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Comparison of Hydrodynamic and Water Quality Models of the Chesapeake Bay: Results of the IOOS Coastal Ocean Modeling Testbed

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Abstract

The Environmental Protection Agency (EPA) has developed a set of Total Maximum Daily Load (TMDL) allotments of nutrients and sediments for the six states that make up the Chesapeake Bay Watershed in order to elevate the health of the Bay, primarily in regards to dissolved oxygen concentrations. In developing the TMDLs, the EPA employed a coupled watershed-estuarine numerical modeling system together with an extensive set of monitoring data. Utilization of a multiple model approach when evaluating the status and recovery of the Bay system could enhance the overall confidence in model projections and better define model uncertainty. Open-source modeling systems such as the Regional Ocean Modeling System (ROMS) offer a cost effective way of utilizing the knowledge base of a large group of people form multiple institutions to address management issues within a single system. This study compares the relative skill of a set of ROMS-based models to the EPA regulatory model in terms of the seasonal variability of the Chesapeake Bay. Throughout the main stem of the Bay both model types achieve a similar model skill score in regards to dissolved oxygen (DO), the primary indicator of Bay health by the EPA, but vary significantly in terms of their ability to reproduce chlorophyll and nitrate.

Objective

Statistically compare output from a set of three open source estuarine models of varying biological complexity to the biologically sophisticated EPA regulatory model in terms of reproducing the mean and seasonal variability of temperature, salinity, stratification, dissolved oxygen, chlorophyll-a, and nitrate.

Methods

- Simulations from the EPA regulatory model and three ROMS-based models were analyzed (Fig. 1, Table 1):
  - CH3D – ICM: EPA
  - ROMS – RCA: UMCES
  - ChesNENA: VIMS
  - ChesROMS – BGC: UMCES

  (Biological Complexity ↑)
- Model output was compared to Chesapeake Bay Program monitoring data using a best time match system for roughly 17 cruises at 10 main stem station in 2004 (Fig. 2).
- Analyzed variables included surface and bottom temperature, salinity, dissolved oxygen, chlorophyll-a, and nitrate, as well as stratification.
- Model ability to reproduce the mean and seasonal variability of each variable was evaluated via Target Diagrams (Fig. 3).

