Exploring Baroclinic Mode 2D ADCIRC to Capture Inter/Intra-annual Sea Surface Variations

Overall Concept, Implementation Using File I/O, and Preliminary Results

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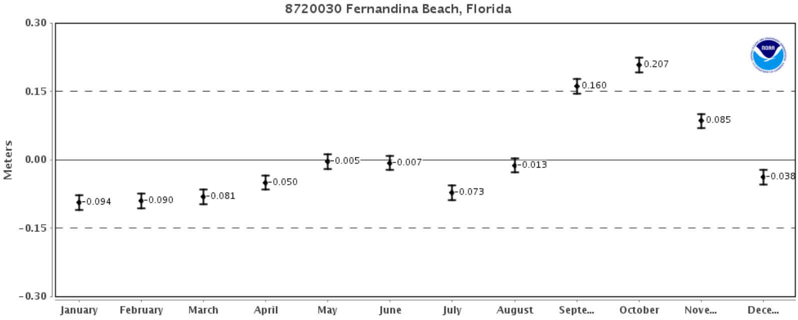
Thursday, April 12, 2018

Outline

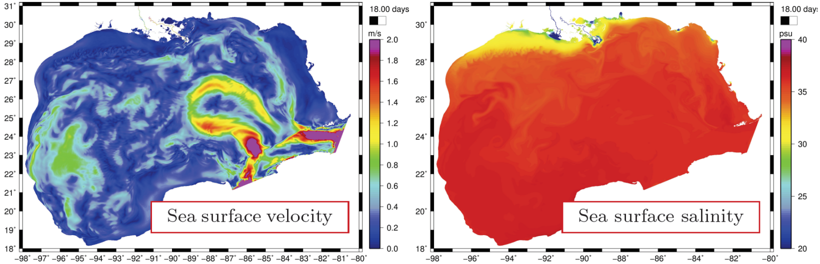
Background

- Flooding risks for coastal cities change based on inter-annual and intra-annual variability
  - Long-term warming of the ocean
  - Seasonal warming and cooling
  - Changes in the Gulf Stream fluxes affect the sea surface height on the US East and Gulf Coasts
  - The interaction of winds and nearshore stratification also affect US East Coast water levels



Problem

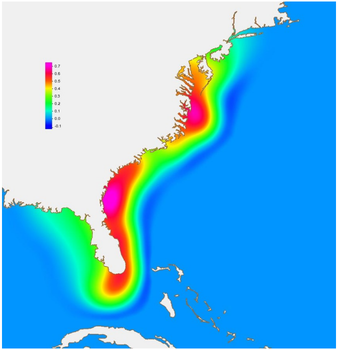
- The processes mentioned are primarily **baroclinic**, but ADCIRC storm surge analysis almost always computed in 2DDI barotropic mode
- 3D baroclinic ADCIRC has recently made great progress, but still difficult and horizontal resolution must be sacrificed



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 Circulation, 2017. *In Preparation.*

Solutions

- Hindcast mode: geoid offset (constant or spatially varying) that can be tuned
- Forecast mode: pseudo atmospheric pressure field that drives an inverted barometer effect (Rick's talk last year)



- **This Study**: 2DDI baroclinic mode ADCIRC that is fed information from a widely used and validated operational 3D baroclinic model (e.g. HYCOM)

Background: 3D Baroclinic Mode ADCIRC

- Splits-up the external (fast, barotropic) and internal (slow, baroclinic) modes because of the disparate timescales
- The 3D and baroclinic information is passed from the internal model to solve the external mode solution (and external mode also passed back to internal mode)
- Different time step for each mode can be used

