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

Task I: Model Implementation, verification

Water quality processes

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SCHISM

Outline

- Main Bay Model (MBM) framework
- Water quality model (ICM) update (details)
  - *Modeling approach follows Cerco and Noel, 2019*
- Existing problems
- Approaches and decisions

MBM framework

SCHISM ICM update

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

ICM model update

Living resources implementation & degree of complexity

Shallow water capability

Climate change implementation

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

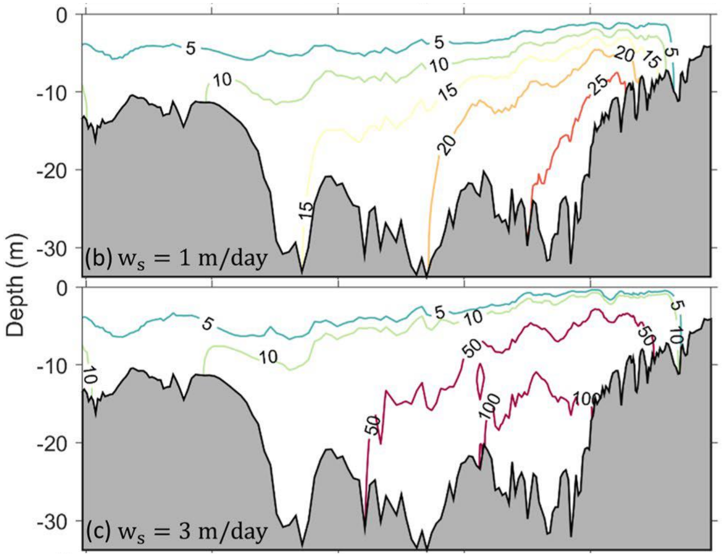
MBM framework: State variables to be simulated

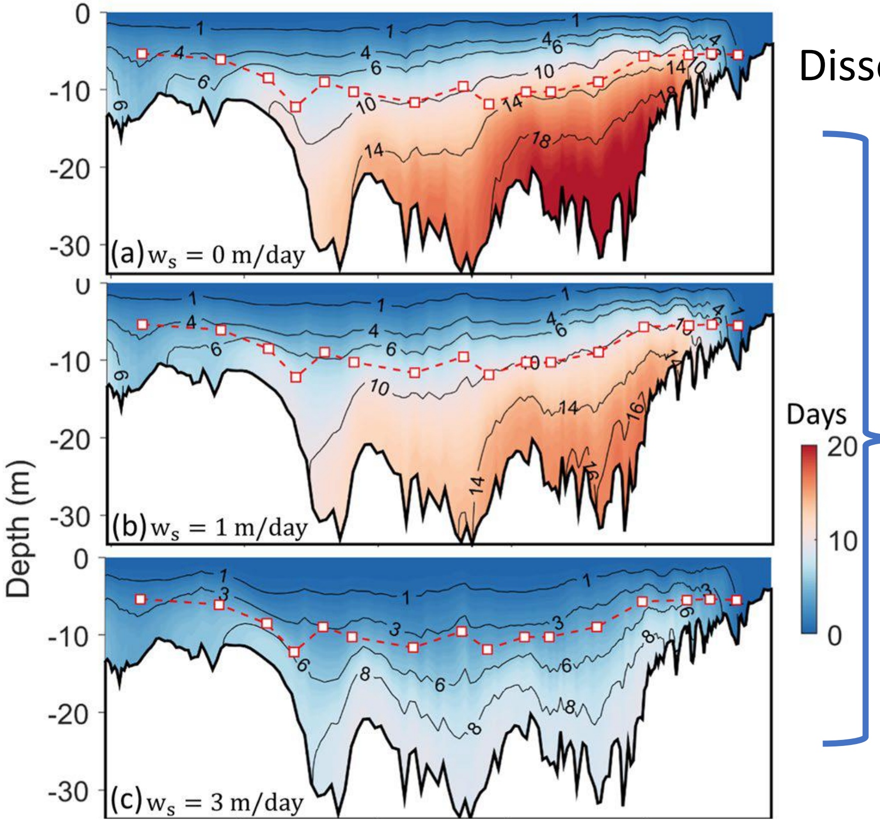
- Algae (three assemblages)
- Carbon (RPC, LPC, DOC)
- Nitrogen (RPN, LPN, DON, NH4, NO23)
- Phosphorus (RPP, LPP, DOP, PO4: partition to dissolved and particulate)
- Silicate (particulate biogenic silica, dissolved silica)
  - P is the primary limiting nutrient in spring. little or no information on loading of particulate biogenic silica. Silicate will not be simulated
- DO
- Do we need to add a slow reactive DOC to account for watershed input
- Simulate PIP directly instead of using partition of total (shoreline erosion/watershed)
- Simulate reactive dissolved DIP
- Add slow refectory variables for C, N, P. Labile, refectory, and show refractory particulates in water are routed directly to G1,G2, and G3 in the sediment.
  - Adding slow refractory particulates is mainly for handling shoreline erosion
  - Adding three state variables that may slow model running time

Particulate Age in water

- Model uses fast settling velocity in water and slow settling (net settling) velocity at the bottom layer to account for resuspension
- Particulates with high settling velocity stay in a short time in the water
- The same approach will be used

With resuspension





Dissolved

Net settling velocity

Xiong and Shen, 2022

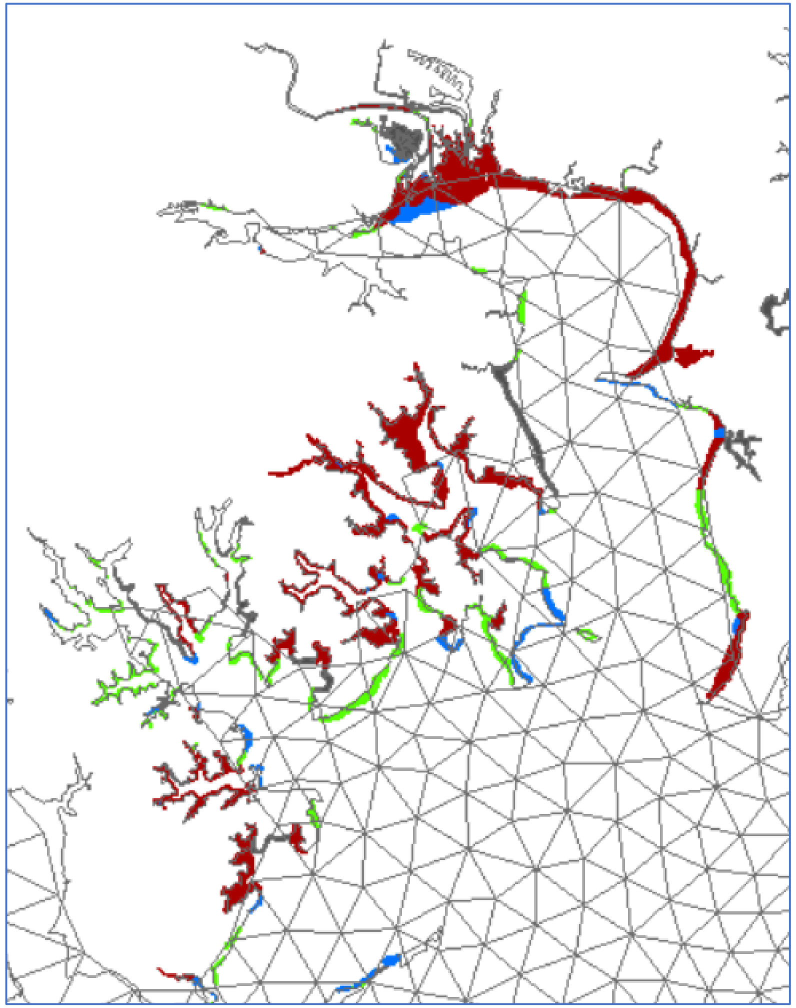
State variables to be simulated

- Current SCHISM model uses particulate organic carbon as a surrogate for particulates (light function, *phosphate sorption*), which is not a sound approach
- If we direct simulate PIP, it is not needed for computing sorption
- Do we need to simulate inorganic sediment (it is important to light)?
  - How many sediment classes to be simulated ? (clay, silt, and sand)
  - Do we need to simulate waves using complex wave model, or use current bay model approach (simplified wave model) to simulate wave?
  - It is more accurate to use complex wave model and it can be important for SAV bed.
  - Current Bay model simulates sediment in ICM. Should we simulate it in a coupled or decoupled mode?
  - There are multiple ways to do it and more considerations are needed.

