# Mid-Bay Dissolved Oxygen Trends as a Function of Nutrient Loads *and Strength of Stratification*

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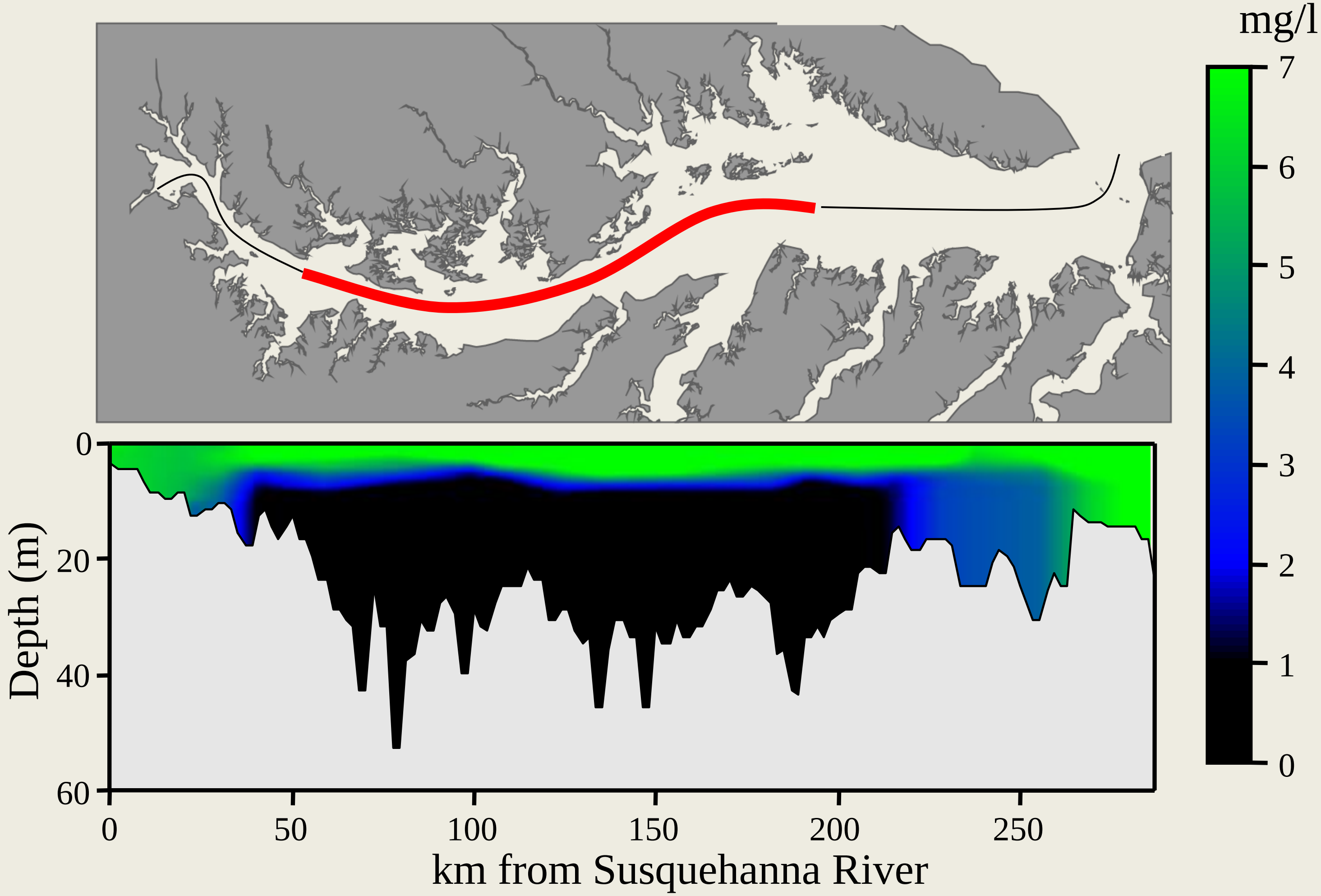
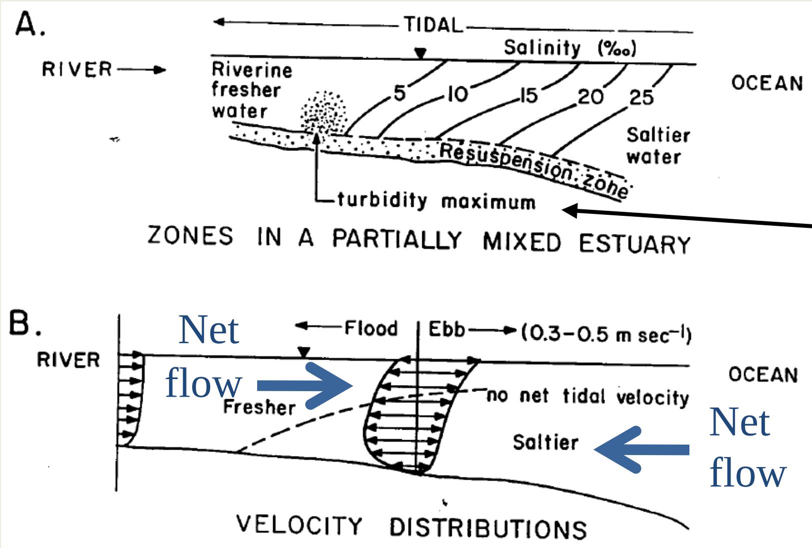
CBEO
Chesapeake Bay Environmental Observatory

