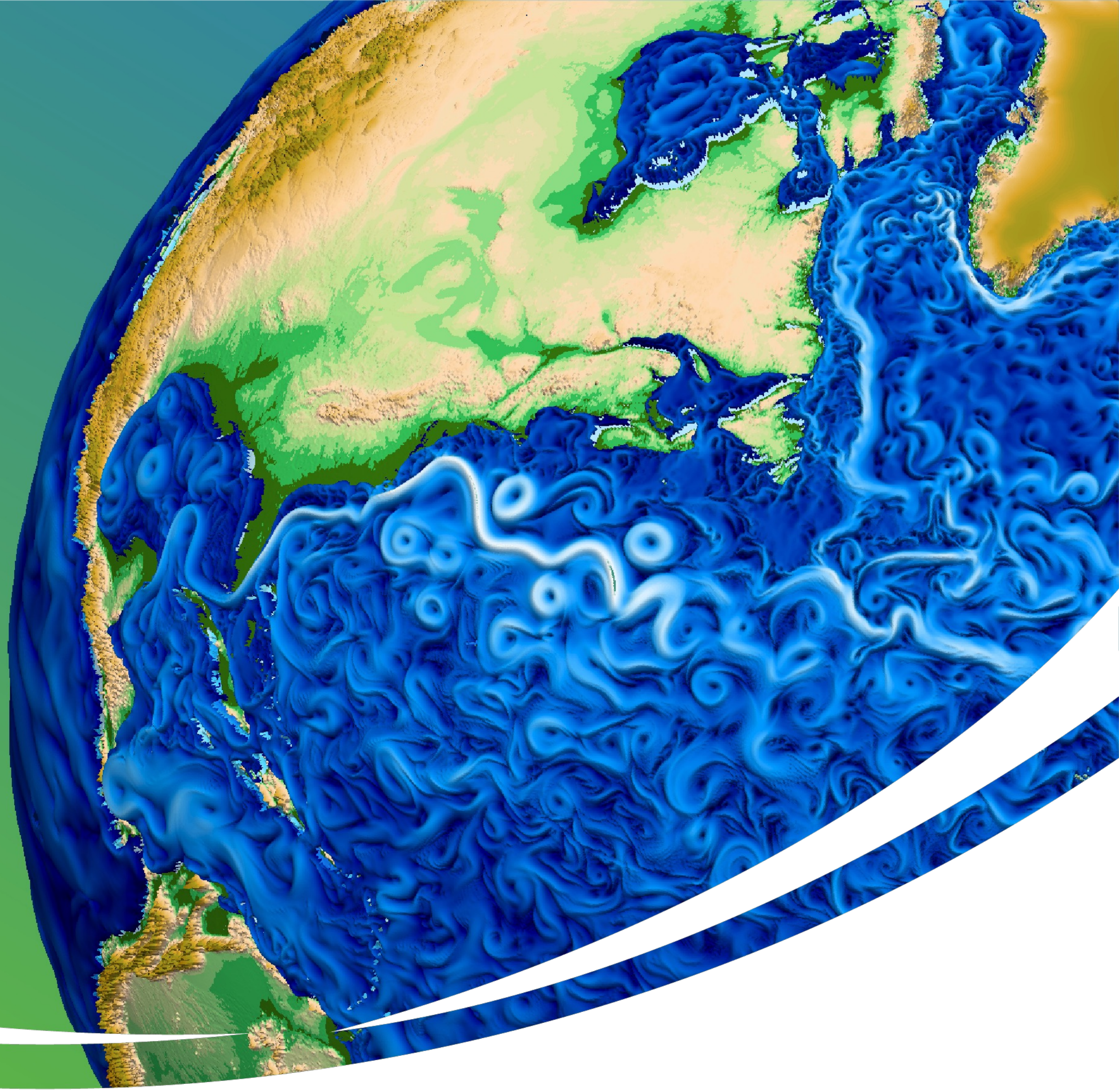
Assessing climate impacts on coastal-urban flooding through high-resolution barotropic and baroclinic ocean coupling



Steven Brus
Coleman Blakely

Argonne National Laboratory

U.S. DEPARTMENT OF ENERGY

E3SM
Energy Exascale Earth System Model

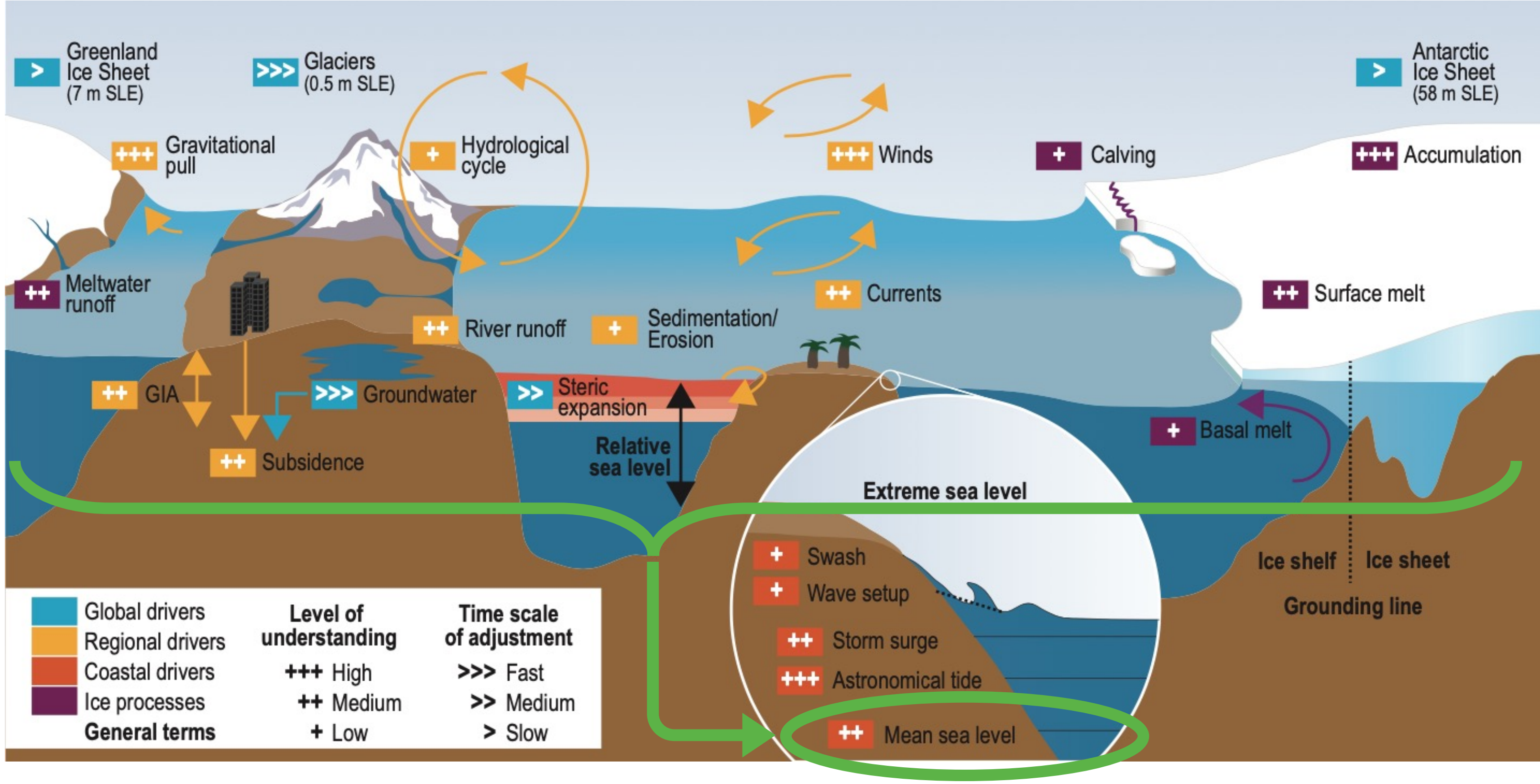
Climate Change Processes Affecting Sea Levels

Global and Regional Sea Level Drivers

- Ice sheet melting
- Steric expansion
- Glacial isostatic adjustment
- Ocean currents
- **Requires global-scale resolution and coupling**

Coastal-Urban Extreme Sea Level Drivers

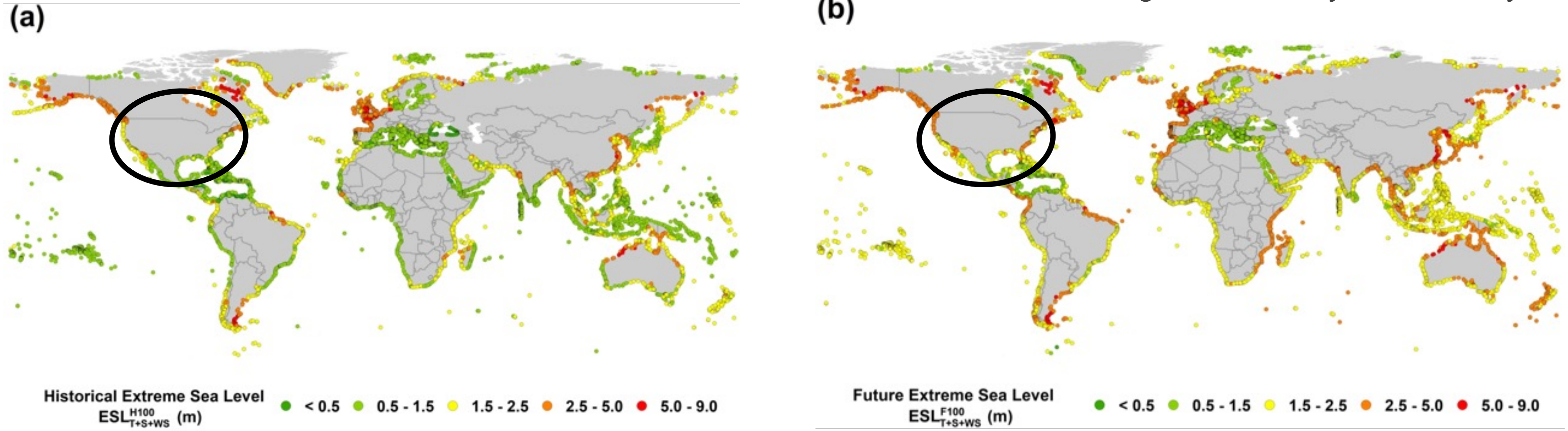
- Tides
- Storm Surge
- Wave Setup
- **Requires high resolution at coasts**



IPCC Special Report on the Ocean and Cryosphere in a Changing Climate

Future Extreme Sea Levels

For RCP8.5, increase of 48% of world's land area at risk from flooding from a 100 year event by 2100



