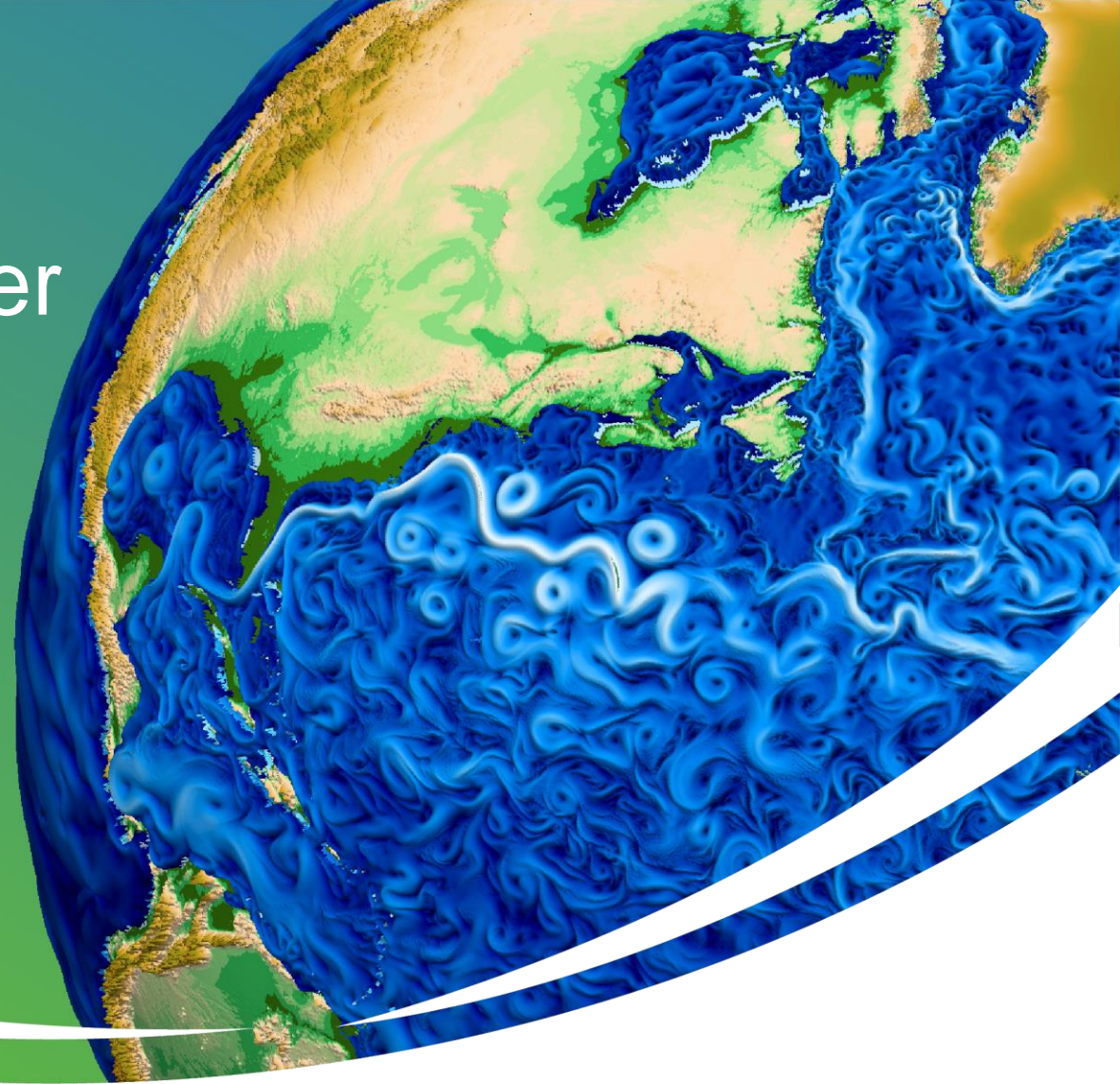


Multi-resolution coupling for simulating extreme coastal water levels and flooding in E3SM

Steven Brus
Coleman Blakely

Argonne National Laboratory



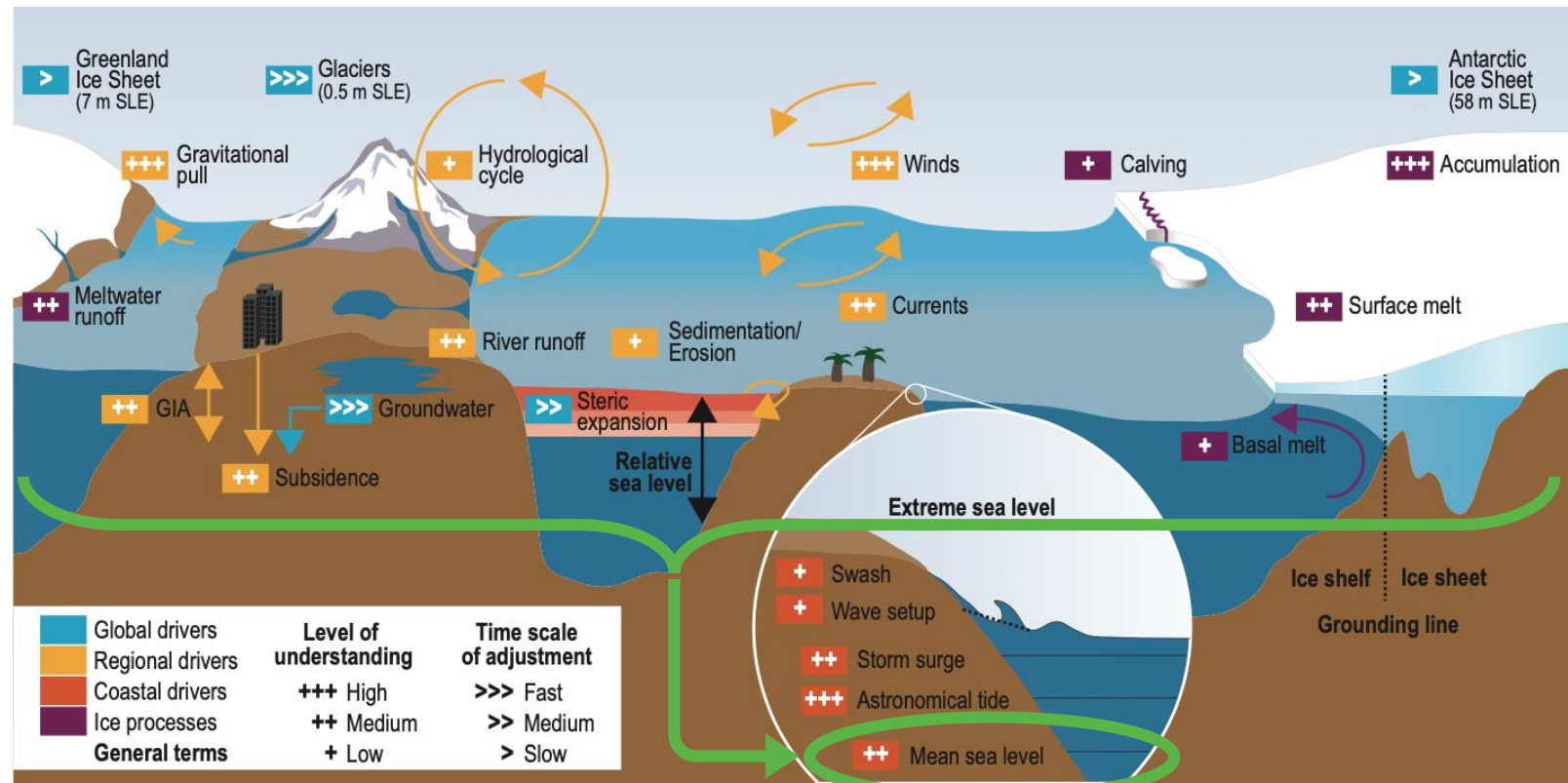
Climate Change Processes Affecting Sea Levels

