Chesapeake Bay hypoxia coastal ocean modeling testbed

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Chesapeake Bay Hypoxia
Coastal Ocean Modeling Testbed

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\textsuperscript{1}VIMS  \textsuperscript{2}Anchor QEA  \textsuperscript{3}UMCES  \textsuperscript{4}WHOI

Federal Partners: Aijun Zhang (CO-OPS/NOS/NOAA)
Lewis Linker (CBP/EPA)
Gary Shenk (CBP/USGS)
Motivation – Why Chesapeake Bay?

The Chesapeake Bay:

- Largest estuary in U.S.
- Benefits derived from Bay > $100 Billion annually
- Major anthropogenic impacts threatens Chesapeake's economic/social services
- Additional impacts of climate change are not yet known
- One of longest & most comprehensive data sets (1985-present)
Motivation – Why focus on hypoxia?

Hypoxic (low oxygen) waters:

- Impact ecological resources in Bay, particularly demersal fish (low catches where DO < 3 mg/L)
Chesapeake Hypoxia Testbed

COMT Chesapeake Hypoxia Objectives:

• Evaluate short-term forecast skill of hypoxia events
• Transition hypoxia forecasts to operations
• Work with stakeholders to better understand how they prefer to receive this forecast information
• Evaluate scenario-based forecasts
  • How will decreased nutrient inputs impact hypoxia?
  • How will climate change impact hypoxia?
• **Short-term operational forecasts** *(M. Friedrichs/A. Bever)*
  - Review of Year 3 accomplishments
  - Quasi-operational forecasts *(VIMS website)*
  - Operational forecasts *(dev) (CBOFS website)*
  - Additional skill assessment of forecasts

• **Improvements to Hypoxia-SRM** *(M. Scully/C. Friedrichs)*

• **Seasonal patterns in P biomass & PP variability** *(R. Hood/H. Wang)*

• **Scenario-based operational forecasts** *(I. Irby/M. Friedrichs)*
  - Evaluating uncertainty in forecasts of nutrient reduction impacts
  - Assessing impacts of climate change on nutrient reduction impacts

• **Year 5 plans** *(M. Friedrichs)*
Previous COMT work identified and compared skill of multiple Chesapeake Bay oxygen models

Models:

- Eight models were compared, including multiple physical and biogeochemical variants

Available data:

- Models were assessed by monthly data (semi-monthly in summer) at multiple locations throughout Bay from 1985-present
- Data includes S, T, DO and multiple other ecological parameters
Results:

Year 2-3: Multiple model comparison (Irby et al. 2016):
- Simple models performed as well as more complex models
- Mean of multiple models performed best

Year 3: Examined nowcast vs. hindcast skill of CBOFS bottom DO:
- Nowcast bottom DO skill > hindcast bottom DO skill!

Year 3: Quasi-operational forecasts came online on VIMS website:
- Focus Groups & Stakeholder Workshops
Stakeholder Workshop summary:

- Strong enthusiasm for hypoxia forecasts as complementary tool with other information sources.

- Several captains already use real-time observations for planning (e.g., water clarity, temperature, wave heights) and/or short-term model forecasts (e.g., currents from CBOFS).

- Little interest in hypoxia forecasts beyond 2-3 days because of limited trust in detailed weather/wind forecasts beyond 2-3 days.

- Provided specific feedback on website presentation.
Year 4 Forecast improvements:

- Forecast now uses CBOFS operational forcing
- Forecast now shows mean of two models
  - SRM = Simple Respiration Model
  - ECB = Estuarine Carbon Biogeochemistry model
- SRM has been improved with seasonally variable respiration rate
- New (more detailed) color scale
- Improved appearance on mobile devices
Blues → High bottom oxygen
   = Good bottom water
   = Bottom fish and crabs

Yellow/green → Moderate to low oxygen
   = Poor bottom water
   = Fewer bottom fish and crabs

