Assessing 2035 Climate Change Risk to the Chesapeake TMDL using a next-generation unstructured-grid model

-- The Main Bay Model (MBM) Work Plan and Initial Work Underway

VIMS team: Joseph Zhang, Jian Shen, Harry Wang, Marjy Friedrichs, Pierre St-Laurent, Zhengui Wang, Qubin Qin

CBPO: Nicole Cai

UMCES team: Jeremy Testa

University of Maryland
CENTER FOR ENVIRONMENTAL SCIENCE
HORN POINT LABORATORY

Modeling Workgroup Quarterly Review
Jan 4, 2022

VIMS | WILLIAM & MARY
VIRGINIA INSTITUTE OF MARINE SCIENCE

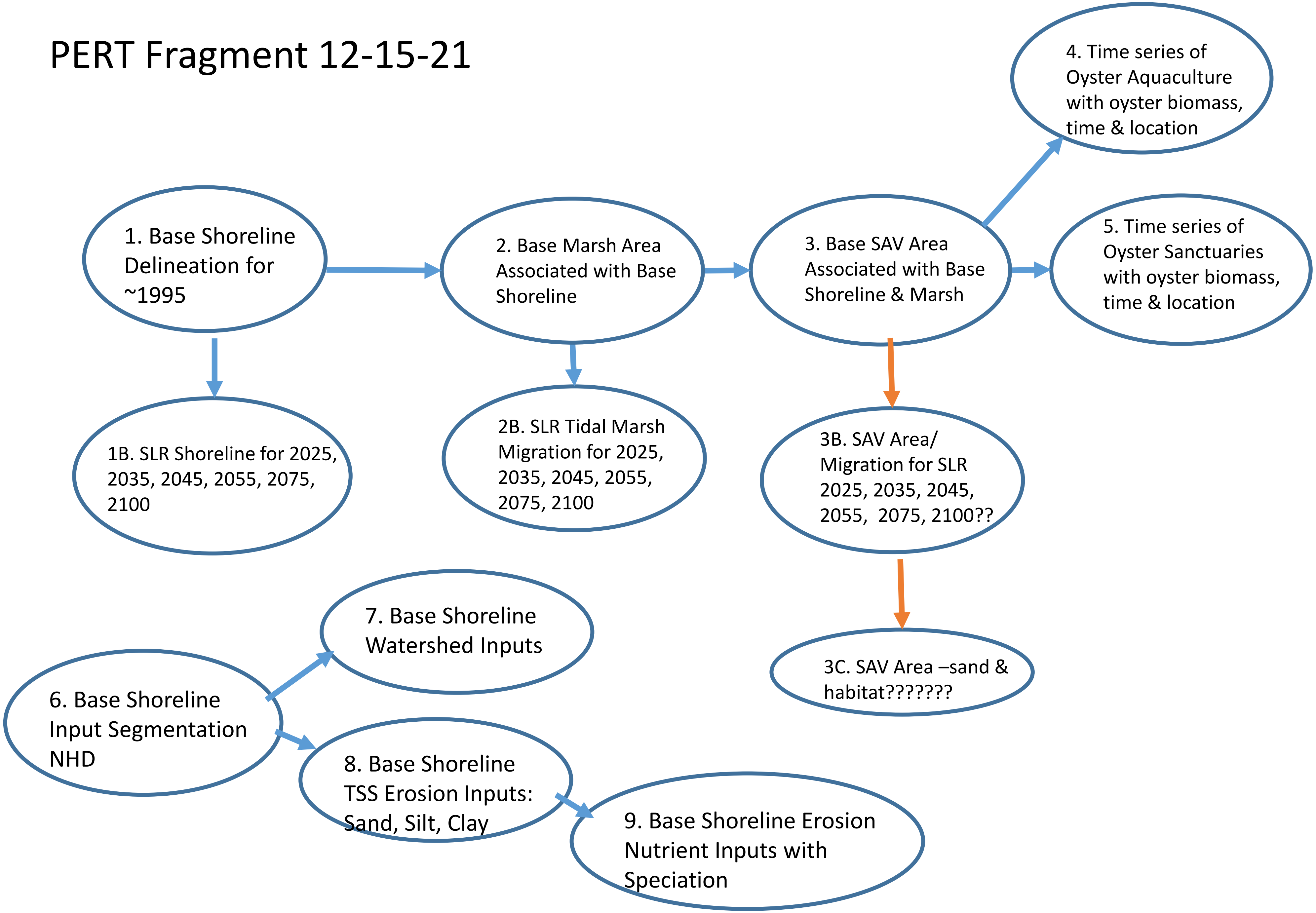
SCHISM

Background

- Previously, CH3D-ICM hydrodynamic-water quality models has been used by CBP to assess Chesapeake Bay TMDL since 1980s
- Modeling Workgroup and CBPO supporting staff have recognized limitations in the CBP Partnership's current estuarine model, especially in the simulation of physical, chemical, and biological processes in the shallowest, most productive regions of the Bay and its tidal tributaries and embayments *at scales* and levels of confidence required to support management decision-making
- Climate change was recognized as a future challenge in assessing water quality conditions for the Bay
- The current 2017 MPA version of the CH3D hydrodynamic model has reached its limit of spatial resolution in the Chesapeake tidal waters at approximately 57,000 cells

- A more detailed unstructured grid model is needed to accurately assess water quality standards: dissolved oxygen (DO), chlorophyll, clarity, and submerged aquatic vegetation (SAV) throughout the Bay
- In a visioning community workshop convened in Jan 2018, it was widely recognized that the next Bay model should consider adopting the latest unstructured-grid modeling technology to allow for increased flexibility and fidelity at fine scales
- An RFA was issued in August 2021 to start the estuarine model transition process to the next generation
- The new model is expected to be fully operational in January 2025!

PERT Fragment 12-15-21



c/o Lew Linker

Management plan

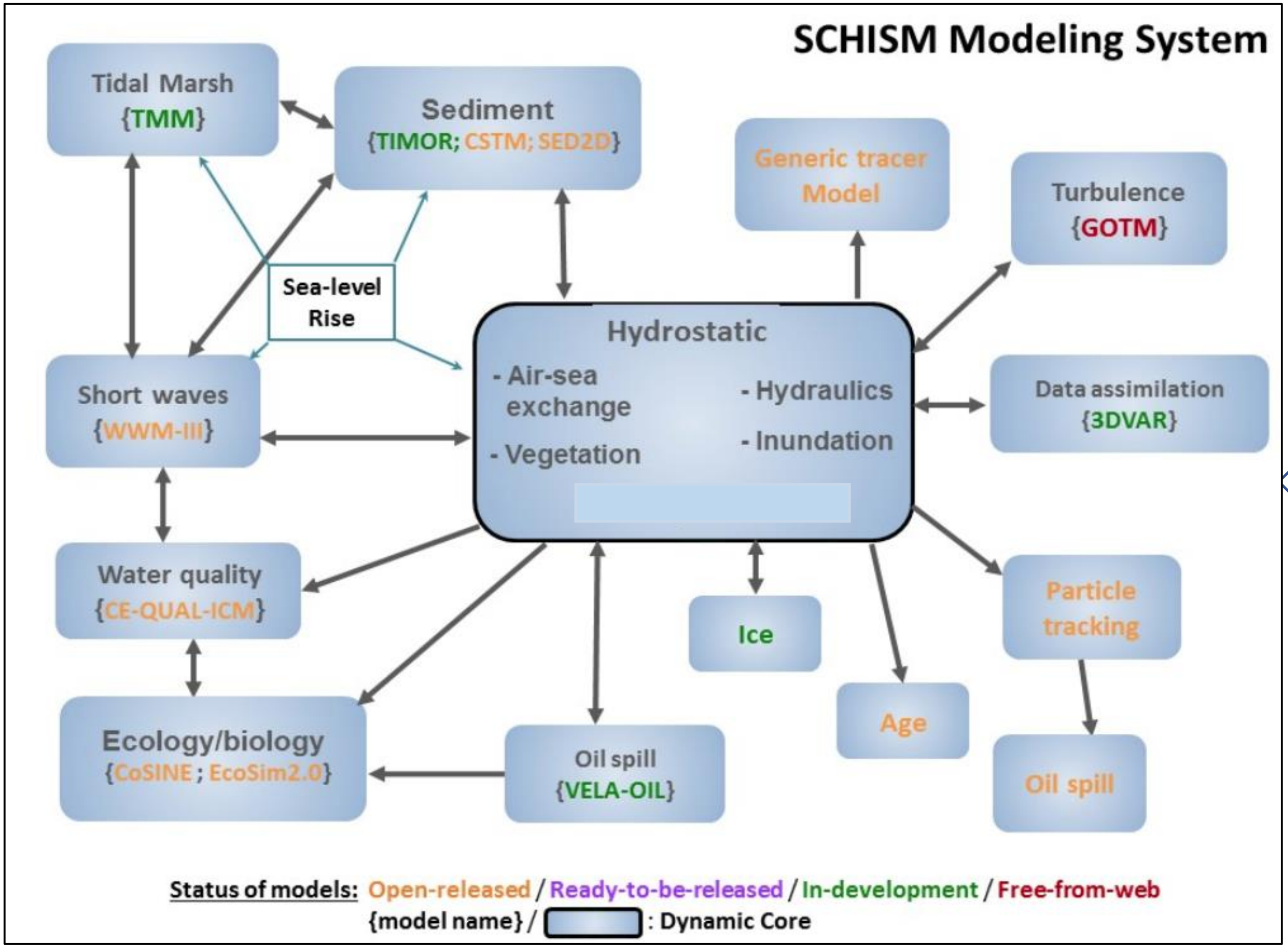
- VIMS and UMCES teams have joined force to tackle the challenges mentioned in the RFA
  - Besides traditional TMDL standards, our new work will also look into living resource based WQ standards (zooplankton, SAV, and benthic invertebrates)
  - Addition of living resource metrics will not reduce efficiency for management purposes
- We have also assembled an ad hoc Advisory Committee for consultation whereas guidance is directly through CBP Modeling Workgroup
- Synergy with concurrent projects from universities, non-profit organization, NOAA, state and foreign agencies that use the Chesapeake Bay as the target area for research and applications
- Continue to seek inputs from the wider community as we make progress
- Monthly meetings within the project group; quarterly meetings with CBP and Modeling Workgroup
- Annual reports will include code documentation, model preparation, calibration and validation results, and data analysis

