Impacts of Sea Level Rise on Hypoxia—A Model Intercomparison

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Outline

Overview

We are investigating the impacts of sea level rise (SLR) on hypoxia using different models of the bay. This intercomparison is motivated by recent studies showing improvements in bottom DO with SLR (e.g., Irby et al. 2018) but also increased hypoxic volume (Ni et al. 2018).

The experiments assume realistic conditions for the period **1991–1995** and use the same riverine forcing (Phase-6 CXXBASE).
We consider four scenarios:

1. No SLR: base run / control
2. SL raised by 0.17 m at the oceanic model boundary (2025)
3. SL +0.50 m (2050)
4. SL +1.00 m (2100)

The SL is the only thing that is different between the simulations (e.g., no warming).

Experiments completed

Model CH3D (physics) + ICM (biology):

- +0.17 m 1991–1995 (physics & biology)

Model ChesROMS-ECB:

- +0.17 m 1991–1995
- +0.50 m 1991–1995
- +1.00 m 1991–1995

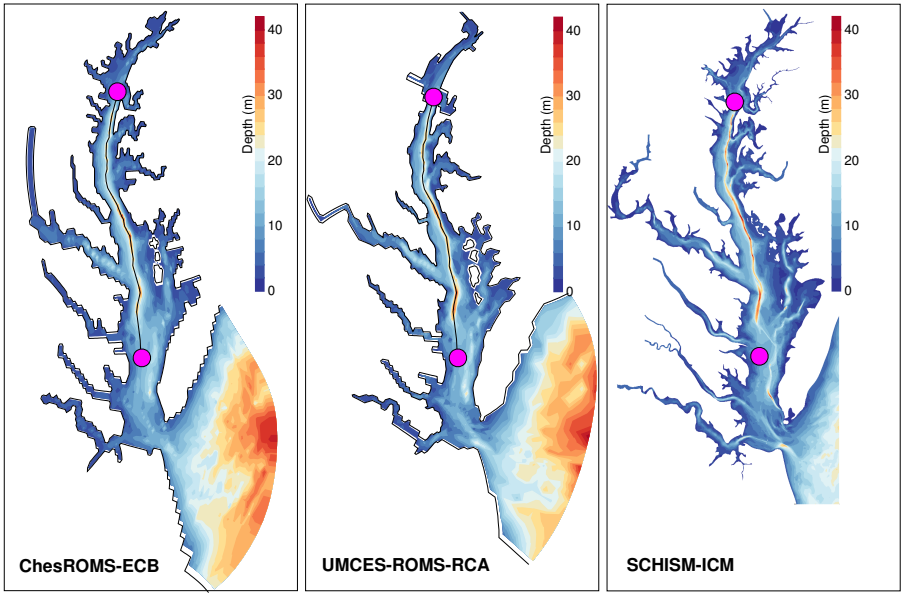
Model UMCES-ROMS (physics) + RCA (biology):

- +0.17 m 1991–1995 (physics & biology)
- +0.50 m 1991–1995 (physics & biology) **coming soon**
- +1.00 m 1991–1995 (physics & biology)

Model SCHISM (physics) + ICM (biology):

- +0.17 m 1991–1995 (physics & biology)
- +0.50 m 1991–1995 (physics & biology)
- +1.00 m 1991–1995 (physics & biology)

Model domains

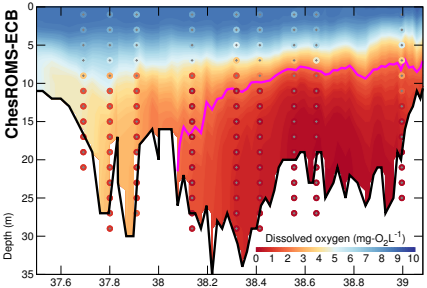


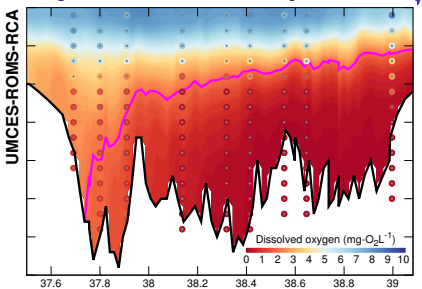
Oceanic boundary of models (SCHISM: extends beyond the continental slope)

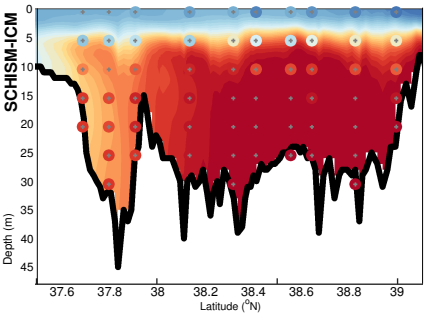
"Deep channel" where hypoxia is concentrated.

Transect from Rappahannock River (south) to Chester River (north).

Model evaluations: DO, July 1991–1995 (max hypoxia)







Dissolved oxygen (mg-O_2L^{-1})

0 1 2 3 4 5 6 7 8 9 10

Contour line: 2 mg L^{-1}

Circles: Data from WQMP

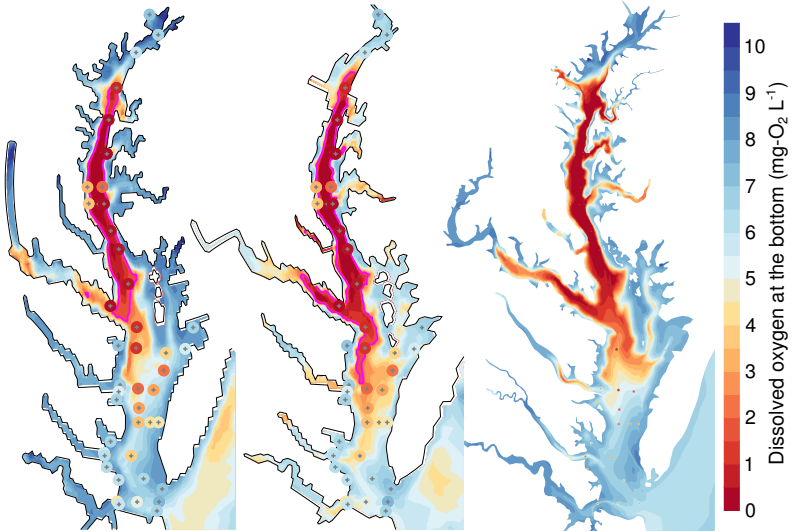
All the models reproduce observations of S, T, DO reasonably well.

July: Month of max hypoxia, climatology 1991–1995.

ChesROMS-ECB and SCHISM-ICM overestimate DO at 37.8°N.

SCHISM-ICM: Oxycline a bit too high.

Model evaluations: Bottom DO, July 1991–1995 (max hypoxia)



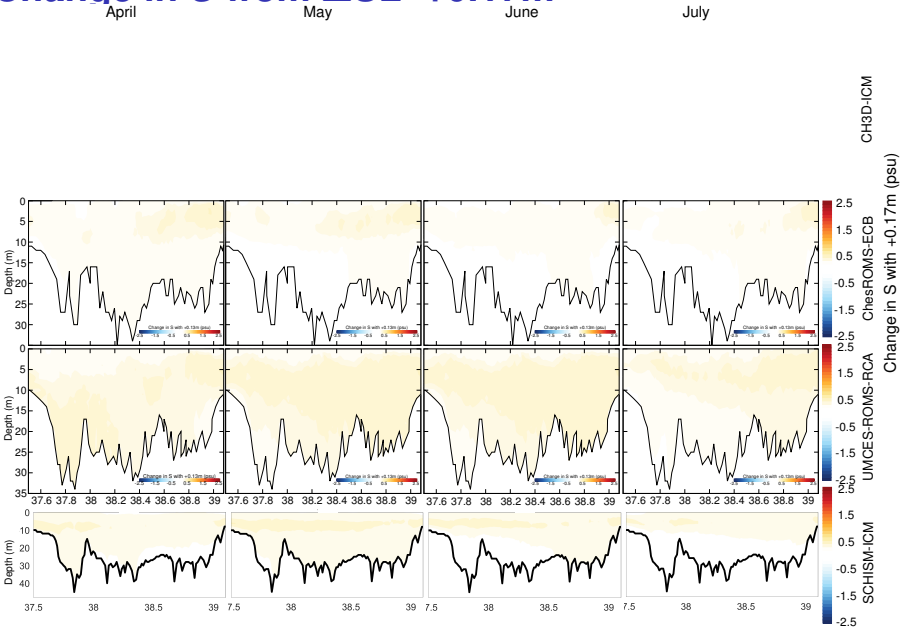
Observed distribution of summer hypoxia reasonably well reproduced.

The three models look very similar.

ChesROMS-ECB and SCHISM-ICM overestimate DO south of Rapp. River (same as previous slide). UMCES-ROMS-RCA does a bit better.

Physical changes caused by ΔSL

Change in S from ΔSL=+0.17m



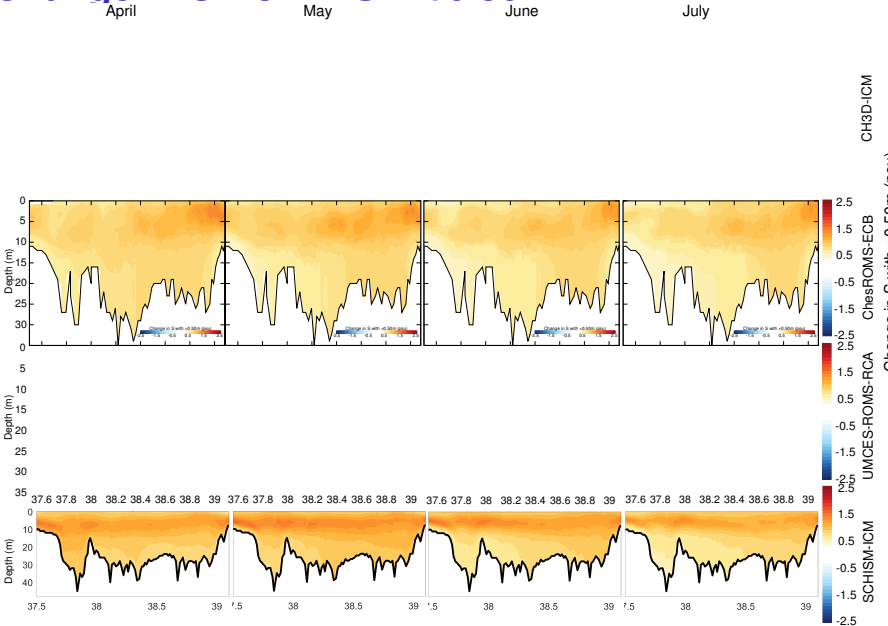
"Depth=0 m" $\Leftrightarrow$ mean sea level in case without ΔSL.