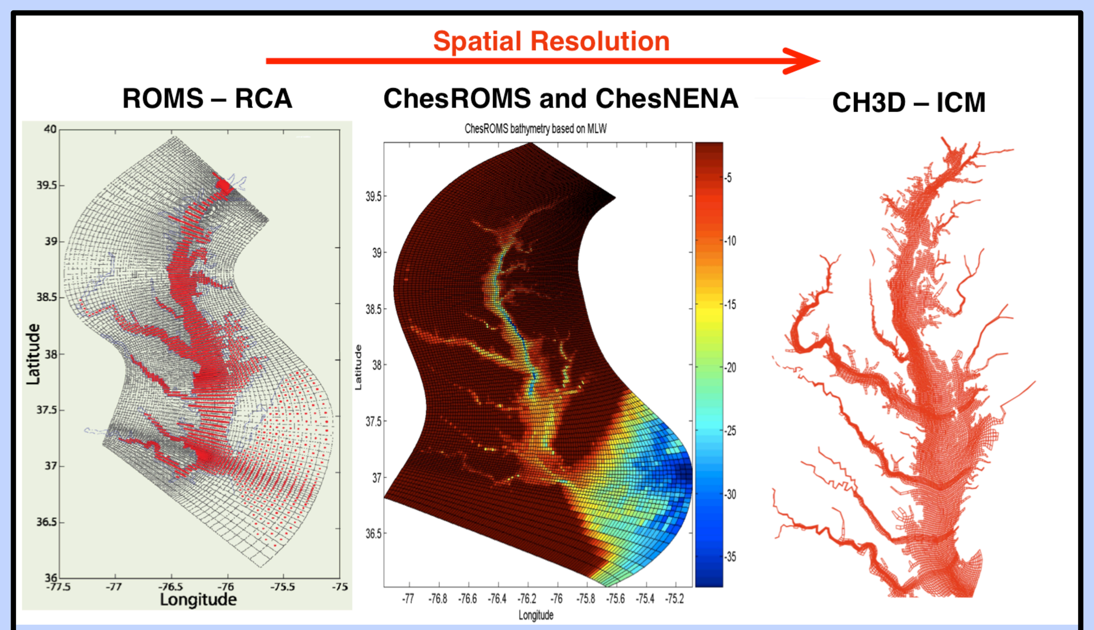

Figure 1. Horizontal grid structure for the multiple models. ROMS models employ curvilinear grids over land and water. ROMS – RCA utilize 80 x 120 cells. ChesROMS and ChesNENA utilize 100 x 150 cells. CH3D – ICM has 11,000 wetted rectangular horizontal surface cells.

	CH3D - ICM	ChesNENA	ChesROMS - BGC	ROMS - RCA
Nutrients Simulated	N, P, Si	C, N	N	N, P, Si
Biogeochemical Sediment Component	Yes	No	No	Yes
Number of Algal Groups	3	1	1	2
Horizontal Resolution	0.25 - 1km²	~ 1km²	~ 1km²	~ 1km²
Vertical Grid	z: ~ 5ft	σ: 20 layers	σ: 20 layers	σ: 20 layers

Table 1. Characteristics of the individual models

Analysis

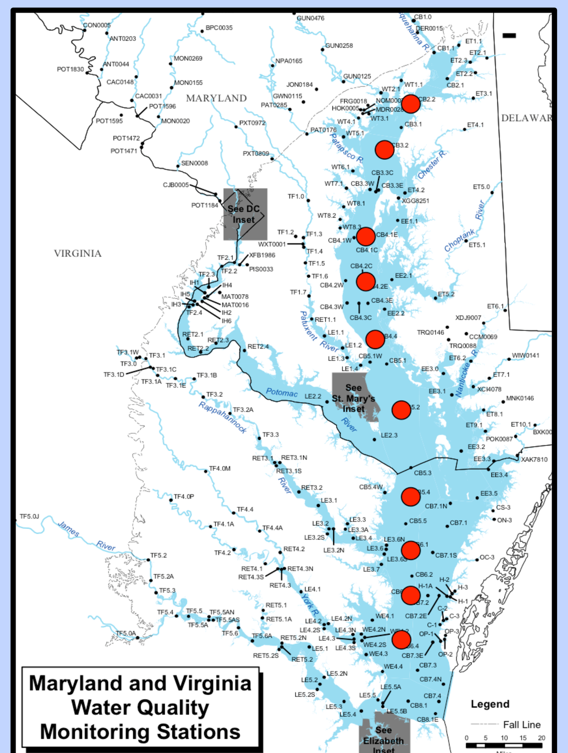

Figure 2. Location of the 10 Chesapeake Bay Program monitoring stations utilized in the study.