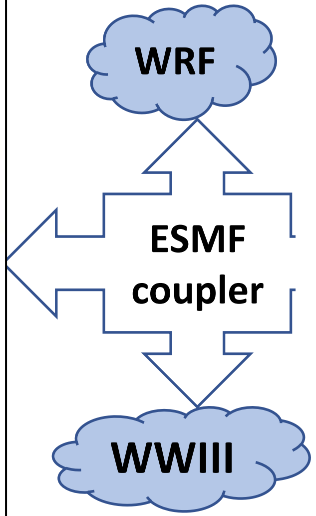
Table 1. Advisory Committee

Name	Affiliation
Lee Currey	MDE
Courtney Harris	VIMS
Denice Wardrop	CRC, Exec Dir.
Carl Hershner	VIMS
Rebecca Murphy	CBP/UMCES
Raleigh Hood	UMCES
Carl Friedrichs	VIMS
William Moore	Hampton Univ.
Ray Najjar	Penn State
Kirk Havens	VIMS

SCHISM: Semi-implicit Cross-scale Hydroscience Integrated System Model

- Solves 3D Navier-Stokes equations in hydrostatic form with Boussinesq approximation
- Galerkin finite-element and finite-volume approach: generic unstructured grids
- Semi-implicit time stepping: no mode splitting → large time step and no splitting errors
- Eulerian-Lagrangian method (ELM) for momentum advection → efficiency & robustness





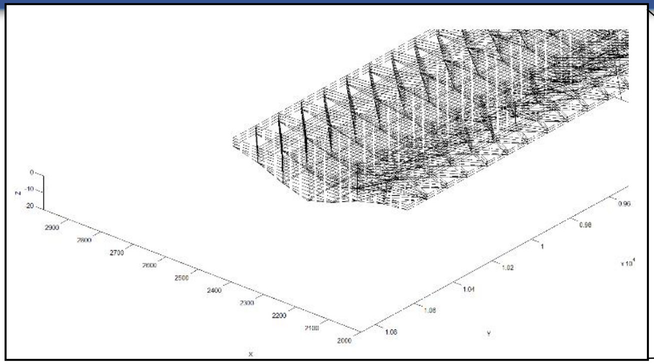
- Mixed grids (tri-quads)
- Flexible LSC^2 vertical grid
- Higher-order, monotone transport: TVD^2; WENO3;
- Higher-order momentum advection (ELM with ELAD)
- ESMF ready

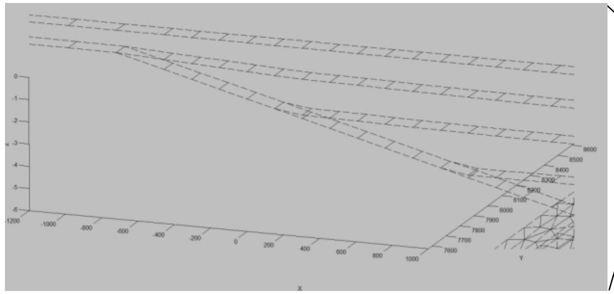
SCHISM offers the capability of multi-scale physics/biology and
the following technological advantages:

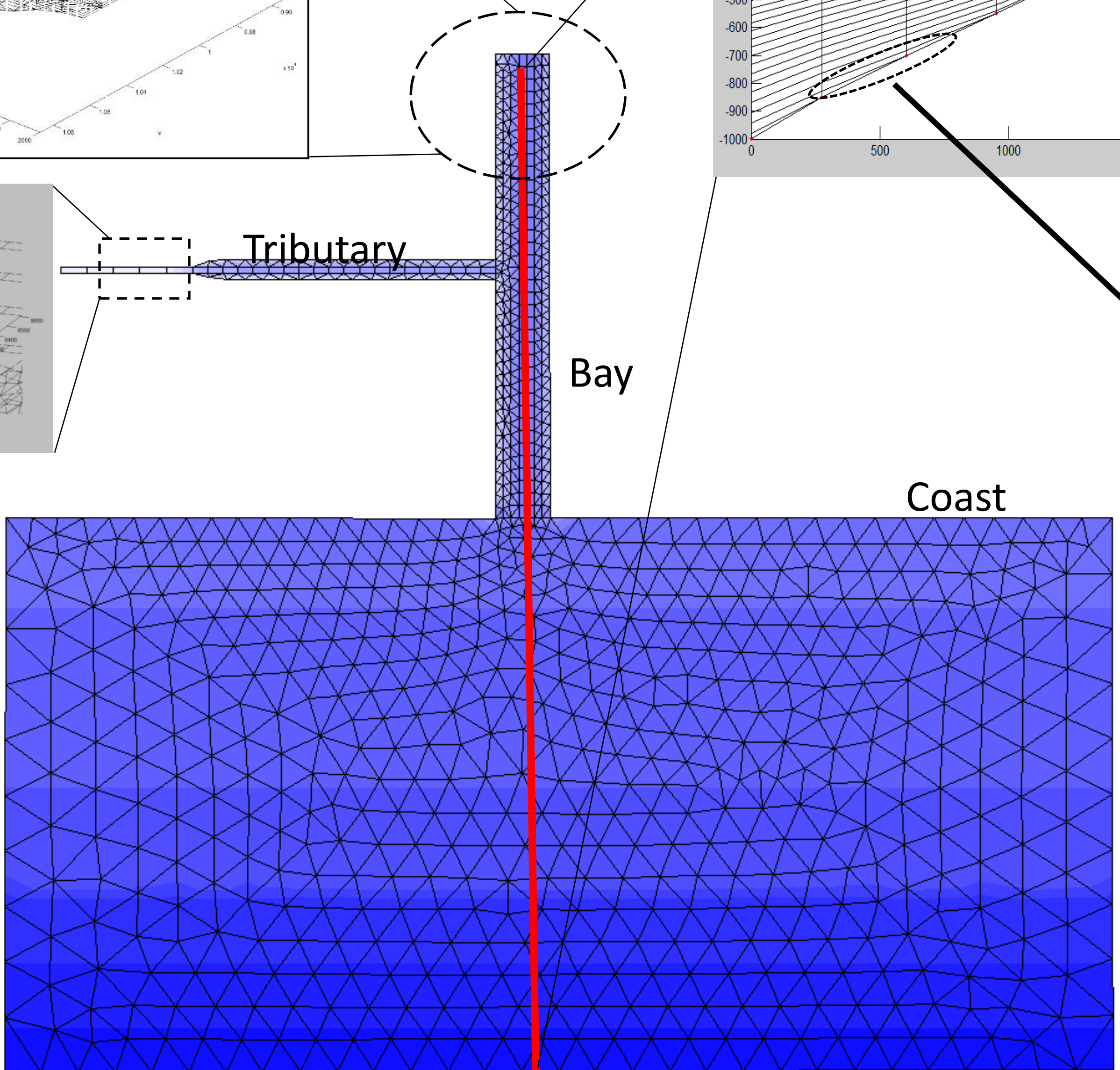
- Unsmoothed bathymetry
- Polymorphism
- Resolution on demand (skew elements)
- Robust seamless creek-to-ocean, Summit-to-Sea capability