With ΔSL, the surface goes above the 0 m mark.

For a sea level of +0.17m...

$\Delta S \approx +0.2$–0.3 psu

Change in S from ΔSL=+0.50m

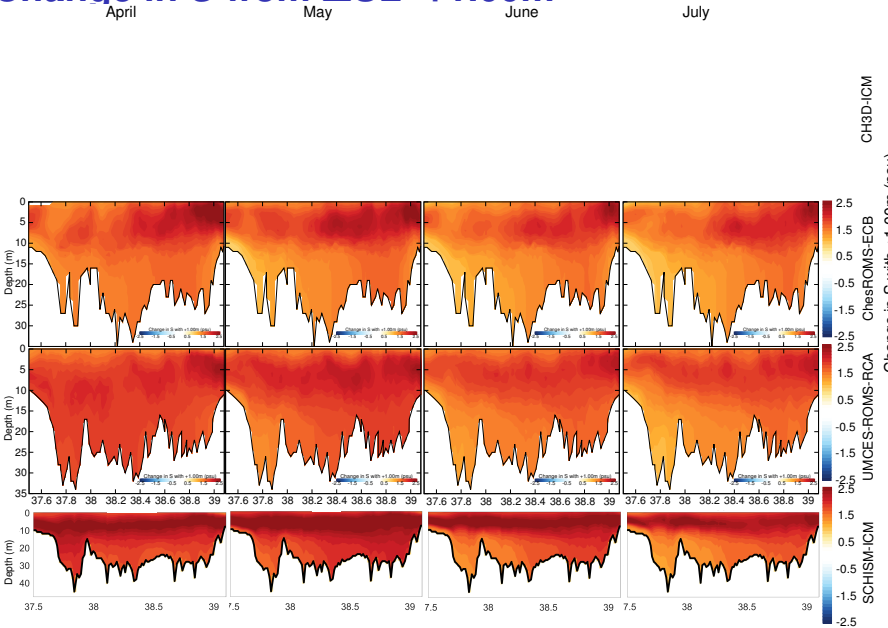


For a sea level of +0.50m...

$\Delta S \approx +0.7$ psu
Hong&Shen 2012:
$\Delta S \sim 0.75$ psu

ΔS largest in top 10 m. Halocline shifted $\uparrow$ by ΔSL.

Change in S from ΔSL=+1.00m

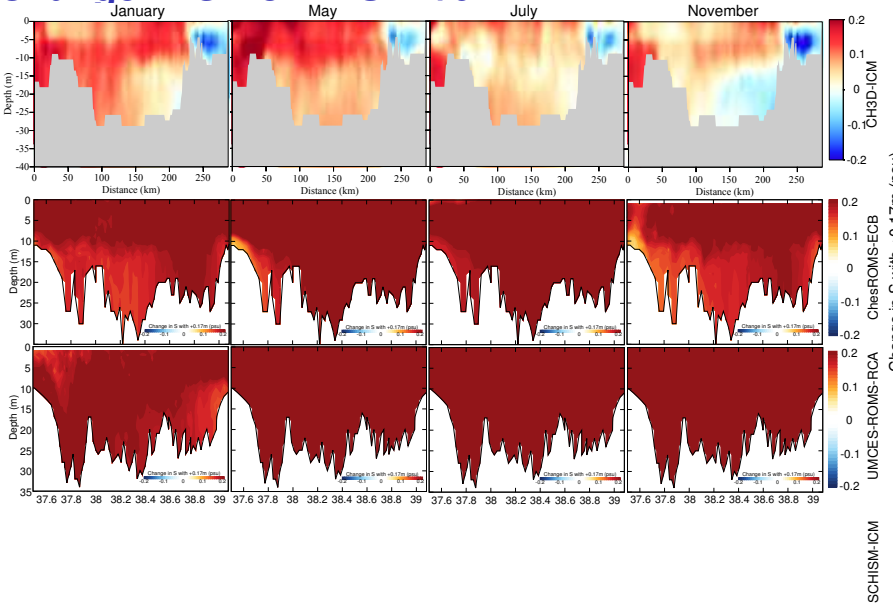


For a sea level of +1.00m...

$\Delta S \approx +1.5$ psu
Hong&Shen 2012:
$\Delta S \sim 1.5$ psu

ΔS largest in top 10 m. Halocline shifted $\uparrow$ by ΔSL.

Change in S from ΔSL=+0.17m



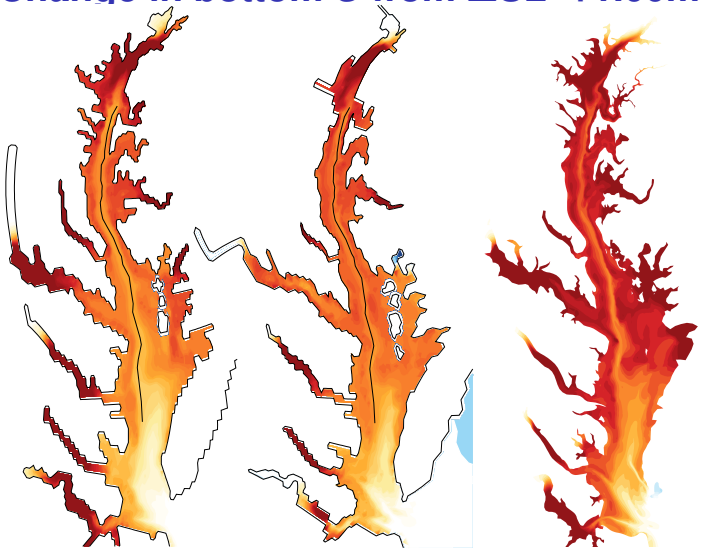
We go back to case +0.17 m to compare with CH3D-ICM:

Narrower scale: ± 0.2 psu in place of ± 2.5 psu

Slightly different set of months: JanMayJulNov in place of AprMayJunJul.

CH3D-ICM suggests smaller ΔS.

Change in bottom S from ΔSL=+1.00m (average 1991–1995)



A bay-wide perspective on ΔS at the bottom:

Cases +0.17m,+0.50m look similar (just smaller values).

Larger ΔS in shallow water ($\uparrow$ shift of halocline).

Relatively small ΔS on the shelf (white). Key changes are inside the Bay.

Change in S from ΔSL: Summary

The models agree on:

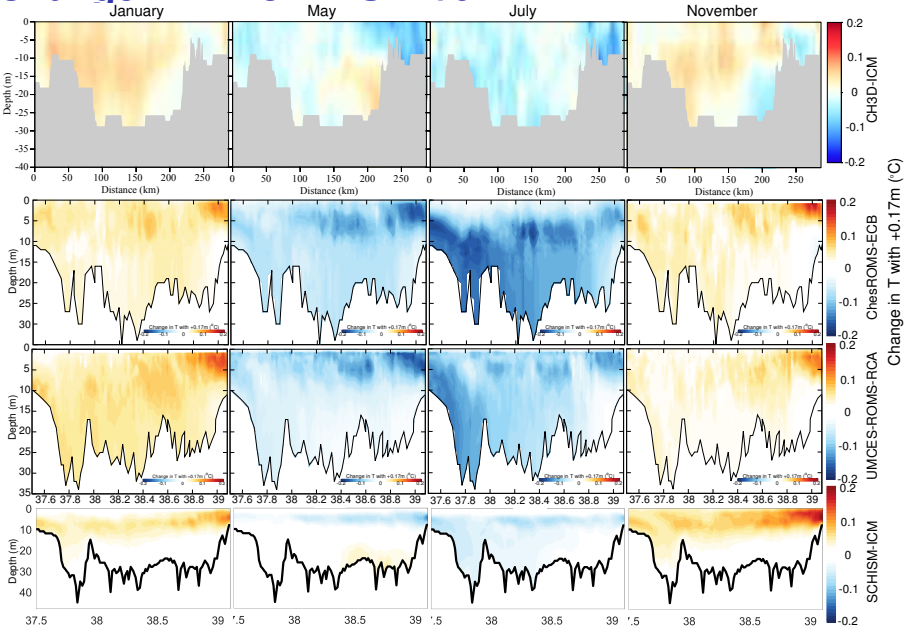
- $\Delta S > 0$ everywhere and at all time (except perhaps for CH3D-ICM).
- No seasonality apparent in ΔS. ΔS is amplified with SLR.
- Larger ΔS in upper 10 m. ΔS concentrated inside the Bay.
- ΔS values are quantitatively close between models.

Reminder: These results are obtained without a change in S on the continental shelf.
The ΔS are consistent with the literature (Hong&Shen 2012).

The models disagree on:

- CH3D-ICM suggests lower ΔS; presumably due to the position of its oceanic boundary.

Change in T from ΔSL=+0.17m



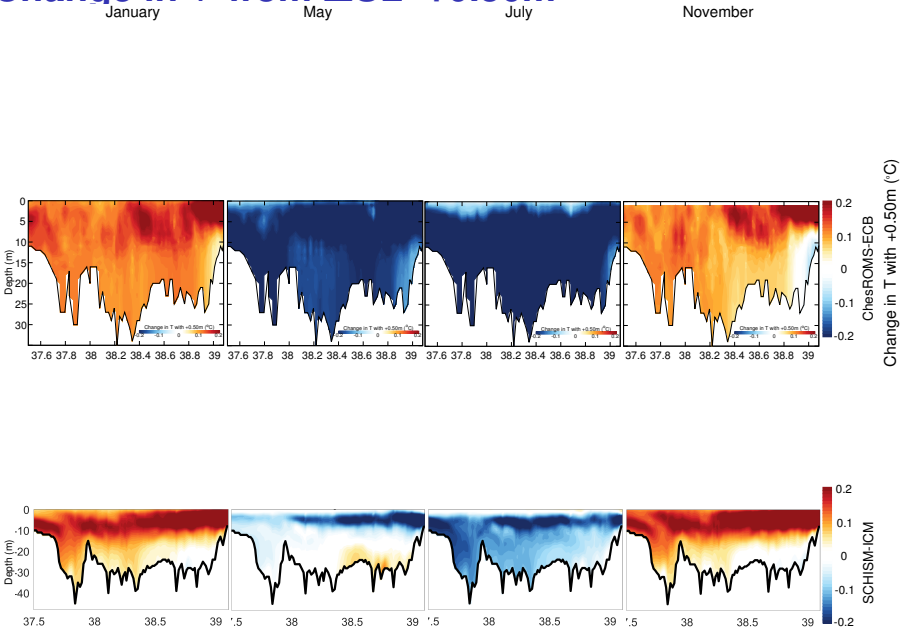
All models show the same **seasonal pattern**.

