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

Task I: Model Implementation, verification

Task IV: Communication and model documentation

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Special thanks to Dr. Carl Cerco for his advice!

Modeling Workgroup Quarterly Review
Oct 5, 2022

VIMS | William & Mary
Virginia Institute of Marine Science

SCHISM

Status update for Task I: Model Implementation, verification

- Almost completed updating our ICM to 2019 CBPO version
- Regression tests of all code changes
- Preliminary results using 1-step approach (SCHISM_ICM_WWM_SED3D)
  - Used to test the new code and also to set a new benchmark for the eventual 2-step approach
  - Calibration of SCHISM_WWM_SED3D: Jiabi's talk
- Work on shoreline boundary (Andy & Karinna)
- Drafted plans for incorporating living resources

1. Remove silica and zooplankton for this project
2. Add slow refectory variables for C, N, P
3. Simulate PIP and DIP directly without using partition
4. Simulate suspended sediment and wave
5. Include re-suspension in the lower bay (via the wave and sediment transport modules)
6. Revise algal respiration formulation using CBPO version
7. Revise algal predation formulation (1st and 2nd order)
8. Add shallow water capability (with spatially variable inputs)
9. Add benthic algae formulation of CBPO version
10. Simulate SAV: re-initialized each year or dynamically
11. Simulate wetland/marsh using a simplified approach (schematized)
12. Add new diagnostic outputs for easy debugging
13. *Oyster and clam (benthic feeder approach in ICM works): not done yet*
14. *Climate Change Consideration: temperature effect on growth and respiration will be examine during calibration*

SCHISM ICM update

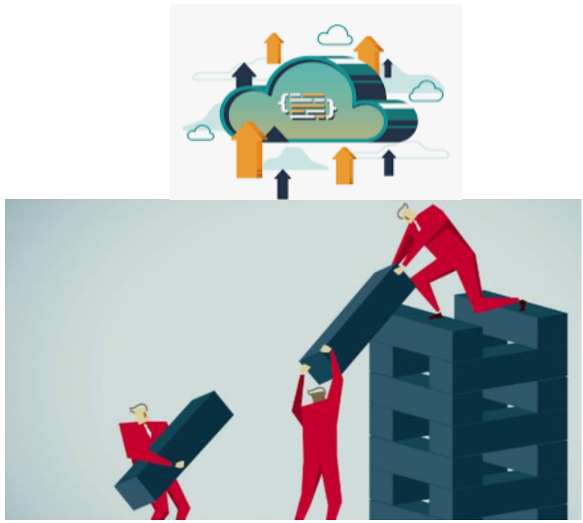
- Integrate the latest ICM changes into MBM
- Update code to meet the needs of MBM
- *ICM code development*

ICM model update → State variables; Biochemical processes; Living resources implementation & degree of complexity

Shallow water capability → Benthic algae; Marsh and SAV

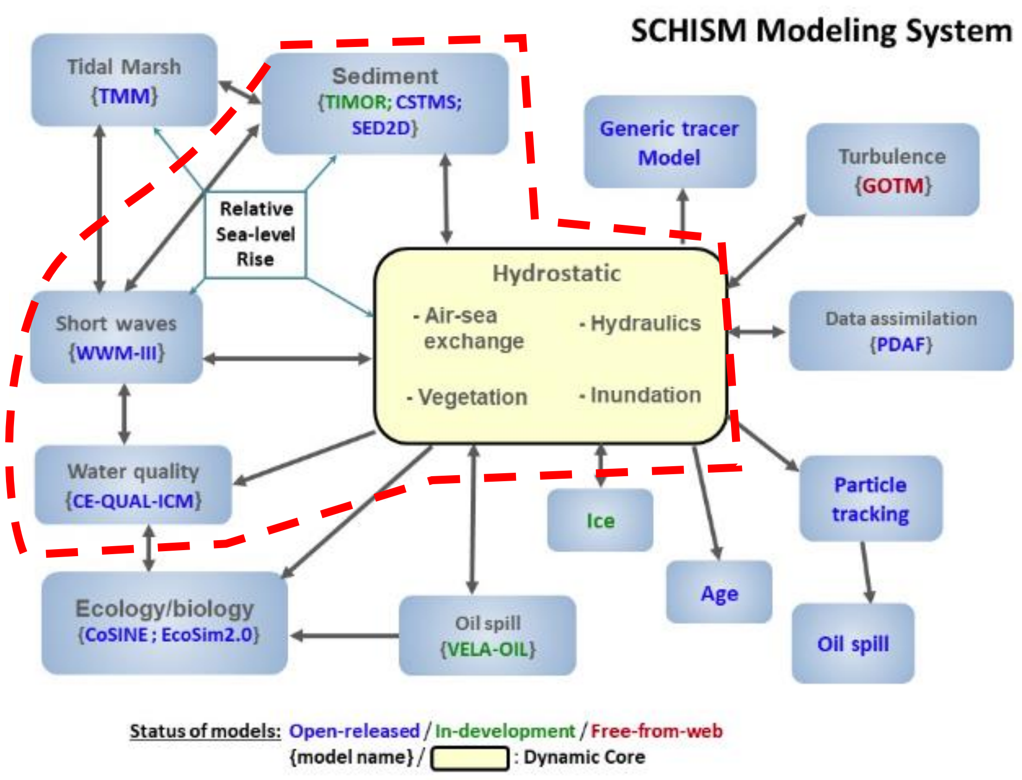
Climate change implementation → P-T curve; Boundary conditions

Enhancement of model capability to improve model performance (water quality)



Infrastructure-as-code (IaC)

MBM design



MBM consists of several modules of SCHISM system

- Hydrodynamics (including vegetation physics)
- Water quality (ICM, including vegetation biochemistry)
- Waves (WWM)
- Sediment transport (CSTM→SED3D)
- Sea-level rise capability
- For efficiency, MBM will eventually consist of two steps
- As first validation, we are testing the new code using the 1-step approach

Step 1

1. Hydro step: fully coupled SCHISM+WWM+VEG
• Schematized representations of wetland & SAV to control mesh size (mesh resolution can be high locally)
• Self-consistent physics
• The most expensive component is the wave module (WWM), and we expect the fully coupled model to run ~2 SYPD even on high resolution
• This step is done occasionally
• Save outputs for Step 2: T,S, bottom stress, and other forcing variables (e.g. light etc)

Step 2

2. ICM + SED
• Read in the saved outputs from Step 1
• With inputs from airshed and watershed models, solve for all WQ state variables, plus (optional) living resources, wetland
• Aim for performance (~10 SYPD) for massive number of simulations

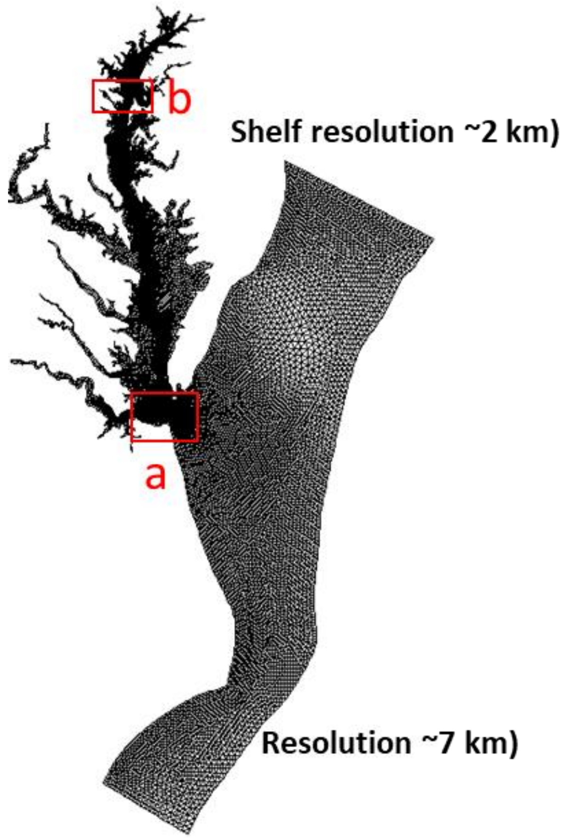
Step 1 + Step 2: SCHISM+WWM+SED+VEG+ICM

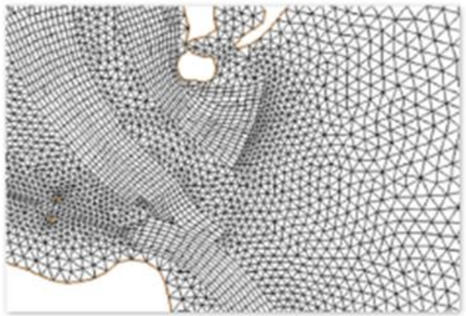
- hindered settling
- Effect of suspended organic matter on the bottom shear stress
- Algal effect
- Interaction with the sediment flux module

