Effects of sea level rise on hypoxia in the Chesapeake Bay

A model intercomparison

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Modeling hypoxia in Chesapeake Bay

Models allow us to focus on specific parameters influencing future hypoxia:
TMDL, Sea Level Rise (SLR), river discharge $\nearrow$,
water temperature $\nearrow$...

Temperature has the largest impact on hypoxia, but here we focus on **SLR** specifically.

- A +0.50 m increase in SL (year 2050) decreases summer anoxia (DO $< 0.2\,\mathrm{mg\ L^{-1}}$). (Regulatory model CH3D-ICM, Wang et al. 2017)
- A +0.50 m increase in SL improves bottom DO in specific regions. (ChesROMS-ECB, Irby et al. 2018)
- a +0.50 m increase in SL increases both hypoxia and anoxia. (UMCES-ROMS-RCA, Ni et al. 2017)

Model intercomparison to **clarify impact of SLR on hypoxia**.
4 models, *same methodology*.

Methods

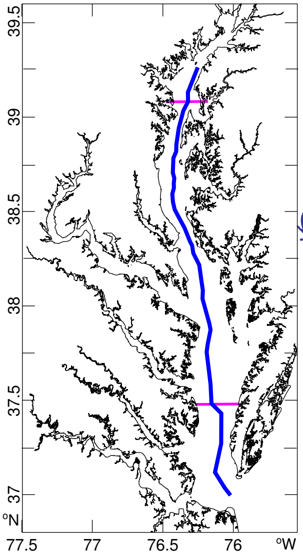
Table: Model experiments conducted in the study. The experiments are identical to the reference simulation except for the change in sea level (SL). Experiments for which model results are available are indicated by the X symbol. All four model experiments have a duration of 1826 days (5 years).

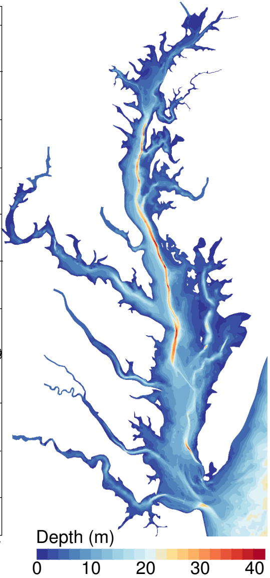
Model experiment	CH3D-ICM	ChesROMS-ECB	UMCES-ROMS-RCA	SCHISM-ICM
1. Reference run (1991–1995)	X	X	X	X
2. ΔSL $= +0.17$ m (ca. 2025)	X	X	X	X
3. ΔSL $= +0.50$ m (ca. 2050)	X	X	X	X
4. ΔSL $= +1.00$ m (ca. 2100)		X	X	X

All models assume the **same riverine fluxes**. Experiments are preceded by a spin-up. Results presented as **monthly climatology** for each of the four experiments.

Results of ChesROMS-ECB & UMCES-ROMS-RCA were directly available for analyses. Other participants conducted analyses ‘in house’ and provided figures for intercomparison.

Methods





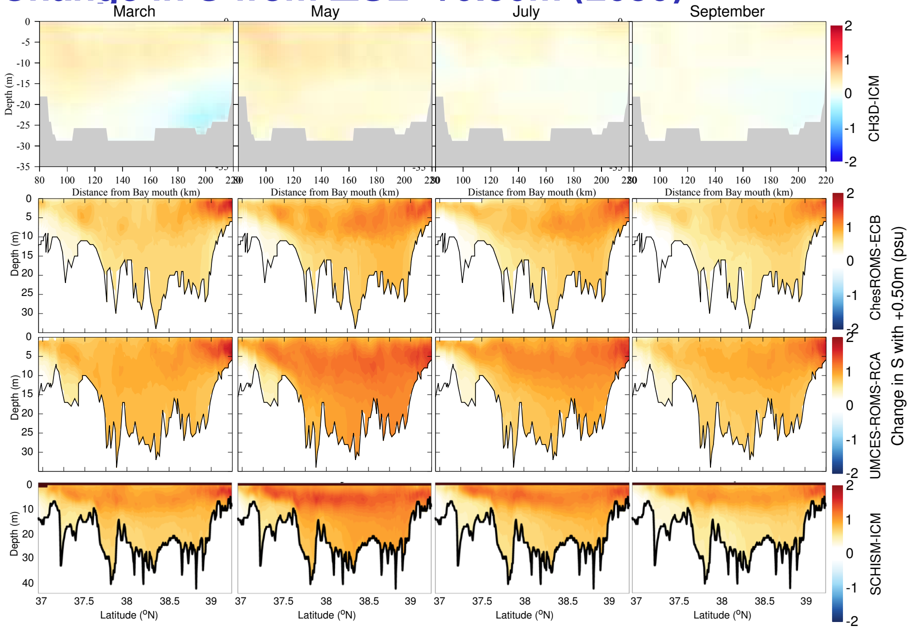
← Bathymetry of Chesapeake Bay:

Deep channel with residence time $>$ 200 days (see Du & Shen 2015).