Warmer during winter.

Cooler during summer.

SCHISM-ICM: ΔT anomalies not apparent below $\sim$ 20m.

Change in T from ΔSL=+0.50m



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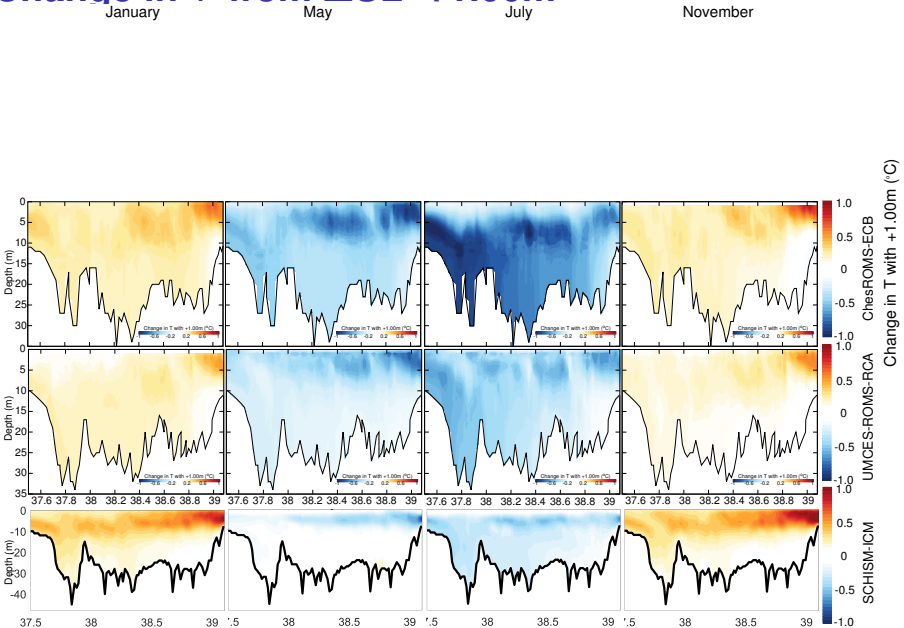
Anomalies are **amplified** with SLR.

Change in T from ΔSL=+1.00m



(Change in scale: from ± 0.2°C to ± 1.0°C)

Warmer during winter.

Cooler during summer.

Anomalies are **amplified** with SLR.

Change in T from ΔSL: Partial summary 1

The models agree on:

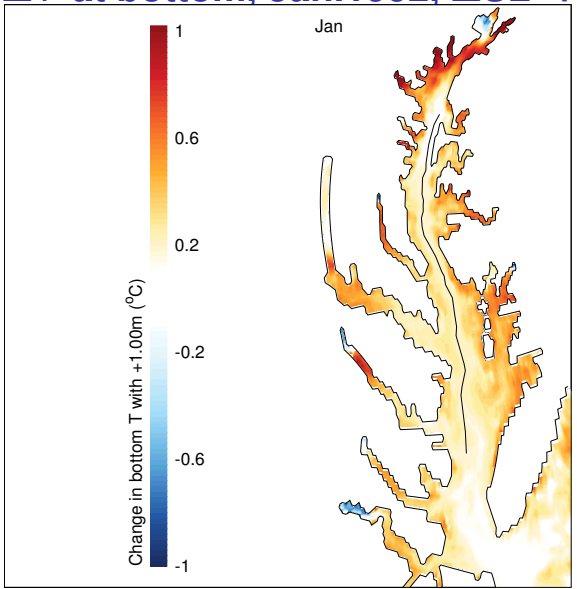
- The presence of a seasonal pattern: $\Delta T > 0$ in winter, $\Delta T < 0$ in summer.
- These ΔT anomalies are amplified with SLR.

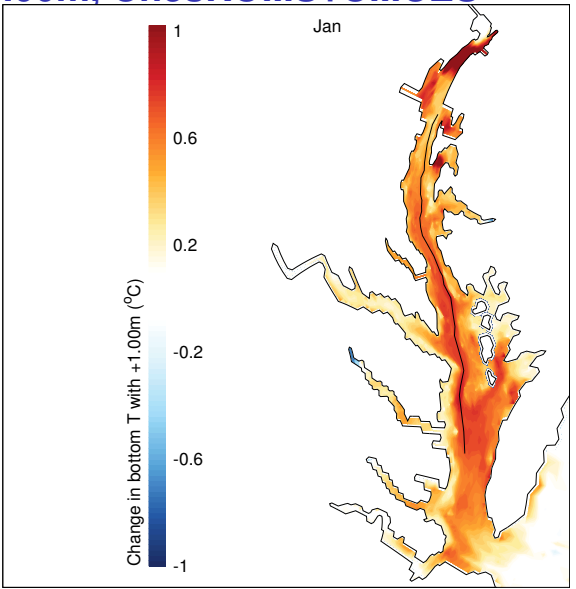
The models disagree on:

- The precise value of the warming/cooling.
- How deep the warming/cooling anomaly are apparent in the water column (shallower in the case of SCHISM-ICM).

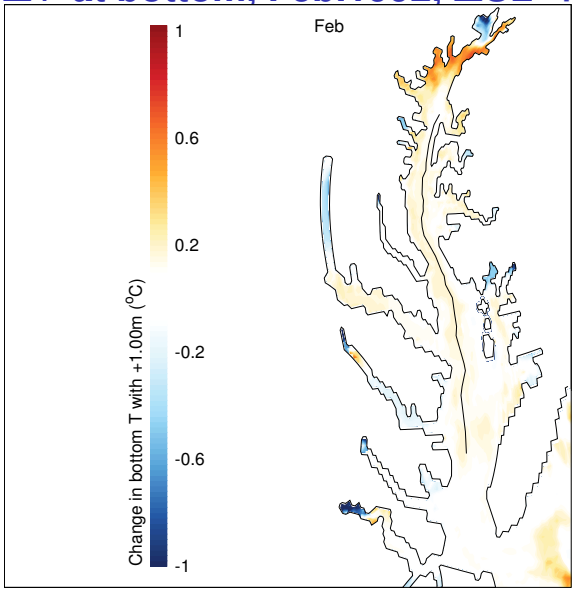
Next slides: A bay-wide perspective on the ΔT anomalies.

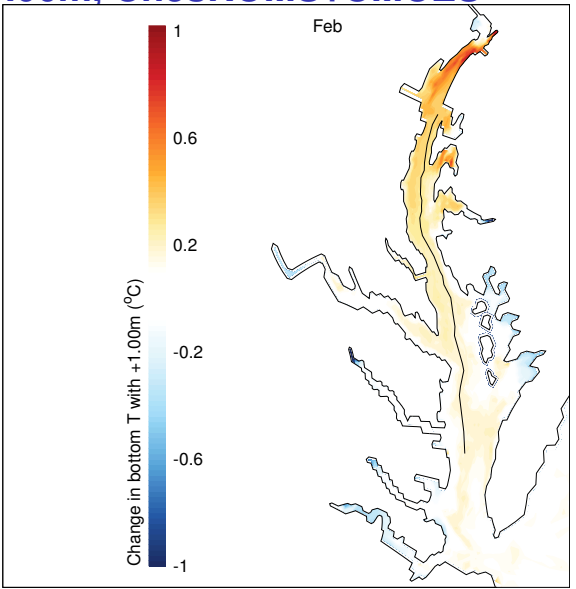
ΔT at bottom, Jan.1992, ΔSL=+1.00m, ChesROMS+UMCES



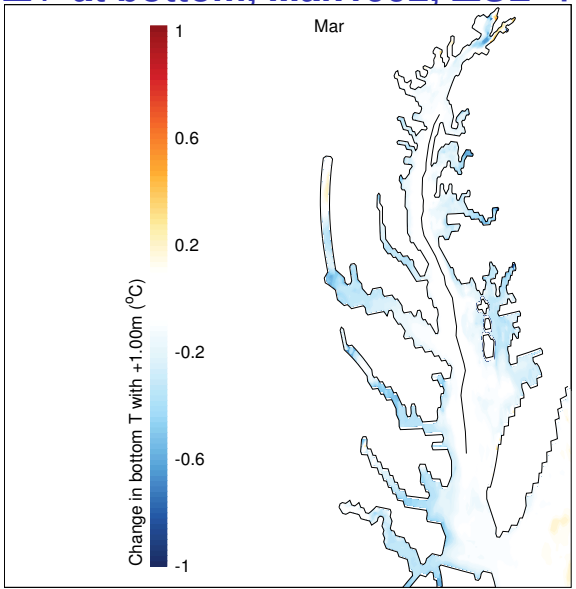


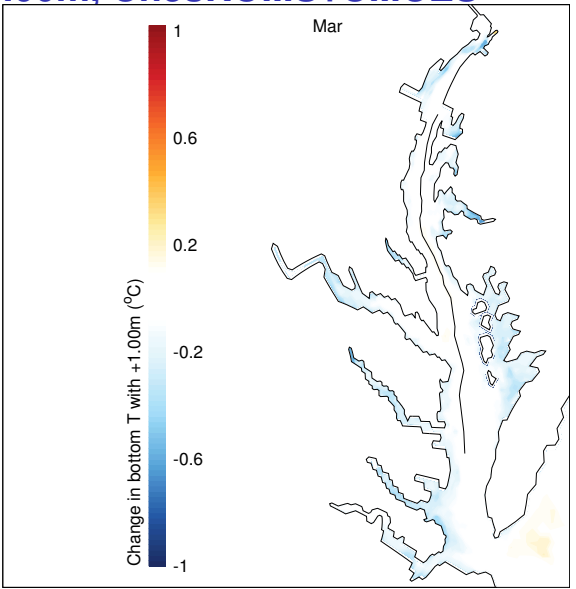
ΔT at bottom, Feb.1992, ΔSL=+1.00m, ChesROMS+UMCES



