A Simple Model for Oxygen Dynamics in Chesapeake Bay

Center for Coastal Physical Oceanography

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Community Surface Dynamics Modeling System (CSDMS)
2011 Meeting; Boulder, CO

Outline:

1) Background and Motivation
2) Simplified Modeling Approach
3) Importance of Physical Forcing to Seasonal Variations in Hypoxic Volume
    1) River Discharge
    2) Heat Flux / Temperature
    3) Wind (Magnitude and Direction)
4) Inter-annual Variation in Hypoxic Volume
5) Conclusions

Testbed to Improve Models of Environmental Processes on the U.S. Atlantic and Gulf of Mexico Coasts

Estuarine Hypoxia Team

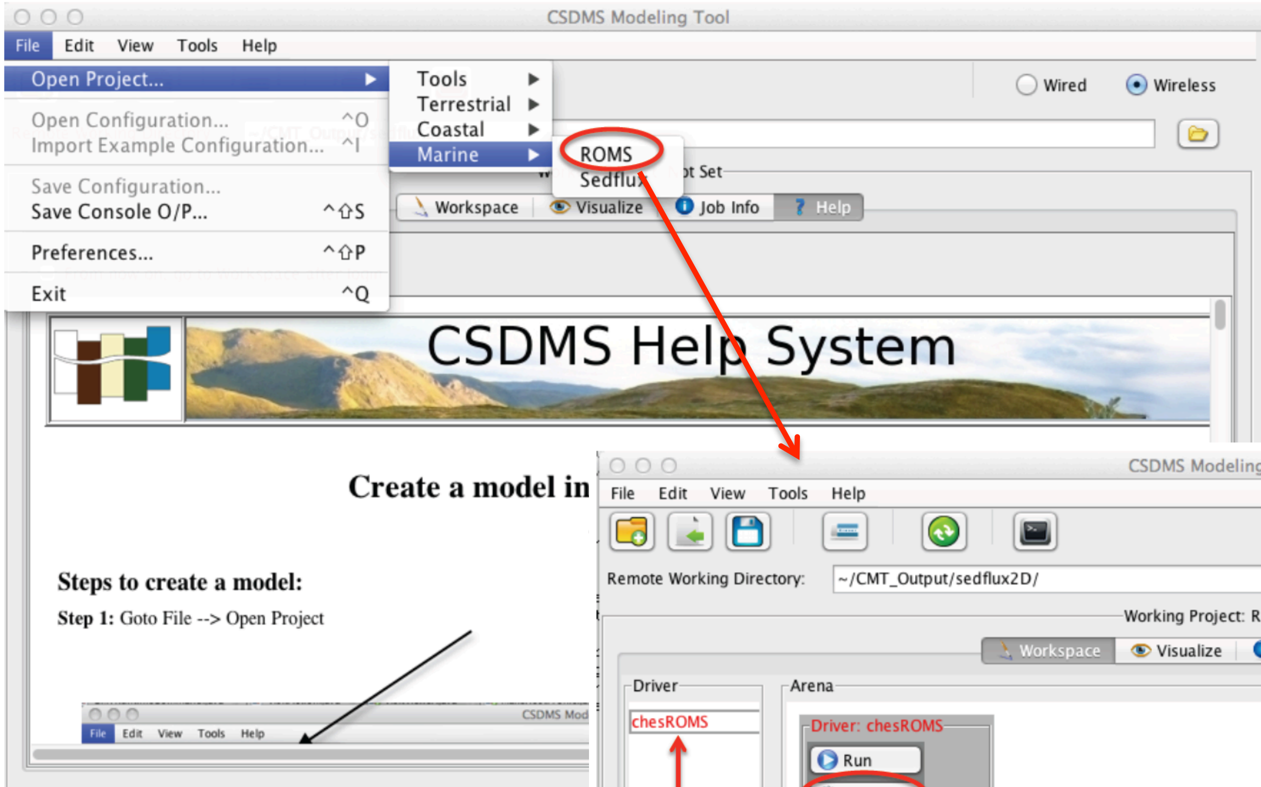
Federal partners

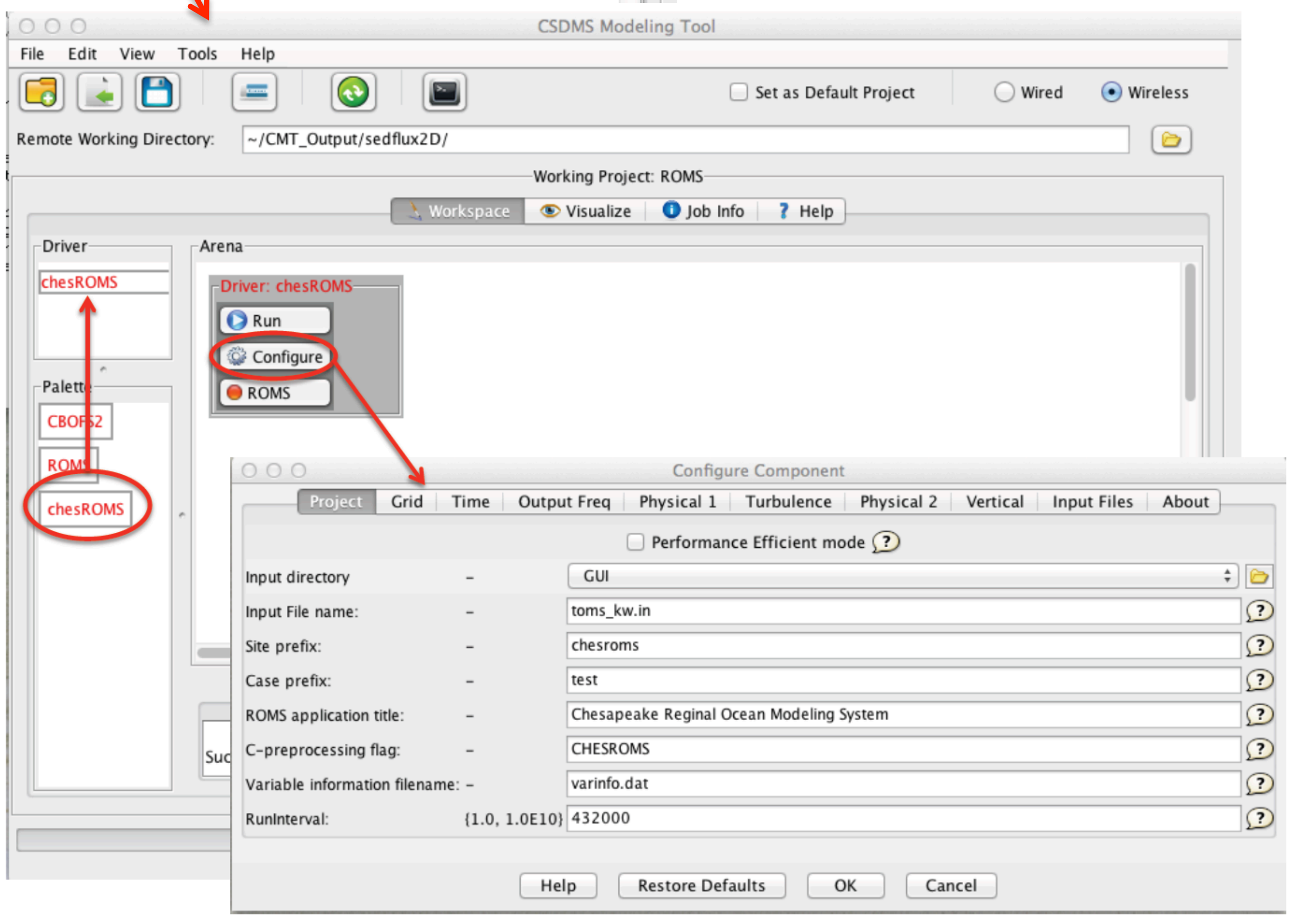
- David Green (NOAA-NWS) – Transition to operations at NWS
- Lyon Lanerole, Rich Patchen, Frank Aikman (NOAA-CSDL) – Transition to operations at CSDL; CBOFS2
- Lewis Linker (EPA), Carl Cerco (USACE) – Transition to operations at EPA; CH3D, CE-ICM
- Doug Wilson (NOAA-NCBO) – Integration w/observing systems at NCBO/IOOS

CSDMS partners

- Carl Friedrichs (VIMS) – Project Coordinator
- Marjorie Friedrichs, Aaron Bever (VIMS) – Metric development and model skill assessment
- Ming Li, Yun Li (UMCES) – UMCES-ROMS hydrodynamic model
- Wen Long, Raleigh Hood (UMCES) – ChesROMS with NPZD water quality model
- Scott Peckham, Jisamma Kallumadikal (UC-Boulder) – Running multiple models on a single HPC cluster
- Malcolm Scully (ODU) – ChesROMS with 1 term oxygen respiration model
- Kevin Sellner (CRC) – Academic-agency liason; facilitator for model comparison
- Jian Shen (VIMS) – SELFE, FVCOM, EFDC models

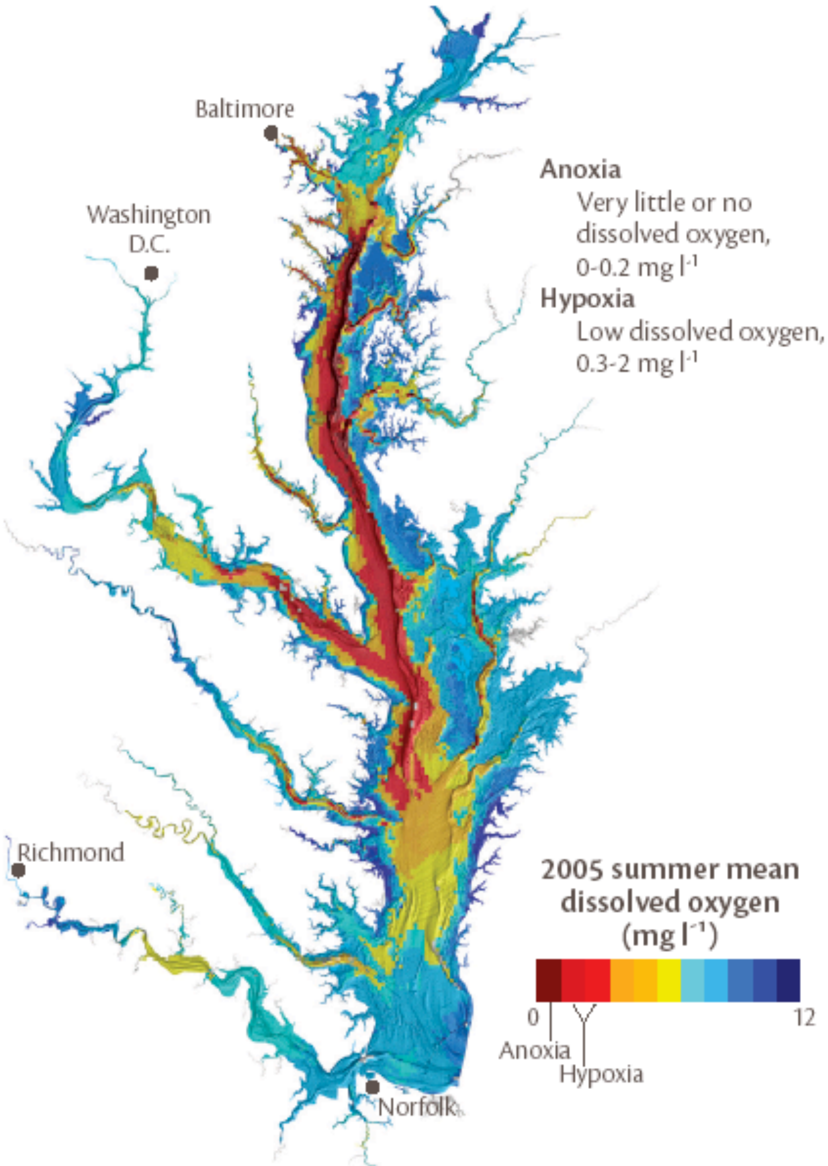
ChesROMS and two other flavors of ROMS are already incorporated into CSDMS.