State variables to be simulated

- *Zooplankton will not be simulated for model calibration*
- *Living resources (oyster, clam etc.)*
  - Filter feeders have a large effect on phytoplankton in shallow water
  - Filter feeders are also considered as implantation in restoration
  - *Do we need to simulate them for MBM calibration*
- SAV
  - Grid size may not match to SAV area
  - Considering determining SAV area for each grid element (fraction)
  - May need to modify model code to account for partial grid element (initialization of mass and mass-height relationship)
  - The impact of SAV on dynamics will be considered (form drag)
  - Using VIMS 1990 data to initialize SAV (estimate areas)
  - How to deal with area change in each year during the calibration period?
    - Using light or other methods ?
  - Input area for each year as re-initialization (area correction)
  - More investigation is needed to find the suitable way to simulate SAV

2010 SAV distribution



State variables to be simulated

- Plan to simulate wetland in a simplified approach same as the current Bay model for MBM

  Removal of nutrients and DO consumption have been observed

  - Nitrogen removal through denitrification
  - Nitrogen removal through burial
  - Phosphorus removal through burial
  - Production and burial of organic solids
  - Burial of organic and inorganic solids
  - Dissolved oxygen (DO) consumption through respiration

Wetland: using removal rates and area to determine nutrient removal

- DO respiration

Net DO uptake is represented in equation 3:

$$V \cdot \frac{dDO}{dT} = Transport + Kinetics - f(DO) \cdot f(T) \cdot WOC \cdot Aw$$

where:

DO	=	DO concentration (g m^{-3})
f(DO)	=	limiting factor: DO/(Kh + DO)
Kh	=	DO concentration at which uptake is halved (g m^{-3})
WOC	=	wetlands oxygen consumption (g m^{-2} d^{-1})

If oxygen consumption is reduced by oxygen availability in the water column, chemical oxygen demand equivalent to the reduction is released from the wetlands so the total respiration, in oxygen equivalents, is constant.

Table 4-2. Summary of Wetlands Process Observations Used in Parameterizing and Validating the Module

CBPS	C Deposition ($g\ m^{-2}\ d^{-1}$)	N Deposition, ($g\ m^{-2}\ d^{-1}$)	P Deposition, ($g\ m^{-2}\ d^{-1}$)	Denitrification ($g\ N\ m^{-2}\ d^{-1}$)	Solids Deposition ($g\ m^{-2}\ d^{-1}$)	Respiration ($g\ DO\ m^{-2}\ d^{-1}$)
BSHOH		0.008 to 0.032	0.001 to 0.006			
CHOMH		0.053 to 0.074	4.9 e-4 to 0.005			
CHSMH		0.02 to 0.064	0.01 to 0.019		3.6	
FSBMH	0.39 to 0.82				0.3	
MPNOH	0.42 to 0.93	0.034 to 0.082	0.006 to 0.026		2.8 to 14.2	
NANMH	0.22 to 0.43				1.61 to 8.12	
NANOH	0.22 to 0.43				1.61 to 8.12	
PAXOH		0.037	0.006		3.8	
PAXTF		0.037 to 0.064	0.006 to 0.01	0.054 to 0.098	3.8	
PMKOH	1.42	0.05		0.023		1.12 to 2.77
POTTF	1.27			0.043 to 0.06	6.35	
WICMH	0.22 to 0.43	0.037	2.74 e-5 to 0.004		1.61 to 8.12	

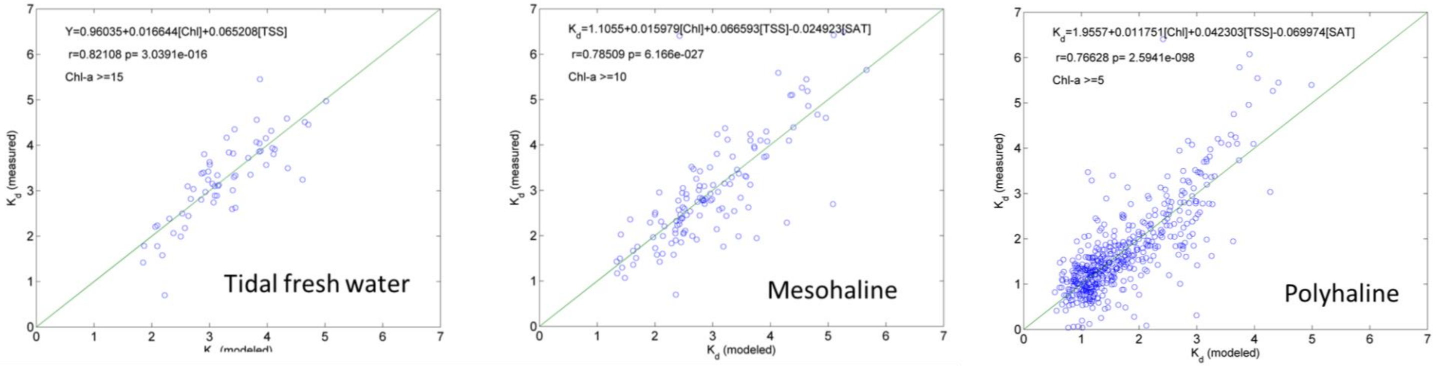
Notes: C = carbon; CBPS = Chesapeake Bay Program Segment; $g\ m^{-2}\ d^{-1}$ = grams per square meter per day; N = nitrogen; P = phosphorus.

Cerco & Noel, 2019

Water quality model (ICM) update

- Testa et al. (2013) revised the denitrification formulation in the original diagenesis model. This will be implemented to SCHISM-ICM
- Light function
  - Using hourly light input (better for simulating diel DO and algal variation)
    - Do we have hourly data from 1990-2000 period (NCEP)
  - SCHISM uses empirical functions to compute light attenuation (solid/POC, algae, CDOM (salinity), background)
  - Bay model uses an empirical equation to compute light attenuation coefficient Ke

    Ke= background +a2 TSS + a3 SALT
  - Using variable background value
  - Do we need to use different functions for different regions (shallow water) besides of background value?



Algal is excluded in the TSS

Water quality model (ICM) update

- Algal respiration

$$R = Presp \times G + BM \times e^{KTb \times (T - Tr)}$$

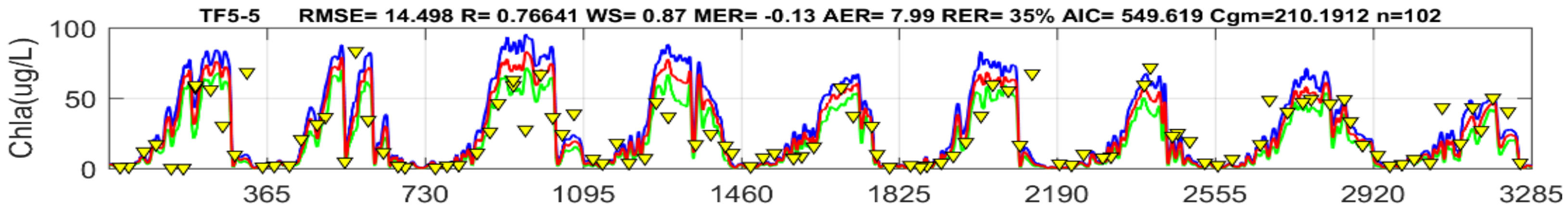
where:

$$Presp = \text{photorespiration } (0 \le Presp \le 1)$$
$$BM = \text{metabolic rate at reference temperature Tr } (d^{-1})$$
$$KTb = \text{effect of temperature on metabolism } (^{o}C^{-1})$$
$$Tr = \text{reference temperature for metabolism } (^{o}C)$$

- Algal removal term (suggest to add)
  - Increase due to algal aggregation when concentration is high, but predation is low.
  - ROMS model has this term
  - It works well for HABs

$Mag = \tau M^2$

James



Water quality model (ICM) update

- Algal Predation

$$PR = F \times B \times M \qquad (12)$$

where: B = algal biomass, expressed as carbon

F = filtration rate ($m^3\ g^{-1}$ predator C d^{-1})

M = planktivore biomass (g C m^{-3})

Detailed specification of the spatial and temporal distribution of the predator population is impossible. One approach is to assume predator biomass is proportional to algal biomass, M = γ B, in which case equation 12 can be rewritten as equation 13:

$$PR = \gamma \times F \times B^2 \qquad (13)$$

- Nutrient limitation
  - Current model structure for checking nutrient limitation has a problem when nutrient is limiting, which can cause mass unbalance (especially in shallow water with high algal biomass)
  - Modify to check nutrient availability for three algal assemblage and its distribution to each algal assemblage.