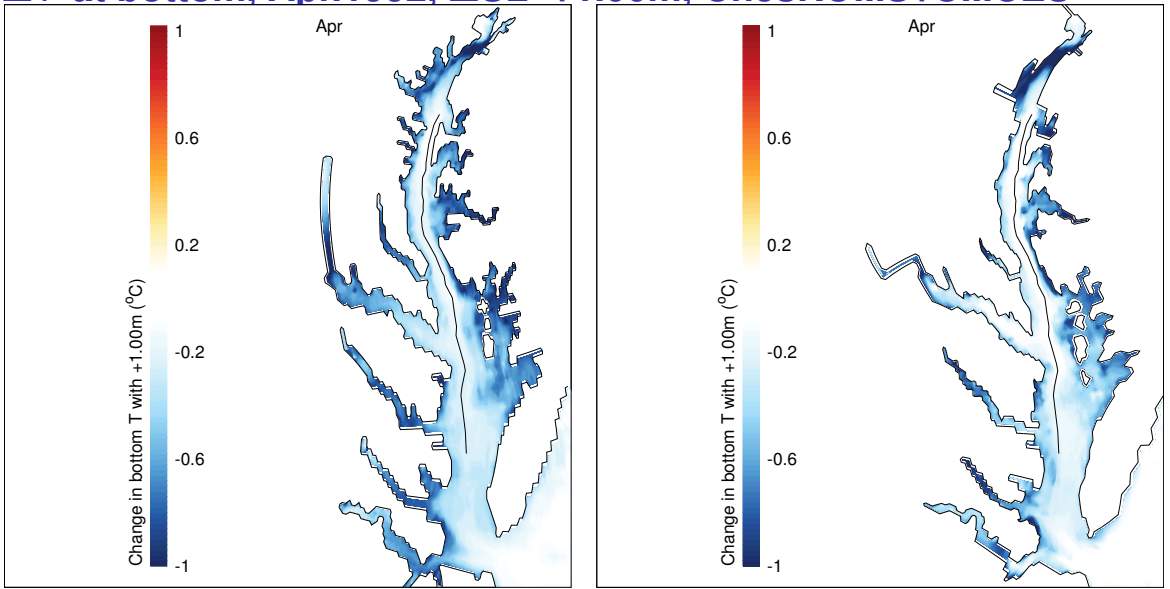


ΔT at bottom, Mar.1992, ΔSL=+1.00m, ChesROMS+UMCES

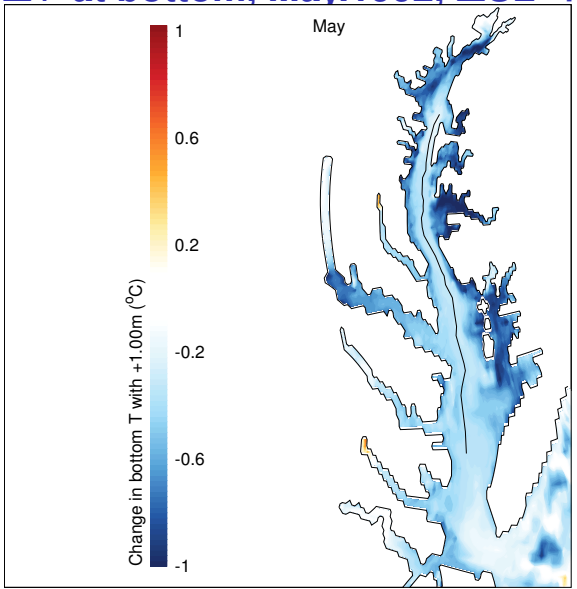


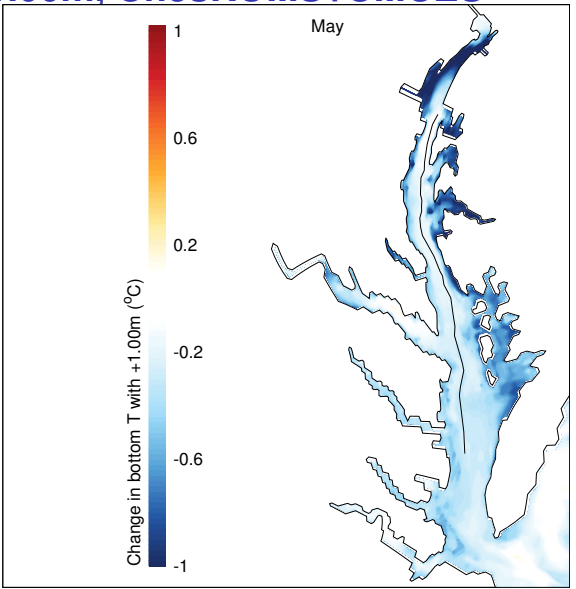


ΔT at bottom, Apr.1992, ΔSL=+1.00m, ChesROMS+UMCES

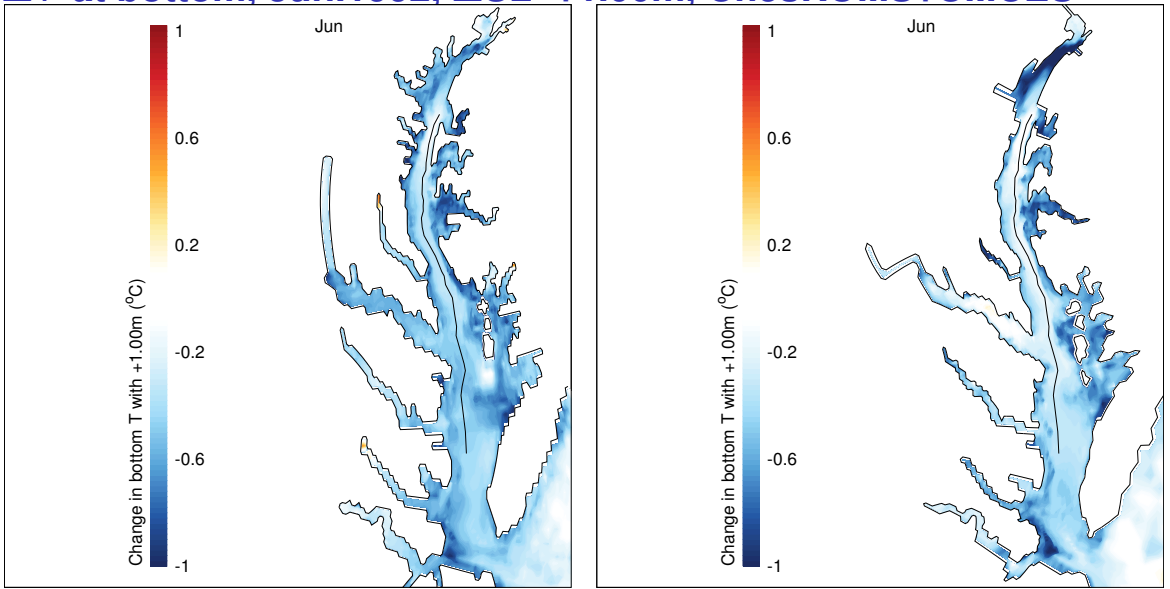


ΔT at bottom, May.1992, ΔSL=+1.00m, ChesROMS+UMCES

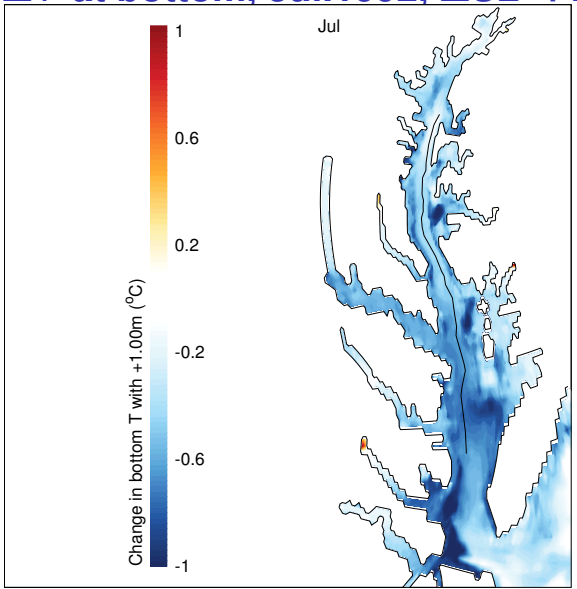


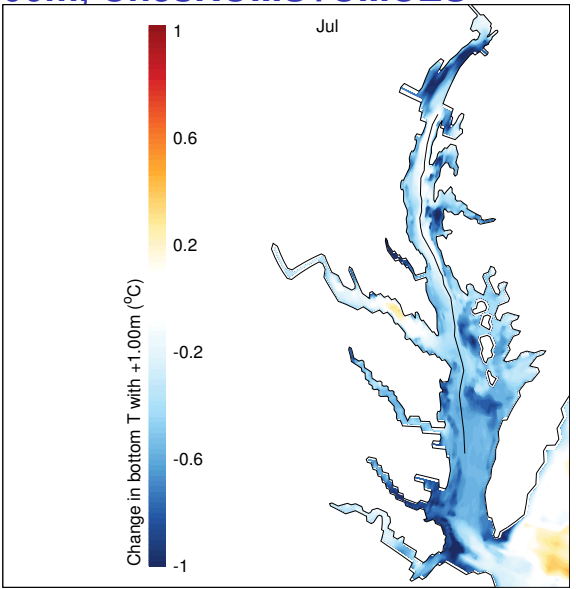


ΔT at bottom, Jun.1992, ΔSL=+1.00m, ChesROMS+UMCES

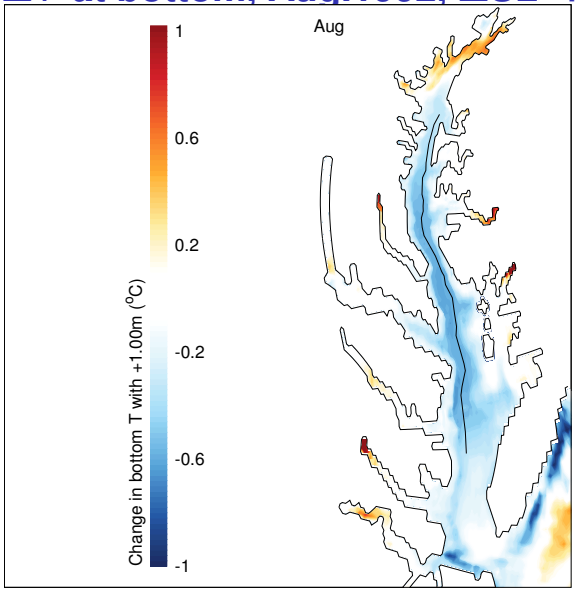


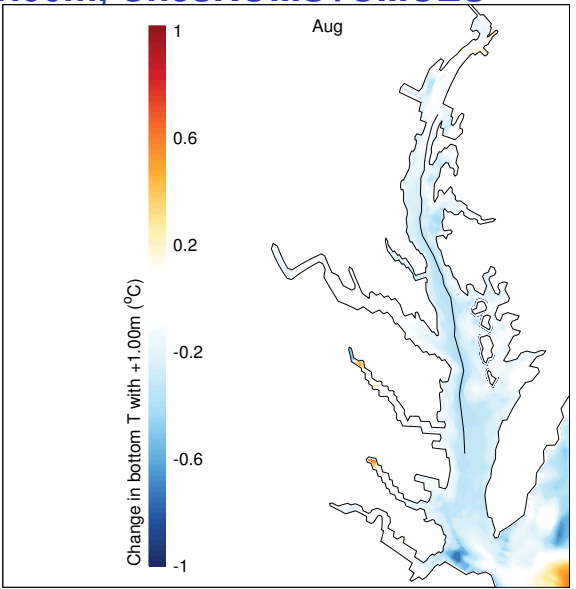
ΔT at bottom, Jul.1992, ΔSL=+1.00m, ChesROMS+UMCES