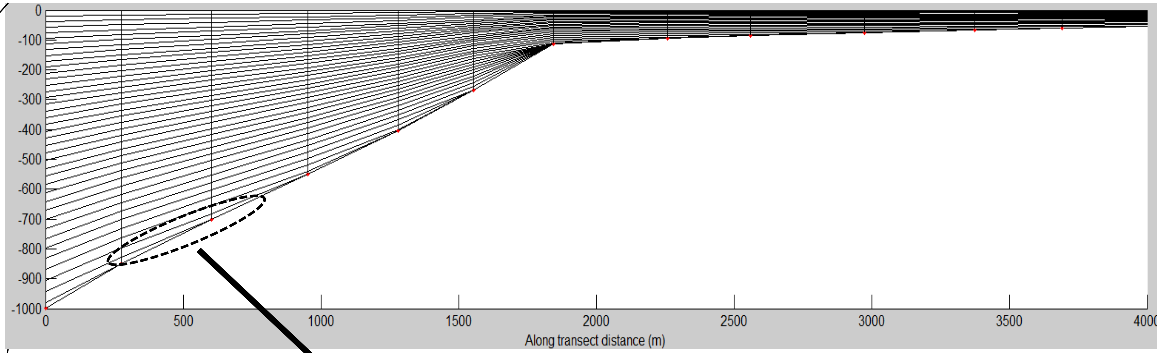
… the goal is to minimize grid nesting as much as possible

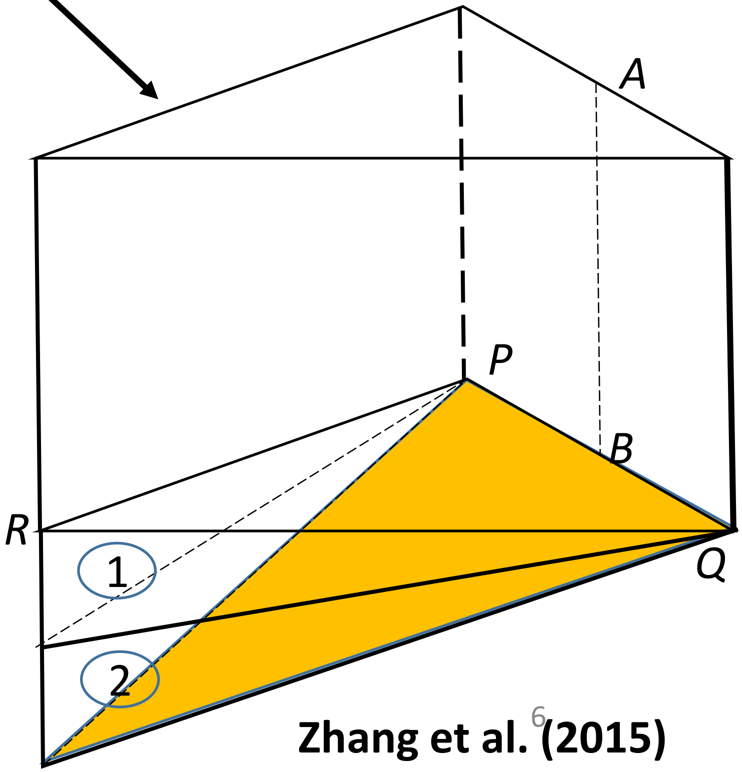
Polymorphism











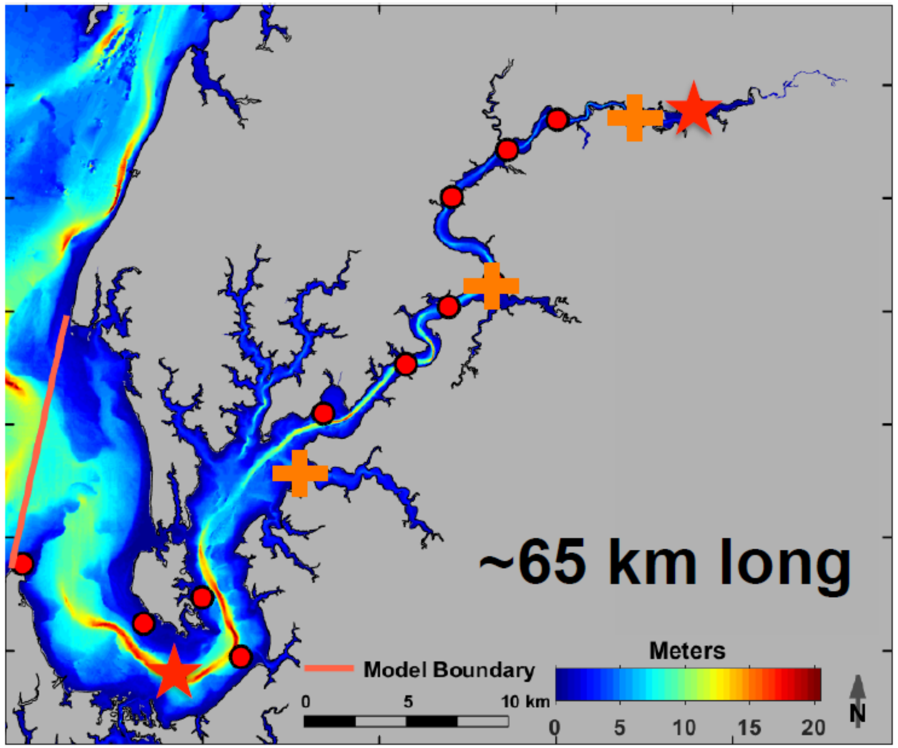
- A single SCHISM grid incorporates 1D/2DV/2DH/3D cells
- Efficiency and flexibility
- Shaved cells for bottom controlled processes
- As a result, the underlying bathymetry can be faithfully represented, including steep slopes

Zhang et al. (2015)

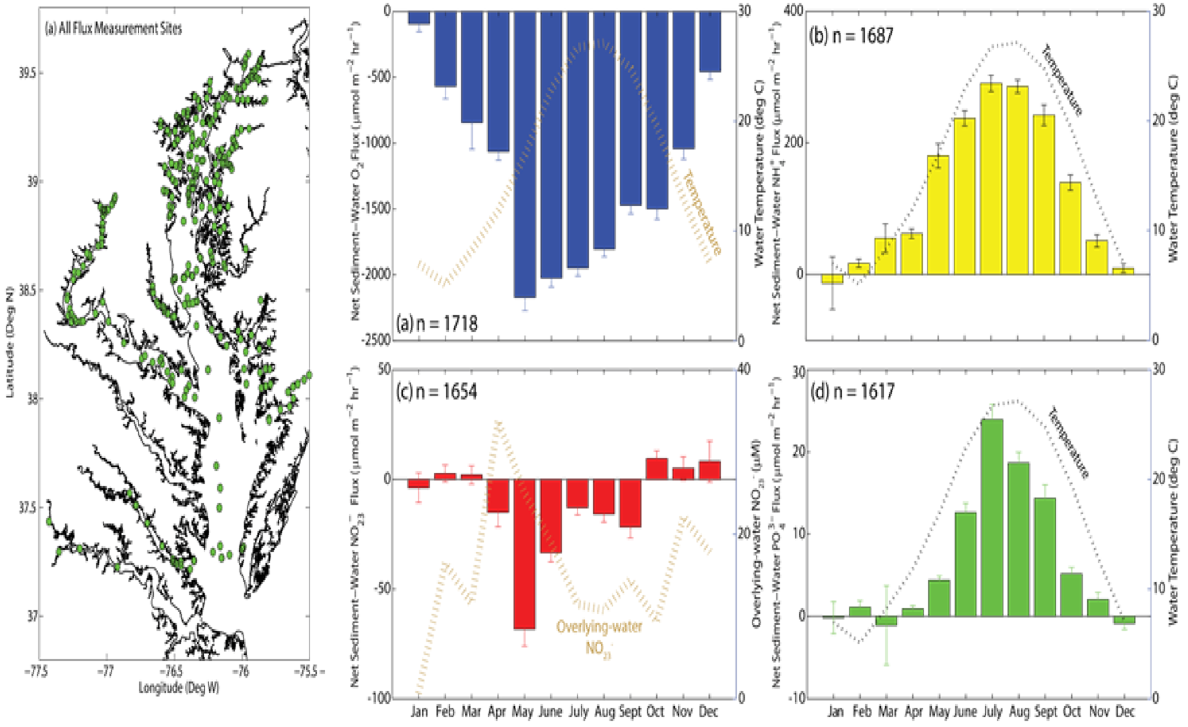
Setting the stage

- Shallow water project (Friedrichs et al.): studied a shallow-water system (Chester River) using multiple models
- Testa synthesized a Bay-wide high-frequency DO dataset (181 stations) to quantify the impacts of past and future climate and eutrophication on the dynamics of DO in the shallow waters of the Bay
- Testa led a multi-disciplinary team to study the interactions between ocean acidification and eutrophication in the Bay
- Zhang leads a NERRS project that explores the feasibility of a basin-to-creek BGC model with the Bay as a focus area, during which we have successfully FABM-ized a few WQ models
- Preliminary tributary work by VIMS team