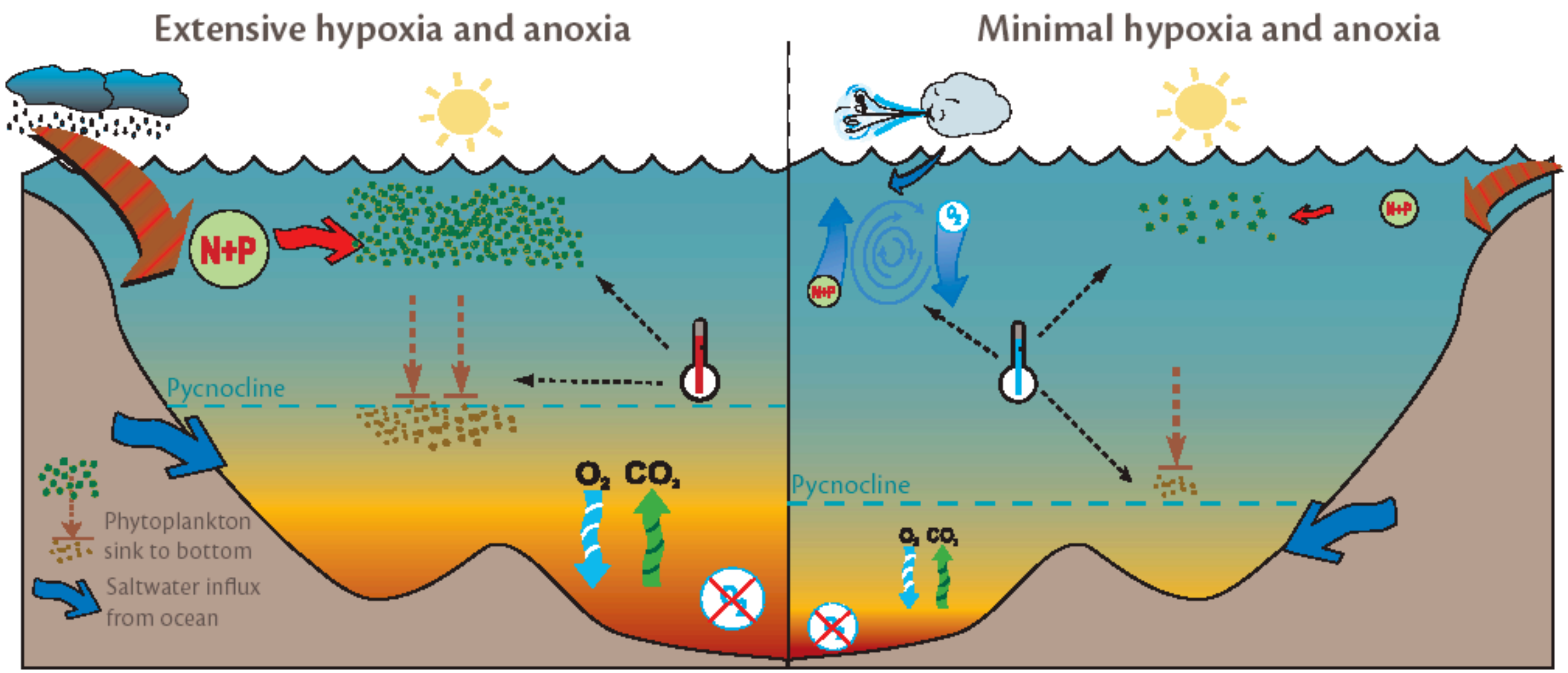
1) Run CSDMS Modeling Tool
2) "File" → "Open Project"
 → "Marine" → "ROMS"
3) Drag selected "Palette" ("chesROMS" in this case) into Driver;
4) Choose "Configure", adjust settings as desired;
5) Run chesROMS

Map of Mean Bottom Dissolved Oxygen -- Summer 2005



- Low DO has significant impact on a wide array of biological and ecological processes.
- Large regions of Chesapeake Bay are impacted by hypoxia/anoxia.
- Over $ 3.5 billion was spent on nutrient controls in Chesapeake Bay between 1985-1996 (Butt & Brown, 2000)
- Assessing success/failure of reductions in nutrient loading requires understanding of the physical processes that contribute to the inter-annual variability.

From Chesapeake Bay Program newsletter: http://ian.umces.edu/pdfs/do_letter.pdf



	Loads	Phytoplankton	Decomposition	Temperature	Wind event
Large amount of low dissolved oxygen	Large nitrogen and phosphorus loads	Elevated nutrients cause large phytoplankton blooms	High oxygen consumption by decaying phytoplankton	Warm water a) Stimulates decomposition b) Stratifies water column c) Stimulates phytoplankton	No wind event: water column remains stratified
Little amount of low dissolved oxygen	Small nitrogen and phosphorus loads	Less nutrients lead to small phytoplankton blooms	Low oxygen consumption by decaying phytoplankton	Cool water: a) Slow decomposition b) Mixed water column c) Slow phytoplankton growth	Wind events destratifies water column: a) Bottom water aerated b) Nutrients move to surface

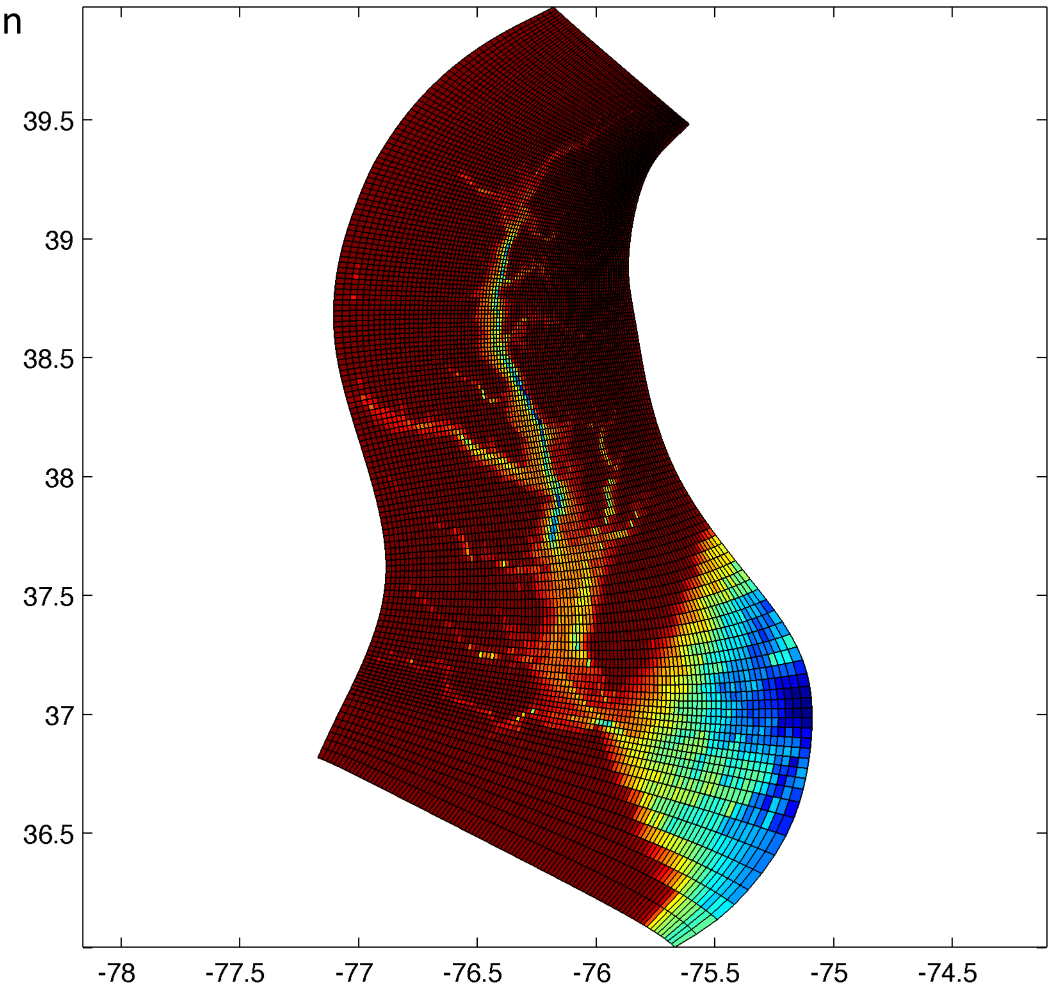
Figure 2: This conceptual diagram illustrates the factors that affect dissolved oxygen in Chesapeake Bay.

Regional Ocean Modeling System (ROMS)

<u>Model forcing</u>

- Realistic tidal and sub-tidal elevation at ocean boundary
- Realistic surface fluxes from NCEP (heating and winds)
- Observed river discharge for all tributaries.
- Temperature and salinity at ocean boundary from World Ocean Atlas.

ChesROMS Model Grid

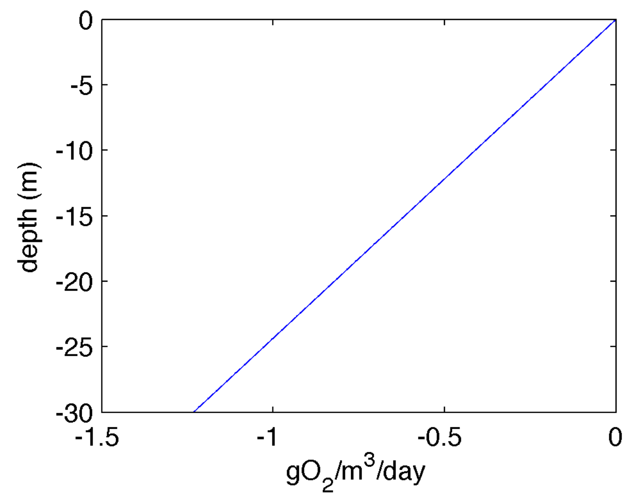


Oxygen Model

- Oxygen is introduced as an additional model tracer.
- Oxygen consumption (respiration) is constant in time, with depth-dependent vertical distribution.
- No oxygen consumption outside of estuarine portion of model
- No oxygen production.
- Open boundaries = saturation
- Surface flux using wind speed dependent piston velocity following Marino and Howarth, 1993.
- No negative oxygen concentration and no super-saturation.

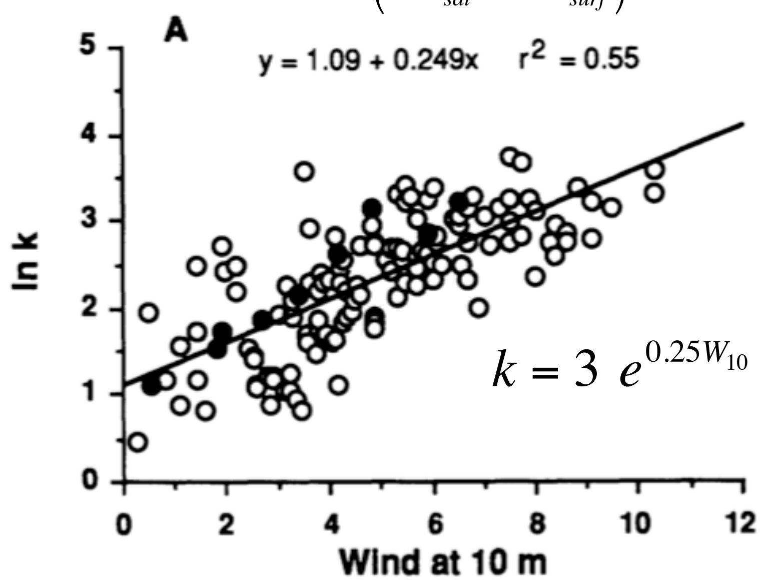
Model assumes biology is constant so that the role of physical processes can be isolated!

Depth-dependent Respiration Formulation



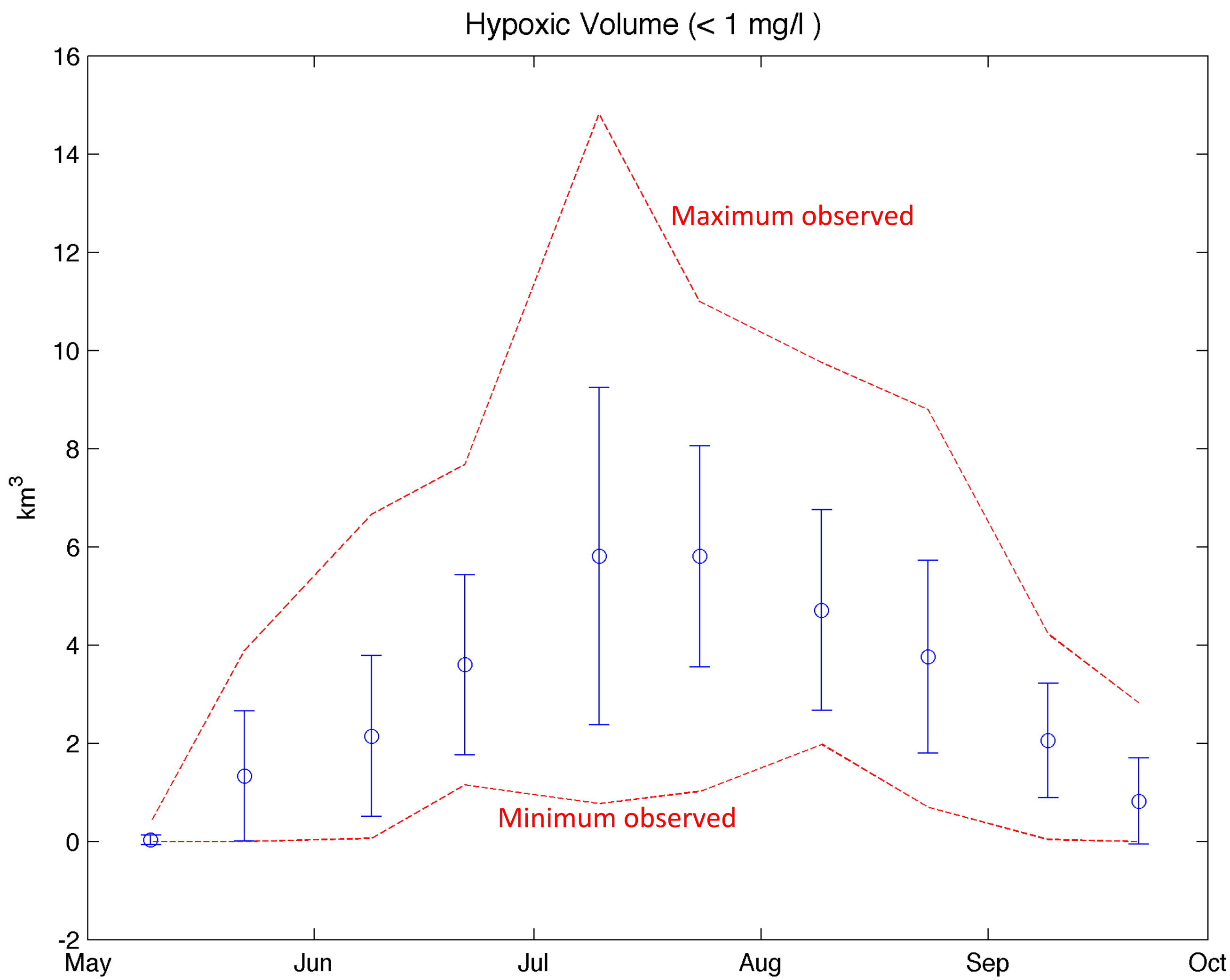
Surface Oxygen Flux using Piston Velocity:

$$Flux = k\left(DO_{sat} - DO_{surf}\right)$$



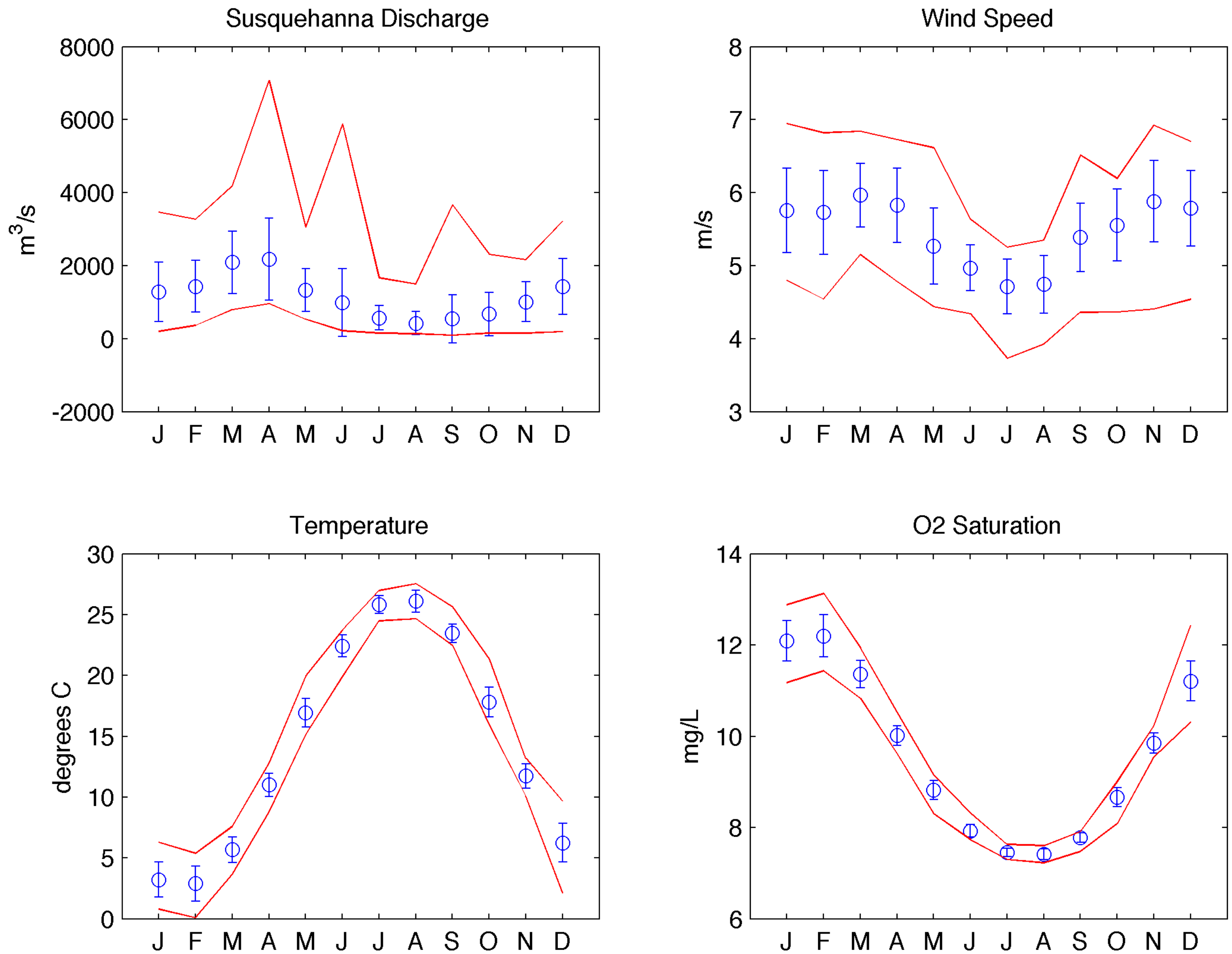
From Marino and Howarth, Estuaries, 1993

Seasonal and Inter-Annual Variability in Hypoxic Volume (from CBP data 1984-2009)



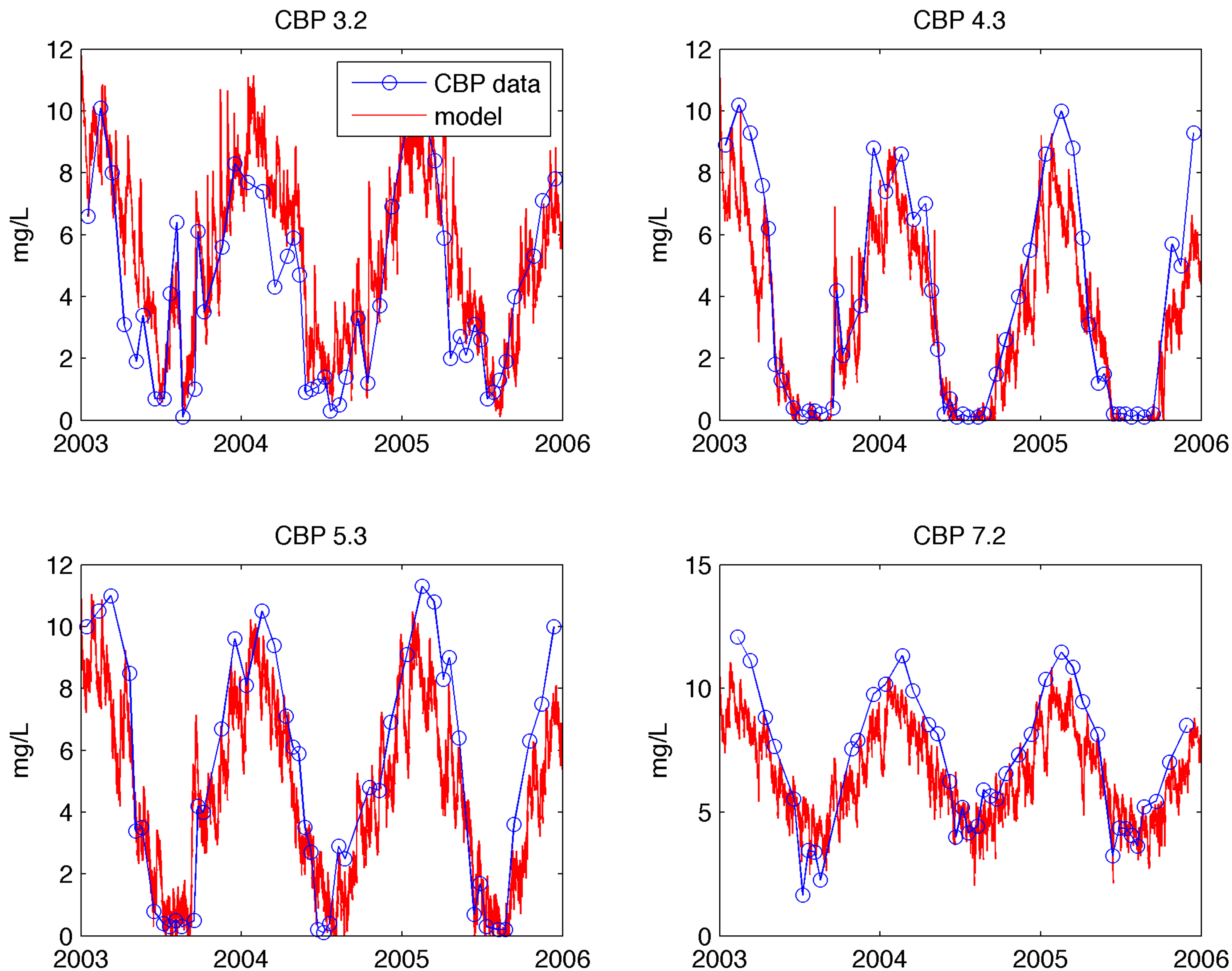
Data compiled from Murphy et al. (submitted)

Variability of Physical Forcing



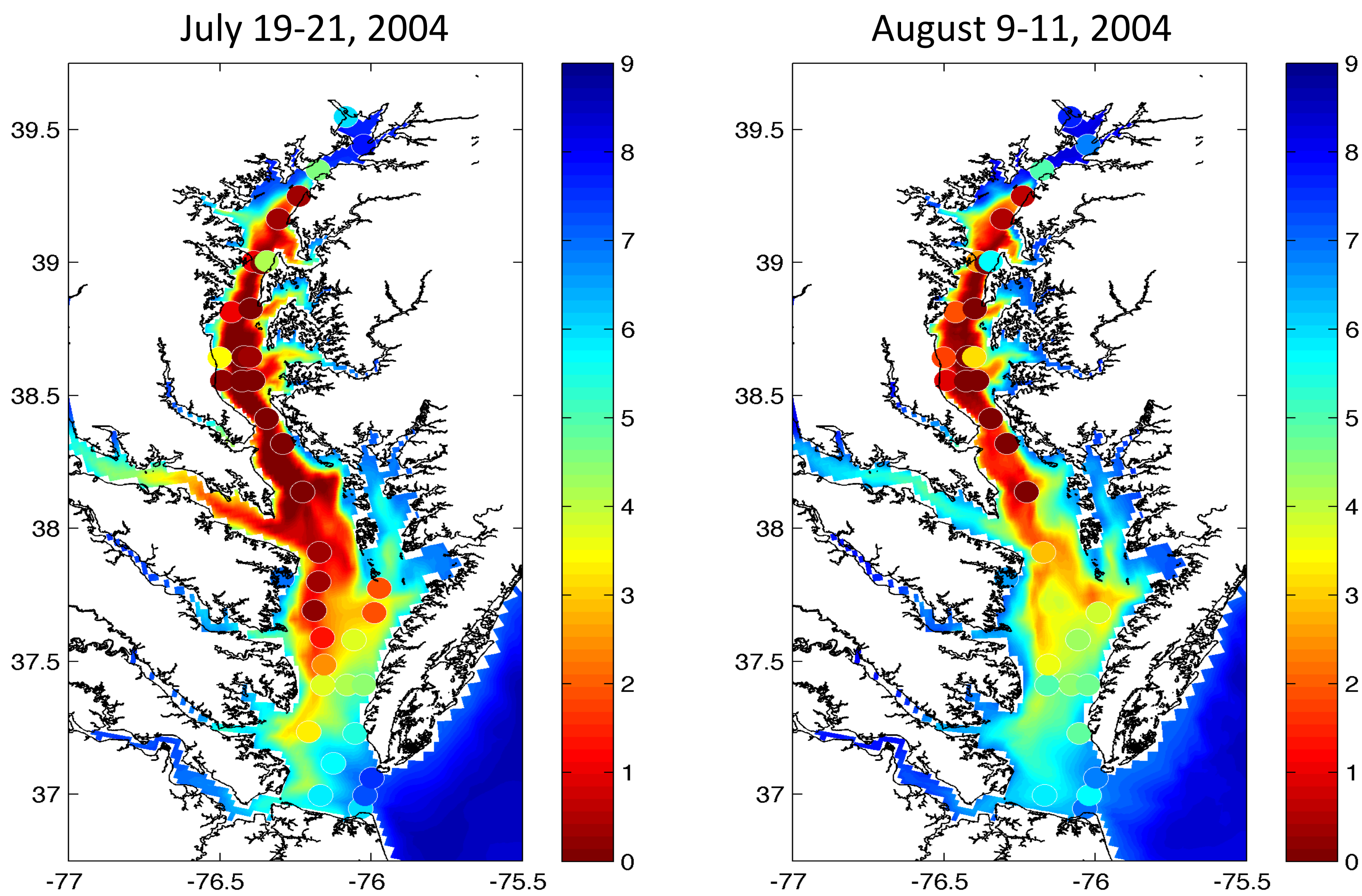
What is relative importance of different physical forcing in controlling seasonal and inter-annual variability of hypoxia in Chesapeake Bay?

Comparison with Bottom DO at Chesapeake Bay Program Stations

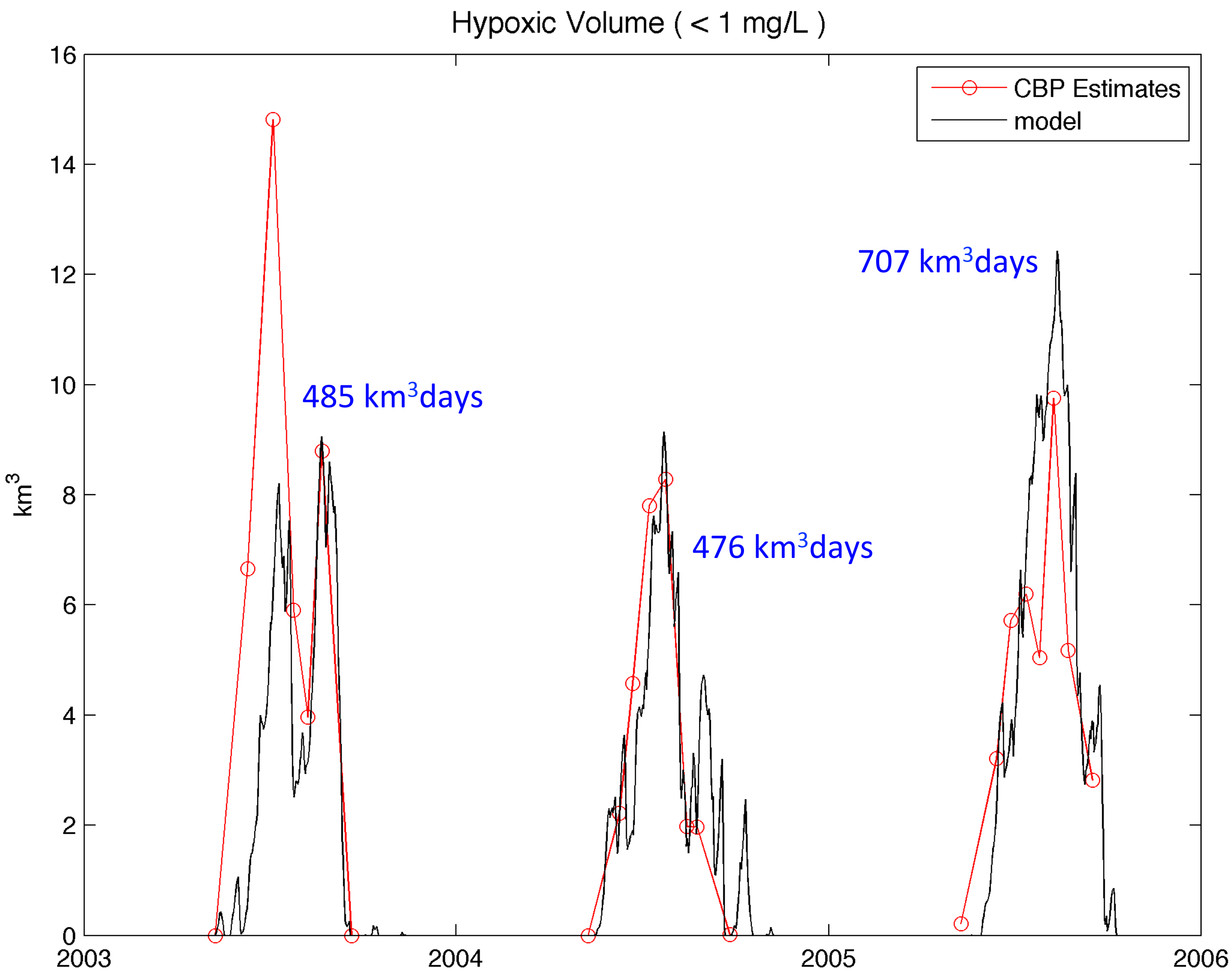


Comparison with Chesapeake Bay Program Data

Bottom Dissolved Oxygen Concentration (mg/L)



In addition to seasonal cycle, model captures some of the inter-annual variability



Model predicts roughly 50% more hypoxia in 2004 than in 2005, solely due to physical variability.