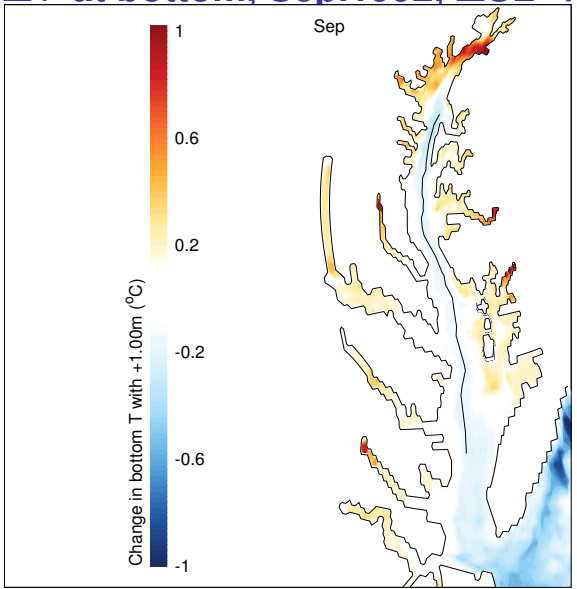


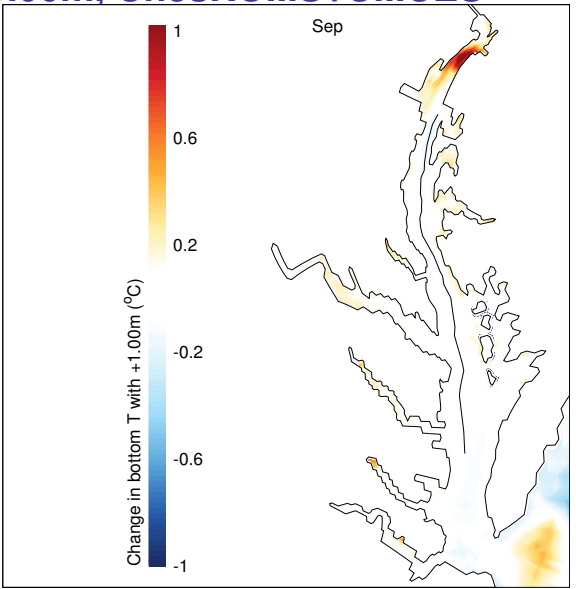
ΔT at bottom, Aug.1992, ΔSL=+1.00m, ChesROMS+UMCES



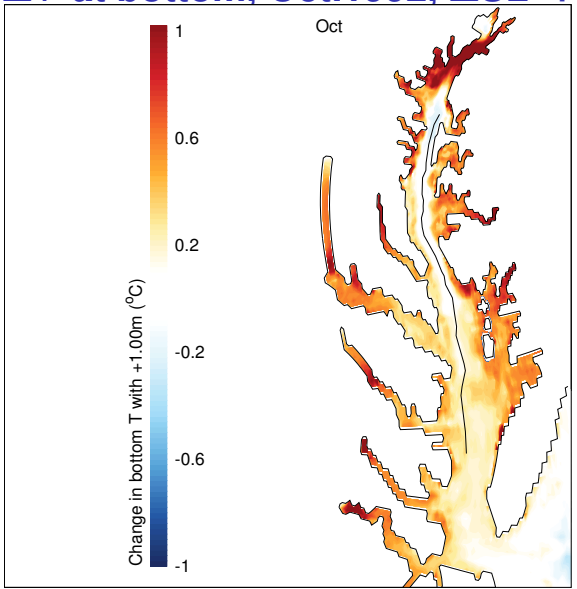


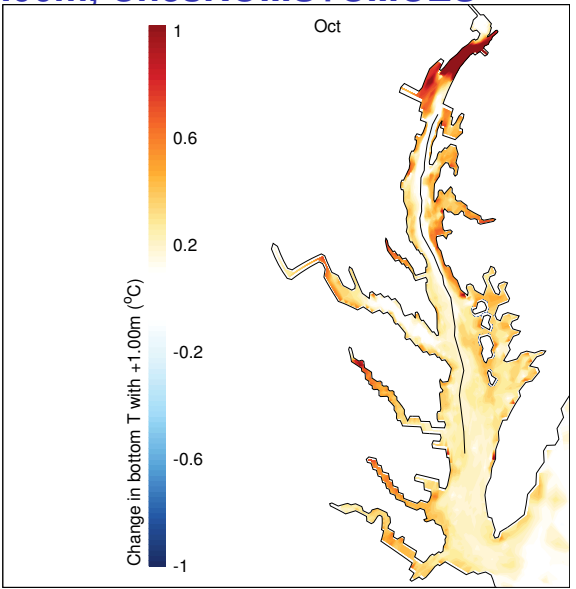
ΔT at bottom, Sep.1992, ΔSL=+1.00m, ChesROMS+UMCES



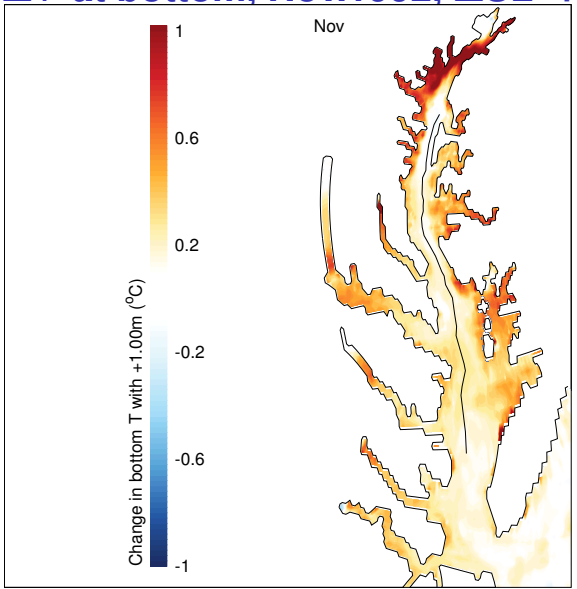


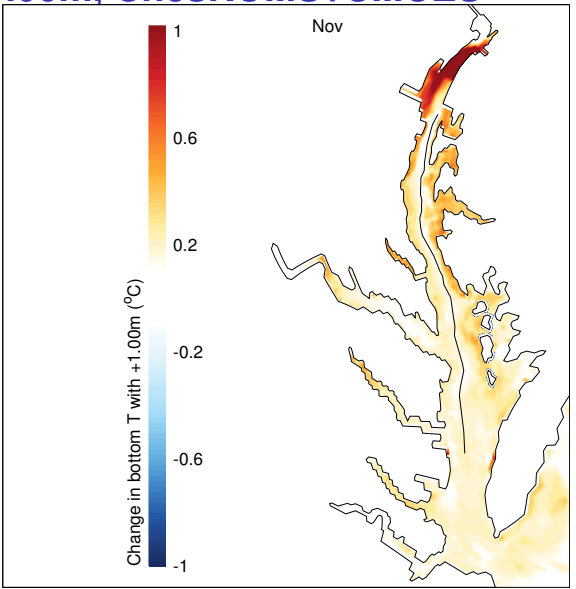
ΔT at bottom, Oct.1992, ΔSL=+1.00m, ChesROMS+UMCES



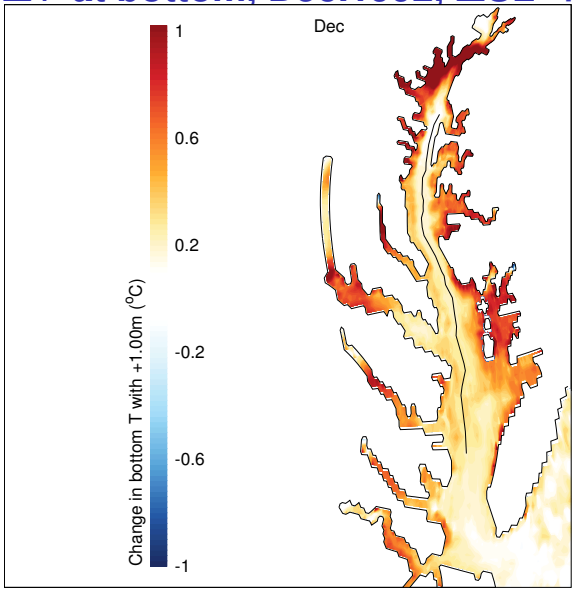


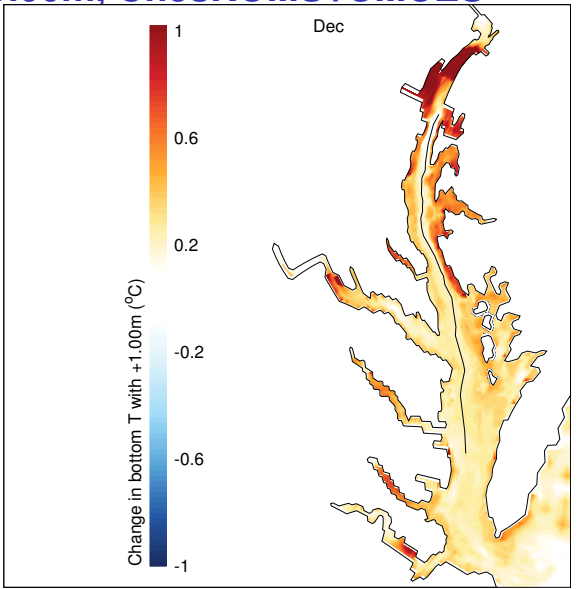
ΔT at bottom, Nov.1992, ΔSL=+1.00m, ChesROMS+UMCES





