Cross-scale modeling from creek to ocean: implications for Delaware Inland Bays

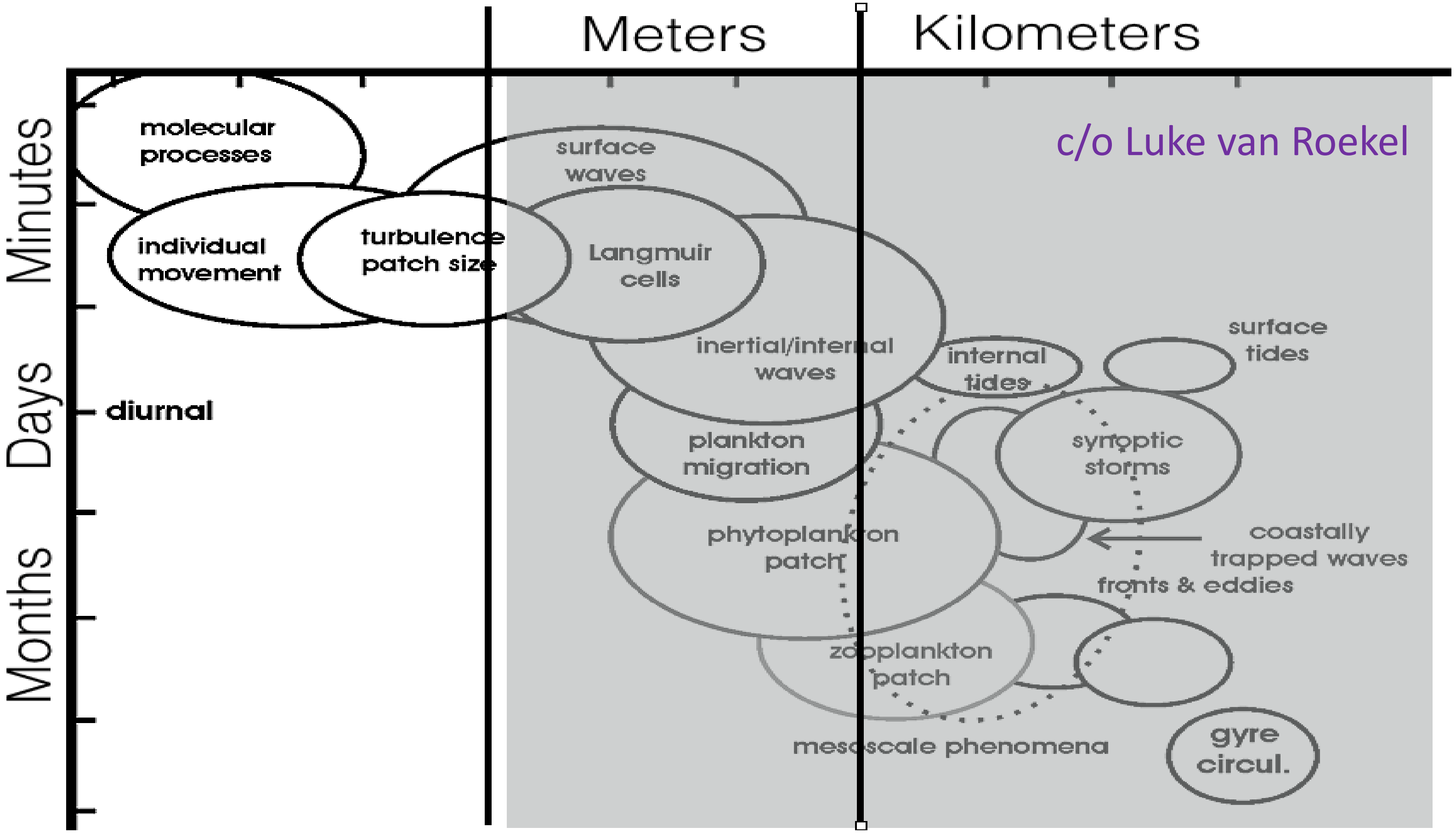
Joseph Zhang*, Harry Wang, Jian Shen, Nicole Cai, Fei Ye, Zhengui Wang, Karinna Nunez, Zhuo Liu

Virginia Institute of Marine Science

Overview of the talk

- Motivation
- Seamless cross-scale modeling with SCHISM: an overview of enabling technology and capabilities
- Recent work on Chesapeake Bay, San Francisco Bay & Delta and other estuaries (including vegetation effects)
- Conclusions
- Recommendations for DE Inland Bays (DIB)

Motivation: estuarine and oceanic processes are inherently multi-scale….



- There is growing interest in understanding the interaction between multiple scales
- However, simulating multi-scale processes remains a significant challenges
- New generation of unstructured-grid models can help

For Chesapeake Bay, examples of muti-scale processes include:

1. Physical and geological processes: storm surge and inundation; shallow water and riparian dynamics; estuary-coast exchange
2. Biological processes: effects of SAV, HAB, and wetland on water quality (e.g. 'triblet'-Bay interaction)
3. Chemical and sedimentary processes: the effect of loading from fluvial river on Bay dynamics

Nomenclature

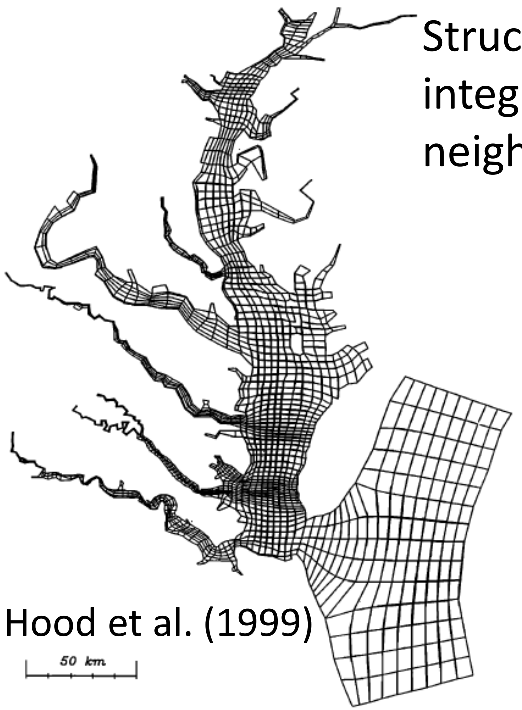
schism

[siz-uh m, skiz-]

noun

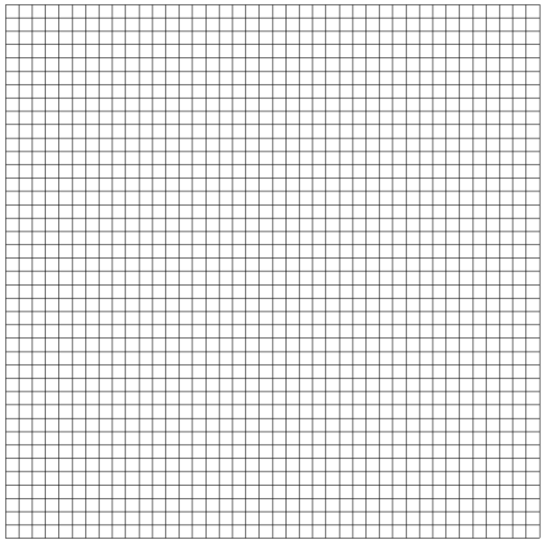
1. the division of a group into opposing factions
2. the factions so formed
3. division within or separation from an established Church, esp the Roman Catholic Church, not necessarily involving differences in doctrine

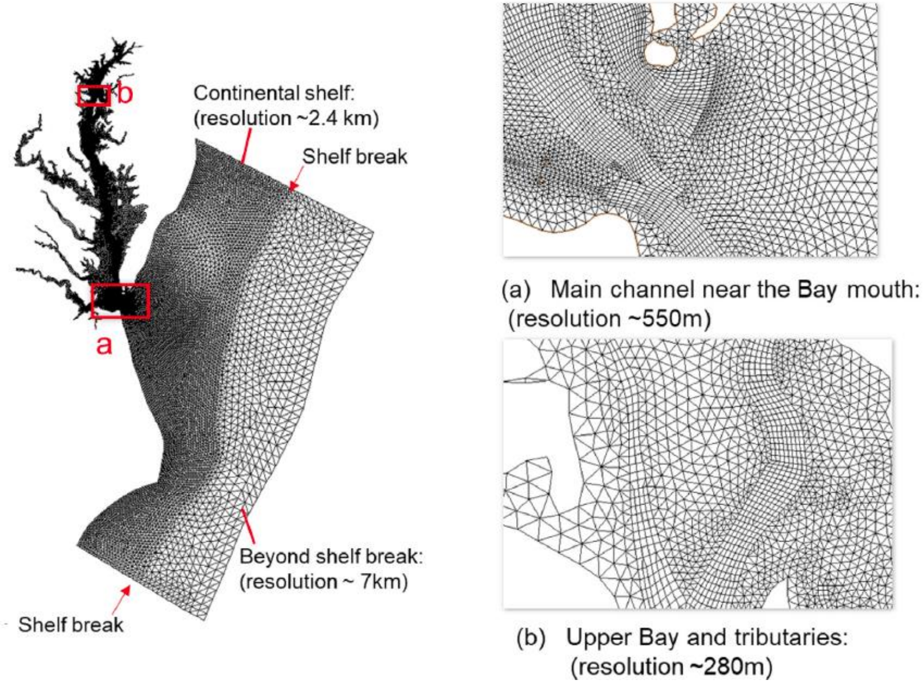
Origin of SCHISM model: split from SELFE in 2014 due to doctrinal differences and license disputes with original licensee of SELFE



Hood et al. (1999)

Structured grids: can be mapped to a square (so a pair of integers can completely describe a 2D cell and its neighborhood)





Unstructured grids (SG is a special case): flexibility in local refinement; boundary resolving/feature capturing

*Also previous version of Delaware Inland Bay model (Cerco et al. 1994)

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

- From SELFE to SCHISM
  - A derivative product of SELFE v3.1, distributed with open-source Apache v2 license
  - Substantial differences now exist between the two models
  - Active community participation: ~70 developers/power users via svn

SELFE/SCHISM

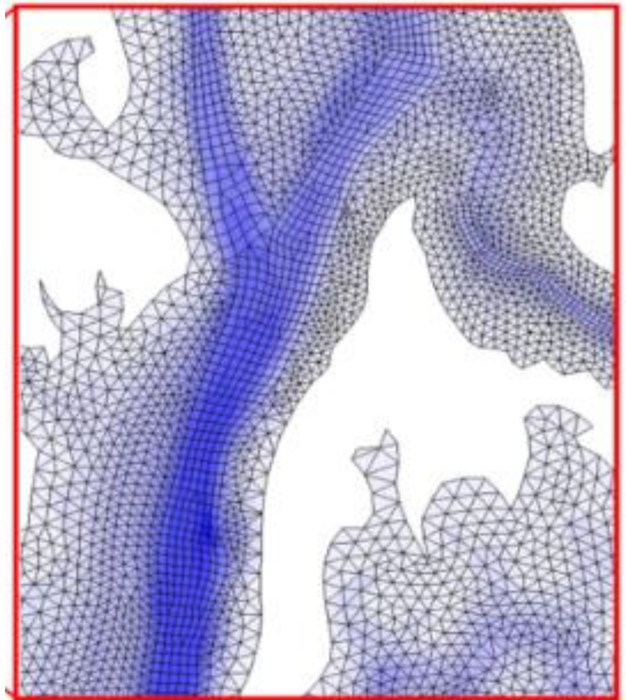
- Solves Navier-Stokes equations in hydrostatic form with Boussinesq approximation
- Galerkin finite-element and finite-volume approach: generic unstructured grids
- Semi-implicit time stepping: no mode splitting → large time step and no splitting errors
- Eulerian-Lagrangian method (ELM) for momentum advection → efficiency & robustness
- Major differences from SELFE v3.1

SCHISM

  - Apache license
  - Mixed grids (tri-quads)] **polymorphism**
  - LSC^2 vertical grid
  - Implicit TVD transport (TVD^2); WENO3; *all with monotonicity enforced*
  - Higher-order ELM with ELAD
  - Bi-harmonic viscosity
  - Implicit treatment of vegetation effects