Validation of new code: model setup for hydrodynamics

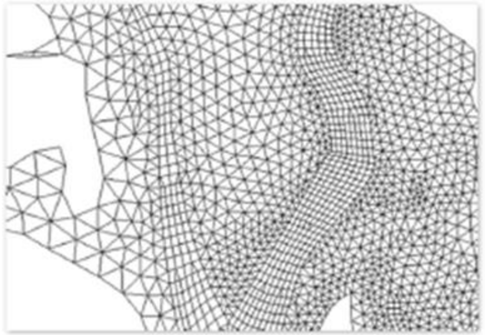
- SCHISM based Main Bay Model
- In its current incarnation
  - Horizontal mesh has ~30K nodes, 60K triangular-quadrangular elements
  - Vertical grid has 1-51 layers (LSC^2), ~8 layers on average
  - No bathymetry smoothing: DEMs were used directly without smoothing
  - Full physical forcing: tides, vegetation, ocean, rivers, air
  - Model has shown good skills for physical variables
  - >10 SYPD on 160 cores

Ye et al. (2018)

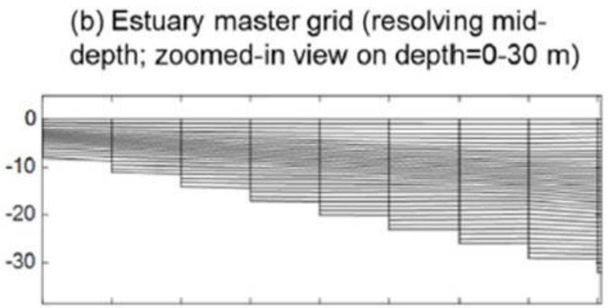


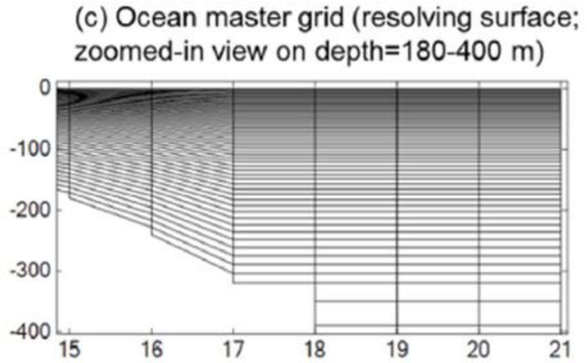


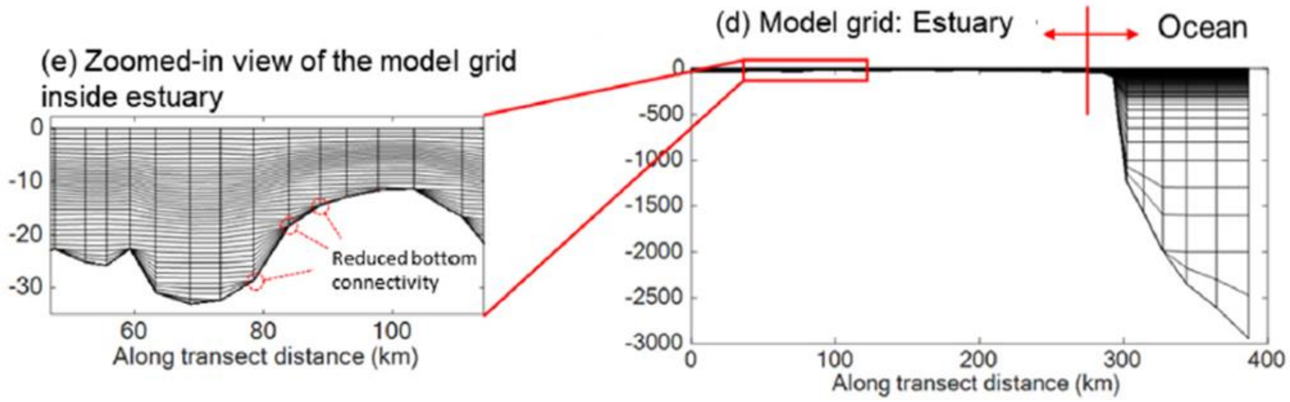
(a) Main channel near the Bay mouth: (resolution ~550m)



(b) Upper Bay and tributaries: (resolution ~280m)



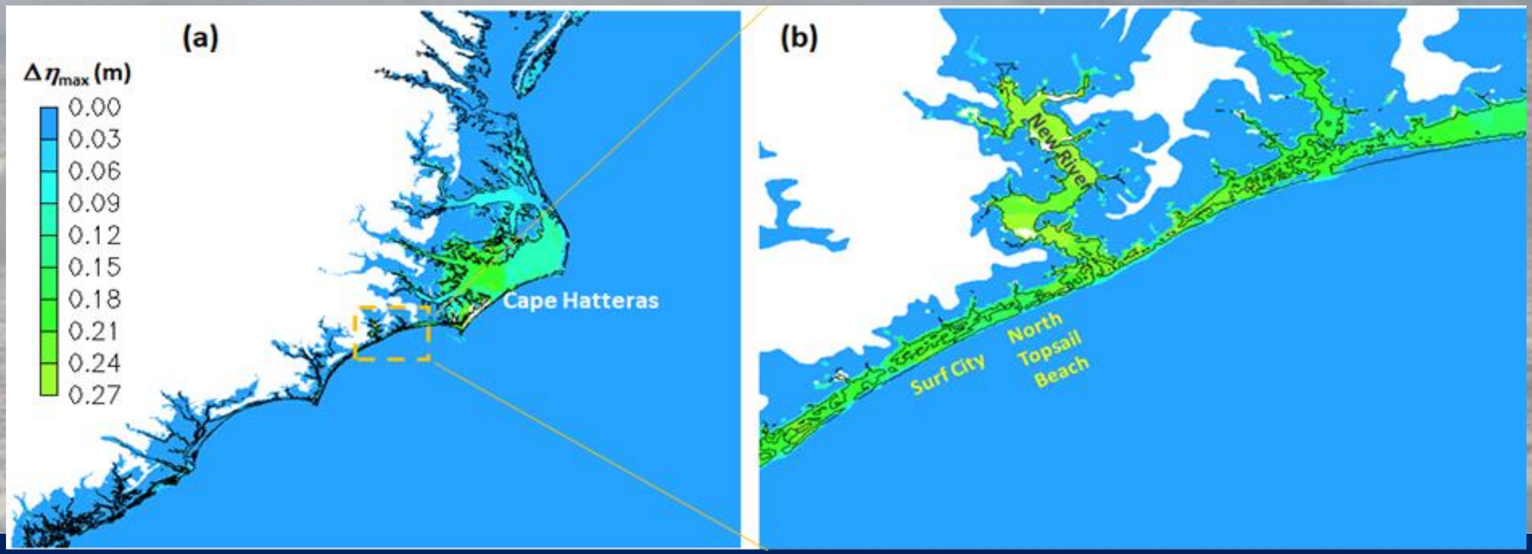




Validation of new code: model setup for waves

- Wind Wave Model (WWM)
  - Third-generation spectral wave model on unstructured grid (Roland et al. 2013)
  - Similar to UG version of WWIII
  - Unified physics from deep to shallow water
  - Fully integrated into SCHISM as a subroutine
  - Two models share same mesh and domain decomposition schemes
- Source and dissipation formulations follow latest WWIII (Ardhuin 2010)
- Wave-current coupling formulations
  - Longuet-Higgins and Stewart (2D)
  - Ardhuin's vortex formalism (3D)
- SCHISM_WWM has been extensively validated in multiple applications under storm and non-storm conditions
  - Wave effects are significant nearshore
  - Responsible for barrier island overtopping etc
- Inputs for WWM
  - Initial condition from Ifremer's global WWIII
  - Boundary condition also from WWIII
  - Send back wave forces, wave-enhanced bottom shear stress, and wave induced turbulence

Differences in the water elevation during Hurricane Florence (wave-nowave)