# Location of Chesapeake Bay Hypoxic Zone

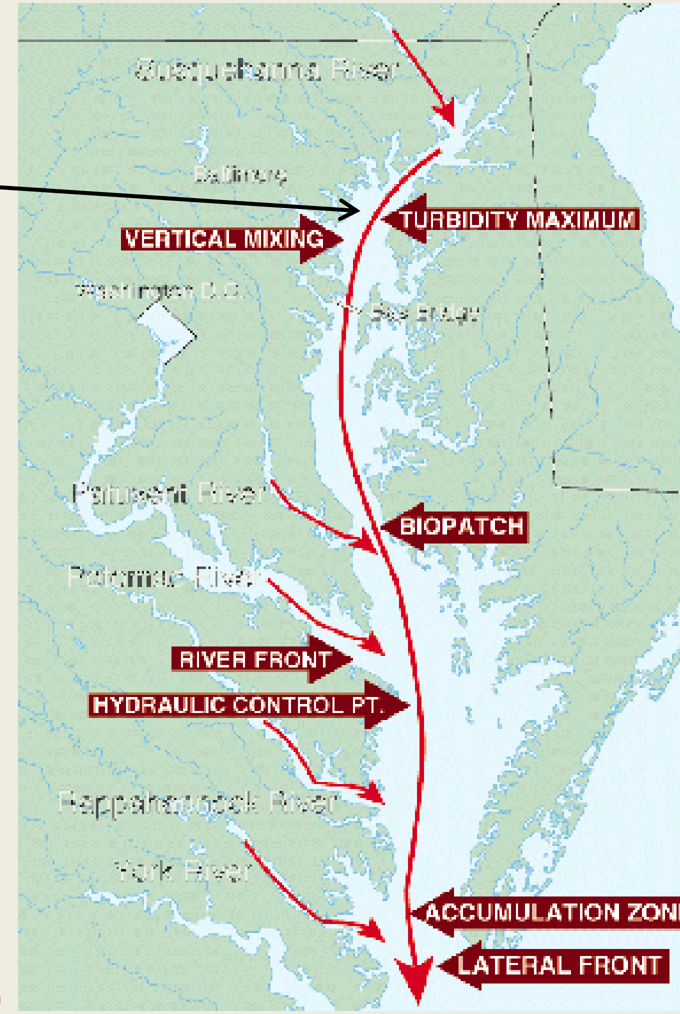



(Hagy 2002 Thesis, UMD)
graphic courtesy of W.M. Kemp

# Stratification Control of Vertical Location of Hypoxia




(from Brush and Brush, 1994; after Pritchard 1967)