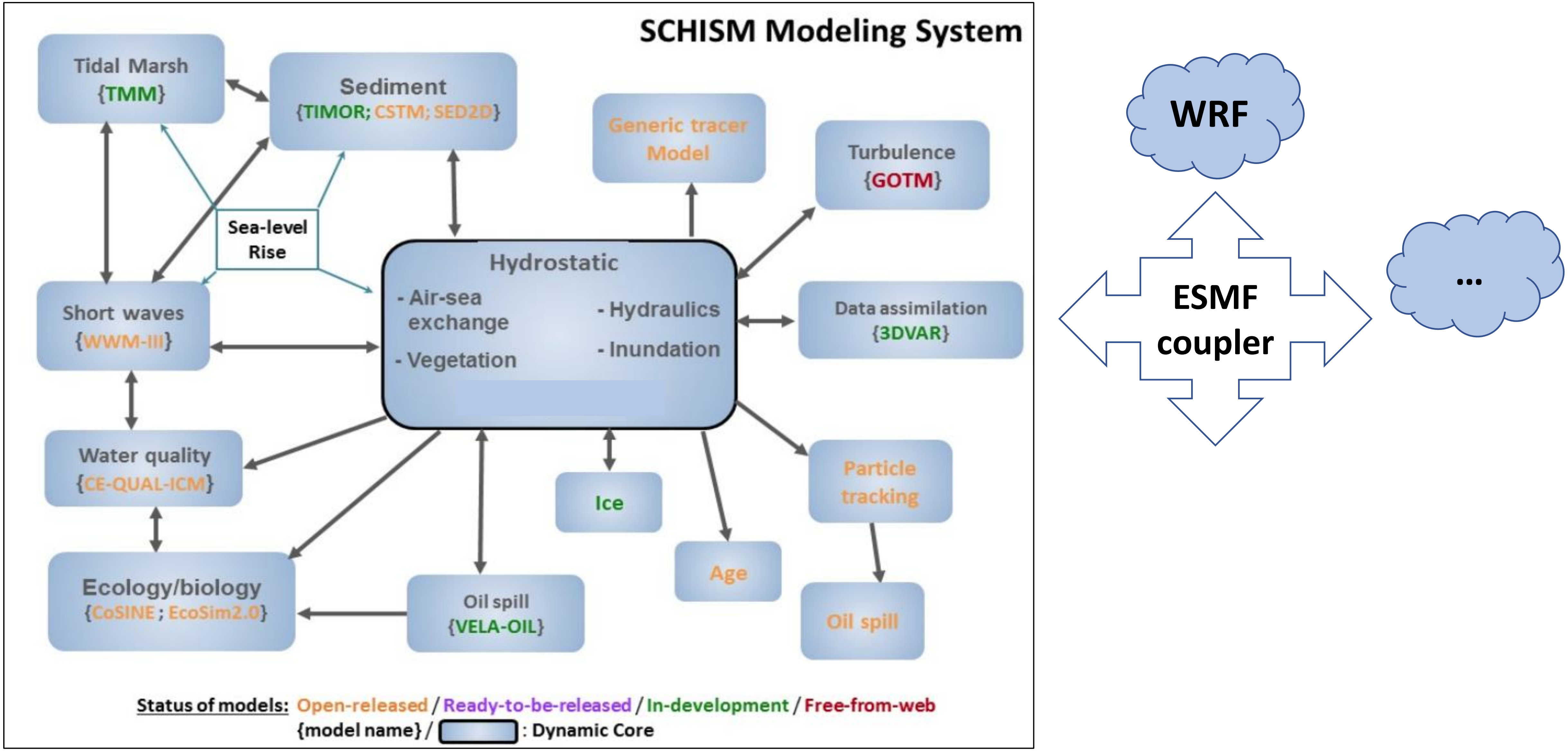
Eddying regime (Zhang et al. 2016)

visit schism.wiki



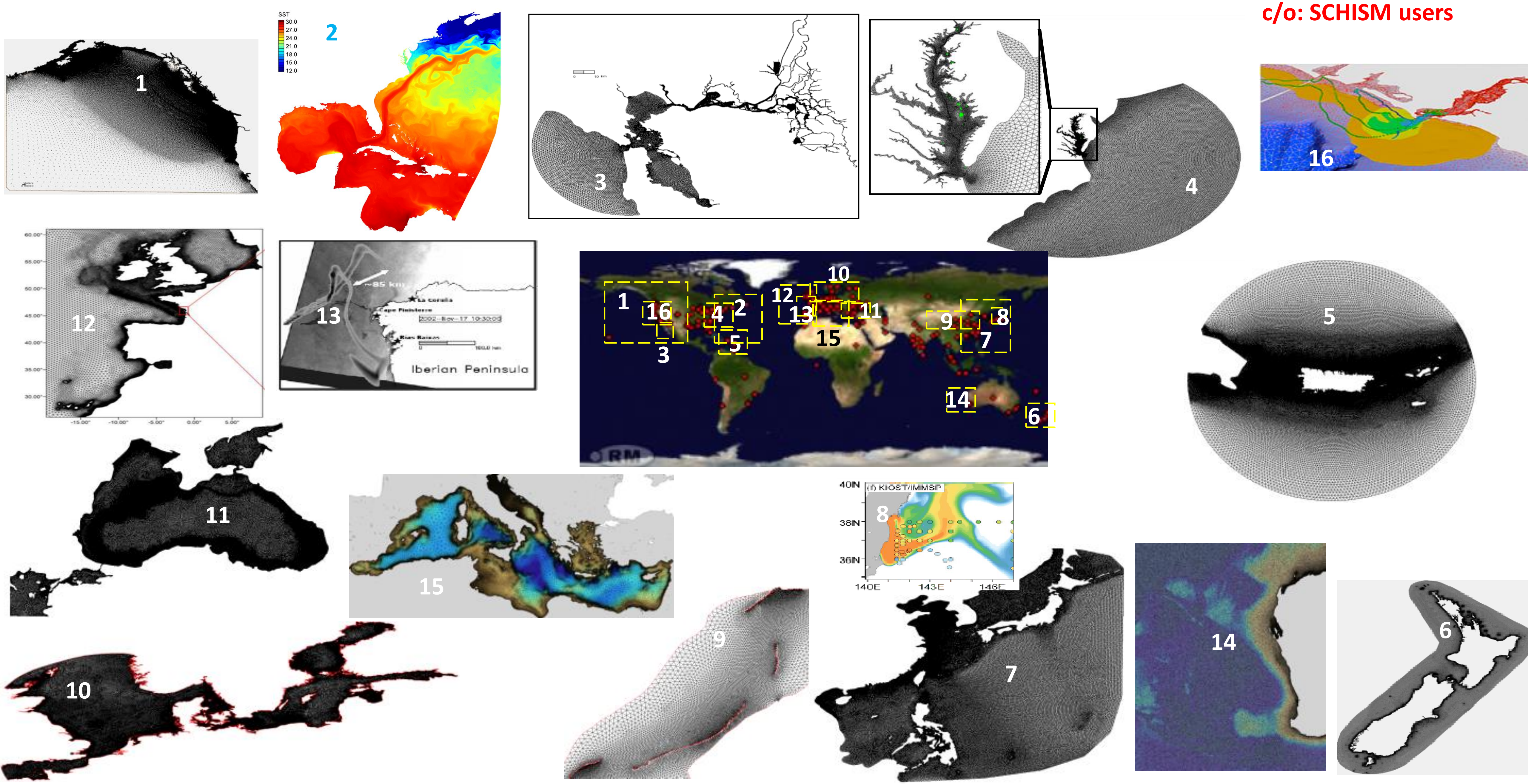
Why SCHISM?

- Major differentiators from peer models
  - No bathymetry smoothing or manipulation necessary: faithful representation of bathymetry is key in nearshore regime (Ye et al. 2018)
  - *Implicit* FE solvers → superior stability → very tolerant of bad-quality meshes (at least in non-eddying regime), an extremely useful feature
  - Accurate yet efficient: implicit + low inherent numerical dissipation (balance between numerical diffusion and dispersion)
  - Flexible gridding systems in both horizontal and vertical (polymorphism): 'creek to ocean'
  - Need for grid nesting is minimized; resolution on demand
- Well-benchmarked (via multiple projects)
- Fully parallelized with domain decomposition (MPI+openMP) with strong scaling (PETSc solver)
- Operationally tested and proven:
  - CA-DWR, NOAA, CWB (Taiwan), HZG (Germany) …
  - Preliminarily approved by EU-Danubius Research Infrastructure for operational use
- Open source, with active community participation

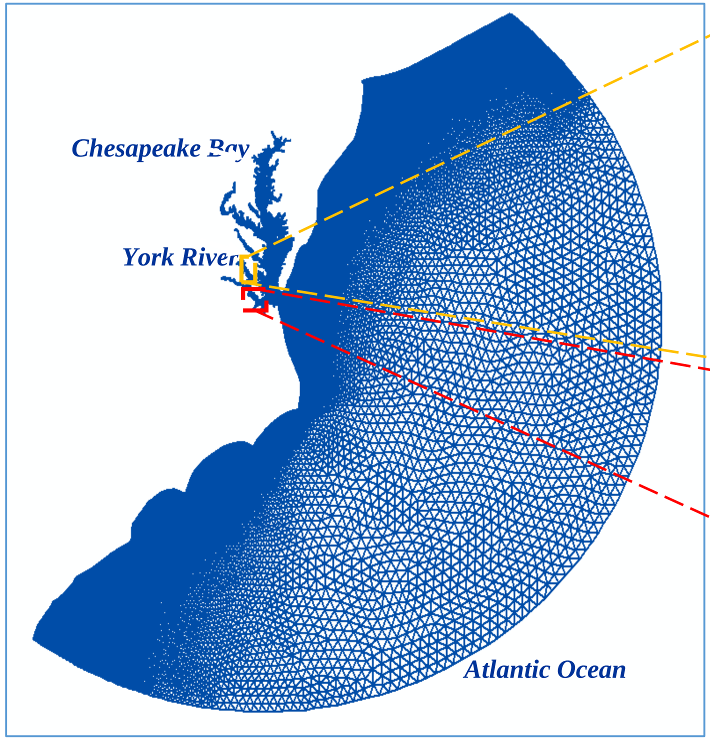

SCHISM Modeling System
Tidal Marsh
{TMM}
Sediment
{TIMOR; CSTM; SED2D}
Generic tracer
Model
Turbulence
{GOTM}
Sea-level
Rise
Hydrostatic
- Air-sea
exchange
- Vegetation
- Hydraulics
- Inundation
Short waves
{WWM-III}
Data assimilation
{3DVAR}
Water quality
{CE-QUAL-ICM}
Ice
Particle
tracking
Age
Ecology/biology
{CoSINE ; EcoSim2.0}
Oil spill
{VELA-OIL}
Oil spill
Status of models: Open-released / Ready-to-be-released / In-development / Free-from-web
{model name} / : Dynamic Core
WRF
ESMF
coupler
...