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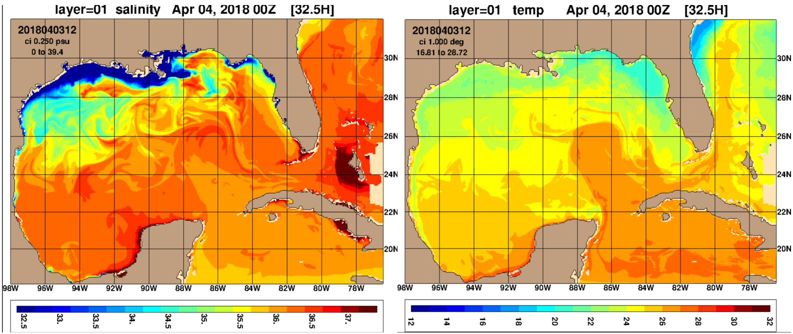
BUT, both modes are computed on the same horizontal grid...

Difficult to obtain high horizontal resolution because of vertical dimension and many more computational operations than 2DDI

This Study: 2DDI Baroclinic Mode ADCIRC

- Do the mode splitting between **separate models** (e.g. HYCOM and ADCIRC)
- Allows us to obtain really high horizontal resolution at the coast (in the ADCIRC model) while absorbing the 3D baroclinic information
- Leverages on the quality of existing widely used and validated 3D baroclinic models



Depth-integrated Momentum Equation

$$\frac{\partial \boldsymbol{u}}{\partial t} + (\boldsymbol{u} \cdot \nabla)\boldsymbol{u} + f\mathbf{k} \times \boldsymbol{u} = -\nabla \left[\frac{p_s}{\rho_0} + g(\zeta - \zeta_{EQ} - \zeta_{SAL}) \right] + \frac{\nabla M}{H} - \frac{\nabla D}{H} - \frac{\nabla B}{H} + \frac{\boldsymbol{\tau}_s}{\rho_0 H} - \frac{\boldsymbol{\tau}_b}{\rho_0 H} - \mathcal{F}_{IT} \quad (1)$$

- Baroclinic pressure gradient:

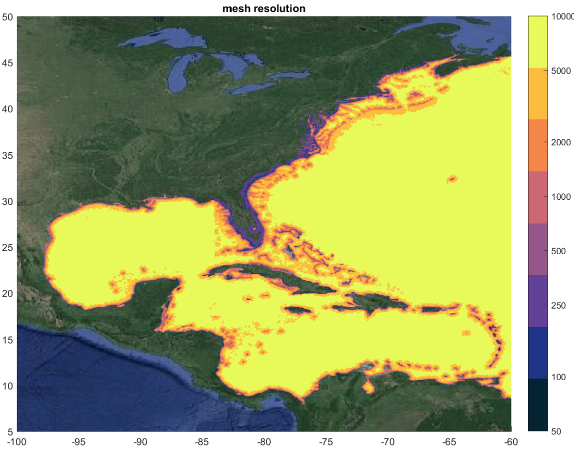
$$\nabla B = \int_{-h}^{\zeta} \left(g\nabla \left[\int_{z}^{\zeta} \frac{\rho - \rho_0}{\rho_0} \right] dz \right) dz$$

- Internal tide induced barotropic energy dissipation:

$$\mathcal{F}_{IT} = C_{IT} \frac{[(N_b^2 - \omega^2)(\tilde{N}^2 - \omega^2)]^{1/2}}{\omega} (\nabla h \cdot \boldsymbol{u}) \nabla h$$

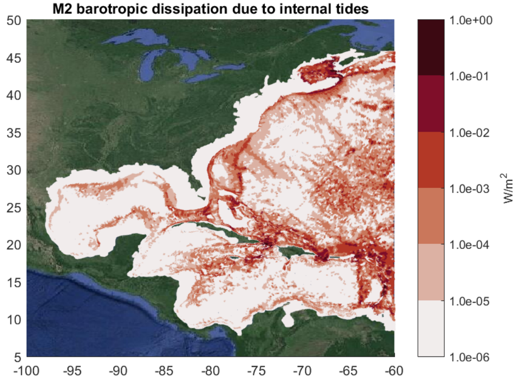
Application: US East Coast Gulf Coast (ECGC)

- 2.46 million nodes
- $\sim$60 m minimum element size at the coast
- Floodplain up to 10 m above LMSL
- Stable time step of **5 sec** in explicit model (full advective terms everywhere)



- Built using OceanMesh2D toolbox by Keith
- Come see us on Friday afternoon for hands-on session!