Physical Controls on Hypoxia in Chesapeake Bay

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Virginia Institute of Marine Sciences, Seminar
October 21, 2011

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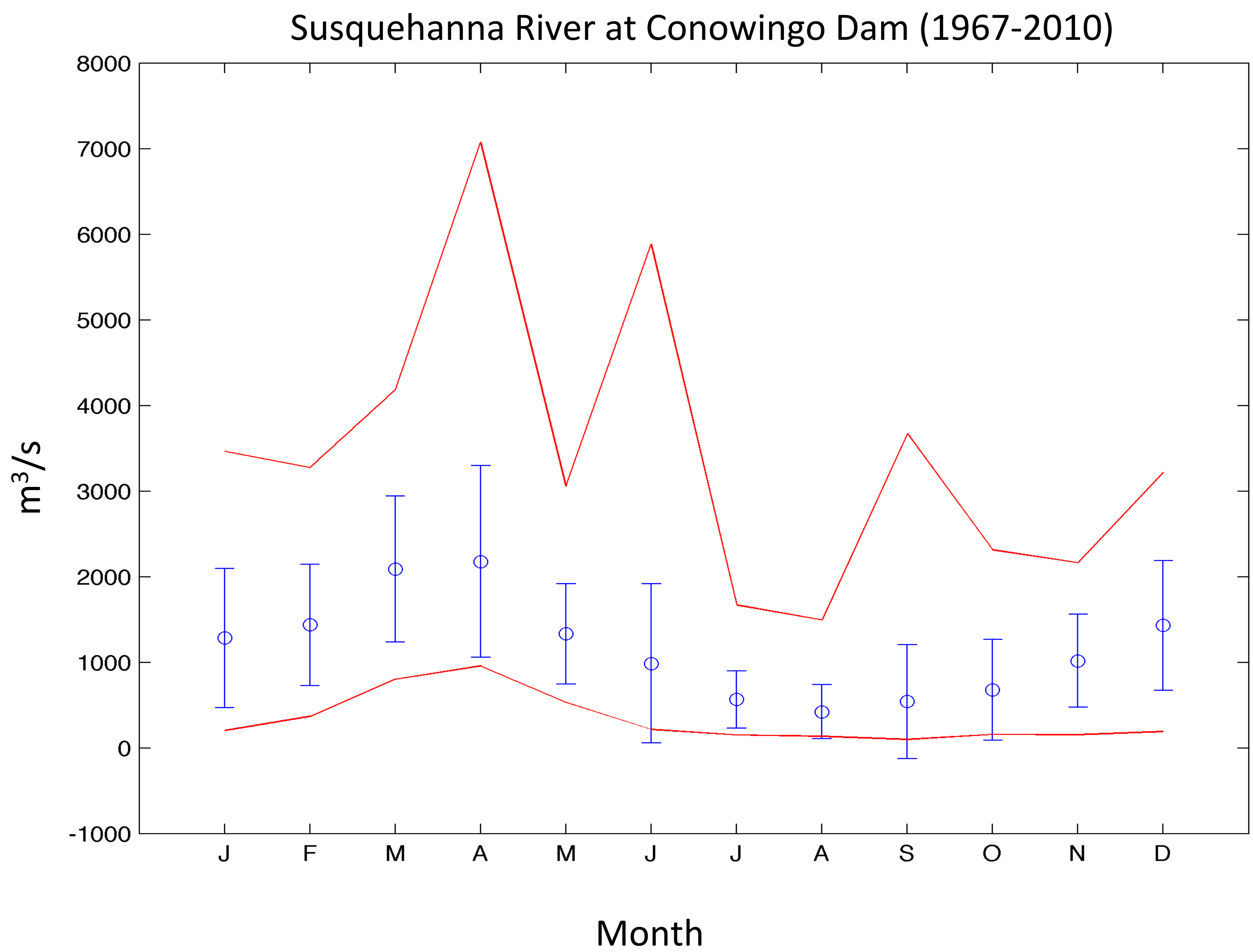
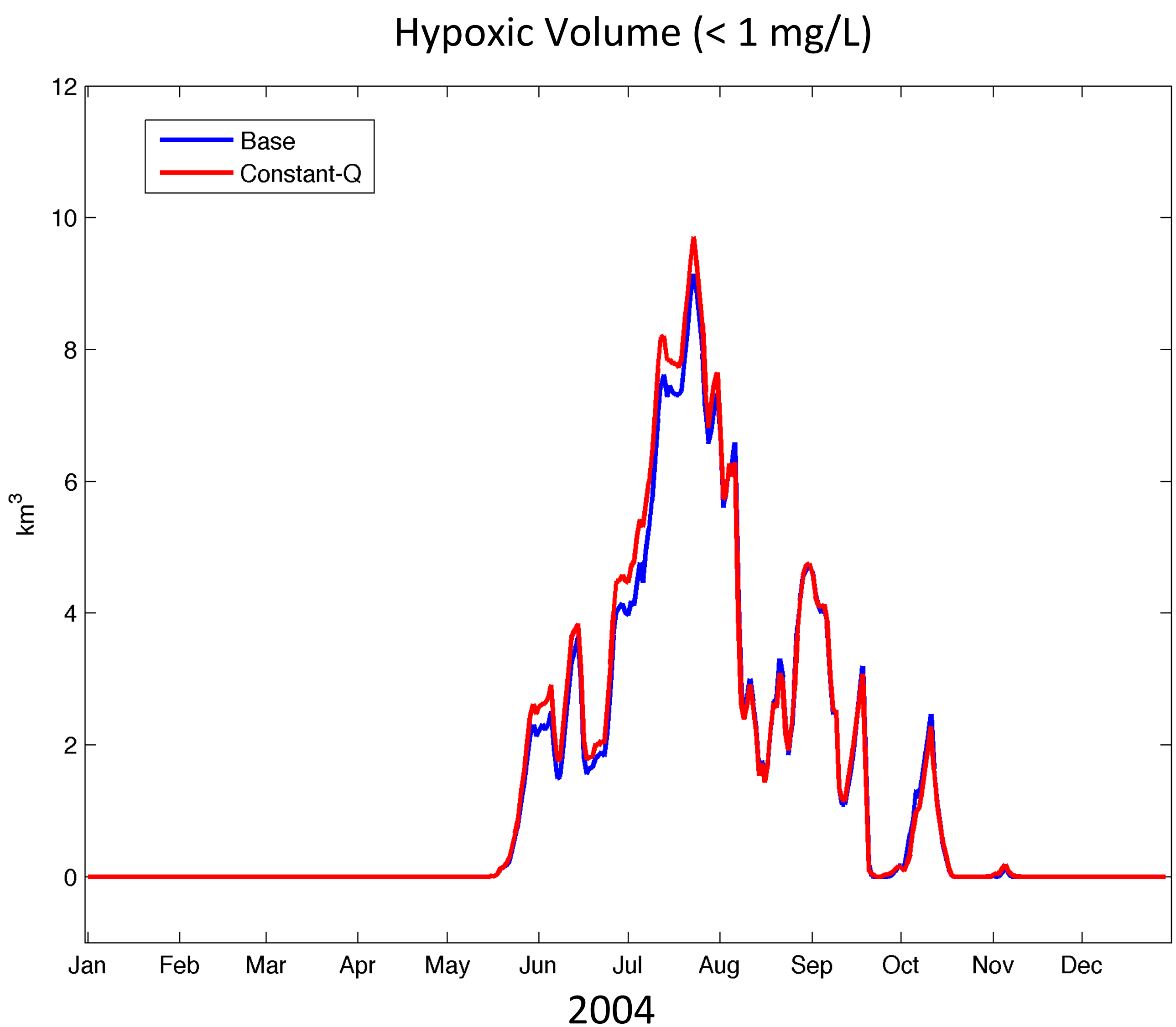
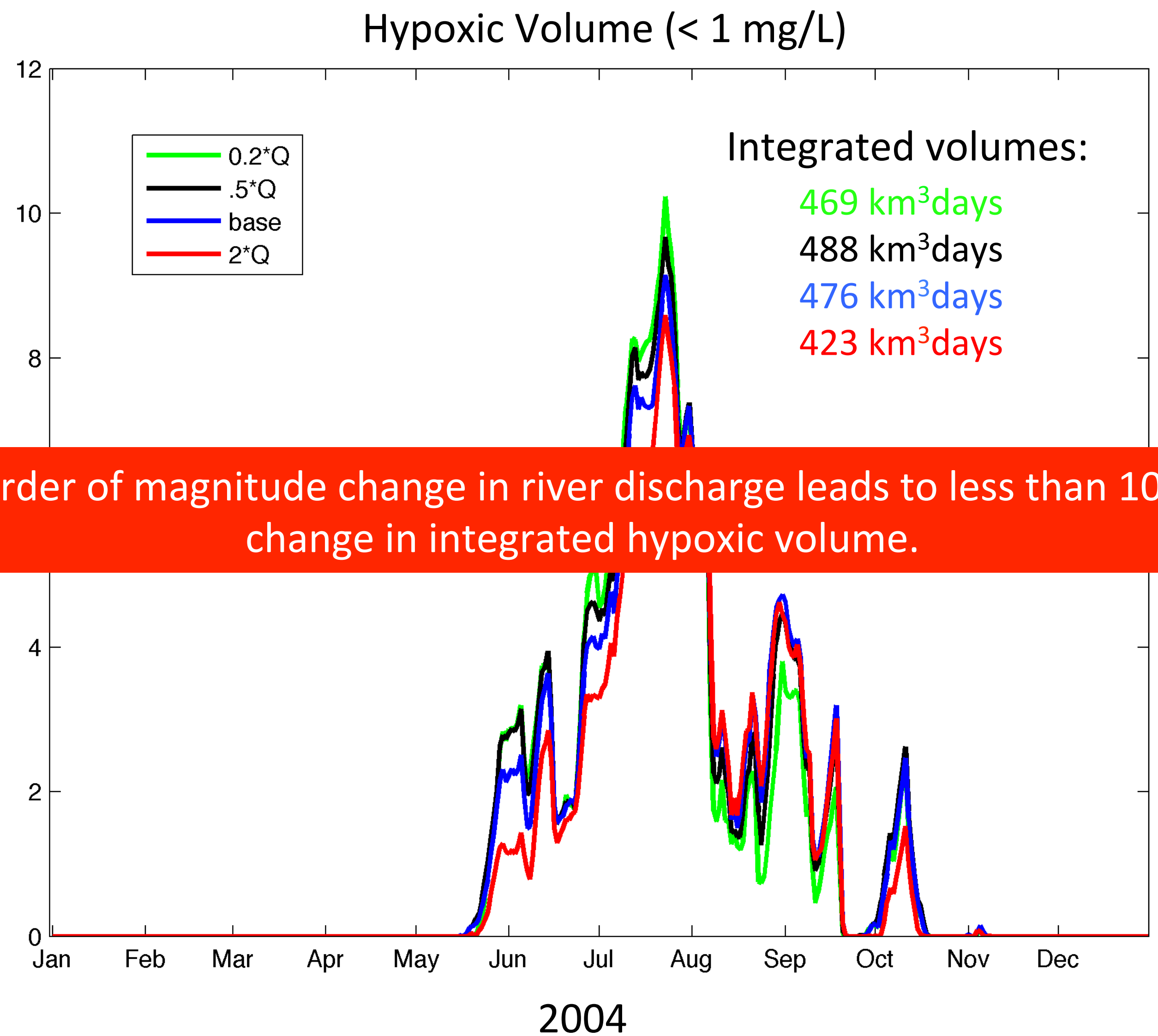
River Discharge Monthly Climatology