Application cases

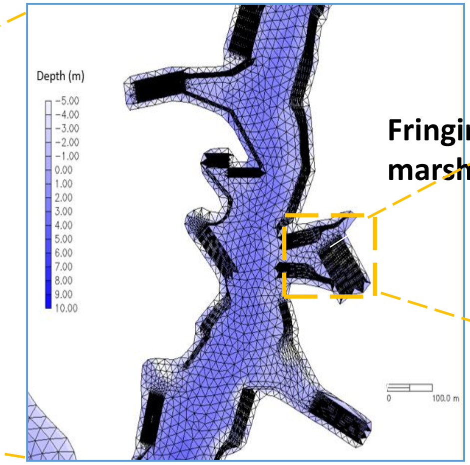
c/o: SCHISM users

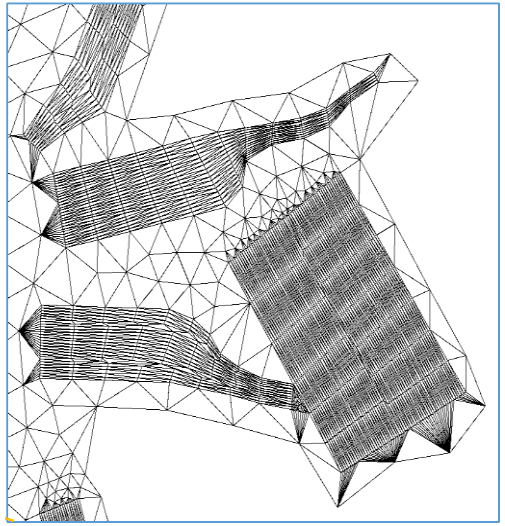


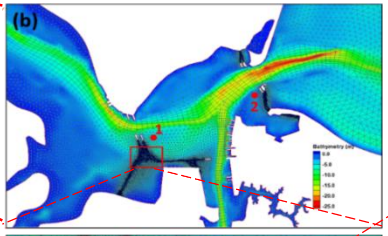
Resolution on demand

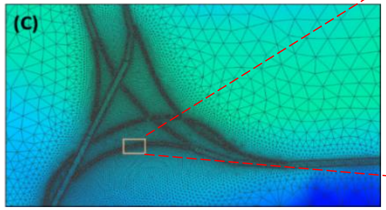


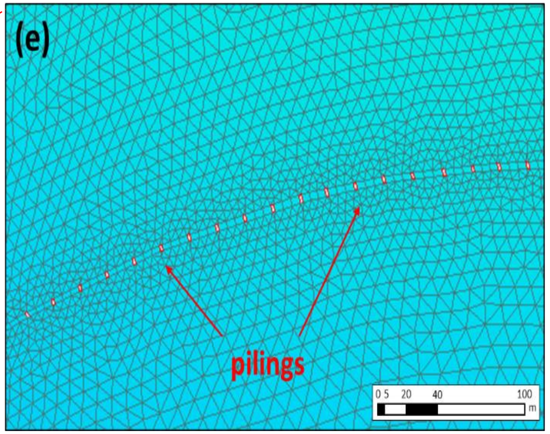
(Liu et al., Ocean Dyn. 2018)





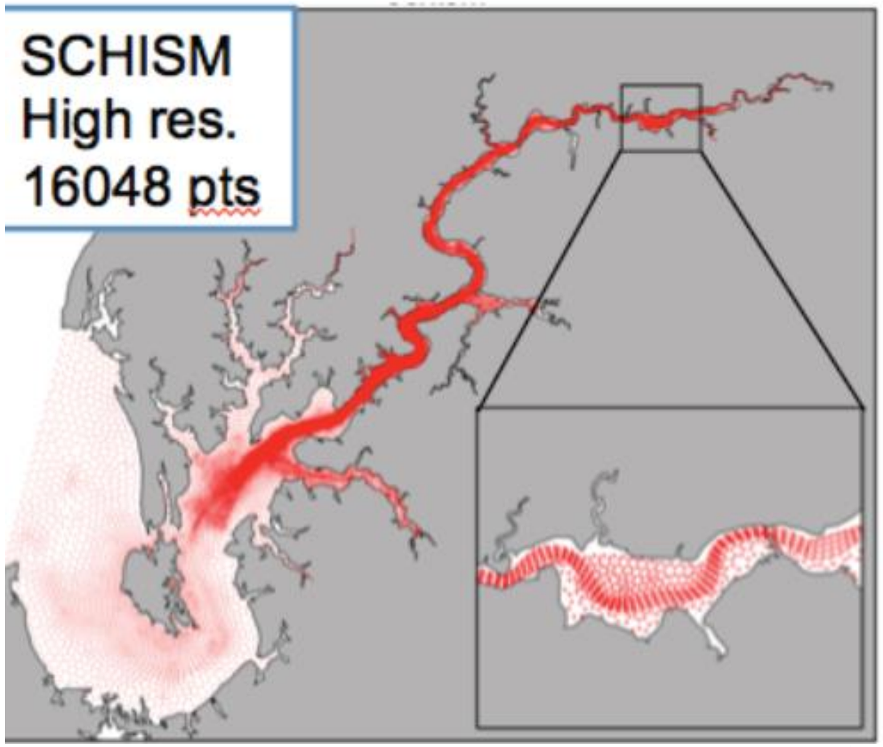




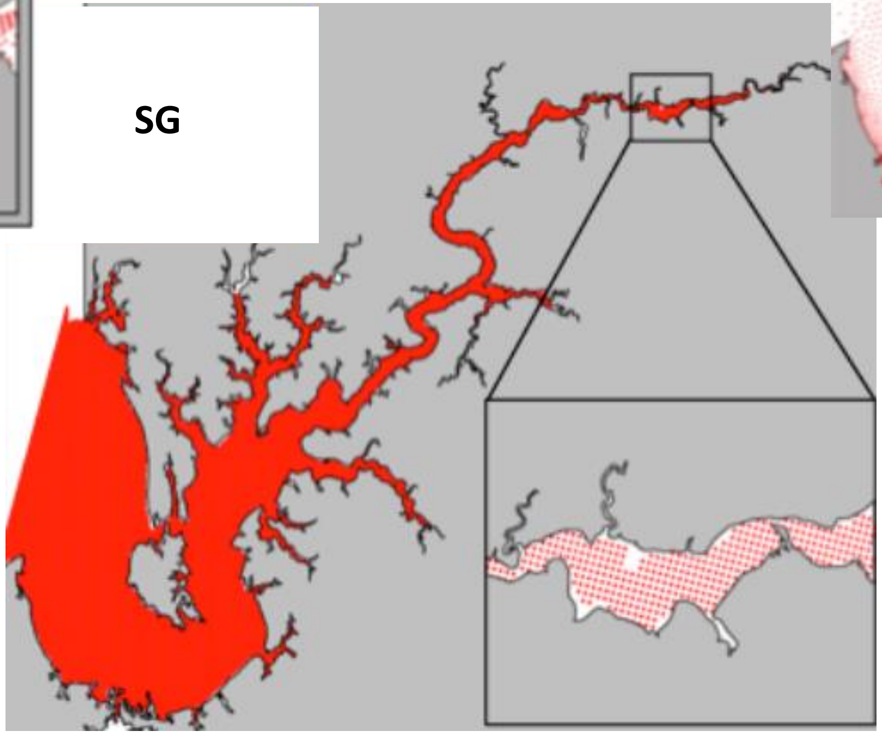


- Resolution on demand is where unstructured-grid (UG) models shine
- In reality however, many challenges hinder true multi-scale modelling, many of which are numerical ones
- The implicit FE formulation in SCHISM makes it very tolerant of ‘bad’ meshes
- ‘Smooth grids’ are often too expensive and cumbersome to generate
- SCHISM’s superior stability and robustness allow high resolution to be applied anywhere *at will*