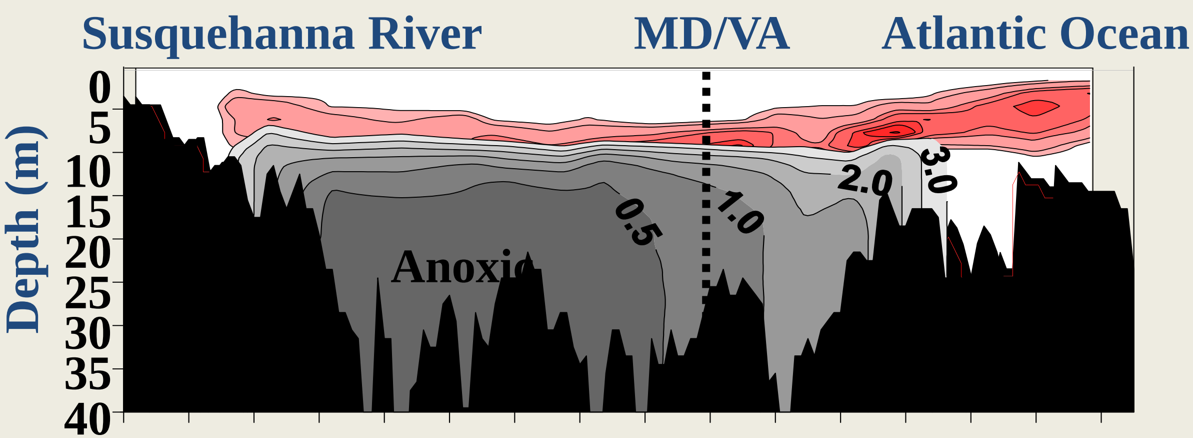
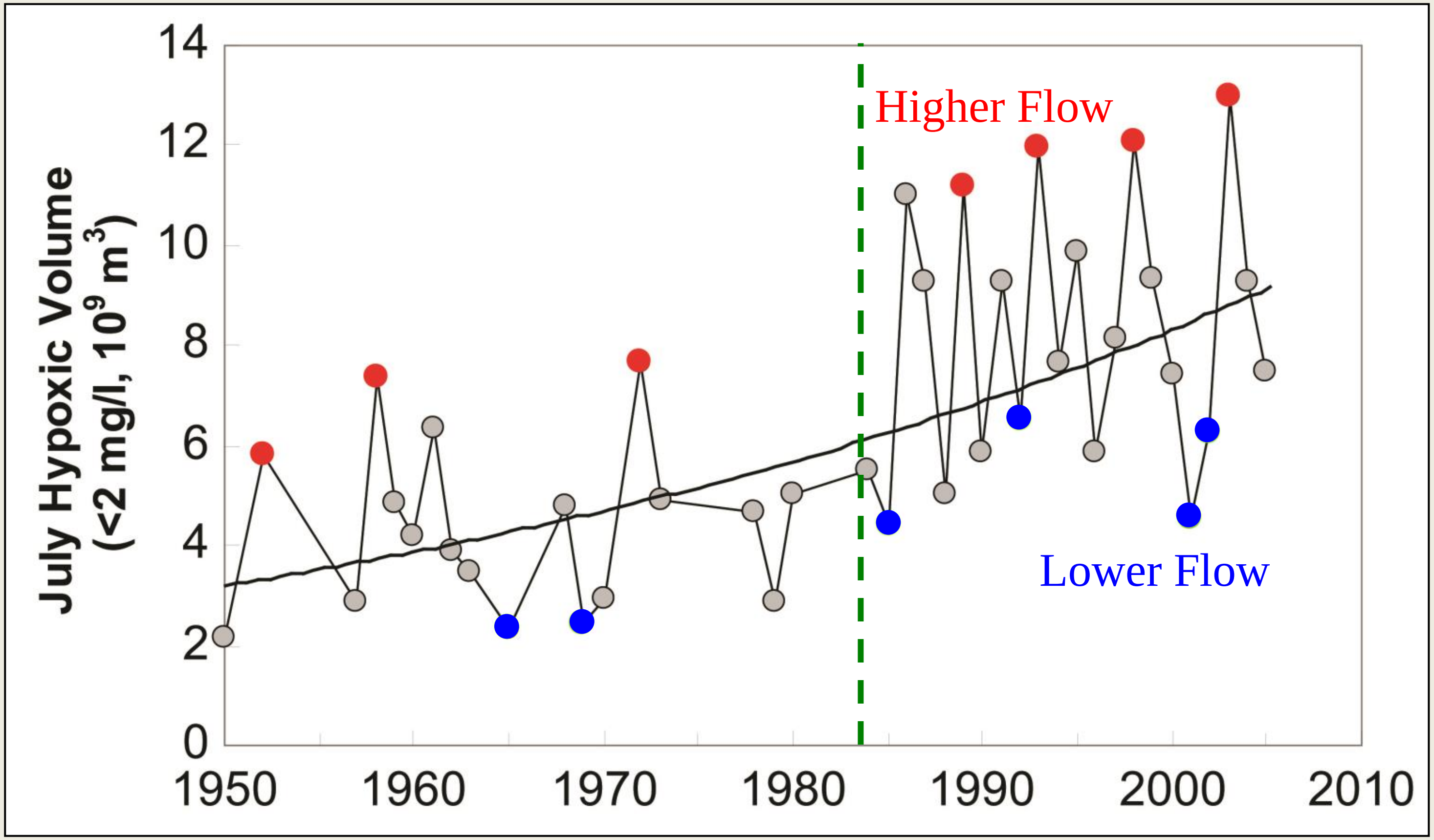