Hypoxia is concentrated along the channel.

Figures: South→North **transect**.

Change in S from ΔSL=+0.50m (2050)



≈No seasonality

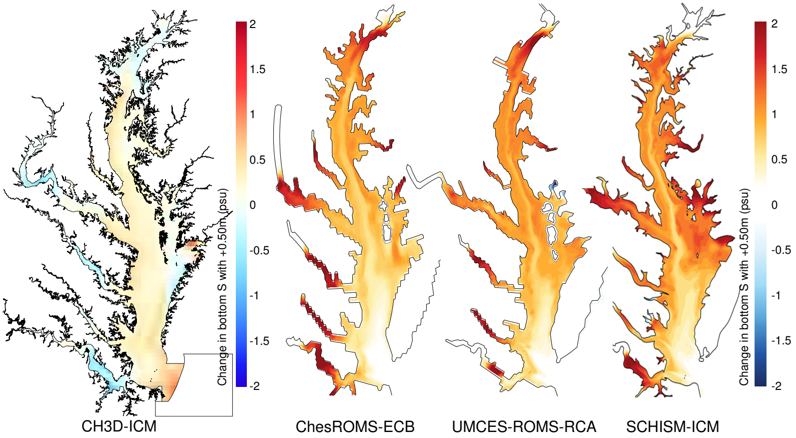
S increases throughout water column

Increase is strongest in the upper 10 m

ΔS amplified by SLR but patterns remain the same

CH3D-ICM shows smaller changes.

Change in July bottom S from ΔSL=+0.50m (2050)



A Bay-wide perspective:

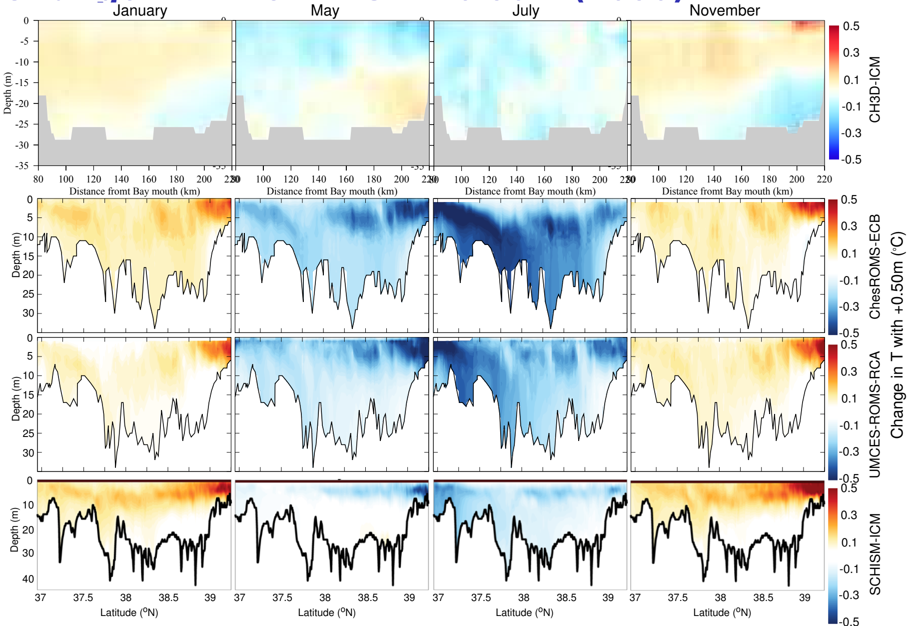
$\approx$No changes in bottom S on the shelf (except CH3D-ICM)

Changes are largest where bottom depth $\lesssim$ 10 m

Reasonable agreement between models

Similar to earlier studies (Hong & Shen 2012).

