Improving cross-scale hydrodynamic simulations in the Chesapeake Bay with physically based calibration

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Chesapeake Bay Program

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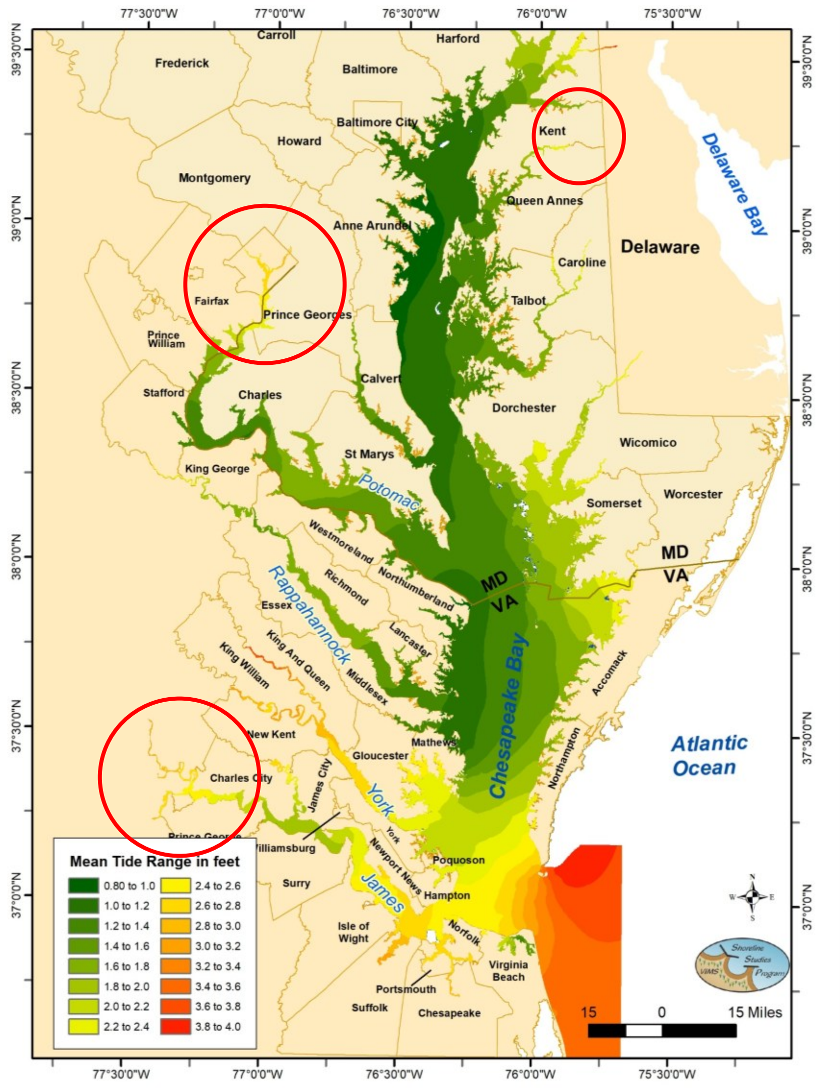
Overview

- We use observation-derived parameters to calibrate 3D unstructured-grid model
- High turbidity in upper estuary and tributaries affects solar radiation penetration
- Mud layers facilitate tidal propagation and saltwater intrusion in tributaries
- The present study reduces temperature & salinity errors by ~60% relative to previous studies
- Defensible calibration (starting from DEM) builds confidence on models

Background: challenges in cross-scale modeling

- ❑ Small-scale topographic structures (e.g., creeks and tributaries) pose key challenges for cross-scale modeling, as they often exhibit more complex hydrodynamic process than the open waters



- Tidal amplification is widely observed in funnel-shaped tributaries
- Tidal resonance may exist in certain tributaries
- Bottom friction typically dominates tidal damping in shallow regions
- Creeks/tributaries are often highly turbid

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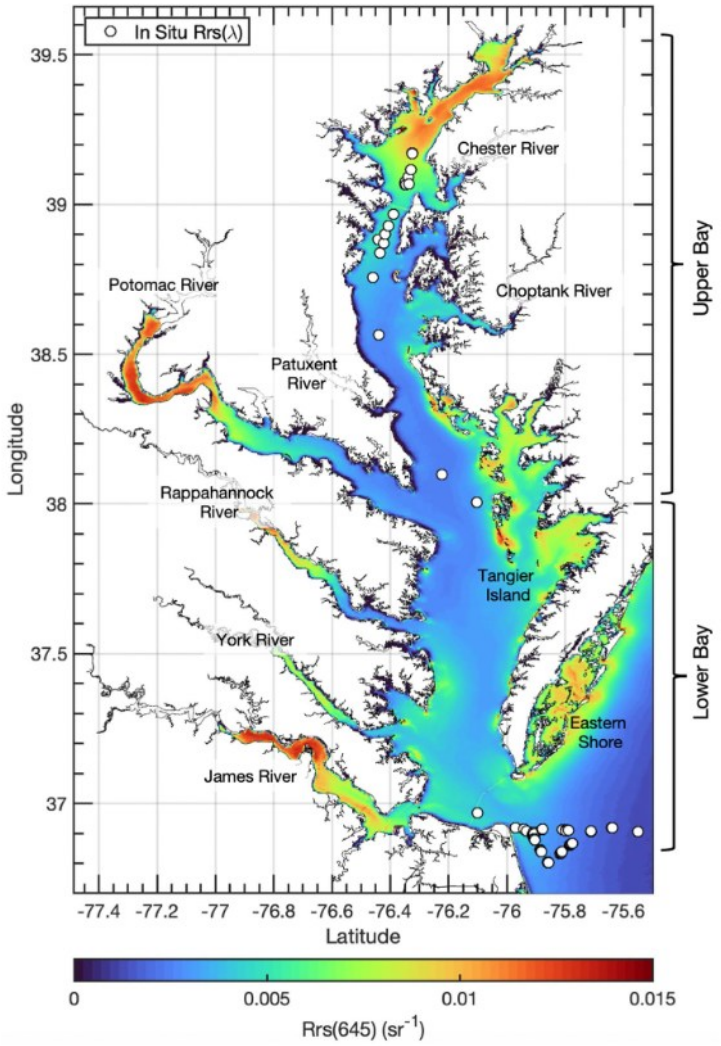
- Accurate bathymetry and high spatial resolutions are required to resolve these small-scale features
- Important to capture the original bathymetry without smoothing (Ye et al. 2018; Cai et al. 2021; Zhang et al. 2024), as done in MBM

Background: challenges in cross-scale modeling

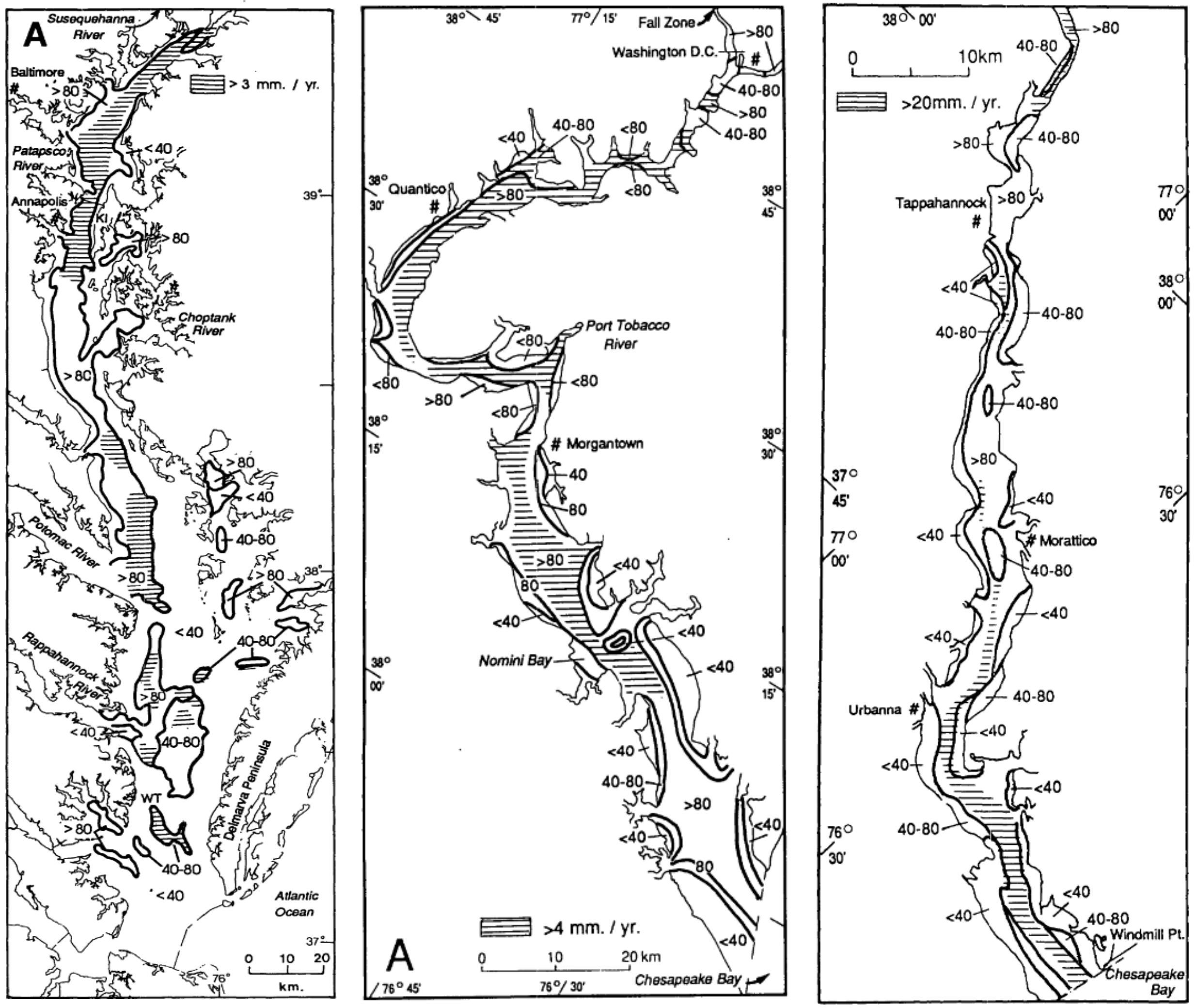
- Hydrological characteristics in a cross-scale estuary continuum exhibit significant spatial heterogeneity (e.g., water clarity & sediment types)