Water quality model (ICM) update

- Carbon to Chl a ratio
  - Using fixed ratios for different species and different regions
  - Using varying ratios (Cerco and Noel, 2004)

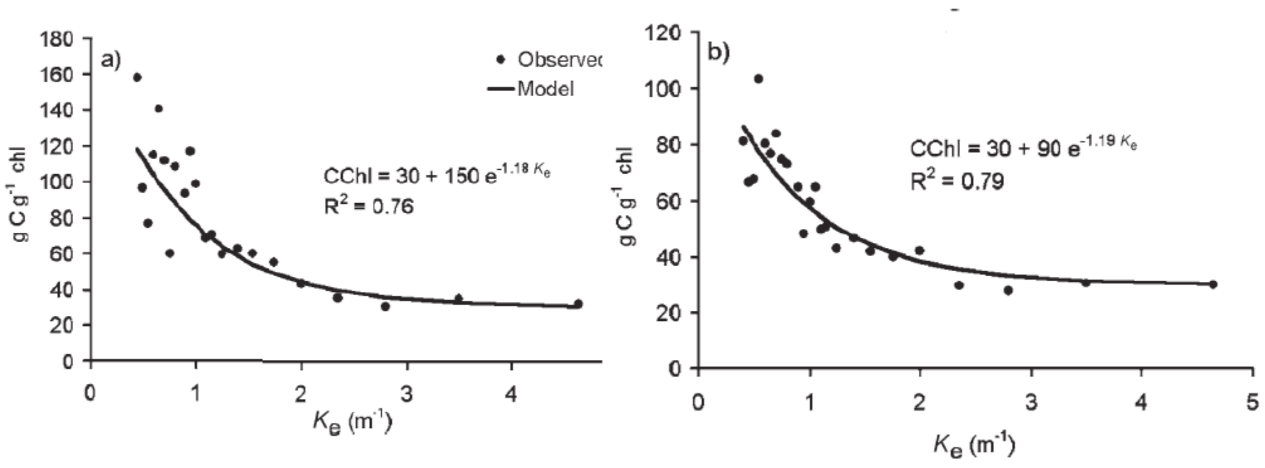


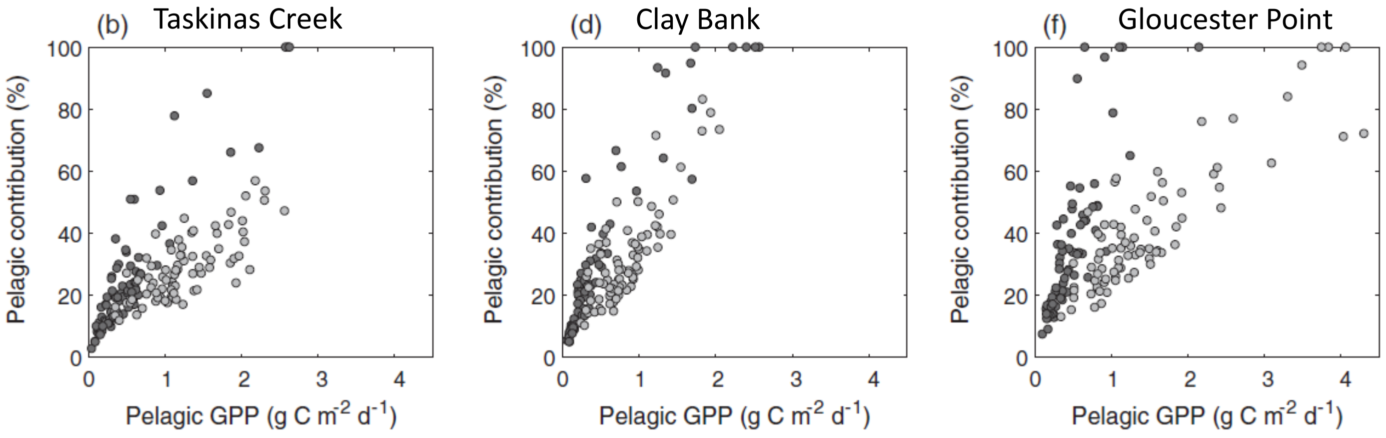
Figure 3-1-3: Observed and modeled carbon to chlorophyll rations (CChl) versus light attenuation for (a) spring and (b) winter group (Cerco and Noel, 2004).

When applied in the James River, model skill was improved (Shen and Qin, 2019)

Shallow water capability

- Diel DO variation
- High benthos contribution to both nutrient recycle and low DO
- Benthic microalgae and macroalgae
- Shallow water has limited contribution to MBM DO
- It will be used for tributary models

York River



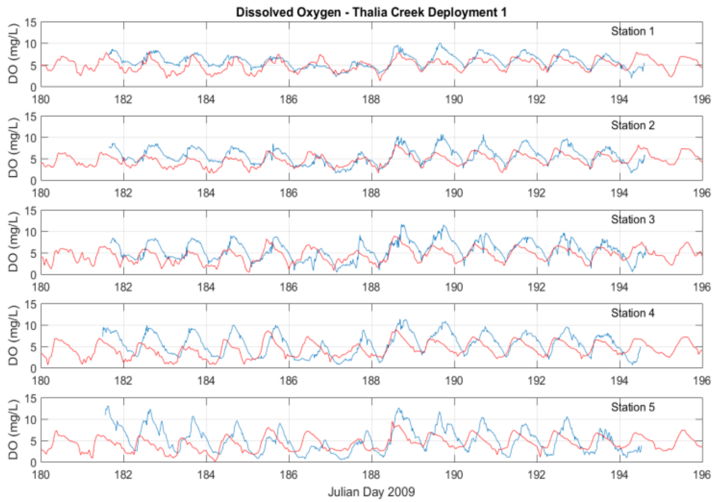
Qin and Shen, 2019 L&O

Lynnhaven River

Table 3.3. Mean of gross primary production and respiration by station in September 2018

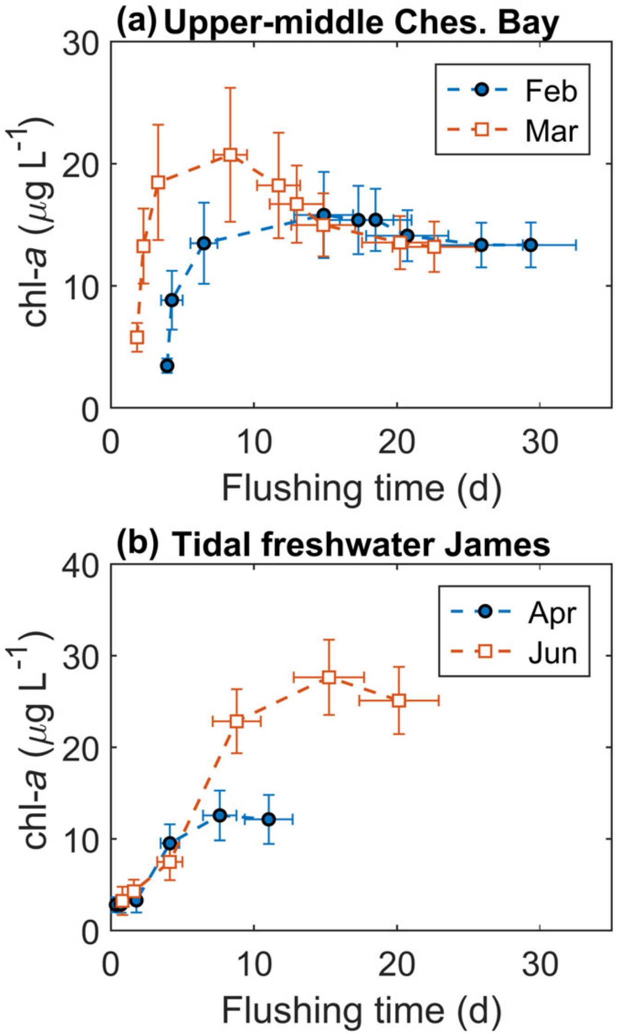
Station	Ecosystem GPP g O_2 m^{-2} d^{-1}	Ecosystem GPP g C m^{-2} d^{-1}	Pelagic GPP g C m^{-2} d^{-1}	Pelagic contribution	Respiration g O_2 m^{-2} d^{-1}	N
Buch. 1	8.406	3.152	0.439	13.7%	11.369	
Buch. 2	8.662	3.248	0.563	20.8%	13.276	
Buch. 3	10.281	3.855	0.598	28.3%	15.736	
Boundary	12.151	4.557	0.806	17.3%	12.826	
Thalia	4.387	1.876	0.531	37.1%	8.313	
Wolfsnare	18.362	6.886	1.042	14.9%	24.073	