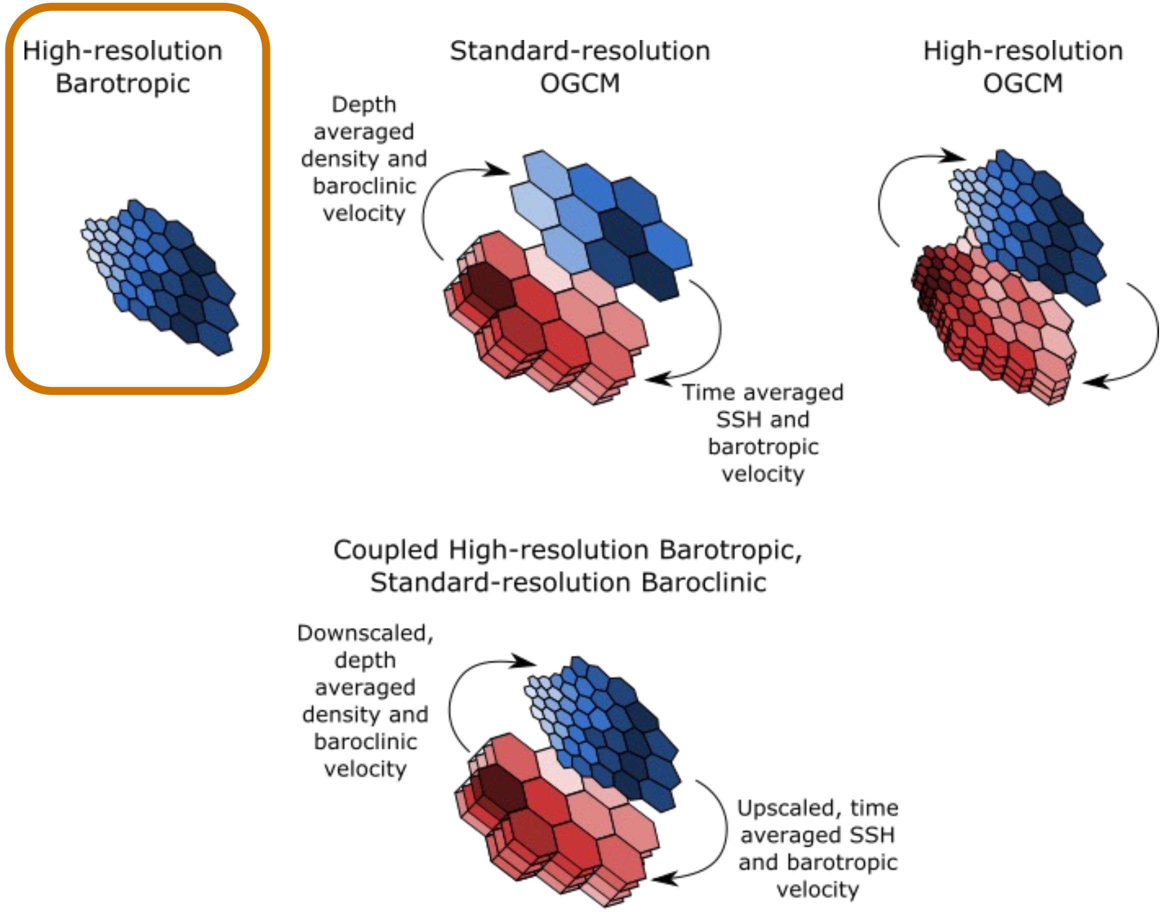
Kirezci et al., *Scientific Reports* (2020)

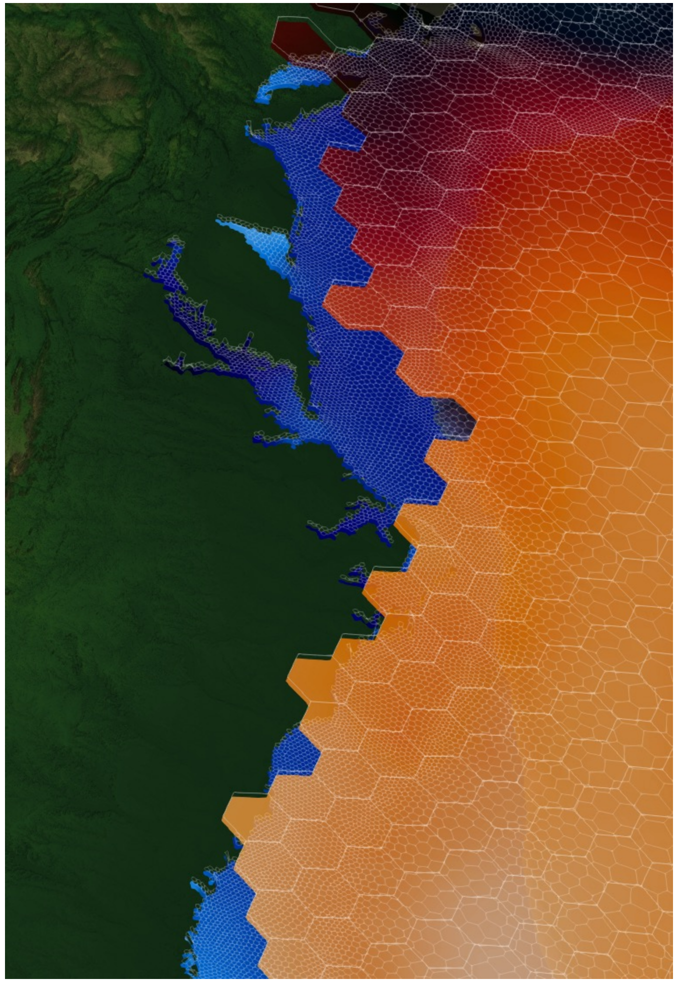
- Future extreme sea levels are projected to rise in many areas along U.S. coastlines
- Many global studies lack high coastal resolution
- Linear superposition of sea level drivers is often assumed
- "Bathtub" model for sea level rise and inundation is a popular assumption
- Changes in tides are neglected
- Water level variations due to thermohaline circulation neglected

Coupling of surface waves and density-driven flow

Barotropic Coastal Models

- 2D free surface model with depth averaged currents and constant density (barotropic).
- Accurately captures long-wavelength tidal and storm surge processes
- Unstructured meshes efficiently resolve coastal conveyances and floodplains at scales of 10-100m

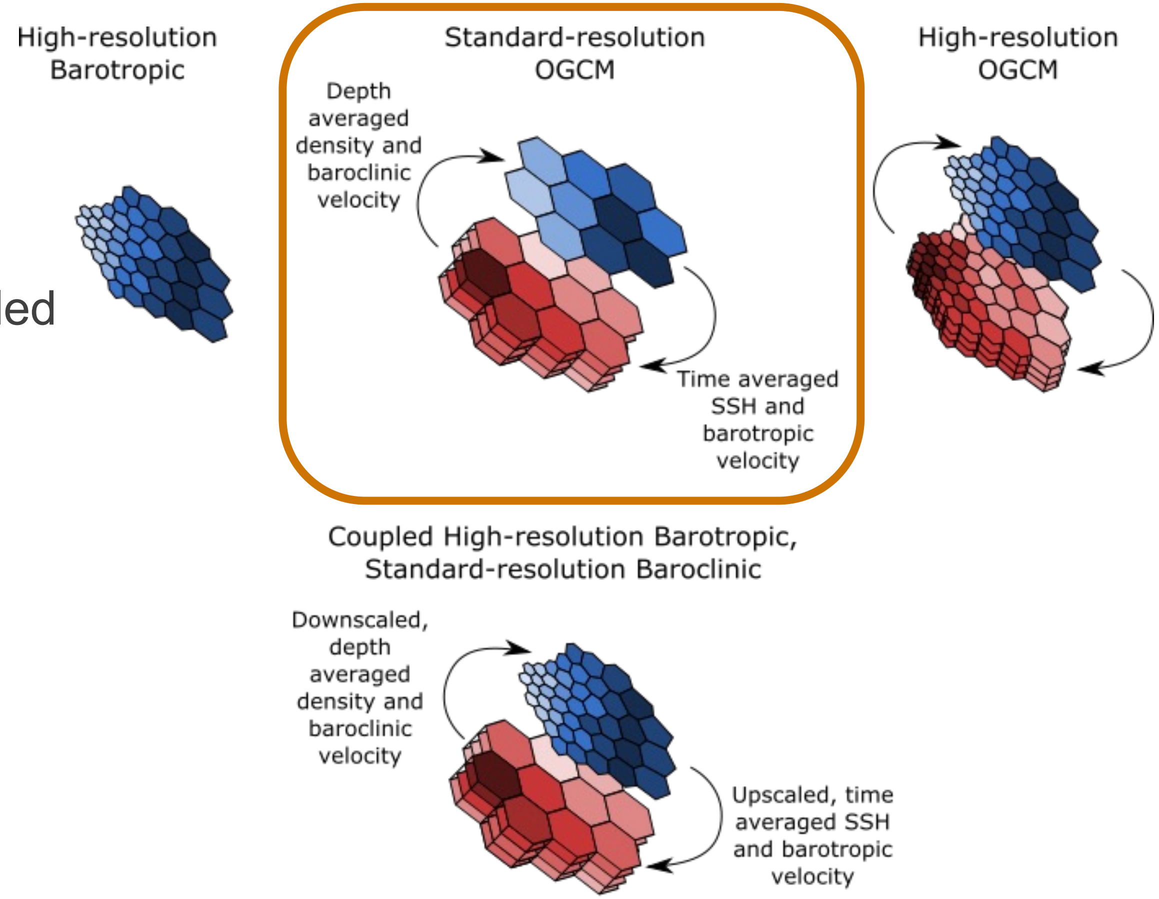


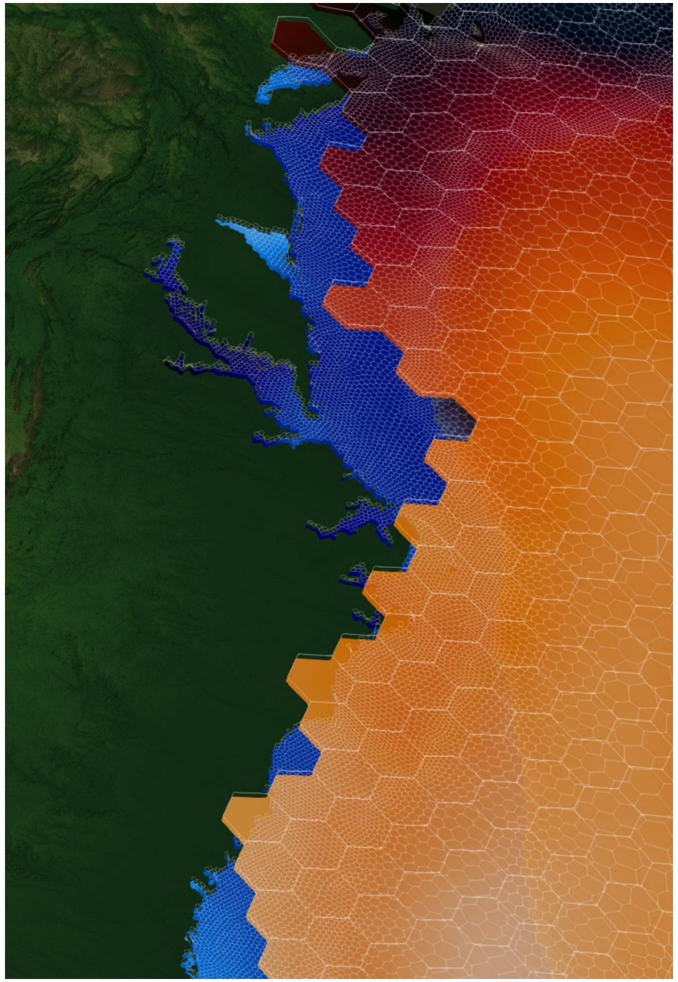


Coupling of surface waves and density-driven flow

Ocean General Circulation Models

- 3D free surface model
- Typical resolution for coupled climate applications: 30-60km with 60 vertical layers
- Captures global circulation patterns due to density-driven flow (baroclinic)
- Time stepping is typically split between barotropic mode (small dt) and baroclinic mode (large dt).