Water clarity in the Bay



Turner et al. (2001)

Mud content in the Main bay, Potomac, and Rappahannock Rivers

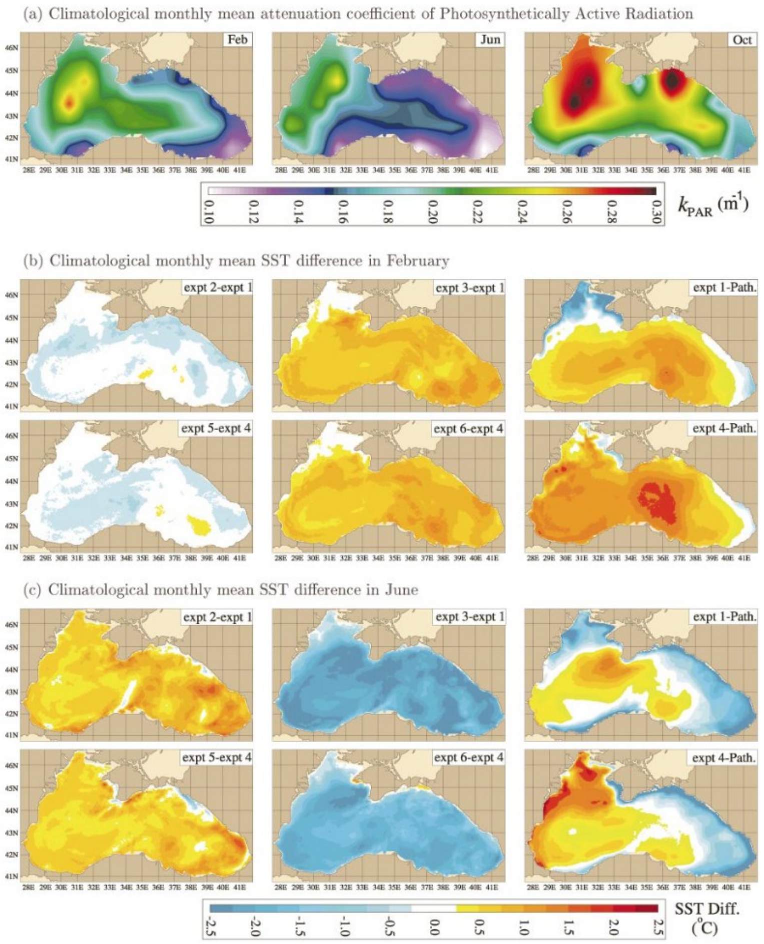


Nicolas et al. (1991)

Background: water clarity

- Previous studies have shown the importance of water clarity on temperature simulations

Black Sea (Kara et al., 2005)



Baltic Sea (Löptien & Meier, 2011)

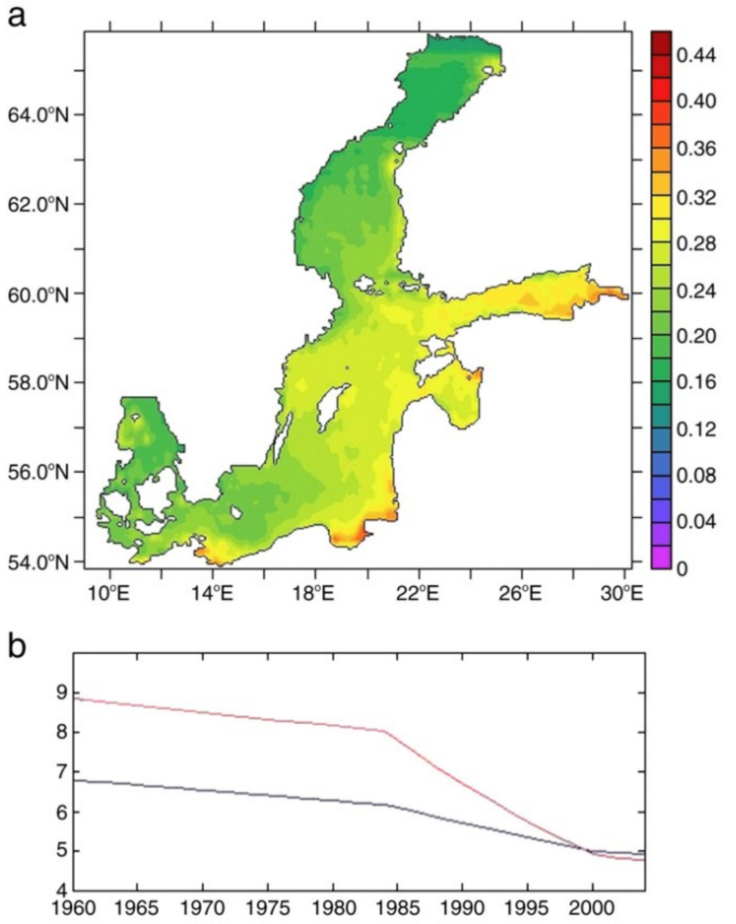
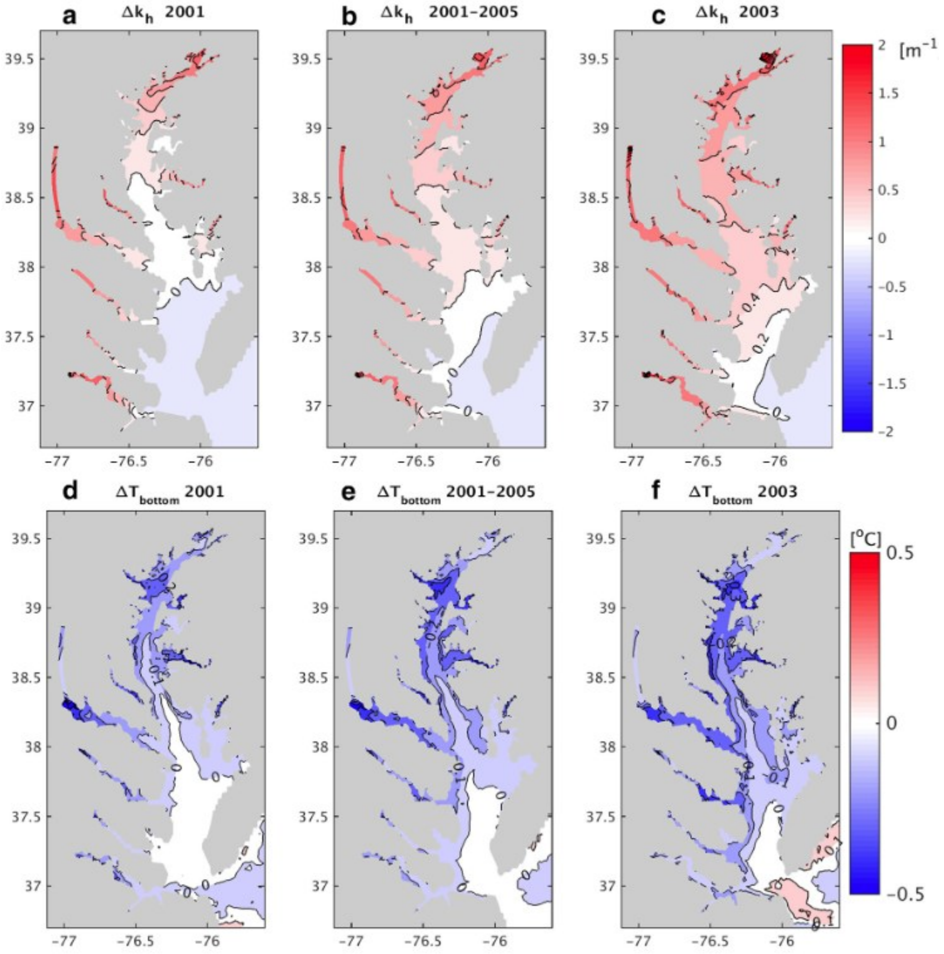


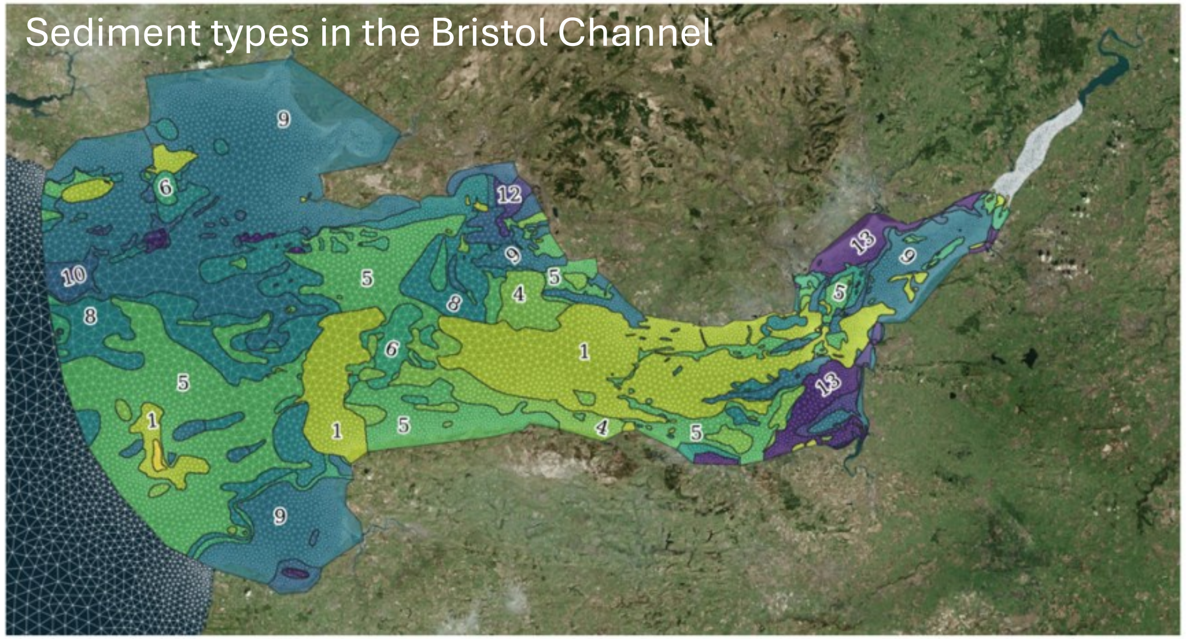
Fig. 1. (a) Climatological mean value of KD_v in summer (JJA) in m^{-1}. (b) Assumed trends in Secchi depth for the experiments TREND1 (blue line) and TREND2 (red line) in the Baltic proper in July.