Importance of Seasonal Variations in River Flow



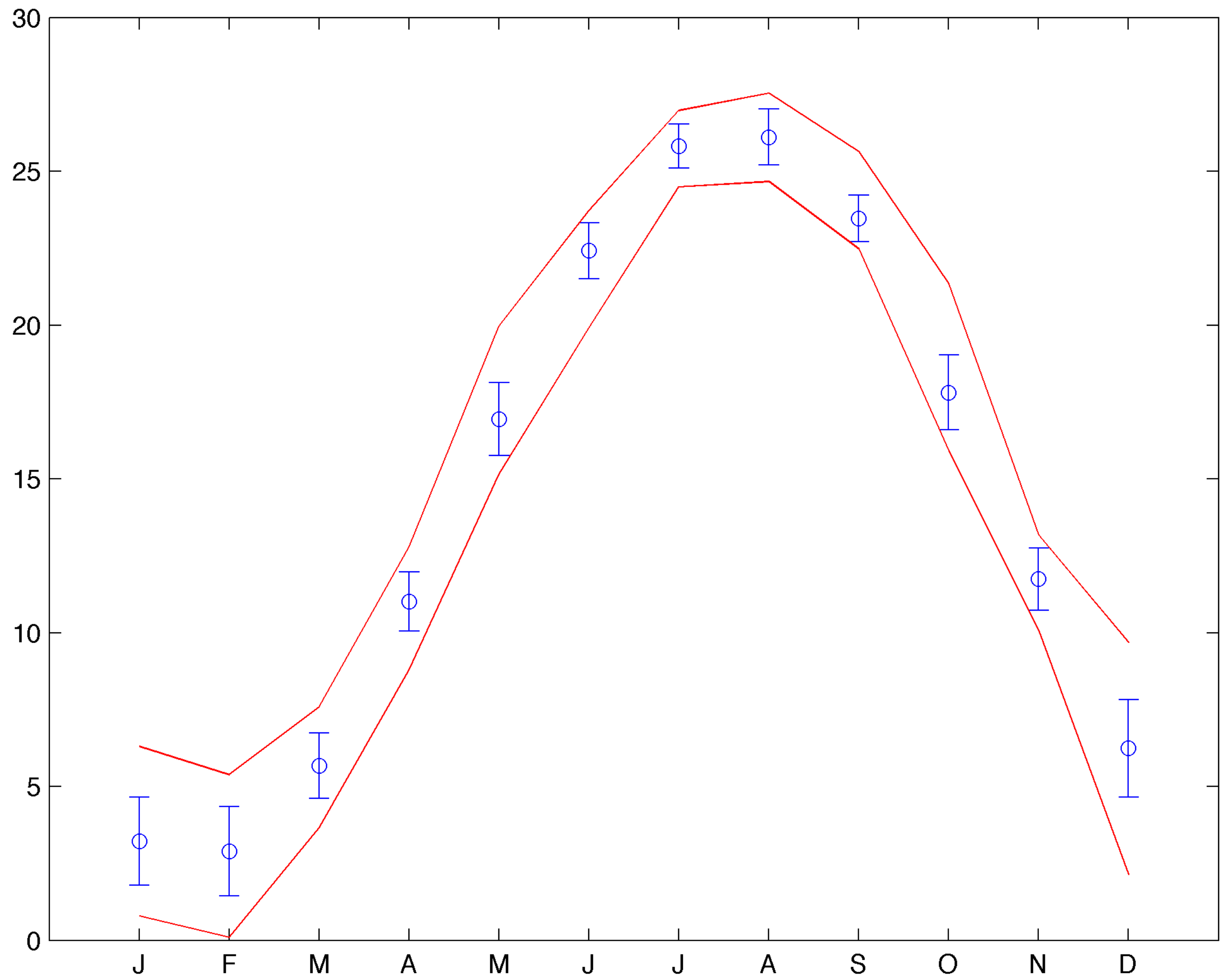
Sensitivity to River Discharge



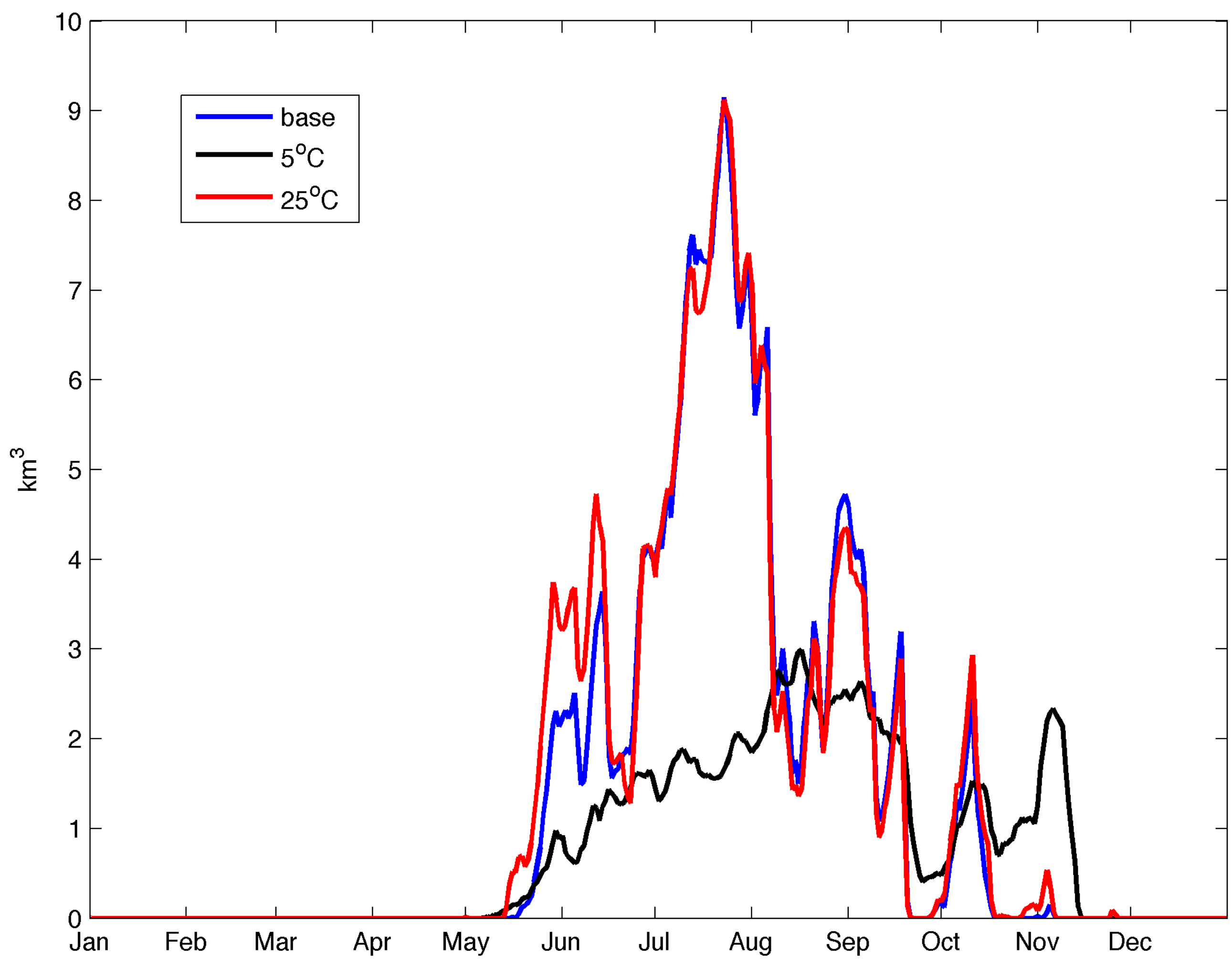
Order of magnitude change in river discharge leads to less than 10% change in integrated hypoxic volume.

Water Temperature

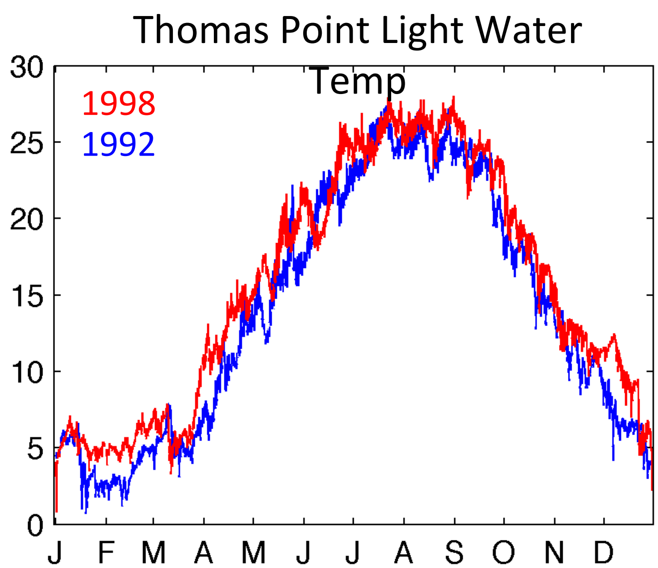
Monthly climatology at Thomas Point Light (1986-2009)

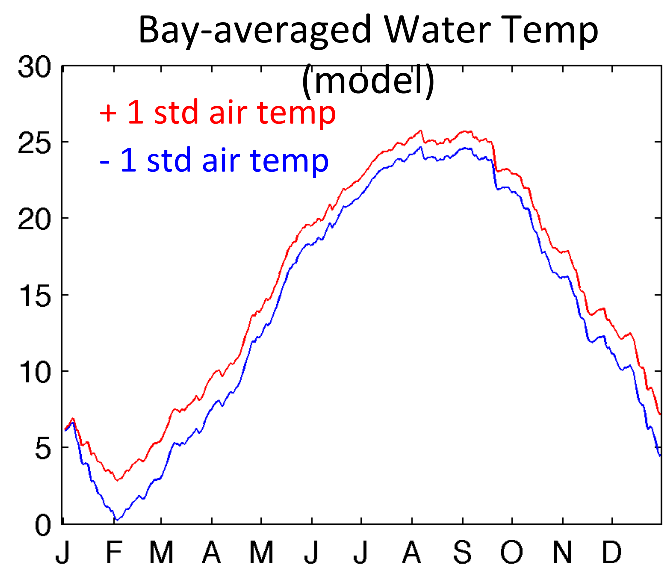


Importance of Seasonal Variations in Temperature

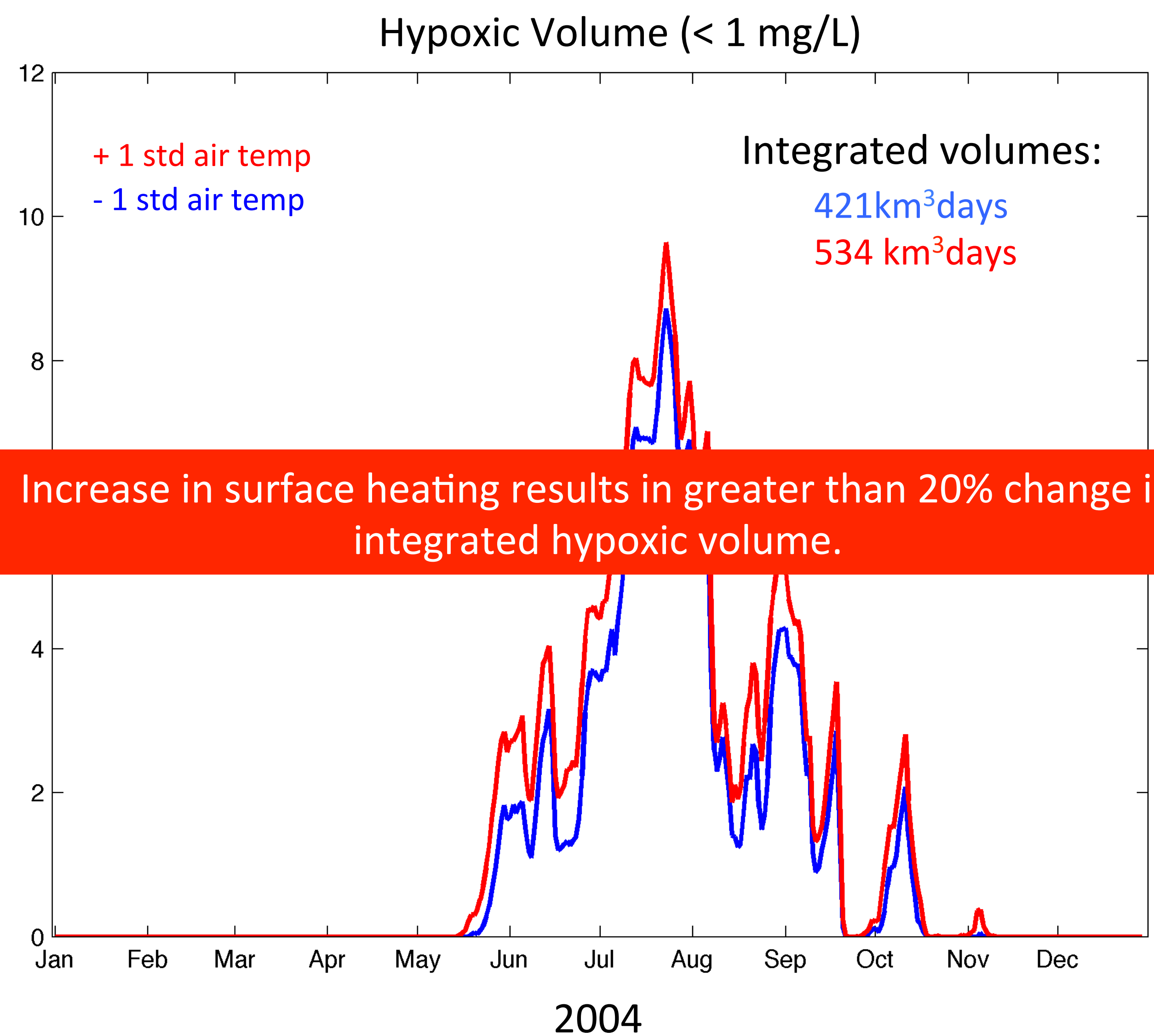


To simulate realistic variability in temperature forcing, model was run changing the air temperature by ± one standard deviation based on monthly climatology for air temperature.