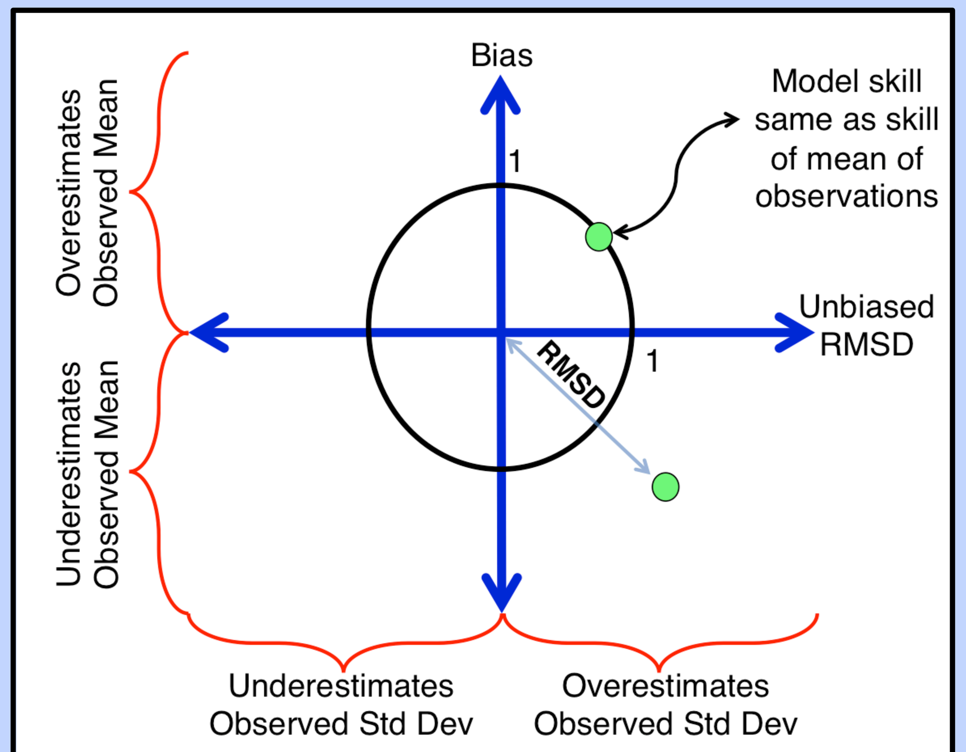

Figure 3. Target Diagram analysis: the total root mean square difference between the observations and the model results, normalized by the standard deviation of the observations. Normalized bias is shown on the y-axis and normalized unbiased RMSD is on the x-axis. (Jolliff et al., 2009, JMS, doi10.1016/j.jmarsys.2008.05.014).

	CH3D - ICM	ChesNENA	ChesROMS - BGC	ROMS - RCA
Temperature Surface	0.14	0.09	0.18	0.09
Temperature Bottom	0.21	0.33	0.21	0.19
Salinity Surface	0.23	0.31	0.43	0.36
Salinity Bottom	0.33	0.51	0.53	0.82
Stratification	1.11	1.36	1.34	1.33
DO Surface	0.71	0.51	0.74	0.66
DO Bottom	0.46	0.52	0.77	0.48
Chlorophyll Surface	1.17	1.25	1.70	2.08
Chlorophyll Bottom	0.88	1.05	1.28	1.54
Nitrate Surface	0.76	0.61	1.49	0.43
Nitrate Bottom	0.72	0.51	1.98	0.54

Table 2. Total normalized RMSD computed for each model for multiple variables using observations from cruises in 2004 at the 10 main stem stations shown in Figure 1. Shading indicates model results that perform better than the mean of the observations.