Figure courtesy M. Kemp; from J. Hagy 2002 Thesis, UMd)

(from CBP website)

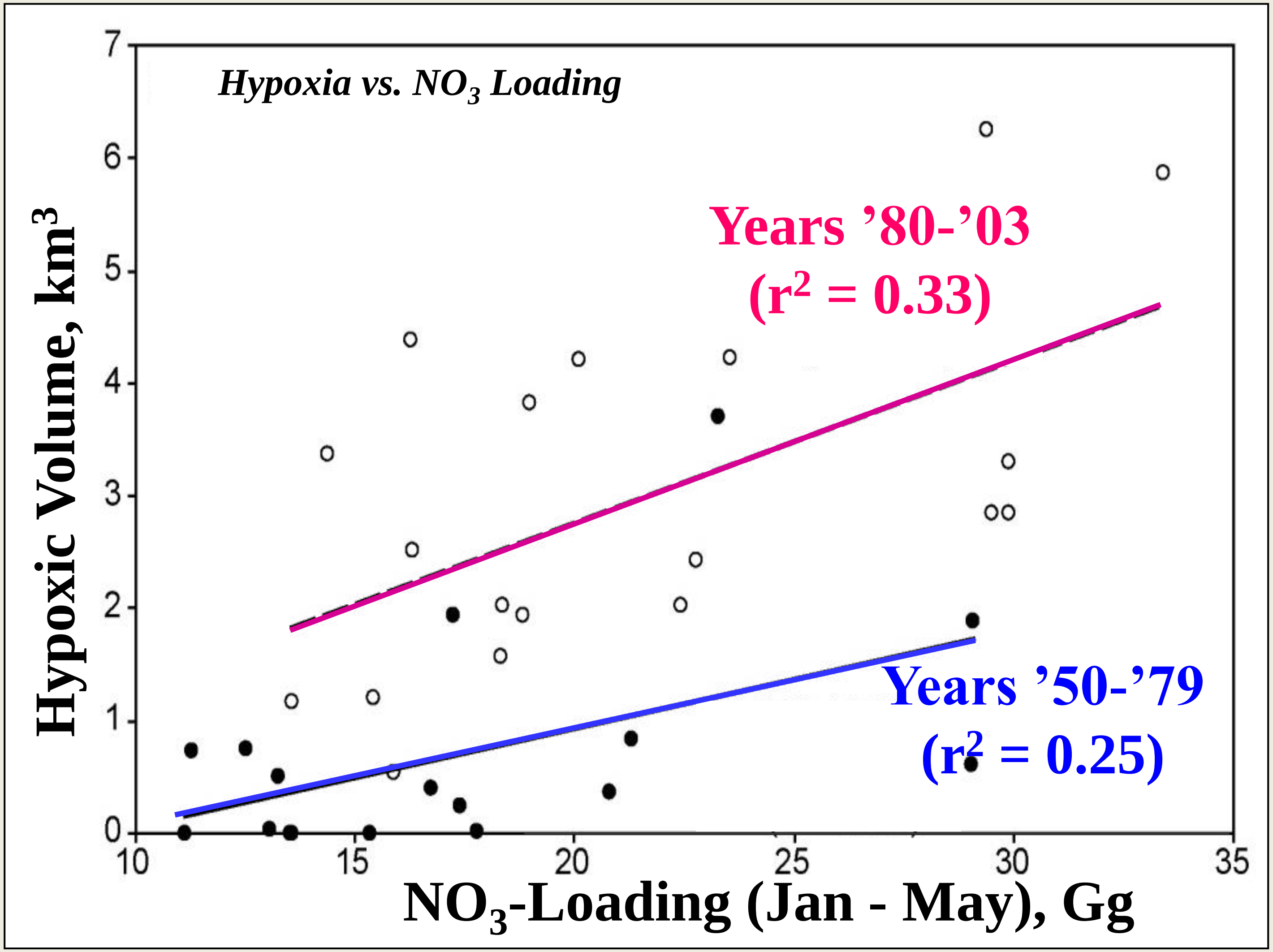
- Settling and decomposing phytoplankton deplete $O_2$ in deeper water
- Pycnocline controls position of low $O_2$ water.
- Landward transport replenishes deep $O_2$ pools (more so near mouth).