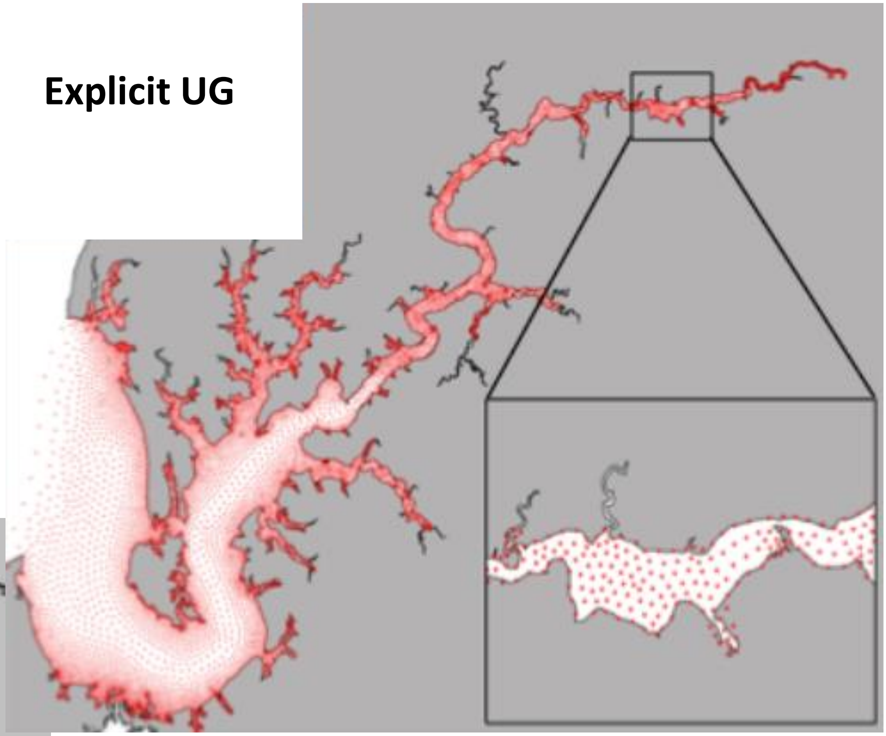
Resolution on demand



SG



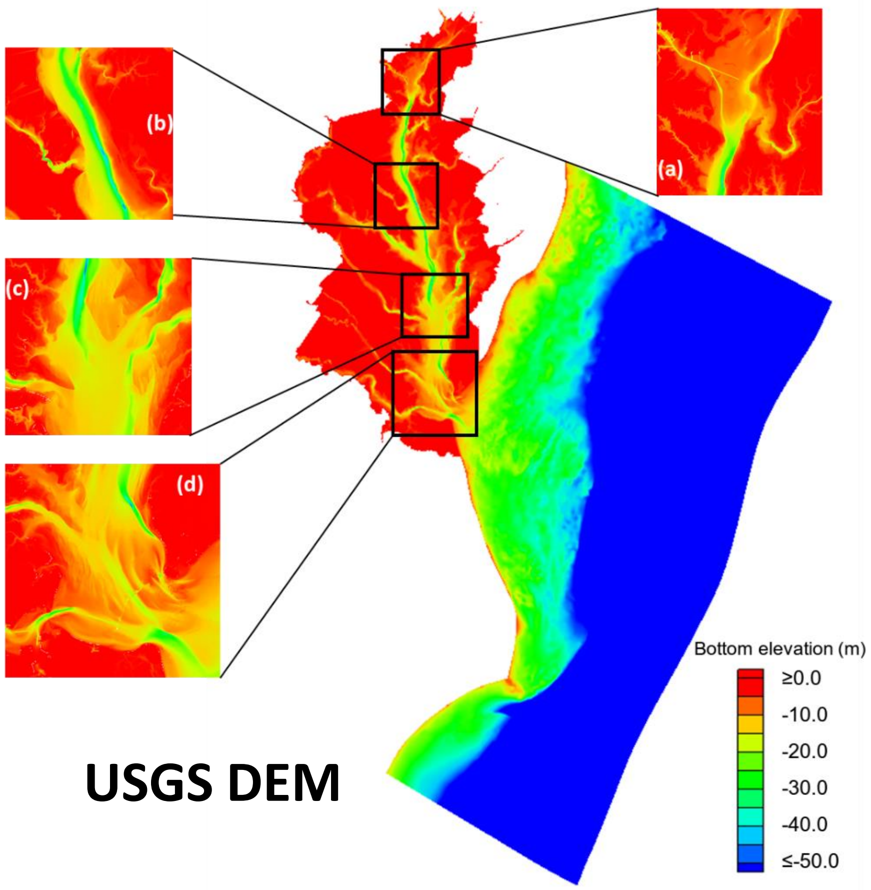
Explicit UG



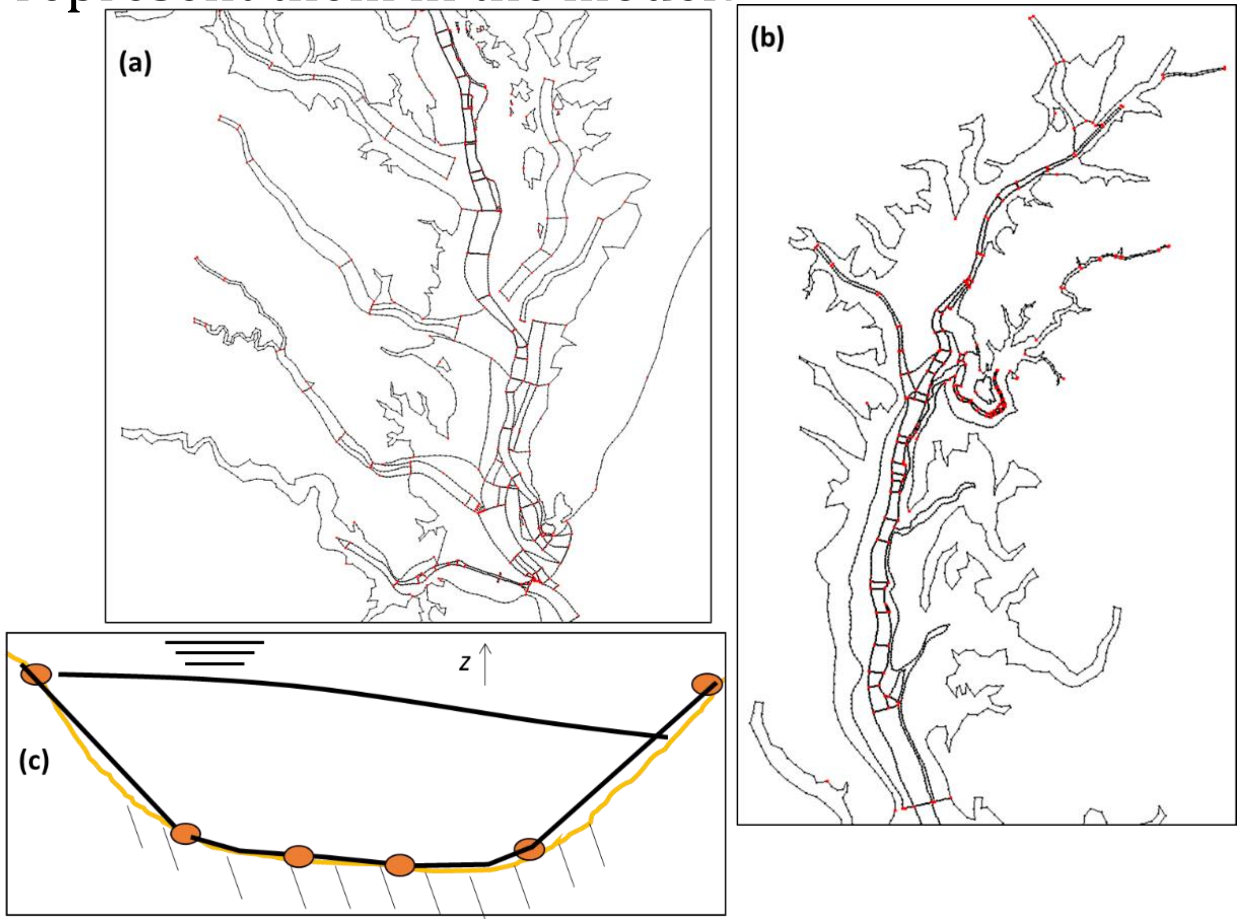
c/o Marjy Friedrichs

Horizontal grid design

Complex channel systems. How to accurately represent them in the model?

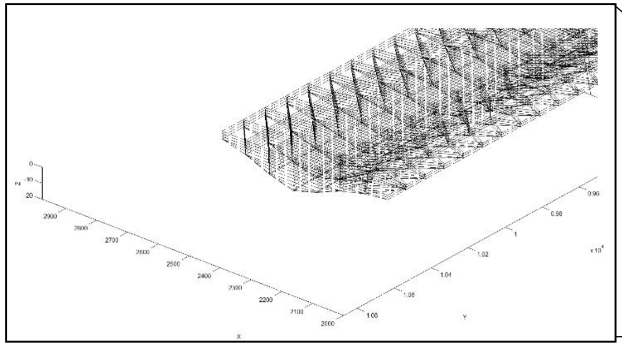


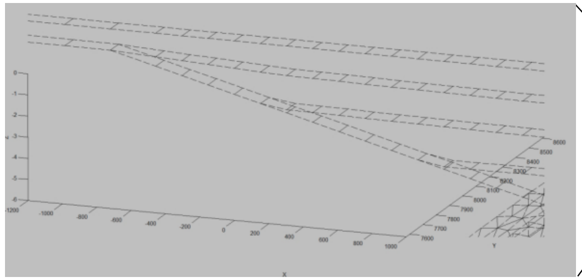
USGS DEM

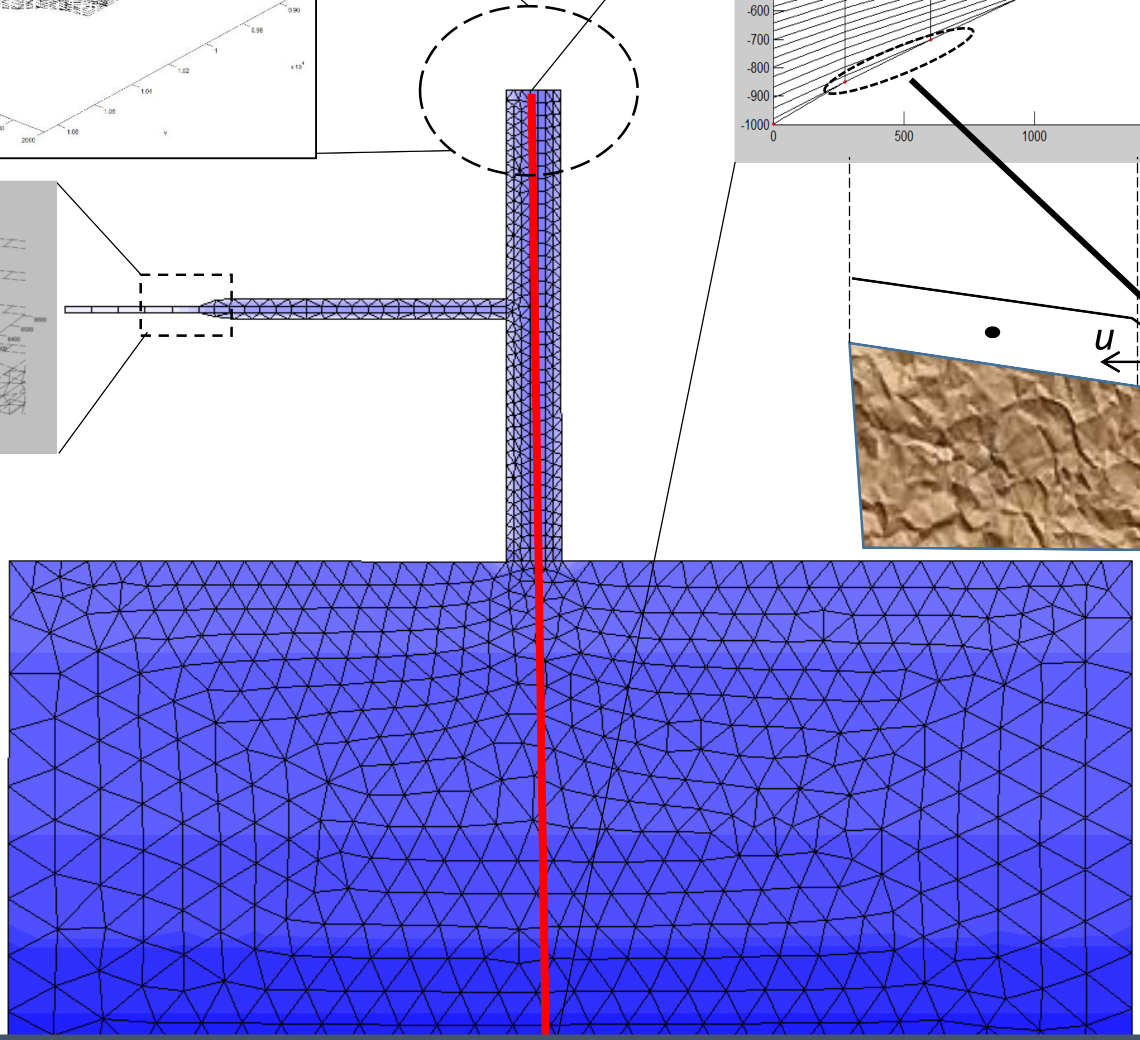


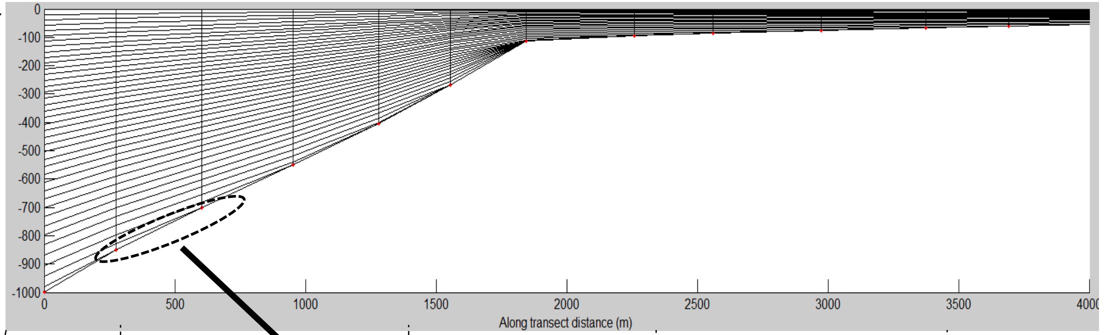
- Key ‘choke points’ need to be adequately resolved
- Skew elements are almost unavoidable if we want to faithfully represent key features like channel
- Although a smooth transitioned grid is theoretically preferred, it’s often impractical (e.g. at steep slopes)
- On the other hand, mixing regimes should be different across those steep slopes

