Chesapeake Bay Program, Dissolved Oxygen Assessment in the Chesapeake Bay
Community Seminar, May 7, 2013

# Using circulation models to understand the role of physical processes in controlling inter-annual variations of hypoxia in Chesapeake Bay

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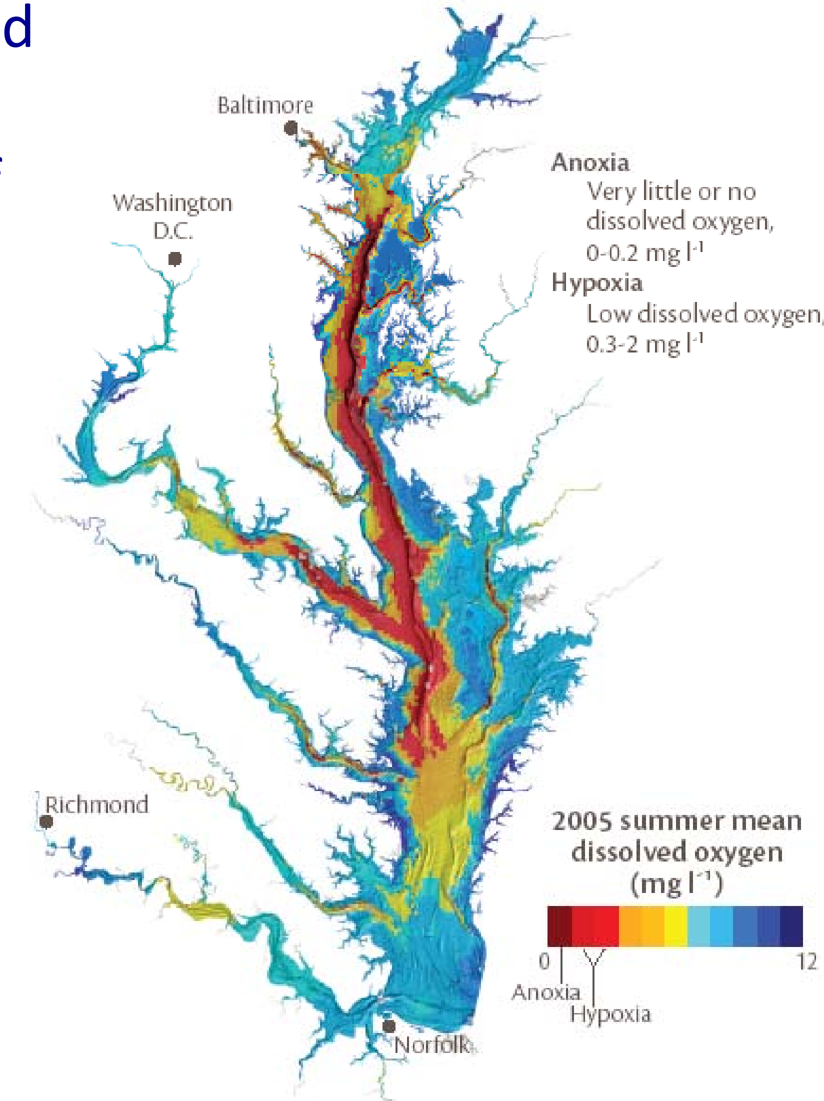


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# Outline For Presentation:

1) Description of numerical circulation model with a simple 1-term dissolved oxygen model.
2) Simulation of inter-annual variability in hypoxic volume (1991-2005).
3) Consistency of model with observations of hypoxic volume.
4) Evaluation of model residuals.
5) Importance of accurate wind measurements/models.

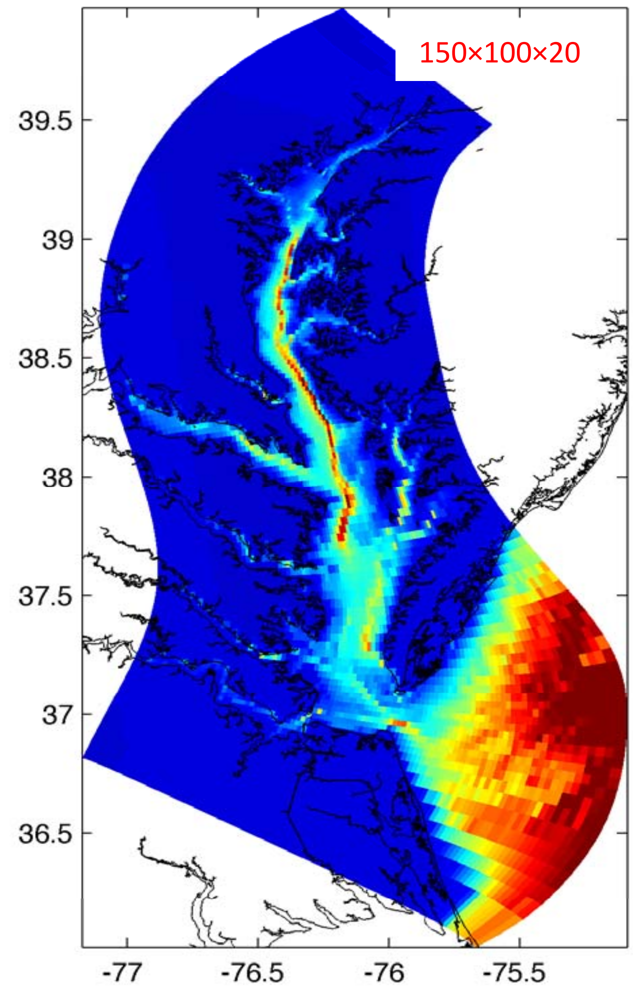
# Numerical Circulation Modeling of Dissolved Oxygen

## 3-dimensional Circulation Model: Regional Ocean Modeling System (ROMS)

Model forcing

- Realistic tidal and sub-tidal elevation at ocean boundary
- Heat flux from NCEP NARR model
- Observed winds at Thomas Point Light (assumed spatial uniform)
- Observed river discharge for all tributaries.
- Temperature and salinity at ocean boundary from World Ocean Atlas.
- **Very simple** oxygen model