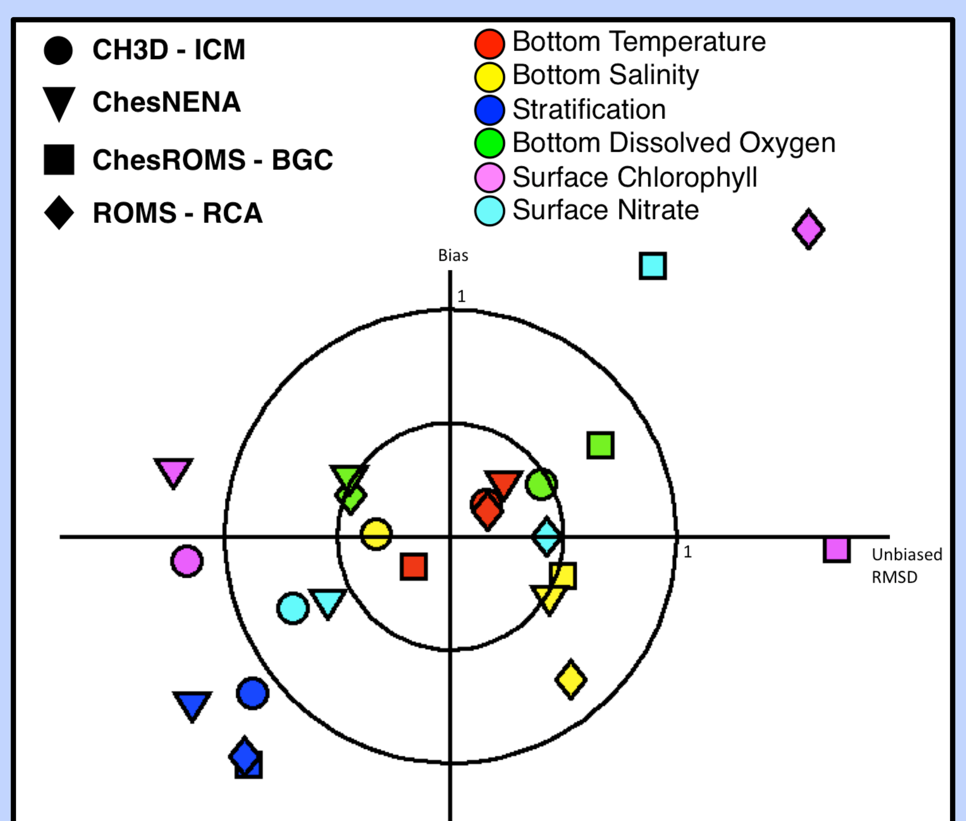

Figure 4. Normalized target diagram illustrating how well the four models perform in terms of reproducing the observed means and spatial and seasonal variability for six variables.