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**

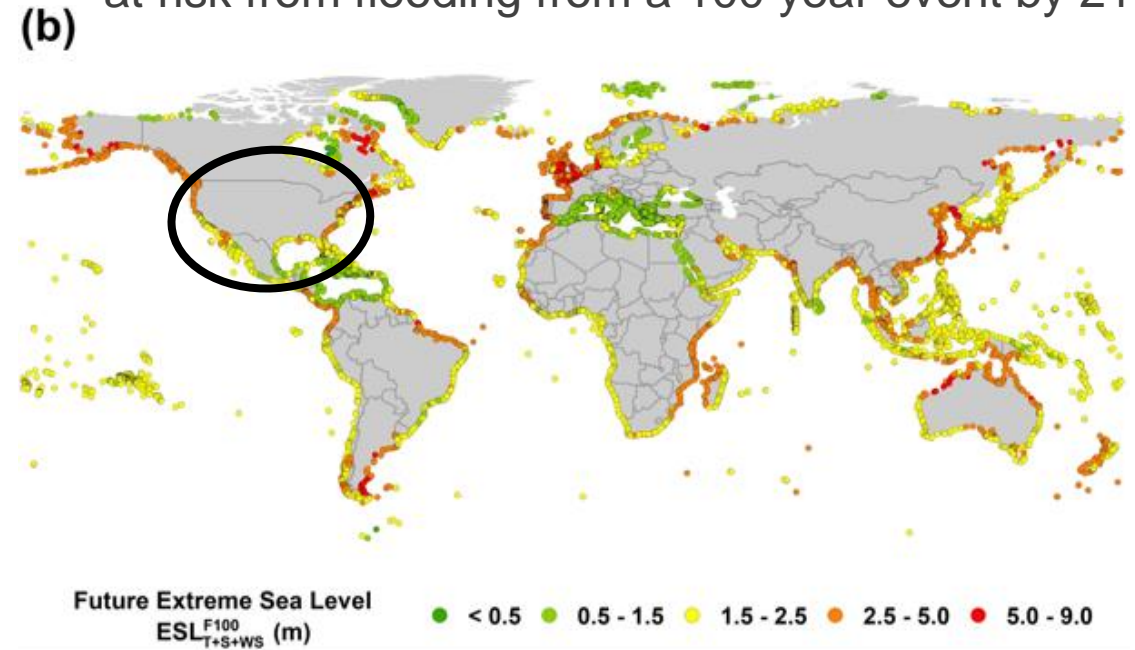
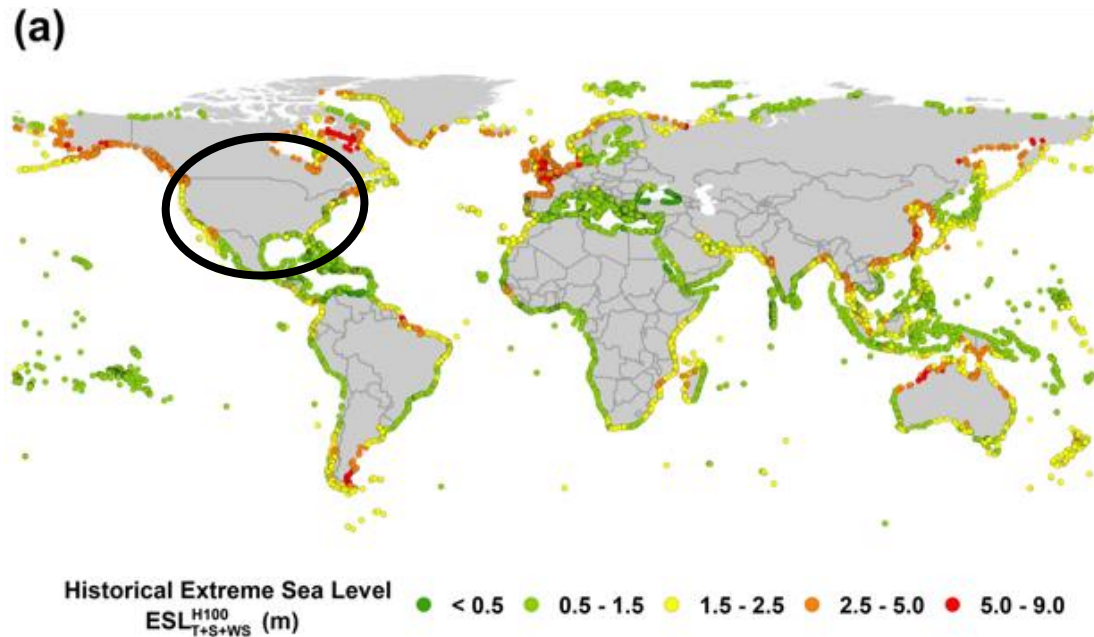


IPCC Special Report on the Ocean and Cryosphere in a Changing Climate



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)

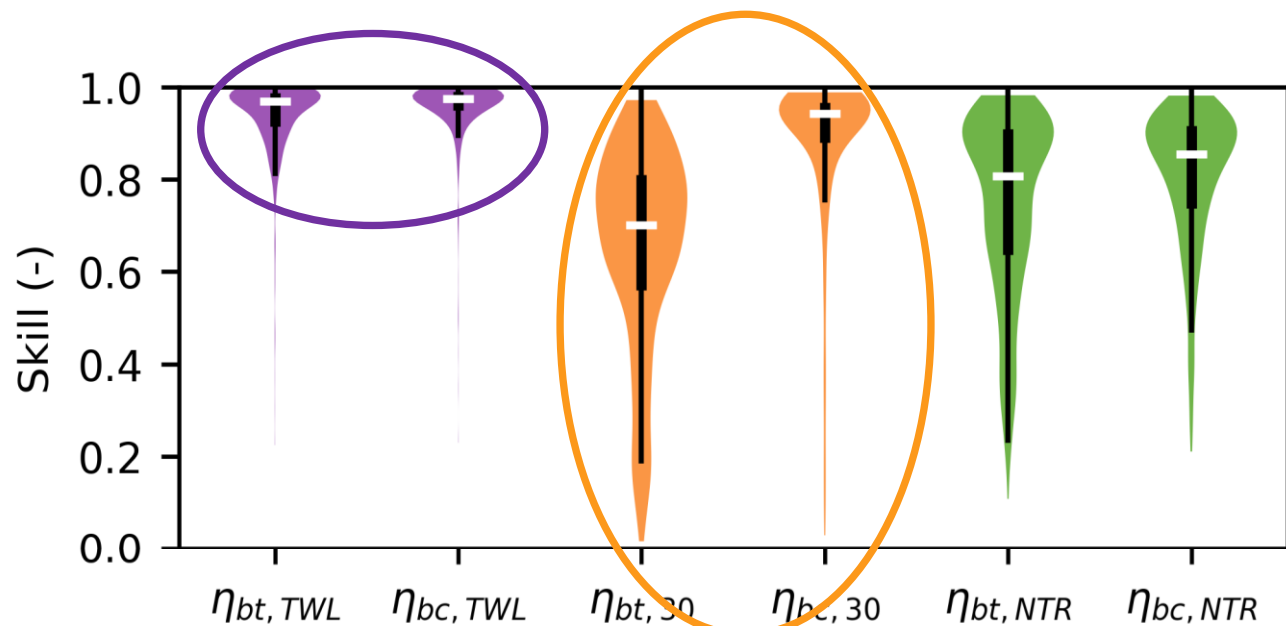
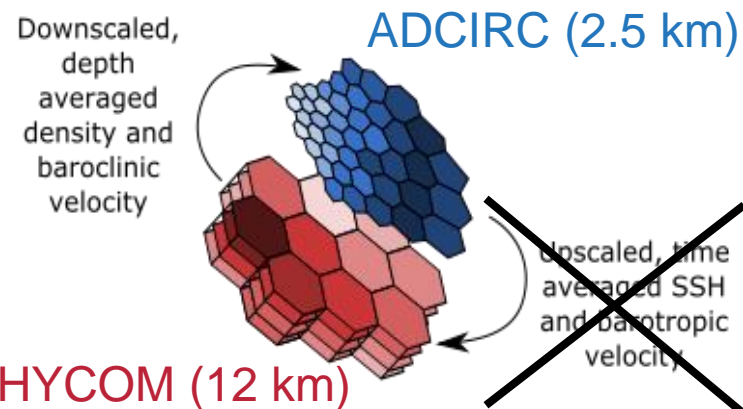
- Future extreme sea levels are projected to rise in many areas along U.S. coastlines
- Many global studies lack high coastal resolution
- Linear superposition of sea level drivers is often assumed
- “Bathtub” model for sea level rise and inundation is a popular assumption
- Changes in tides are neglected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