Chesapeake Bay (Kim et al., 2020)



Background: sediment types

- [Warder et al. (2022)] improved the tidal range simulation in Bristol Channel using sediment-dependent bottom roughness



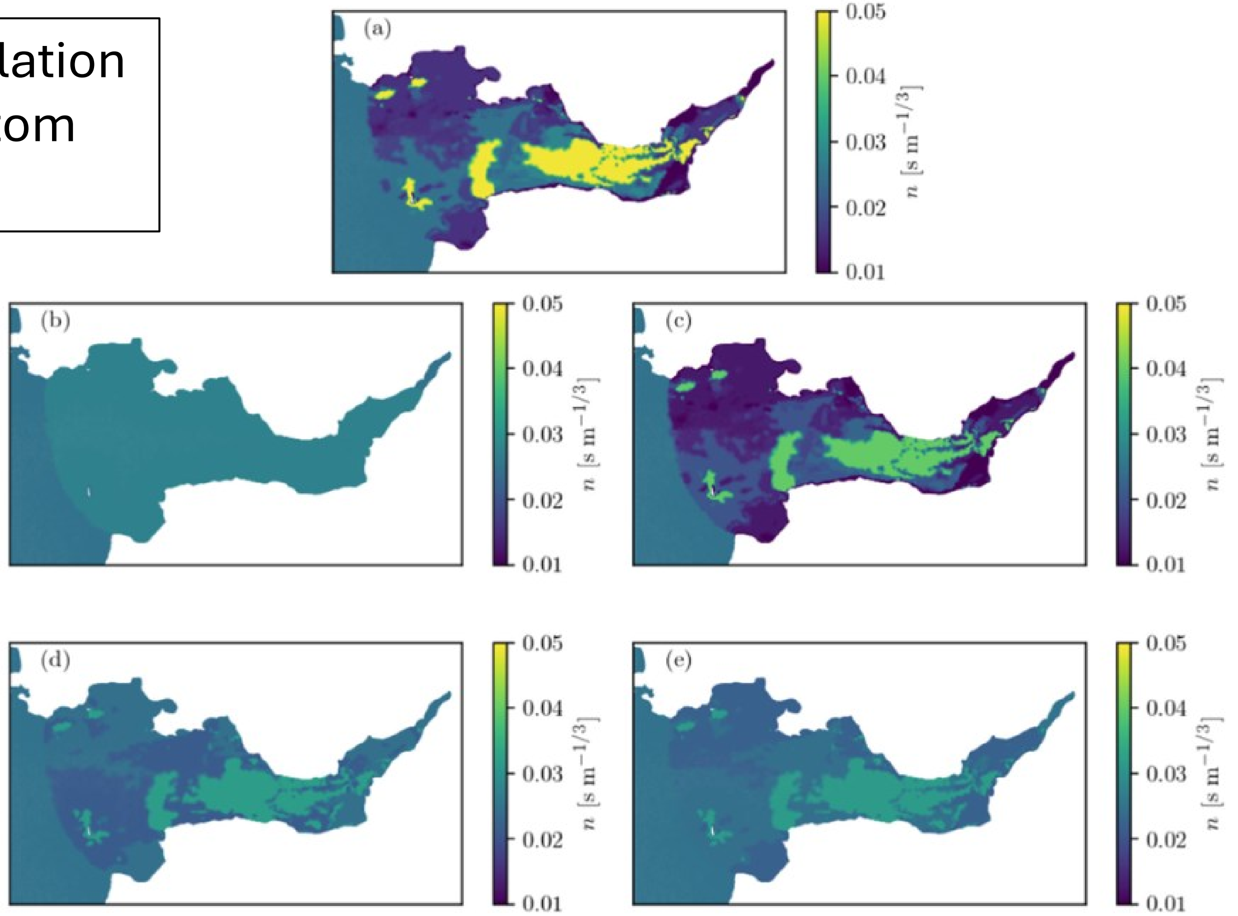


Fig. 5 Manning coefficient fields used for model validation. **a** Standard sediment-based parameters. **b** Result of experiment A. **c** Result of experiment B. **d** Result of experiment C1. **e** Result of experiment C2

Warder, S. C., Angeloudis, A., & Piggott, M. D. (2022). Sedimentological data-driven bottom friction parameter estimation in modelling Bristol Channel tidal dynamics. *Ocean Dynamics*, *72*(6), 361-382.

Background: Chezy-Manning formulation

- Spitz and Klinck (1998) applied Chezy-Manning formula to improve the tidal simulation in the Chesapeake Bay, but with a constant Manning's coefficient (n=0.02)

In practice, the bottom drag coefficient c_D varies with water depth, seabed composition and phase of the tide. It is parameterized as

$$c_D = \frac{g}{C^2}, \qquad C = \frac{h^\alpha}{n}, \tag{7}$$

where h is the undisturbed water depth, C ($\mathrm{m}^{1/2}\ \mathrm{s}^{-1}$) is the Chezy coefficient, and n is the Manning's roughness [*Officer*, 1976]. Typical values for α and n are 1/6 and 0.02, respectively, giving a drag coefficient of ~ 0.002 for a depth of 10 m. The two parameters α and n only depend on time and are estimated during the assimilation procedure.

The equations are solved by means of finite difference analogs [*Ozer et al.*, 1990] on a uniform staggered grid (Arakawa C-grid) The time-stepping scheme is a semi-implicit, alternate direction method (ADI) [*Beckers and Neves*, 1985], which is unconditionally stable

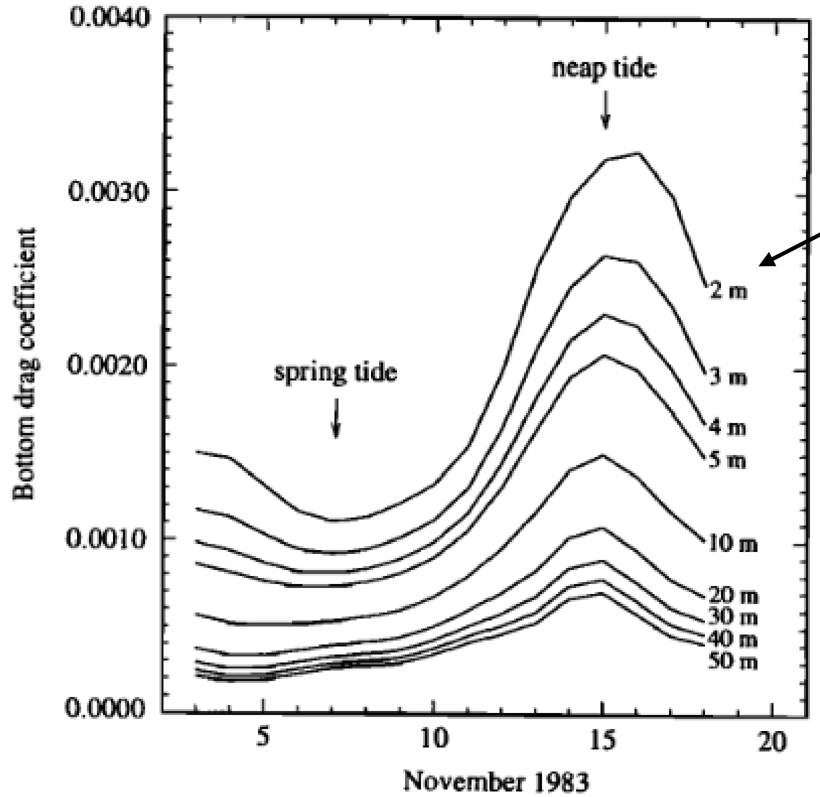
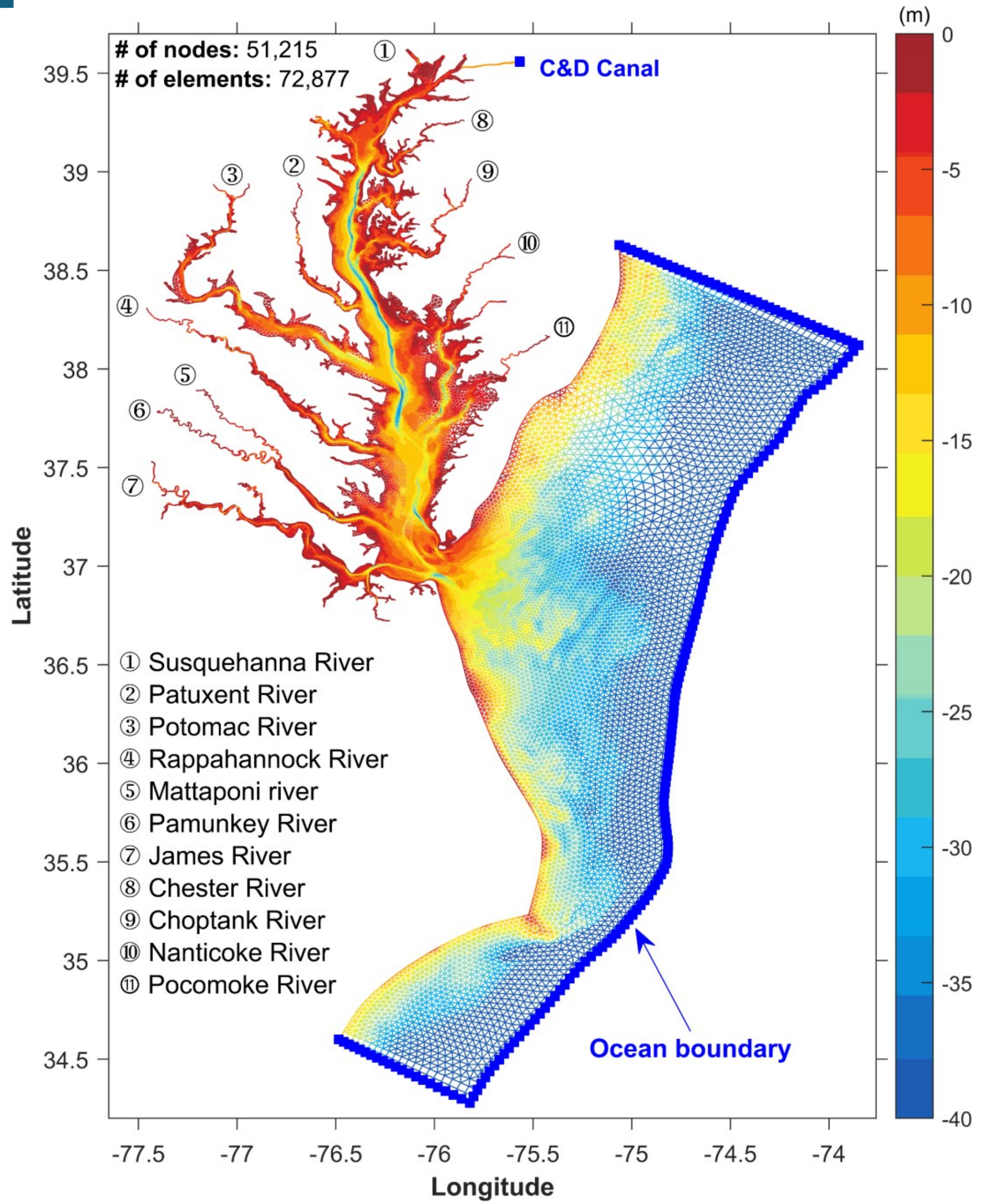