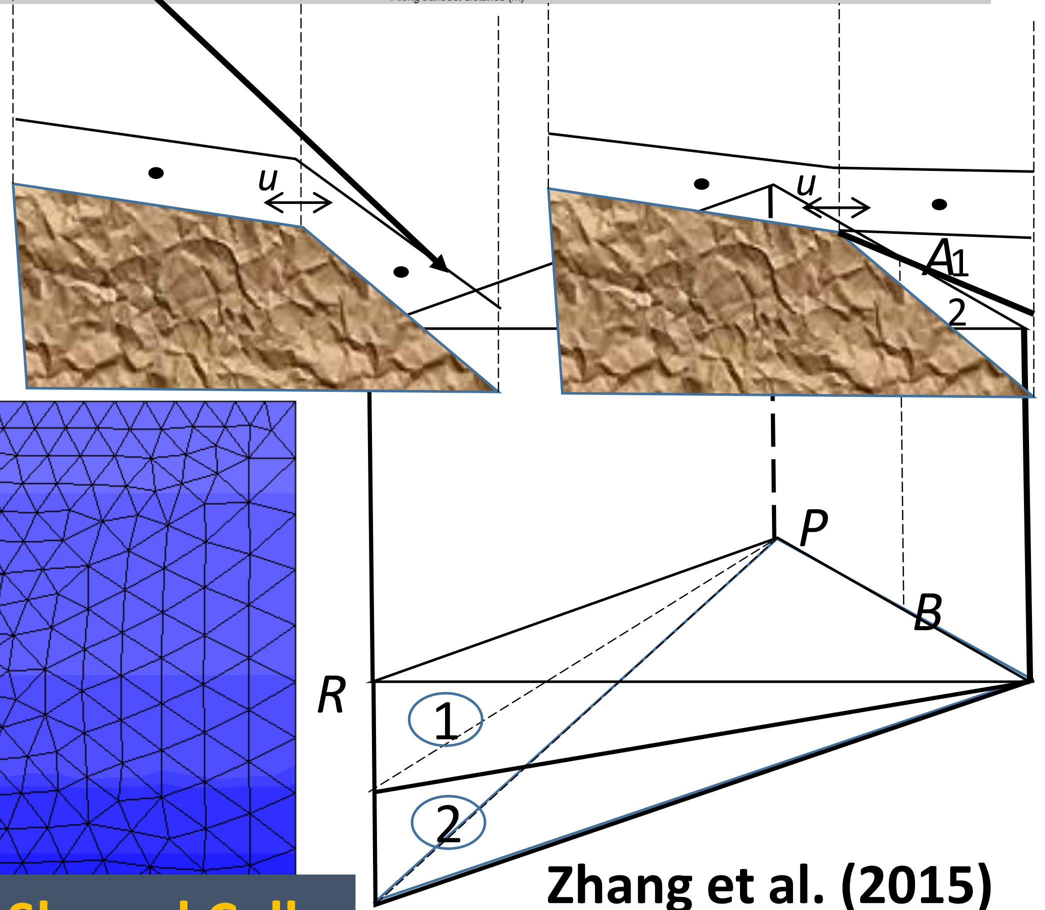
Model polymorphism











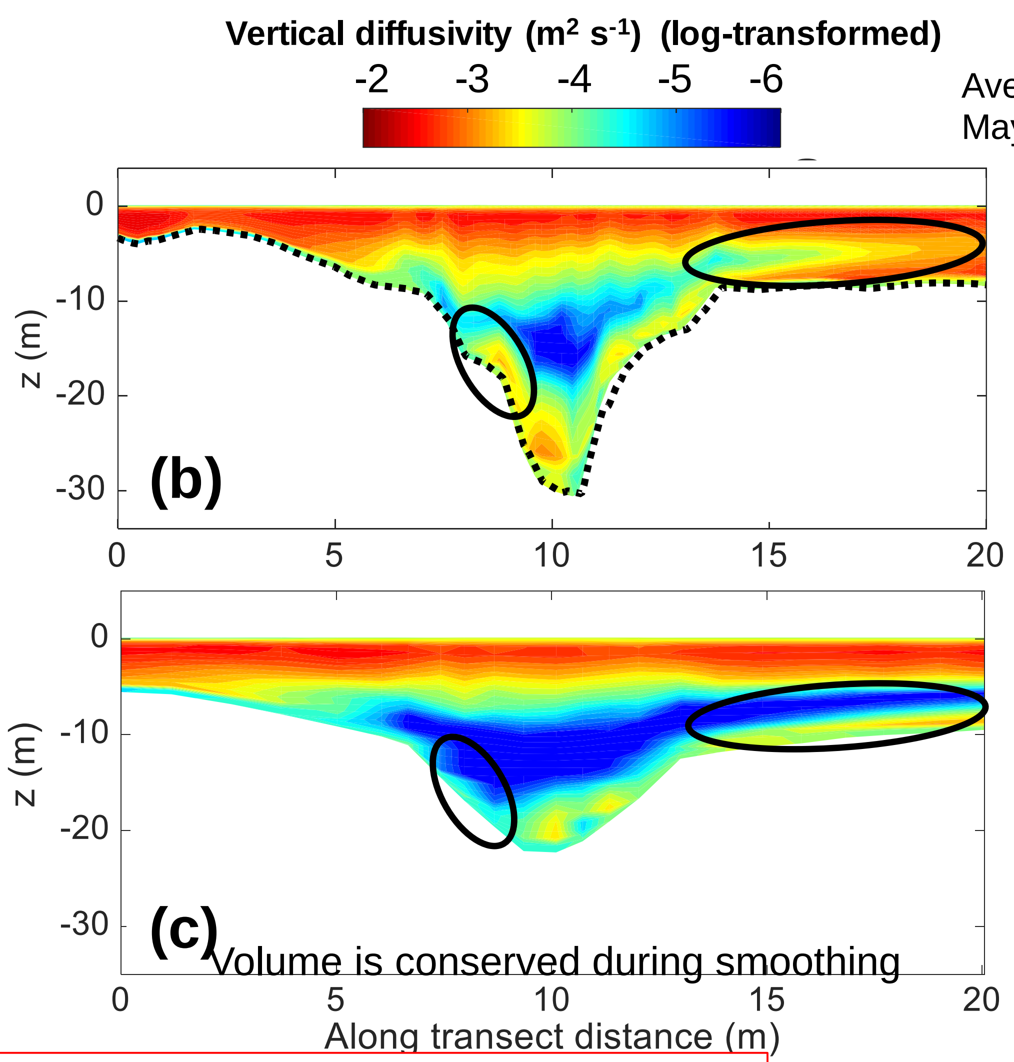
- † Polymorphism: a single SCHISM grid can seamless morph between 3D, 2DH, 2DV and quasi-1D grid
- † Shaved cells are important for bottom controlled processes
- † A judicious design of LSC² grid is key in capturing shoal-channel contrast

Zhang et al. (2015)

LSC²= Localized Sigma Coordinates with Shaved Cells

Respect bathymetry! Bathymetry smoothing alters the physical processes

Smoothing in a critical region where the center channel constricts and bends, with multi-channel configurations



Averaged through May-Oct, 2012

Original bathymetry

Low mixing-zone (blue) confined in the main channel

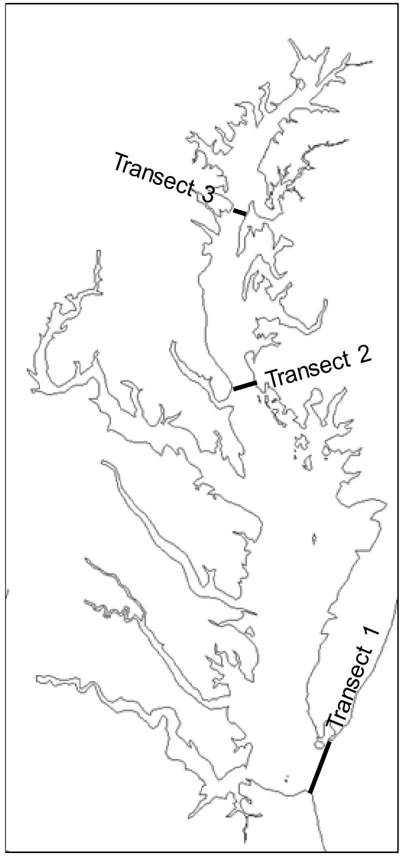
Smoothed bathymetry

Low mixing-zone (blue) extending to the shoal

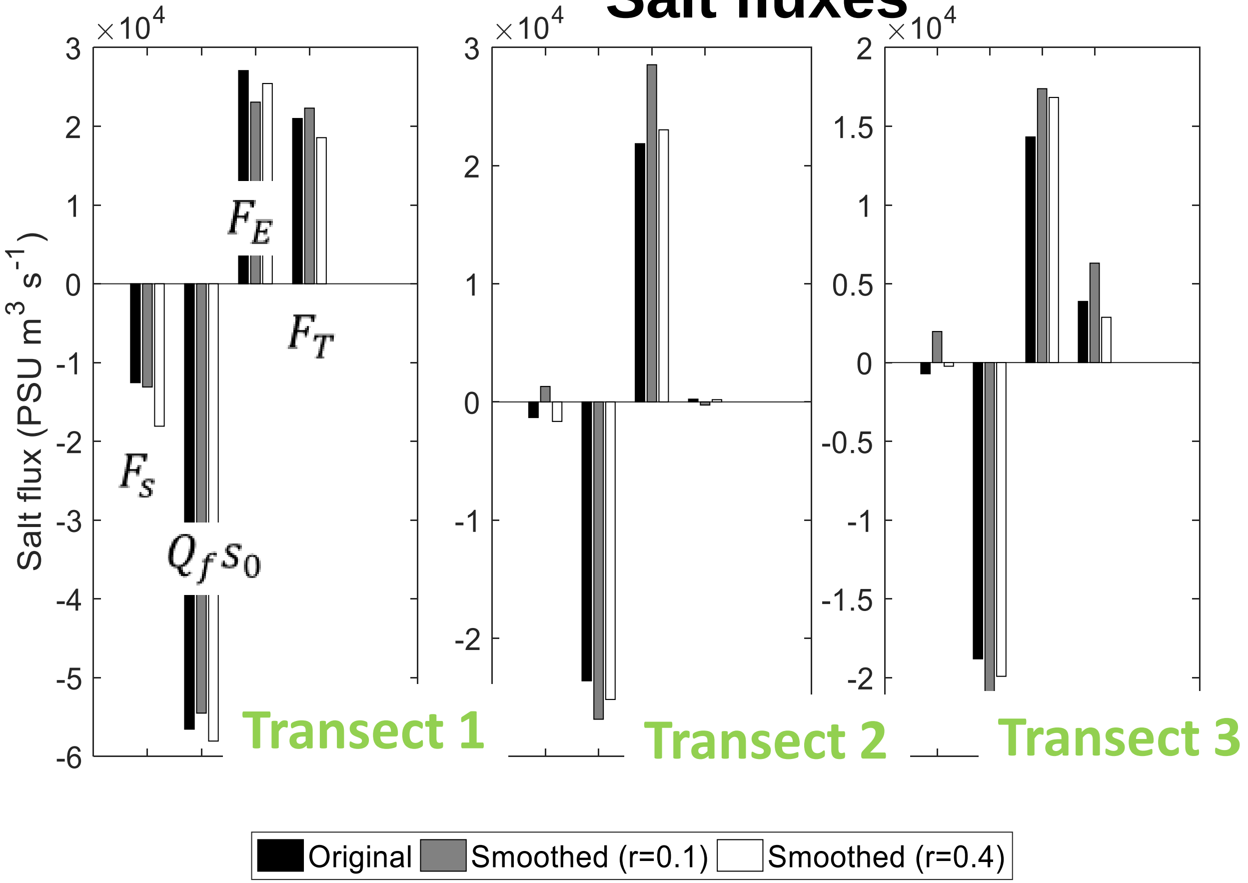
- Physical mixing is under-estimated; as a result, numerical dissipation can be masked
- Similar reduction of turbulence is observed near channel constrictions ('choke points')
- It's hard to recover the original mixing pattern by tuning the dissipation
- Bathymetry smoothing represents a divergence error as the resolution is increased

(Ye et al. 2018)

Bathymetry smoothing alters fluxes



Salt fluxes



$$F_s \approx Q_f s_0 + F_E + F_T$$

F_S: total salt flux;
F_E : estuarine circulation flux;
F_T: tidal oscillatory flux;
$Q_f s_0$: salt flux from river discharge and Stokes transport

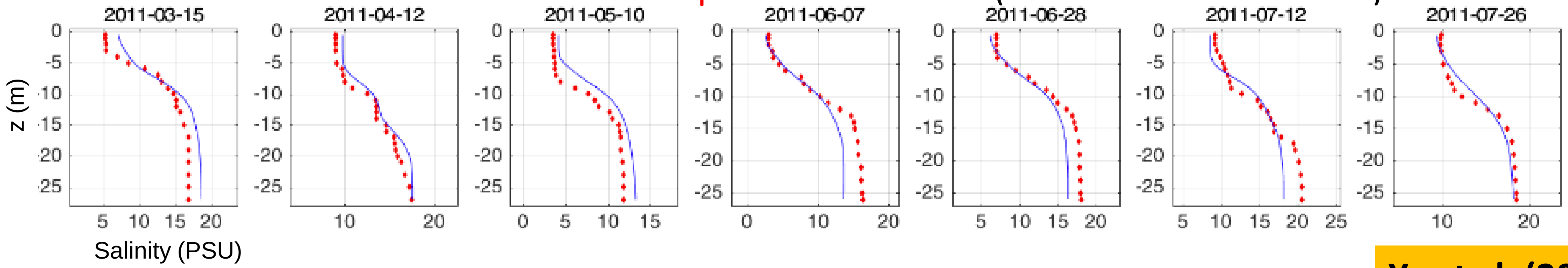
(Lerczak et al., 2006)

- Two thresholds of smoothing are compared against original non-smoothed bathymetry
- Larger salt flux due to estuarine circulation and tidal oscillation, leading to larger total flux
- Total salt flux is off by at least 74% on average even with a generous threshold (*r*=0.4)

Model skill (vertical salinity profiles)

