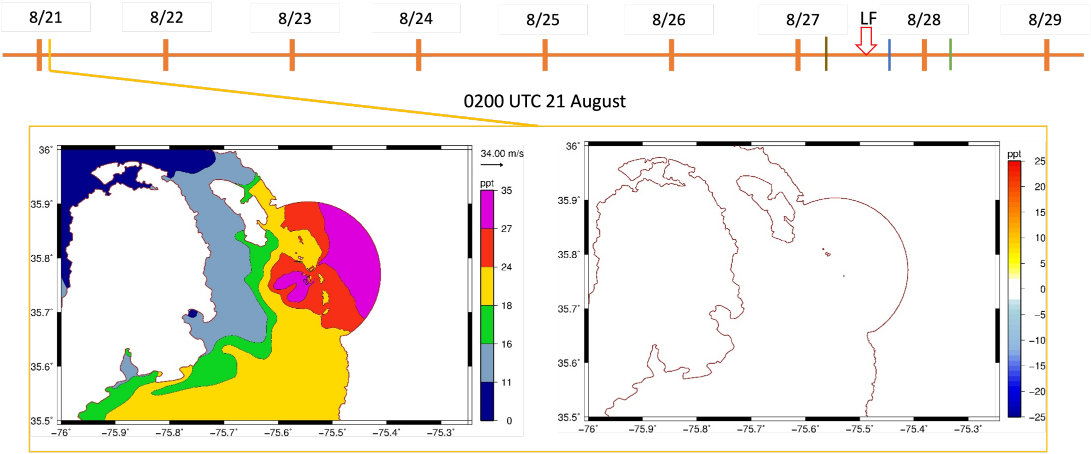
Analyze responses of mesohaline, polyhaline, euhaline zones

- Optimal living conditions for blue crabs (polyhaline/euhaline) and oysters (mesohaline/polyhaline/euhaline)



2.3 Results

Evolution of Surface Salinities near Roanoke Island



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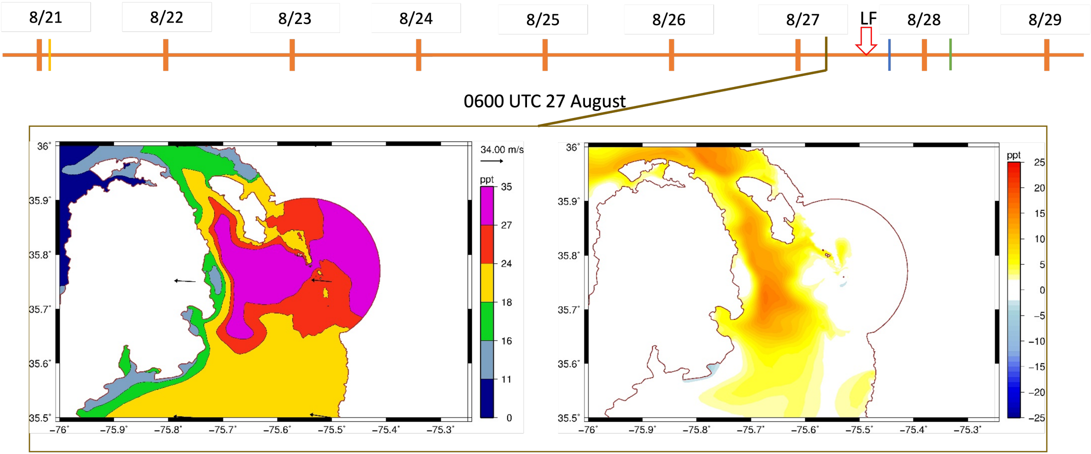

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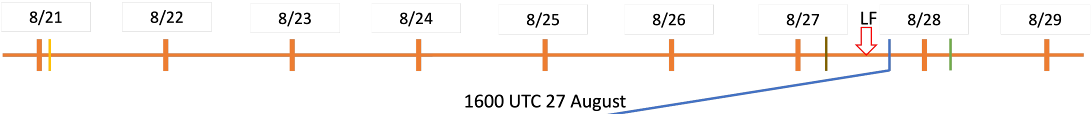