Change in T from ΔSL=+0.50m (2050)



Seasonal pattern:

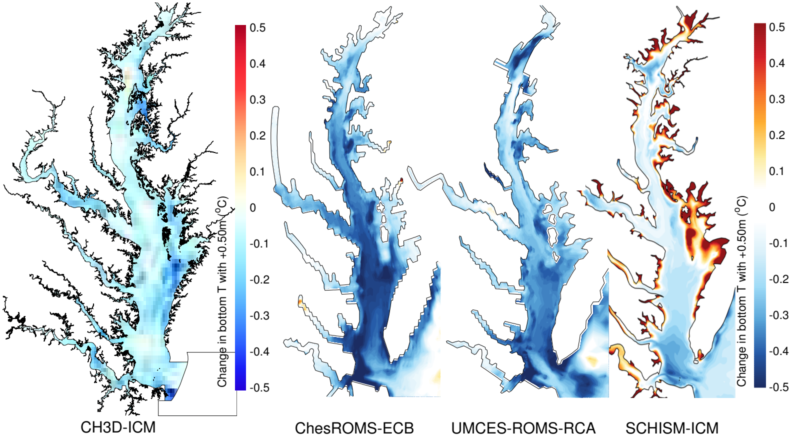
Warmer in winter

Cooler in summer

Amplified by SLR but patterns same

Some variations in magnitude, vertical structure

Change in July bottom T from ΔSL=+0.50m (2050)



A Bay-wide perspective:

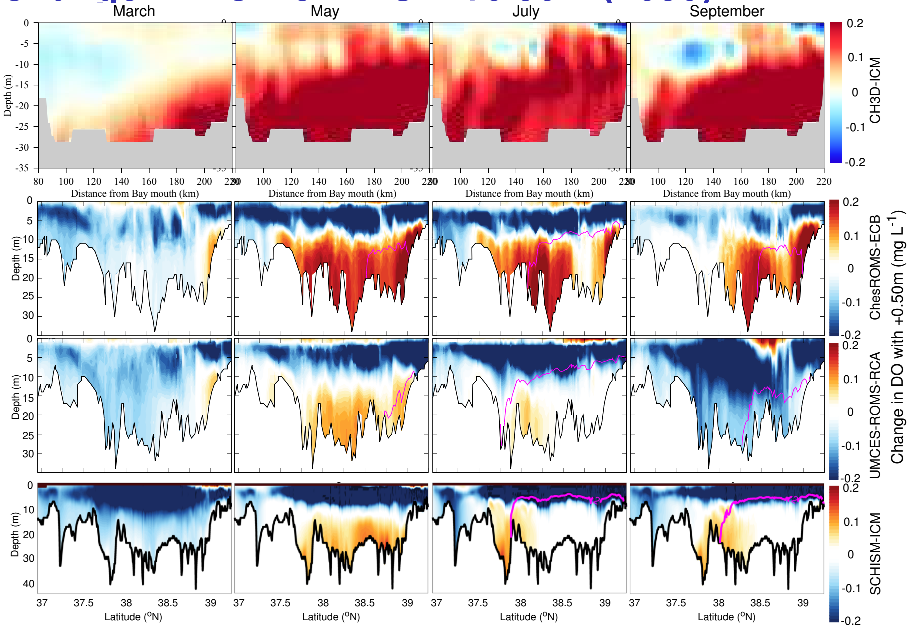
"Summer cooling" affects **entire Bay** at once.

"Summer cooling" strongest in ChesROMS-ECB, weakest in SCHISM-ICM.

No obvious patterns between regions.

Main disagreement: SCHISM-ICM shows $\Delta T > 0$ in nearshore regions.

Change in DO from ΔSL=+0.50m (2050)



In most cases:

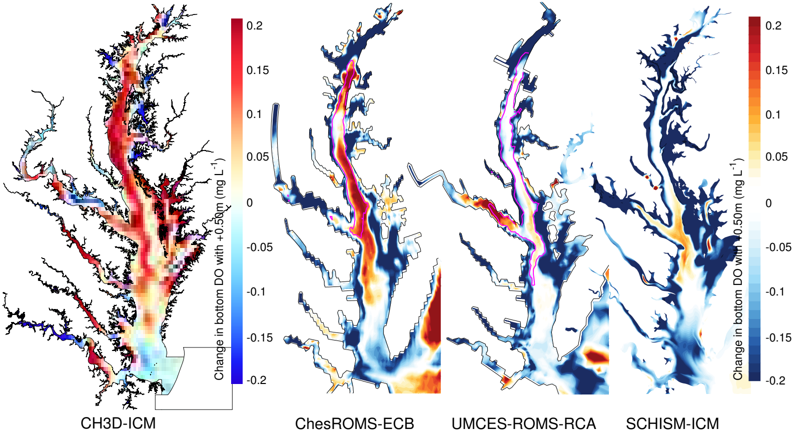
< 0 above 10m,
≥ 0 below 10m

Similar features in May, but models diverge in following months.