ΔT at bottom, Dec.1992, ΔSL=+1.00m, ChesROMS+UMCES





Change in T from $\triangle$SL: Partial summary 2

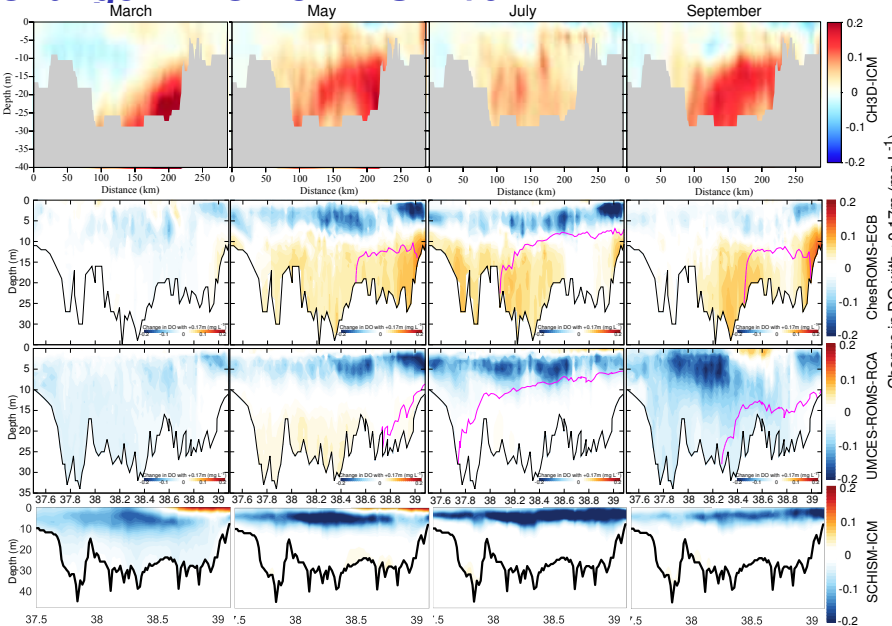
- The ΔT anomalies appear **throughout the bay** at nearly the same time.
- They appear **quickly**; ΔT can be ~ 0 (white) in one month and $-0.5°$C the next month.
- SL is the only thing that changed between the model simulations.
  The same surface air temperature and the same surface longwave/shortwave fluxes are used in all the model runs.

A **lag** in the vertical diffusion of T is the most likely mechanism: $\partial T/\partial t \approx \partial/\partial z\,(K\,\partial T/\partial z)$.
As the water column becomes thicker with SLR, it takes longer to cool it (during winter) or to warm it (during summer).
The result is a $\Delta T > 0$ during winter and a $\Delta T < 0$ during summer.

The magnitude of ΔT would ultimately depend on the strength of the stratification and the vertical diffusivity of each model. It can explain the small differences between the models.

Changes in DO caused by ΔSL

Change in DO from ΔSL=+0.17m



For a sea level of +0.17m. . .

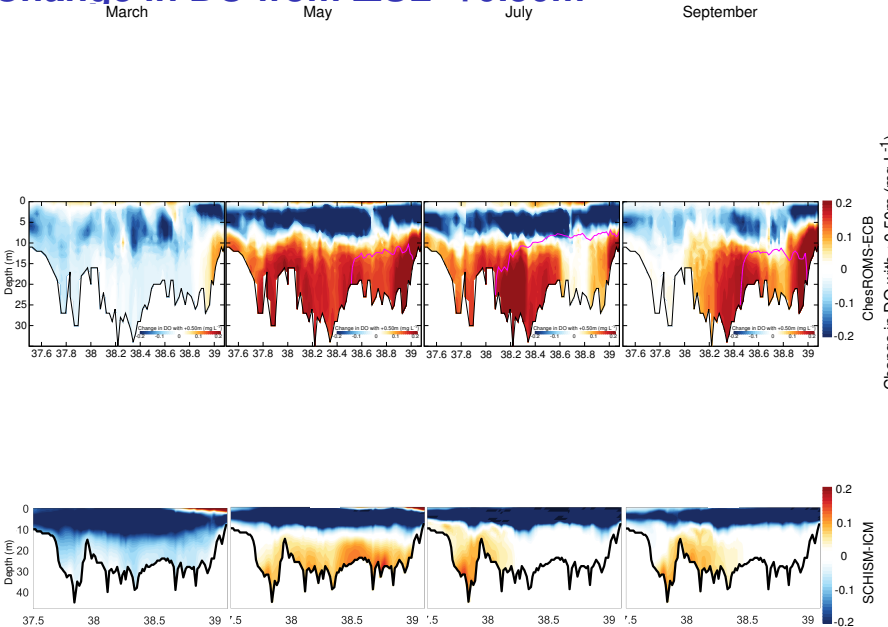
Less DO in upper 10m.

More DO below 10m: CH3D-ICM, ChesROMS-ECB.

UMCES-ROMS-RCA: Mixed response.

SCHISM-ICM: No visible improvement in bottom DO.

Change in DO from ΔSL=+0.50m

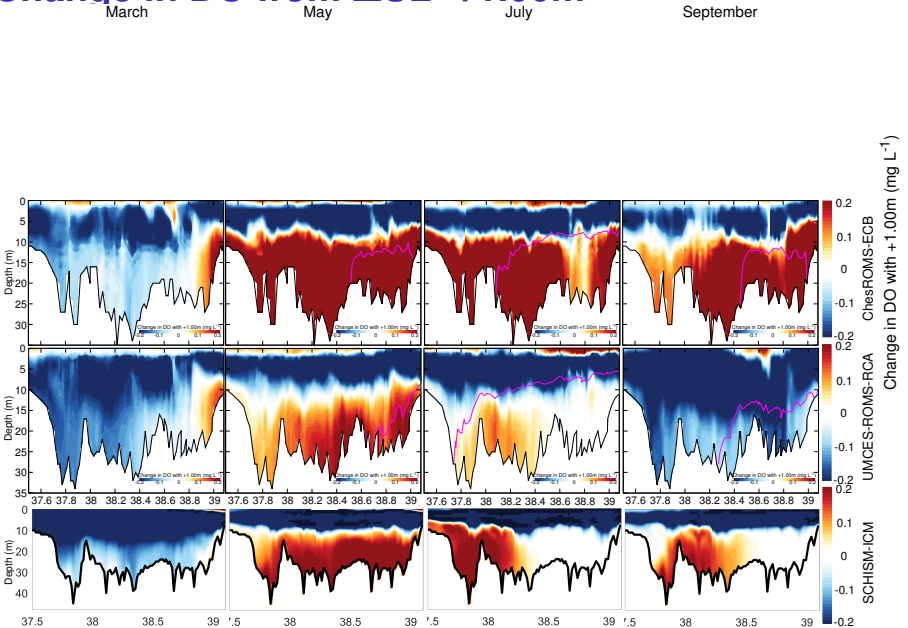


For a sea level of +0.50m. . .

Patterns above/below 10m are amplified.

SCHISM-ICM: **More DO** below 10m.

Change in DO from ΔSL=+1.00m



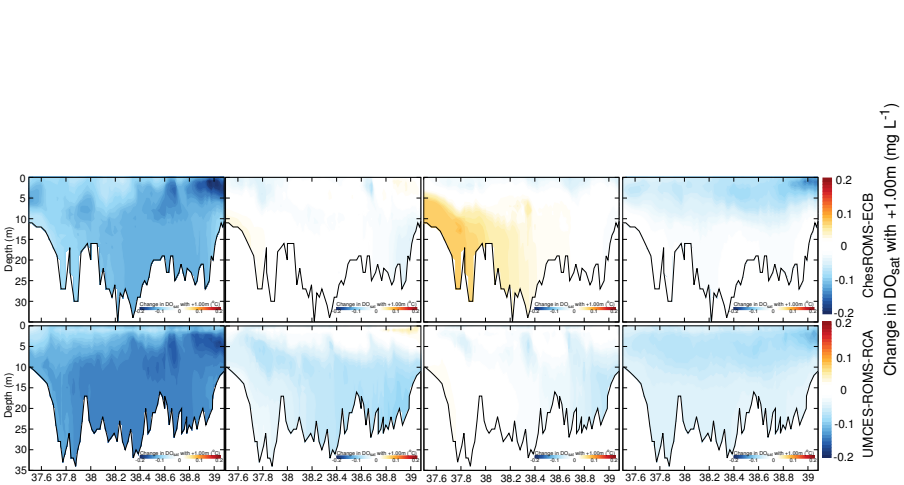
Patterns above/below 10m are amplified.

All the models show improvements in bottom DO in May–July.

The DO>0 **persists** in ChesROMS-ECB and SCHISM-ICM.

UMCES-ROMS-RCA: DO>0 disappears.

Change in DO solubility from ΔSL=+1.00m



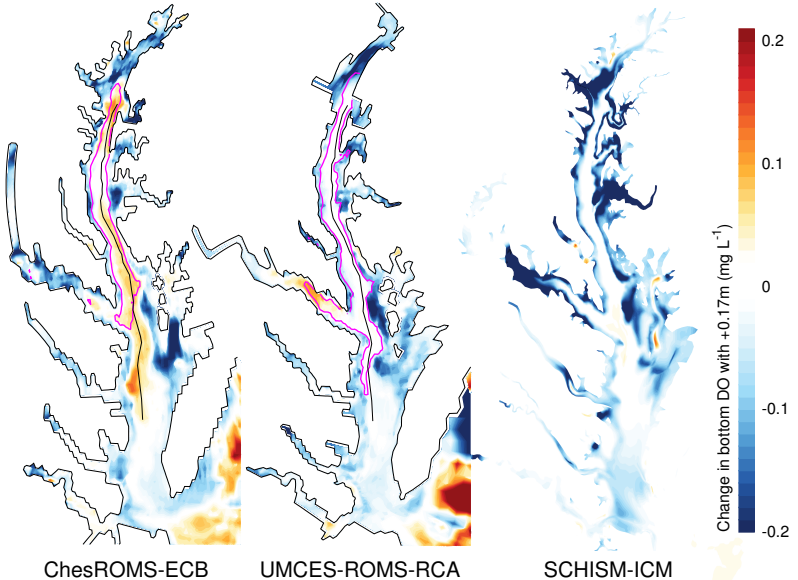
Can ΔT,ΔS explain ΔDO?
$T \searrow$, $DO_{sat} \nearrow$
$S \nearrow$, $DO_{sat} \searrow$

In March–July, the two effects offset each other.