# Trend in Chesapeake Bay Average July Hypoxic Volume




after Hagy et al., *Estuaries* 2004
graphic courtesy of W.M. Kemp

# Trend in Chesapeake Bay
# Average July Hypoxic Volume

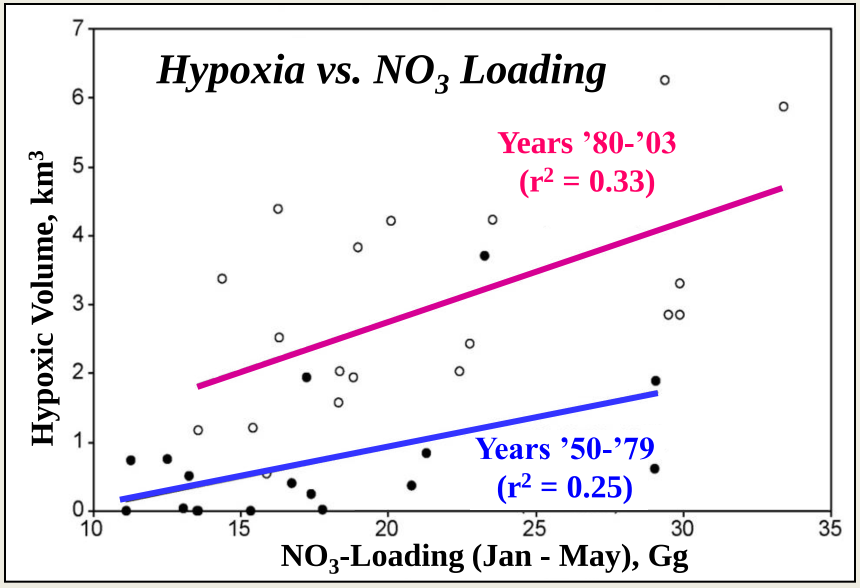



(Hagy et al. *Estuaries* 2004 ;

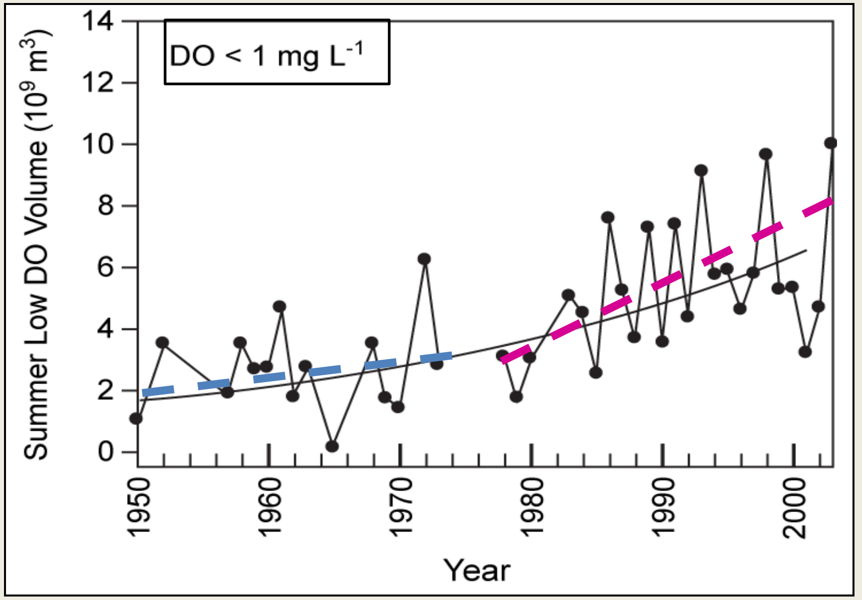
Kemp et al. *Marine Ecology Progress Series*. 2005)