Chester River

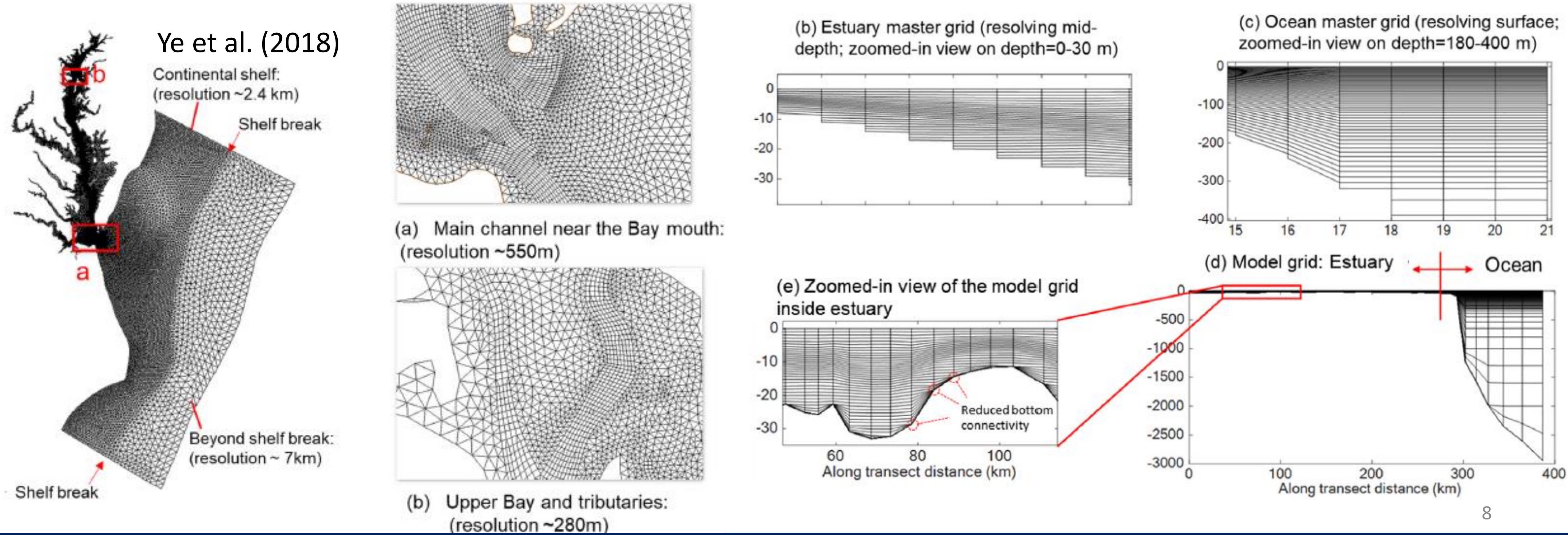


Bay-wide synthesis of sediment-water fluxes and Water quality



SCHISM-based Chesapeake Bay model

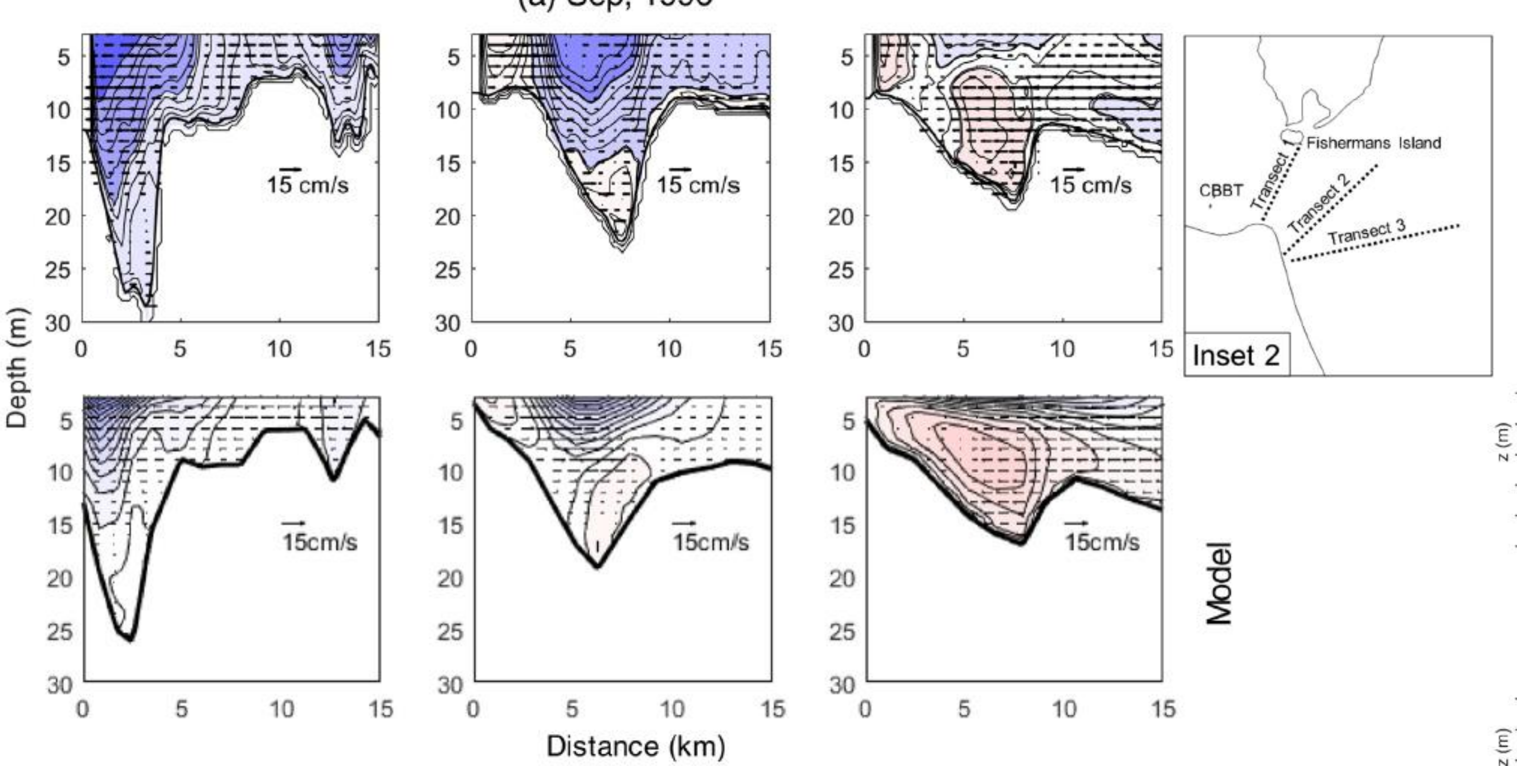
- SCHISM based Bay model has been in development since 2000s
- In its current incarnation
  - Horizontal mesh has ~30K nodes, 60K triangular-quadrangular elements
  - Vertical grid has 1-51 layers (LSC^2), ~8 layers on average
  - No bathymetry smoothing: DEMs were used directly without smoothing
  - Full physical forcing: tides, ocean, rivers, air
  - Model has shown good skills for physical and WQ variables



Chesapeake Bay hydrodynamic model

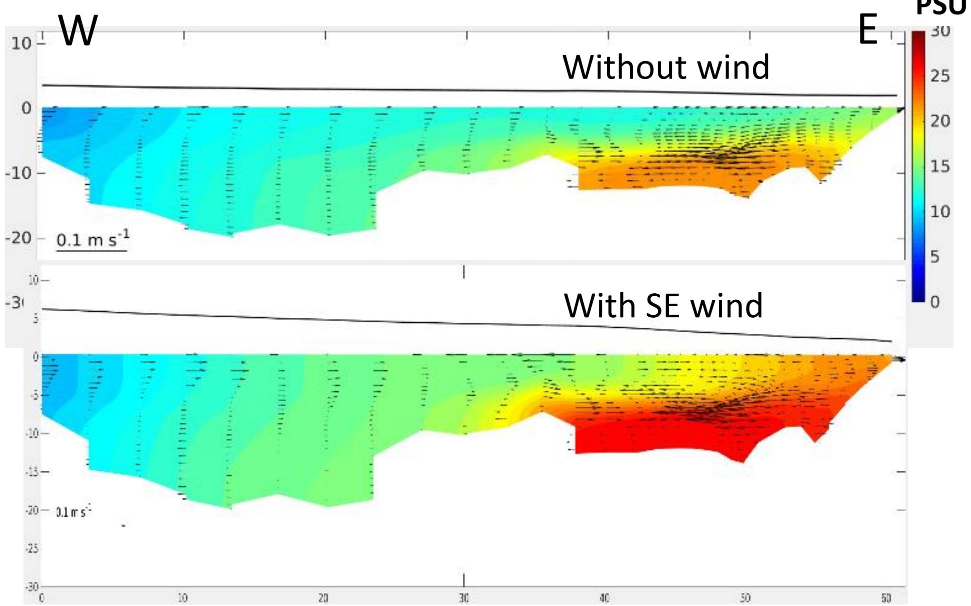
- The model faithfully reproduced many important physical processes in the Bay
  - Salt intrusion
  - Lateral circulation
  - Periodic stratification/destratification
  - Plume