DO_{sat} can only explain a small fraction of the improvement in bottom DO.

Same outcome for +0.17m, +0.50m.

Change in July bottom DO from ΔSL=+0.17m



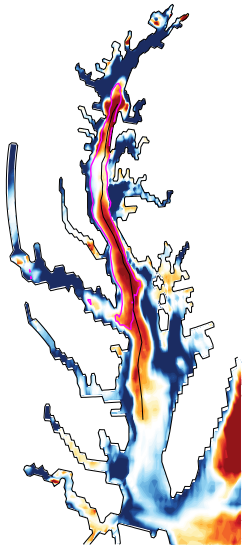
For a sea level of +0.17m...

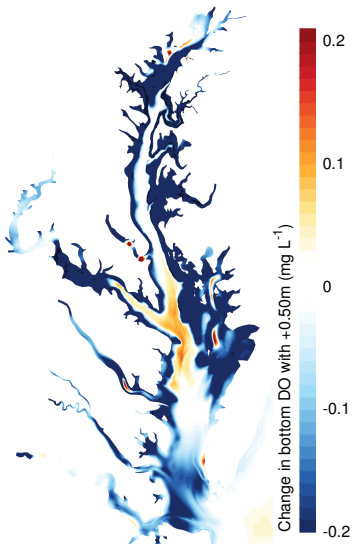
Bottom DO worsens in **shallow water** (depths < 10 m, as in previous slides).

Deep water: Bottom DO shows either little changes (white) or an improvement.

This is the main disagreement between the models.

Change in July bottom DO from ΔSL=+0.50m





ChesROMS-ECB UMCES-ROMS-RCA SCHISM-ICM

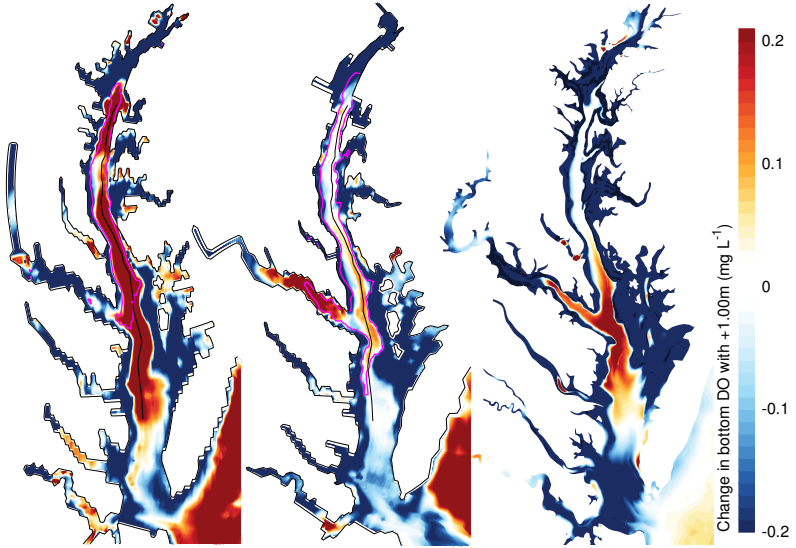
For a sea level of +0.50m. . .

Bottom DO worsens in **shallow water** (depths < 10 m, as in previous slides).

Deep water: Bottom DO shows either little changes (white) or an improvement.

This is the main disagreement between the models.

Change in July bottom DO from ΔSL=+1.00m



For a sea level of +1.00m. . .

Bottom DO worsens in **shallow water** (depths < 10 m, as in previous slides).

Deep water: Bottom DO shows either little changes (white) or an improvement.

This is the main disagreement between the models.

Change in DO from $\triangle$SL: Partial summary 1

The models agree that:

- DO generally worsens above 10 m (except CH3D-ICM).
  This signal is amplified with SLR.
- DO shows *some* improvements below 10 m in the deep channel.
  This signal is amplified with SLR.
- The changes in S, T,solubility cannot explain the improvement in bottom DO.

The models disagree on:

- The **duration** of the improvement in bottom DO:

  Improvement persists until September in ChesROMS-ECB, SCHISM-ICM, CH3D-ICM.
  Improvement gradually goes away after May in UMCES-ROMS-RCA.
- The **magnitude** of the improvement in bottom DO:

  UMCES-ROMS-RCA $<$ SCHISM-ICM $<$ ChesROMS-ECB $<$ CH3D-ICM

Mechanisms leading to $\triangle$DO in the deep channel

Although the **shallow regions** (depth 0–10 m) show DO to be worsening with SLR, these regions are relatively well oxygenated (DO $> 5\,\text{mg L}^{-1}$) and thus less impacted.
Multiple processes could cause the worsening of DO in the upper 10 m:

- Rising SL implies a $\uparrow$ of the pycnocline (and oxycline) relative to the bottom.
- Slower vertical diffusion due to thicker water column (as for T).
- Lower rates of primary production as a result of cooler T during summer.

We have been focusing on the changes in the **deep channel** (where hypoxia is concentrated) to understand:

- what causes the improvement in bottom DO,
- why its magnitude varies between the models.

Mechanisms leading to $\triangle$DO in the deep channel

One way to look at the question: In the bottom layer of the deep channel,

$$\frac{\partial \text{DO}}{\partial t} \approx \text{DO } \textit{Transport} - \textit{Respiration}, \tag{1}$$

where "DO Transport" represents the net effect of DO advection/diffusion and is assumed > 0. No "production" in this bottom layer.

During the summer, Respiration $>$ DO Transport, and thus $\partial \text{DO}/\partial t < 0$.

An improvement in bottom DO implies that $\partial \text{DO}/\partial t$ is *less negative* with SLR.

This happens if there is: (Eq. 1)

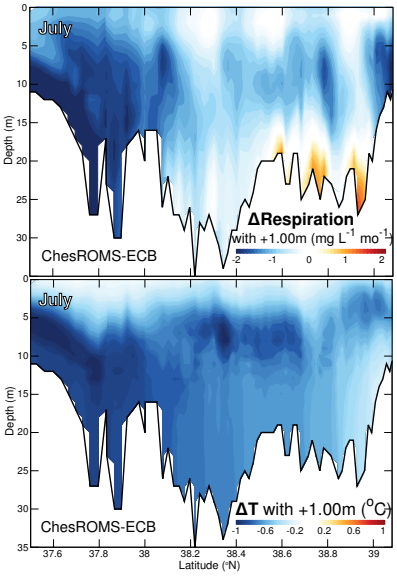
- **More** DO Transport,
- **Less** Respiration.

Mechanisms leading to ΔDO in the deep channel

We find in ChesROMS-ECB that:

- **Less Respiration** is the cause of the improvement in bottom DO within the deep channel.
- The improvement is not caused by an increase in “DO Transport”.

Not surprising: Respiration rates depend on T, and T is lower during summer with ΔSL.



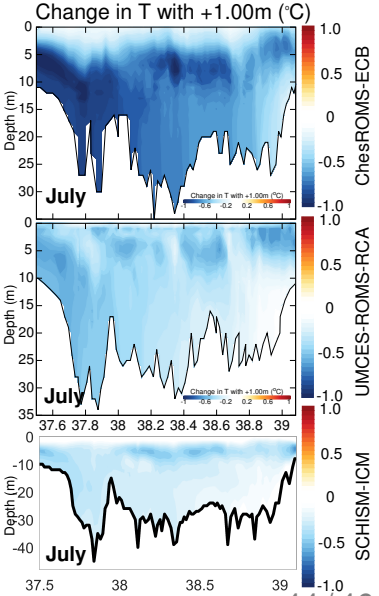
Mechanisms leading to ΔDO in the deep channel

What about the differences between the models?

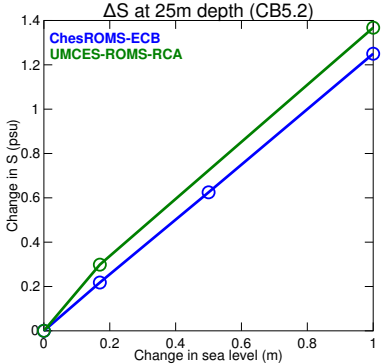
ChesROMS-ECB suggests a stronger cooling during the summer:
$\Delta T \approx -0.9°C$ vs. $\Delta T \approx -0.5°C$ (case ΔSL=+1.00m)

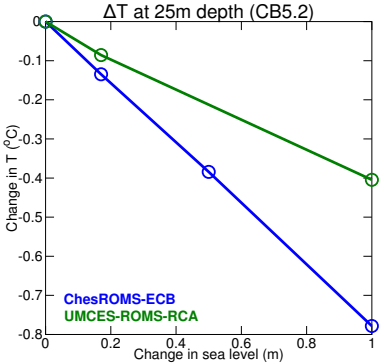
(Consistent with ChesROMS-ECB showing a larger improvement in bottom DO.)

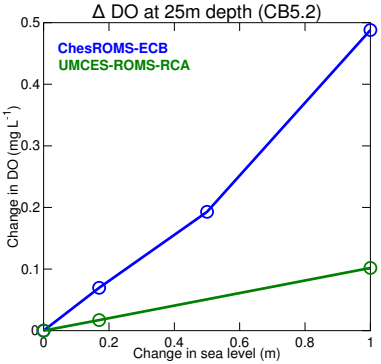
Is ΔT determining the magnitude and duration of the DO improvement in the different models?
This is being tested in UMCES-ROMS-RCA and SCHISM-ICM.