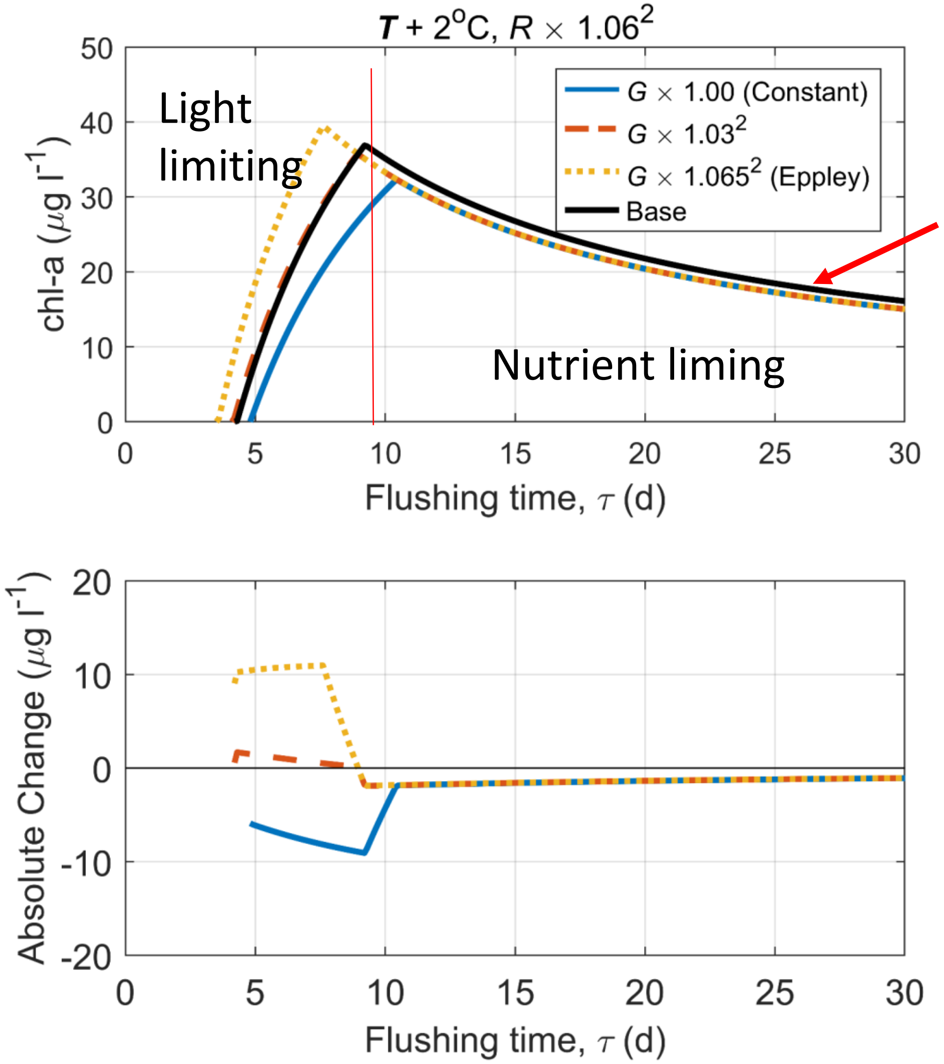
Friedrichs et al., 2019 VIMS report



Model simulation with benthic algae

Climate Change Consideration

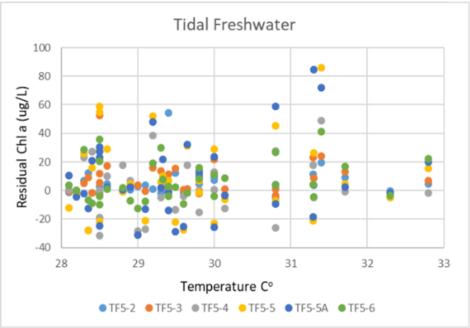


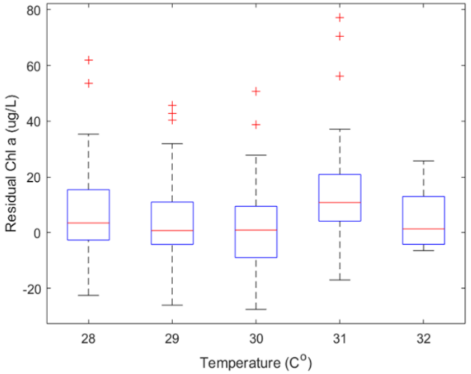


Temperature effect will be reduced under nutrient limitation condition

Qin & Shen, 2021 L&O

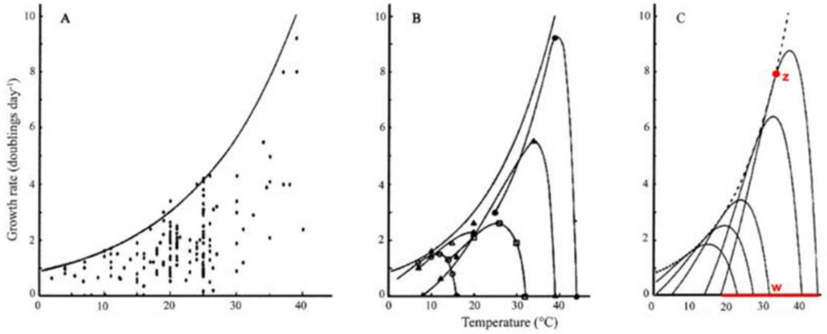
Climate Change Consideration

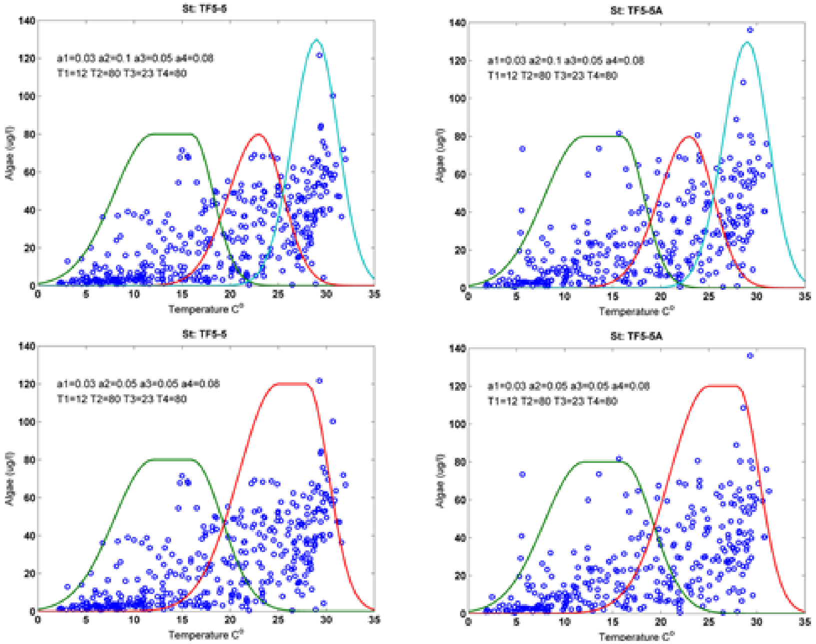




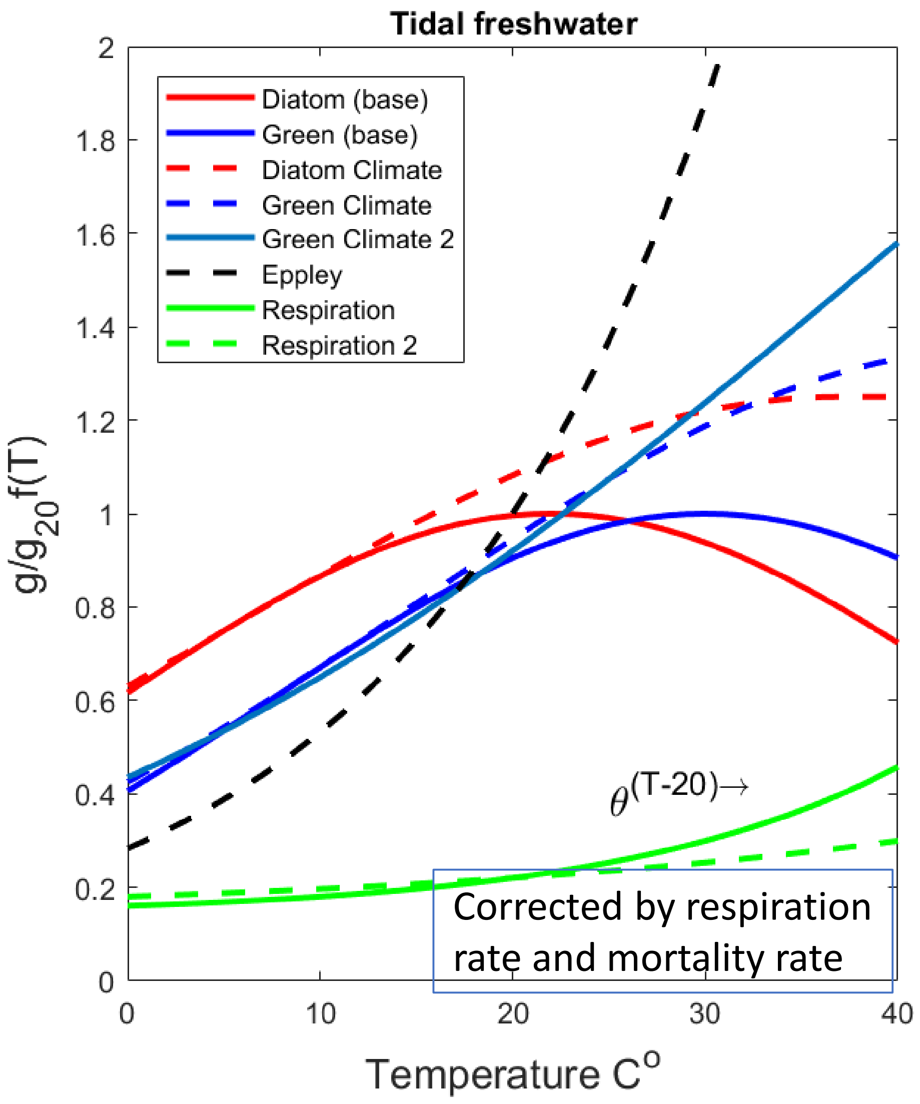
Chl a distribution against temperature after removing influence of flow and nutrient

Eppley (1966, 1972)





Temperature Effect on Growth and Respiration



Testing cases

- Reduced respiration
- Revised curve for diatoms
- Use 2 curves for summer green algae
- Use Eppley curve
- Change grazing

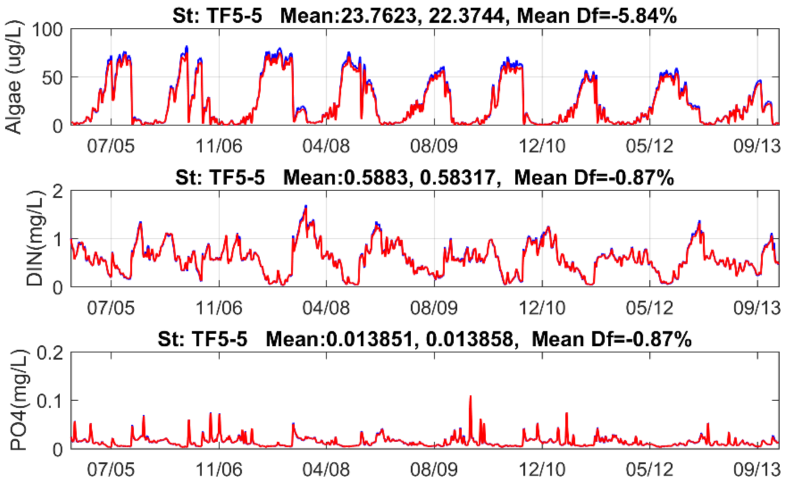
Respiration rate changes faster than growth rate when temperature increases.

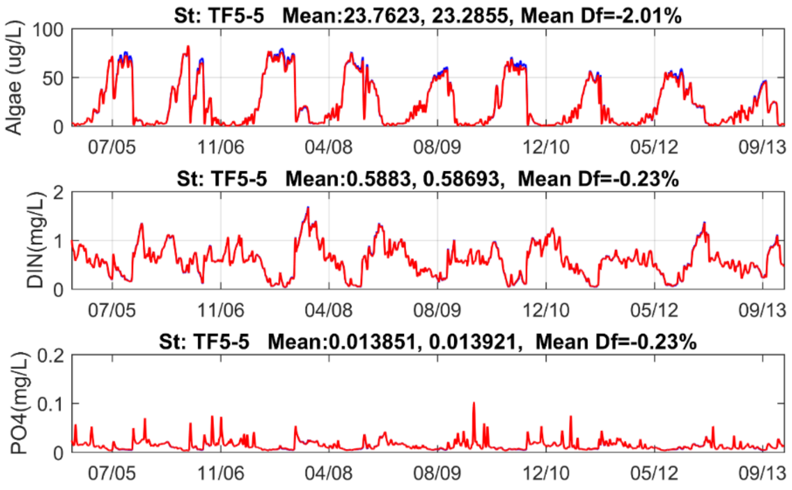
The temperature increase in summer due to climate change ranges from 1-2 °C , and the growth rate does not increase fast enough so that Chl-a could decrease.

If a high growth rate is used, the model calibration is not satisfactory in the James River

Climate Change Consideration

- Use Eppley function (without temperature inhibition)
  - Directly using Eppley curve does not work for the James River (over prediction of algal concentration)
  - Using high temperate related curve does not affect the model (when nutrient and light are limiting)
  - Model can over-predict Chl-a when grazing pressure is low (may increase model prediction by adding aggregation settling)
  - Change of dynamics and volume of water have larger effect than temperature.





Climate Change Consideration

- We don't need to change code, but use different parameters for model calibration (without/reduce temperature inhibition)

Table 1
Revised Algal Parameters for Climate-Change Scenarios

Parameter	Definition	Group 1 Calibration	Group 1 Climate Change	Group 3 Calibration	Group 3 Climate Change
KTg1	effect of temperature below Topt on algal production ($^oC^{-2}$)	0.005	0.0022	0.0035	0.0013
KTg2	effect of temperature above Topt on algal production ($^oC^{-2}$)	0.004	0	0	0
Pm^B	maximum photosynthetic rate (g C g^{-1} Chl d^{-1})	200	250	450	600
Topt	optimal temperature for algal production (^oC)	29	37	25	37