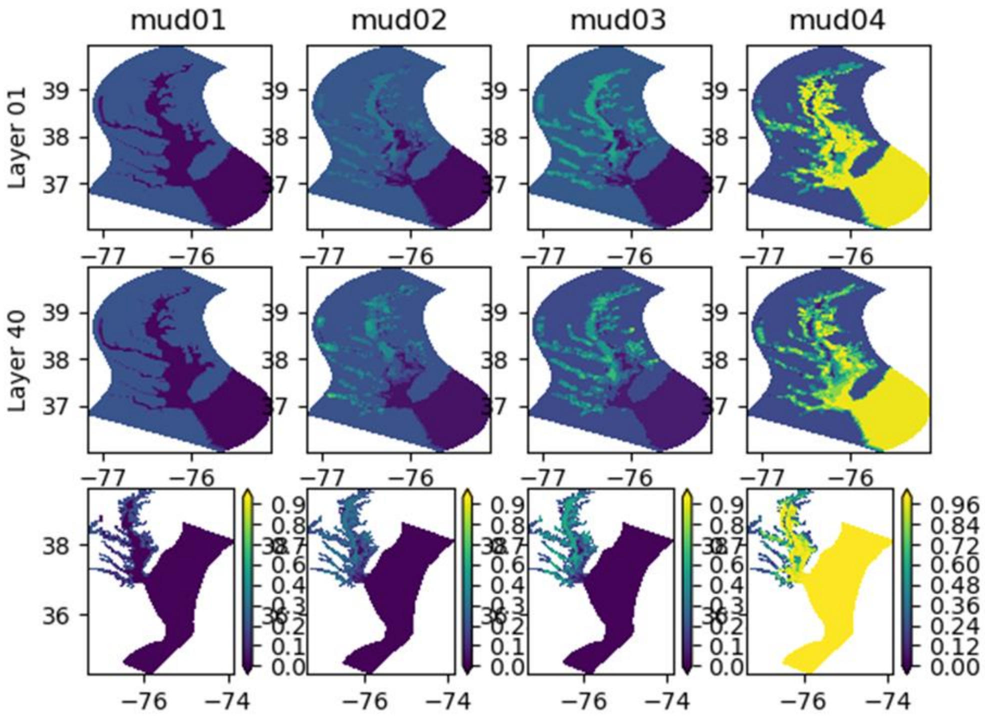


Validation of new code: model setup for sediment transport

- Integrated with Hydro + Wave
  - To hydro: bed composition (roughness), optional morphology (not activated yet)
  - From wave: wave asymmetry induced sediment transport (Elfrink et al. 2006); wave ripple effects on bed form (Nielsen 1992)
- Four sediment classes following Moriarty et al. (2021): sand, silt, and clay (unaggregated and small flocs)
  - Settling velocity, critical shear stress, and sediment fractions from literature or CBP model
  - Accurate initial condition for sediment fractions is key!
  - Single bed layer (also tested multiple layers)
- Morphology turned off at the time

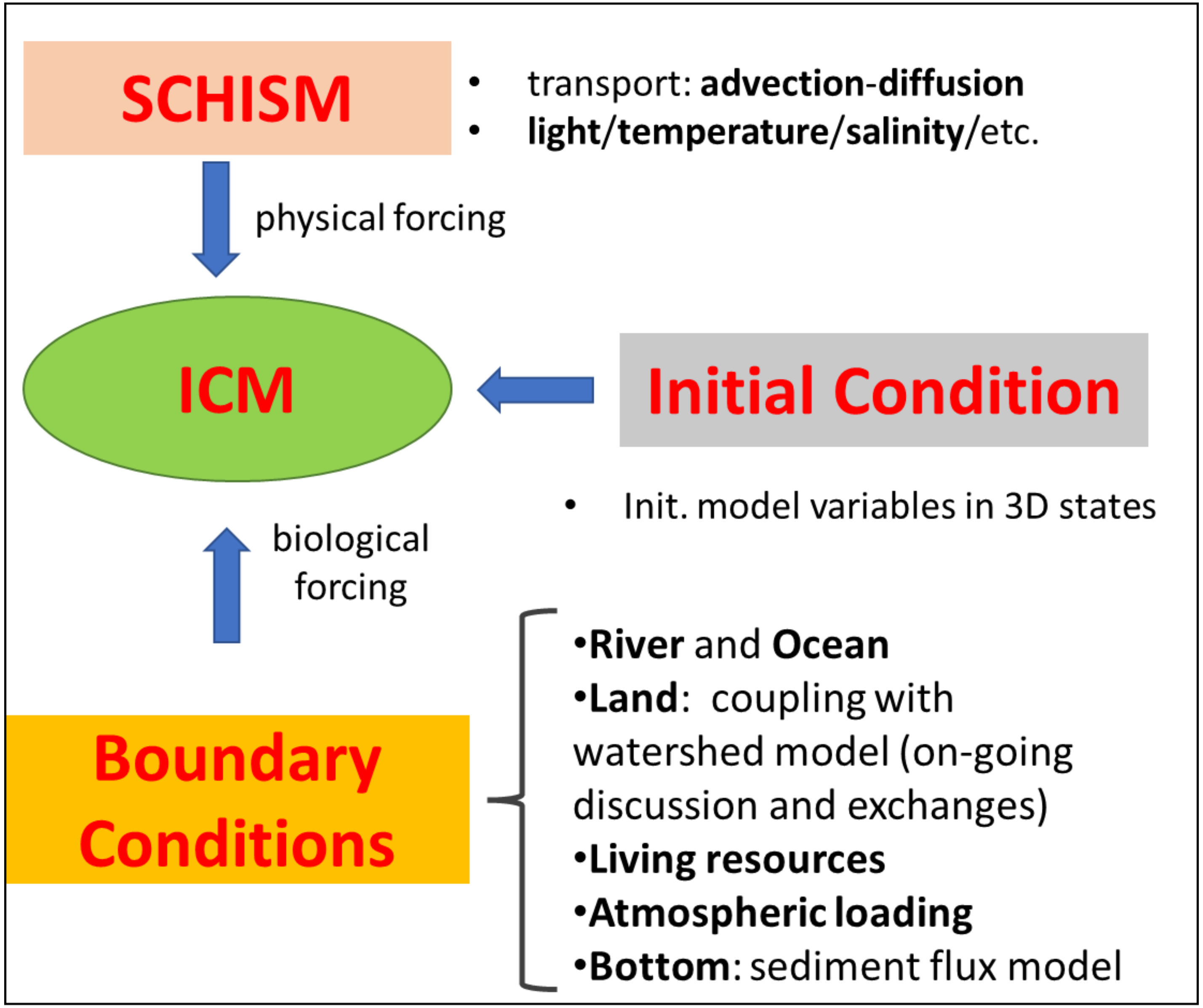
Special thanks to Courtney Harris and Julia Moriarty for their help!

Initial bed fractions interpolated from Moriarty et al. (2021)



Validation of new code: model setup for ICM

New variables: slow refractory C, N, P; benthic algae, and PIP
Removed variables: Si, Zooplankton



Initial condition

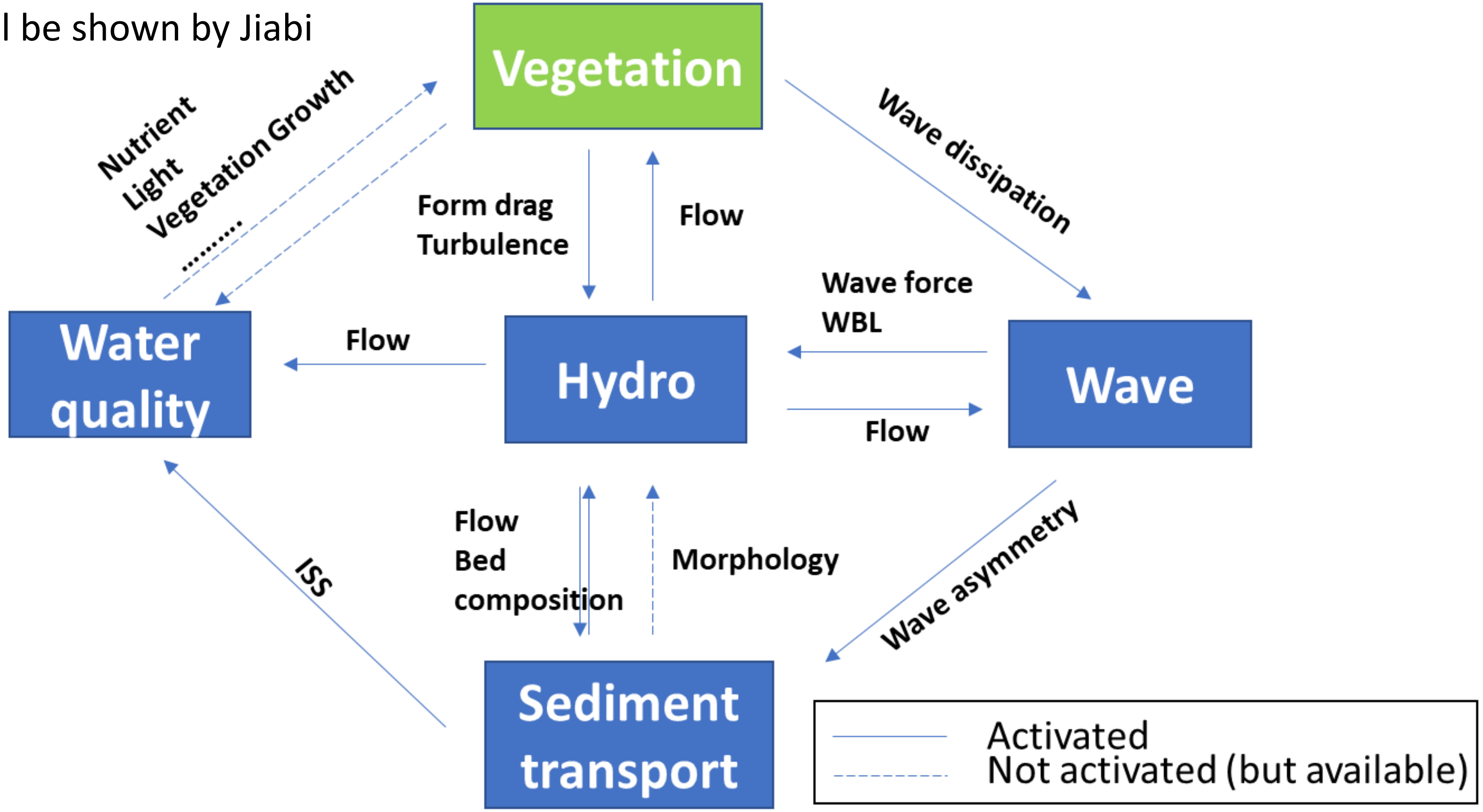
- **Bay**: CBP observational data
- **Ocean**: NCEI ship cruise data (climatology)
- **Sediment nutrients**: starting from constant values and let model warm up