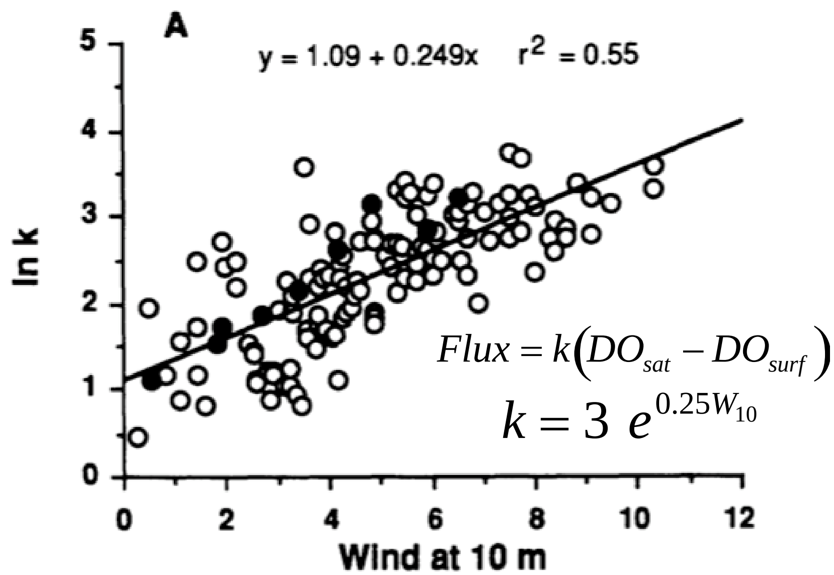
ChesROMS Model Grid



# Simplified Approach to Dissolved Oxygen Modeling

- Oxygen is introduced as an additional model tracer.
- Oxygen consumption (respiration) is constant in time and space (~$0.5 gO_2/m^3/day$) .
- 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

Surface Oxygen Flux using Piston Velocity:




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

$$k = 3\ e^{0.25W_{10}}$$

*From Marino and Howarth, Estuaries, 1993*

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

# Motivation for Simplified Approach

1) DO is modulated by both biological and physical processes, which vary significantly at both seasonal and inter-annual time-scales.

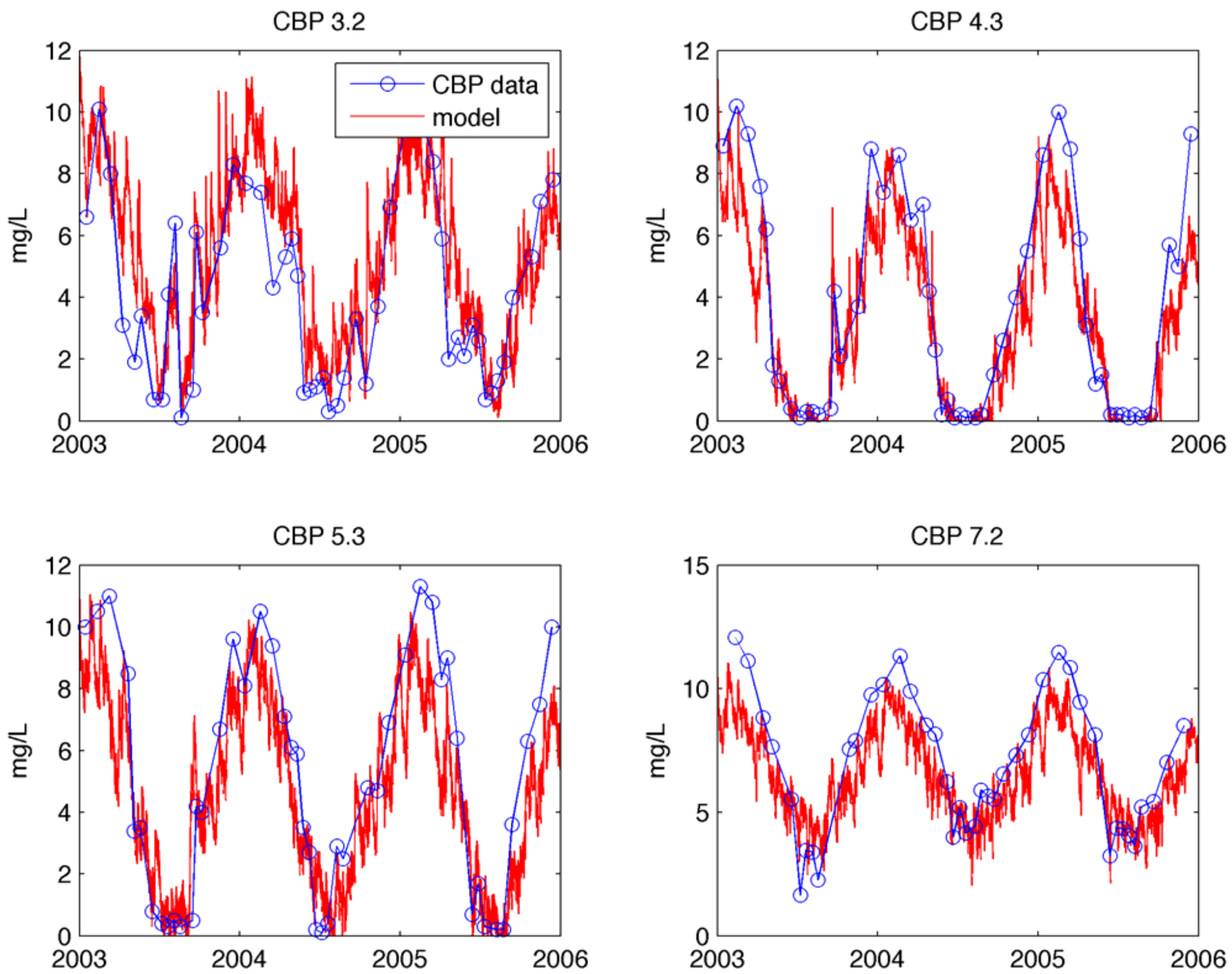
2) In order to assess the success of management actions that focus on nutrient reduction, it is necessary to understand and quantify the role of physical processes (river discharge, wind, density stratification, temperature) in contributing to the inter-annual variability of hypoxia.

1) Most studies approach this problem using multiple regression (Hagy et al. 2004; Scully 2010; Murphy et al., 2011; Lee et al. 2013).

   - Because there is significant covariance/colinearity between the key variables, inferences based on regression models may be misleading or erroneous.