Dissipation due to Internal Tides

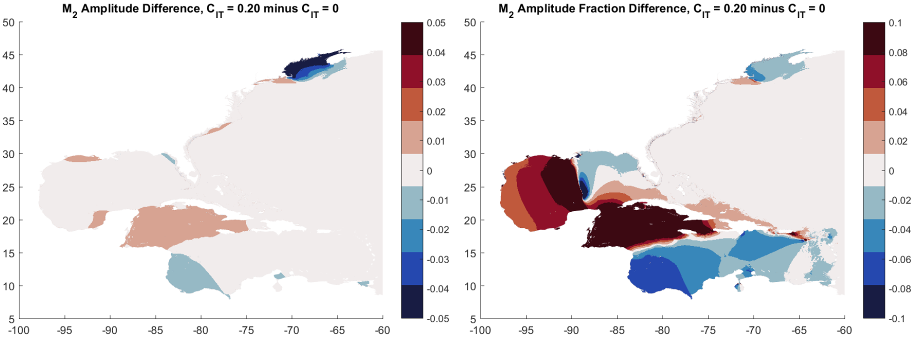


- Globally ≈30% of barotropic dissipation due to internal tide energy conversion
- ECGC domain ≈14% (11 GW out of 75 GW total)
- Gulf of Maine bed stress dominates
- No significant submarine ridges in domain

$$\mathcal{F}_{IT} = C_{IT}\frac{[(N_b^2-\omega^2)(\tilde{N}^2-\omega^2)]^{1/2}}{\omega}(\nabla h\cdot\boldsymbol{u})\nabla h \qquad (2)$$

C_{IT}: tunable constant: $\sim$0.2, $\tilde{N}$: depth-averaged Brunt-Vaisala buoyancy frequency, N_b: Brunt-Vaisala buoyancy frequency at seabed, ω: frequency of dominant tide (M_2), h: ocean depth at rest, $\boldsymbol{u}$: depth-averaged velocity

Effect of Internal Tide Dissipation on M_2 Tide



- Decreases amplitudes in Gulf of Maine and Southern Caribbean Sea
- Amplitudes actually increase in Gulf of Mexico and Northern Caribbean Sea

Change in Integrated Average Error

$$D = \left(0.5 \sum_k \left[(A_0^k)^2 + (A_m^k)^2 - 2A_0^k A_m^k \cos(\theta_0^k - \theta_m^k)\right]\right)^{1/2}$$

$$\overline{D}_{tpx} = \frac{\iint D\,dA}{\iint dA}$$

Table 1: Integrated RMS Discrepancy versus TPXO8, $\overline{D}_{tpx}$

		Model	
Region	Tidal Wave	$C_{IT} = 0$ $\overline{D}_{tpx}$ (SD_{tpx})	$C_{IT} = 0.20$ $\overline{D}_{tpx}$ (SD_{tpx})
Deep $h > 500$ m	M_2	1.25 (4.51)	0.74 (3.01)
	K_1	0.27 (0.34)	0.21 (0.32)
	All	1.51 (4.52)	0.97 (3.06)
Shelf $h < 500$ m	M_2	3.72 (7.32)	3.34 (7.26)
	K_1	0.86 (1.35)	0.87 (1.36)
	All	4.74 (7.60)	4.37 (7.59)

Baroclinic Pressure Gradient Term

- Fully depth-integrated term:

$$\nabla B = \int_{-h}^{\zeta} \left(g \nabla \left[\int_{z}^{\zeta} \frac{\rho - \rho_0}{\rho_0} \right] dz \right) dz$$