Ye et al. (2018)

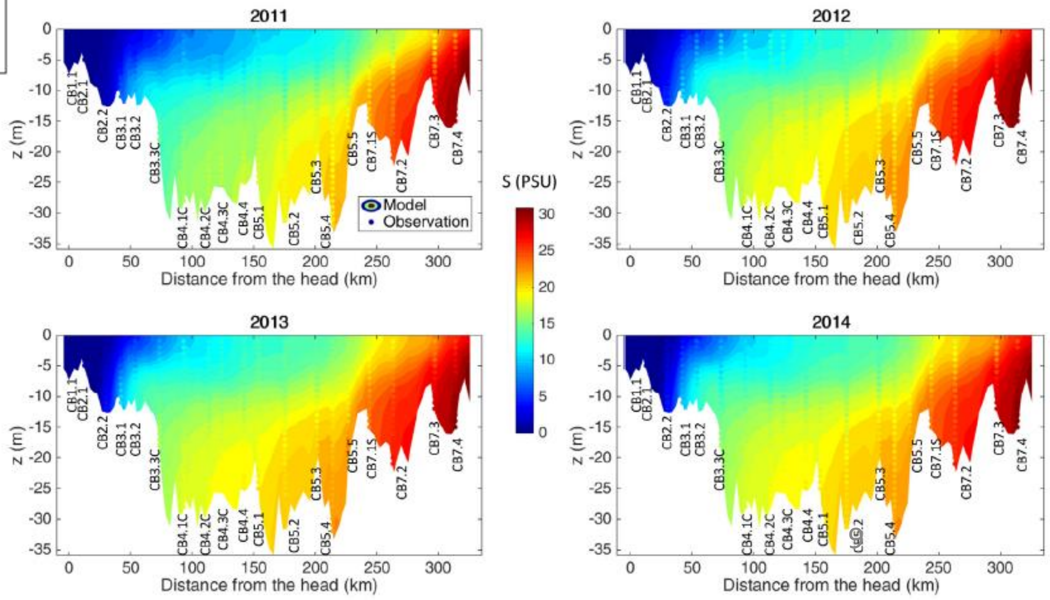


Sub-tidal frequency flows at each transect measured in (a) September and (b) November 1996. Looking upstream, shaded areas indicate up-estuary flow perpendicular to the transect; vectors indicate lateral flow

Salinity and velocity exchange across Bay and Rappahannock River



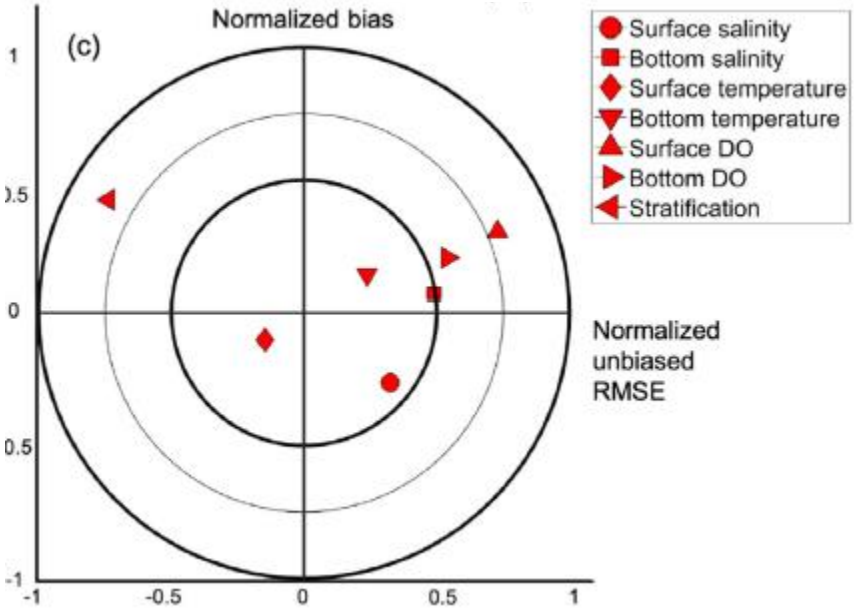
Verified inter-annual salt intrusion over main stem of the Chesapeake Bay

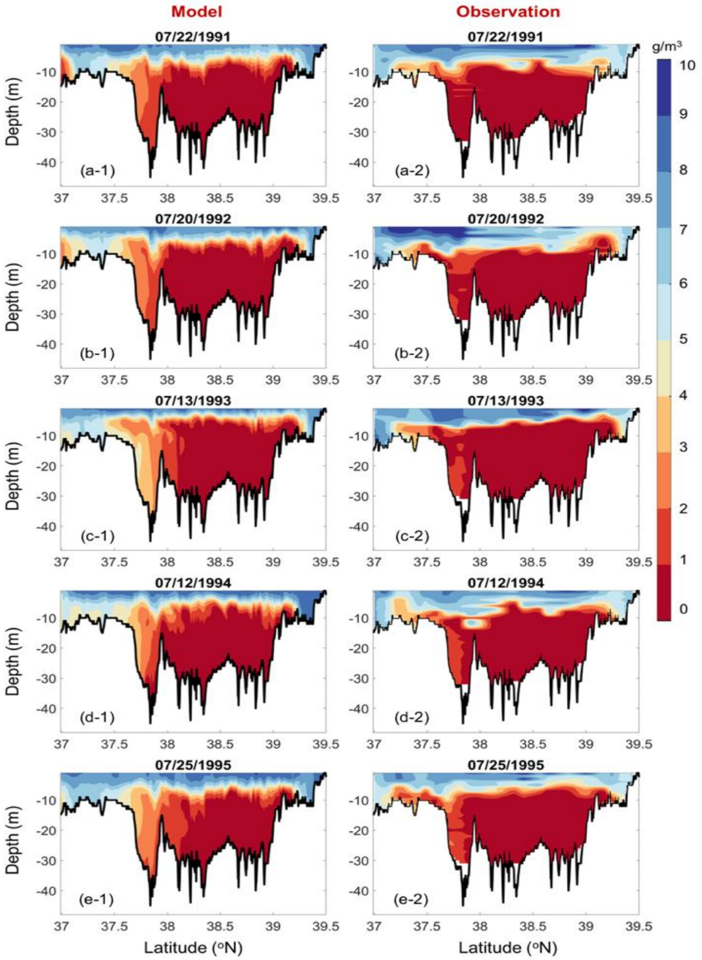


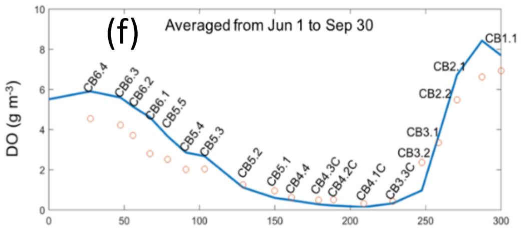
Chesapeake Bay water quality model

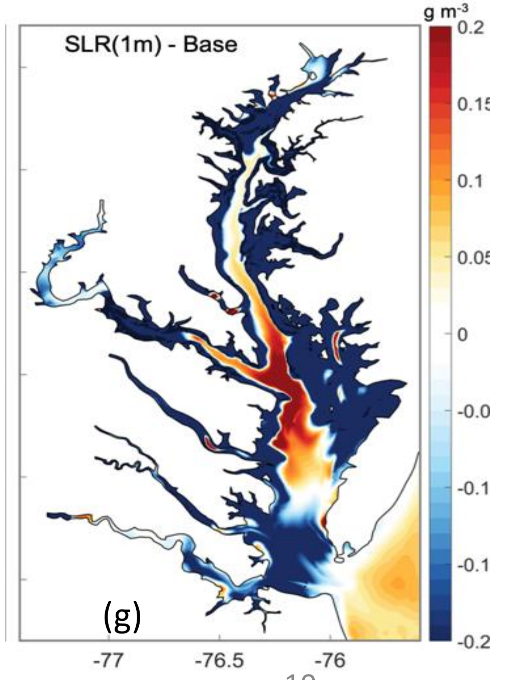
- SCHISM is fully coupled with ICM (2-way or 1-way)
  - Offline transport (with ICM using saved SCHISM flow field results) is added for performance
  - Hybridized TVD-ELM transport solver to turbo charge the performance
  - Need to reconcile versions of ICM next
- Nutrient loadings from Phase 6

Cai et al. (2021)