# Can a simple model with no biological variability capture seasonal cycle of oxygen in Chesapeake Bay?

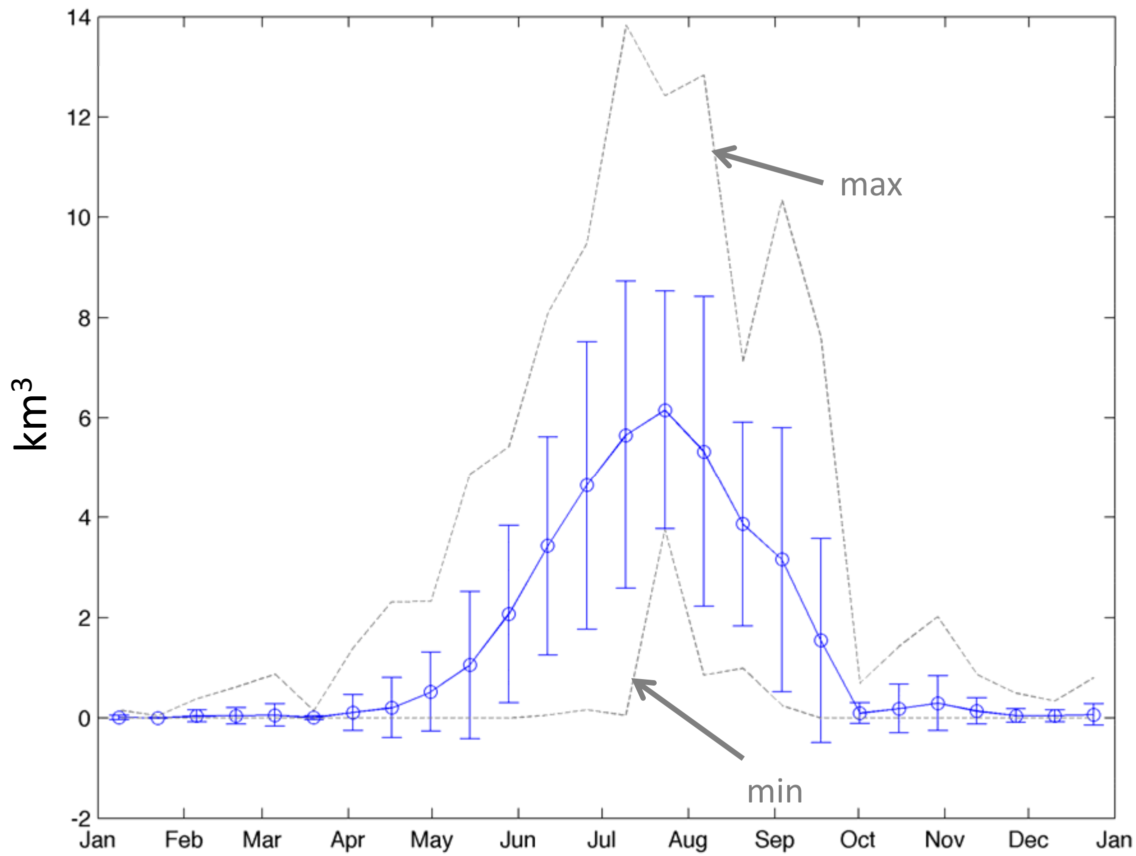
Comparison of 1-term model with select CBP DO data



# What about inter-annual variability?

## 15-year simulation (1991-2005)

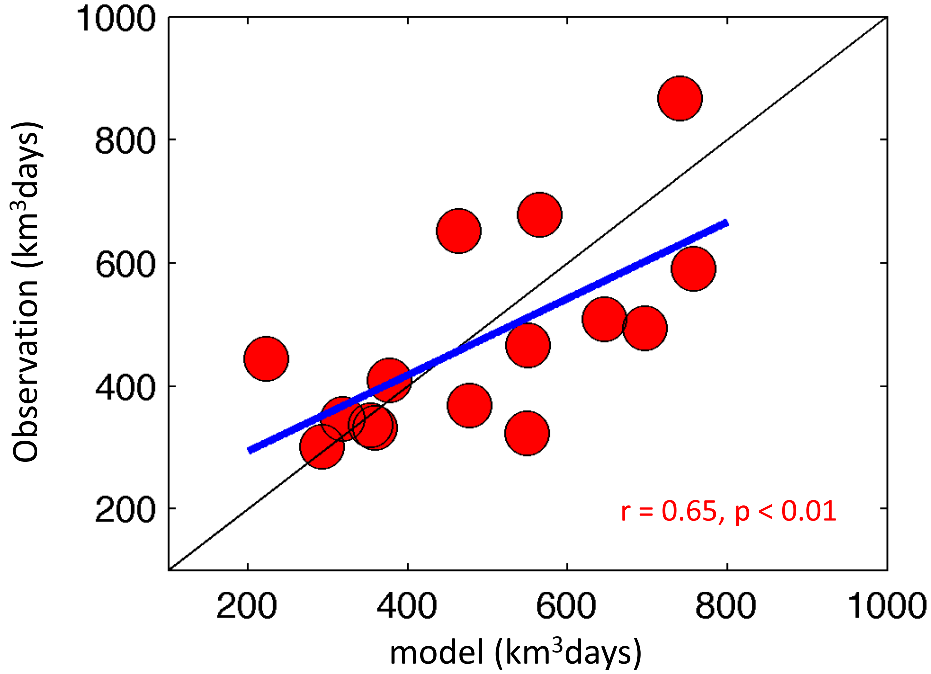
Hypoxic Volume (< 1 mg/L) averaged biweekly




Maximum predicted integrated hypoxic volume = 757 $km^3$days (2005)
Minimum predicted integrated hypoxic volume = 222 $km^3$days (1994)

# How does model compare to observations?

Comparison between 1-term numerical model and CBP observations of integrated hypoxic volume (1991-2005)




Data from Murphy et al. (2011)