- In ADCIRC User Guide, for 2DDI ADCIRC if ρ is assumed to be uniform over the depth (this formula is in timestep.F)... Depth-averaged term:

$$\nabla B = gH \left[\frac{\rho_{2D} - \rho_0}{\rho_0} \nabla \zeta + \frac{H}{2} \nabla \left(\frac{\rho_{2D} - \rho_0}{\rho_0} \right) \right]$$

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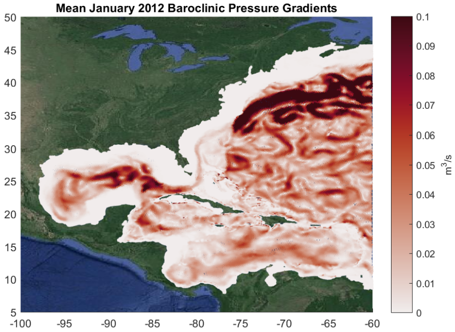
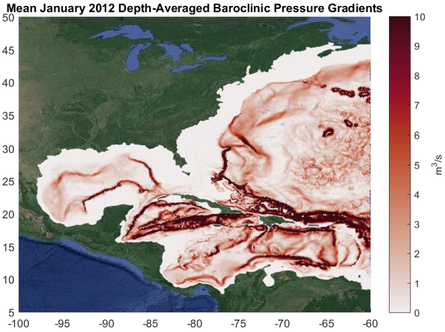
- BUT, ρ is *not* uniform over the depth, leads to incorrect specification:





Current Implementation

- The mode splitting is one-way (HYCOM $\rightarrow$ ADCIRC)
- Compute baroclinic pressure gradient, ∇B and internal tide dissipation parameter, $\mathcal{F}_{IT}$ offline (I do this in MATLAB)
- Pass the various parameters through file I/O basically using existing ADCIRC options
  1. Made a IDEN $=$ -5 option specified in **fort.15** and enabled a switch for 2DDI baroclinic mode

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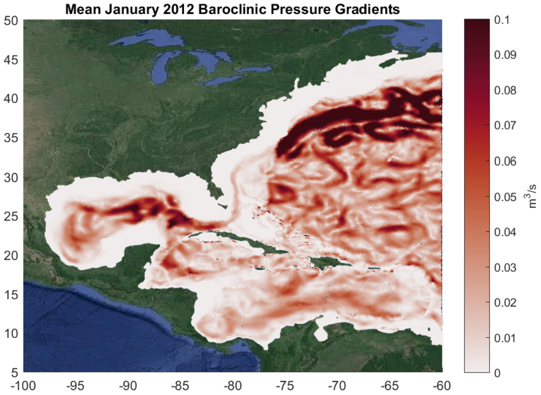
  4. Open boundary elevation specified conditions are the periodic tidal frequencies (TPXO9 harmonic constituents) + non-periodic elevations specified from a **fort.19** (elevations are extracted from HYCOM, they do not simulate ocean tides)

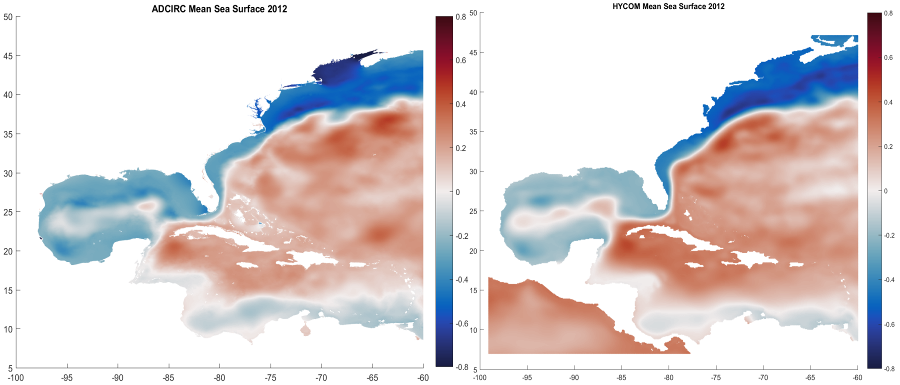
Fully Forced Yearlong Simulation (2012)