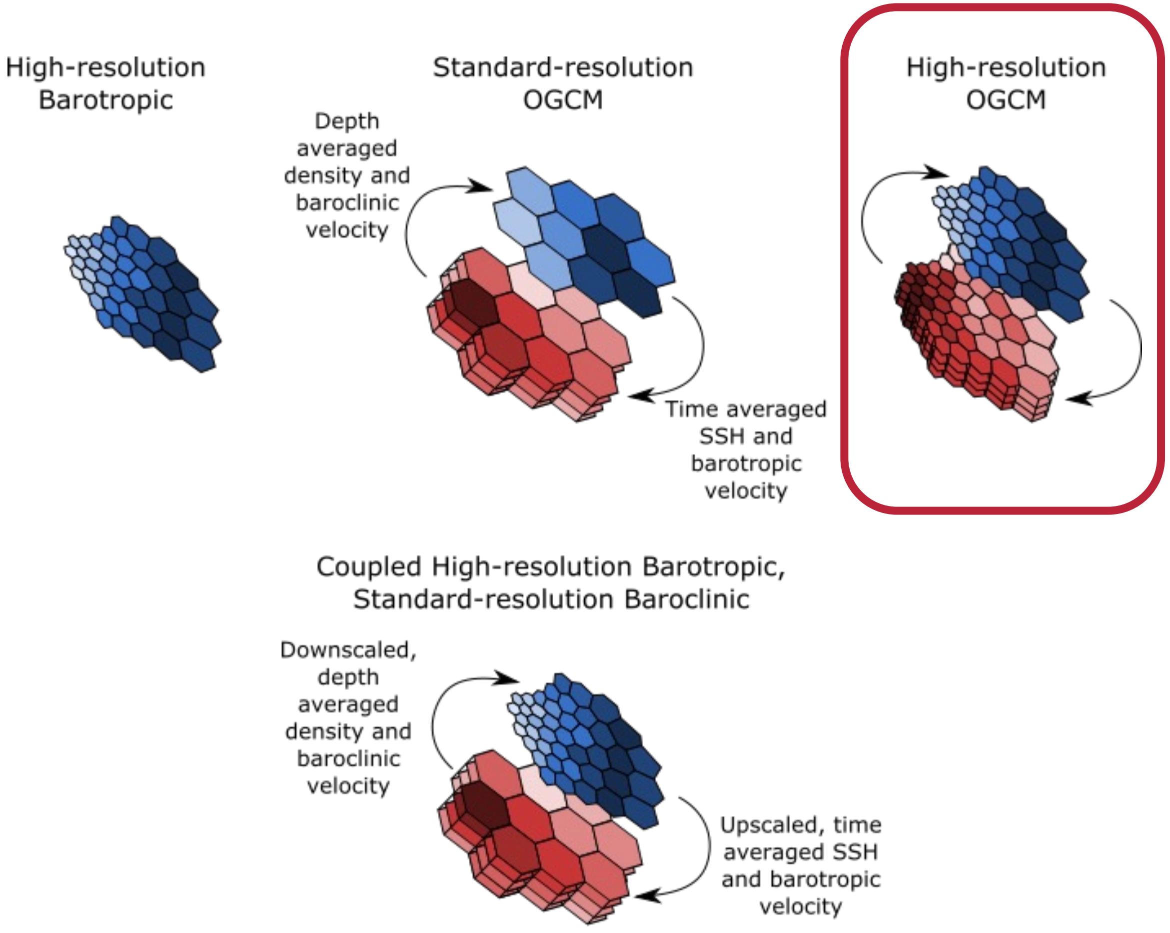
Coupling of surface waves and density-driven flow

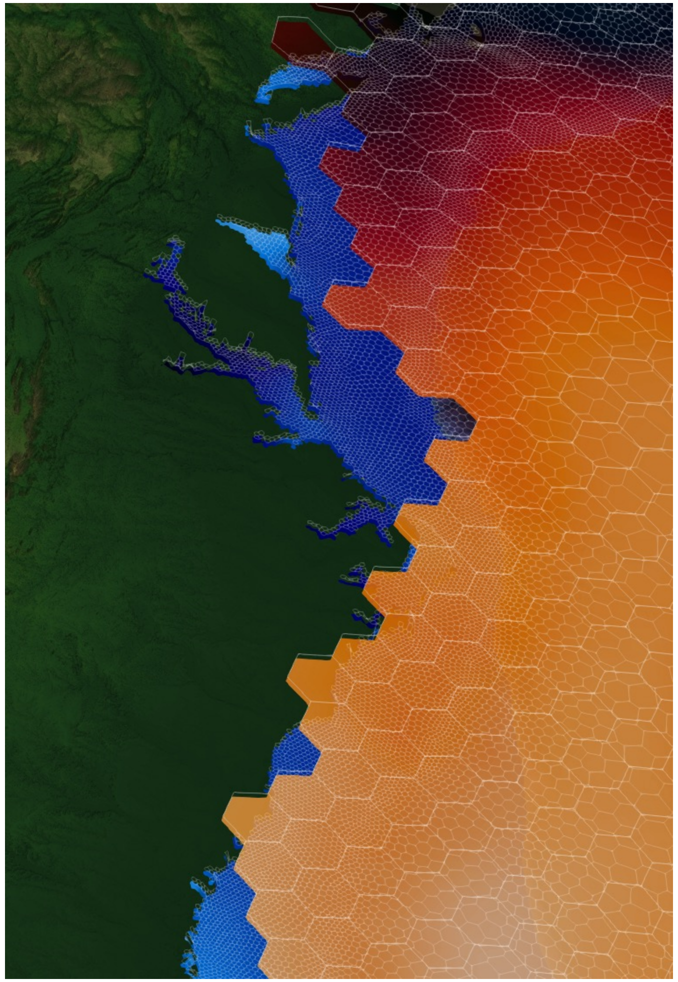
High resolution OGCM

- Resolving 3D model to high-resolution coastal scales is prohibitively expensive

- Coastal-scale baroclinic processes have minor impact on extreme coastal water levels

- Transitions between mesoscale eddy permitting/parameterized regions are problematic for variable resolution meshes