Figure 12. Time series of estimated bottom drag coefficient c_D for depths between 2 and 50 m.

Higher bottom drag in shallow waters

Spitz, Y. H., & Klinck, J. M. (1998). Estimate of bottom and surface stress during a spring-neap tide cycle by dynamical assimilation of tide gauge observations in the Chesapeake Bay. *Journal of Geophysical Research: Oceans*, *103*(C6), 12761-12782.

Model baseline: MBM



Bathymetry: integrate multiple datasets (e.g., BlueTopo, CoNED)

Atmospheric forcing: ERA5 dataset

Initial Condition: <u>from previous long-term run</u>

- **Open boundary#1: Ocean boundary**

GLORYS-Reanalysis

Boundary inputs: temperature, salinity , and sub-tidal elevation/velocity

Boundary nudging: temperature, salinity

Tidal forcing: FES2014

- **Open boundary#2: C&D canal**

ET2.1 (CBP station)

temperature, salinity

Reedy Point, DE (NOAA CO-OPS water level station)

sub-tidal elevation

Experiment design

Table 1. The sensitivity experiments with varying water types and bottom drag coefficients.

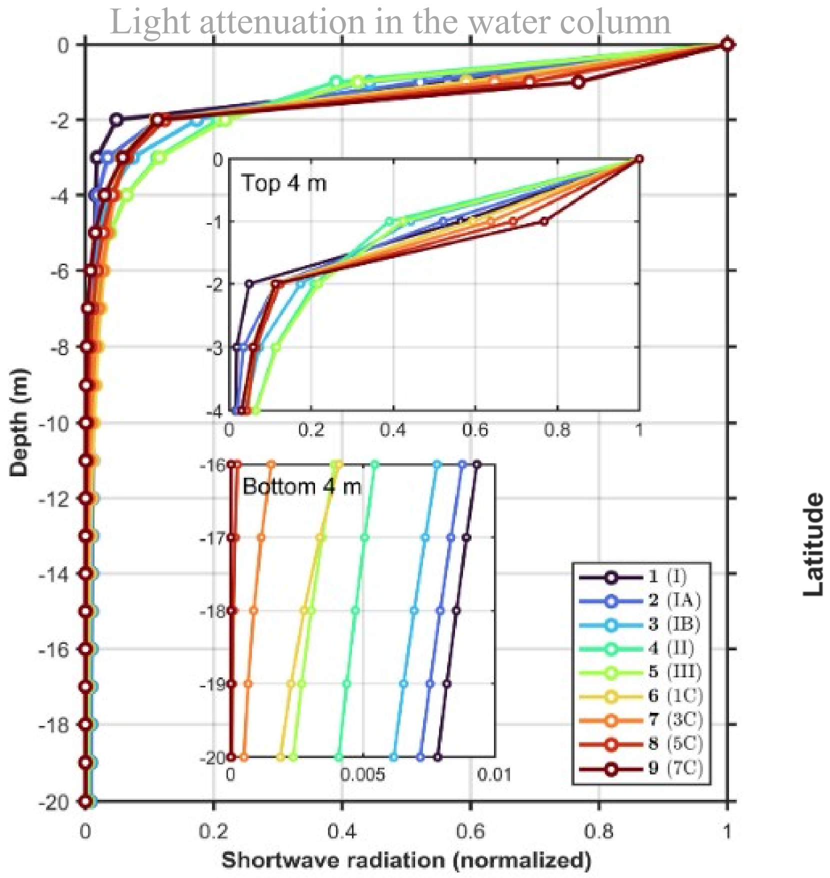
Experiment	Water type	Bottom drag coefficient
RUN01a (base run)	Type 4 (moderate turbidity)	$C_d = 0.0025$
RUN02a	Type 7 (high turbidity)	$C_d = 0.0025$
RUN02b	Type 4	Chezy-Manning ($n = 0.02$)
RUN03a	Kd490-dependent	$C_d = 0.0025$
RUN03b	Type 4	Chezy-Manning (n is sediment-dependent)
RUN04a (calibrated run)	Kd490-dependent	Chezy-Manning (n is sediment-dependent)

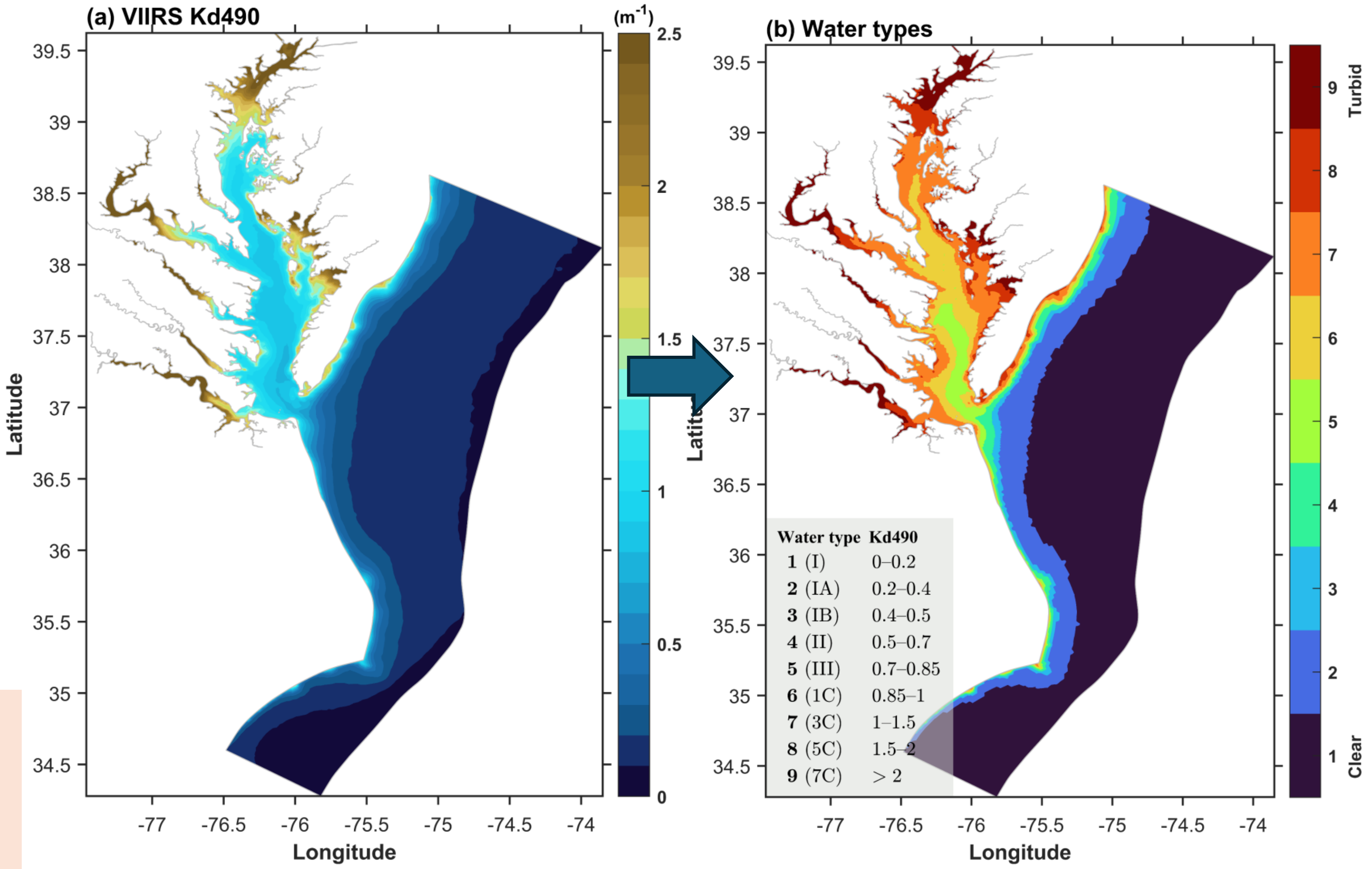
n = 0.02 essentially assumes a purely sandy seabed in the entire domain

- ❑ **RUN01a** (base run) aims to expose the cross-scale modeling challenges in the Bay
- ❑ **RUN02a/2b** does NOT consider the spatial heterogeneity of turbidity/sediment
- ❑ **RUN03a/3b** considers the spatial heterogeneity of turbidity/sediment
- ❑ **RUN04a** shows the integrated performance of combined approaches

Jerlov water types

- ❑ A pronounced spatial gradient of turbidity exists across the domain





- ➢ In clear water, shortwave radiation penetrates deeper, potentially heating the seabed in shallow regions.
- ➢ In turbid water, shortwave radiation is largely absorbed by the upper layers.