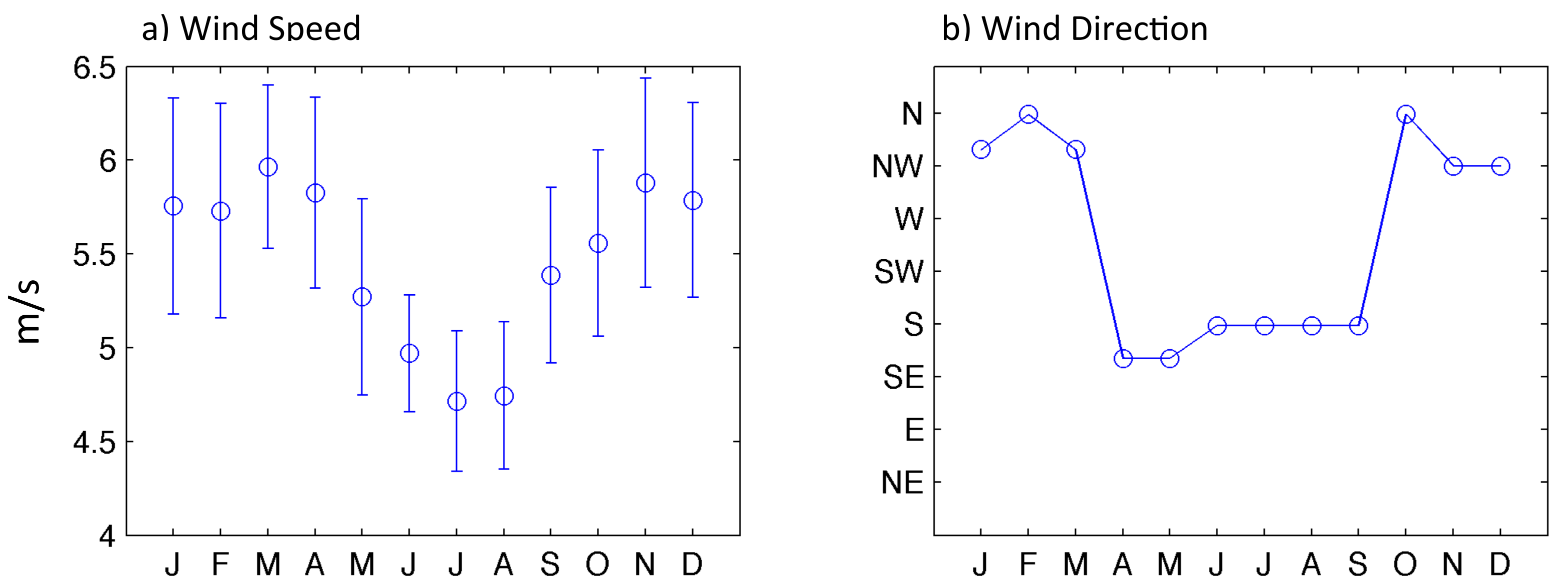
Sensitivity to Temperature



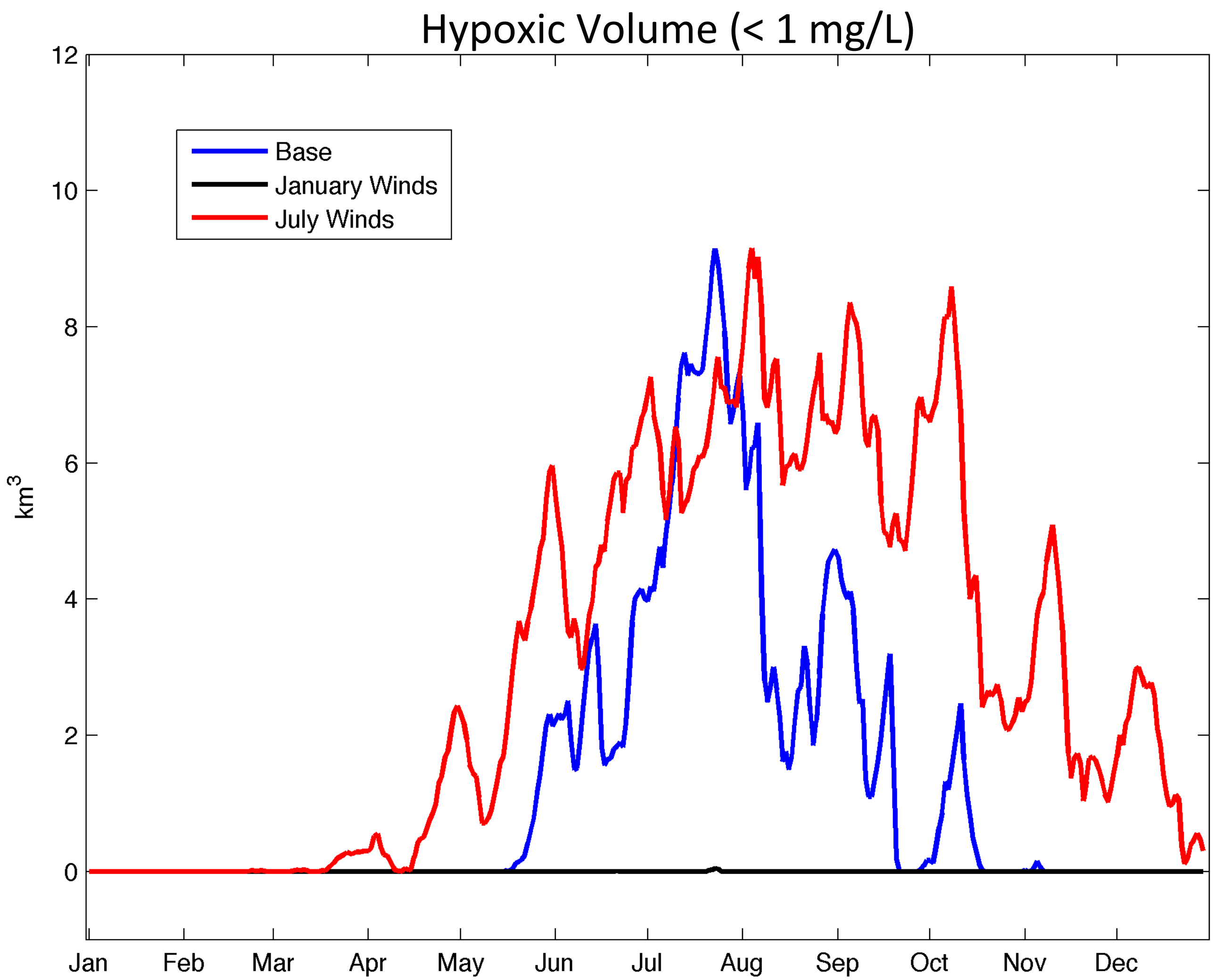
Increase in surface heating results in greater than 20% change in integrated hypoxic volume.

Wind Forcing

Wind Climatology from Thomas Point Light (1986-2010)



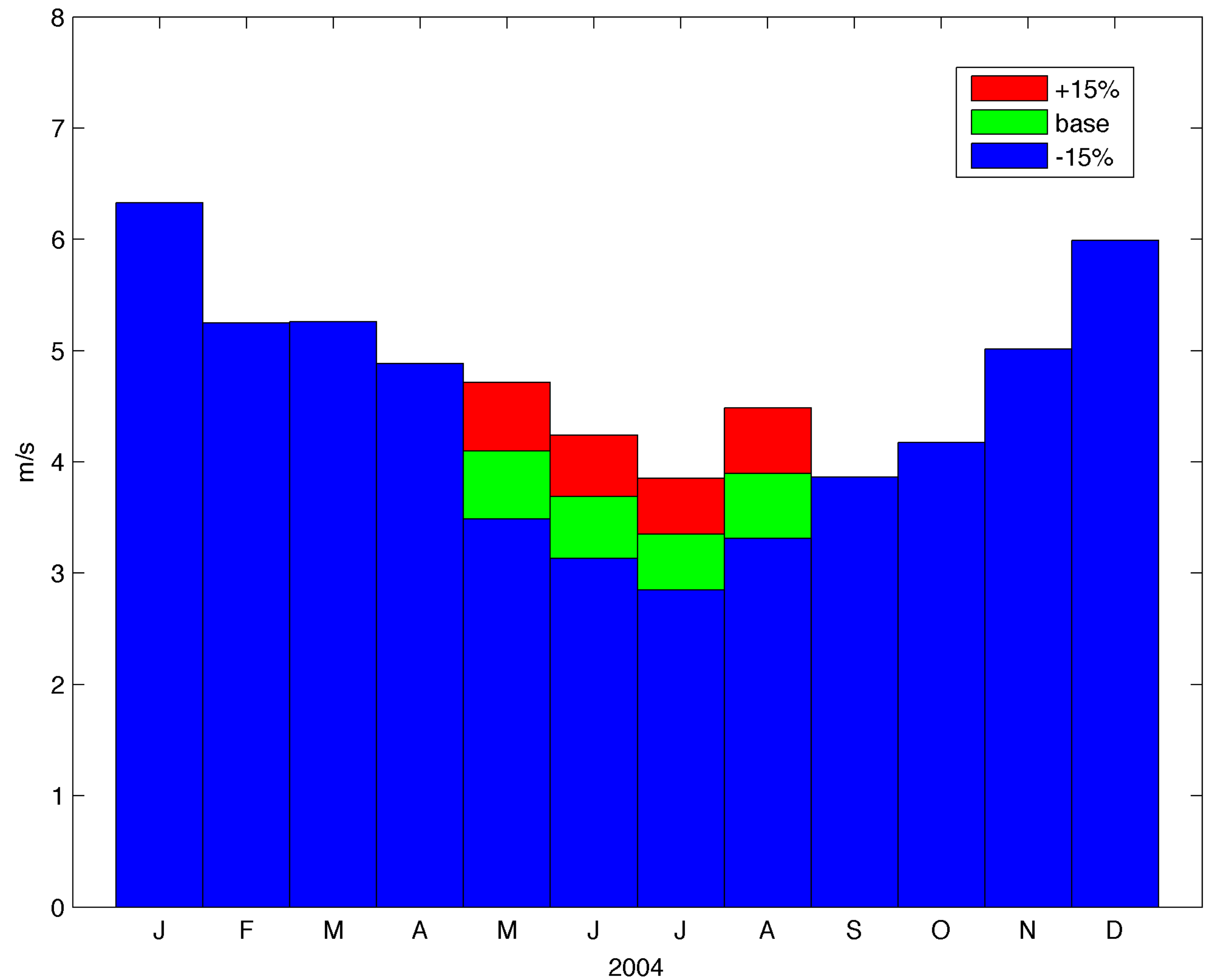
Importance of Seasonal Variations in Wind



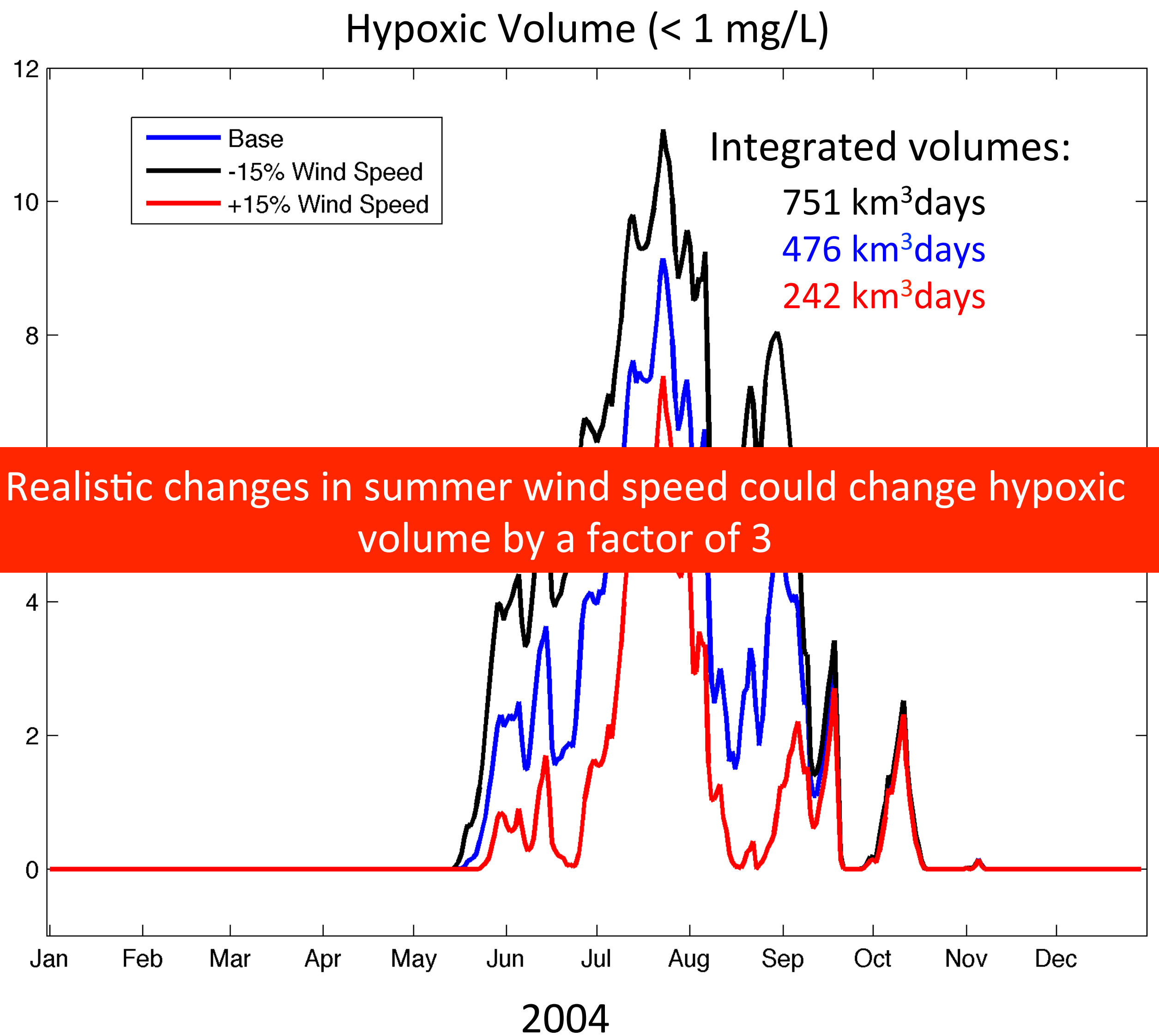
2004

To simulate realistic variability in wind forcing, May-August wind magnitudes were increased/decreased by 15%.