Magnitude of the improvement in bottom DO:

CH3D-ICM
$>$ChesROMS-ECB
$>$SCHISM-ICM
$>$UMCES-RCA

Change in July bottom DO from ΔSL=+0.50m (2050)



A Bay-wide perspective in July:

In most cases:

$<$ 0 in water shallower than 10m,

$\geq$ 0 where water is deeper than 10m (deep channel, Potomac R.)

$\therefore$ All 4 models suggest *some* improvement in bottom DO (particularly in May), but its magnitude and duration differ substantially.

Solubility of oxygen

- Solubility of O_2 is often **a driver of ΔDO** in climate studies.

- $DO_{sat}(T, S)$: $T \nearrow$ $DO_{sat} \searrow$
  $S \nearrow$ $DO_{sat} \searrow$

- $\Delta T \sim -0.3°C$ $\Delta S \sim +0.7\,\mathrm{psu}$ (+0.50 m)

  $\Delta DO_{sat} \sim +0.04\,\mathrm{mg\,L^{-1}}$ (cooling)
  $\Delta DO_{sat} \sim -0.03\,\mathrm{mg\,L^{-1}}$ (salifying)

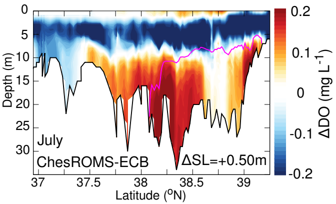
- SLR causes **small** changes in solubility.

  Same conclusion when generalizing this calculation to all months/depths/scenarios.

Changes below 10 m depth

Key feature:

$\Delta DO \geq 0$
below 10m



Why does SLR produce this anomaly?

Oxygen budget for the **bottom layer of the deep channel**:

$$\frac{\partial}{\partial t} \iiint \text{DO}\, dV = \textit{Transport} + \textit{Respiration}$$

See, e.g., Li et al. 2015, 2016.

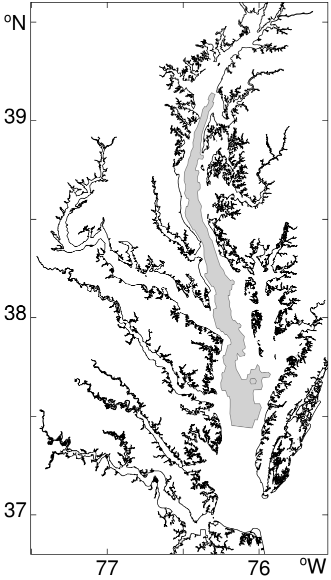
Transport (> 0): *Net effect* of DO advection and DO diffusion.

Respiration (< 0): Water-column respiration + sediment oxygen demand.

"Bottom layer" defined as depths > 10 m (i.e., a control volume of fixed size.)

No "production" term (below euphotic depth).

Changes below 10 m depth



← Control volume for the bottom layer (depth > 10m)

$$\frac{\partial}{\partial t}\iiint \mathrm{DO}\, dV = \mathit{Transport} + \mathit{Respiration}$$

A positive ΔDO indicates that:

- SLR has increased the "transport" of DO, **and/or,**
- SLR has decreased the "respiration".

The budget is computed for the models for which outputs are directly available (**ChesROMS-ECB** and **UMCES-ROMS-RCA**). The two are representative of the "spectrum" of model results.

Changes below 10 m depth

How SLR affects the oxygen budget:

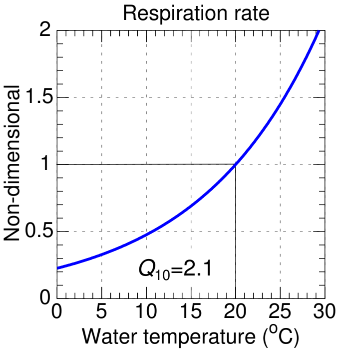
1. Both models exhibit a **reduction in respiration**.
2. The reduction in respiration is larger in ChesROMS-ECB than in UMCES-ROMS-RCA: 5% and 3% (respectively), as expected.
3. The transport term is *smaller* in both models, throughout the year. Therefore, the **physical transport does not contribute** to the $\Delta DO > 0$ of the bottom layer.