Bottom drag coefficient (C_d)

❑ Chezy-Manning formulation

$$Cd = \frac{n^2 g}{\max(h, 5)^c}$$

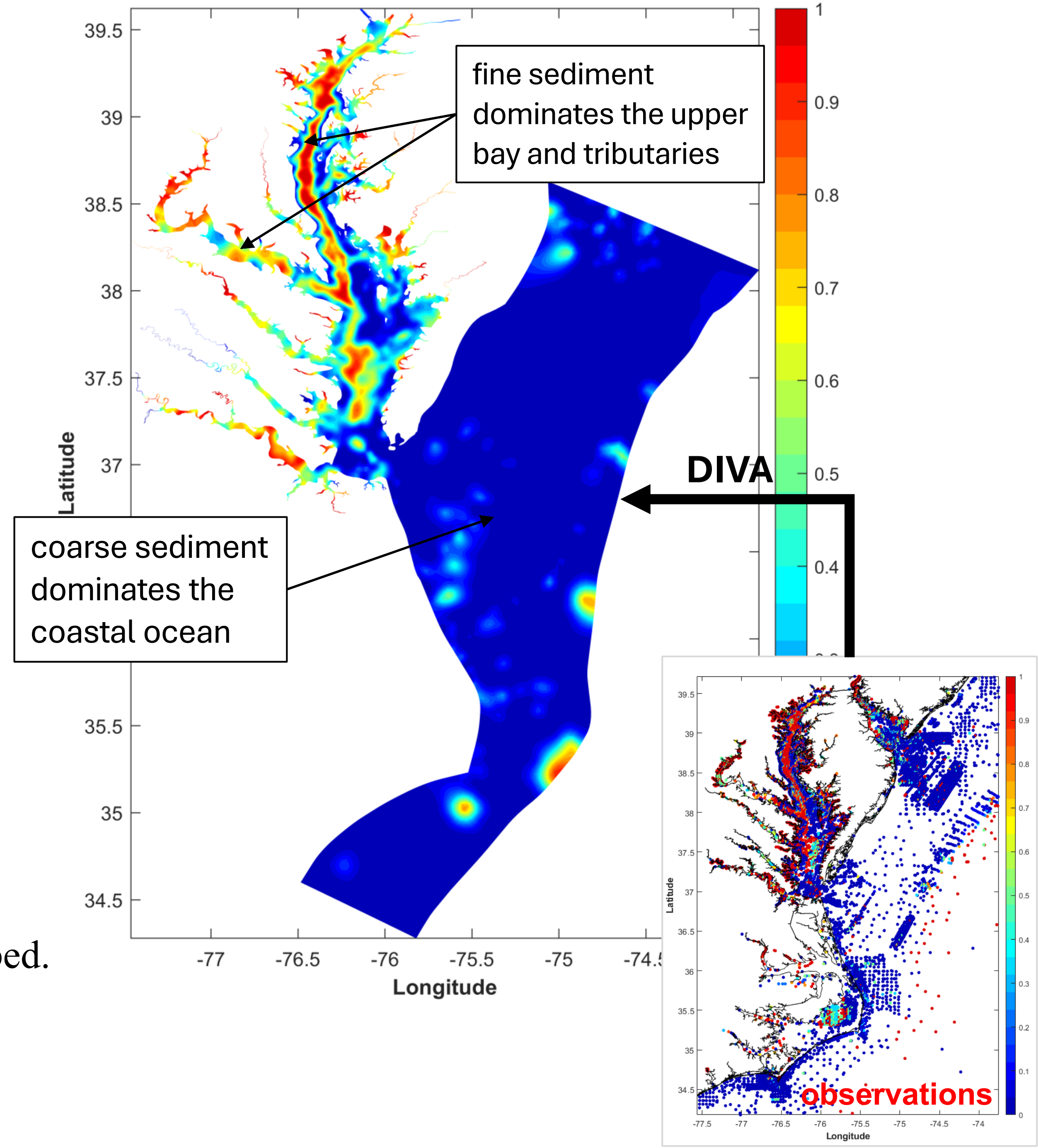
n is manning coefficient;
h is the water depth;
g is the gravitational acceleration (9.810);
c is a constant (1/3);

sediment-weighted average manning coefficient:

$$n = R_{mud}*0.01 + R_{sand}*0.02 + R_{gravel}*0.03$$

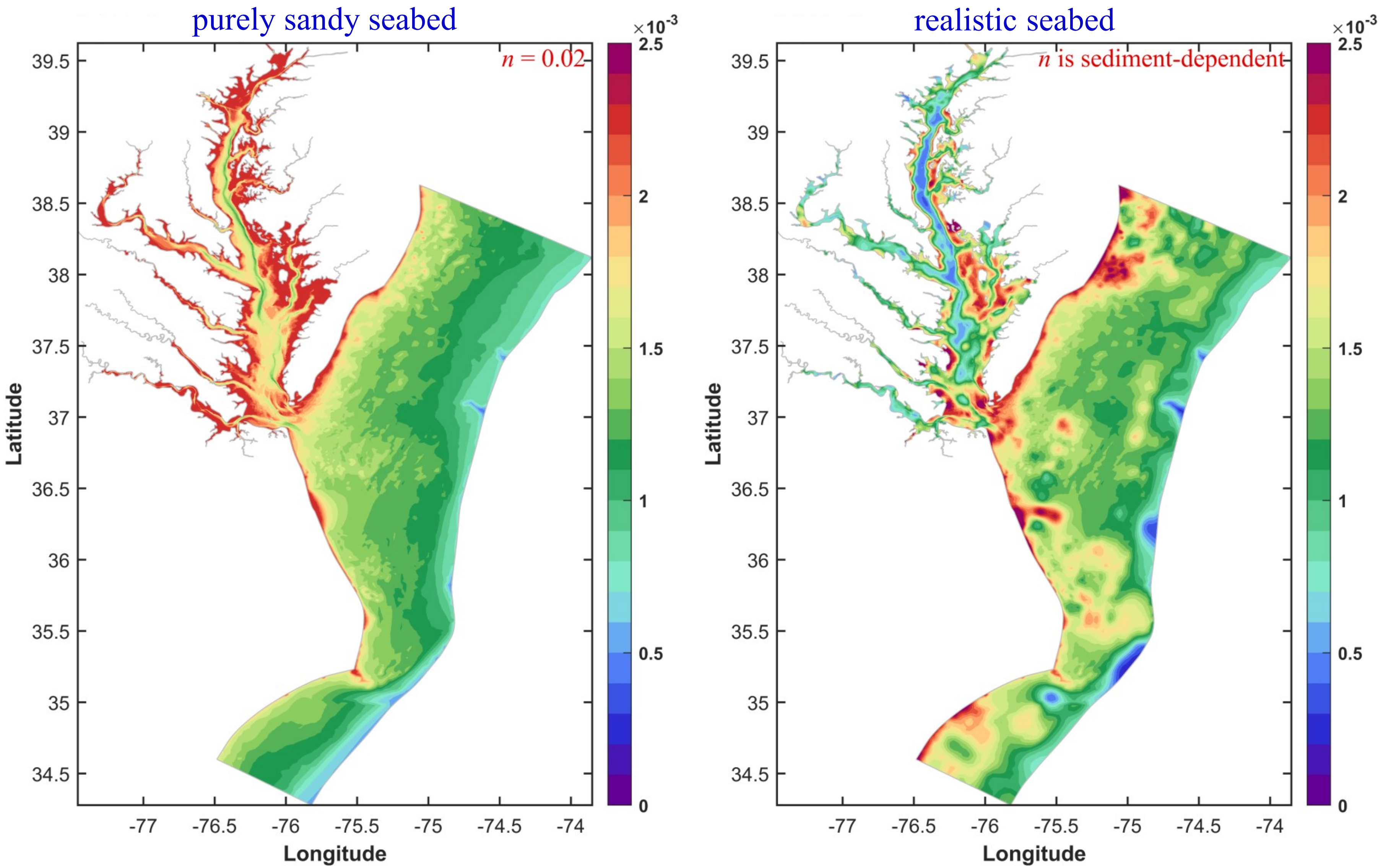
where R is the proportion (0-1) of mud/sand/gravel at the seabed.