# How does model compare to observations?

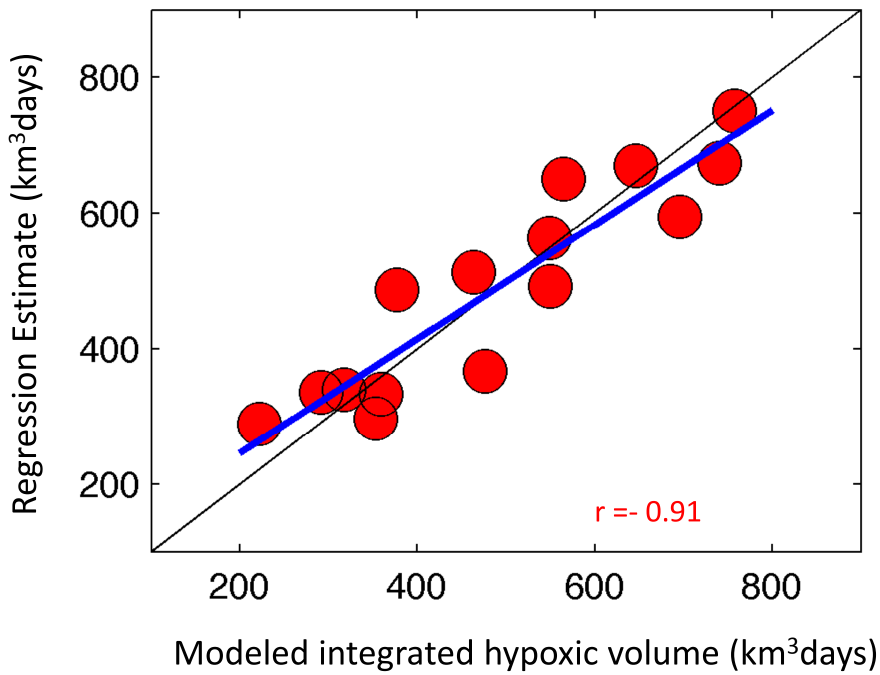
Correlation (r) between numerical simulations and various observations for inter-annual variability in hypoxia (1991-2005)

| | Murphy et al (2011) Volumes | | | Bever et al (2013) Volumes | | |
|---|---|---|---|---|---|---|
| | Averaged HV | Integrated HV | Maximum HV | Averaged HV | Integrated HV | Maximum HV |
| < 2 mg/L | 0.658 | 0.639 | 0.605 | 0.658 | 0.641 | 0.519 |
| < 1 mg/L | 0.673 | 0.651 | 0.578 | 0.676 | 0.661 | 0.489 |
| < 0.2 mg/L | 0.550 | 0.416 | 0.473 | 0.320 | 0.200 | 0.276 |

Red values indicate significance at 95% CI

# With realistic forcing which physical variables contribute most to inter-annual variability in **model**?

Simple regression that considers only summer (May-Sept) wind speed explains nearly 85% of variance in numerical simulations of hypoxic volume

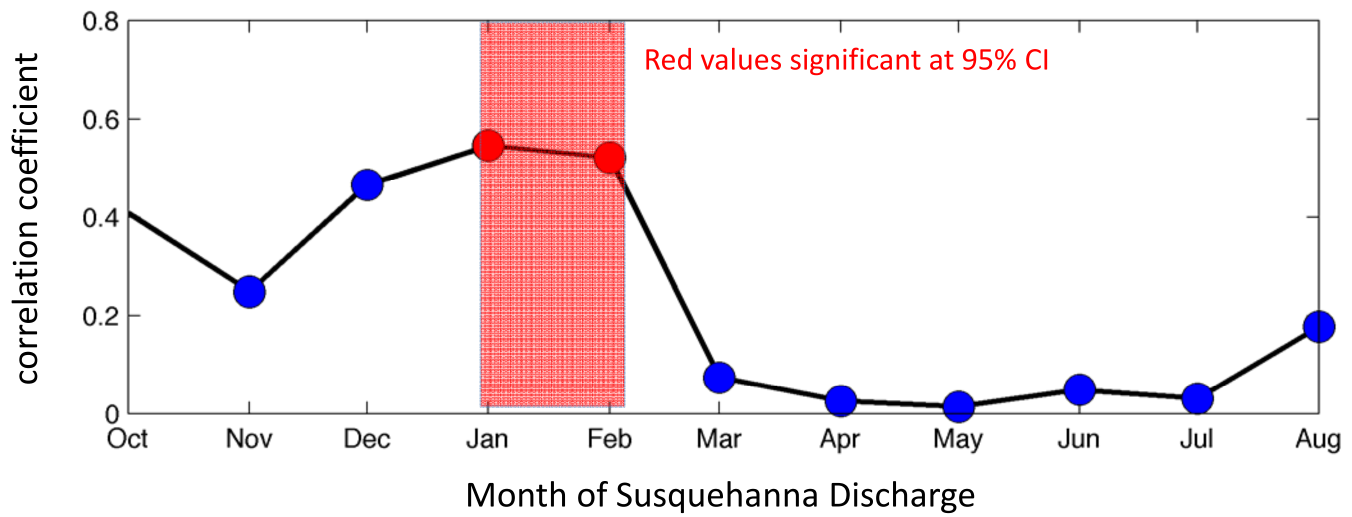



For same time period (1991-2005) observed integrated hypoxic volume (< 1 mg/L) exhibits significant negative correlation with summer winds observed at TPL ($r = -0.71$, $p < 0.01$)

# With realistic forcing which physical variables contribute most to inter-annual variability in **model**?

Because nutrient load and river discharge are nearly linearly related, it is difficult to separate the physical response to increased river discharge (i.e. stratification) from the biological response to nutrient inputs (i.e. bloom) using statistical models.

Correlation between specific month of Susquehanna River discharge and numerical model prediction of hypoxic volume (1991-2005)




Numerical model suggests increased Jan-Feb river discharge increases hypoxic volume, independent from biological response to nutrient loading.