# Decadal-Scale Shift in Relationship between Chesapeake Bay Hypoxia and Nitrogen Load

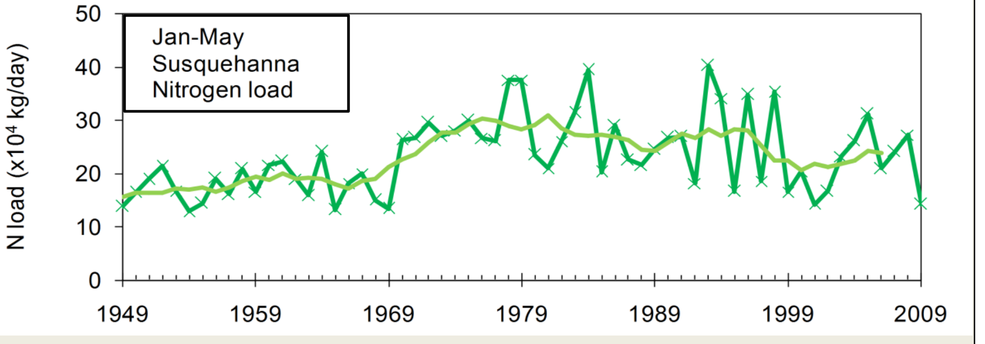
- **Increase in slope of hypoxia-nitrate relation for 1980-2003 relative to 1950-1979**
- **1980-2009 : Average July hypoxia rising despite level or decreasing nitrate loading. Why?**
-




(Hagy et al. *Estuaries* 2004 ;
Kemp et al. *Marine Ecology Progress Series*. 2005)

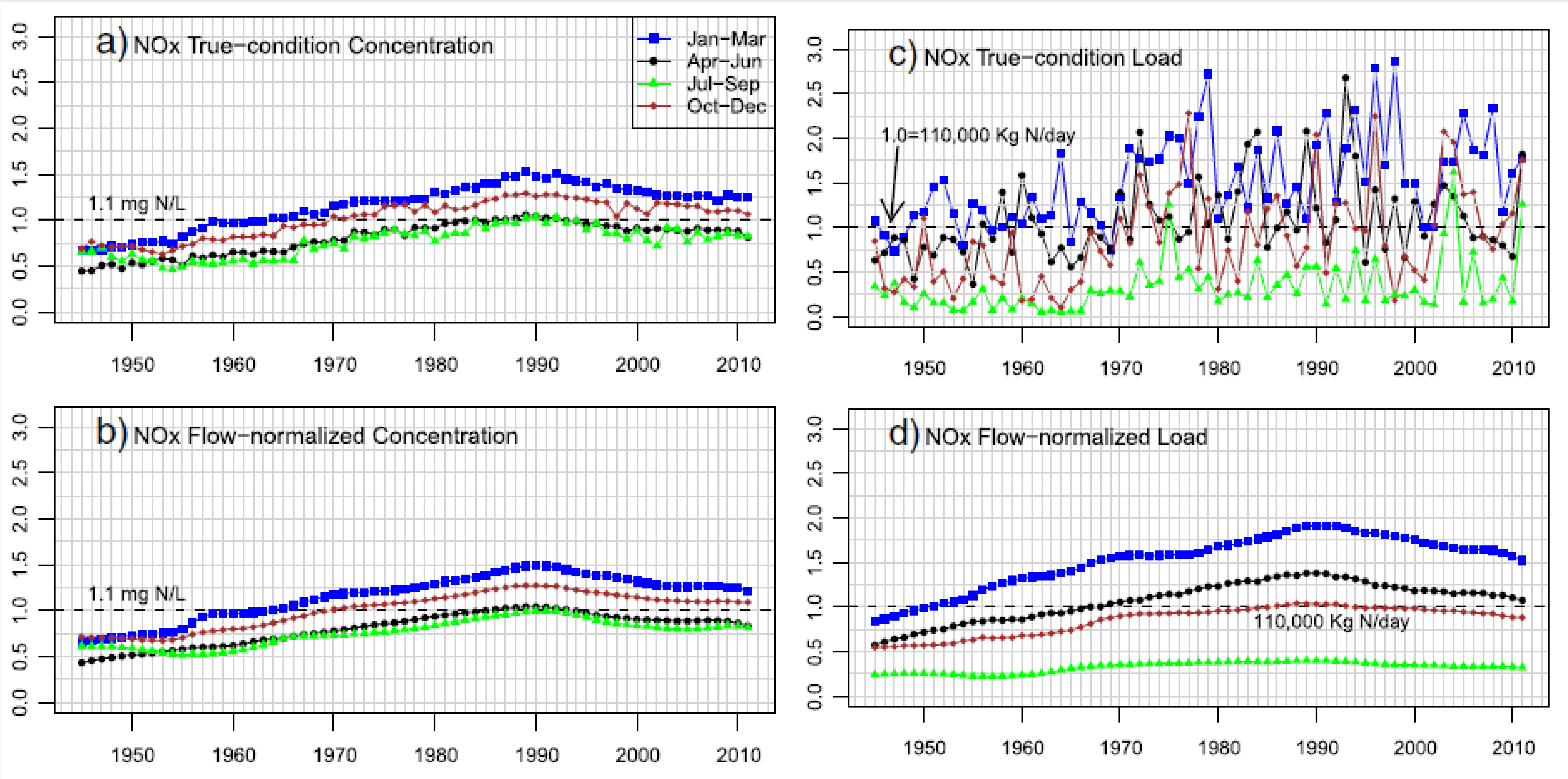



(Hagy et al. *Estuaries* 2004)