Mud content (0-100%) in the model domain

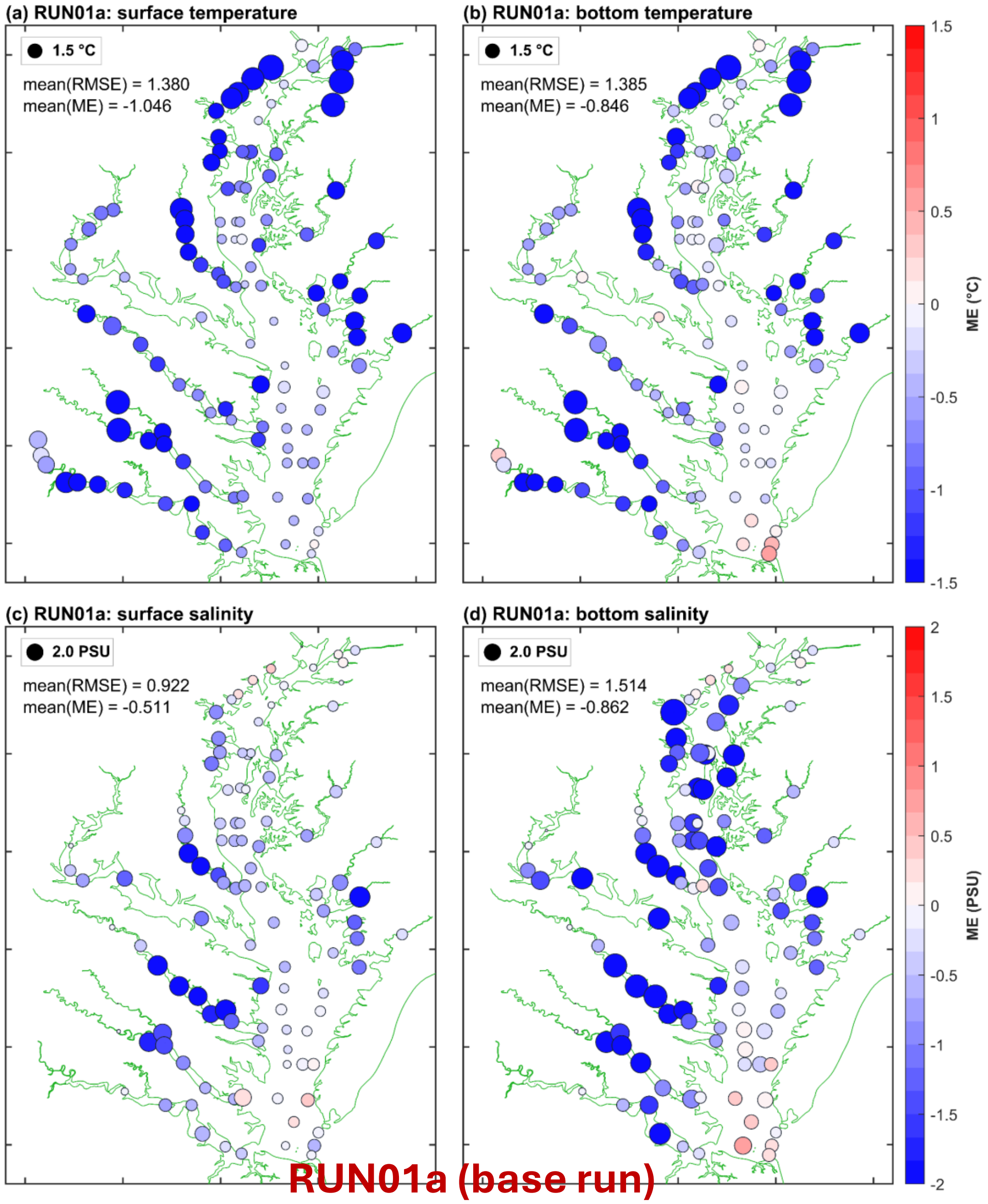


Bottom drag coefficient (C_d)

- *n=0.02* yields much higher C_d values in the Bay (especially in the tributaries), mostly due to shallow water depths there.



Challenges in baseline simulations: hypotheses



Temperature shows notable underestimation

- More notable in the surface layer (*ME* = -1.046)
- More notable at upstream stations of tributaries

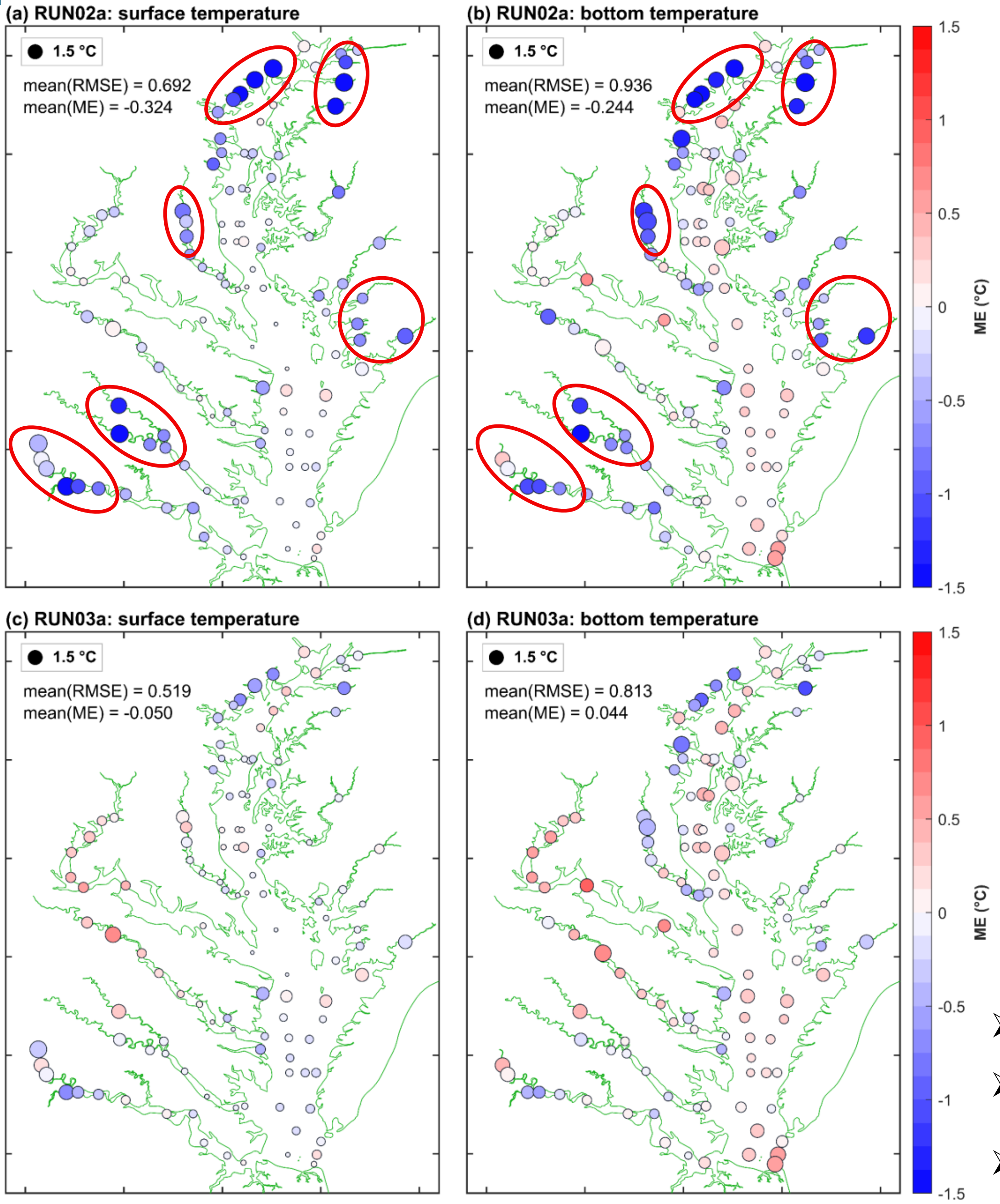
Temperature errors primarily originate from the surface process?

Salinity also shows notable underestimation

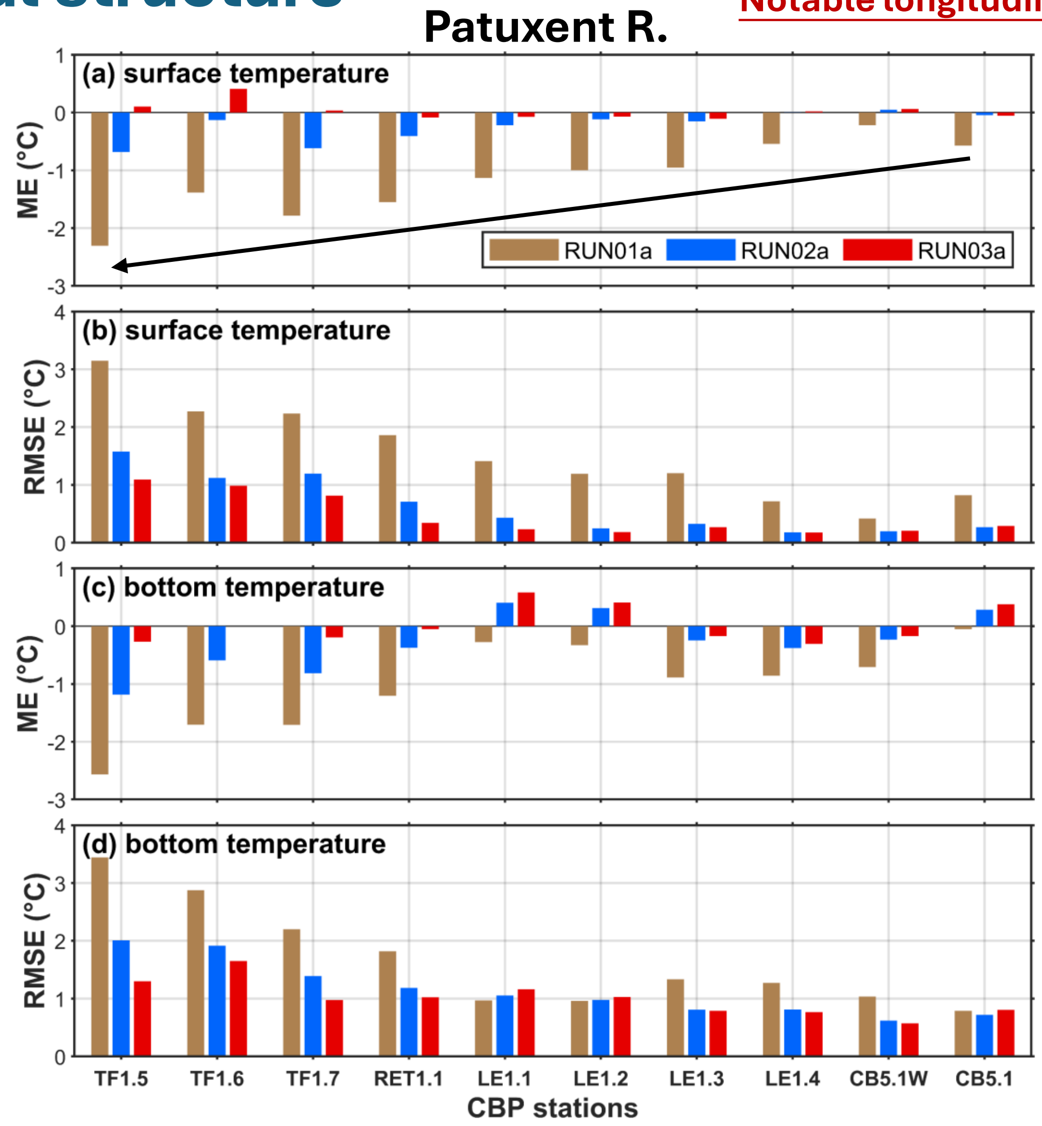
- More notable in the bottom layer (*ME* = -0.862)
- More notable in the upper bay and tributaries

Salinity errors primarily originate from the bottom process?