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.



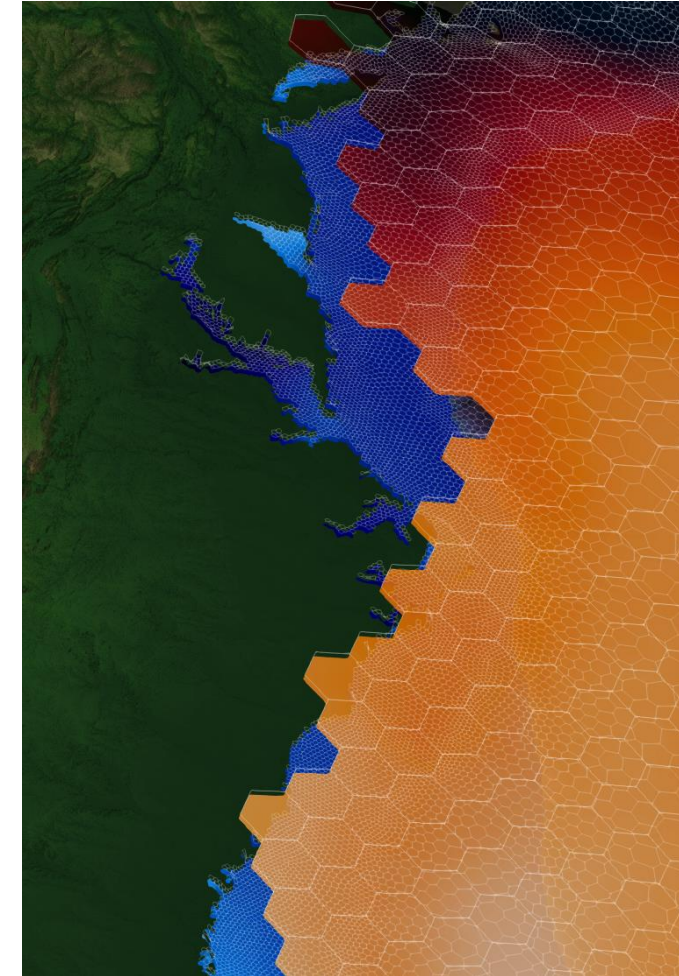
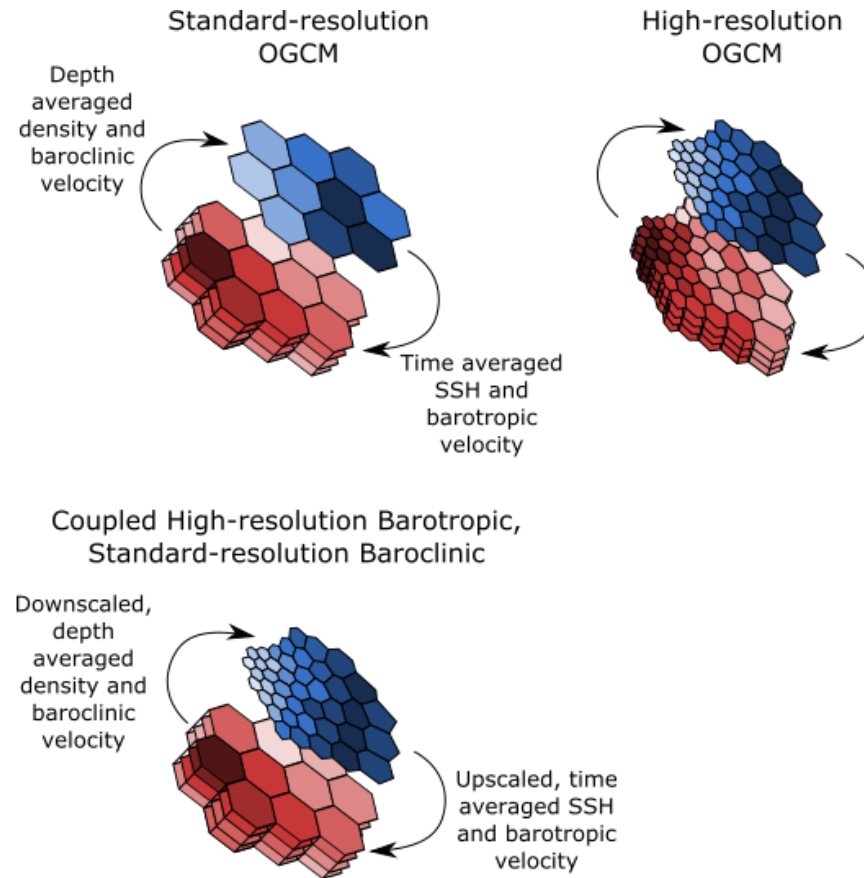
- Baroclinic coupling had previously degraded total water level accuracy vs. purely barotropic results
- Coleman's work corrected this so that the **baroclinic coupling is just as accurate for total water level with much better 30-day averaged water levels** at 568 GESLA water level stations



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

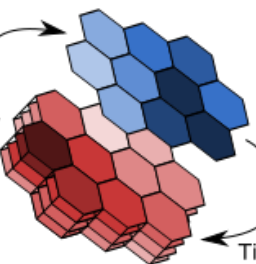
- 3D free surface model
- Typical resolution for coupled climate applications: 30-60km with 60 vertical layers
- Captures global circulation patterns due to density-driven flow (baroclinic)
- Time stepping is typically split between barotropic mode (small dt) and baroclinic mode (large dt).