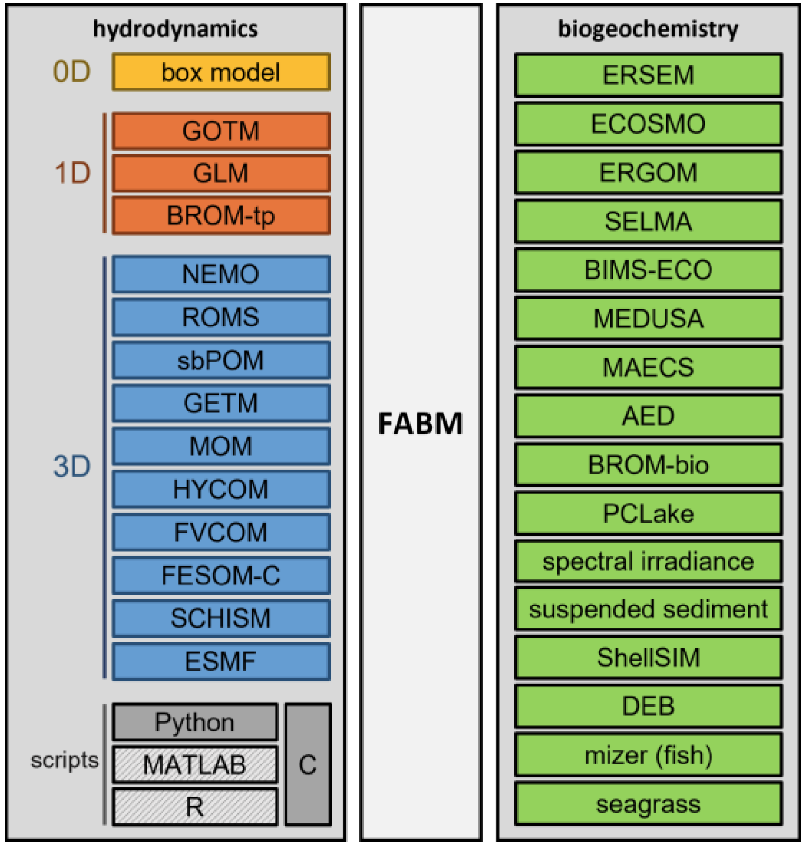




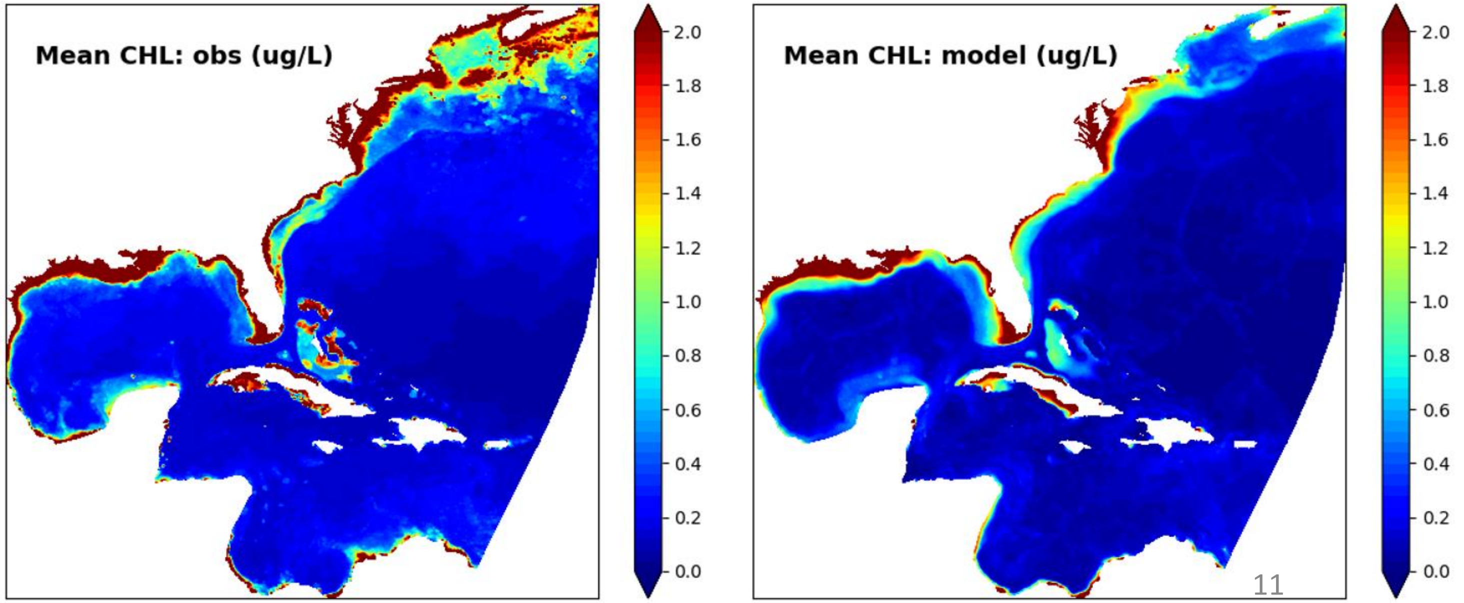


Creek-to-ocean biogeochemical model

- NOAA-NERRS project
  - Pursue the concept of a creek-to-ocean BGC model
- Utilize a flexible biological modeling framework: FABM
  - Fortran 2003 programming framework for biogeochemical models
  - Acts as match maker between a wide range of hydrodynamic (‘host’) and biogeochemical models
  - Space agnostic: 0D, 1D, 2D, 3D
  - Under this and other projects, we are FABM-izing ICM to make it interoperable with other BGC models



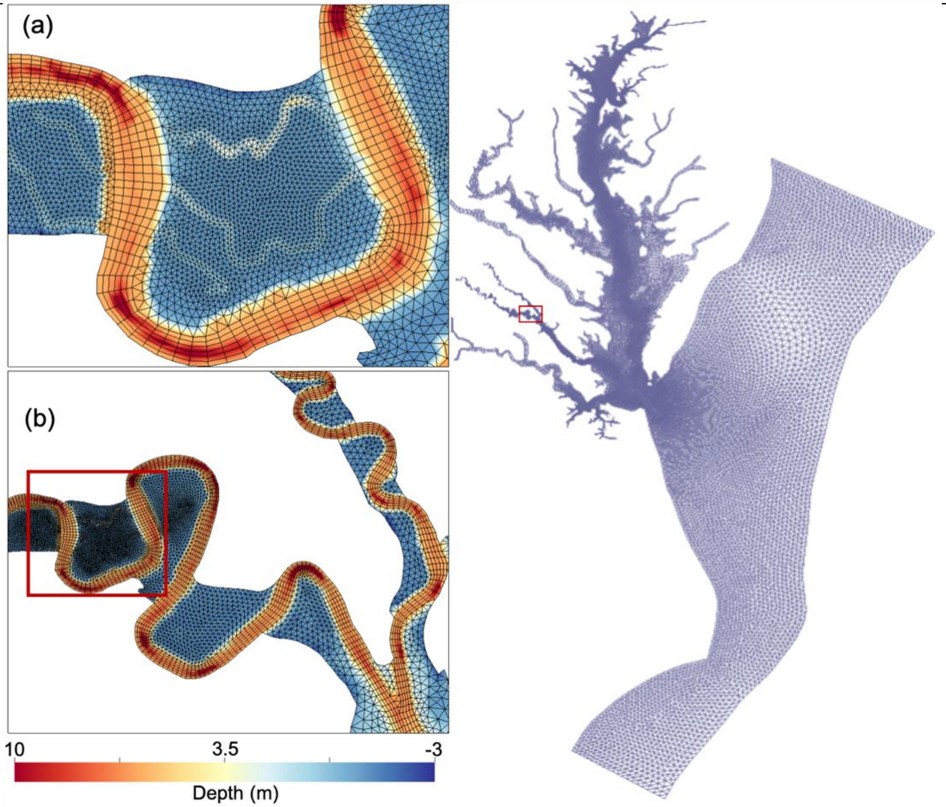
Chl-a results from FABM-ized SCHISM-CoSiNE for east coast