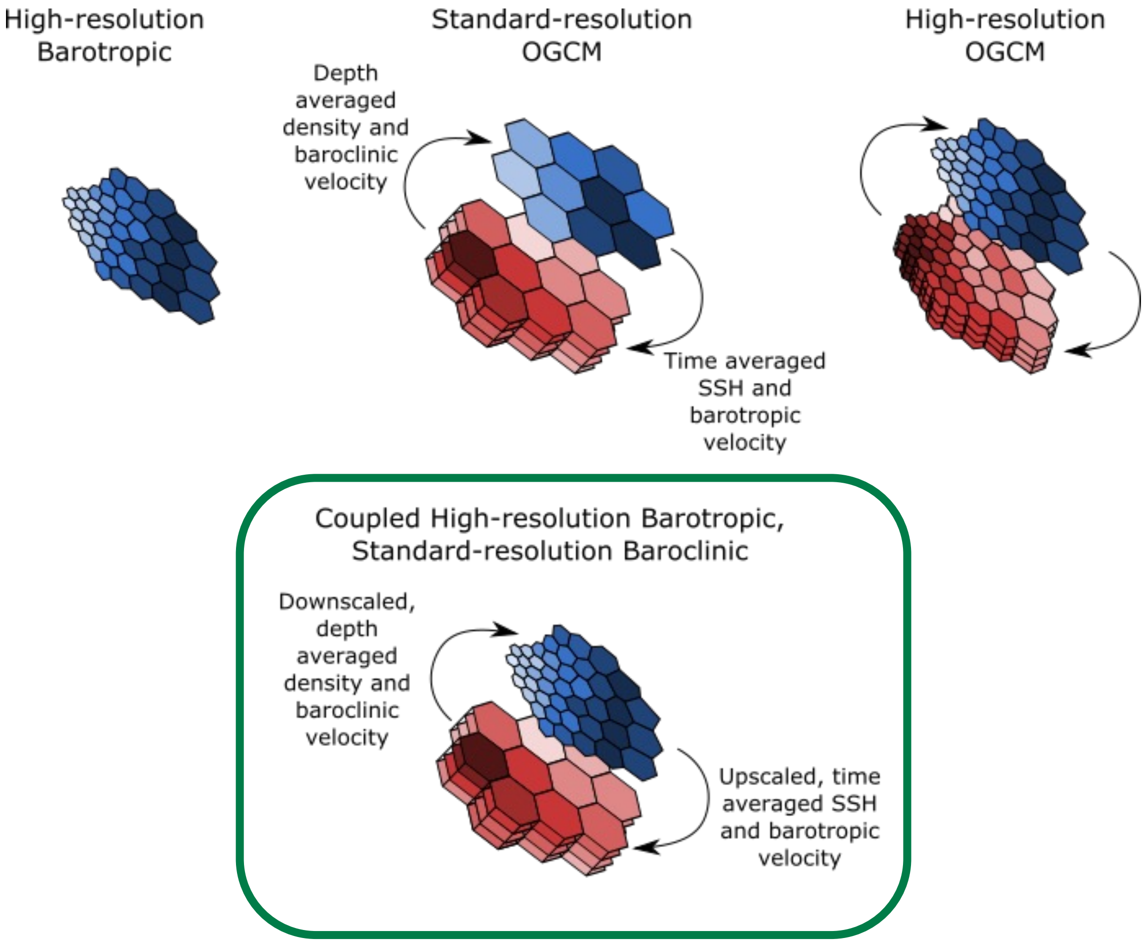


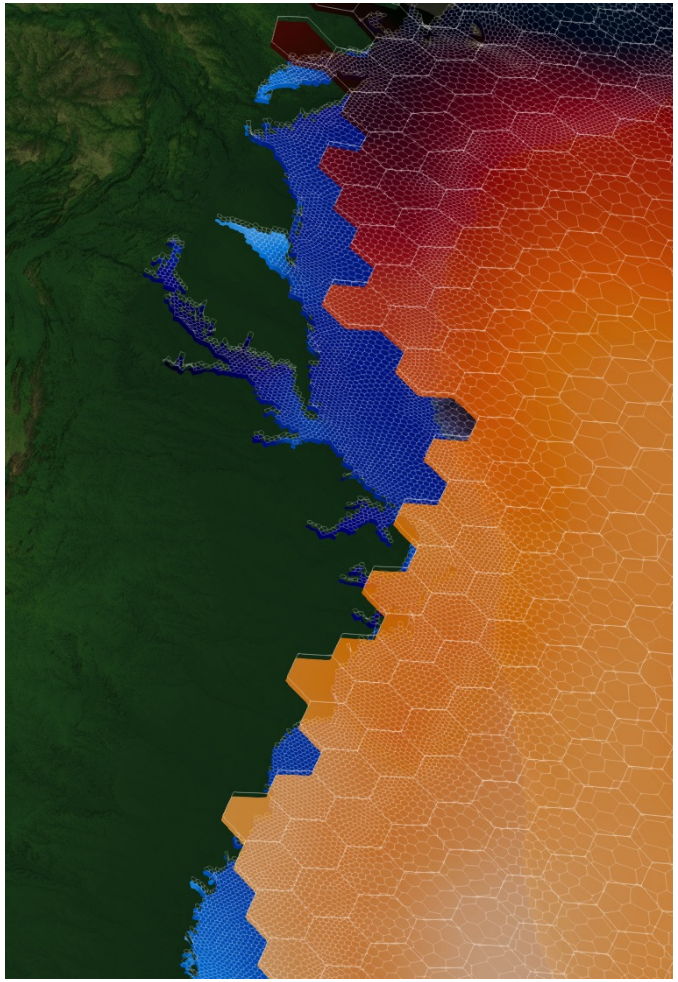


Coupling of surface waves and density-driven flow

Coupled Approach

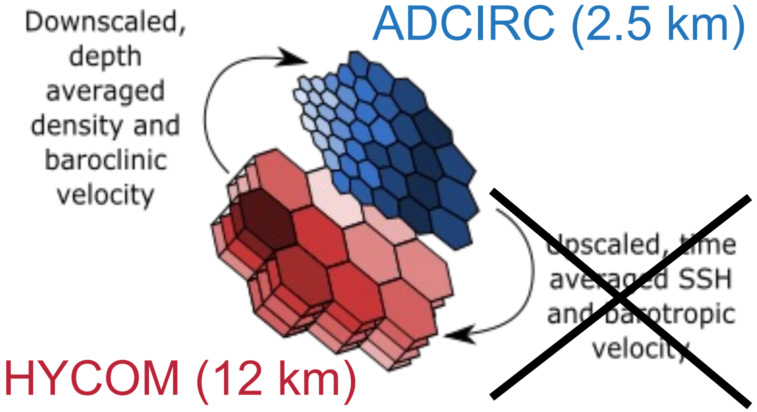
- Provide high resolution in coastal regions to capture extreme flooding due to tides and storm surge
- Integrate sea level rise drivers: thermohaline circulation and connections to other Earth system components.
- Enable comprehensive projections of total water level under climate change

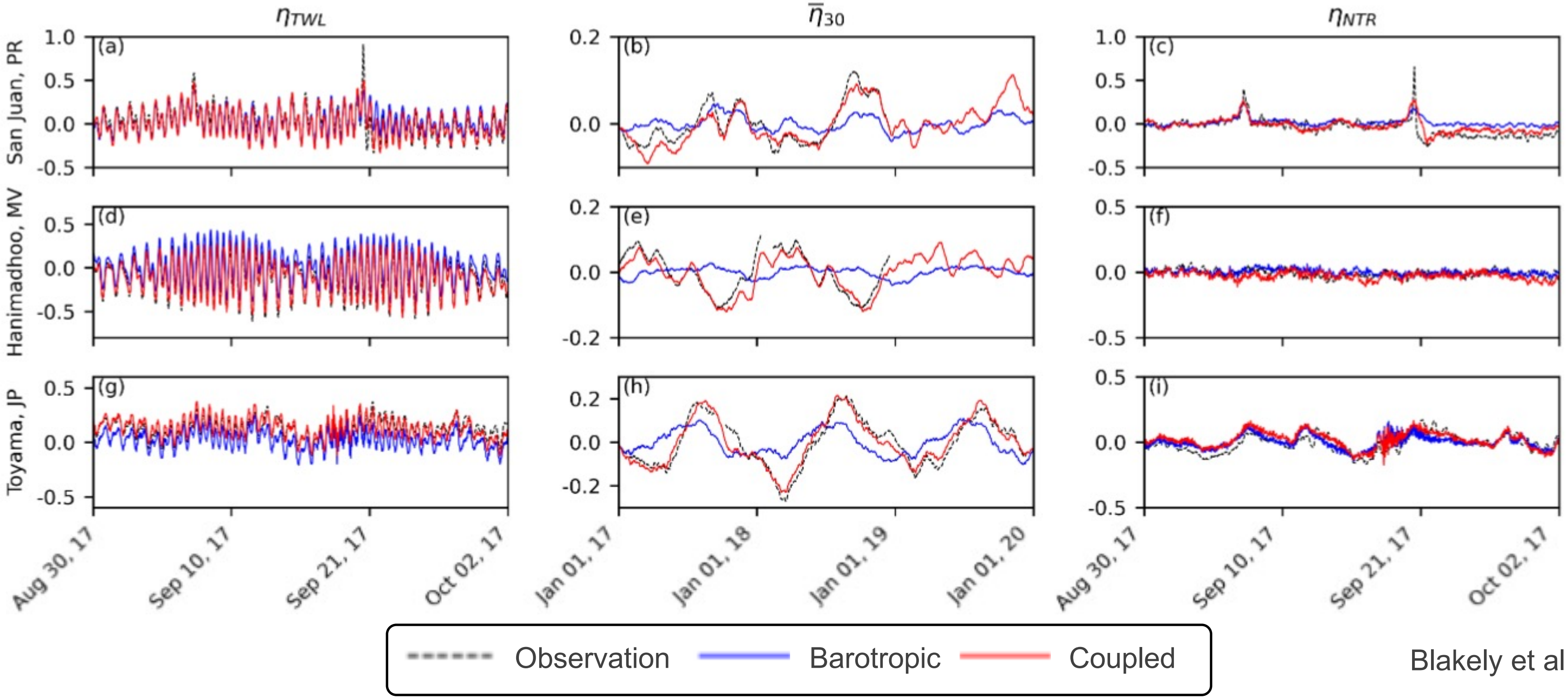




Motivation: One-way offline coupling

- Project postdoc Coleman Blakely worked with a one-way version of this coupling between separate models for his Ph.D.

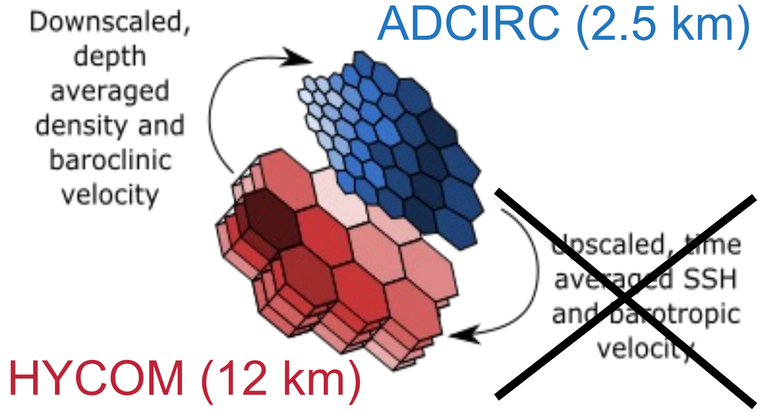


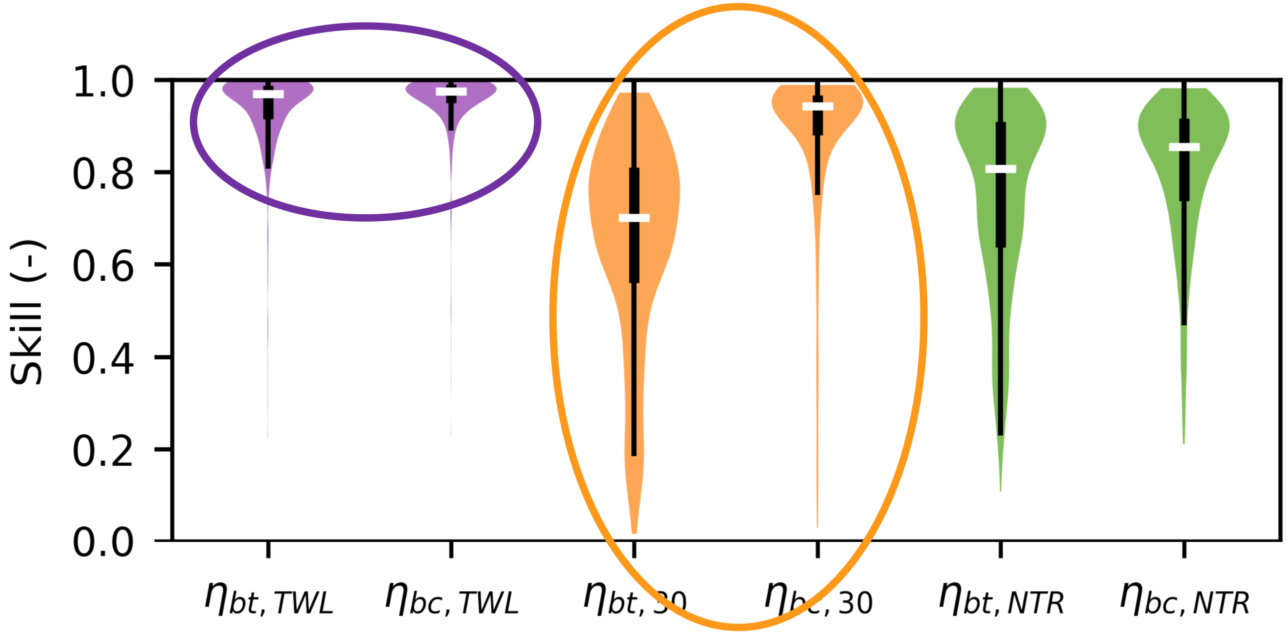


Blakely et al. 2024, in prep.

Motivation: One-way offline coupling

- Internal wave dissipation is critical to accurate global tides, parameterized based on tidal velocities
- Baroclinic coupling means depth averaged velocities are no longer purely tidal.





- Baroclinic coupling had previously degraded total water level accuracy vs. purely barotropic results
- Coleman's work corrected this so that the baroclinic coupling is just as accurate for total water level with **much better** 30-day averaged water levels at 568 GESLA water level stations

Blakely et al. 2024, in prep.