Average Monthly Wind Speed from Model Mid-Bay location



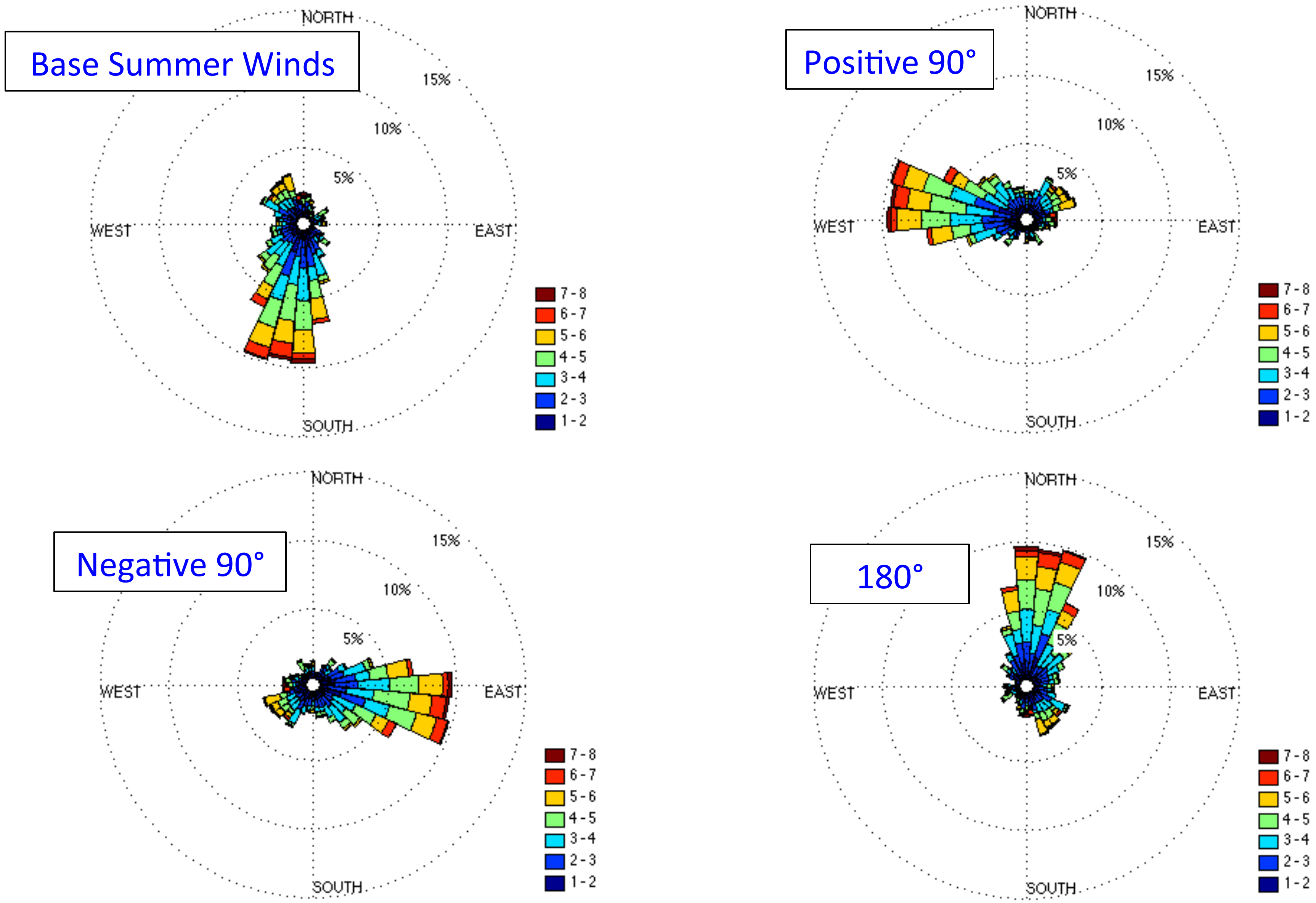
Sensitivity to Wind Speed



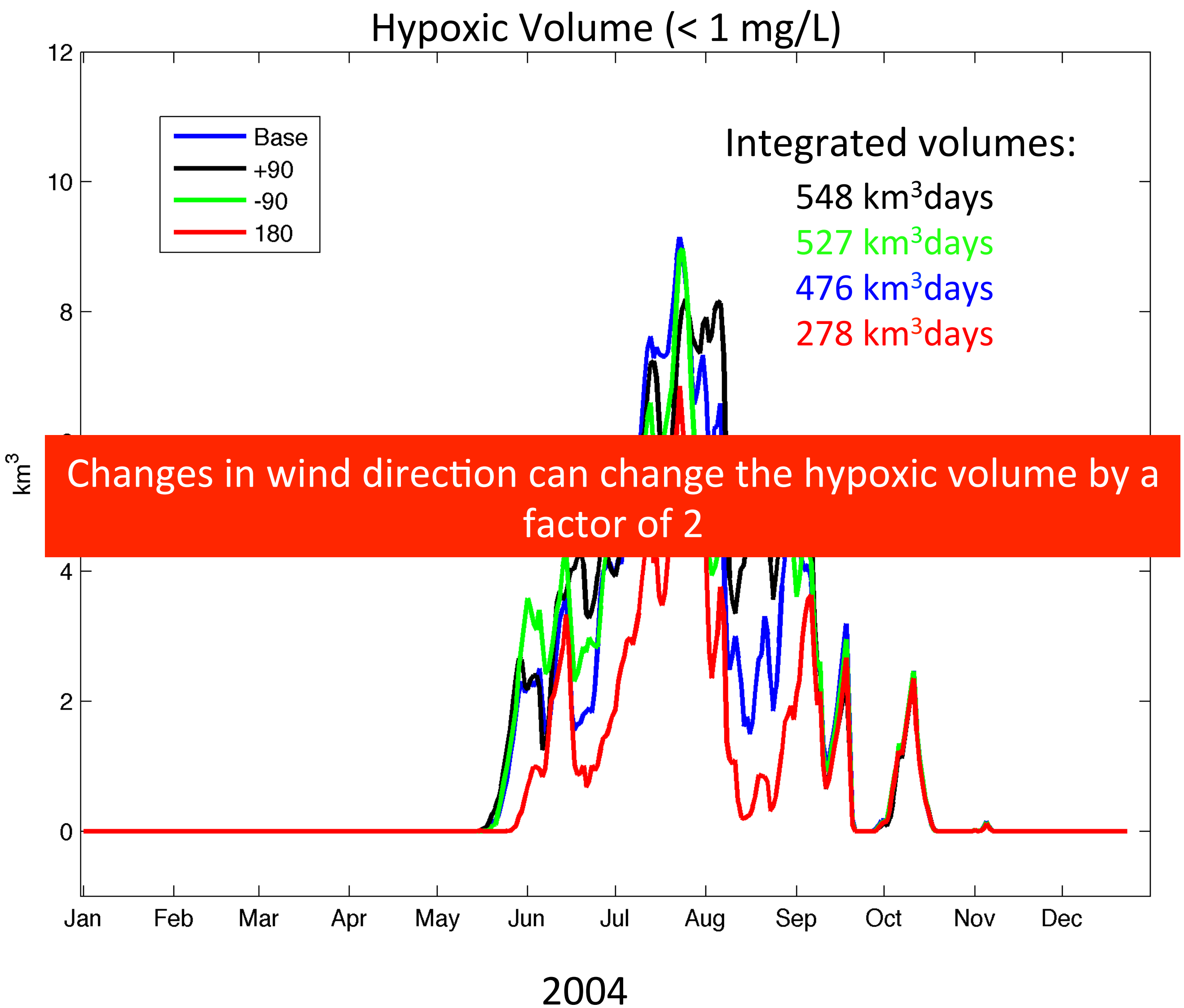
Realistic changes in summer wind speed could change hypoxic volume by a factor of 3

Sensitivity to Summer Wind Direction

Modeled summer wind direction



Sensitivity to Summer Wind Direction



Changes in wind direction can change the hypoxic volume by a factor of 2

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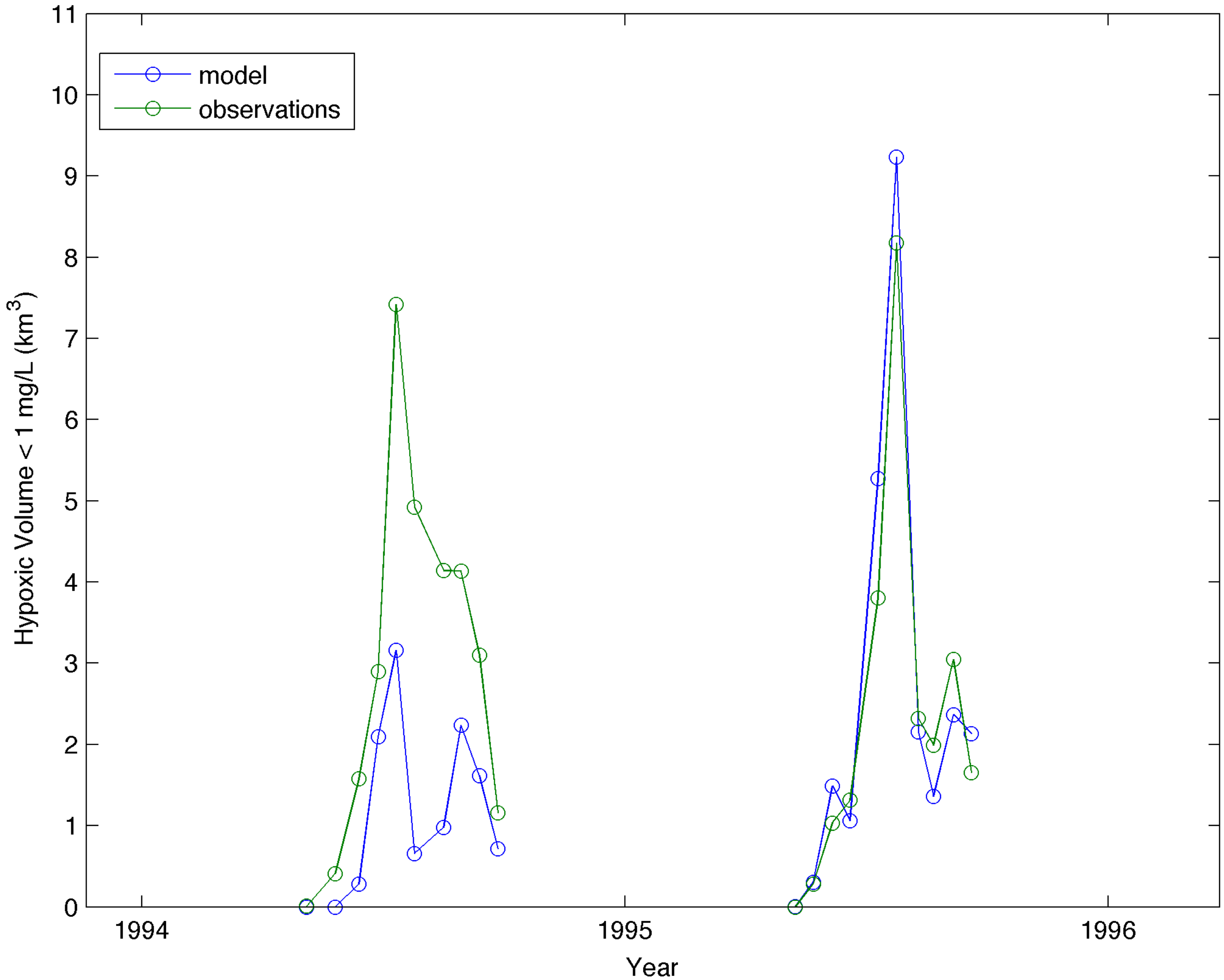
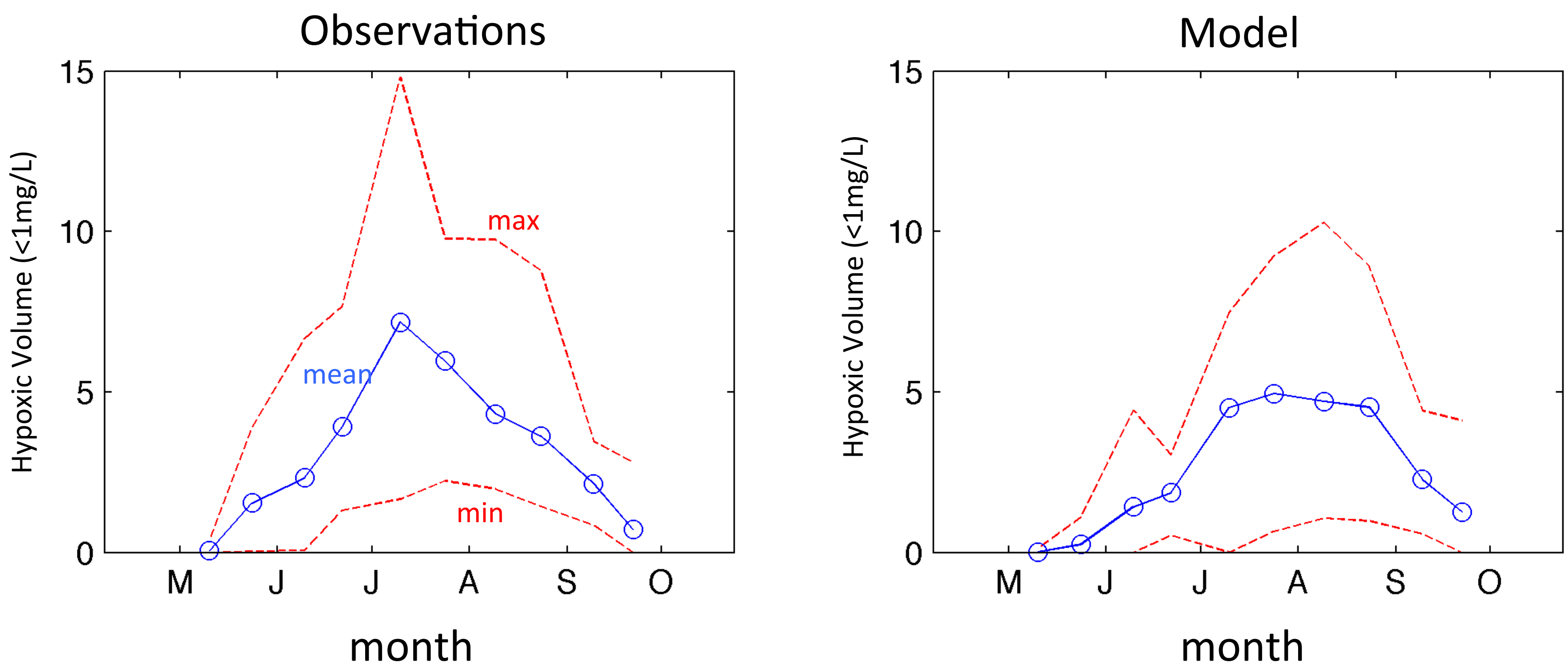
15-year Simulations (1991-2005)