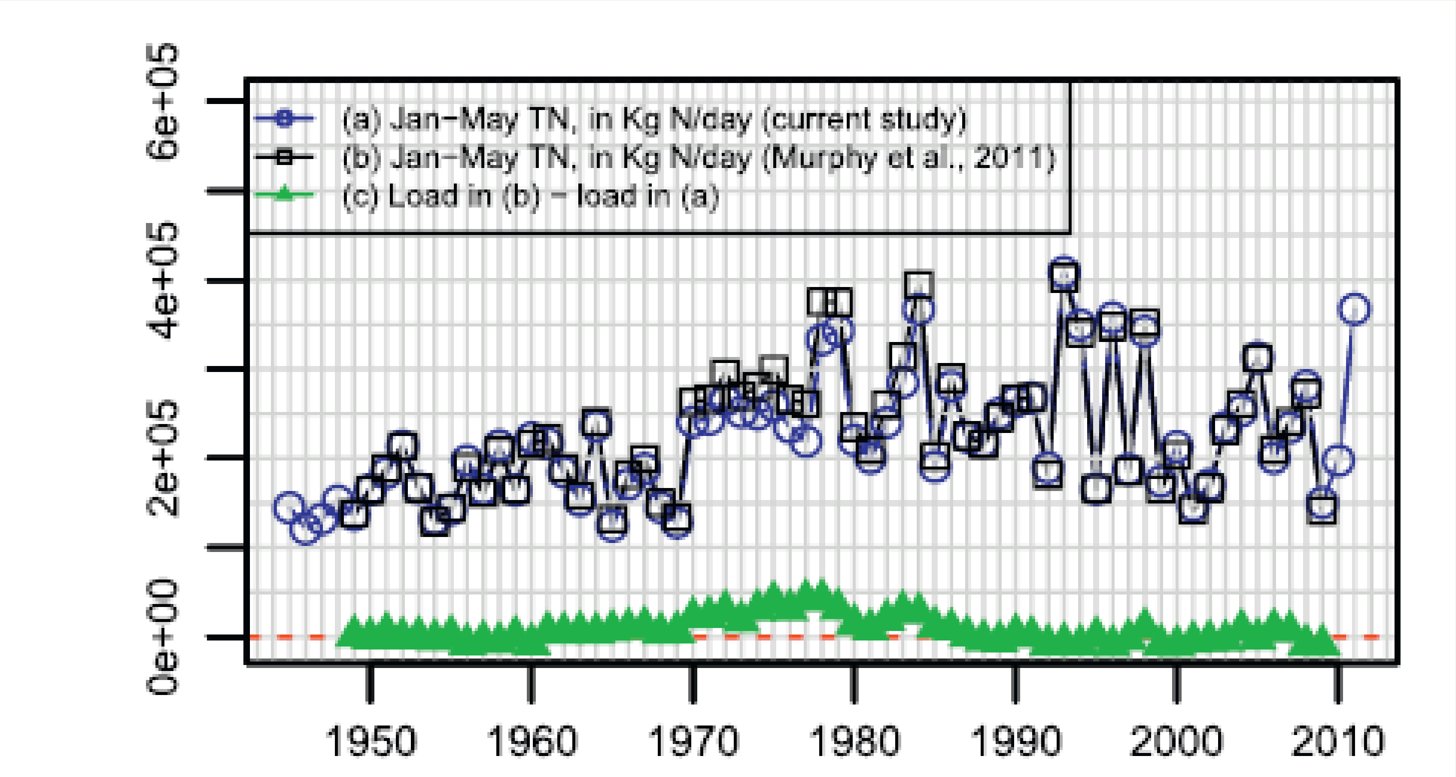

(Murphy et al. *Estuaries and Coasts* 2010)

# Re-Evaluation of Historical Nitrogen Load Using WRTDS




(Zhang et al., *Science of the Total Environment*, 2013)

# Re-Evaluation of Historical Nitrogen Load Using WRTDS




(Zhang et al., *Science of the Total Environment*, 2013)

# CBEO Motivation:
# Understanding Hypoxia Trends in Chesapeake Bay

- The CBEO's science question:
  Why had the observed relationship between Chesapeake Bay hypoxia and nutrient loadings "shifted" in recent decades?