Changes below 10 m depth

Why is the respiration reduced by SLR?

1. The two models assume respiration rates that increase exponentially with T (example $\rightarrow$)

2. The "summer cooling" caused by SLR, $O(-0.4°\mathrm{C})$ for $\Delta\mathrm{SL} = +0.50\,\mathrm{m}$, causes a 3% reduction in respiration, enough to account for the changes in the oxygen budget.



Why are the models not suggesting the same reduction?

1. Although both models have rates $\propto T$, **their degree of sensitivity differ**, with ChesROMS-ECB being more sensitive to T than UMCES-ROMS-RCA (Q_{10}).

2. Observational studies provide guidance on T dependence (Lomas et al. 2002) but there are still substantial differences in the way these processes are represented in models.

Summary

- There are multiple points of convergence in the models' response to SLR for *S*, *T*, and (to a lesser extent), DO.
- The DO anomalies produced by SLR are **small**.
  In the bottom layer, they are caused by changes in respiration of **a few %**.
- Differences in the DO of the two ROMS models reflect differences in the parameterization of respiration processes.
- Points to the need for a careful selection of model parameters, particularly when studying small effects such as those caused by SLR.

Report is available at: `nordet.net/etc/report_slr_october2019.pdf`

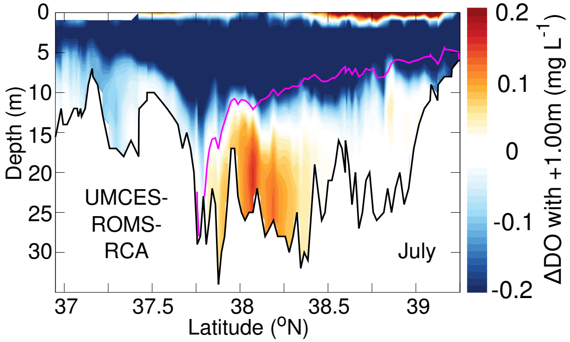
Summary

Hypoxic volume is a commonly used metric, but it doesn't reflect well changes in the DO concentrations of the deep channel (where hypoxia is most prevalent).

Hypoxic boundary often lies in shallow areas where the models project DO to decrease.

Where this happens, the hypoxic volume expands with SLR, regardless of an improvement in the bottom layer.

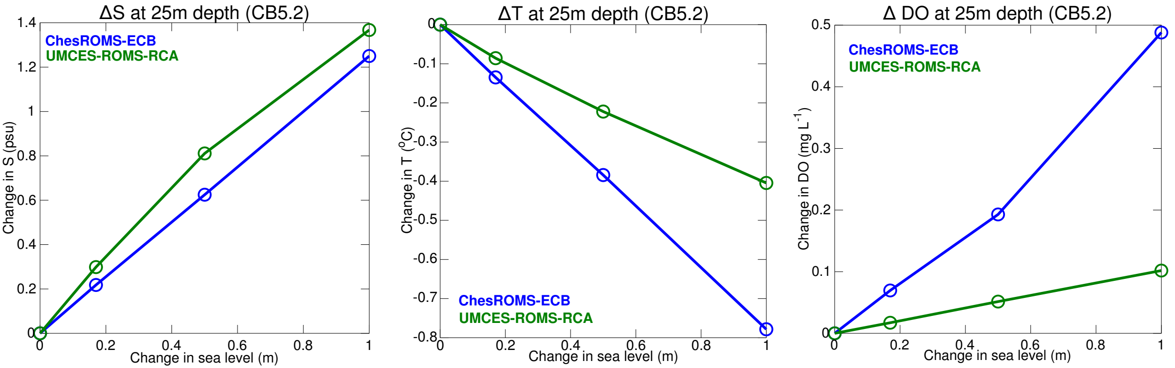
Bay-wide metrics such as HV can make projections from different models appear more different than they actually are.



Hypoxic boundary of the reference simulation

Appendix

Linearity of response to ΔSL



Changes in bottom layer, July, station CB5.2 (deep channel, just north of Potomac River):

- $S \nearrow$, $T \searrow$, DO$\nearrow$
- The few data points available suggest a quasi-linear response to ΔSL.