- Daily *HYCOM + NCODA Global 1/12° Reanalysis* elevations specified at the open boundary (added to tidal constituents)
- Daily baroclinic gradients calculated offline from 3D HYCOM temperature and salinity fields
- Hourly 0.281° ERA5 atmospheric data



- Spin-up plus relaxation period of 30 days

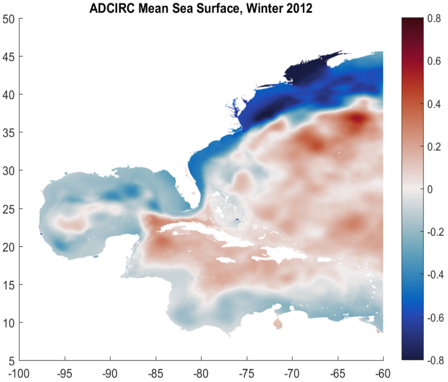
Yearly Mean Sea Surface Height



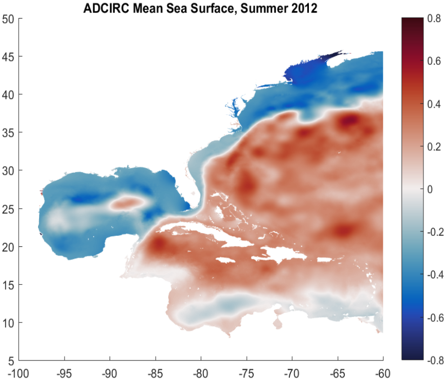
- General ocean surface patterns are reproduced
- Daily outputs but ADCIRC includes tides so average may be slightly biased

Seasonal Mean Sea Surface Height

Winter (Nov - March)

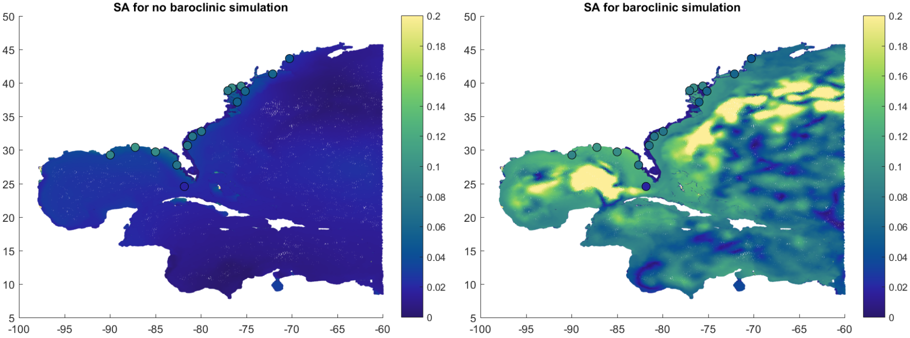


Summer (June - Oct)



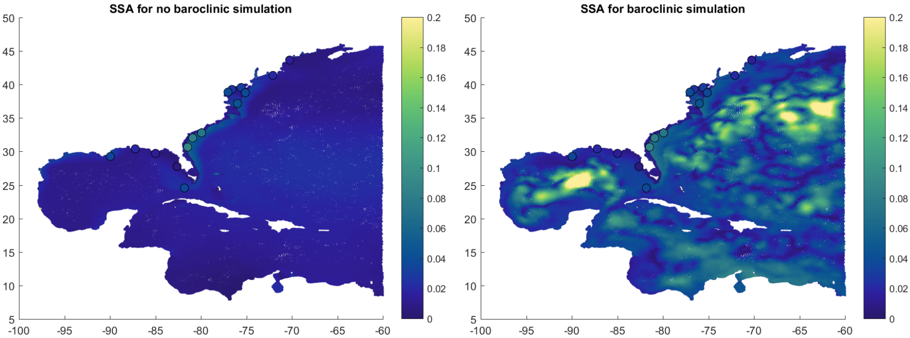
- Able to get higher sea surface in summer than winter in general