High-resolution Barotropic



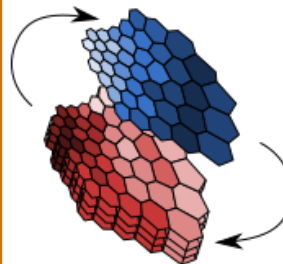
Standard-resolution OGCM

Depth averaged density and baroclinic velocity



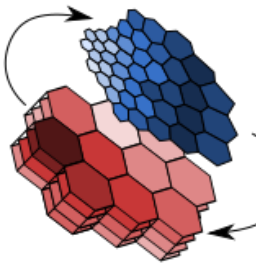
Time averaged SSH and barotropic velocity

High-resolution OGCM

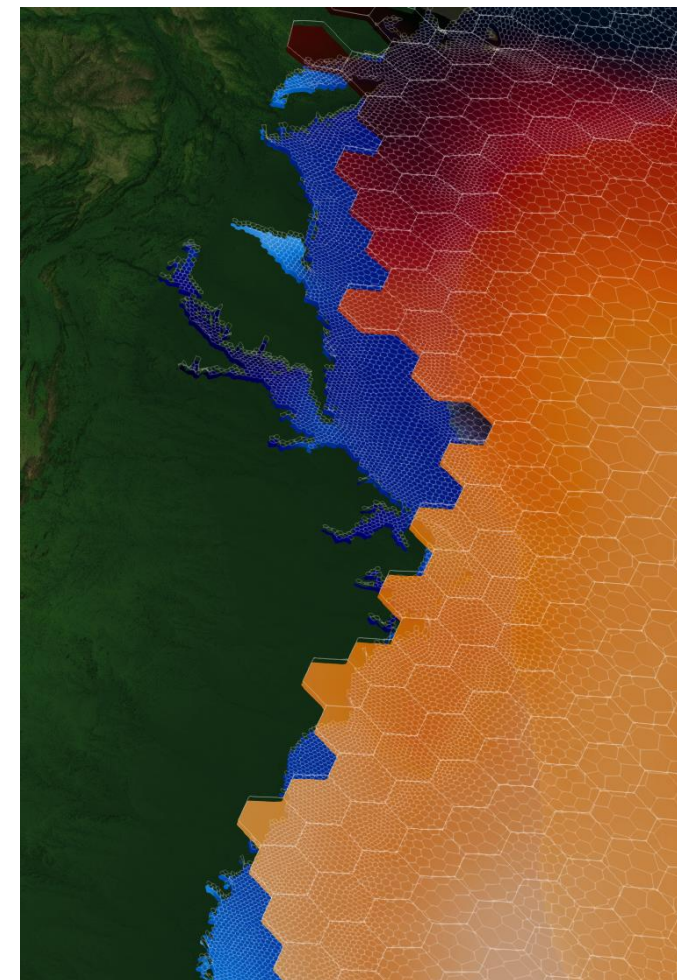


Coupled High-resolution Barotropic, Standard-resolution Baroclinic

Downscaled, depth averaged density and baroclinic velocity



Upscaled, time averaged SSH and barotropic velocity

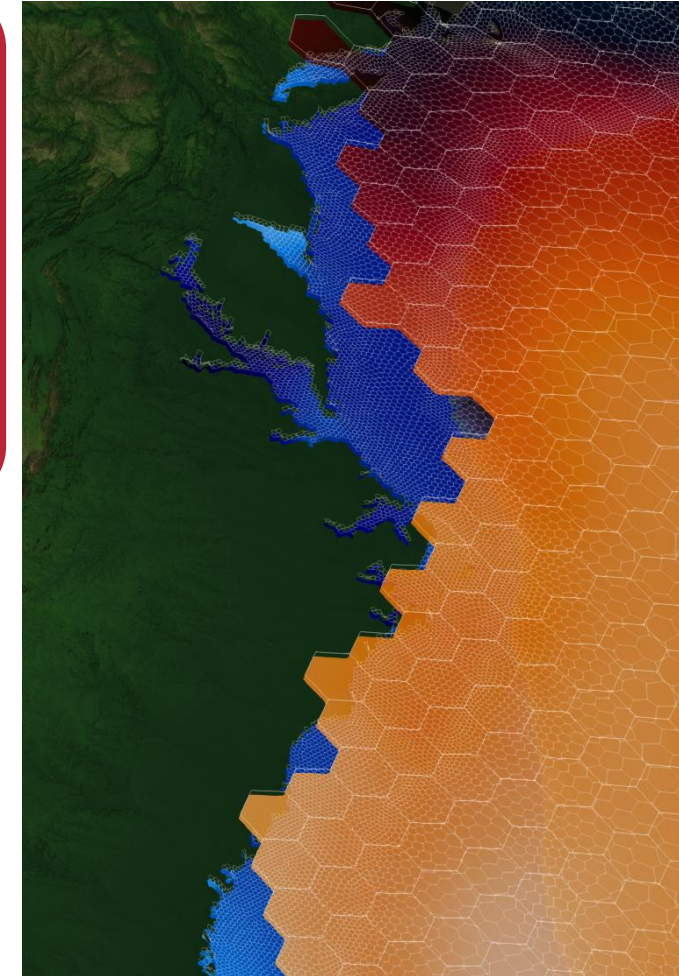
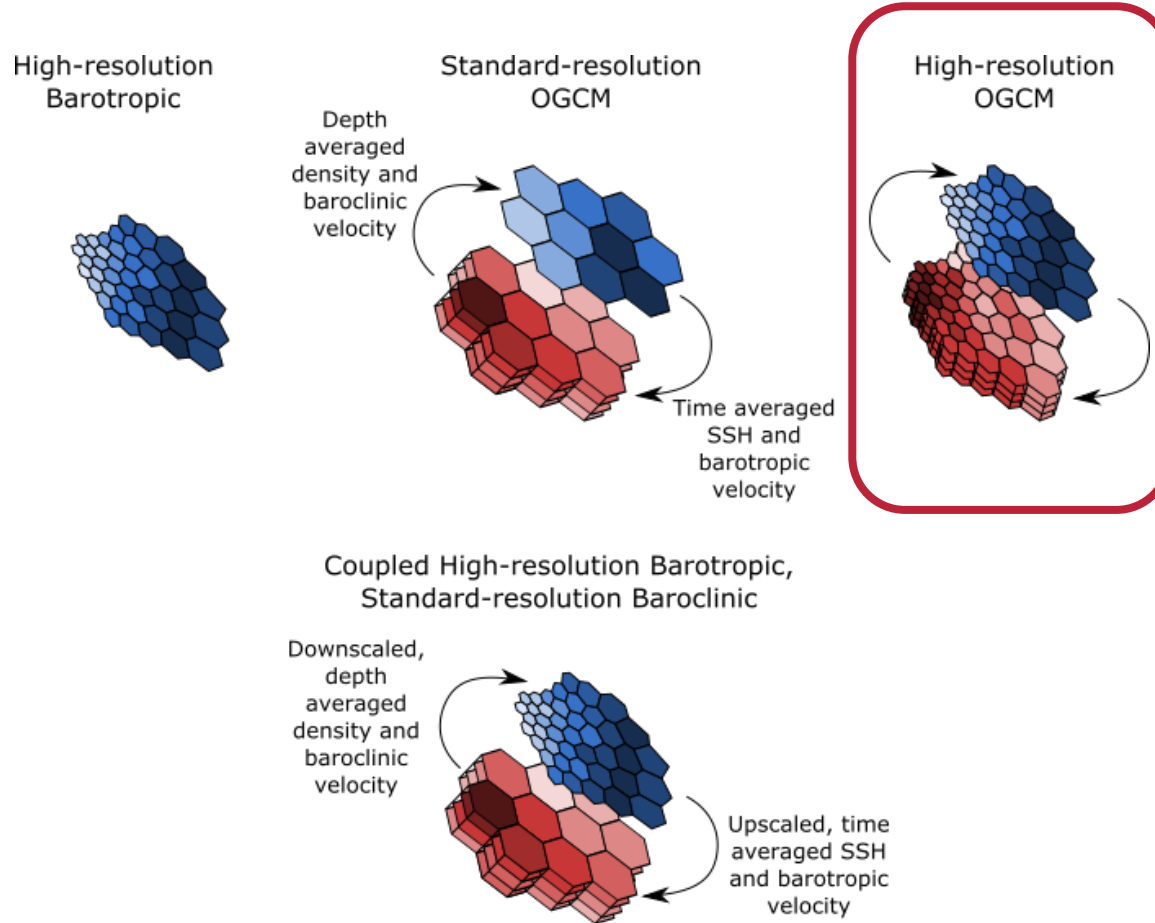