E3SM Energy Exascale Earth System Model

Task 1: Development of spatial baroclinic-barotropic coupling

Primitive equations:

$$\nabla \cdot \mathbf{u} + \frac{\partial w}{\partial z} = 0$$

$$\frac{\partial \mathbf{u}}{\partial t} + (\mathbf{u} \cdot \nabla)\mathbf{u} + w\frac{\partial \mathbf{u}}{\partial z} + f\mathbf{k} \times \mathbf{u} = -g\nabla\left(\eta + \int_z^{\eta}\left(\frac{\rho(\Theta, S) - \rho_0}{\rho_0}\right) dz'\right) + D$$

Velocity Separation:

Baroclinic Barotropic

$$\mathbf{u}' = \mathbf{u} - \bar{\mathbf{u}}$$

Mode Split Equations:

Barotropic

$$\frac{\partial \eta}{\partial t} + \nabla \cdot (\bar{\mathbf{u}}H) = 0$$

$$\frac{\partial \bar{\mathbf{u}}}{\partial t} + f\mathbf{k} \times \bar{\mathbf{u}} = -g\nabla\eta + G$$

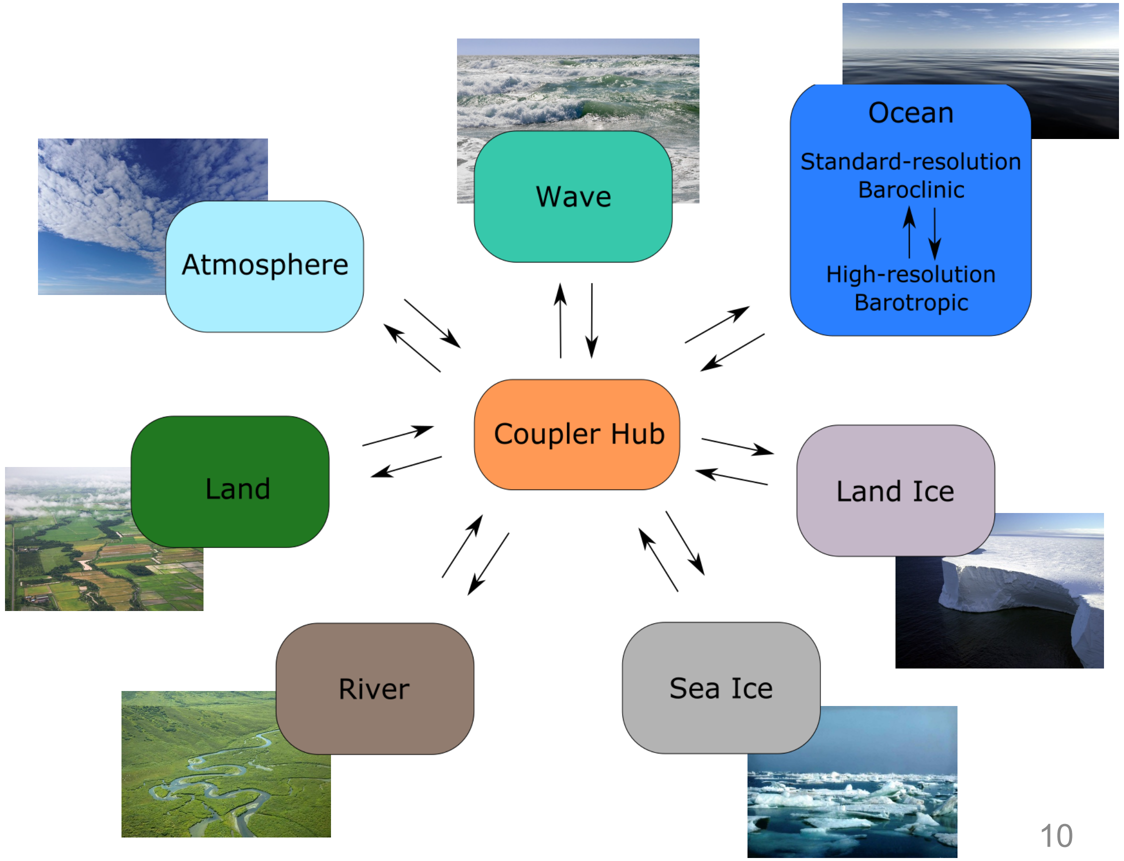
Remap sub-cycle average from high res to standard res $\bar{\mathbf{u}}H$

Remap from standard res to high res G

Baroclinic

$$\frac{\partial \mathbf{u}'}{\partial t} + (\mathbf{u} \cdot \nabla)\mathbf{u} + w\frac{\partial \mathbf{u}}{\partial z} + f\mathbf{k} \times \mathbf{u}' = -g\nabla \int_{-z}^{\eta}\left(\frac{\rho(\Theta, S) - \rho_0}{\rho_0}\right) dz' + D - G$$

- For efficiency, barotropic/baroclinic coupling requires more direct communication, separate from inter-component coupler hub



Task 2: Enable steric water level

- The Boussinesq approximation used in MPAS-Ocean means that the model is volume (not mass) conserving
- This approximation ignores the expansion/contraction of the water column from density changes
- Boussinesq ocean models can be converted to non-Boussinesq through the following modifications:
  - Exchange roles of sea surface height and bottom pressure in boundary conditions
  - Reverse direction of integration in hydrostatic equation
  - Substitute specific volume for density in hydrostatic equation

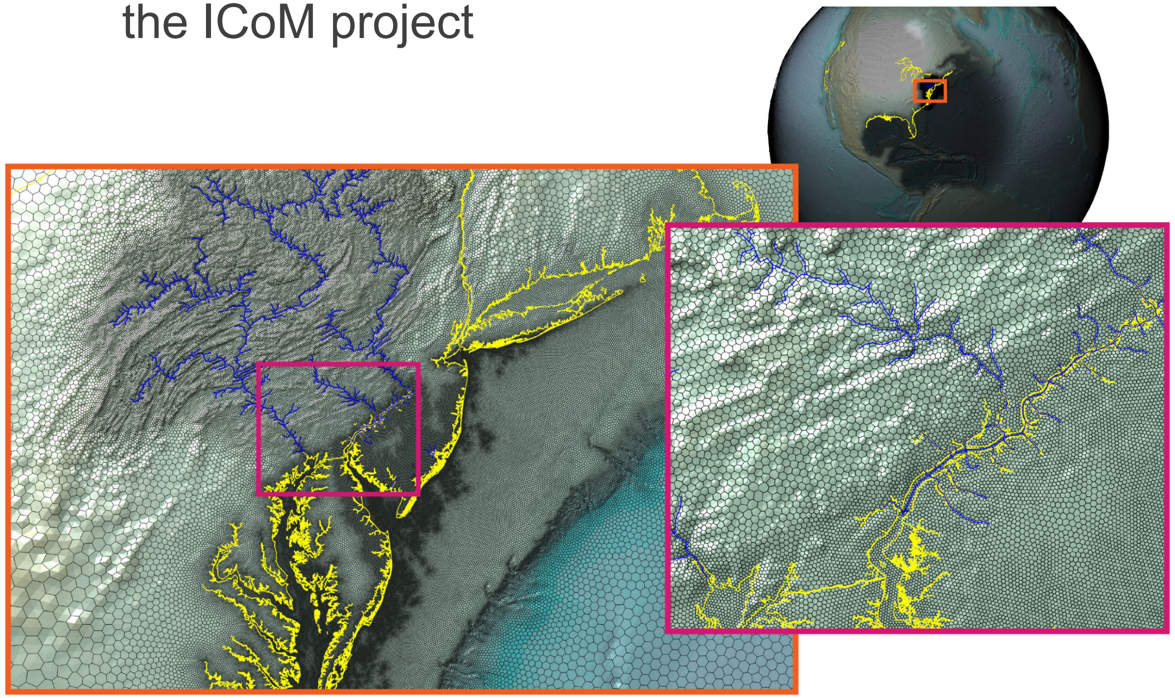
Boussinesq Equations in z coordinates		**Non-Boussinesq Equations in pressure coordinates**
$\frac{D\mathbf{u}}{Dt} = -\nabla_z \left(\frac{p}{\rho_0}\right) - f\mathbf{k}\times\mathbf{u} + \mathbf{F}$	$\leftrightarrow$	$\frac{D\mathbf{u}}{Dt} = -\nabla_p M - f\mathbf{k}\times\mathbf{u} + \mathbf{F}$
$\frac{1}{\rho_0}\frac{\partial p}{\partial z} = -g(\rho - \rho_0)/\rho_0$	$\leftrightarrow$	$\frac{\partial M}{\partial p} = -\alpha + \rho_0^{-1}$
$\nabla_z \cdot \mathbf{u} + \frac{\partial w}{\partial z} = 0$	$\leftrightarrow$	$\nabla_p \cdot \mathbf{u} + \frac{\partial \omega}{\partial p} = 0$
$\frac{D\theta}{Dt} = Q$	$\leftrightarrow$	$\frac{D\theta}{Dt} = Q$
$\frac{DS}{Dt} = Q_S$	$\leftrightarrow$	$\frac{DS}{Dt} = Q_S$
$\frac{D}{Dt} = \left(\frac{\partial}{\partial t}\right)_z + \mathbf{u}\cdot\nabla_z + w\frac{\partial}{\partial z}$	$\leftrightarrow$	$\frac{D}{Dt} = \left(\frac{\partial}{\partial t}\right)_p + \mathbf{u}\cdot\nabla_p + \omega\frac{\partial}{\partial p}$
$w = \frac{Dz}{Dt}$	$\leftrightarrow$	$\omega = \frac{Dp}{Dt}$

De Szoeke and Samelson, JPO (2002)

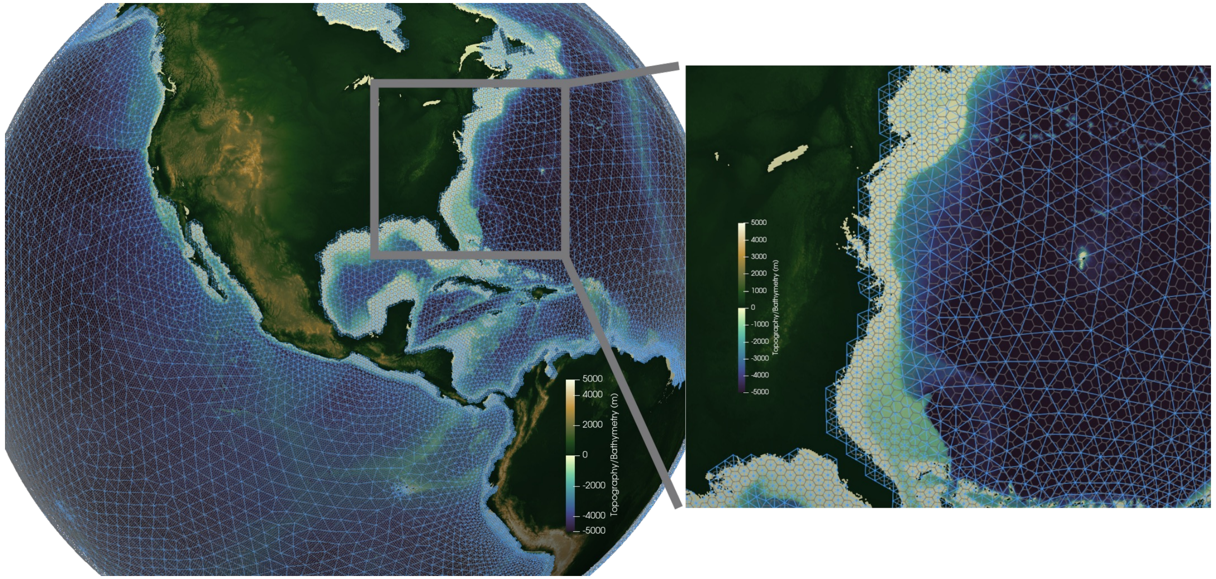
Task 3: Integration within land-river-ocean coupling

- This capability will be integrated with the land-river-ocean coupling developed under the ICoM project

- Wave model coupling developed on the E3SM project will be extended to capture water level variation due to wave setup