SA Constituent Map



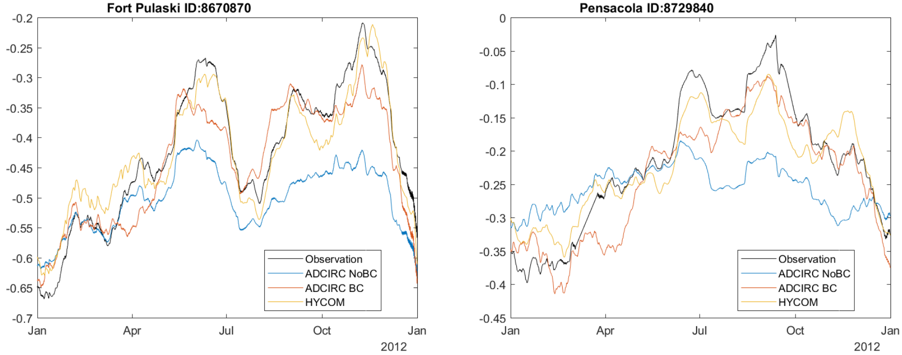
- No baroclinic mode induces notable SA only in the Florida panhandle coastal region (direct seasonality of winds and pressure)
- Baroclinic mode induces much larger SA in general due to the changes in the Gulf Stream, heating-cooling, and warm core eddies

SSA Constituent Map



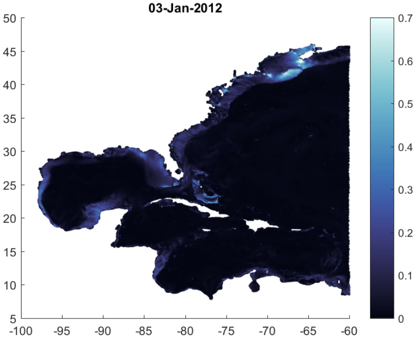
- No baroclinic mode induces large SSA only in the South Atlantic bight
- Baroclinic mode larger SSA, particularly in the Gulf and the northern Atlantic

Yearly 30-day Moving Mean Time Series at Tide Gauges



- From July onwards baroclinic mode can capture the seasonal rise that non baroclinic model cannot
- Around April the baroclinic mode misses something, problems:
  1) Open ocean boundary (mis-match between ADCIRC & HYCOM)?
  2) Nearshore/estuarine density gradients?

Ocean Currents



- Geostrophic ocean currents are generated by baroclinic pressure gradient terms that are otherwise not present in non-baroclinic 2DDI ADCIRC

Conclusions

- Representing around 14% of M_2 tidal dissipation, internal tide induced dissipation improves tidal solutions in ECGC region
- Inclusion of baroclinic pressure gradient terms in 2DDI ADCIRC drive geostrophic ocean currents
- Geostrophic ocean currents in 2DDI ADCIRC induce mean sea surface heights similar to 3D baroclinic HYCOM model
- Greater intra-annual variability in baroclinic mode versus non-baroclinic mode demonstrated (e.g. SA, SSA)
- Complete hydrodynamic modeling system that does not require ad-hoc data manipulation

Going Forward

Problems to solve:

- May need to reconcile discrepancy between ADCIRC and HYCOM at open boundary through e.g. sponge type layer
- What to do with densities in nearshore/estuarine areas where HYCOM has no data/resolution?

Online implementation:

- Directly read in HYCOM temperature and salinity to calculate ∇B and $\mathcal{F}_{IT}$ online (in ADCIRC)
- Make use of ESMF framework and libraries for interpolation
- **3D** terms?? (dispersion, mixing, bottom stress)
- Final aim is ESMF compliant operational model, possibly **two-way coupled** with a 3D baroclinic model (ADCIRC can be used to provide 3D model with accurate coastal elevations)