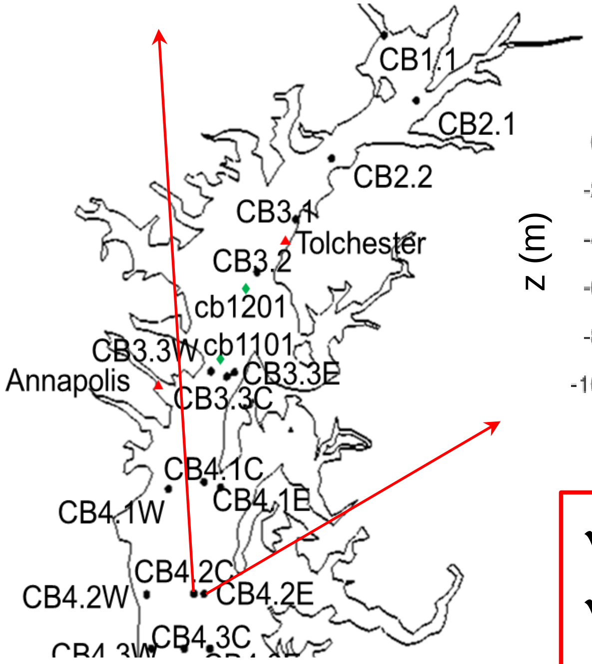
Data   Model

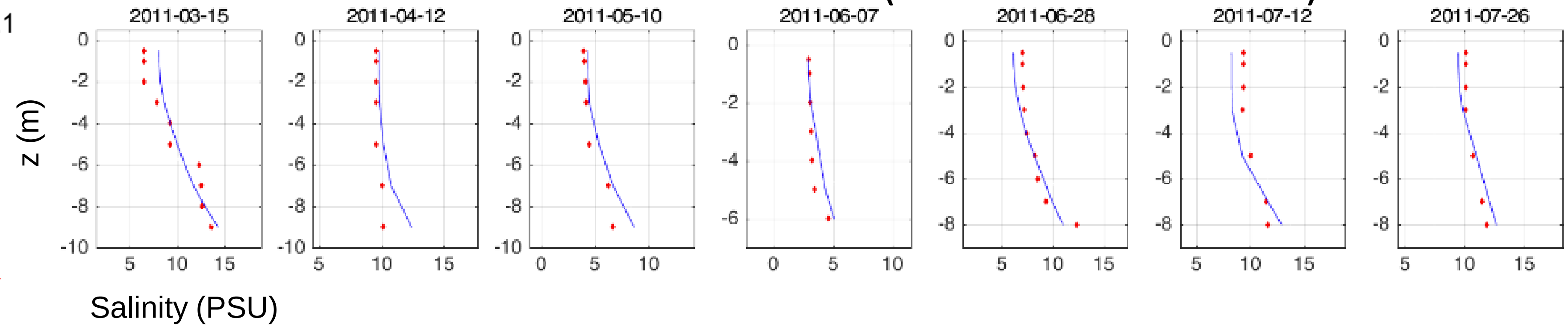
Deep channel: CB4.2C (stratified at most times)



Ye et al. (2018)

Shallow shoal: CB4.2E (mixed at most times)

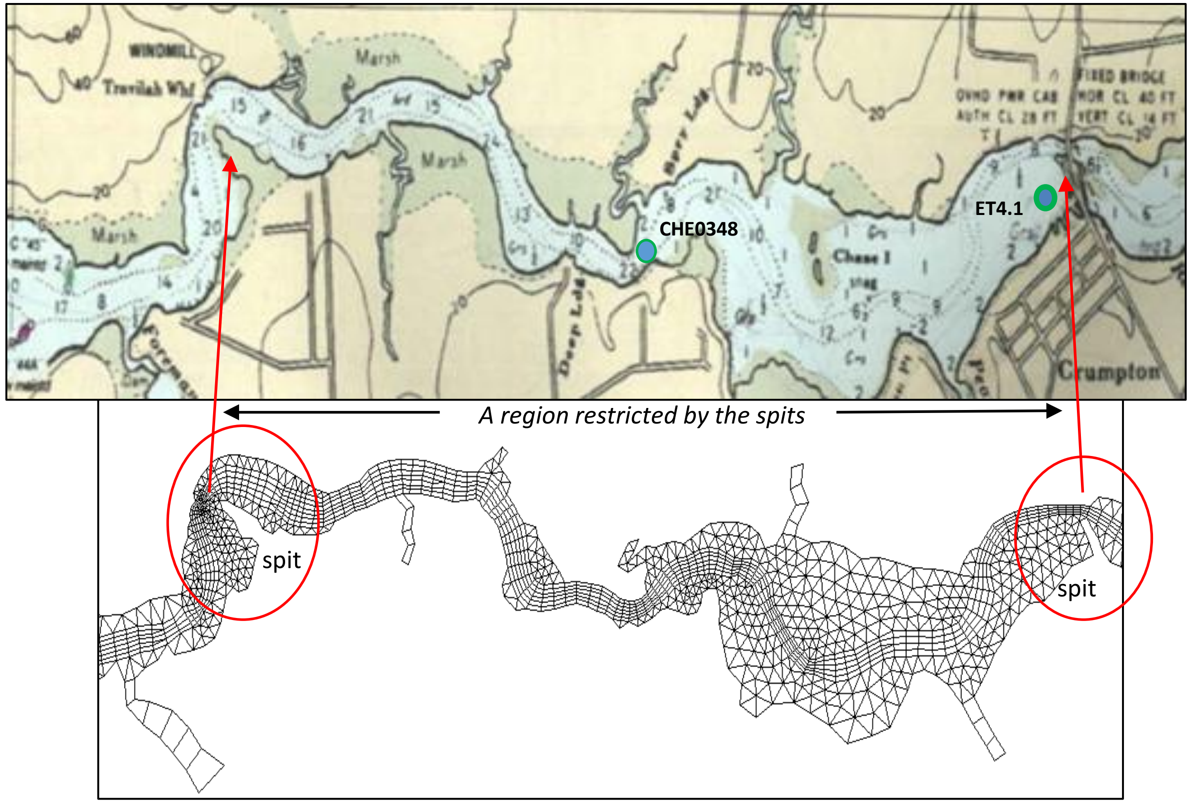


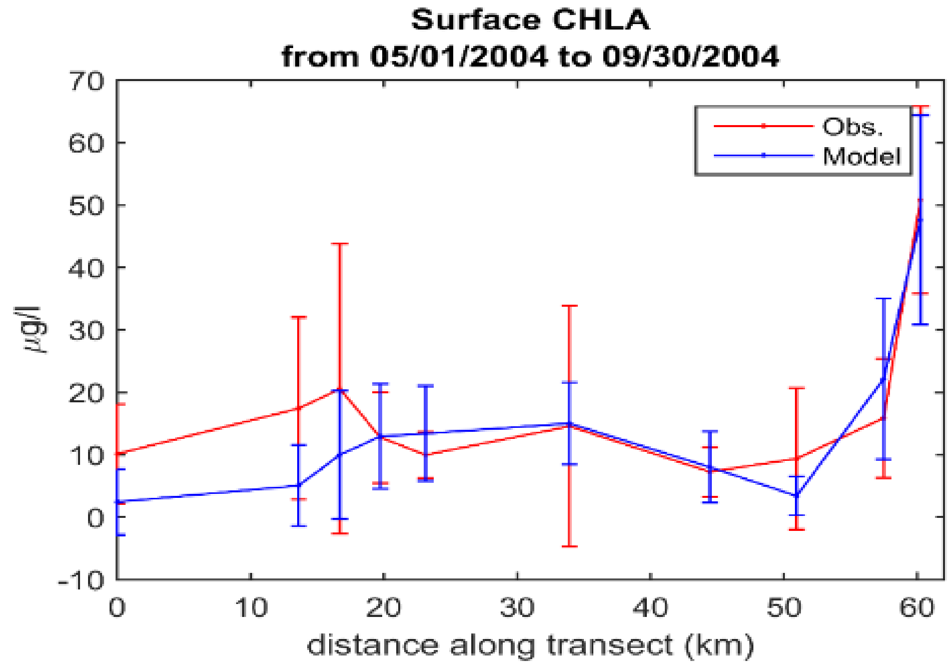


- ✓ No obvious spatial bias between the deep channel and the shallow shoal
- ✓ Average RMSE: 1.7PSU for S, 1.5°C for T, which demonstrates the essential benefit of faithfully representing the bathymetry features

Chlorophyll dynamics in Chester River

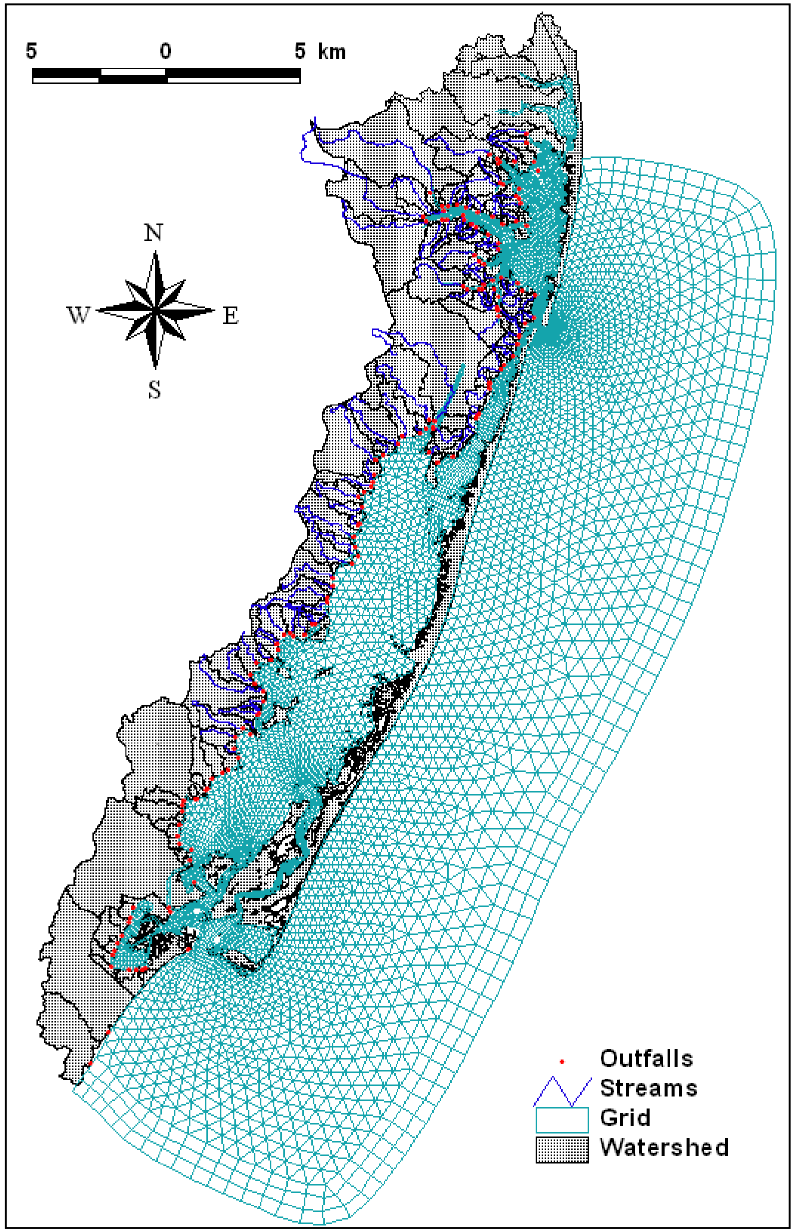
Shallow-water project (Chester River)