Courtesy of Cerco

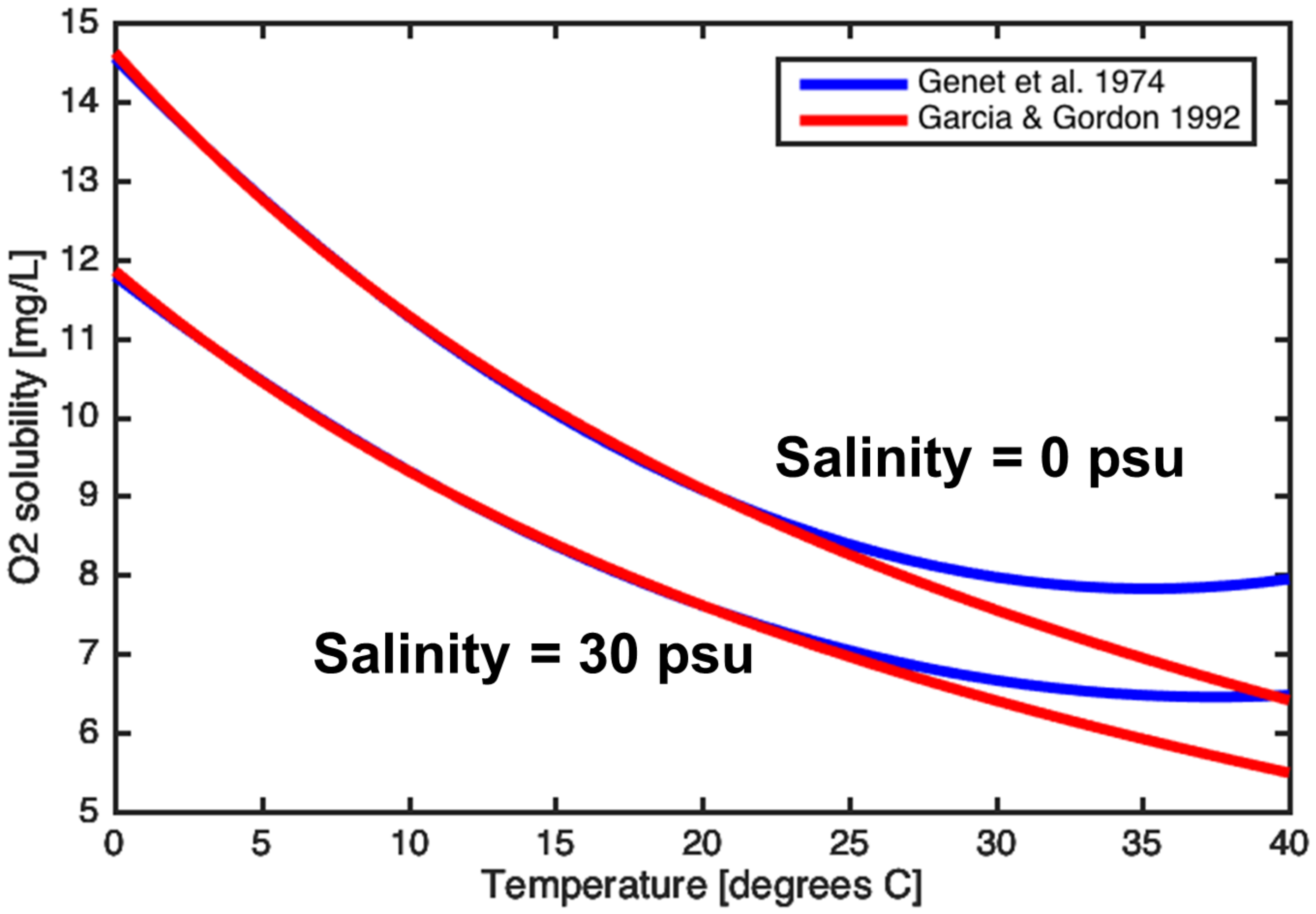
Climate Change Consideration

- It is unclear if removal rates of DO and nutrients are same
- Some publications show that fluxes of DOC, DIN, and DIP vary with watershed. DOC, DIN, and DIP fluxes from wetlands can increase under sea level rise (SLR)
- As SLR, tidal range will change and marshes and wetlands can experience changes (Cai et. under review)
- Cai et al. (2021) shows primary production will increase in shallow areas when SLR. It is important to determine a boundary region along the shoreline to be inundated.

Climate Change Consideration

It is noted that there are discrepancy to compute DO saturation based on Different curve.

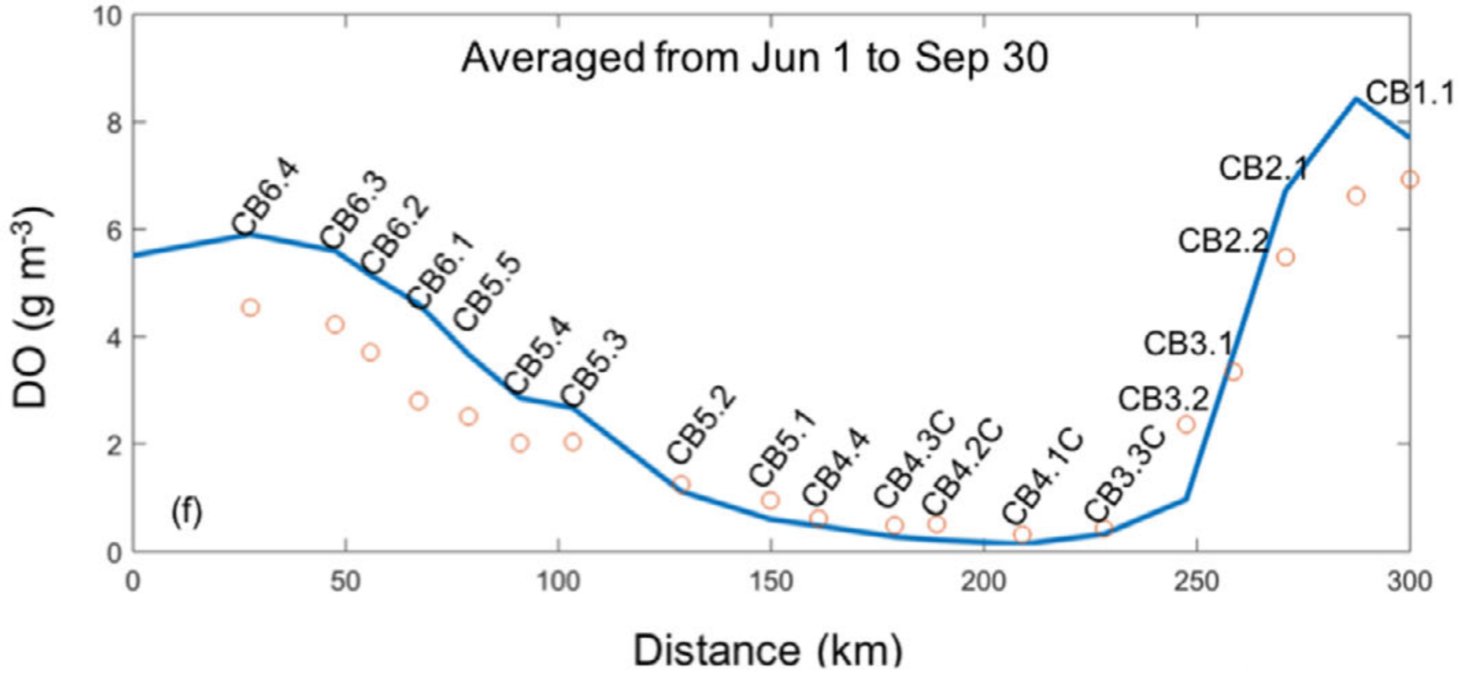
It is more reasonable to use Garcia & Gordon 1992 curve



Courtesy of Marjy

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

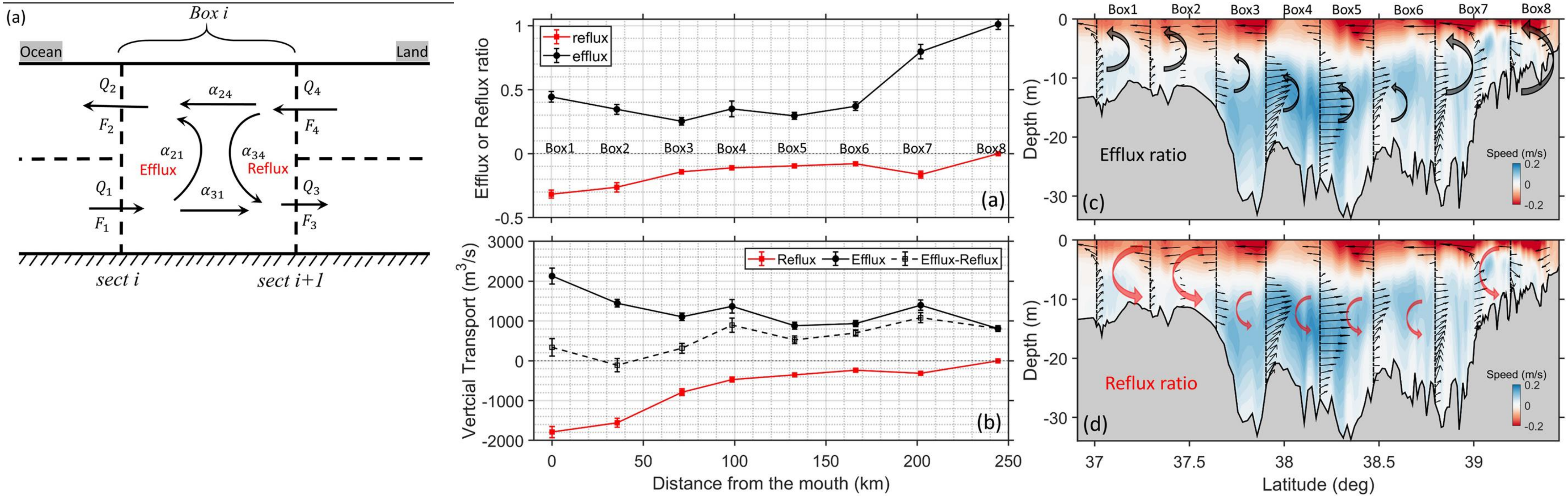
- DO simulation
  - DO simulation is good in general in the middle to upper Bay
  - It is difficult to simulate DO accurately in the lower Bay
  - Extension of low DO area to the upper lower Bay is important