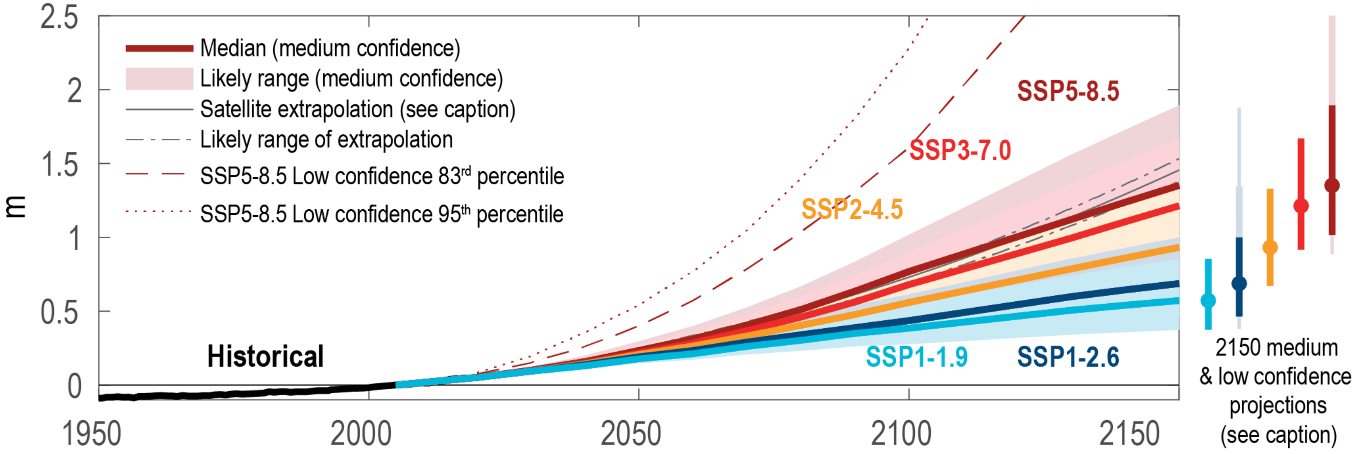
Engwirda and Liao (2021)



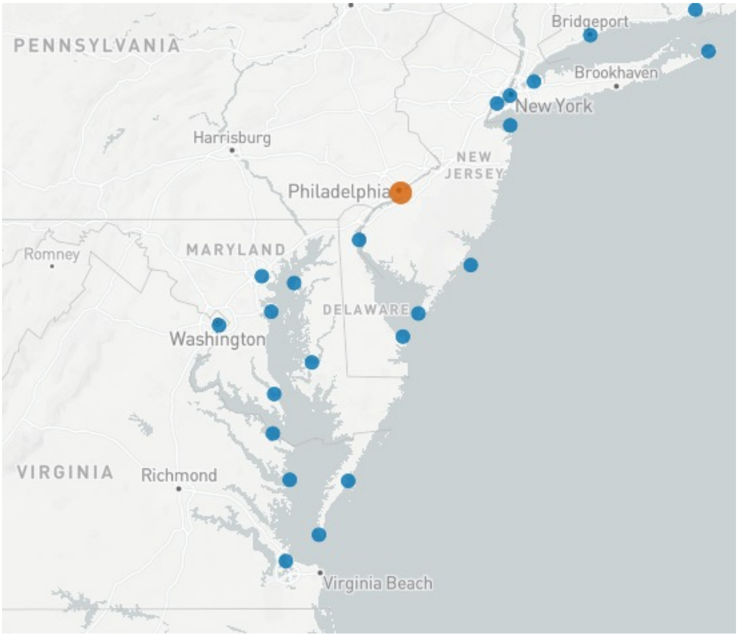
Target is to have ~100m barotropic resolution around U.S. coastlines, use subgrid theory to incorporate effects of O(1 m) scale bathymetry

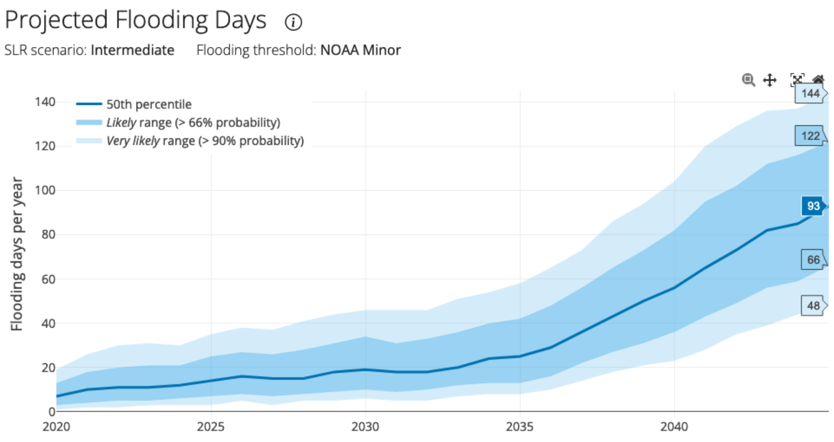
Task 4: Exploration of climate change effects on flooding

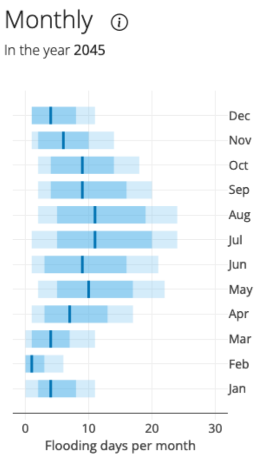
Projected global mean sea level rise under different SSP scenarios



IPCC 6th Assessment Report







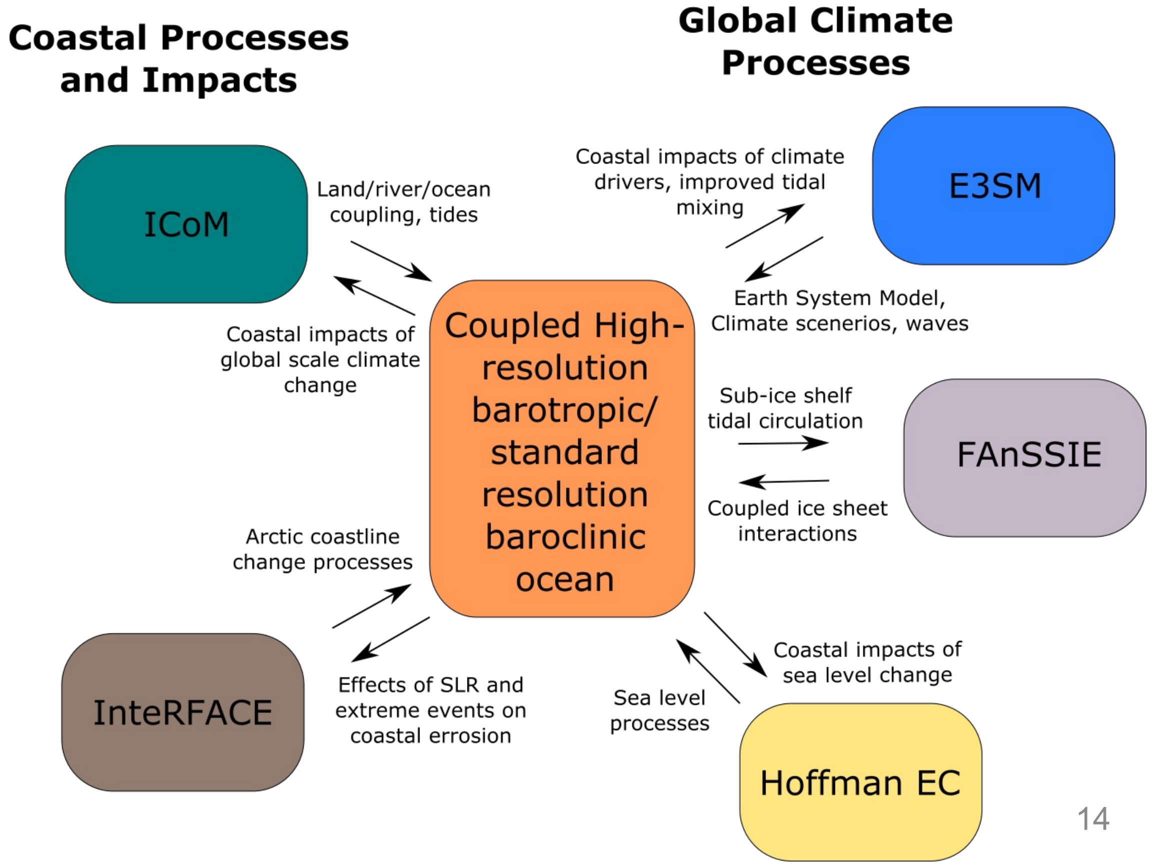
NASA Sea Level Change Team Flooding Analysis Tool

- Use the high resolution coupling to provide comprehensive total water level projections under different climate scenarios
- Investigate the major regional drivers for shifts in flooding distributions
- Quantify the importance of internal climate variability on coastal flooding

Synergies with other BER Projects

- High coastal resolution is a missing link for delivering on the actionable science ambitions of E3SM
- The goal is for this capability to sit at the middle of a variety of needs among E3SM "eco-system" projects

Questions	Near-term (3-yr) experiments using v1	Medium-term (6-yr) experiments using v2	Long-term (10-yr) experiments using v3/v4
Water Cycle How does the hydrological cycle interact with the rest of the human-Earth system on local to global scales to determine water availability and water cycle extremes?	How will more realistic portrayals of features important to the water cycle (resolution, clouds, aerosols, snowpack, river routing, land use) affect simulations of river flow and associated freshwater supplies at the watershed scale?	What are the relative impacts of global forcing versus regional effects of human activities on flood and drought risks in North America?	What are the moisture sources for precipitation over land? Do models converge with increasing resolution, and what controls this behavior? How will the moisture sources and precipitation over land change in the future?
Biogeochemistry How do the biogeochemical cycles interact with other Earth system components to influence energy-sector decisions?	What are the effects of nitrogen and phosphorous on climate-biogeochemistry interactions, and how sensitive are these interactions to model structural uncertainty?	What are the implications of different energy futures for the biogeochemical cycle through changes in land use land cover, water availability and extreme events?	What are the impacts of different energy and land use on the biogeochemical cycle and water availability? How might terrestrial-aquatic processes influence terrestrial and marine biogeochemistry?
Cryosphere Systems How do rapid changes in cryospheric systems evolve with the Earth system and contribute to sea level rise and increased coastal vulnerability?	What are the impacts of ocean-ice shelf interactions on melting of the Antarctic Ice Sheet and implications to sea level rise?	How will the atmosphere, ocean and sea-ice systems mediate sources of sea-level rise from the Antarctic ice sheet over the next 30 years?	What processes and their model representations contribute to key uncertainties in projecting regional sea level rise? What are the implications to coastal inundation that result from interactions between sea level rise and extreme storms?