Coupling of surface waves and density-driven flow

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

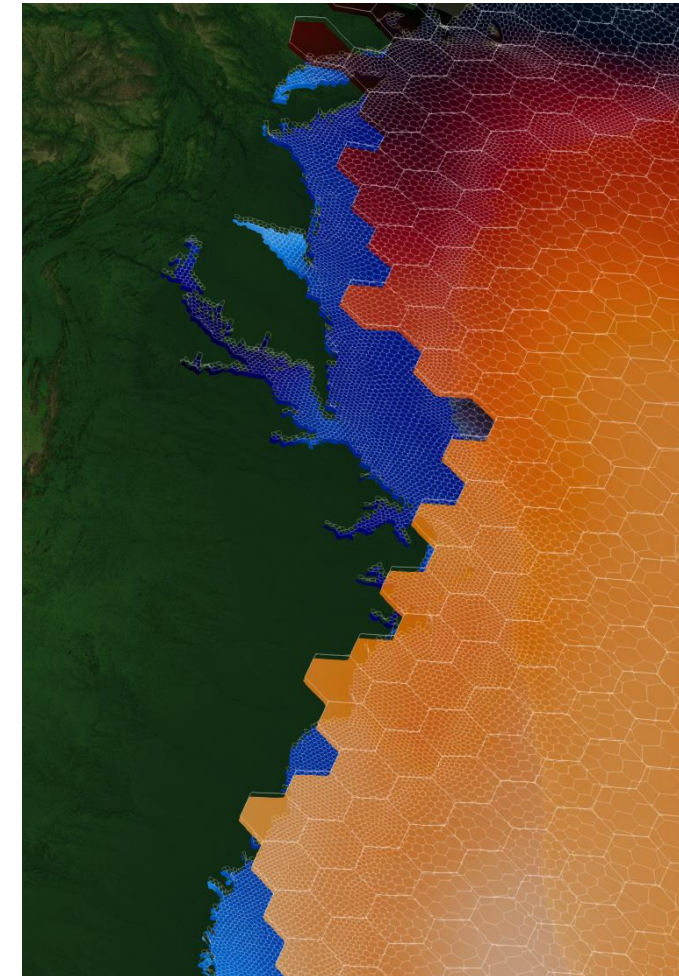
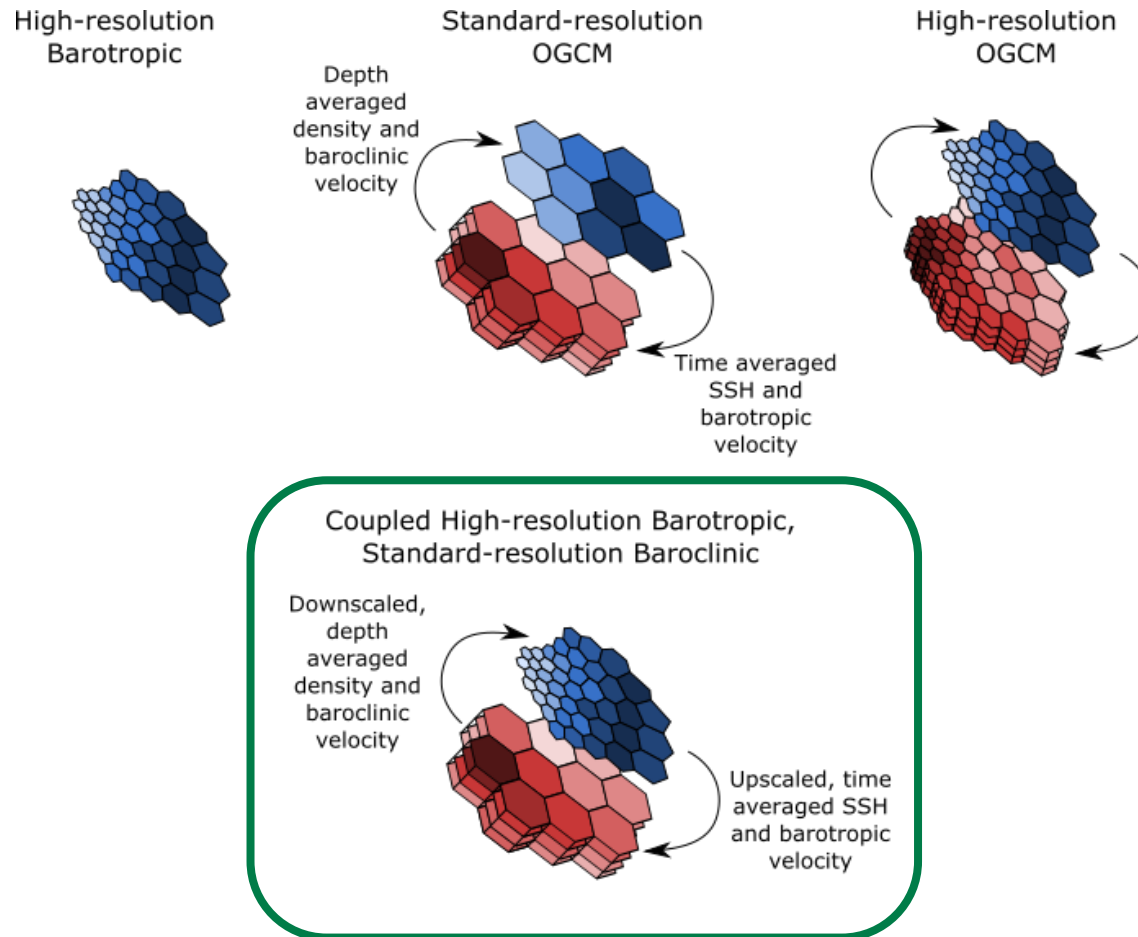