# Is response of model to physical forcing consistent with observations?

Correlations between integrated hypoxic volume (< 1 mg/L) and physical variables

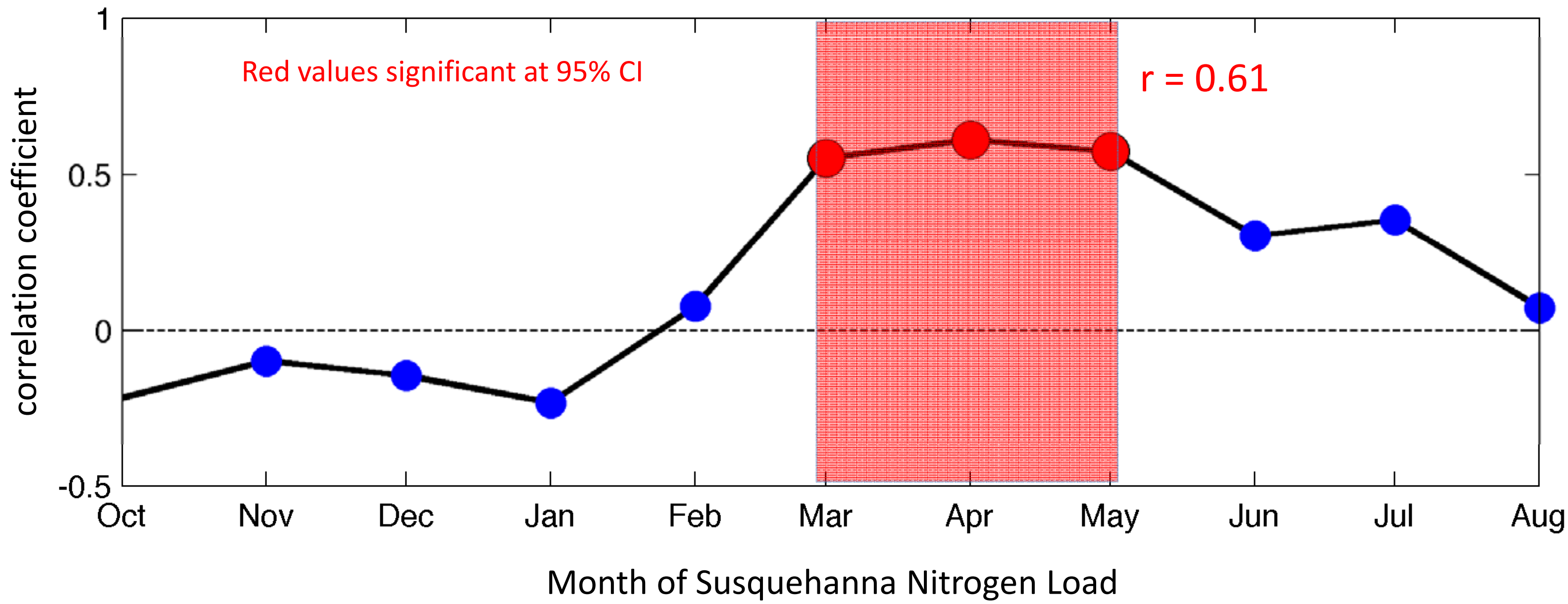
| Variable | 1-term Model | Murphy 2011 | Bever 2013 |
|---|---|---|---|
| Summer (May-Sept) Wind Speed | -0.91 | -0.71 | -0.74 |
| Winter (Dec-Feb) Susquehanna Discharge | 0.54+ | 0.39 | 0.40 |
| Spring (March-April) Stratification* | 0.67+ | 0.78 | 0.79 |

*modeled stratification

+even though winter discharge and spring stratification are significantly correlated with modeled hypoxic volume, neither increase the adjusted $r^2$ when included in multiple regression.

# Analysis of Residual (Observations minus Numerical simulations)

Correlation between model residuals and Susquehanna River total nitrogen loading by month




Simple model accounts for role of physical process but **<u>NOT</u>** response to nutrient loading

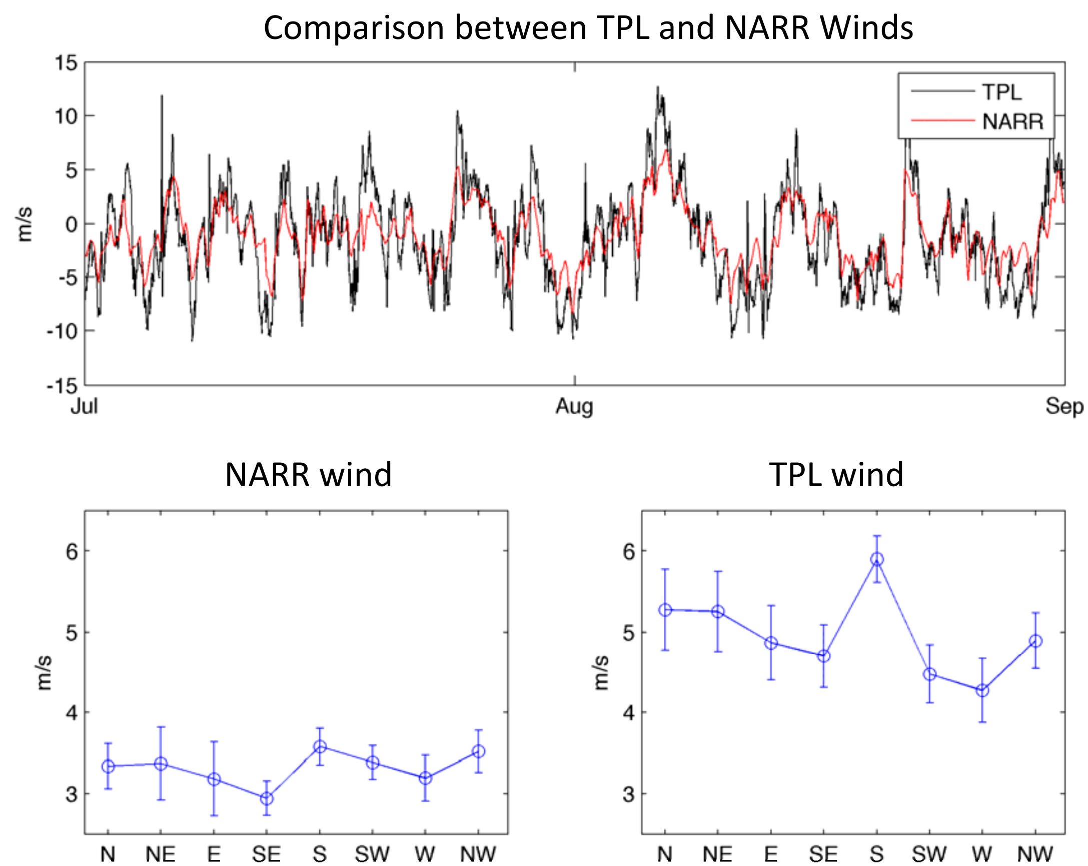
## Correlation between hypoxic volume (1991-2005) and Susquehanna River discharge by month

Correlations with residuals (observations minus numerical model) suggests March-May is key period for nutrient delivery.