Linearity of response to ΔSL







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

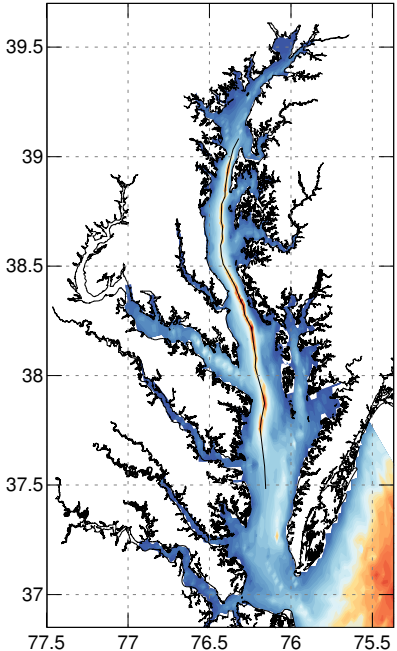
- $S \nearrow$, $T \searrow$, DO$\nearrow$
- Changes are very close to being linear with ΔSL.

Summary

Summary

1. All models reproduce the observed summer DO reasonably well.
2. There is considerable agreement in how SLR affects S, T (models are quantitatively close).
3. All models show *some* improvement in the bottom DO of deep channel.
   Models disagree in the magnitude/duration of this improvement:
   UMCES-ROMS-RCA $<$ SCHISM-ICM $<$ ChesROMS-ECB $<$ CH3D-ICM
4. Solubility cannot explain the improvements in bottom DO: ΔS offsets ΔT.
5. DO worsens in the upper $\sim$ 10 m of the water column but the changes are relatively smaller.
6. Summer cooling and decreased respiration cause the improvement in ChesROMS-ECB.
7. We are testing quantitatively whether differences in ΔT among models are the cause of the disagreement in the magnitude/duration of DO improvements.
8. Changes in S, T,DO are $\approx$ linear with ΔSL.

Appendix



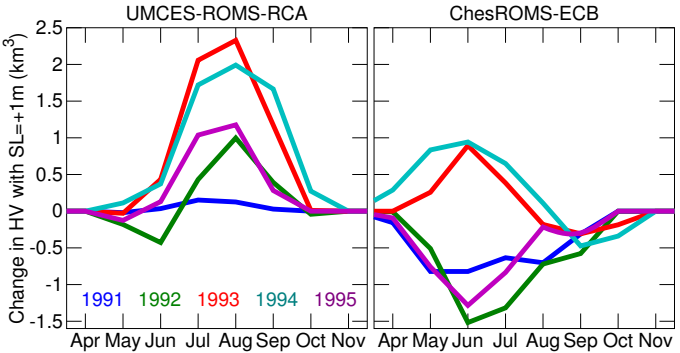
Position of the transect used in the figures:

Change in hypoxic volumes (DO$<$ 2mg L^{-1}) with ΔSL = +1.00m

Although all 3 models show some improvement in bottom DO with ΔSL=+1.00m, the improvement is:

- much **smaller** in UMCES-ROMS-RCA,
- mostly in $\sim$May.

Particularly apparent when plotting the ΔHV (whole bay):



UMCES-ROMS-RCA: The improvement is limited to $\sim$May–June and limited to 2 out of the 5 years. HV is worse over the rest of the summer.

We saw earlier that the 2 mg L^{-1} contour line extends into the upper 10 m, where DO **worsens** with ΔSL. This is particularly the case with UMCES-ROMS-RCA.

Impacts of ΔS,ΔT on DO solubility (case +0.17 m)

Could ΔT,ΔS contribute to the ΔDO through solubility?

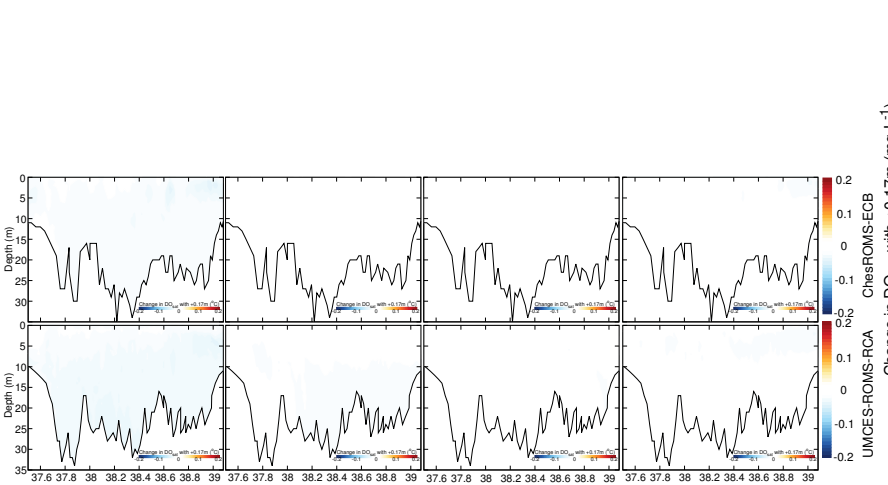
Bottom layer of main stem in July: $T \sim 24°C$, $S \sim 21$ psu
$\Delta SL = +0.17$ m causes $\Delta T \sim -0.1°C$, $\Delta S \sim +0.3$ psu

$DO_{sat}(T, S) = 7.465$ mg L^{-1}
$DO_{sat}(T + \Delta T, S) = 7.478$ mg L^{-1}
$DO_{sat}(T, S + \Delta S) = 7.452$ mg L^{-1}

Changes in T,S offset each other (mostly).
ΔDO_{sat} is much smaller than the ΔDO seen in previous slides.

Solubility alone would not explain the ΔDO. Note, however, that this conclusion would likely change if other climate changes (e.g., a long term increases in water temperature) would be taken into account. These model runs only include SLR.

Change in DO_{sat} from ΔSL=+0.17m



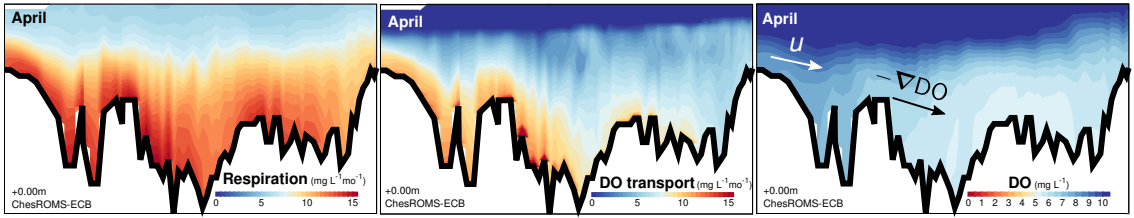
Can ΔT,ΔS explain ΔDO?
T ↘, DO_{sat} ↗
S ↗, DO_{sat} ↘

The two effects largely offset each other.
Compare figures with the actual ΔDO calculated by the model.

DO_{sat} cannot explain the improvement in bottom DO.

Example of Respiration, DO Transport (April 1991-1995)

Bottom layer: $\partial \mathrm{DO}/\partial t \approx \mathrm{DO}\ \textit{Transport} - \textit{Respiration}$

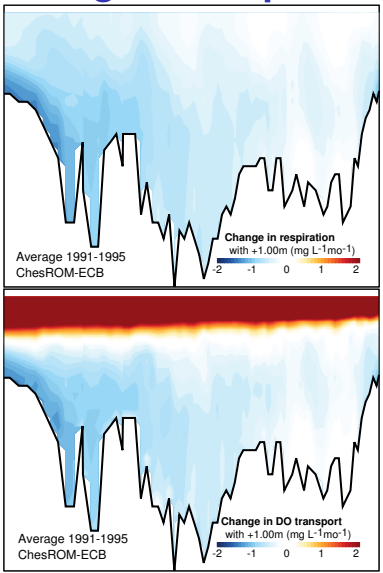


Respiration $>$ Transport, so bottom DO is decreasing during this month.

Interpreting the Transport term:
Recall that advection is $\mathbf{u} \cdot (-\nabla \mathrm{DO})$, a 'source' when the two are aligned.
Inside bottom layer, $-\nabla \mathrm{DO}$ is $\rightarrow$, a combination of respiration and age of water (Du&Shen 2015).
Spatial pattern and magnitude of 'transport' is largely influenced by $\nabla \mathrm{DO}$.

$\leftarrow$ now if we go back to the previous slide...

Change in Respiration, DO Transport due to ΔSL=+1.00 m



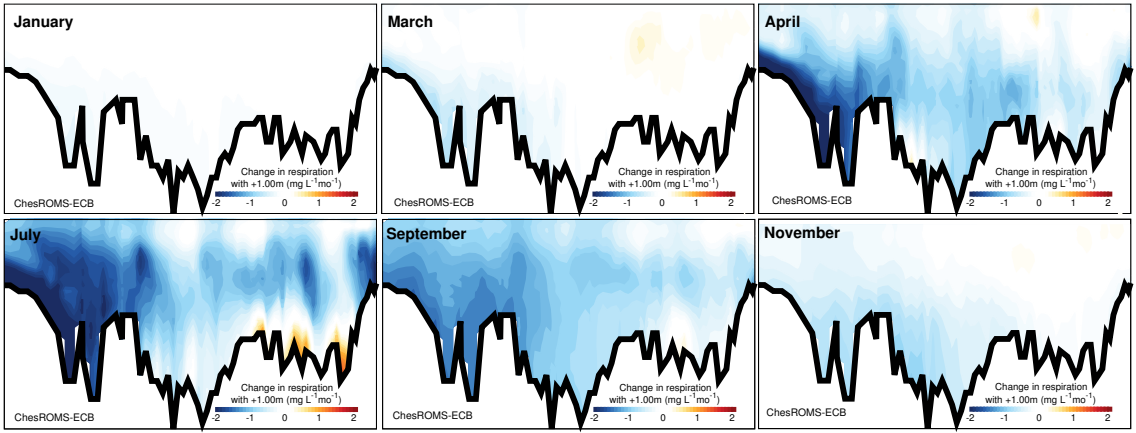
Top:
Less respiration with ΔSL, consistent with the improvement in bottom DO.

Bottom:
Less DO transport in bottom layer. DO Transport cannot explain the improvement in bottom DO.

How is DO Transport smaller with ΔSL? The bottom circulation (u, slide 15) is unlikely to have slowed down.
However, advection depends on ∇DO (slide 13), and ∇DO decreases when the respiration decreases.

(The dark red anomaly at the top of the figure represents changes in $\partial \mathrm{DO}/\partial z$ and vertical diffusion)

Change in Respiration due to ΔSL=+1.00 m (ChesROMS-ECB)



The seasonal cycle and spatial distribution of ΔRespiration are consistent with the ΔT.