Effect of water turbidity on thermal structure

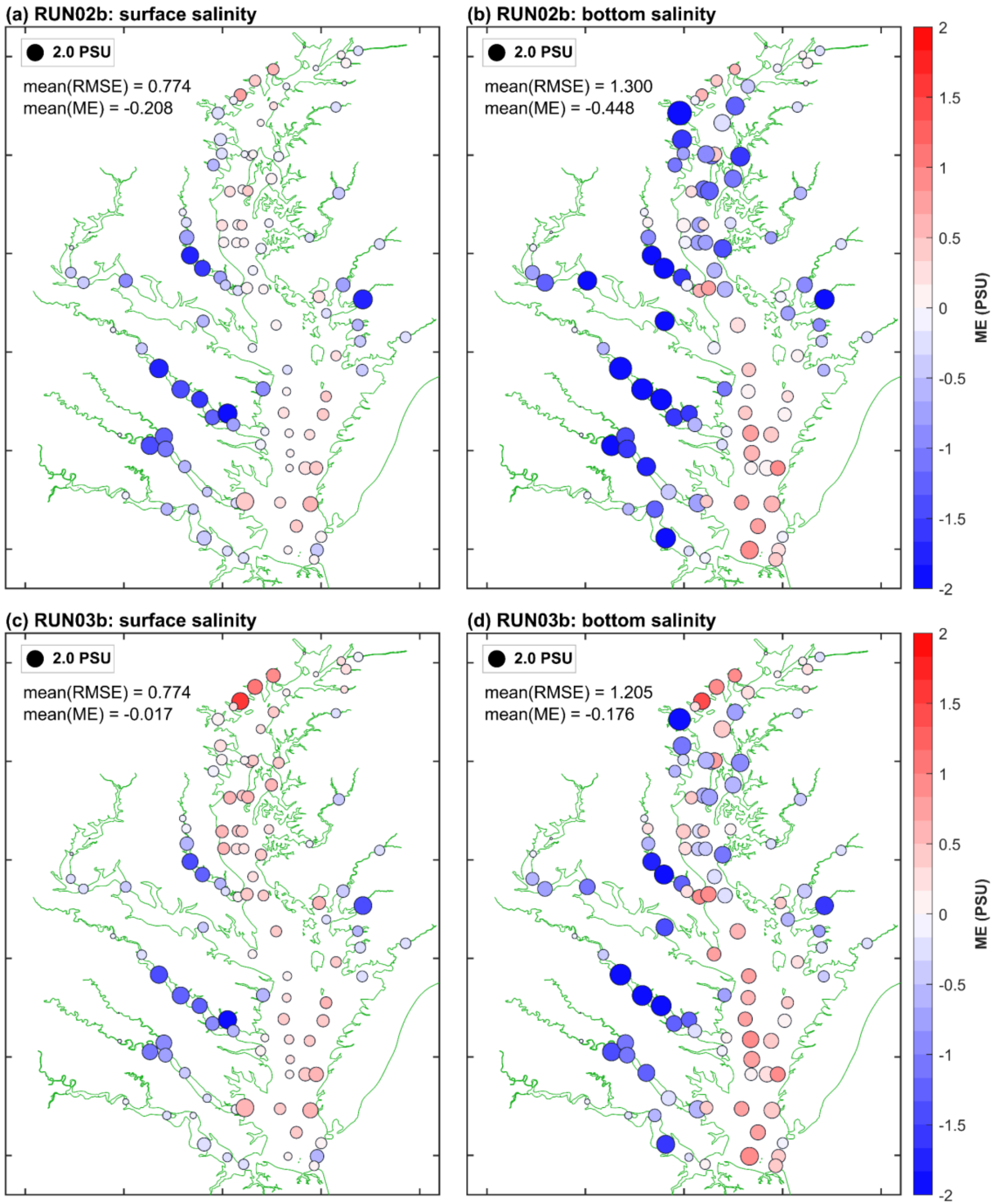


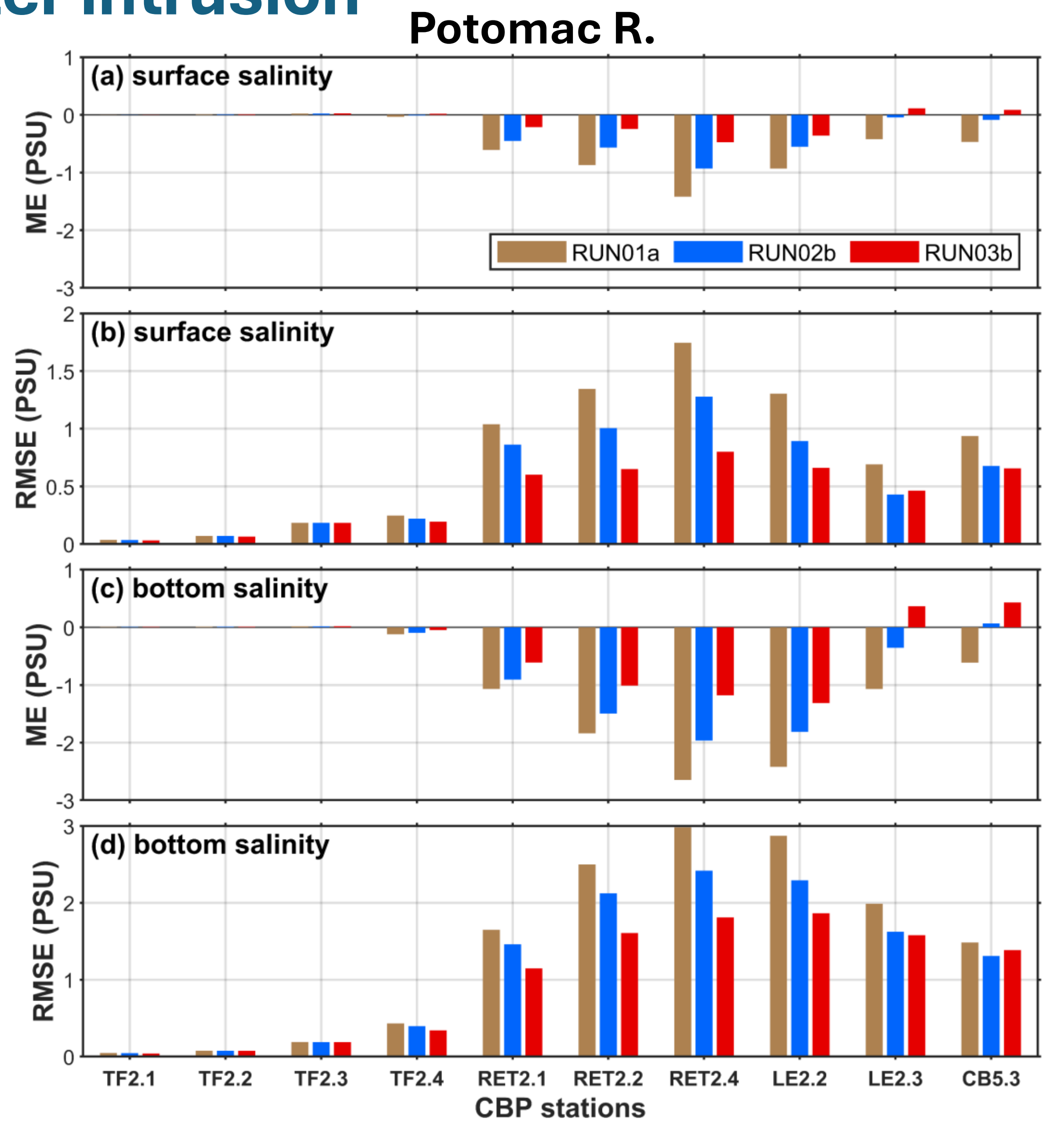
Notable longitudinal feature



- Larger water types can effectively mitigate the temperature underestimation
- **RUN02a (single type)** did not address temperature underestimation in highly-turbid tributary heads
- **RUN03a (various type)** well addressed this issue