Red/orange → Very low bottom oxygen
   = Bad bottom water
   = No bottom fish or crabs
Friday’s Nowcast

Bottom Oxygen: Nowcast
July 28, 2017

White areas indicate no results where model bathymetry < 5m in depth

Friday’s Forecast

Bottom Oxygen: Forecast
July 30, 2017
Blue $\rightarrow$ Increasing oxygen
(Improving bottom water in western Bay)

Red $\rightarrow$ Decreasing oxygen
(Degradating bottom water in eastern Bay)

Due to forecast of strong NNW winds over the weekend
Chesapeake Hypoxia Forecast: www.vims.edu/hypoxia

U.S. News
VIMS' New Forecast Tool Can Help Anglers Find Good Fishing
VIMS' new dead zone forecast tool can help anglers find good fishing.

Daily Press
VIMS' new dead zone forecast tool can help anglers find good fishing

The Washington Post
VIMS' new forecast tool can help anglers find good fishing
From July 2017
“Quasi-operational” forecasts
on VIMS website:
http://www.vims.edu/hypoxia

Transition
(Hypoxia_SRM now in ROMS trunk!!)

“Truly operational” forecasts
on NOAA CBOFS (dev) site:
https://tidesandcurrents.noaa.gov/ofsd/dev/cbofs/cbofs.html
Chesapeake Hypoxia Forecast Transition

Operational Forecast Site

Surface Temperature

Surface Salinity

Bottom Oxygen

Time/Date: 0200 (EDT) 04/26/17
Outline

- **Short-term operational forecasts** (M. Friedrichs/A. Bever)
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  - Operational forecasts (dev) (CBOFS website)
  - **Additional skill assessment of forecasts** (A. Bever)

- **Improvements to Hypoxia-SRM** (M. Scully/C. Friedrichs)

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- **Year 5 plans** (M. Friedrichs)
Additional Year 4 objectives:

- How does the nowcast skill of SRM vs. ECB compare?
- How does the forecast skill of both models degrade over 6 - 48 hours?

Methods:

- Improve SRM by imposing seasonally varying respiration rate
- Apply identical forcing to both models
- Run 2.25 day simulation every six hours for the full 2.75 years, generating continually overlapping nowcasts and forecasts (6h, 12h, 18h, 24h, 30h, 36h, 42h, 48h)
Compare nowcast skill of ECB vs. SRM

Chesapeake Hypoxia Forecast - Testing

Bottom DO [mg/L]

CB3.2 Bottom: Dissolved Oxygen

CB5.1 Bottom: Dissolved Oxygen

Atlantic Ocean

2014 2015 2016
ChesROMS-ECB and ChesROMS-SRM produce nowcasts with similar skill (and that are equally skillful as hindcasts)

WHAT ABOUT FORECAST SKILL?

- Do forecasts predict same timing of DO events as nowcasts?
- Are forecasts skillful enough at predicting relatively large changes in DO, such that stakeholders can use the forecasts to plan their daily activities?
Methods:

- Significant “events” were defined as daily averaged bottom DO changing by ≥ 2mg/L over ≤ 2 days.
Methods:

• Significant “events” were defined as daily averaged bottom DO changing by $\geq 2$mg/L over $\leq 2$ days

• Error (lag/lead time) of forecast is determined by time-shifting the forecast output and determining the time shift with the highest $r^2$ value between the nowcasted and forecasted DO

• Examined results at 11 stations for both models
Chesapeake Hypoxia Forecast - Testing

Forecast leads nowcast by 4.3h, for SRM at CB4.1C
Error in 48 hour forecast is ~6h (ECB) to 7.5h (SRM)
Next year’s work (Year 5):

• Complete transition of hypoxia forecasts to operational CBOFS site (AJ Zhang)
• Provide forecast information for posting on MARACOOS Ocean Obs site (K. Knee)
• Examine feasibility of improving hypoxia forecasts by incorporating bottom oxygen data (A. Bever)
• Examine feasibility of including habitat suitability information for HABs & pathogens (R. Hood)
• Improve presentation of information provided on VIMS site through outreach with end-users (S. Musick)
  • Add salinity, temperature (HABs, vibrio?)
  • Add time series
  • Add climatological information
Outline