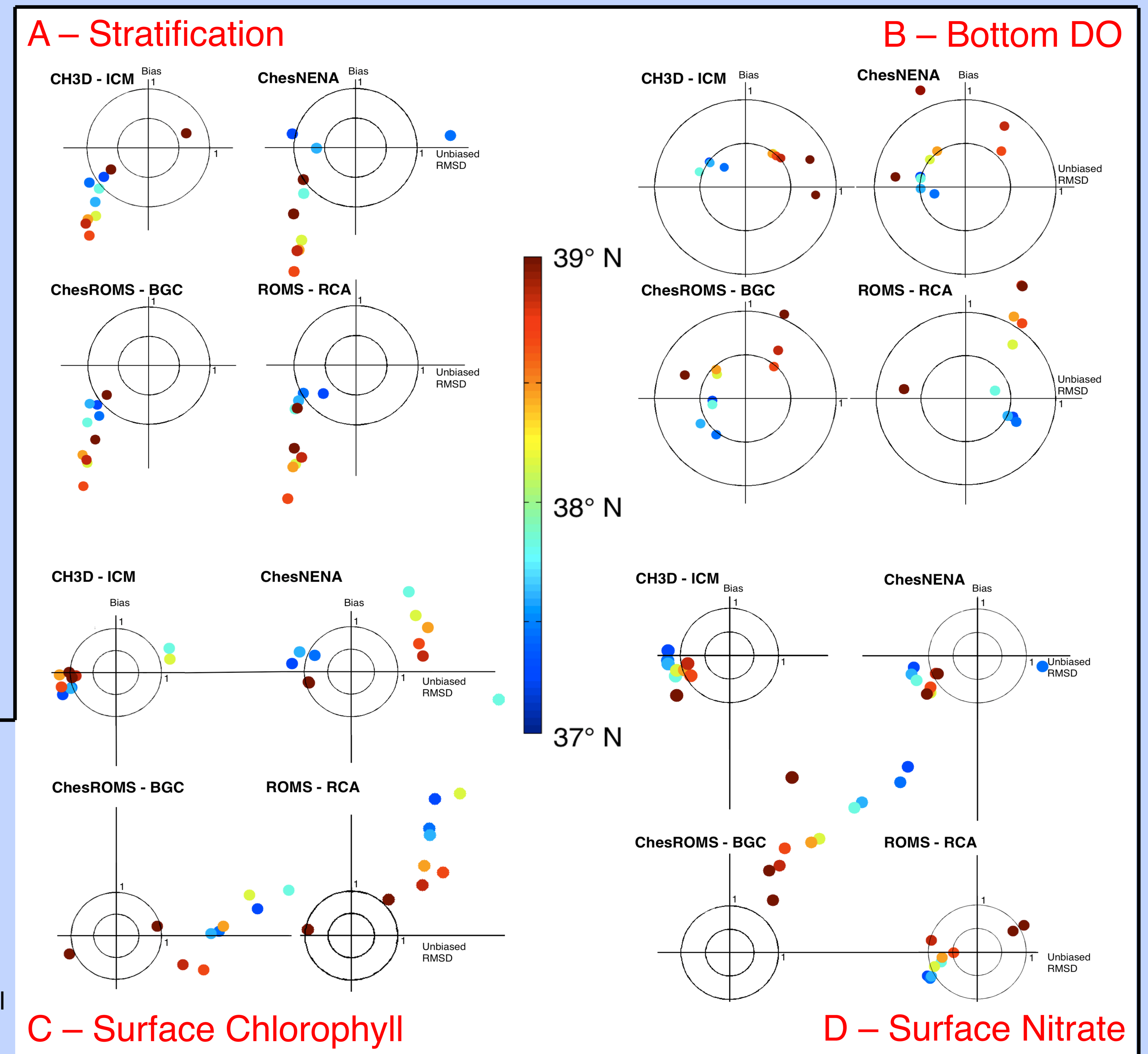

Figure 5. Normalized target diagrams showing how well the models reproduce the observed mean and seasonal variability at 10 main stem stations for four variables:
5A – Stratification
5B – Bottom Dissolved Oxygen
5C – Surface Chlorophyll
5D – Surface Nitrate.
Colors represent latitude. Stratification is defined as the maximum value of dS/dz in the water column of the model compared to that of the observations.

Results

- The skill of all four models are similar to each other in terms of temperature, salinity, stratification, and DO, but the models vary significantly in terms of their chlorophyll and nitrate (Fig. 4, Table 2).
- All models consistently underestimate both the mean and standard deviation of maximum stratification, particularly at the northern stations (Fig. 5a).
- Despite the models' inability to resolve stratification, the models reproduce the mean and variability of DO quite well. All models perform better at the southern stations than the northernmost stations (Fig. 5b).
- Model skill for surface chlorophyll varies significantly between models, with the regulatory CH3D – ICM model performing best (Fig. 5c). ROMS – RCA is particularly challenged at the southern stations.
- Model skill for surface nitrate varies significantly between models, with two of the ROMS-based models performing as well or better than CH3D – ICM (Fig. 5d). ChesROMS is particularly challenged at the southern stations.

Conclusions

- Overall, models with lower biological complexity and lower resolution achieve similar skills scores as the EPA regulatory model in terms of seasonal variability along the main stem of the Chesapeake Bay.
- Multiple variables exhibit latitudinal dependence of model skill that is consistent throughout all four models, e.g. mean stratification is underestimated most and model skill for DO is lowest in the north.
- All four models do substantially better at resolving bottom DO than they do at resolving three variables that are primary influences on DO: stratification, chlorophyll, and nitrate. This follows because DO's variability is sensitive to temperature as a result of the solubility effect, and the models reproduce temperature very well.
- **In terms of TMDL development, these findings offer a greater confidence in CH3D – ICM predictions of seasonal variability since a model does not necessarily need to perform well in terms of stratification, chlorophyll, or nitrate in order to resolve the mean and seasonal variation of DO.**

Future Work

Examine the skill of these multiple models in terms of interannual variability, with the goal of formulating a ROMS-based model that performs as well as the EPA regulatory model for both seasonal and interannual variability of DO and hypoxic volume.

Acknowledgements

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