Coupling of surface waves and density-driven flow

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





Development goal: 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

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

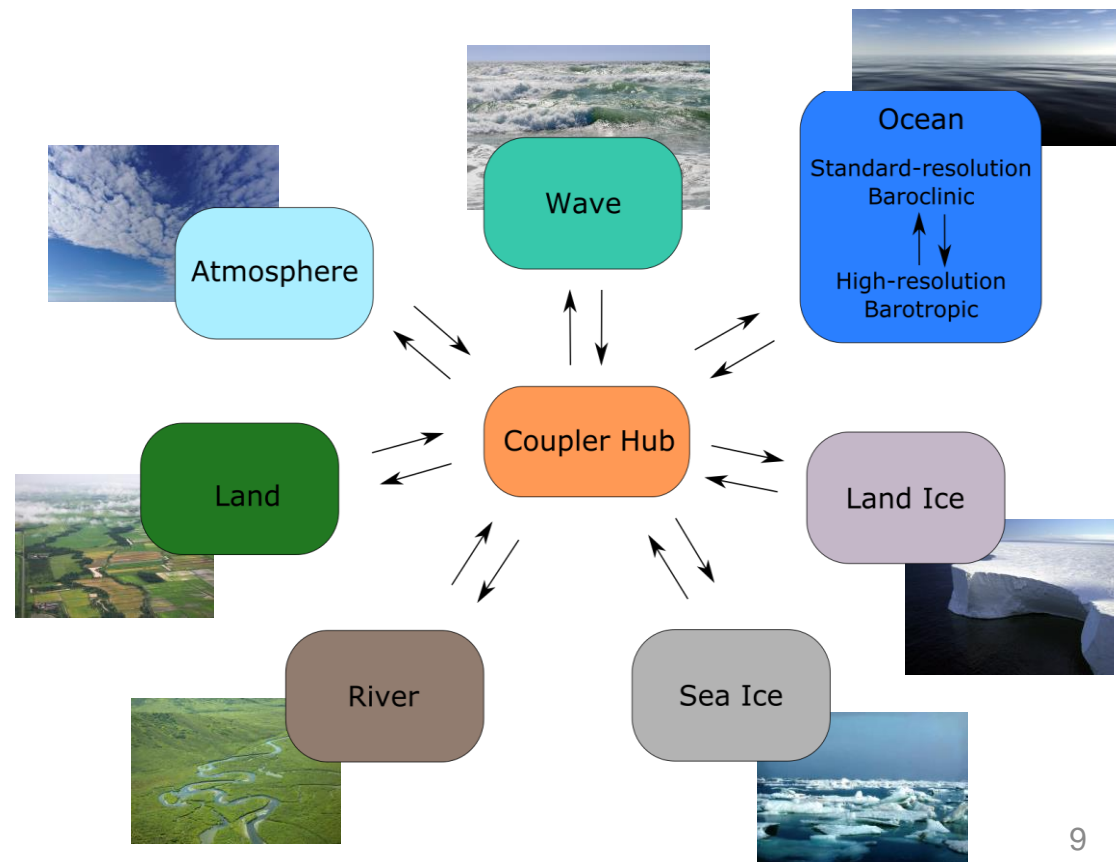
$$\begin{aligned} \frac{\partial \eta}{\partial t} + \nabla \cdot (\bar{\mathbf{u}}H) &= 0 \\ \frac{\partial \bar{\mathbf{u}}}{\partial t} + f \mathbf{k} \times \bar{\mathbf{u}} &= -g \nabla \eta + G \end{aligned}$$

Remap from standard res to high res

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





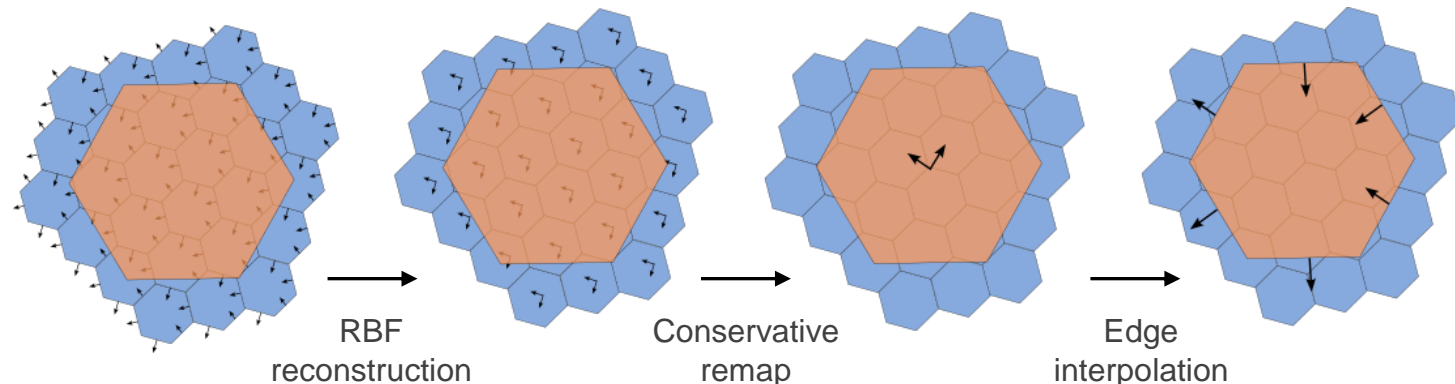
New Remapping Approaches

Barotropic

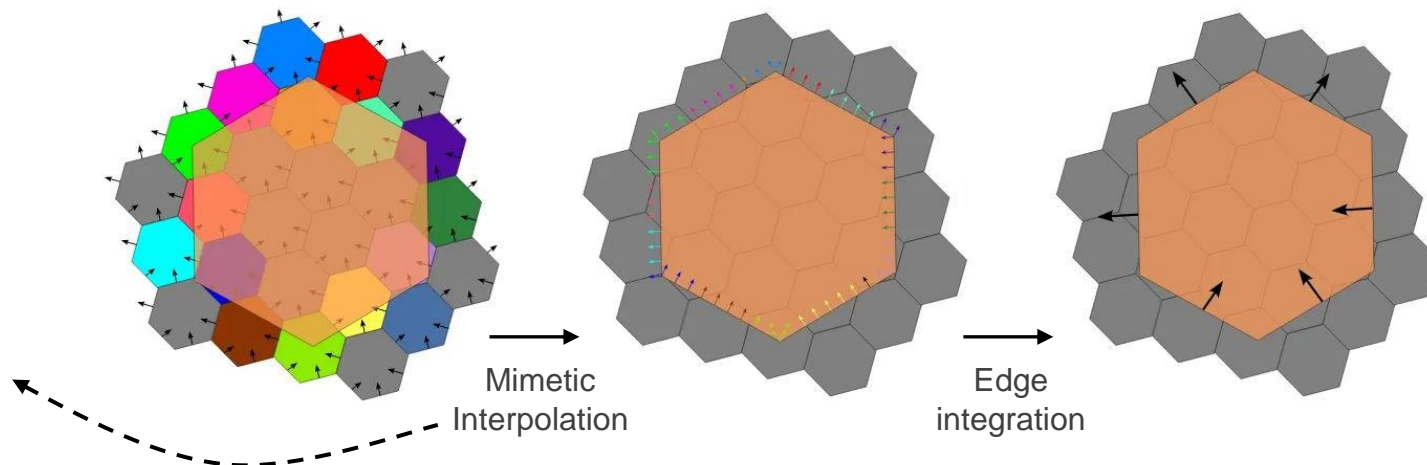


Baroclinic

Existing



In Development

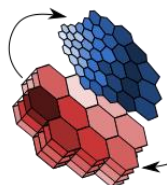


- Remapping development

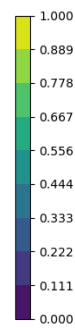
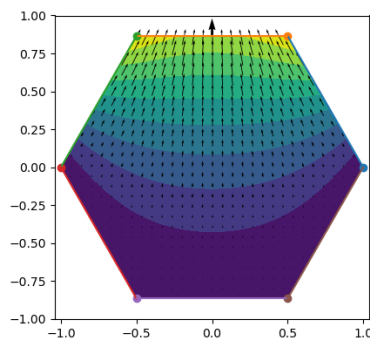
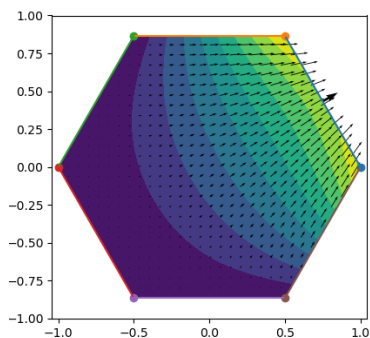
- Existing cell-center based remapping approaches are not well-suited to this application
- Need a technique that conserves horizontal fluxes