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• **Year 5 plans** (M. Friedrichs)
Goals and Motivation:

- Develop a method for estimating Primary Production (PP) from time-series measurements of dissolved oxygen ($O_2$) that can provide estimates of fundamental rates to rigorously test biogeochemical models.
- Incorporate a light-dependent formulation for PP into a simple model for $O_2$ that is suitable for operational forecast modeling.

Outline:

- Method for estimating PP and fundamental rates from observed $O_2$.
- Validation of the method with output from biogeochemical model (ECB).
- Modeling results from simple 1-term model with improved representation of biological processes (oxygen production).
Method for Estimating PP from O$_2$ Time-Series

\[
\frac{dO_2}{dt} = P_m \tanh\left(\frac{\alpha I}{P_m}\right) + C
\]

(Jassby & Platt 1976)

\(\alpha = \) init. slope of P-I curve  
\(P_m = \) Max. growth rate  
\(I = \) Irradiance (Light)

**Data Needs:**

- Continuous (hourly) measurements of near surface O$_2$ (CBIBS buoys)
- Continuous estimates of incoming solar radiation (NARR model)

**Procedure:**

- Calculate time-rate of change of oxygen (dO$_2$/dt) from buoy data.
- Estimate coefficient (C) by taking the average value of dO$_2$/dt at night (this represents both biological drawdown and physical processes).
- Perform least-squares fit to \(P_m \tanh(\alpha I/P_m)\) to obtain estimates of \(P_m\) (maximum phytoplankton growth rate) and \(\alpha\) (initial slope of P-I curve) over a 20-day moving window.
Method for Estimating PP from \( \text{O}_2 \) Time-Series

Example from CBIBS Goose’s Reef Buoy for July-August 2013

Instantaneous \( \text{dO}_2/\text{dt} \)

\( \text{dO}_2/\text{dt} \) (mmoles\text{O}_2/m^3/s)

\( \text{dO}_2/\text{dt} \)

Bin-averaged \( \text{dO}_2/\text{dt} \)

\( \text{dO}_2/\text{dt} \) (mmoles\text{O}_2/m^3/s)

\( P_m \text{ tanh}\left( \frac{\alpha I}{P_m} \right) + C \)

\( C \)

Daily Variation in Light

Surface Irradiance (W/m²)

Daily Variation in \( \text{dO}_2/\text{dt} \)

\( \text{dO}_2/\text{dt} \) (mmoles\text{O}_2/m^3/s)

\( C \)
Application of Method to ECB Output

y-axes are PP in units of $O_2/vol/time$

ECB = direct PP output

$PP_{\text{est.}} = P_m \tanh\left(\frac{\alpha I}{P_m}\right)$
inferred from near-surface ECB $O_2$
Estimates of Primary Production from CBIBS Buoys

Increasing Nutrient Limitation

Light limited

PP in units of O$_2$/vol/time
Evidence for Light Limitation at Susquehanna Buoy

Primary Production

- PP/max(PP)
- NTU/max(NTU)

2015

Primary Production

- PP (mmolesO₂/m³/s)

Turbidity (ntu)

0 5 10 15 20 25

0 0.5 1 1.5 2 x 10⁻³
Simple $O_2$ Model including Primary Production

\[
\frac{\partial O_2}{\partial t} = PP + CR + u \nabla O_2 + \frac{\partial}{\partial z} \langle O_2'w' \rangle
\]

Temperature dependent slope of P-I curve

\[PP = P_m \tanh\left( \frac{\alpha I}{P_m} \right)\]

Temperature dependent maximum growth rate

Depth-invariant seasonally-varying oxygen consumption. Modeled as simple Gaussian function with max at end of July

Relationships derived from CBIBS Buoys

Max Growth Rate ($P_m$)

Slope P-I curve ($\alpha$)
Previously, the Simple Respiration Model assumed that surface oxygen concentration was maintained at saturation value.