- Under prediction of primary production
- Due to dynamics in the lower Bay

Cai et al., 2020

Different dynamics in Chesapeake Bay

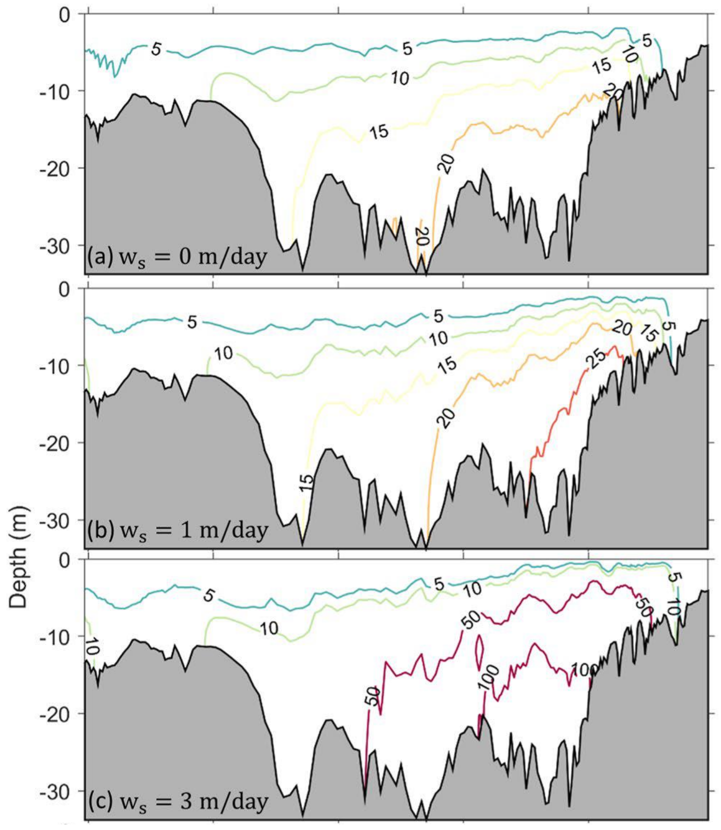


Xiong et al., 2021 JGR

Particulate Vertical Age

- High resuspension in the lower Bay suggests that resuspension of bottom sediment may improve the DO simulation in the lower Bay
- Should we consider it in the new model?
- Aerobic layer can quickly reach equilibrium
- Resuspension from anaerobic layer is possible

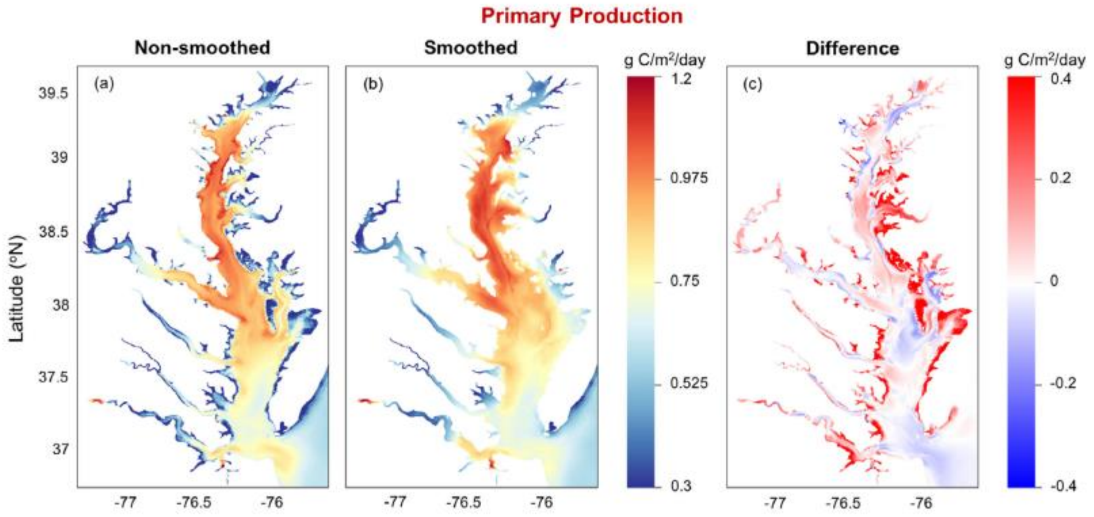
With resuspension



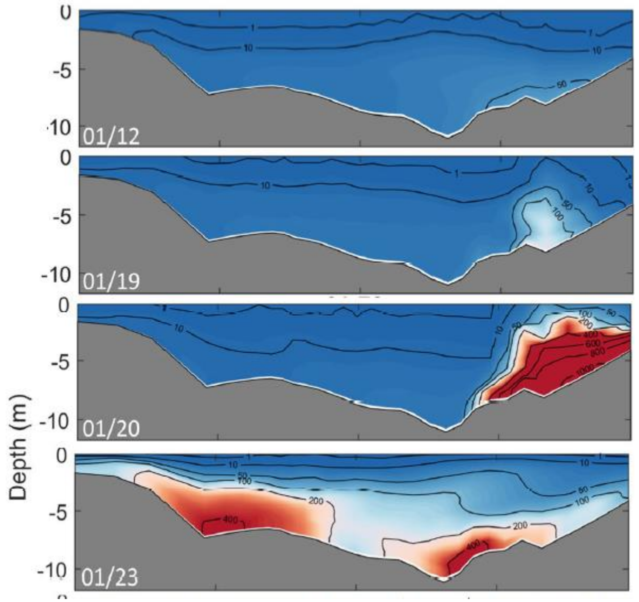
Xiong and Shen, 2022 JGR

Shallow water production and lateral circulation

- The SCHIM has a better representation of shallow water. The high product in shallow water can be better simulated. The deposited POC in the sediment can be suspended during high flow/wind conditions.