Coupled High-resolution Barotropic,
Standard-resolution Baroclinic

Downscaled,
depth
averaged
density and
baroclinic
velocity



Upscaled, time
averaged SSH
and barotropic
velocity

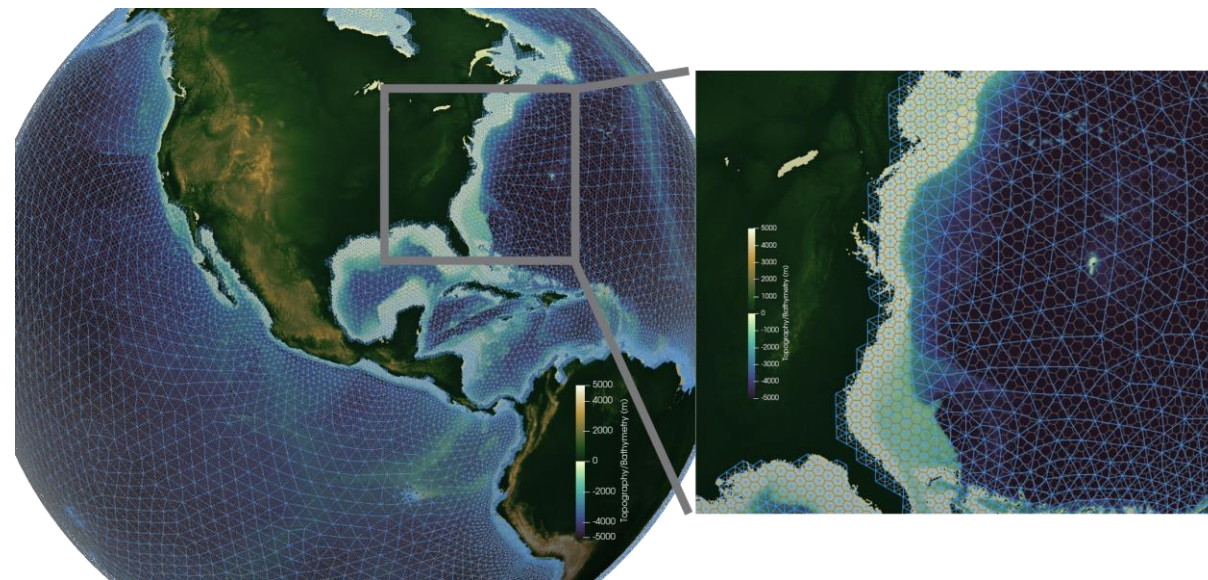
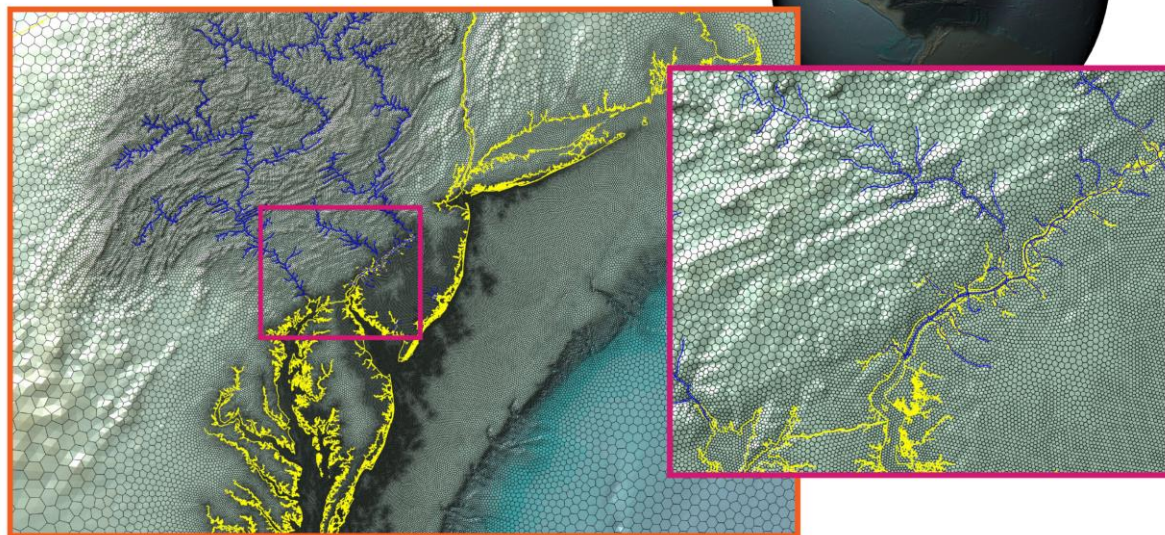
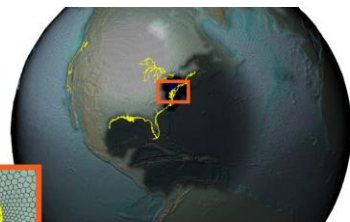