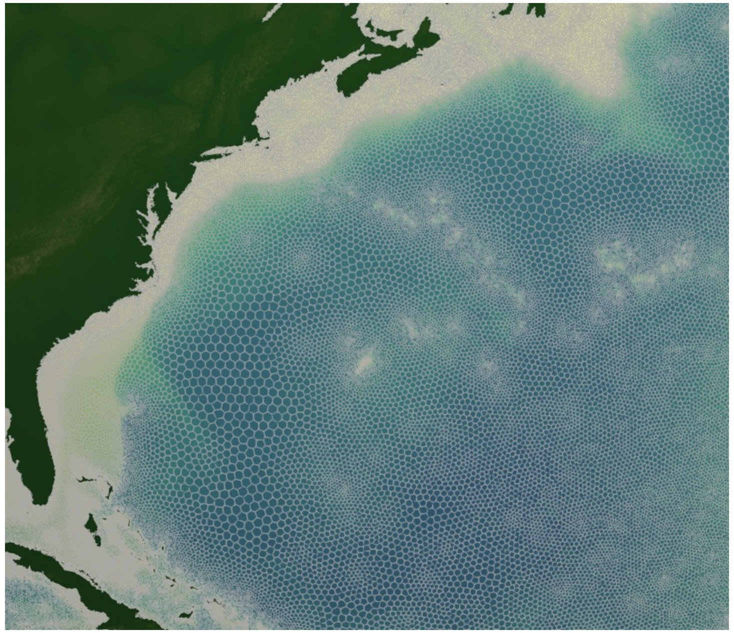


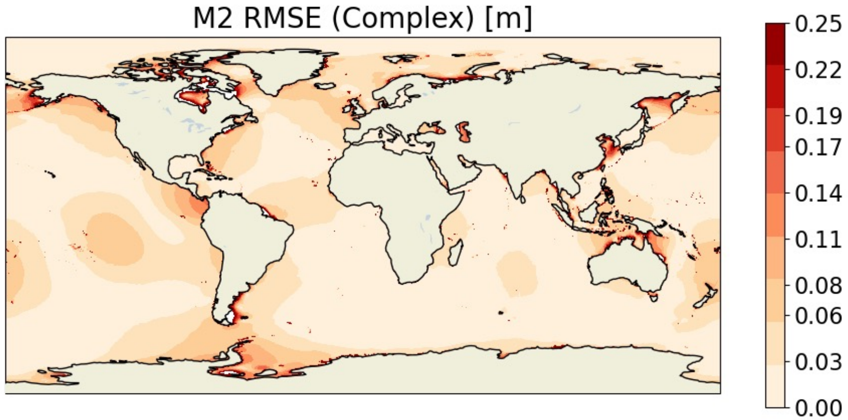
Other synergies with E3SM

- **Variable Resolution Tides (collaboration with ICoM)**
  - MPAS-Ocean is now capable of accurately simulating tides
    - Inline self attraction and loading (Barton et al. 2022, Brus et al. 2023)
    - Ice shelf cavities (Pal et al. 2022)
    - Topographic wave drag
  - Variable resolution meshes are required to resolve coasts, shelf-breaks, mid-ocean ridges.
  - These meshes are not practical for baroclinic applications.
  - Tides are dynamically changing: SLR, ocean stratification, ice shelf geometry (Barton et al. in prep).

  - The two-way barotropic-baroclinic coupling can be used to bring accurate tides into E3SM.
    - Estuarine tidal exchanges
    - Ocean mixing
    - Sub ice shelf tidal currents

Variable resolution mesh: 45 to 5 km

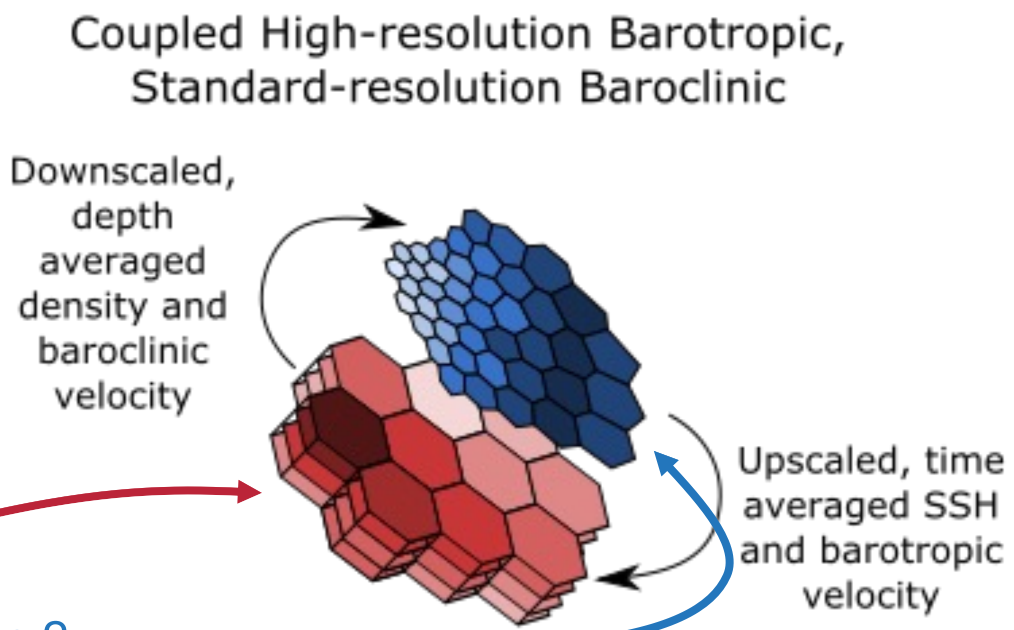


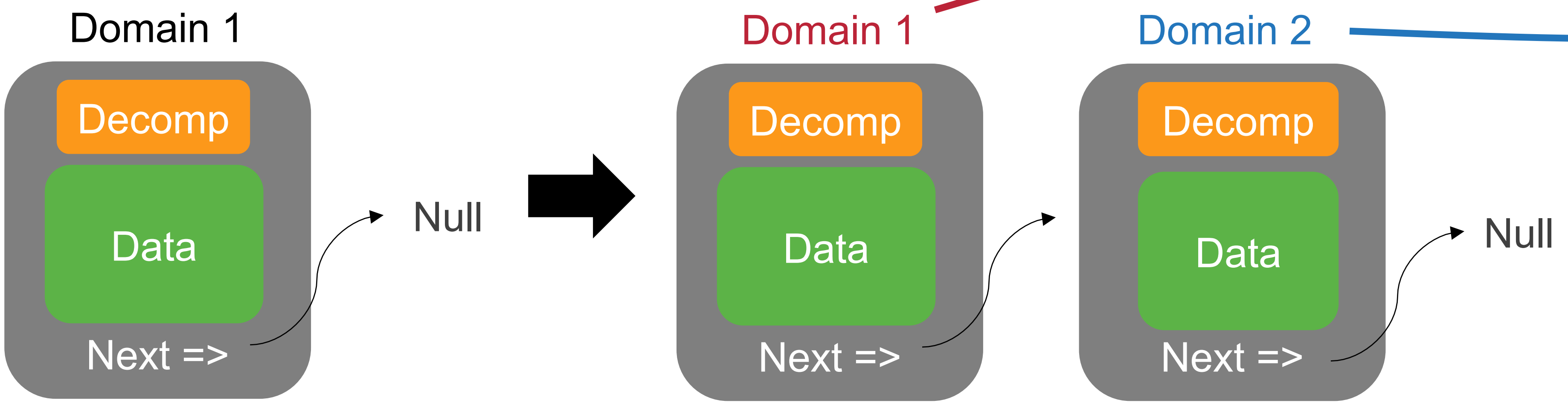


Complex RMSE: Global = 5.011 cm; Deep = 3.298 cm; Shallow = 12.734 cm

Progress to Date

- **MPAS-O development**
  - MPAS domain type is a linked list
  - Can now accommodate second mesh within MPAS-Ocean
  - Utilizing this ability to initialize/run MPAS-Ocean with two separate meshes