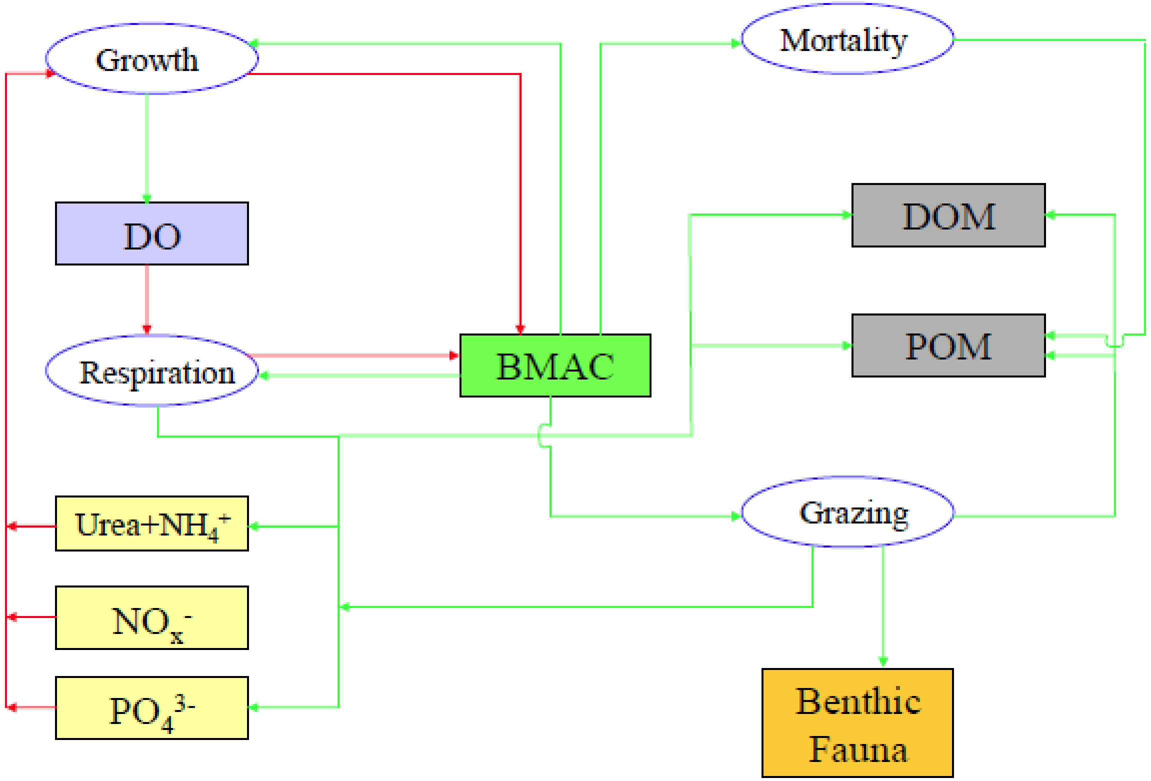




- ✓ The location where the algae prone to bloom in this river is situated in a stretch of the upstream river restricted by two large spits
- ✓ Resolving the spits increases the residence time and facilitates the algal growth
- ✓ This is consistent with the high spatial gradients observed between upstream and downstream
- ✓ This demonstrates the importance of resolving features

A fully coupled hydrodynamic, water quality, wave and sediment transport model

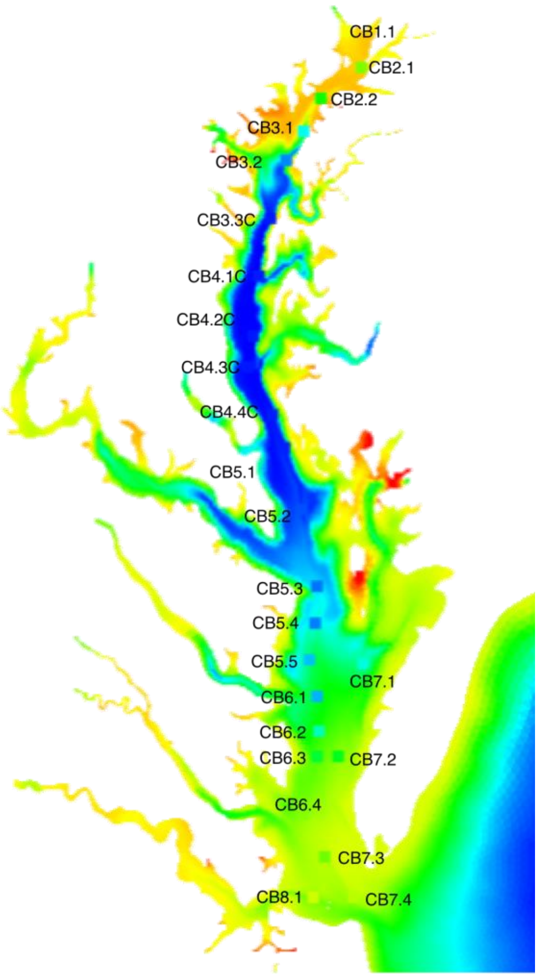


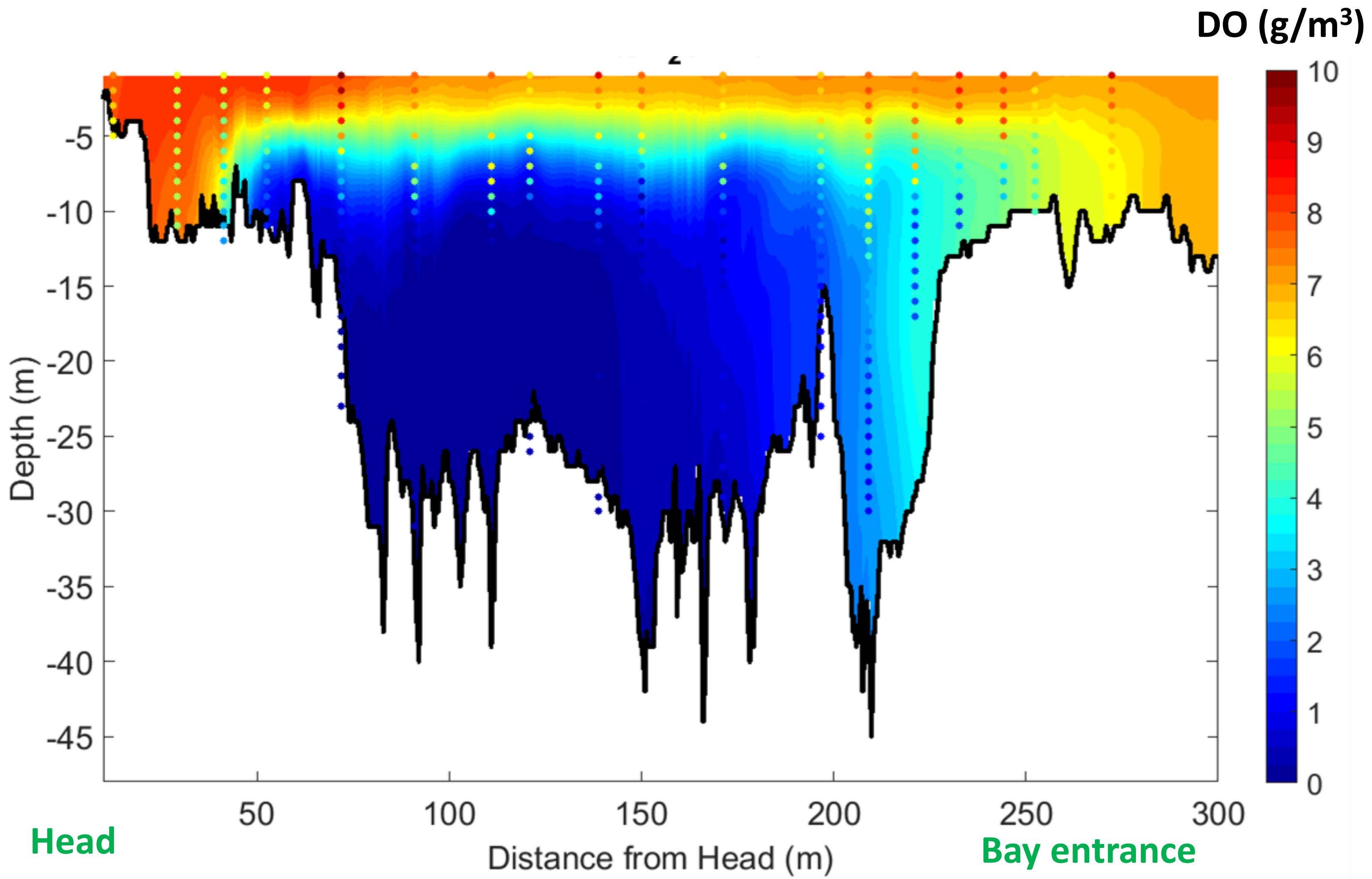


Benthic macroalgal module (T. Wang 2009)

MD coastal bays

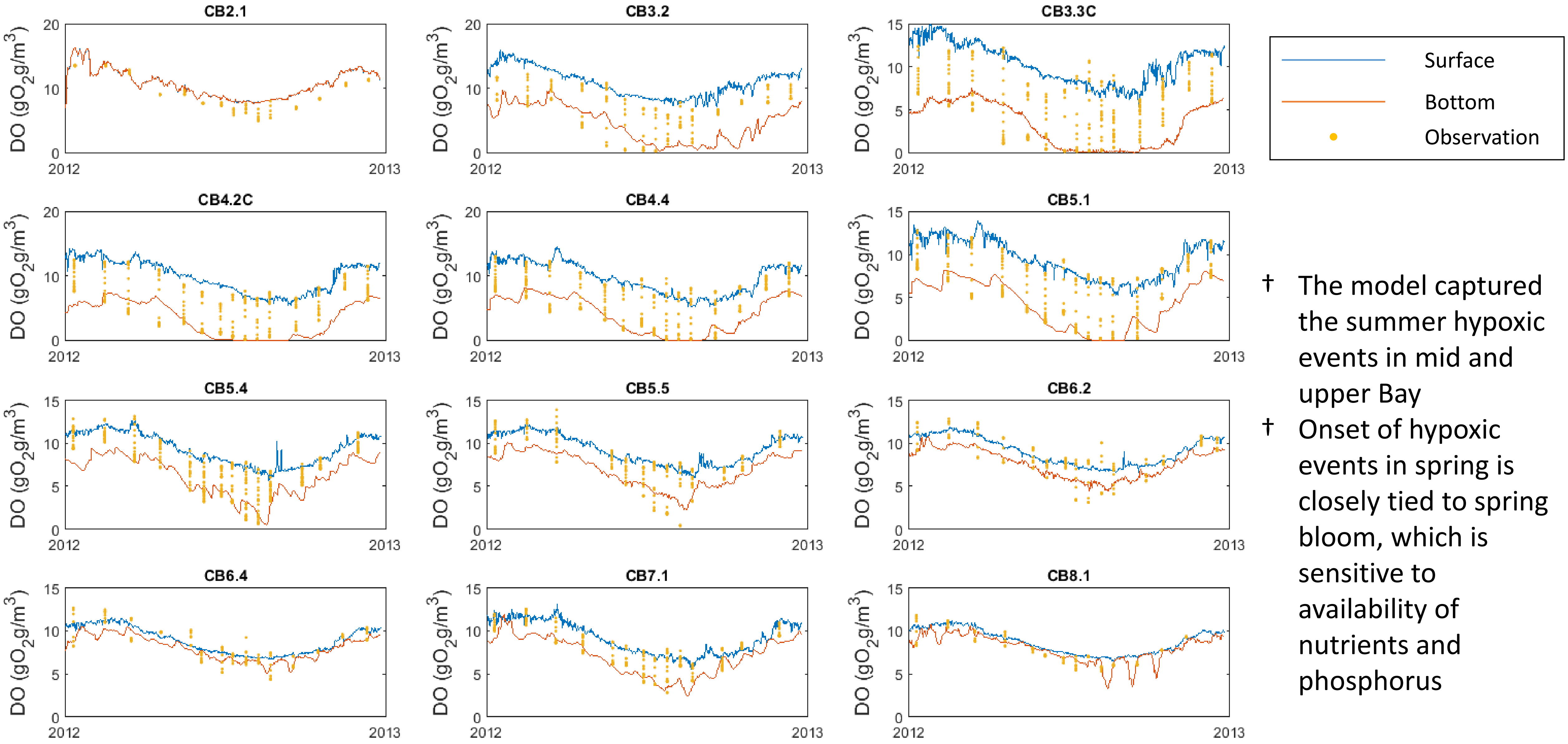
Chesapeake Bay WQ model





- † Includes: sediment fluxes, benthic algae
- † Closely work with CBPO on this effort
- † Working on diel DO swing and feedback of sediment transport to water clarity

Chesapeake Bay WQ model



- The model captured the summer hypoxic events in mid and upper Bay
- Onset of hypoxic events in spring is closely tied to spring bloom, which is sensitive to availability of nutrients and phosphorus

Comparison of modeled Dissolved Oxygen concentration with observations.