Boundary condition

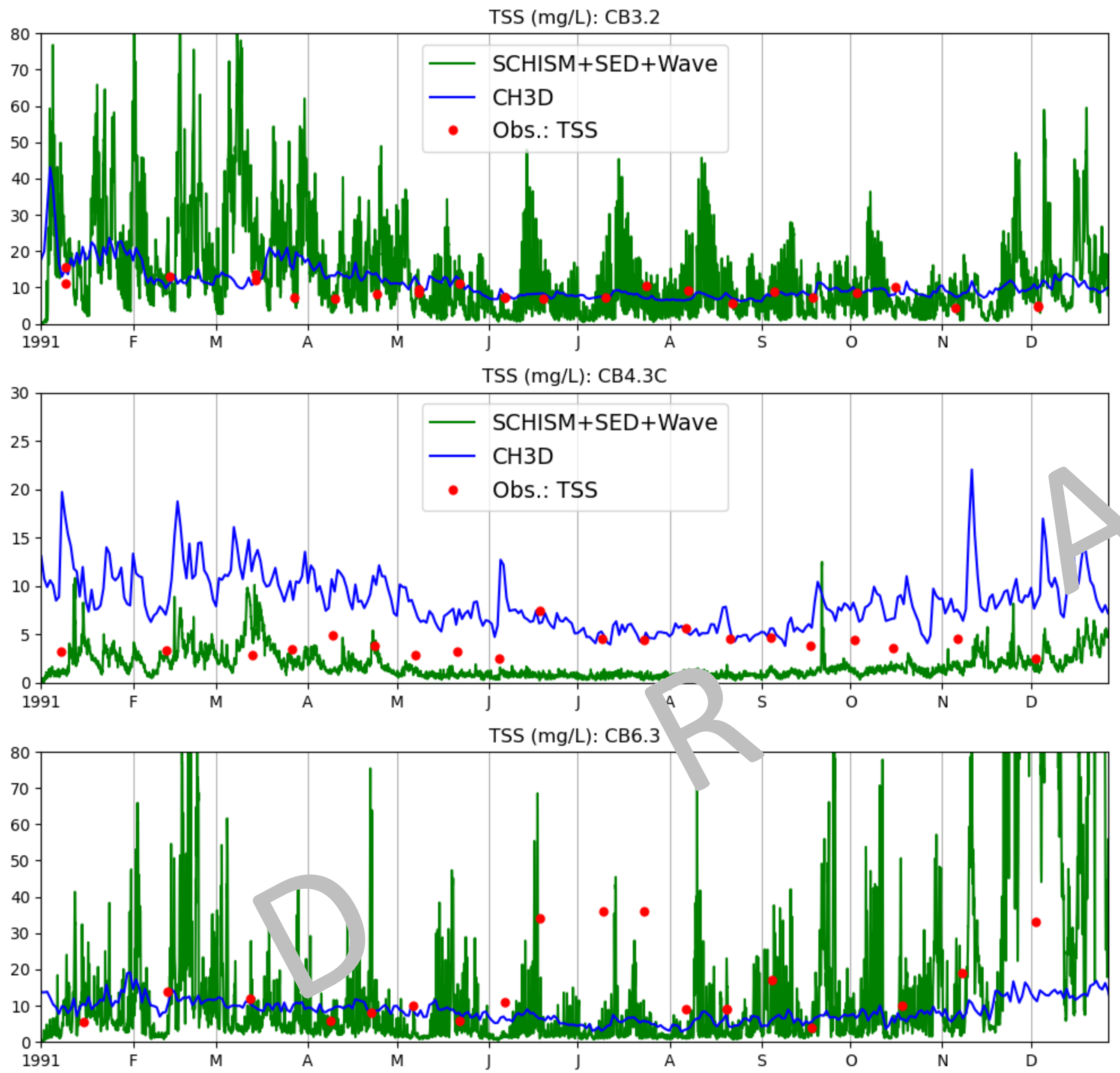
- **Ocean**: NCEI ship cruise data (climatology)
- **River**: watershed Loading (P6) + CBP data
- **Land**: watershed Loading (P6); shoreline erosion data to be sent (PIP)
- **Living resources**: from CBPO
- **Atm. Loading**: will add soon (from CBPO)

Module coupling

- Fully coupled model accounts for most of important processes relevant to WQ in the Bay
  - No external couplers used: all modules are tightly integrated into a single code base for maximum efficiency
  - Vegetation module is actually embedded inside hydro and WQ modules
- Validation of SCHISM_SED_WWM will be shown by Jiabi



First results for validation of new code: TSS

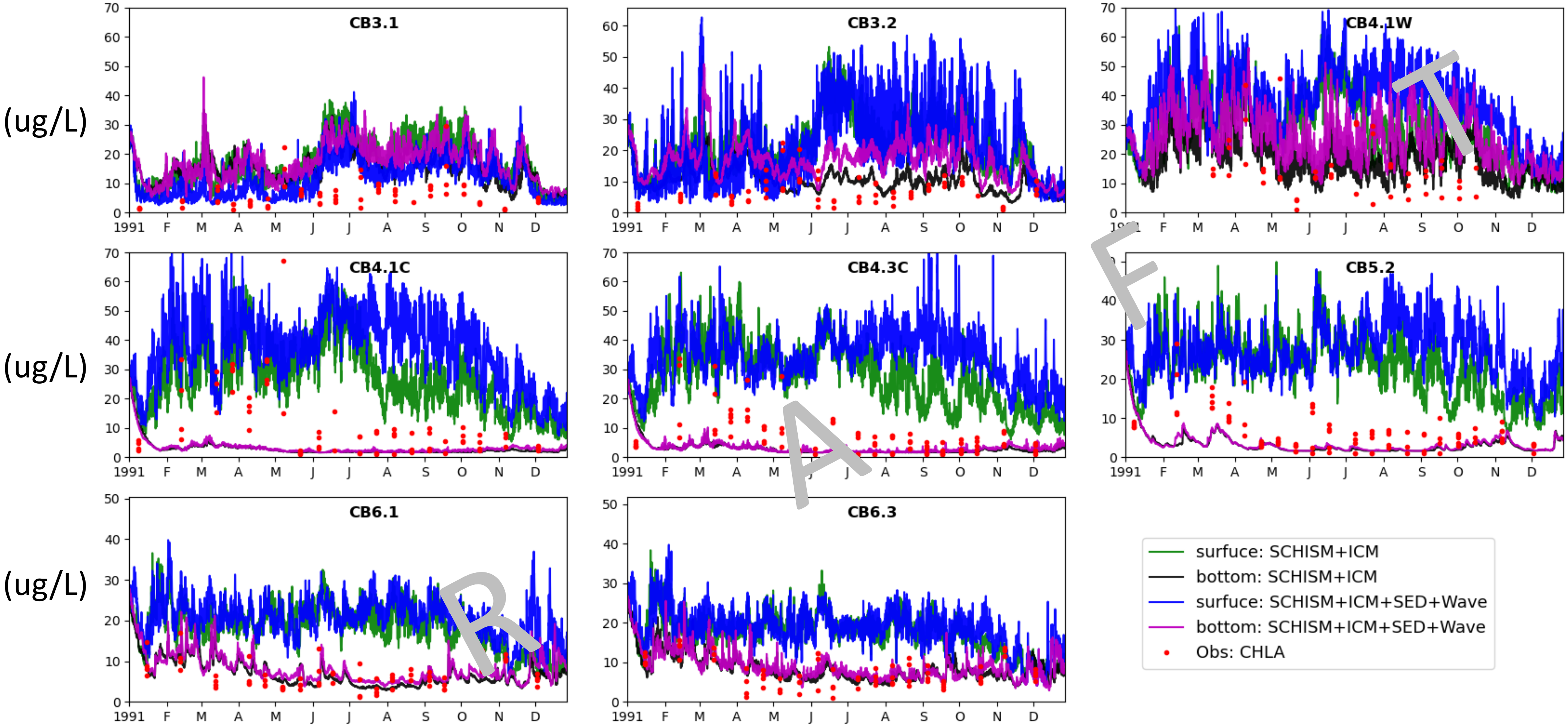


No calibration done yet!