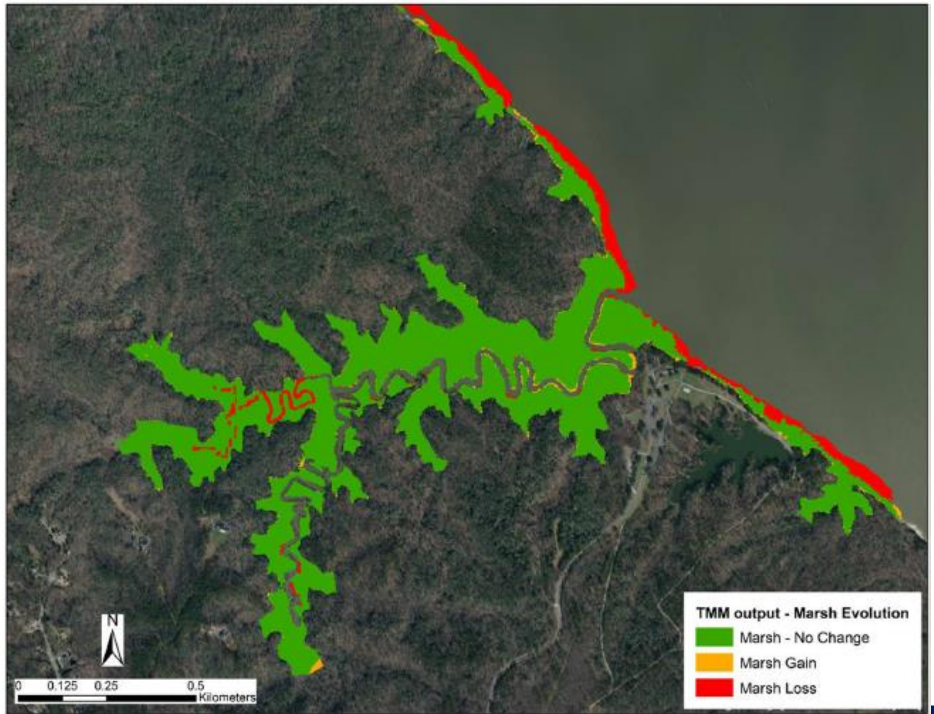
Vegetation modeling

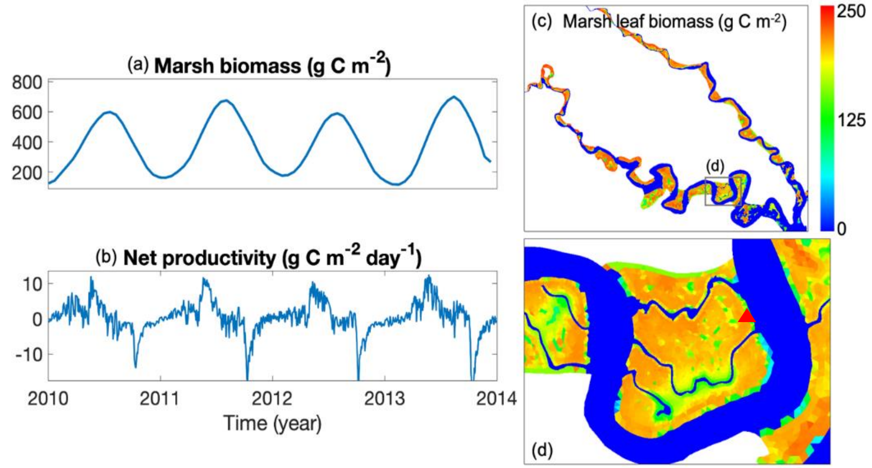
- We have developed a full fledged physical-biochemical model to simulate coastal and riverine vegetation (SAV or marsh)
  - Very high resolution (<10m) near vegetation patches
  - Accounts for vegetation growth (life cycle)
  - Long-term marsh migration study (Nunez et al. 2020, 2021)
- Similar SAV studies have been done for San Francisco Bay & Delta also

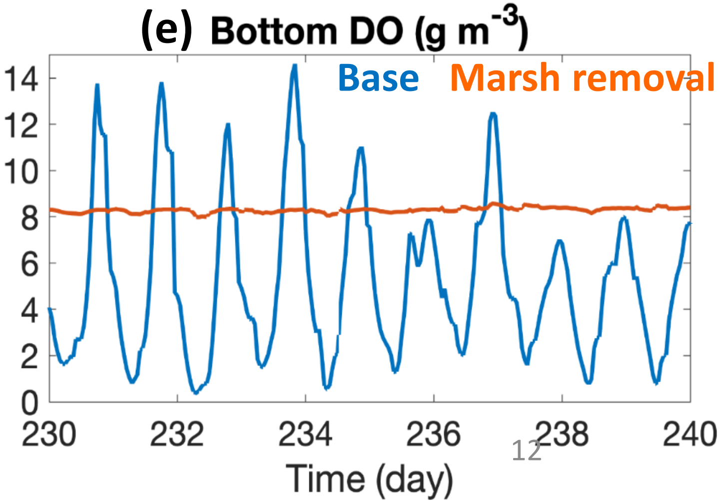
Marshes in upper York River



Changes in marsh boundary in Taskinas Creek after 40 years of simulation with a sea-level rise of 4 mm/yr.

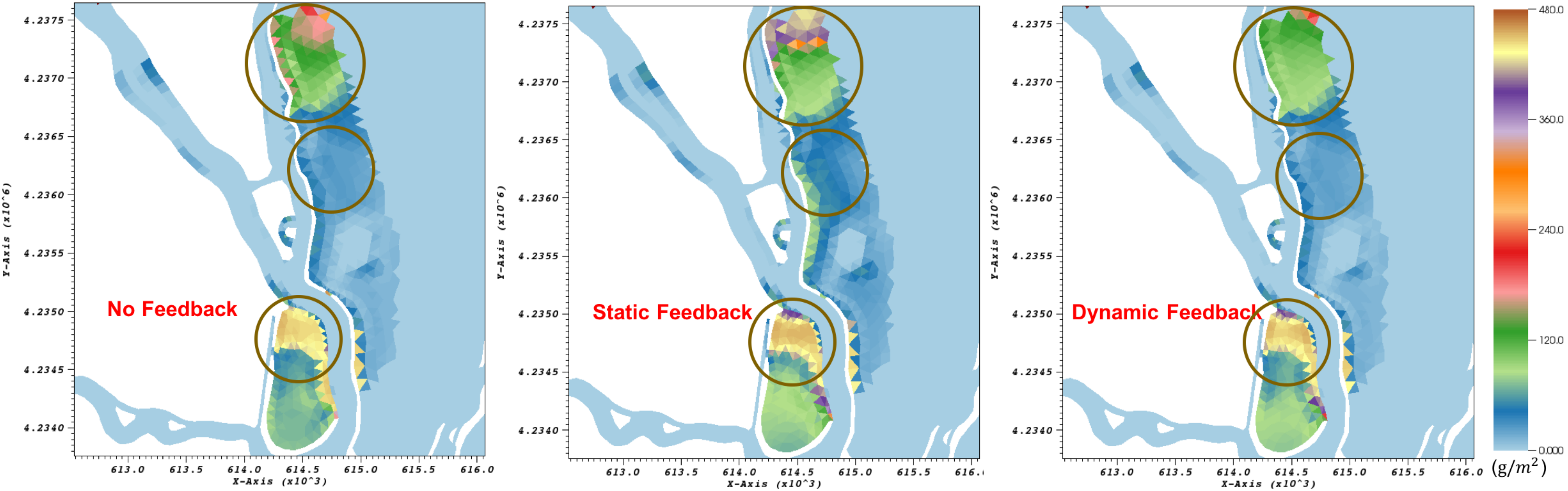






Static, dynamic and no feedback of SAV biomass

Cache Slough, Sacramento-San Joaquin Delta



- SAV biomass is the smallest under no feedback scenario. Biomass in the static feedback scenario is the largest.
- Different SAV biomasses in these three scenarios can be caused by a number of reasons. For instance, the change in the flow pattern leads to differences in the nutrient distribution, which further changes the SAV growth at different depths.

Project Task I: Model Implementation, verification

- Integrate the latest changes in CBP's ICM into SCHISM-ICM (Year 1)

- Revise the current SCHISM Bay mesh and work on tuning the performance of SCHISM-ICM (Year 2)
  - The major performance bottleneck in SCHISM is the explicit horizontal transport solver (>80% of time)
  - To reach the efficiency required, we have to make trade-offs among the 3 most important properties of transport (Boris & Book 1973): (1) Mass conservation; (2) Constancy & shape preservation; (3) Monotonicity (positivity)
  - Besides the fully implicit solver, Eulerian-Lagrangian (ELM) solver is unconditionally stable (but only guarantees conservation in Lagrangian sense), and is ideal for shallow water and watershed
  - Hybridized TVD-ELM transport solver achieved the required performance (~7-8 Simulated Years Per Day)
  - Advancement in HPC resources in the next few years may also help

- Work with watershed, airshed, hydrological modeling groups to ensure the coupling, scale, and the interface mechanisms are properly executed, including C.C. input information (Year 1-2)

- Conduct full calibration and verification of hydrodynamic and WQ model output (Year 2-3)