New formulation captures time variations (including super-saturation) in a much more realistic way.
Model Comparison of Bottom $O_2$ (Scully 2013 data)
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Overarching Questions:

- Do current generation biogeochemical models capture observed seasonal patterns in phytoplankton biomass and primary production variability in Chesapeake Bay?

- What is the role of lateral transport in supplying organic matter to the deep channel of the mainstem Chesapeake Bay?

- Can we use our BGC model as a dynamic interpolator to provide insight into the temporal and spatial variability in denitrification in Chesapeake Bay?
Overarching Questions:

- Do current generation biogeochemical models capture observed seasonal patterns in phytoplankton biomass and primary production variability in Chesapeake Bay?

- What is the role of lateral transport in supplying organic matter to the deep channel of the mainstem Chesapeake Bay?

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Variability of biomass and productivity

Classic Conceptual Model of Biomass and Production Variability:

- Freshet drives the spring diatom bloom and leads to export to the bottom.
- Increasing summer temperatures lead to remineralization of organic matter on the bottom.
- Upward diffusive mixing and transport of nutrients to the surface during summer leads to high summer production.
The spring diatom bloom is associated with freshet, but it's not a productivity maximum. During summer have maximum productivity. This summer production is fueled largely by recycling of organic matter from the bottom that was put there during spring. Also see a shift in size: large diatoms in spring -> smaller flagellates and dinoflagellates in summer.
Variability of biomass and productivity

Model Configuration (ChesROMS BGC):

- Xu et al. (2012)
- Grid: 100x150x20
- Brown et al. (2013), Wiggert et al. (2017)
- Fennel et al. (2006) with water column and benthic denitrification.
Variability of biomass and productivity

Modeled Phytoplankton Biomass:

Models Capture:

- Spring bloom
- Deep chlorophyll accumulation in Spring
- Low biomass during summer
Modeling Primary Production Rate:

- Model captures the seasonal variability of the primary production in some years: e.g., 1994 highest production during summer as observed.

Variability of biomass and productivity
But not in others: e.g., in 1991 see a dramatic drop in the summer which is not consistent with observations.
Role of River Forcing:

- River discharge plays a role in this interannual variability.
- Years with high river nutrient loading during summer tend to capture observed high summertime primary production (e.g., 1994).
- Years with low nutrient loading during summer tend to have primary production rates that are too low during summer (e.g., 1991).
Variability of biomass and productivity

Classic Conceptual Model of Biomass and Production Variability:

Figure courtesy of M. Kemp

- We hypothesize that there is insufficient upward diffusion and mixing of nutrients to support high summertime production in our models when river nutrient inputs during summer are low.
Conclusions:

• Models can capture observed seasonal and vertical variability in phytoplankton biomass but they do not consistently capture seasonal primary production variability.

• Models require lateral nutrient inputs from rivers to maintain high production during summer.

• Low lateral supply during summer results in nutrient limitation and unrealistically low summertime production.

• We hypothesize that there is insufficient upward diffusion and mixing of nutrients to support high summertime production in these models when summertime river nutrient inputs are low.
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• **Year 5 plans** (M. Friedrichs)
Evaluating confidence in the impact of regulatory (TMDL) nutrient reduction on Chesapeake Bay water quality
Impact of Nutrient Reduction

1993 – 1995 conditions from Watershed Model

Regulatory Model CH3D-ICM

Academic Model ROMS-ECB

Prediction of Water Quality Standard Attainment

TMDL Nutrient Reduction from Watershed Model

Regulatory Model CH3D-ICM

Academic Model ROMS-ECB

Prediction of Water Quality Standard Attainment

Assessment of Confidence
Are dissolved oxygen standards attained with nutrient reduction?