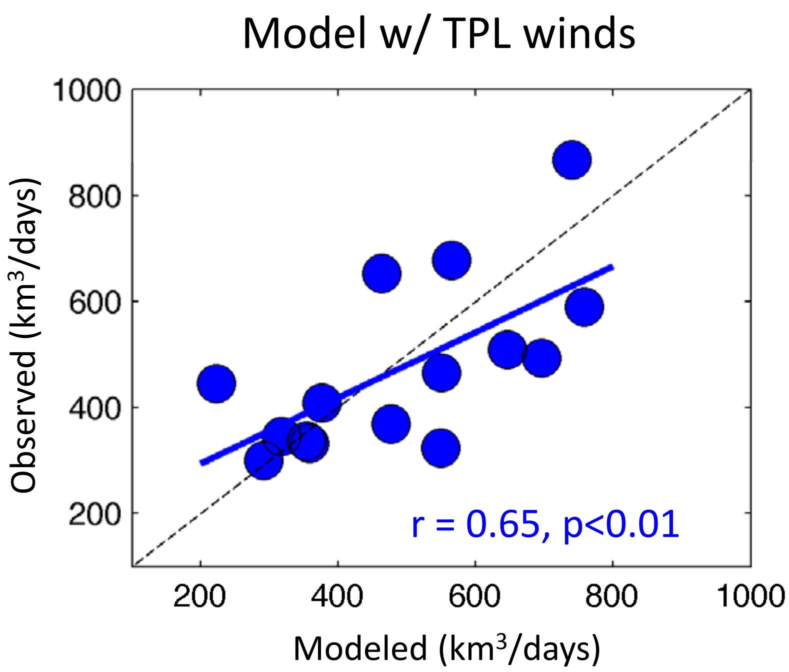
Model with no biology suggest Jan-Feb river discharge is key period for river inputs, which control spring stratification.

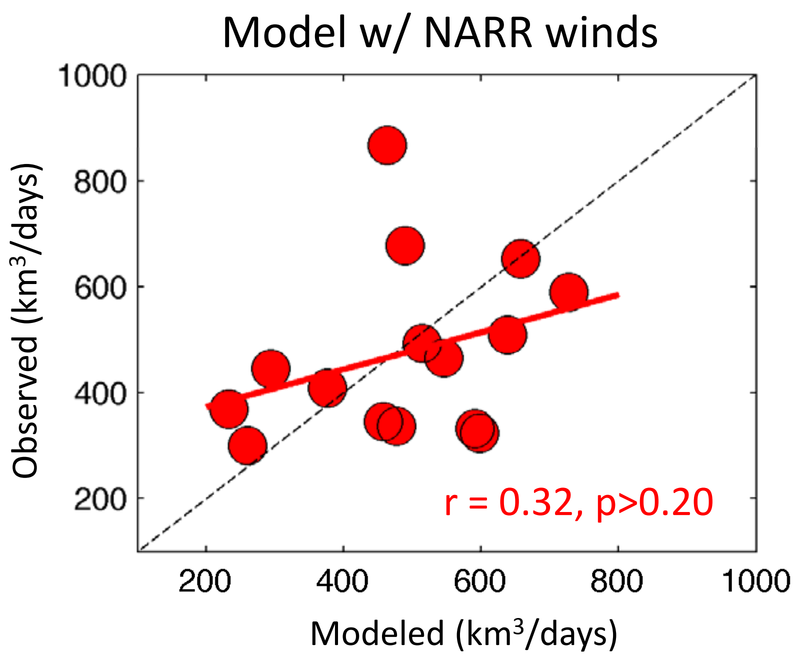
# Most numerical models of Chesapeake Bay use modeled winds

1. To examine the importance of wind forcing on inter-annual predictions of hypoxic volume, I re-ran model with NARR Winds.
2. But, because NARR winds are ~ 30% weaker than TPL, the respiration constant had to be reduced by ~ 35% for the model to predict roughly similar hypoxic volumes!



## Comparison of inter-annual variability in model runs with observed (TPL) vs modeled (NARR) winds



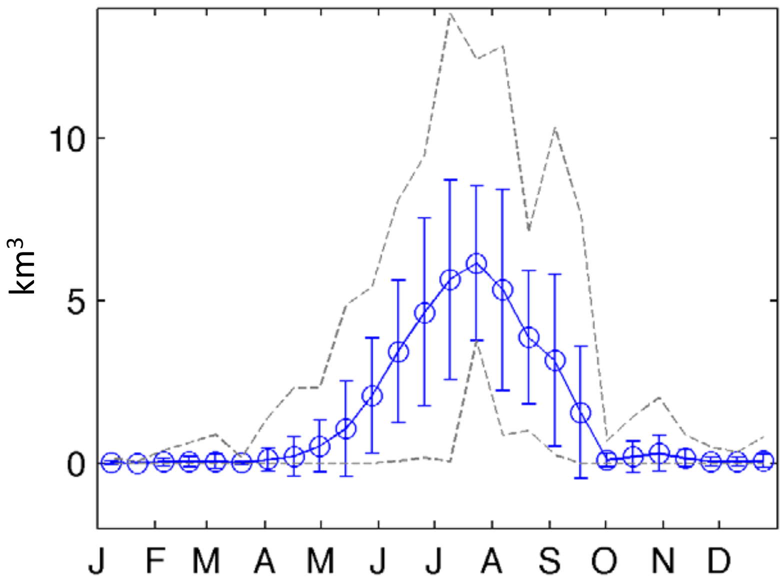




Model results with NARR winds are <u>**NOT**</u> significantly correlated with observed inter-annual variability of integrated hypoxic volume.