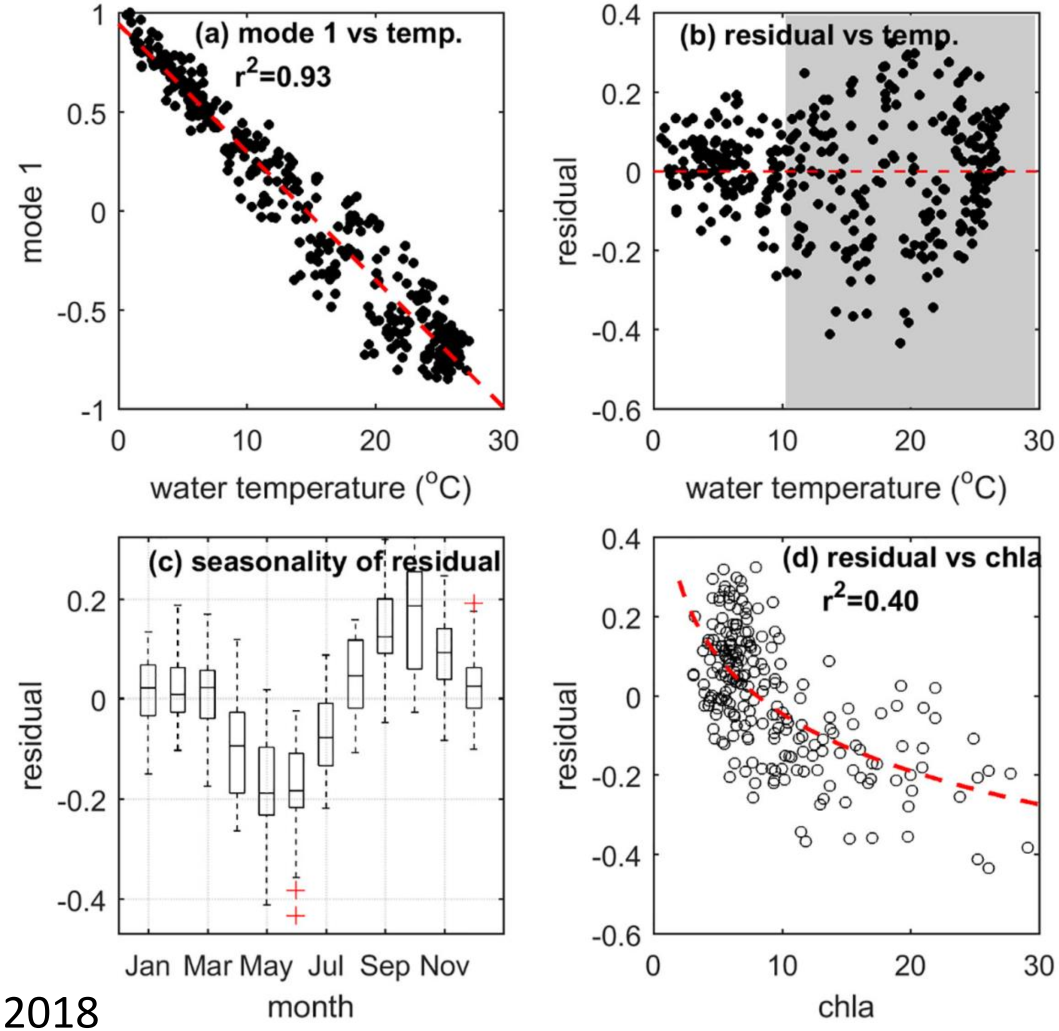
Cai et al., 2021



Xiong & Shen 2022

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

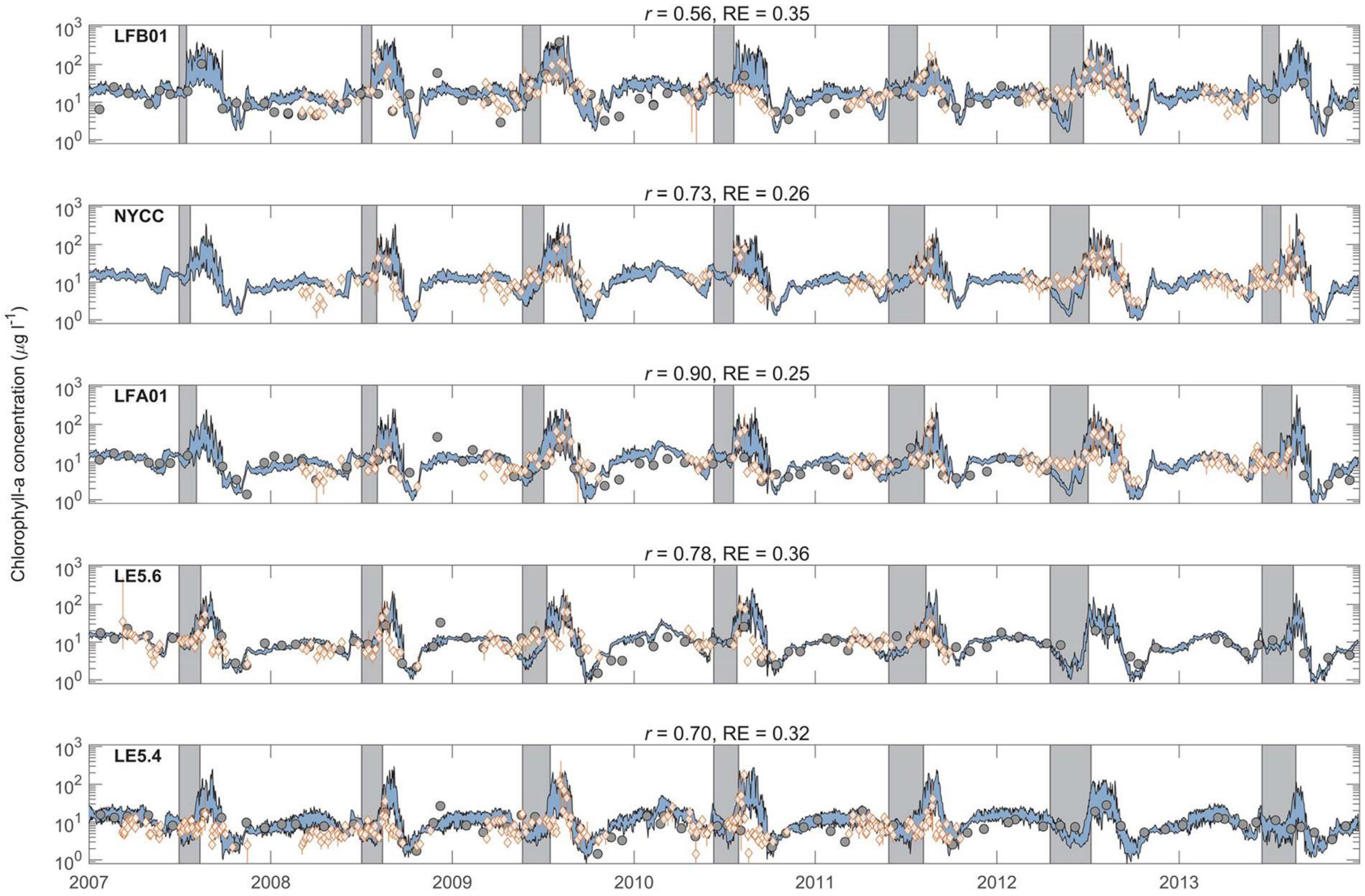
- Algal simulation
  - Algal concentration is highly related to DO
  - There are harmful algal blooms (HABs) in the lower Bay from June-August
  - HAB species has capability to swim upward and downward, can use organic matter
  - HABs were observed less frequently before 2000
  - Blue-green algae are also capable of vertical migration by regulating their buoyancy
  - High algal concentration is difficult to be simulated without including HABs



Du et al., 2018

Phytoplankton Simulation including algal behavior

- Peak bloom can not be correctly simulated without including algal behaviors



Qin et al., 2021. Harmful algae

Approaches and Decisions (Discussion)

- State variables
  - Should we add slow refectory variables for C, N, P ?   Yes (Carl's recommendation)
  - Should we simulate PIP and DIP directly without using partition? Yes (Car's recommendation)
  - How to simulate suspended sediment and wave (Need more discussion as how to do it efficiently)
  - MBM will not simulate silica and zoonplankton   Yes (Carl's recommendation)
- Modules
  - Benthic algae: should they be included in MBM?
  - SAV: Using area as a sub-grid feature; how to account for changing SAV location and area size during simulation period?
  - Wetland/marsh: simplified approach
  - Oyster or clam: should they be included in MBM?
- Boundary of inundation and wetland
  - How to determine boundary along the shoreline to account for inundation and wetland
  - We need to determine it before updating model grid
- Improvement consideration
  - Should we consider re-suspension in the lower bay?
  - Should we consider including algal behaviors in the model?

Simulation steps

1. Hydro step: fully coupled SCHISM-WWM-SED-VEG
   - Schematized representation of wetland, SAV to control mesh size (mesh resolution can be high locally)
   - Full and self-consistent physics!
   - The most expensive component is the wave module (WWM), but we expect the fully coupled model to run ~5SYPD even on high resolution
   - This step is done occasionally
   - Save outputs for Step 2: TSS, T,S and other forcing variables (e.g. light etc)
2. ICM (alone) step
   - Read in the saved outputs from Step 1
   - Solve for all WQ state variables, plus (optional) living resources, wetland
   - Aim for performance (~10SYPD) for massive number of simulations