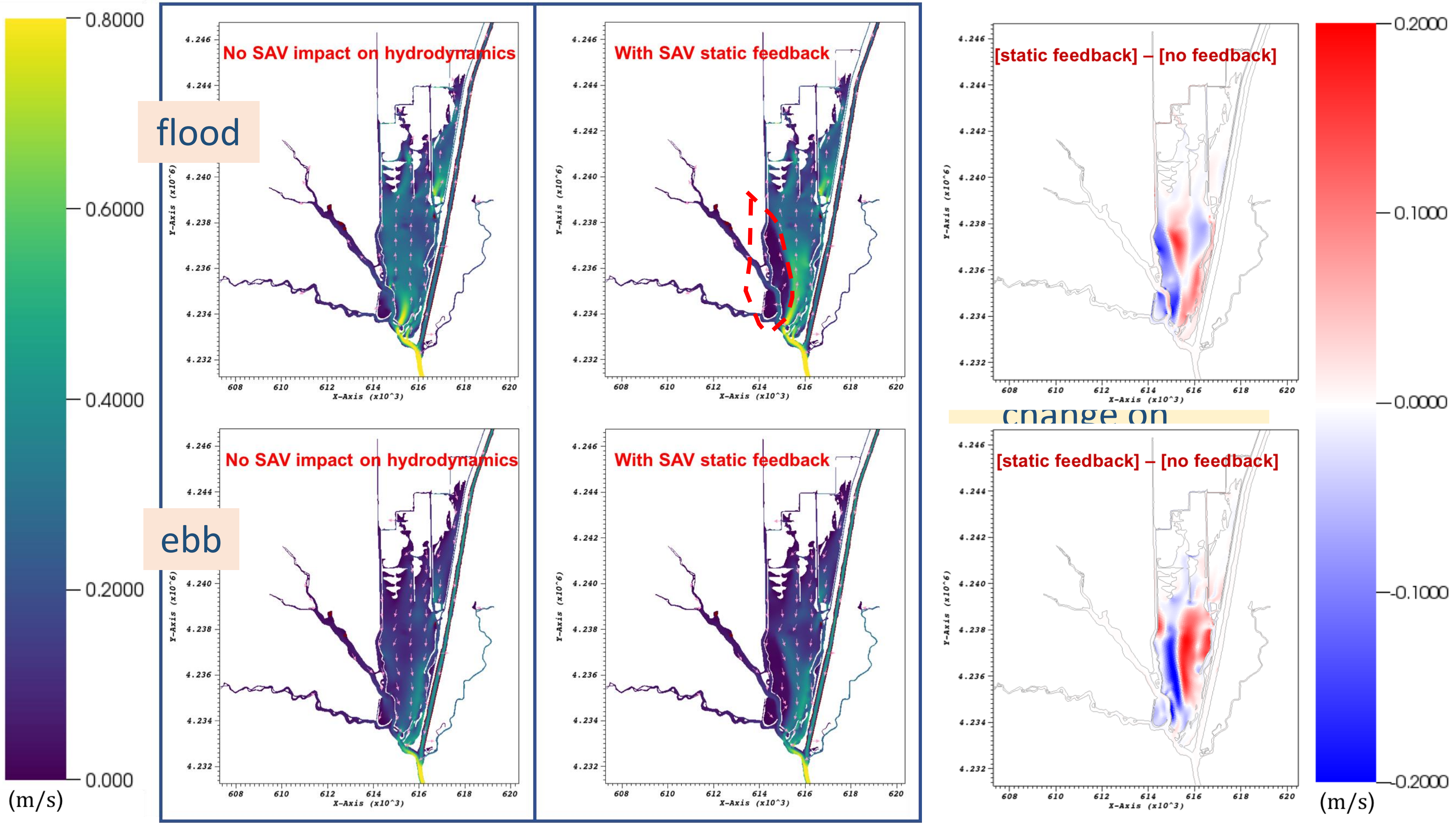
Recent work on vegetation: San Francisco Bay & Delta

- Funded by California Department of Water Resources (DWR) since 2009
  - Initial phase completed (hydrodynamics including hydraulic structures)
  - 2^{nd} phase (2017-2020): waves, vegetation, sediment and water quality
- Horizontal grid: 170K nodes, 183K elements (quads for some channels)
  - 2km in the coast; 100-200m in Bay; 2-70m in Delta (to resolve small canals)
- 14 hydraulic structures (gates, weirs, culverts)
- DWR uses SCHISM modeling system for regulatory and planning missions (drought, flood)

DEPARTMENT OF WATER RESOURCES
STATE OF CALIFORNIA

Bay-Delta SCHISM
3D Hydrodynamics and Transport

Static Feedback vs. No Feedback in Flow Pattern



Conclusions

- We have made good progress on seamless cross-scale modelling during the past decade
- Seamless cross-scale modeling can be achieved effectively with unstructured grids and implicit time stepping
- How far can we cover?
  - Nearshore: upstream rivers/creeks
  - Offshore: regional scale
  - Ultimate goal is to build a seamless modeling platform that covers ocean-shelf-estuary-river-creek continuum without nesting (or at least minimize its use), so as to allow users to look into interplay between complex processes at contrasting scales
- Our team has been helping federal and state government agencies for flow and water quality related issues in Chesapeake Bay, Columbia River, San Francisco Bay & Delta, Maryland coastal bays, European & Taiwan estuaries
  - We are working with NOAA in the Integrated Water Project to link oceanic processes (including Gulf Stream) to National Water Model using SCHISM's 'creek to ocean' capability; proof of concept project: east coast+ GoMeX +Delaware Bay (including DIB)

Recommendations for DIB

- ✓ Support a multi-tiered modeling approach, from simple process-based models to full fledged 3D coupled hydro-WQ model (like ours), to gain confidence on model results and quantify uncertainties
- ✓ Synergy with collection of new data (especially high frequency data)
- ✓ Given our prior experiences with multiple bays & estuaries in this country and overseas, we are ready to help CIB and local scientists with management centric questions and stakeholders engagement
  - ✓ Short term
    - ✓ Diel hypoxia and anoxia in DIB
    - ✓ Coupled (mechanistic) sediment transport and WQ processes
    - ✓ Vegetation
  - ✓ Long term
    - ✓ Data assimilation of WQ data
    - ✓ Higher trophics
    - ✓ Climate studies
    - ✓ SLR & erosion/breach of barrier islands
    - ✓ Extremes: storms, HABs

Thank you!

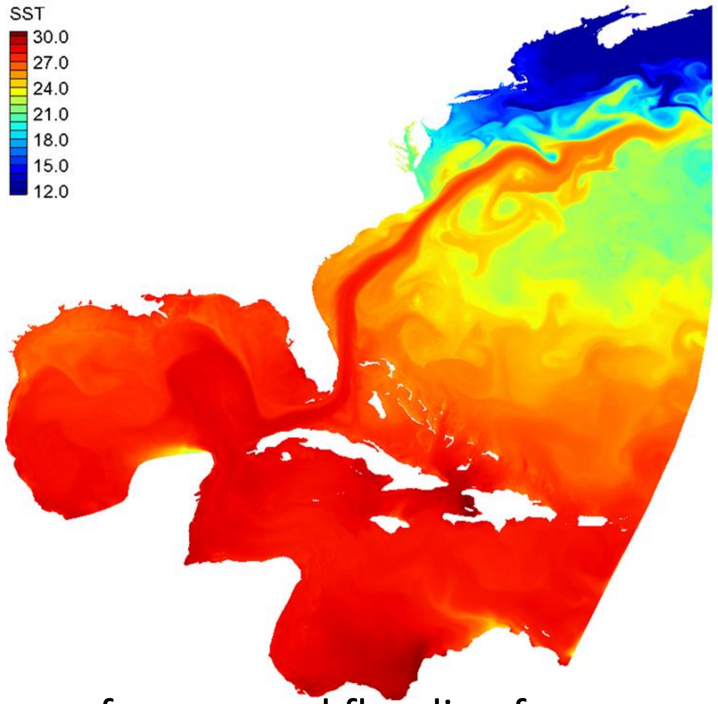
Backup slides

Synergy with NOAA's Integrated Water Project

Current River Forecast Points (~3,600)

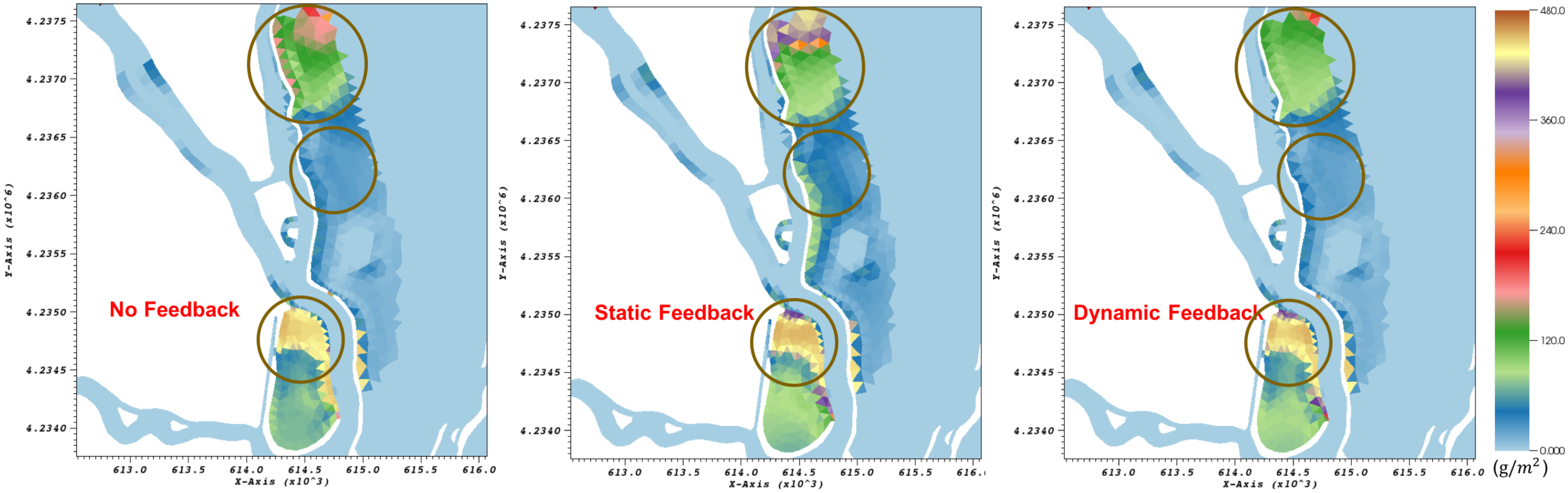
+

NWM Streamflow Output Points (~2.7 mil)



- ✓ A focus for our project is to couple SCHISM with National Water Model to address the issue of compound flooding from coastal ocean surges and river flood
- ✓ National Water Model: a hydrologic model that simulates observed and forecast streamflow over the entire continental United States (CONUS) with high resolution using HPC
- ✓ We are working with NOAA in the Integrated Water Project to link oceanic processes (including Gulf Stream) to upstream rivers/creeks using SCHISM's 'creek to ocean' capability
  - ✓ Proof of concept: east coast+ GoMeX +Delaware Bay (including DIB)
- ✓ Despite the ultra fine resolution (~2m) expected in these applications, time step remains at 120 sec (non split), and the model can readily represent complex features as found in rivers & estuaries (using skew elements)
- ✓ Vegetation effects are incorporated *implicitly* in the model and so do not affect time step!

SAV Biomass for No Feedback, Static Feedback and Dynamic Feedback



- 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.