Modeling Hypoxia & Ecological Responses to Climate & Nutrients

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Structure of CHRP:CB Research Program

• Simulation Studies (Prognostic)
  (1) Predicting hypoxia scenarios at seasonal & interannual scales
  (2) Formal parameter optimization to improve model skill
  (3) Incorporating uncertainty w/ ensemble simulations

• Diagnostic Assessment
  (3a) Understanding climate & nutrient input controls on hypoxia
  (3b) Simulating ecosystem processes & feedback regulation

• Retrospective Analysis
  (4) Focus on mechanisms controlling hypoxia in CB & DIB
  (5) Understand “Regime Shift” in hypoxia per unit nutrient load

• Habitat Evaluation
  (6) Fish/Invert habitat & “production” responses to climate & mgmt?

• Science Education Outreach
Configuration of ROMS model for Chesapeake Bay

- Develop existing implementation of ROMS for Chesapeake Bay
- Curvilinear horizontal coordinates with grid spacing about 1 km.
- Generalized terrain-following vertical coordinate with 20 layers.

(Ming Li et al.)
• Existing implementation of ROMS for Delaware Inland Bays
• Eutrophic lagoonal system with mean depth ~ 2 m
• Problems documented with diel cycling hypoxia
Diagnostic Analysis: Event-Enhanced Production

- Simulation experiments to understand wind-forced productivity.
- Vertical wind mixing stimulates lateral nutrient upwelling
- Model experiments deepen understanding of ecological processes

(Li, Harding)
**Forecasting: Event Induced Pycnocline Tilting**

**Observations (Malone et al. 1986)**

- Model captures observed lateral ‘seiching’ driven by wind events
- Seiching causes upwelling of hypoxic water onto shallow flanks
- Large ecological & economic impacts result from events

(Li, Kemp, Boynton)
Retrospective Analysis: CB Hypoxia Regime Shift

- Volumes of summer hypoxic ($O_2 < 1 \text{ mg/L}$) and anoxic ($O_2 < 0.5 \text{ mg/L}$) clearly related to winter-spring river flow.
- Abrupt increase in slope of time trend from 1950-1980 (blue line) to 1980-2003 (magenta line). Currently, there is more hypoxia per unit $\text{NO}_3$ Loading.

- What factors have contributed to this abrupt “regime shift” leading to more hypoxia per loading?
- Novel approaches are needed to simulate these dynamics

(Kemp, Boynton, et al.)
- Diel variations in O$_2$ reveal night time hypoxia common in summer
- Existing water quality models (blue) do not capture dynamics
- New ROMS biophysical model simulates these patterns well

(Kirby, DiToro, Kemp)
Forecasting: Using Assimilation of MERL Data to Calibrate Biogeochemical Model

Use zero-dimensional models of experimental ecosystems to optimize parameter set and test model uncertainty

(DiToro, Fennel, Kemp)
Forecasting: Data Assimilation

Basic scheme for non-linear parameter optimization:

1. Initial parameter estimates
2. Model Parameters
   - function parameters
   - initial & boundary conditions
3. Forward model
4. Model fields
5. Sensitivity of cost function J to parameters
6. Adjoint model
7. Computed cost function, J
8. If ΔJ<ε; stop

(Katja Fennel)
Habitat Assessment: Suitability Models

3D Hydrodynamic Model
- currents
- salinity
- temperature

3D Biogeochemistry Model
- dissolved oxygen
- plankton food

3D Habitat Suitability Model
- favorable temperature
- favorable salinity
- unfavorable dissolved oxygen
- suitable habitat

Fig. 12. Conceptualization of Habitat Suitability Model.

(North, Secor)
# Sequencing CHRP Research Effort

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Concluding Comments

- We have successfully completed the first year of this study (despite severe budget cuts).

- *Simulation Studies* linking ROMS-RCA model are complete & data assimilation for parameter optimization & model error are underway.

- *Diagnostic Modeling* studies have revealed mechanisms by which wind regulates vertical mixing and channel-flank coupling.

- *Retrospective Analysis* has led to improved understanding of the controls on “Regime Shift” in hypoxia per nutrient loading—key biogeochemical processes have been identified.

- *Habitat Evaluation* has effectively generated oyster habitat models using particle tracking model as basis.

- *Science Education Outreach* has engaged HS teachers into research program and provided online lesson plans and activities.
Epilogue: Biogeochemical Mechanism for Hypoxia-Nitrogen Regime Shift

• Hypothesized that extended low-O$_2$ conditions has led to higher fraction of N-loading being recycled to reinforce phytoplankton growth and eutrophication process.

• This because coupled nitrification-denitrification is lost, and more of NH$_4$ produced in bottom respiration is recycled to overlying water rather than being transformed to bio-unavailable N$_2$ in denitrification.

• In addition, hypoxia-caused loss of benthic macrofauna eliminates their bio-irrigation processes that enhance nitrification-denitrification.

• Analysis of historical data bears this out, and these mechanisms are being added to forecasting models to improve model skill and application for management-relevant scenario simulations.
“Regime Shift” for Hypoxia per N-Load

- Hypoxia volume generally related to Nitrogen loading
- In early 1980s, relation between hypoxia & N-load jumped to upper regime, with 2-3x more hypoxia per N-load
- Many contemporaneous changes in ecosystem; are there parallel biogeochemical feedbacks that would help simulate pattern?
Hypothesis for Hypoxia-Enhanced N-Recycling

(J. Testa & M. Kemp 2009)
Shift in Bottom Water NH$_4$ Pool Tracks Hypoxia per Nutrient Loading

- TN-loading increases until mid-1980s, then fluctuates & declines
- Anoxia volume fluctuates, but increases steadily into 2000s.

- Bottom-water NH$_4$ pool per N-load fluctuations & jumps up in 1980s
Significant Shift in Bottom Water NH$_4$ Pools Since Early 1980s

- Bottom-water NH$_4$ pools generally increase with TN loading.
- In early 1980s the size of the bottom NH$_4$ pools increased (>2x) abruptly.
- Biogeochemical change (hypoxia, macrofauna?)
Other Slides that "Missed the Cut"
Simplified Schematic of Ecological Model (RCA)
Calibrating RCA with MERL (drawing of facility)

MERL Experimental Ecosystems, URI (Nixon, Oviatt et al.)
Stratification Control of Hypoxic Region in Chesapeake Bay

DO declines along landward advecting flow ...
Vertical Exchange between Upper & Lower Layers of Chesapeake Bay

- Vertical exchange is minimal in mid-Bay from May-August
- Corresponds to location and duration of hypoxia (white box).
- How does it vary inter-annually?

(Hagy 2002)
Sources of Oxygen Replenishment in Hypoxic Bottom-Layer of Mid Chesapeake Bay

Average Flow (1990)

21% Vertical Diffusion
34% Net Horizontal Advection
56%

mg l⁻¹