TSS calculated from CH3D-ICM (daily output) and the TSS simulated in SCHISM+ICM+WWM+SED3D (hourly output)

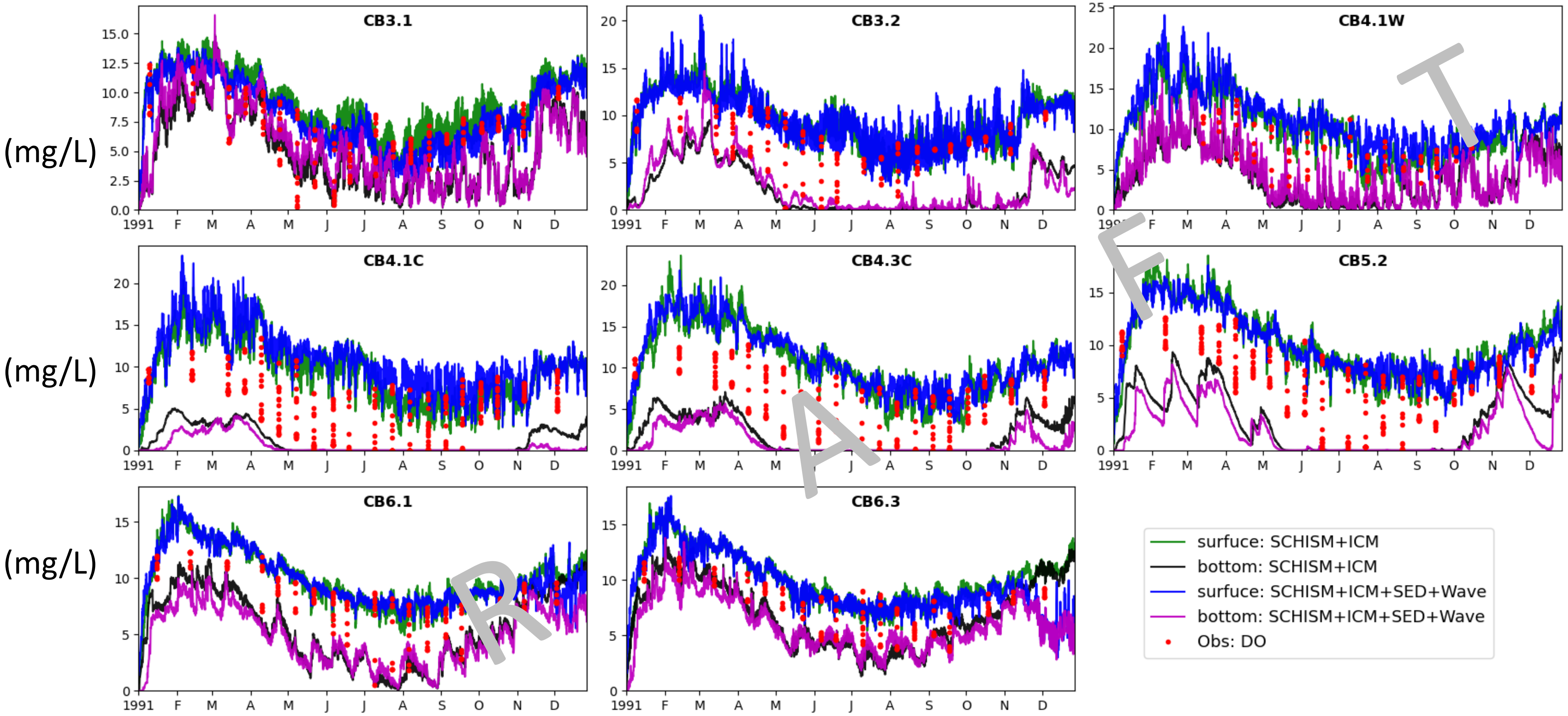
- Both models are qualitatively doing well in upper and lower Bay. In mid bay, TSS from CH3D-ICM seems to overestimate in winter-spring, while TSS from SCHISM underestimates in the summer (Chl-a may also play a role in TSS)
- High-frequency TSS output from our coupled model leads to:
  - more temporal variabilities: diel variation, spring-neap tidal variation, seasonal variation
  - more spatial variabilities for shallow and deep water

First results for validation of new code: CHL-A



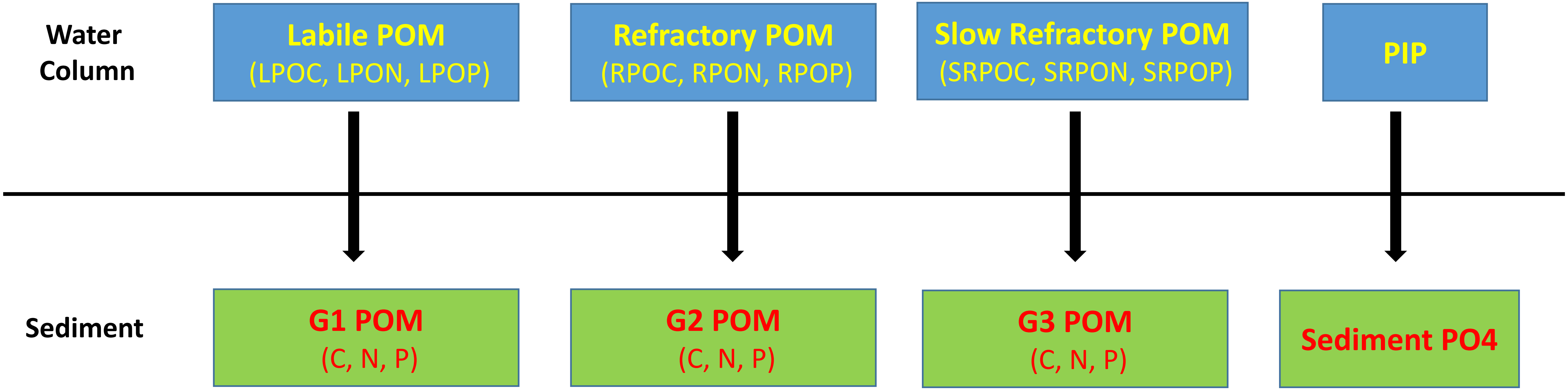
1. The general patterns of simulated CHLA match previous regression results
2. At the upstream stations (e.g. CB3.1, CB3.2), surface CHLA are similar, but bottom CHLA tend to be higher
3. At channel stations (e.g. CB4.1C, CB4.3C), surface CHLA tends to higher (due to improved light condition), but bottom CHLAs are similar

First results for validation of new code: DO



1. The overall patterns of simulated DO match previous regression results
2. In general, the surface DO are similar except at CB3.1, where the surface DO with SED+WWM tend to be lower
3. The bottom DO tend to be higher at shallower stations (e.g. CB3.2, CB6.1), but lower at deep channel stations (e.g. CB4.1C, CB4.3C)
4. Need to recalibrate (next step)