Deep Channel

Observed 1993 – 1995

TMDL CH3D-ICM

TMDL ROMS-ECB

Pass

“Pass”

Fail
Impact of Nutrient Reduction

Confidence Index

- Across habitats
- Across years
- Across methodology

Issues Identified

- Chester River: Regulatory (EPA) Model
- Eastern River: Academic Model
- TMDL regression methodology
Impact of Nutrient Reduction

Results:

• High similarity/confidence in terms of prediction of attainment of water quality standards resulting from planned nutrient reductions

• Large difference in the intermediate steps to get to water quality standard attainment

• Comparing models can elucidate issues in models and methodology
The competing impacts of climate change and nutrient reduction on dissolved oxygen
## Climate Change & Nutrient Reduction

### 2050 Relative to 1993-1995

<table>
<thead>
<tr>
<th>Parameter</th>
<th>2050 Value Relative to 1993-1995</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature</td>
<td>1.75°C</td>
</tr>
<tr>
<td>Sea Level Rise</td>
<td>0.5m</td>
</tr>
<tr>
<td>River Flow</td>
<td>~15% winter</td>
</tr>
</tbody>
</table>

- **Temperature**: 1.75°C
- **Sea Level Rise**: 0.5m
- **River Flow**: ~15% winter

- **Oxygen Solubility**: Decrease
- **Seawater intrusion**: Increase
- **Biologic Rates**: Increase
- **Fresh water**: Increase
- **Bay volume**: Increase
- **Nutrient load**: Increase
Climate Change Scenarios

- Current
- TMDL
- TMDL + Climate Change
- TMDL + Temperature
- TMDL + River Flow
- TMDL + Sea Level Rise
Climate Change & Nutrient Reduction

Impact of TMDL is greater than impact of climate change

A TMDL wet year looks like a current dry year
Climate Change & Nutrient Reduction

Impact of TMDL is greater than impact of climate change

A TMDL wet year looks like a current dry year

Temperature is the biggest driver of climate change impact
Results:

- TMDL > Climate Change
- Higher Temperature > Sea Level Rise & Increased River Flow
- Hypoxia starts ~7 days earlier with climate change
Future Research Directions

CHAMP: Chesapeake Hypoxia Analysis and Modeling Program

- Predict the impacts of future climate change and pollution on hypoxia
- Predict the future effectiveness of various pollution reduction scenarios on reducing hypoxia

Funded by NOAA CSCOR – Coastal Ocean Program, 2016-2021
Climate Change & Nutrient Reduction

**Future Research Directions**

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Funded by NOAA CSCOR – Coastal Ocean Program, 2016-2021
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• **Year 5 plans** (M. Friedrichs)
Year 5 plans

• Scenario-based operational forecasts: CHAMP (NOAA-CSCOR)

• Improvement of Hypoxia-SRM (inclusion of simple PP model)

• Evaluating skill of habitat suitability models for nowcasting/forecasting HAB species and bacterial pathogens

• Expanding hypoxia forecasts
  • Available on MARACOOS site
  • Available on CBOFS site
  • Improved forecasts using available data (CBIBS)
  • Continued work with stakeholder focus groups
Questions?

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Chesapeake Hypoxia Forecasts – Year 4 work

Nowcast skill of ChesROMS bottom DO

Bottom DO [mg/L]

CB6.4 Bottom: Dissolved Oxygen
SRM Nowcast
ECB Nowcast

2014 2015 2016

Bottom DO

Atlantic Ocean

CB3.2
CB3.3C
CB4.1C
CB4.2C
CB4.3C
CB4.4
CB5.1
CB5.2
LE2.3
CB5.4
CB7.1
CB6.2
CB6.4
Updated Real-Time Forecast Figures

Bottom Oxygen at CB4.1C

Average Bottom Layer Oxygen Forecast
2017-05-24
Cerco et al. (2006)
Future Work

Investigating methods for nudging modeled fields to high frequency real-time buoy observations (T, S, DO) at 10 locations.