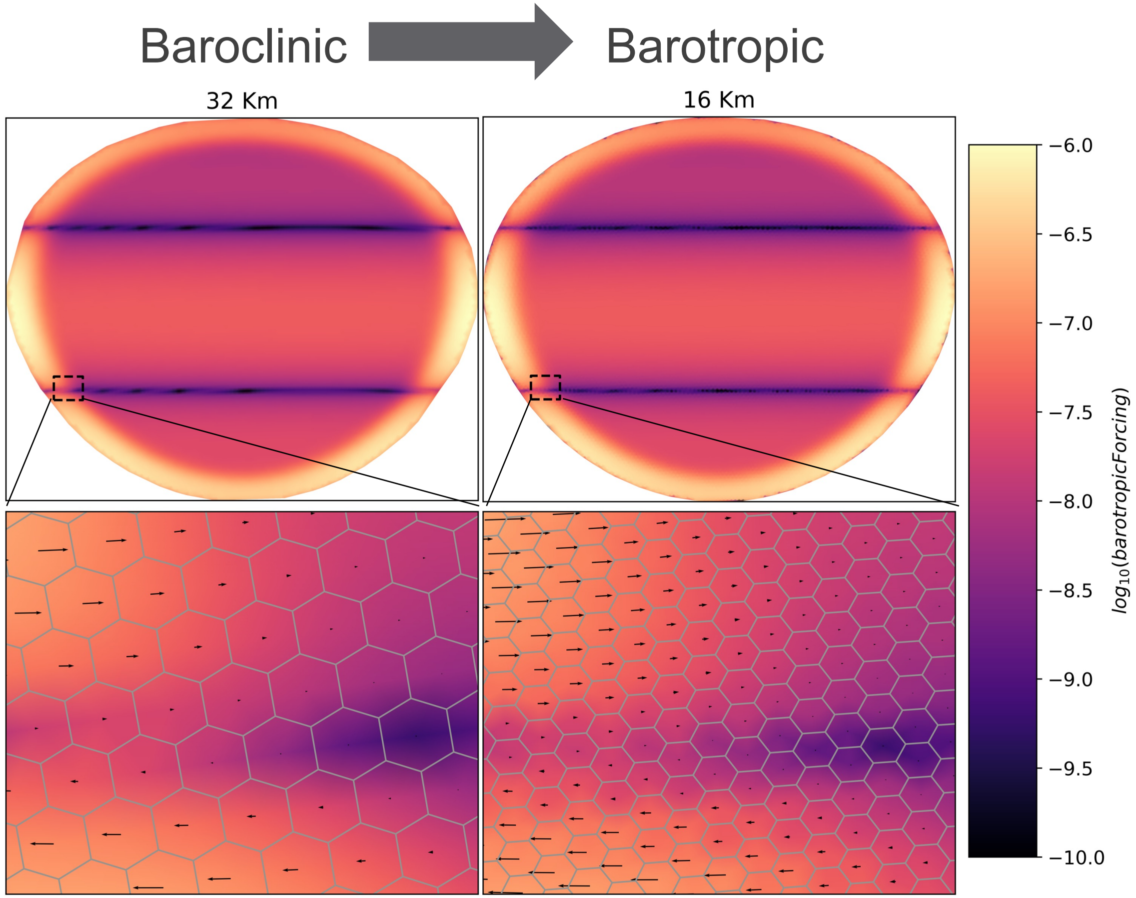


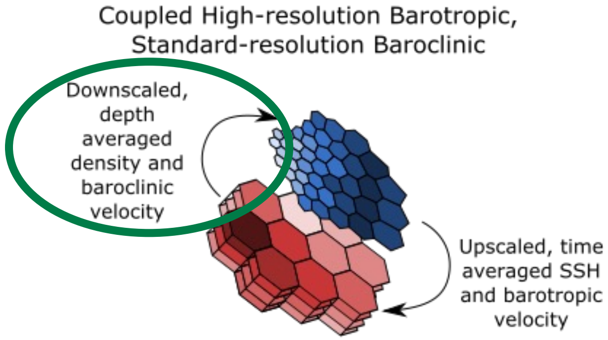


Progress to Date

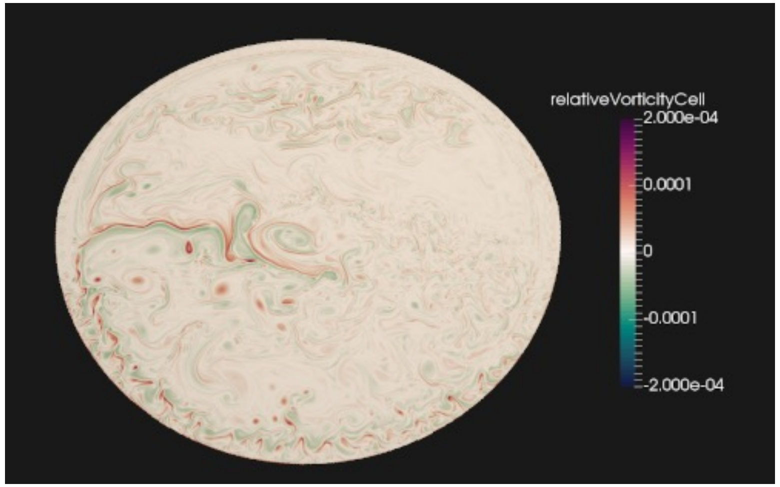
- **MPAS-O development**
  - Using the MPAS-Ocean SOMA test case as an initial proving-ground
  - MOAB has been incorporated into the standalone MPAS-Ocean model (collaboration with the SEAHORCE project).
  - Coleman has implemented the remapping of the barotropic forcing term, G.

Remapped Barotropic Forcing Term



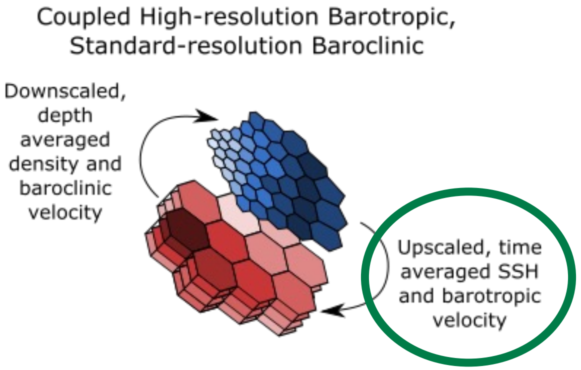


SOMA Test Case

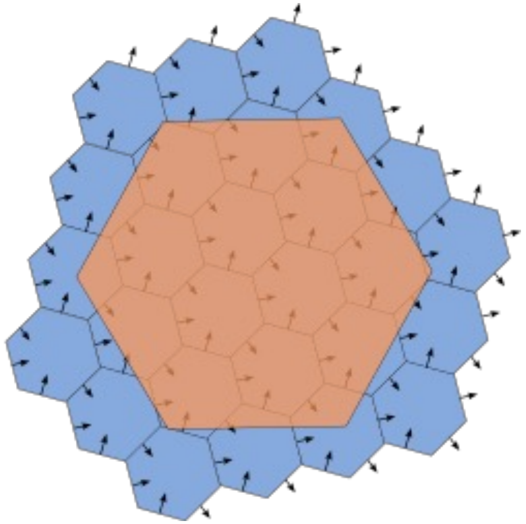


Progress to Date

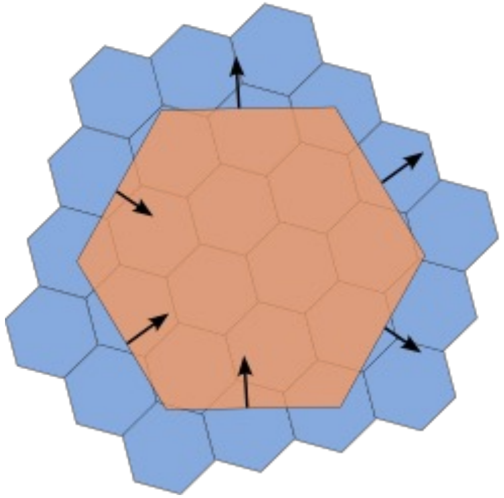
- **Remapping development**
  - Conservative remapping of the barotropic SSH flux is key to enforcing consistency between barotropic and baroclinic modes



Barotropic



Baroclinic



Barotropic SSH subcycle:

$$\zeta_{n+(j+1)/J} = \zeta_{n+j/J} + \frac{\Delta t}{J}(-\nabla \cdot \mathbf{F}_j)$$

$$\mathbf{F}_j = (\overline{\mathbf{u}}_{n+j/J})\left(\widehat{\zeta}_{n+j/J} + \widehat{b}\right)$$

Time averaged barotropic SSH flux:

$$\overline{\mathbf{F}} = \frac{1}{2J}\sum_{j=1}^{2J}\mathbf{F}_j$$

Conservative remap time-averaged flux from barotropic to baroclinic

Enforce that:
remapped barotropic ssh flux
=
sum of baroclinic layer thickness fluxes

$$\overline{\mathbf{F}} = \sum_{k=1}^{N}\widehat{h}_k\mathbf{u}_k \qquad \mathbf{u}_k = \overline{\mathbf{u}}_{avg} + \mathbf{u}'_k$$

Solve for barotropic velocity:

$$\overline{\mathbf{u}}_{avg} = \left(\overline{\mathbf{F}} - \sum_{k=1}^{N}\widehat{h}_k\mathbf{u}'_k\right) \Big/ \sum_{k=1}^{N}\widehat{h}_k$$

Total velocity is then used in layer thickness update:

$$\mathbf{u}_k = \overline{\mathbf{u}}_{avg} + \mathbf{u}'_k$$

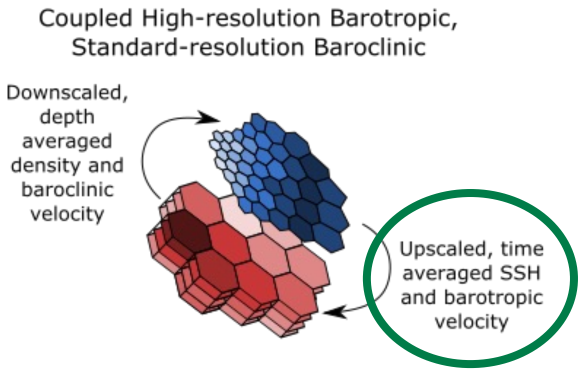
$$h_{k,n+1} = h_{k,n} + \Delta t\left(-\nabla \cdot \left(\widehat{h}_{k,n}\mathbf{u}_k\right) - \frac{\partial}{\partial z}\left(\widehat{h}_{k,n}w_{k,n}\right)\right)$$

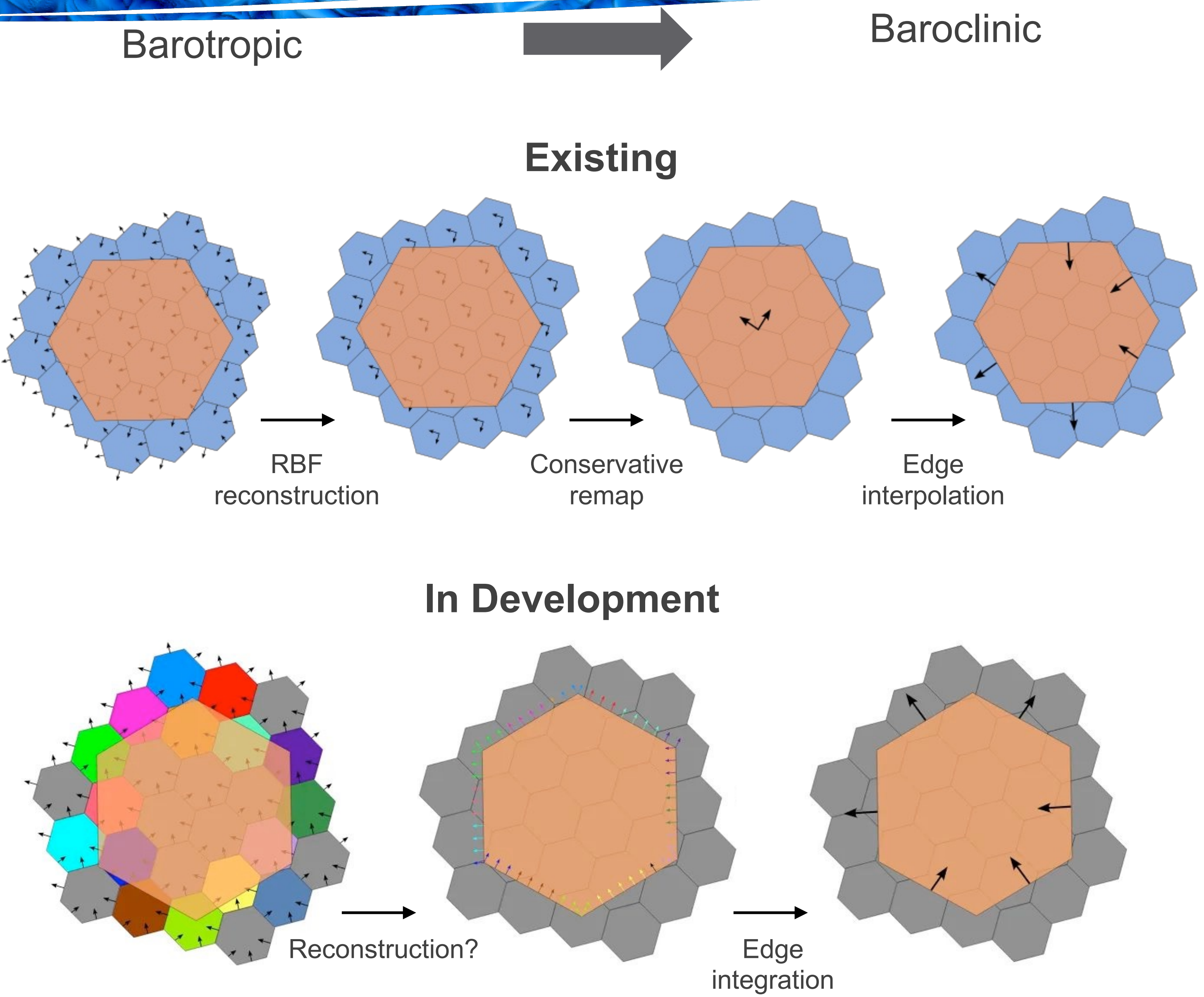
Area average barotropic water column
=
Sum of layer thicknesses

$$\overline{\zeta + b} = \sum_{k=1}^{N} h_k$$

Progress to Date

- **Remapping development**
  - Existing cell-center based remapping approaches are not well-suited to this application
  - Need a technique that conserves horizontal fluxes





Thank you!

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