PIP, G1, G2, G3 approach in sediment and water column



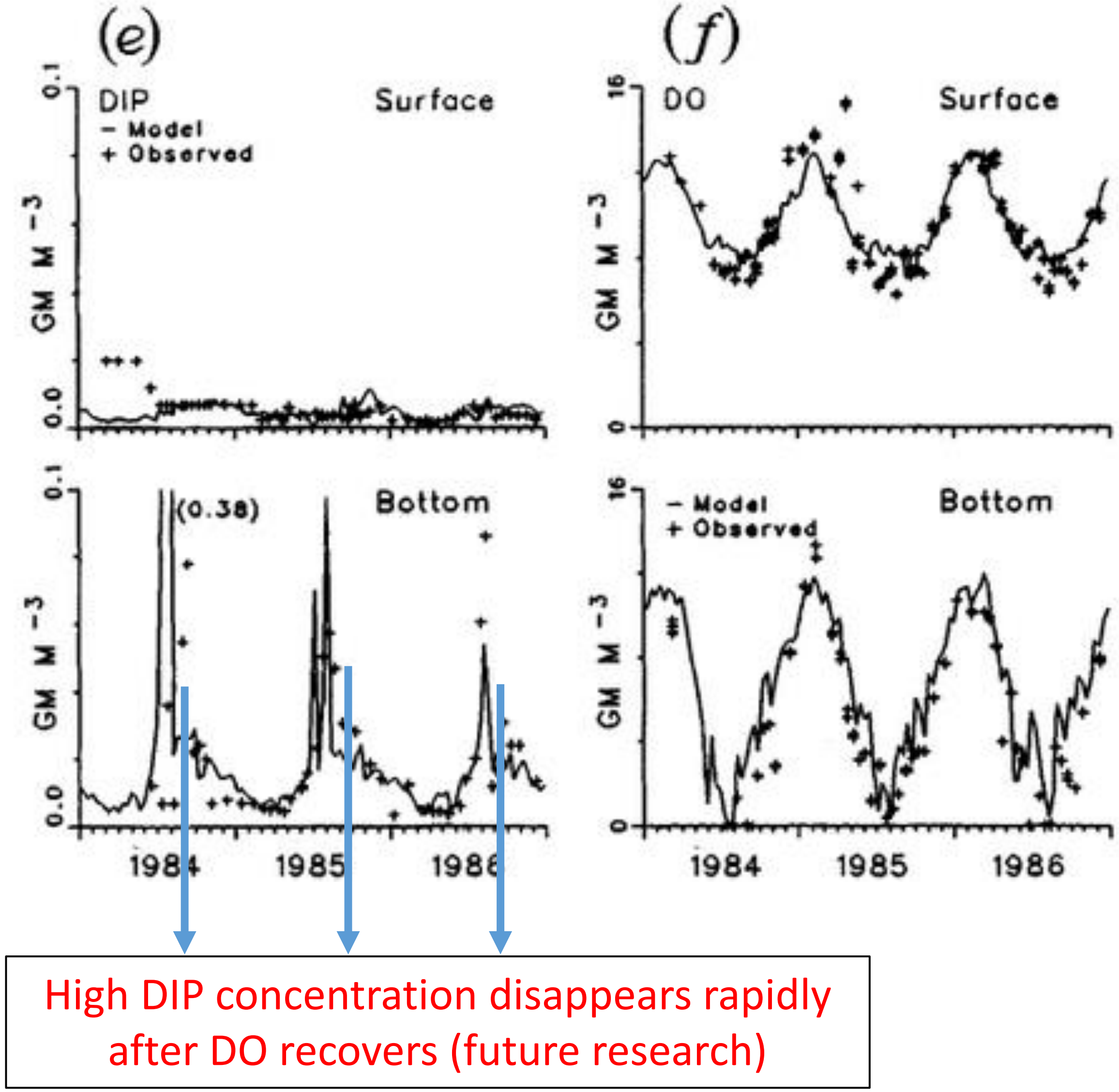
- Sources of slow refractory POM (SRPOC, SRPON, SRPOP) and PIP are from watershed loading (shoreline erosion)

Two forms of PIP's for future study

❖ PIP from shoreline erosion

Suggested method: add them as nutrient sources in the ICM model. They will go through the advection-diffusion process, and settle to the bottom, and enter the sediment PO4 pool

DIP and DO at CB5.2 (from Carl C.)



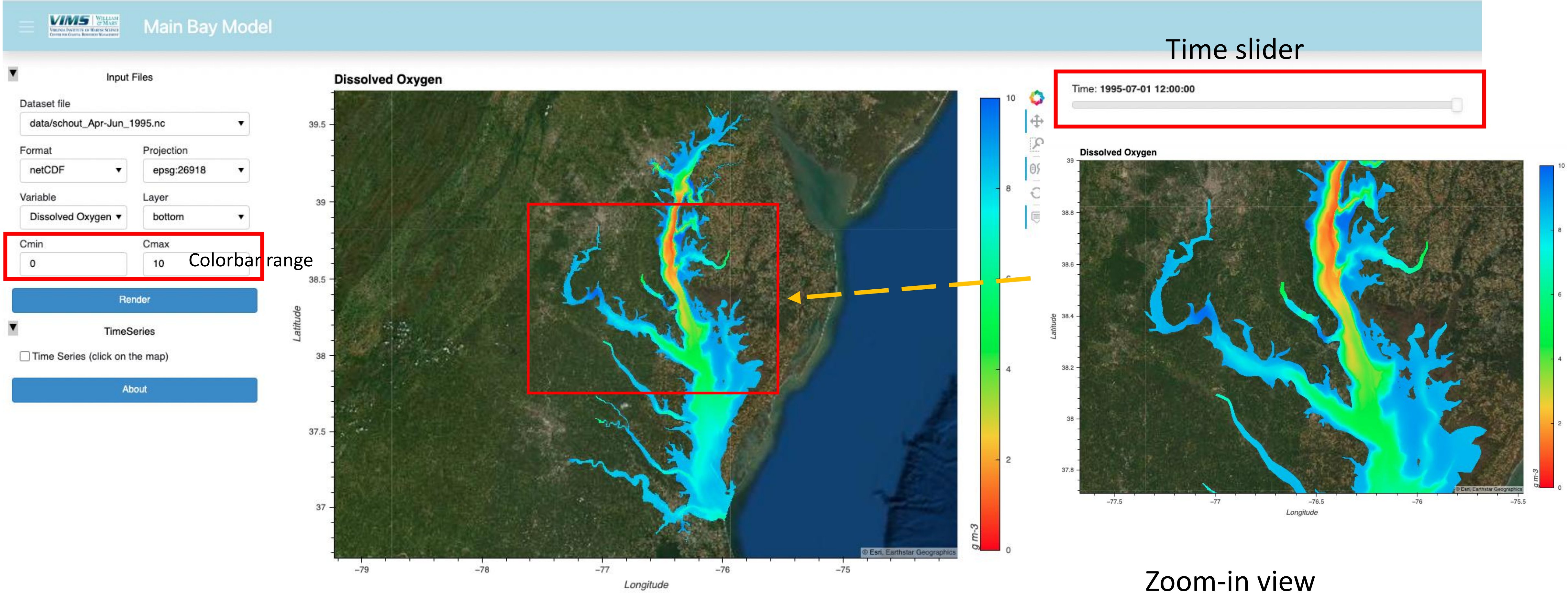
❖ PIP (PO4 sorption) co-precipitation with iron (thanks to Carl's observation)

DIP disappears when bottom-water hypoxia is about to end. We will start with the method of settling PO4 for a brief defined period (keyed to date of year)