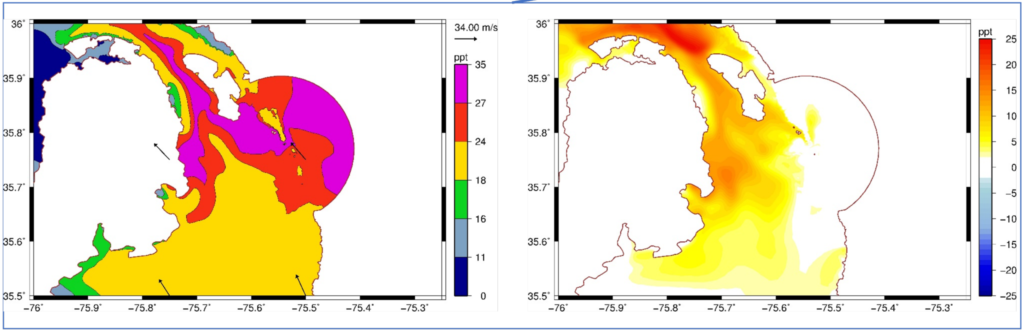

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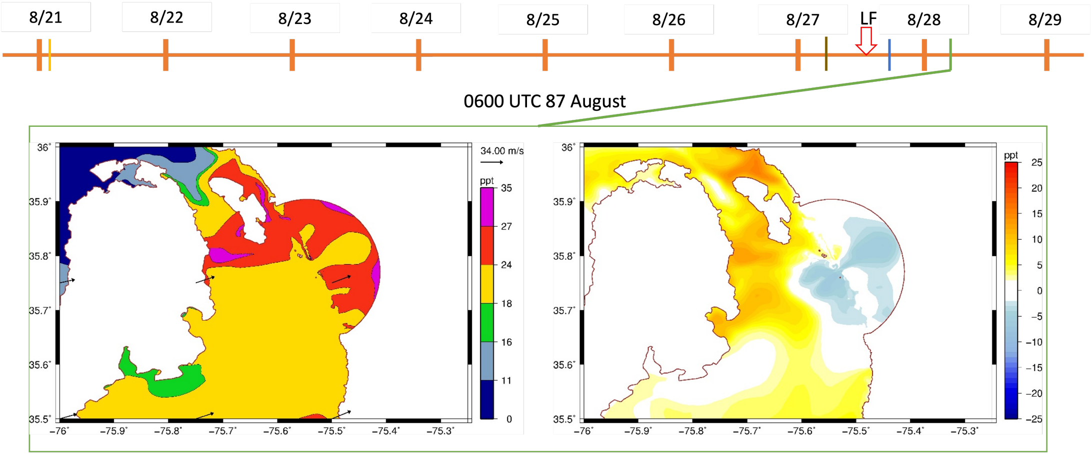

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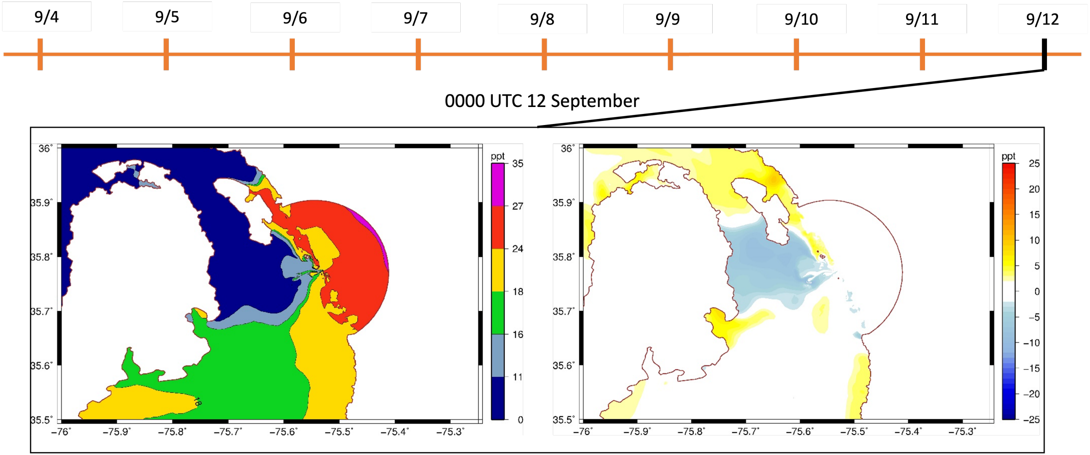

Significant Transport of Saline and Fresh Waters

The main findings from this study were:

- 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.
- Potential for long-duration freshwater intrusions, detrimental to ecosystem

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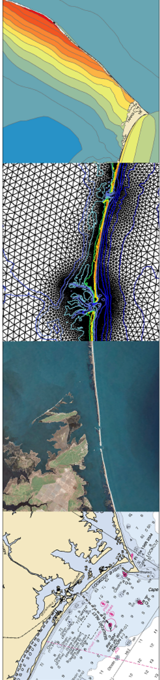

Conclusions and Future Work

Updates to baroclinic 3D ADCIRC:

- Improvements to baroclinic pressure gradients, bathymetry smoothing, viscosity/diffusion operators, and velocity filtering
- Additions have been debugged in a recent ADCIRC version

Storm effects on density stratification in NC estuaries:

- Developed a baroclinic 3D ADCIRC model for Irene (2011) in APES
- Quantified intrusions of brackish and saline waters into Albemarle Sound during the storm, fresh waters past Roanoke Island after the storm

Future work:

- Publish code changes and examples/documentation
- Get these papers out!

Thanks for Your Attention!