Integration goal: Land-river-ocean coupling

- 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

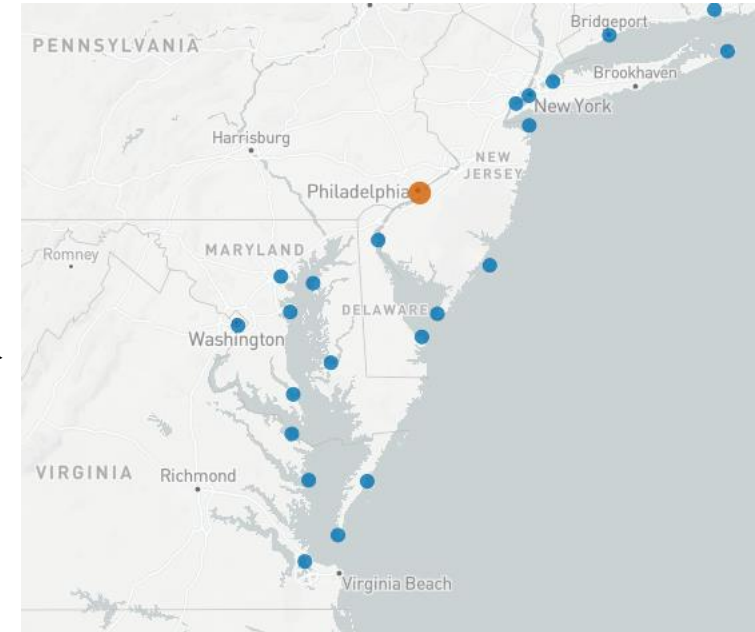
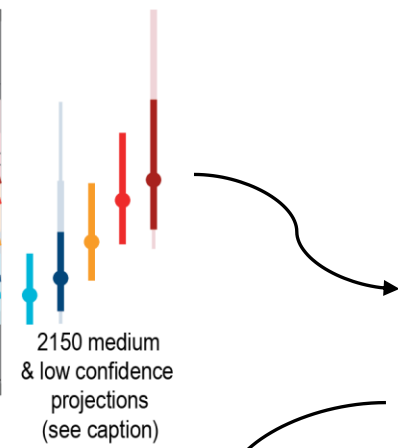
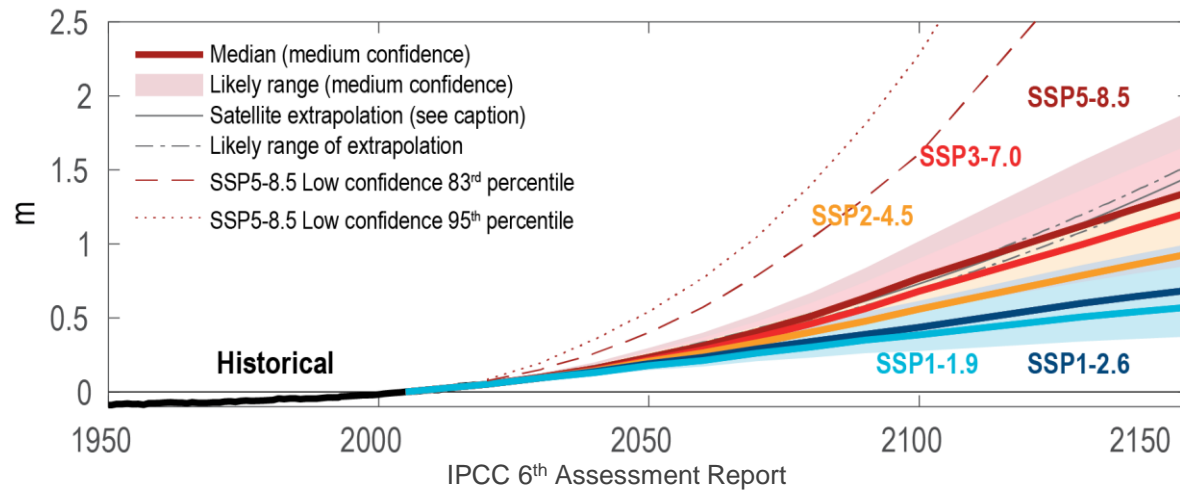


Engwirda and Liao (2021)

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

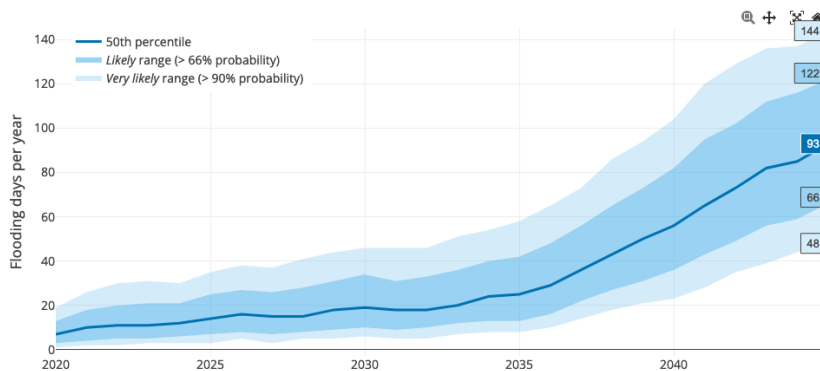
Science Goal: Exploration of climate change effects on flooding

Projected global mean sea level rise under different SSP scenarios



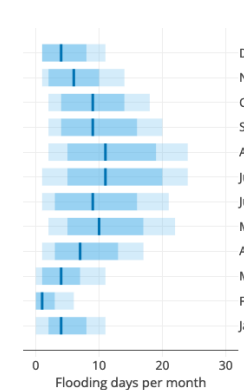
Projected Flooding Days

SLR scenario: Intermediate Flooding threshold: NOAA Minor



Monthly

In the year 2045



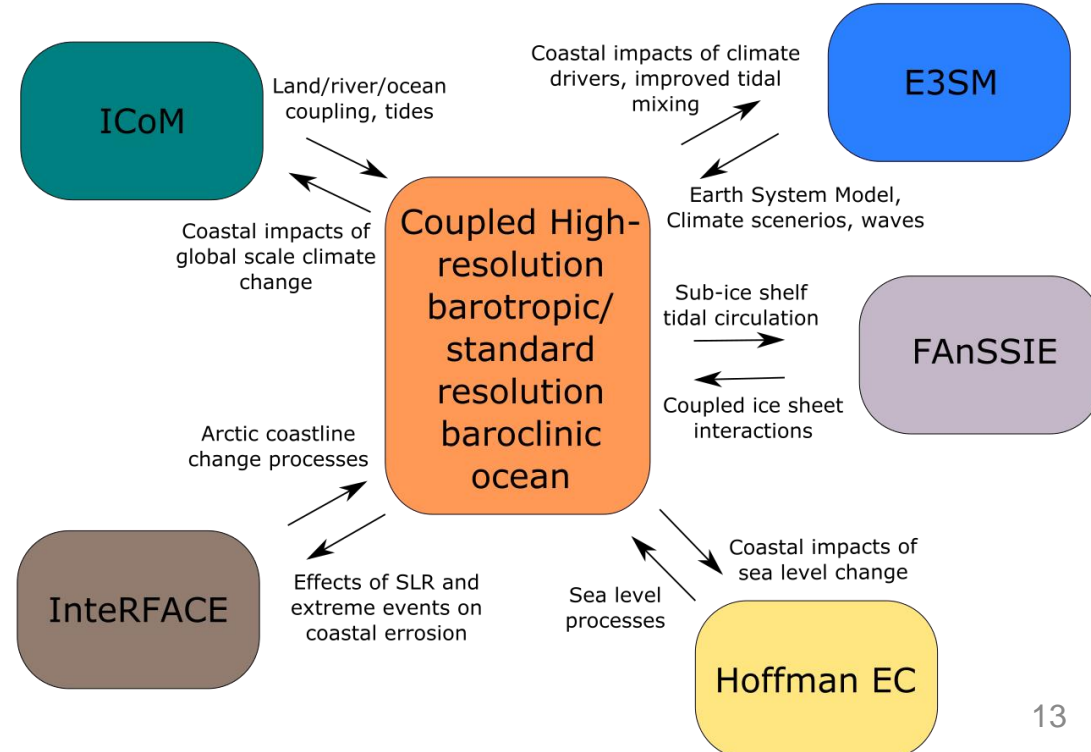
- Use the high resolution coupling to provide comprehensive total water level projections under different climate scenarios
- Investigate the major regional drivers for shifts in flooding distributions
- Quantify the importance of internal climate variability on coastal flooding

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
<p>Water Cycle</p> <p>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?</p>	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?
<p>Biogeochemistry</p> <p>How do the biogeochemical cycles interact with other Earth system components to influence energy-sector decisions?</p>	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 <u>terrestrial-aquatic processes</u> influence terrestrial and marine biogeochemistry?
<p>Cryosphere Systems</p> <p>How do rapid changes in cryospheric systems evolve with the Earth system and contribute to sea level rise and increased coastal vulnerability?</p>	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 <u>coastal inundation</u> that result from <u>interactions between sea level rise and extreme storms</u> ?

Coastal Processes and Impacts





Thank you!

This ECRP project is funded by the Office of Science
Biological and Environmental Research
Earth System Model Development Program Area