Effect of sediment types on saltwater intrusion

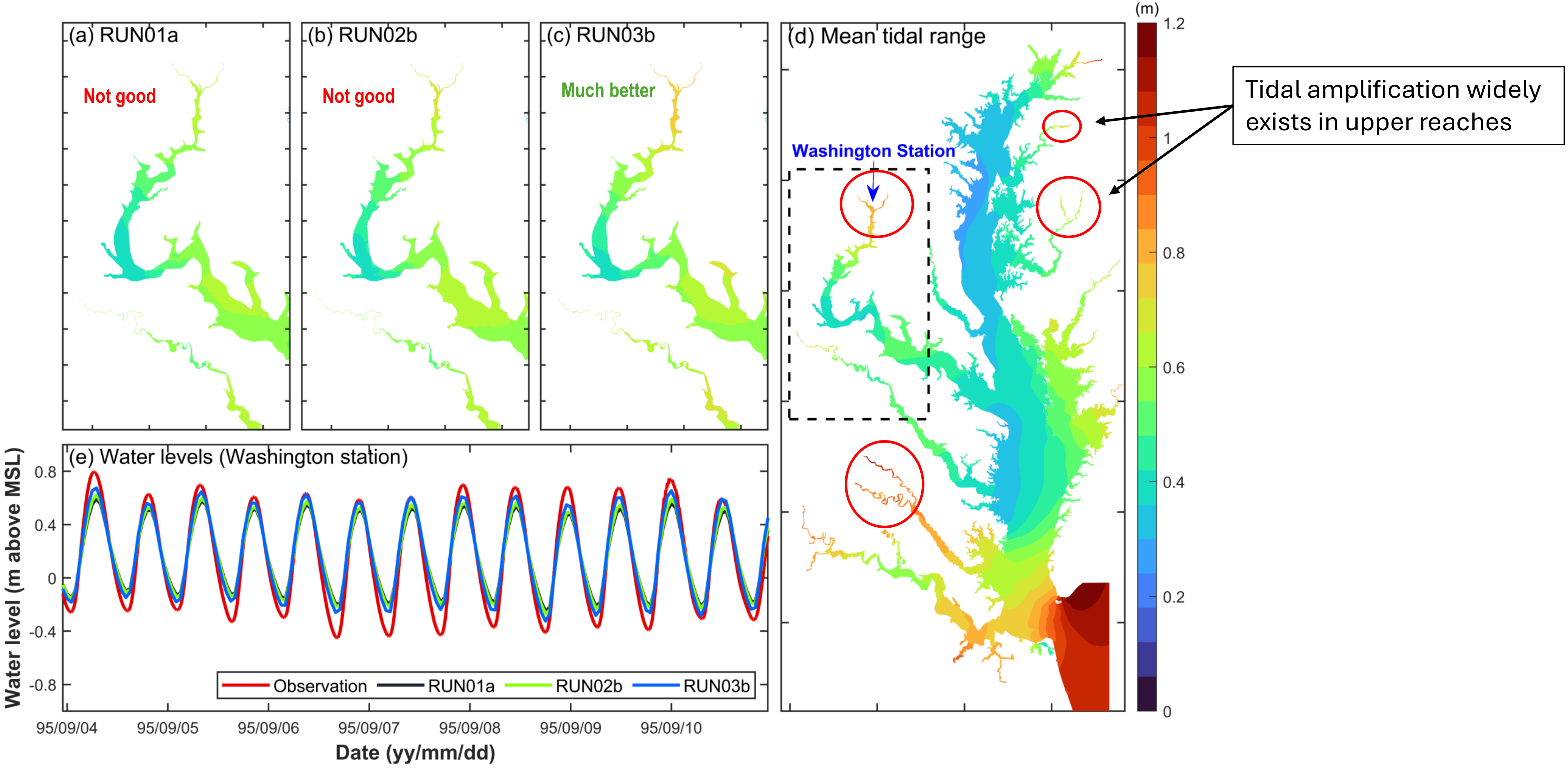




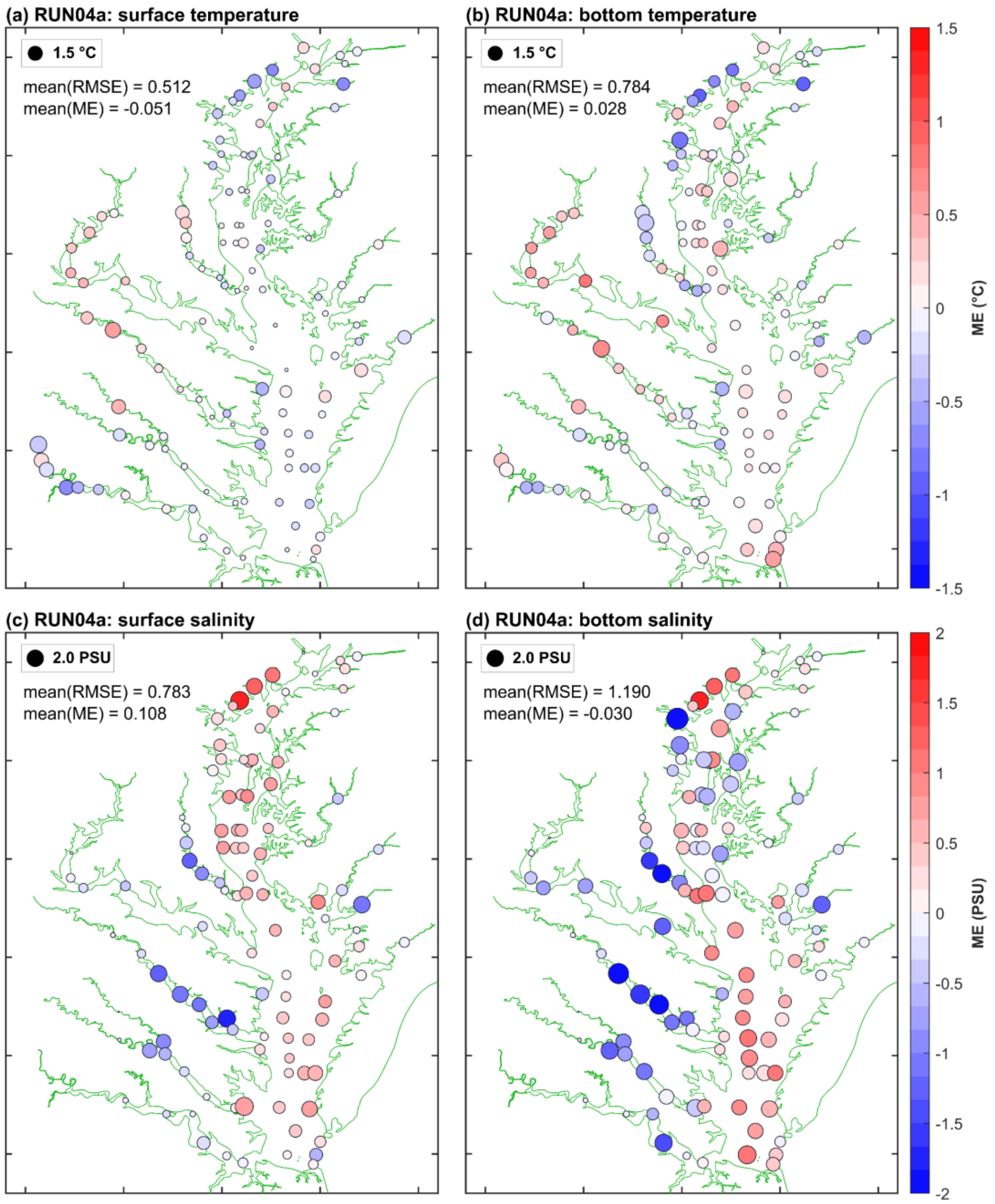
- RUN02b (const *n*) and RUN03b (variable *n*) improve the weak saltwater intrusion
- RUN03b works better for improving saltwater intrusion into upper bay and tributaries

Effect of sediment types on tides

❑ Improved tidal range is a key to saltwater intrusion simulation



Performance of the fully-calibrated run



RUN04a (fully calibrated)

Summary for all experiments

Experiment	RMSE (SST/BT)	RMSE (SSS/BS)
RUN01a	**1.380 (1.385)**	**0.922 (1.514)**
RUN02a	0.692 (0.936)	
RUN02b		0.774 (1.300)
RUN03a	0.519 (0.813)	
RUN03b		0.774 (1.205)
RUN04a	**0.512 (0.784)**	**0.783 (1.190)**

- ✓ **RUN04a** outperforms all other experiments, highlighting the effectiveness of physically based calibration.

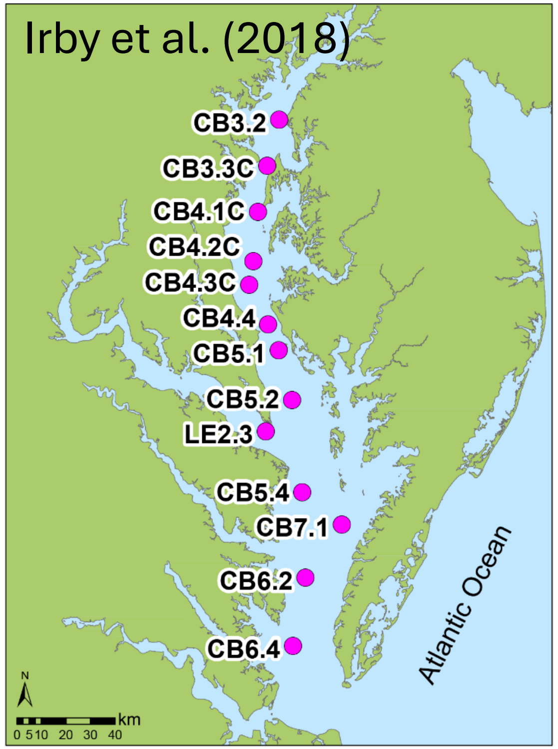
Inter-model comparisons

- **These comparisons further demonstrate the effectiveness of the physically based calibration strategies used in this study.**

Table 2. RMSEs of temperature (T) and salinity (S) from different modeling studies based on the CBP observations. The values outside/inside the parentheses are surface/bottom RMSEs, respectively. Asterisks (*) indicate the studies that calculate RMSE over the full water column.

Reference	RMSE (T, °C)	RMSE (S, PSU)	Simulation period	# of CBP stations
Cerco & Noel (2004)	1.76 (1.94)	1.90 (2.12)	1991–2001	121
Lanerolle et al. (2009)	1.10 (1.18)	2.04 (2.29)	2003–2005	35
*Hoffman et al. (2012)	1.40	2.50	2003	4
*Xu et al. (2012)	1.28	2.28	1991–2005	4
*Urquhart et al. (2013)	1.39	2.47	2003; 2007	12
Irby et al. (2018)	1.23 (2.22)	1.86 (2.17)	1993–1995	23
Cai et al. (2022)	1.47 (2.05)	2.08 (2.04)	1991–1995	62
The present study (RUN04a)	0.33 (0.72)	0.84 (1.48)	1994–1997	23 (mainstem stations)
	0.51 (0.78)	0.78 (1.19)	1994–1997	121

Tributary stations are rarely included in previous evaluations



✓ Temperature/Salinity RMSEs are reduced by ~60% compared to previous studies

Conclusions

- Physically-based calibration strategies are important for cross-scale simulations
  - Builds confidence on models
  - Faithful to original DEM

- This study achieved significant improvements in the cross-scale hydrodynamic simulation of the Chesapeake Bay

- The spatial heterogeneity of hydrological elements (e.g., turbidity and sediment types) needs to be carefully considered in cross-scale simulations

- Limitations/Future work:

  1) Temporal variation of bottom drag/water clarity; 2) Sediment stratification effect on bottom drag;
  3) SAV effect on the bottom drag; 4) Velocity effect on the bottom drag