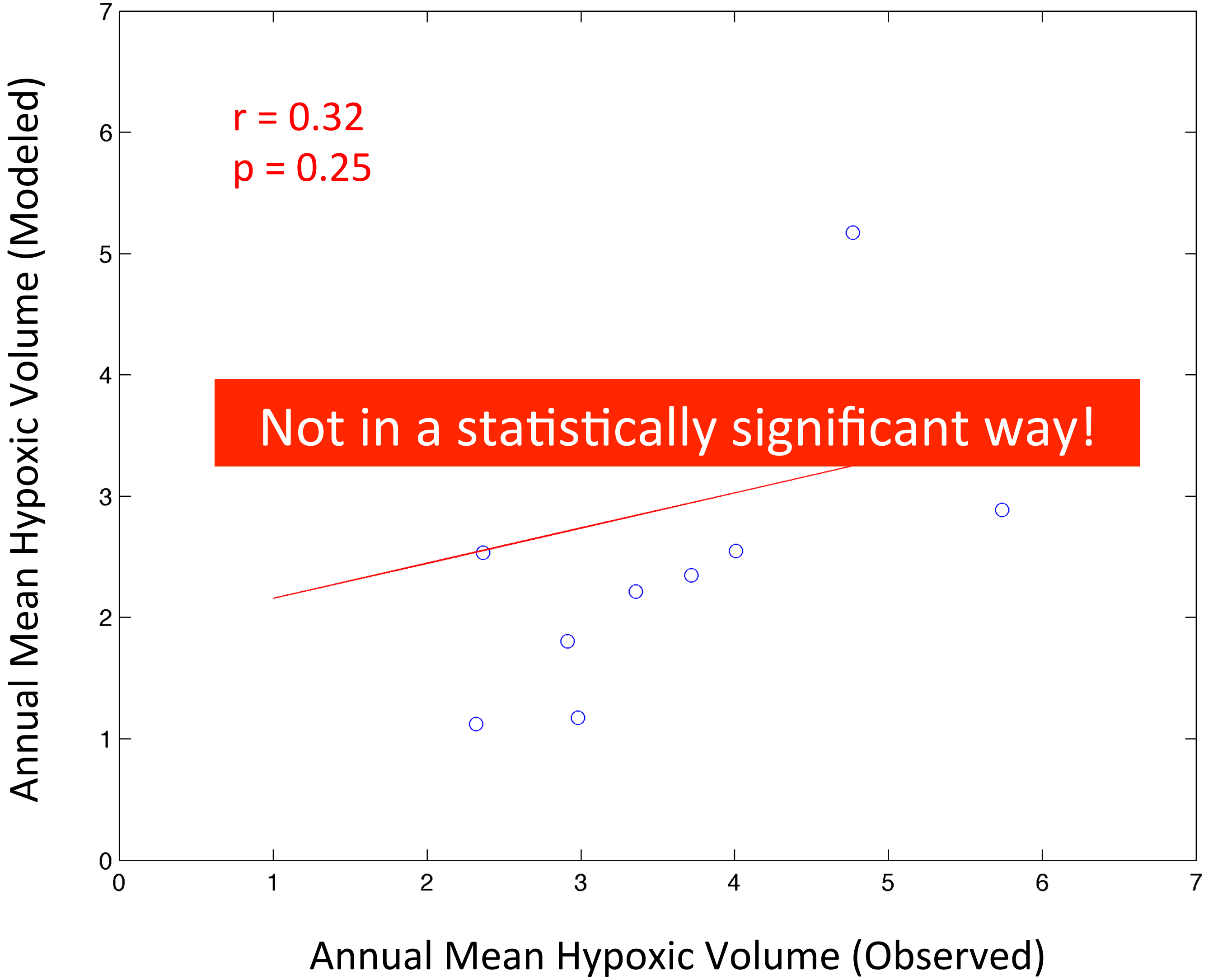
Analysis of 15-year Simulation of Hypoxic Volume (1991-2005)

Bi-monthly Averages

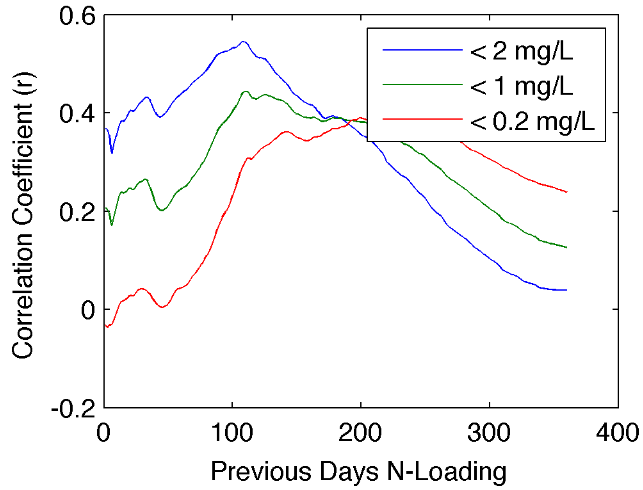


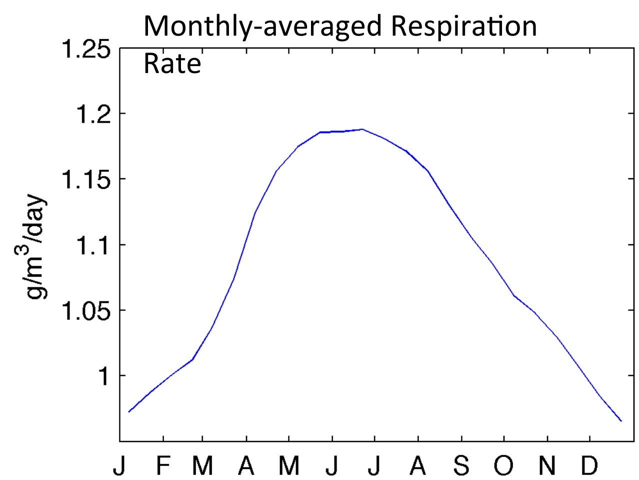
1) Model with no biologic variability shows significant inter-annual variability
2) Observations have greater variability than model
3) Model under predicts in early summer and slightly over predicts in late summer

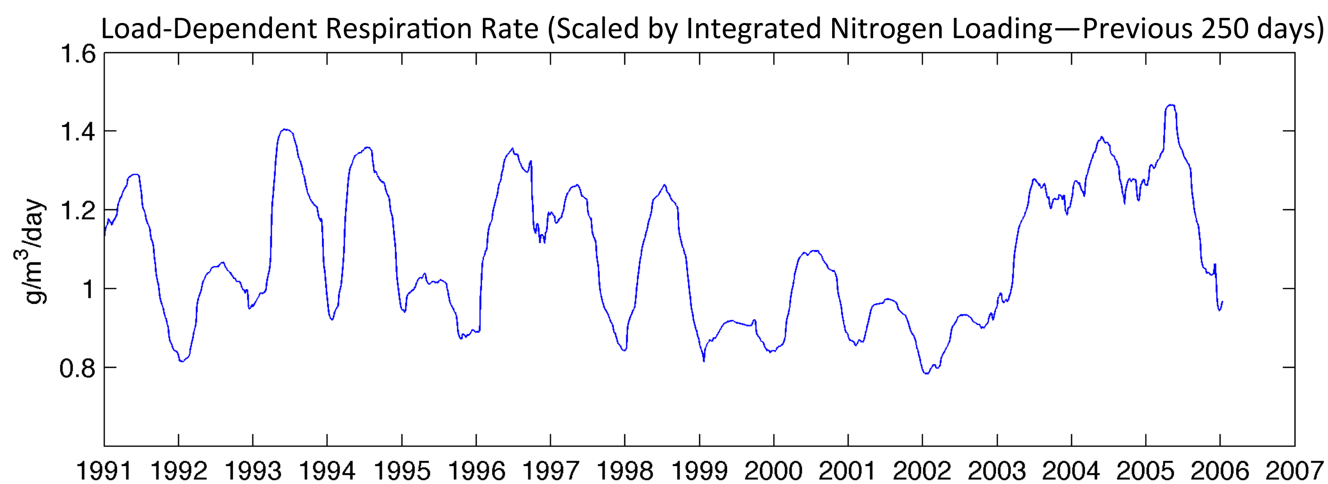
Does variation in physical forcing explain observed inter-annual variability in hypoxic volume?



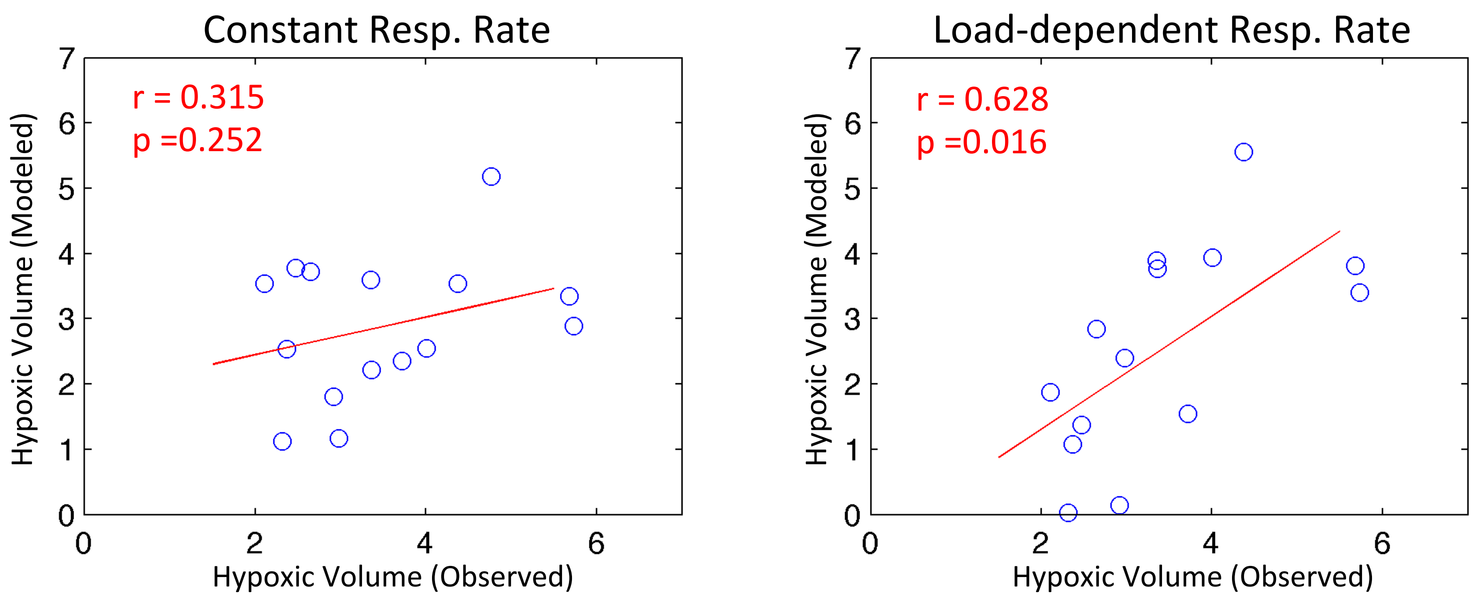
Next Steps: Simplified Load-Dependent Respiration Rate







Preliminary Results with Load-Dependent Respiration Rate



Conclusions

1) A relatively simple model with no biological variability can reasonably account for the seasonal cycle of hypoxia in Chesapeake Bay.
2) Wind speed and direction are the two most important physical variables controlling hypoxia in the Bay.
3) Model results are largely insensitive to variations in river discharge, when the role of nutrient delivery is not accounted for.
4) Changes in air temperature and the associated changes in water temperature via sensible heat flux can have a measurable influence on the overall hypoxic volume.
5) A 15-year model simulation with constant respiration rate produces significant inter-annual variability in hypoxic volume, by largely fails to reproduce the observed variability.
6) Model residuals are significantly correlated with the integrated Nitrogen loading demonstrating the importance of biological processes in controlling inter-annual variability
7) Preliminary attempts to include the effects of nutrient loading though a load-dependent respiration formulation show promise for capturing observed inter-annual variability.