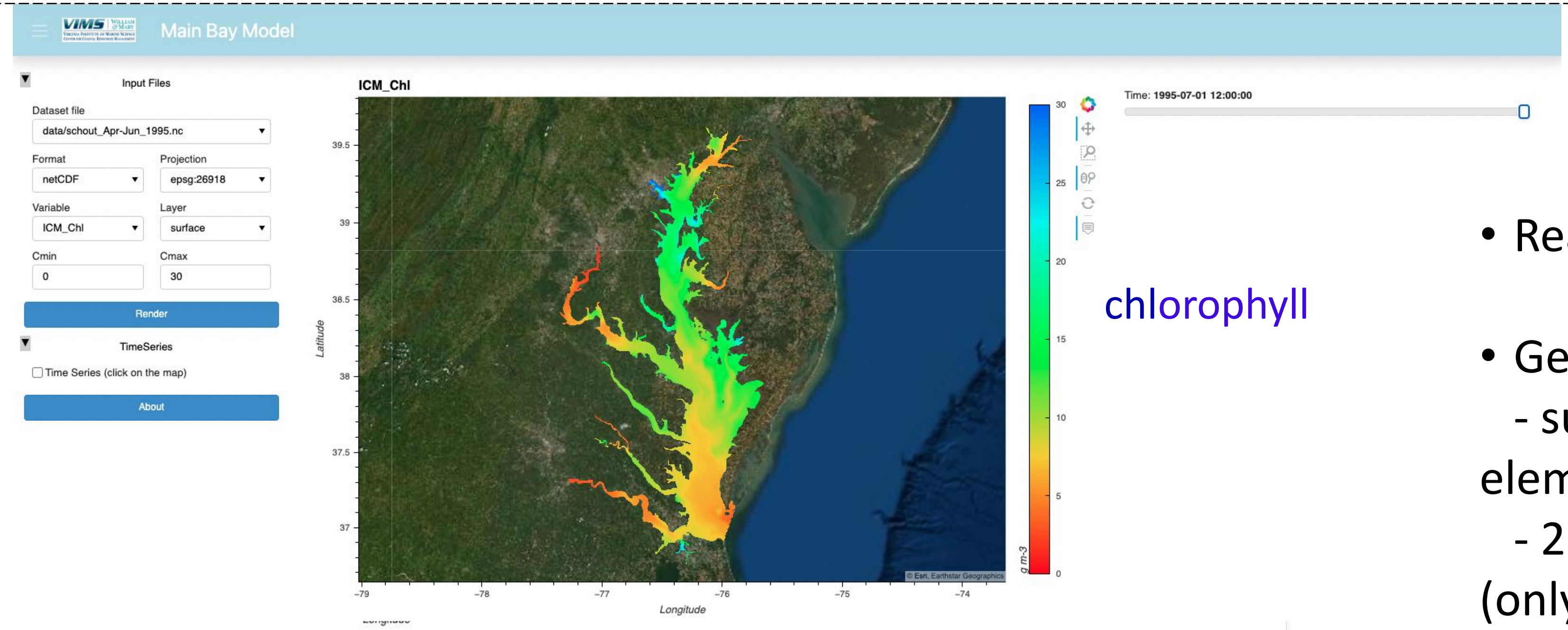
Status update for Task IV

MBM web app

https://meteor.hpc.wm.edu/mainbaymodel

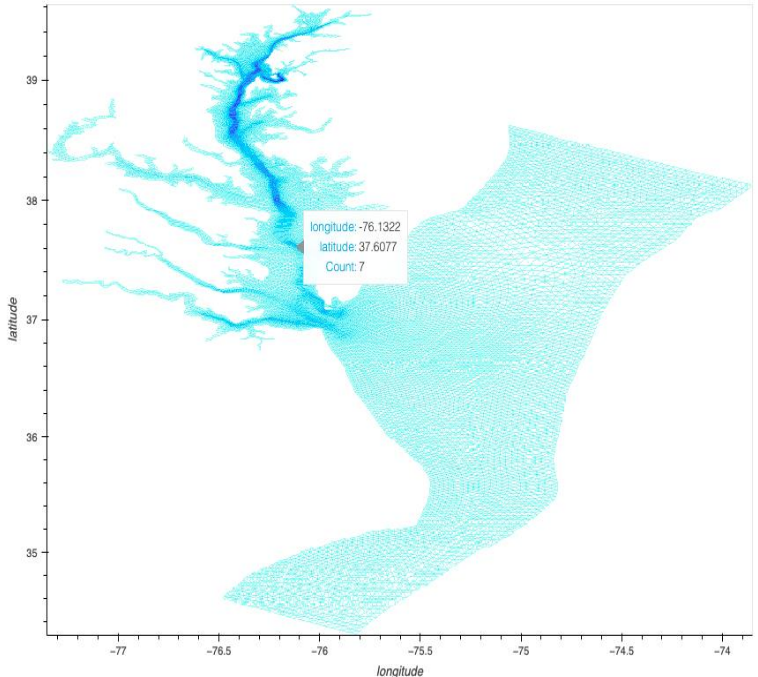


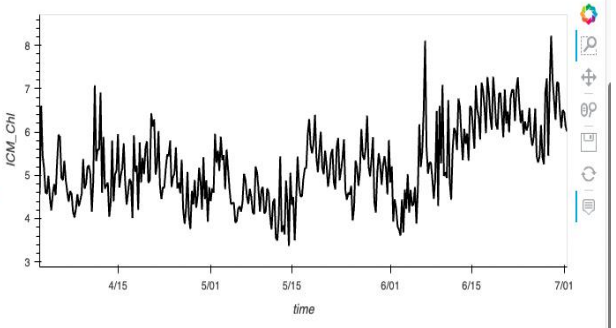
Status update for Task IV



chlorophyll

- Read raw outputs from SCHISM
- Get slab at different layers
  - surface, bottom (for both node- and element-based variables)
  - 2m, 5m, and 10m below the surface (only for node-based vars)
- Dynamically zoomable in the interested areas
- Timeseries at random locations
  - Will add observation stations