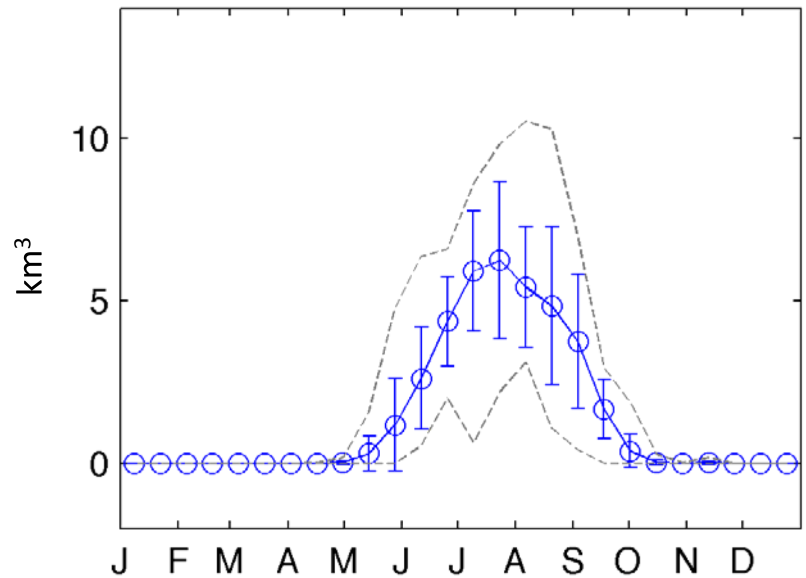
# Comparison of inter-annual variability in model runs with observed (TPL) vs modeled (NARR) winds

15-year hypoxic volume (< 1 mg/L) averaged bi-weekly

Model w/ TPL winds




Model w/ NARR winds




Model results with NARR winds have less inter-annual variability than model results with observed (TPL) winds.

# Importance of Wind Speed



TABLE 1. Correlations with hypoxic volume: Correlation coefficient *r* between observed hypoxic volume and duration of summer winds, estimated January–May nitrogen loading, January–May Susquehanna River discharge, mean summer wind speed, modified BHI, and winter NAO index. Wind duration is calculated as the total time that wind with a velocity greater than 2 m $s^{-1}$ was observed from eight equally spaced compass directions over the period 1 May–31 Jul.

| Hypoxic vol | Duration of summer wind | | | | | | | | Nitrogen loading | River discharge | Wind speed | BHI | Wind NAO index |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | North | Northeast | East | Southeast | South | Southwest | West | Northwest | | | | | |
| <2 mg $L^{-1}$ | 0.00 | 0.08 | 0.18 | −0.49* | −0.37 | 0.04 | 0.69* | 0.32 | 0.36 | 0.16 | −0.03 | −0.42 | 0.55* |
| <1 mg $L^{-1}$ | −0.02 | 0.04 | 0.15 | −0.48* | −0.34 | 0.03 | 0.71* | 0.36 | 0.44* | 0.24 | −0.04 | −0.45* | 0.53* |
| <0.2 mg $L^{-1}$ | −0.11 | −0.08 | 0.05 | −0.42 | −0.17 | −0.10 | 0.55* | 0.30 | 0.62* | 0.33* | −0.11 | −0.47* | 0.58* |

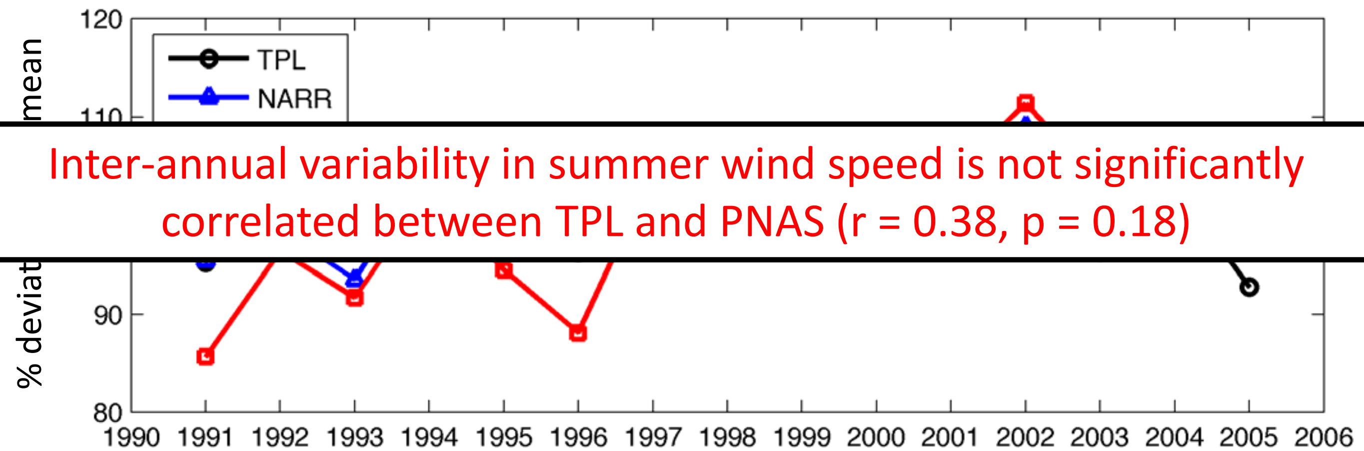
* Indicates significance at Bonferroni adjusted 95% confidence interval (i.e., $\alpha = 0.05/n = 0.0038$).

Scully (2010) (and others) found no correlation between wind speed and hypoxic volume.

Why ????

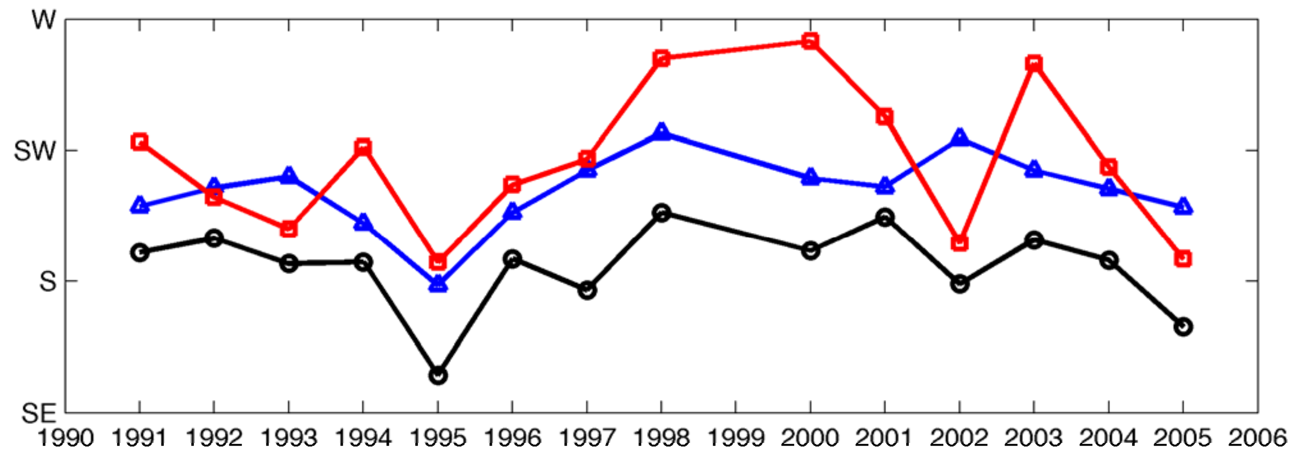
# Inter-Annual Variations in Wind Speed and Direction