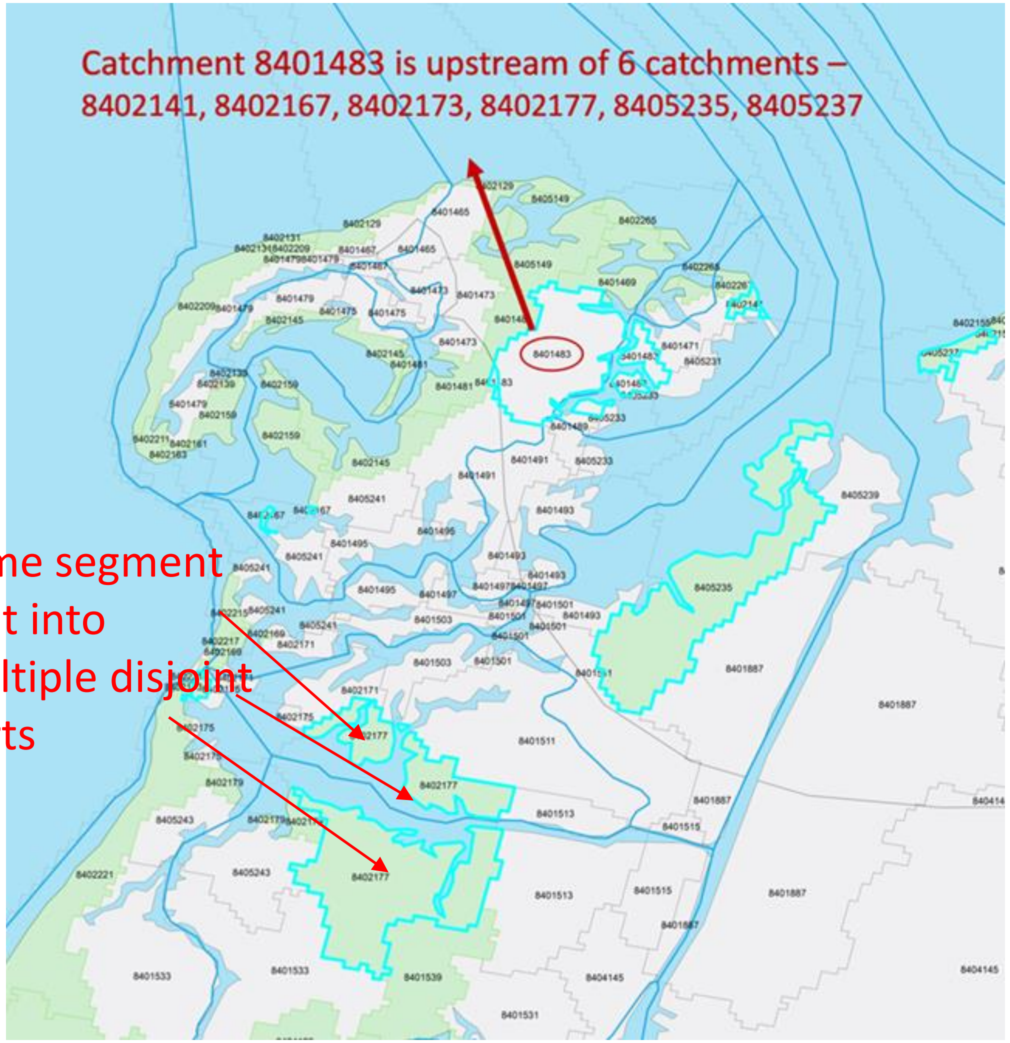
Project Task II: Advancement of ICM Model

- Address some important knowledge gaps in ICM (Year 3)
- Review recent studies related to Bay WQ processes and work with CBP and MW to identify key missing processes, updating the code to address knowledge gaps as they are filled (Year 2-4)
- Transfer the updated code version to CBPO for testing
- Potential synergy with FABM projects

- Utilize SCHISM's data assimilation (DA) module to improve WQ predictions using previously under-utilized datasets, including high-frequency monitoring data, remotely sensed observations (e.g., Chl-a from NASA) and real-time nutrient monitoring in Bay rivers (e.g., USGS Susquehanna)
- Investigate the need for improvement of modeled denitrification processes, by leveraging PI Testa's work in improving the ICM sediment module and incorporating new observations of sediment fluxes (and denitrification) to guide and validate the model
- Simulation of benthic algae, SAV, and living resources (oysters) to specifically incorporate their impacts on WQ. Specifically, we will investigate ways to improve simulations of the interactions of vascular plants (SAV, marshes) on estuarine DO, nutrient exchanges, and hydrodynamics
- Explore uncertainty quantification of parameters by looking into well accepted parameter estimation tools such as PEST++
- Explore linkages of SCHISM to models representing higher trophic-level organisms like finfish and crustaceans. We will discuss possible versions of these models with the estuarine living resource group and explore the ways of coupling models and best forms of models (habitat volume, bioenergetics etc)
- Explore improvement of the light function in ICM via our sediment transport model. We will use our sediment transport model to quantify inorganic and organic particle dynamics on light availability
- We will build on preliminary work to simulate the effects of suspended particles on nutrient cycling via resuspension and particle-solute interactions of suspended particles (e.g., phosphorus)

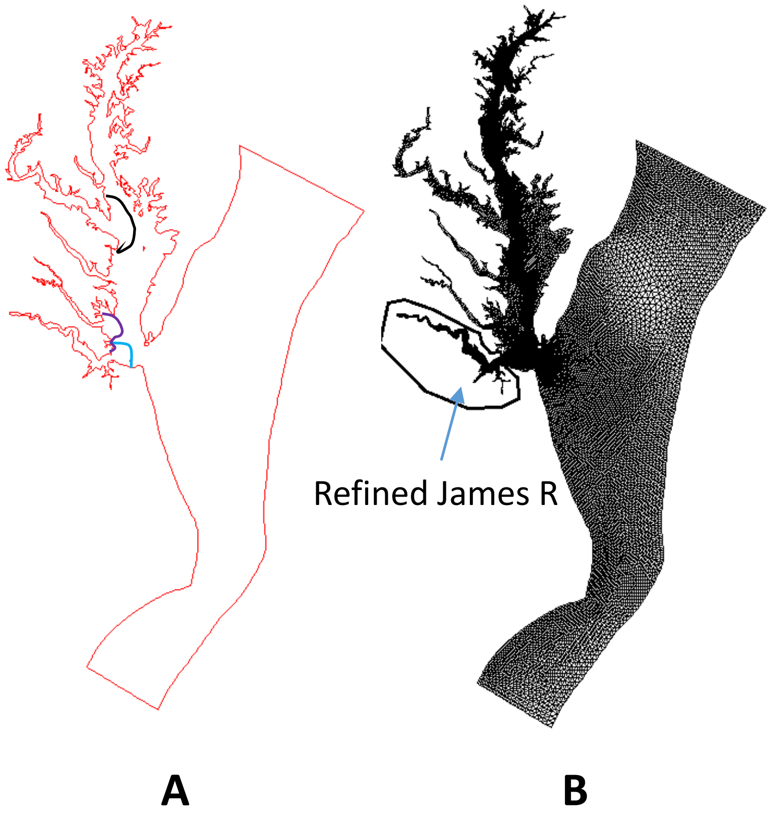
Coupling with watershed model

- We have tested the coupling between a high-resolution 3D estuarine hydrodynamic-WQ model and a high-resolution hydrologic model prototype (NHDplus)
  - The 3D estuarine hydrodynamic model is very robust
- Impact on estuarine circulation is mostly expected
  - Results are similar to P6 in the main stem of the Bay
  - Results in tributaries and sub-tributaries generally show higher salinity gradients
- Impact on WQ needs to be further explored
  - Nonlinear responses are expected especially in smaller systems
- Challenges and future work
  - Refinement of linkage strategy: what do you mean by ‘nearest element’?
  - Odd cases (e.g. multi-part disjoint segments)
  - How to distribute nutrient loadings under high resolution to better capture localized effects?
  - How to adapt the coupling strategy as the watershed model evolves in the future?



Coupling with multiple tributary models

- MBM will provide boundary (and initial?) conditions for MTM
  - Another option is to blend in observation when available
- One-way coupling first: no feedback to MBM
  - MBM needs to possess sufficient skills in the main channels of tribs
- MTM linkage
  - several options: most efficient option may be to separate tribs from MBM
  - Use similar/same mesh designs for trib channels as MBM
  - Vertical grid may differ from MBM
  - Extended shallow areas
  - Finer resolution in shallows
- Eventually may consider 'folding back' knowledge gained from MTM into MBM, or even reverting back to a single model that covers both mainstem and tribs/sub-tribs



Project Task III: Execute scenario simulations of the TMDL and climate change

- Develop and apply management scenarios (including climate change) in consultation with the CBP and MW (Year 4-6)
  - Climate change simulation will benefit from the MBM mesh having been extended onto the shelf
  - Watershed boundary can be extended as well if needed
  - Boundary conditions come from published works (e.g. global tides)

- Document the findings and recommendations in the final report (Year 6)

Project Tasks IV: Communication and model documentation

- Complete documentation on the software package (Year 2-3)
- Transfer the software package to CBPO for operational testing (Year 3)
- Develop user-friendly interfaces with model software and hold trainings for user support (Year 3&6)
    - Pre - processing, template, preliminary setups for 2D and 3D
    - Post-processing, visualization and scenario tools

Project Tasks V: Outreach, education, and publication

- Train the next-generation scientists by retaining existing and entraining new students and training them to become experts and couriers of knowledge related to Bay health and restoration (Year 1-6)

- Maintain a continuous engagement with the wider community including under-served communities (Year 1-6)

- Disseminate our research findings and experiences via 1-2 journal papers each year 2-6

Thank you!