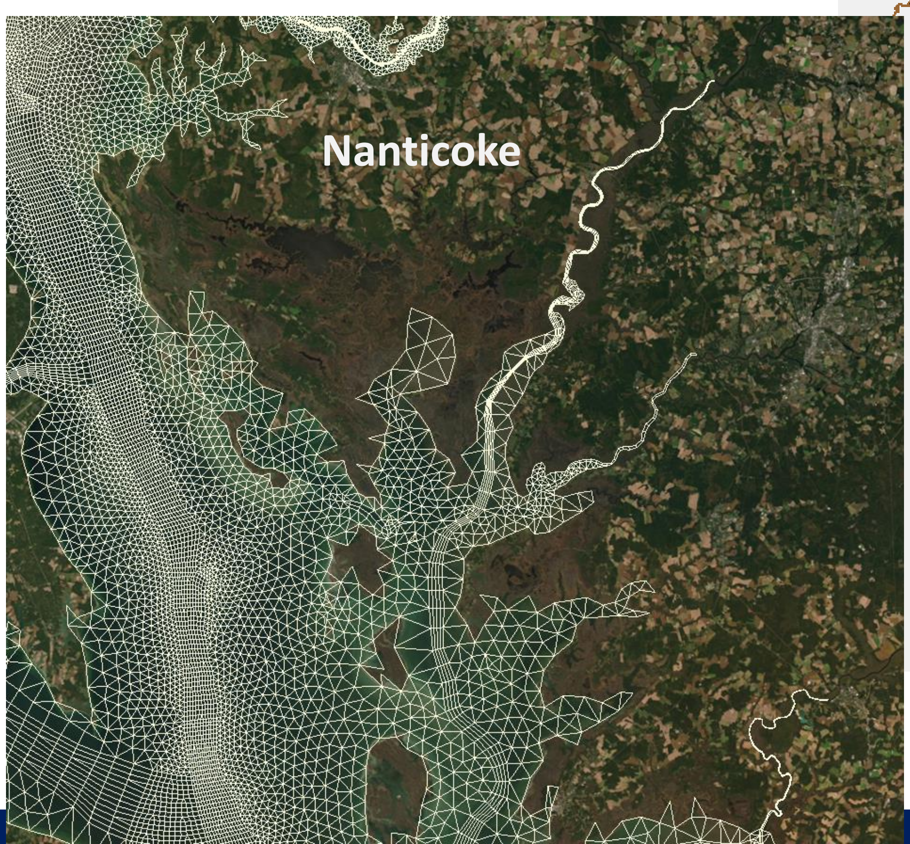


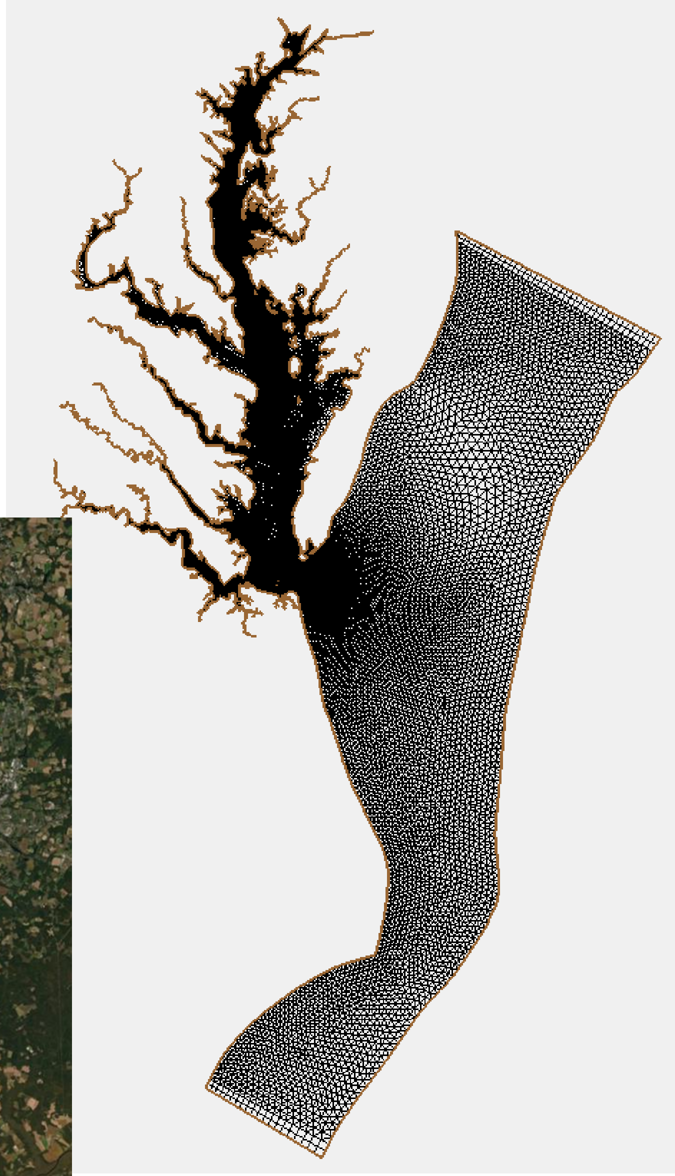


Timeseries

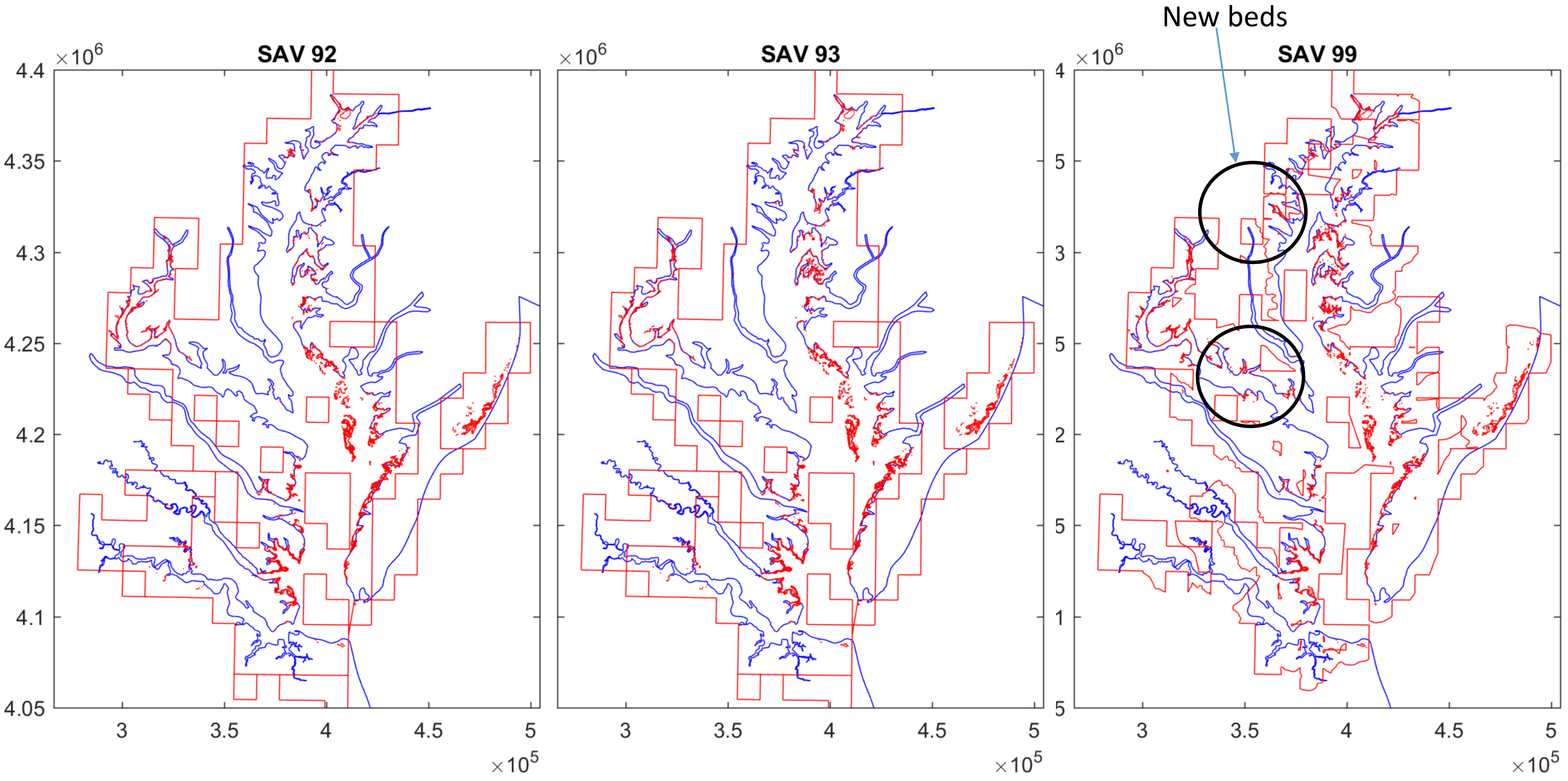
On-going work

- Revision of MBM mesh
    - Fine resolution in tributary channels
    - Shallows for living resources
    - Adjustment of shoreline boundary and eastern shore areas (Andy & Karinna)
- Analysis of shoreline erosion and living resource data from CBPO
- Calibration of the new code
    - Potential adjustment on mesh to account for climate changes
- SCHISM provides maximum flexibility in mesh adjustment





Variation of SAV coverage



SAV simulation options

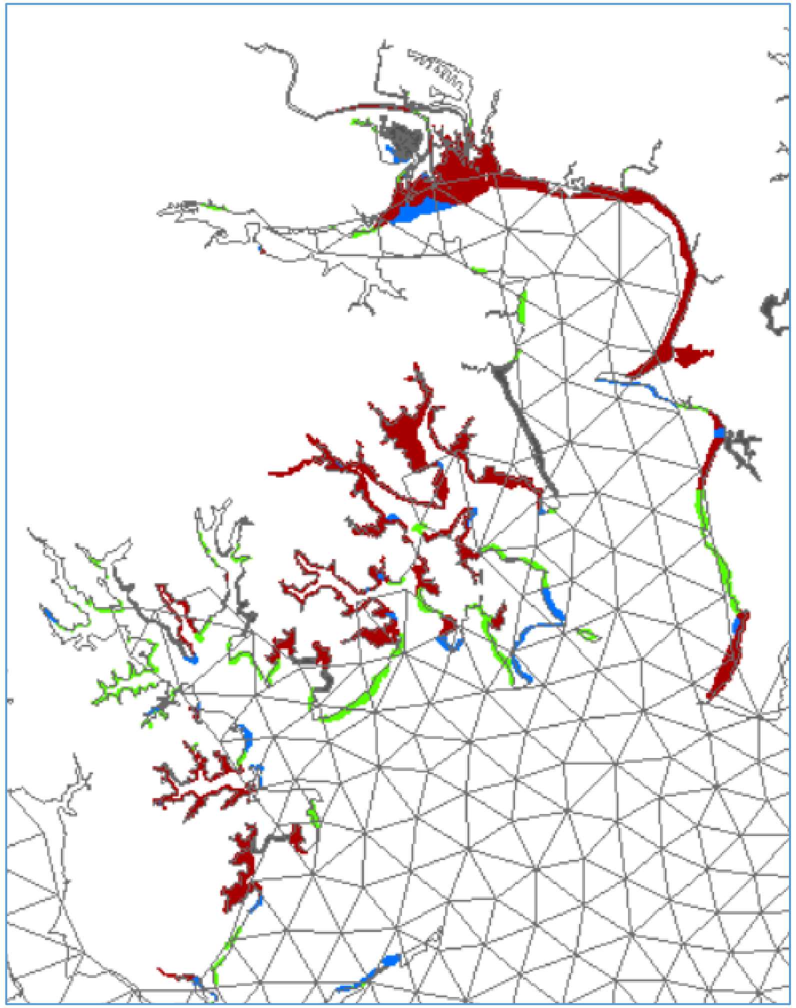
Approach I: for model hindcast

- Determine the SAV seeding area for each grid element and estimate the percentage area for SAV in each grid based on VIMS SAV survey data
- Determine the SAV seeding area for each year and used it as the seeding area for the model inputs
- Re-initialize SAV seeding areas for each year (need to modify model code)
- Apply this approach for hindcast
- May refine the mesh in some SAV areas

Approach II: for climate change simulations?

- Determine cumulative area that has SAV from 1990-2000 (or use available data in all years), i.e. find the 'superset' area that can potentially support SAV
- Seed SAV in this superset area as initial condition
- Simulate SAV growth or loss depending on nutrients and light
- Simulated SAV area will have errors, but the approach is more suitable for climate change simulations

Example of 2010 SAV distribution overlaid on UG



Summary

- We have almost completed the MBM code development and revision based on previous CBP model
  - Removed silica and zooplankton for this project
  - Added slow refectory variables for C, N, P
  - Simulated PIP and DIP directly without using partition
  - Revised algal respiration and predation formulations using CBP version
  - Shallow water capability (with spatially variable inputs)
  - Added benthic algae formulation of CBP version
  - Dynamic coupling with wave, sediment transport and WQ modules
- Regression tests along the way ensured code correctness
- First results with fully coupled SCHISM_WWM_SED_ICM are promising
- We will start calibration process next
  - Revise the mesh based on latest shoreline data and also to account for living resources
  - Need to discuss with CBPO team on some details of watershed loading (shoreline erosion etc)

Thank you!

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)
  - Potential synergy with National Water Model

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

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