Normalized Mean Summer (Jun-July-Aug) Wind Speed

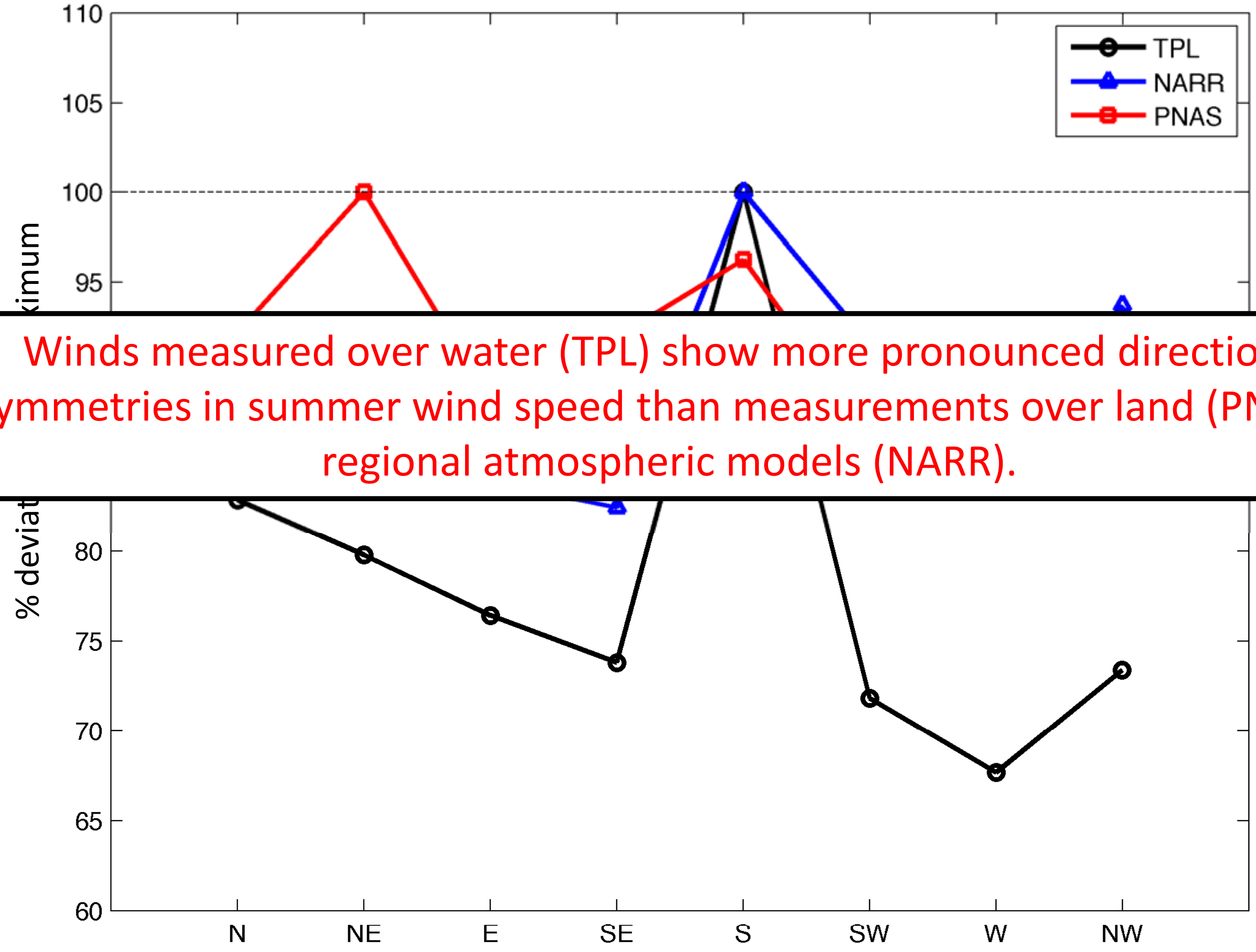



Inter-annual variability in summer wind speed is not significantly correlated between TPL and PNAS (r = 0.38, p = 0.18)

Mean Summer (Jun-July-Aug) Wind Direction



# Normalized Summer Wind Speed as a Function of Direction




Winds measured over water (TPL) show more pronounced directional asymmetries in summer wind speed than measurements over land (PNAS) or regional atmospheric models (NARR).

# Implications for Hypoxia

Correlations with summer (June-July-Aug) wind speed for 1991-2005.

| | CBP max $N^2$ | Hypoxic Vol. (<0.2mg/L) | Hypoxic Vol. (<1.0mg/L) | Hypoxic Vol. (<2.0mg/L) |
|---|---|---|---|---|
| TPL | -0.525 | -0.555 | -0.793 | -0.786 |
| PNAS | -0.098 | -0.352 | -0.109 | -0.058 |

Red values denote significant at 95% CI

1) Summer wind speeds at TPL are significantly correlated with CBP summer stratification. Summer winds from PNAS are **NOT**.
2) Summer wind speeds at TPL are significantly correlated with observed hypoxic volumes (all definitions). Summer winds at PNAS are **NOT**.

# Conclusions

1) A relatively simple model with no biological variability can capture some of the inter-annual variability in observations of hypoxic volume, related to physical processes.
2) This model provides a tool for separating the role of physical from biological processes in controlling hypoxia.
3) Model results and comparisons with observations demonstrates that summer wind speed is the most important physical variable in controlling summer hypoxia.
4) Comparison of model results and model residuals suggests Dec-Feb is key period for freshwater inputs (controlling spring stratification) and March-May is key period for nutrient delivery (fueling bloom).
5) Numerical model results of dissolved oxygen are sensitive to wind forcing and regional atmospheric models (e.g. NARR) may not adequately capture the observed inter-annual variations in wind speed.
6) Winds from Patuxent Naval Air station (PNAS) differ from winds measured over water (TPL) in several important ways.
7) Previous and future studies using PNAS winds need to be interpreted with caution.