- Exploration of alternative hypotheses
  ….using *improved access to data*
  and *more intensive analysis* of historical observations
  - Artifact? Shift in how observational metrics relate to reality?
  - Chemical mechanisms? Decadal-scale shifts in limiting nutrient?
  - Biological mechanisms? Enhanced benthic nutrient recycling?
  - Physical mechanisms? Long-term shifts in stratification?

# Hypoxic Volume Estimation via DO Interpolations

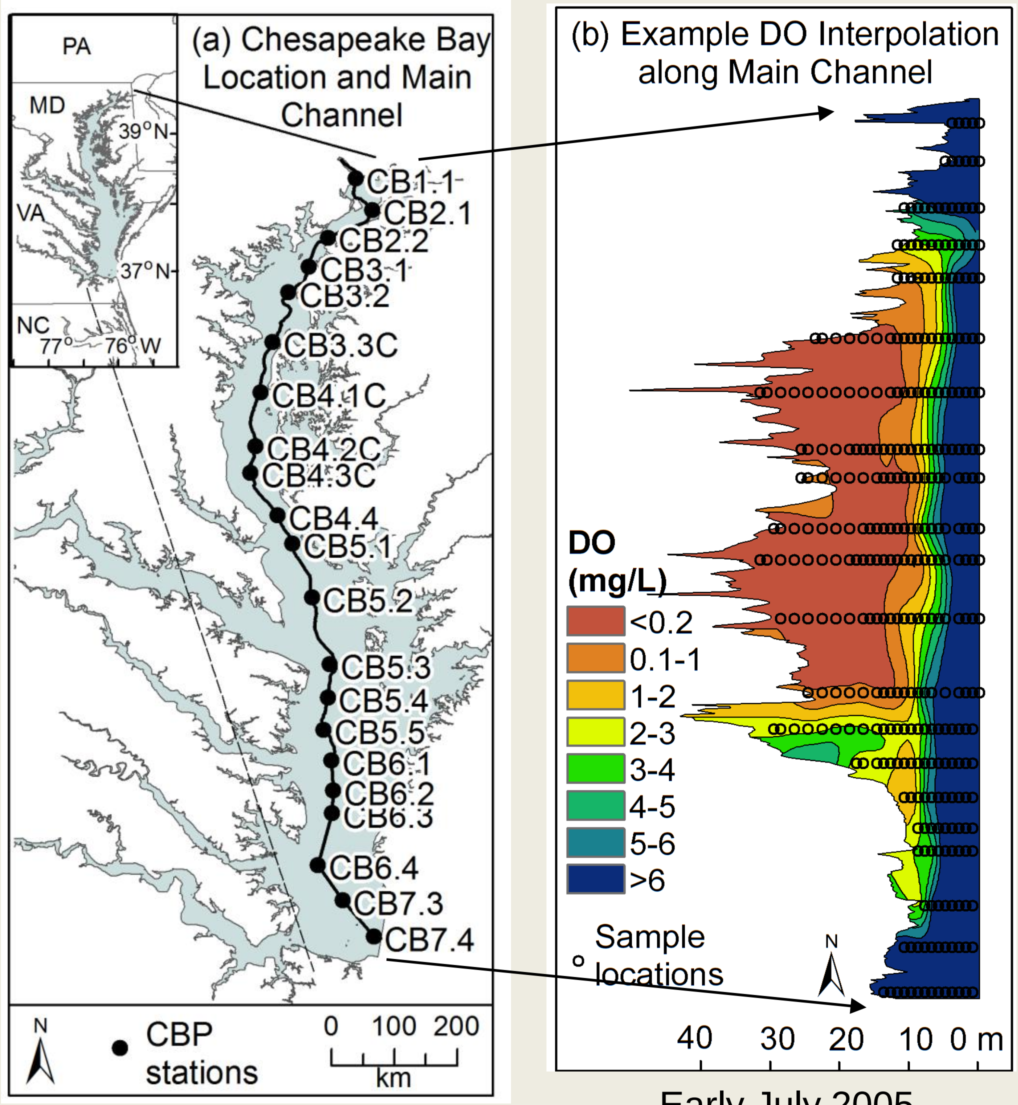
(Rebecca Murphy Ph.D. Dissertation, 2010)

1. Identify DO data collected by CBP (1984-2010) and CBI (1949-1980)

2. Interpolate DO observations to a 2-D grid along main channel

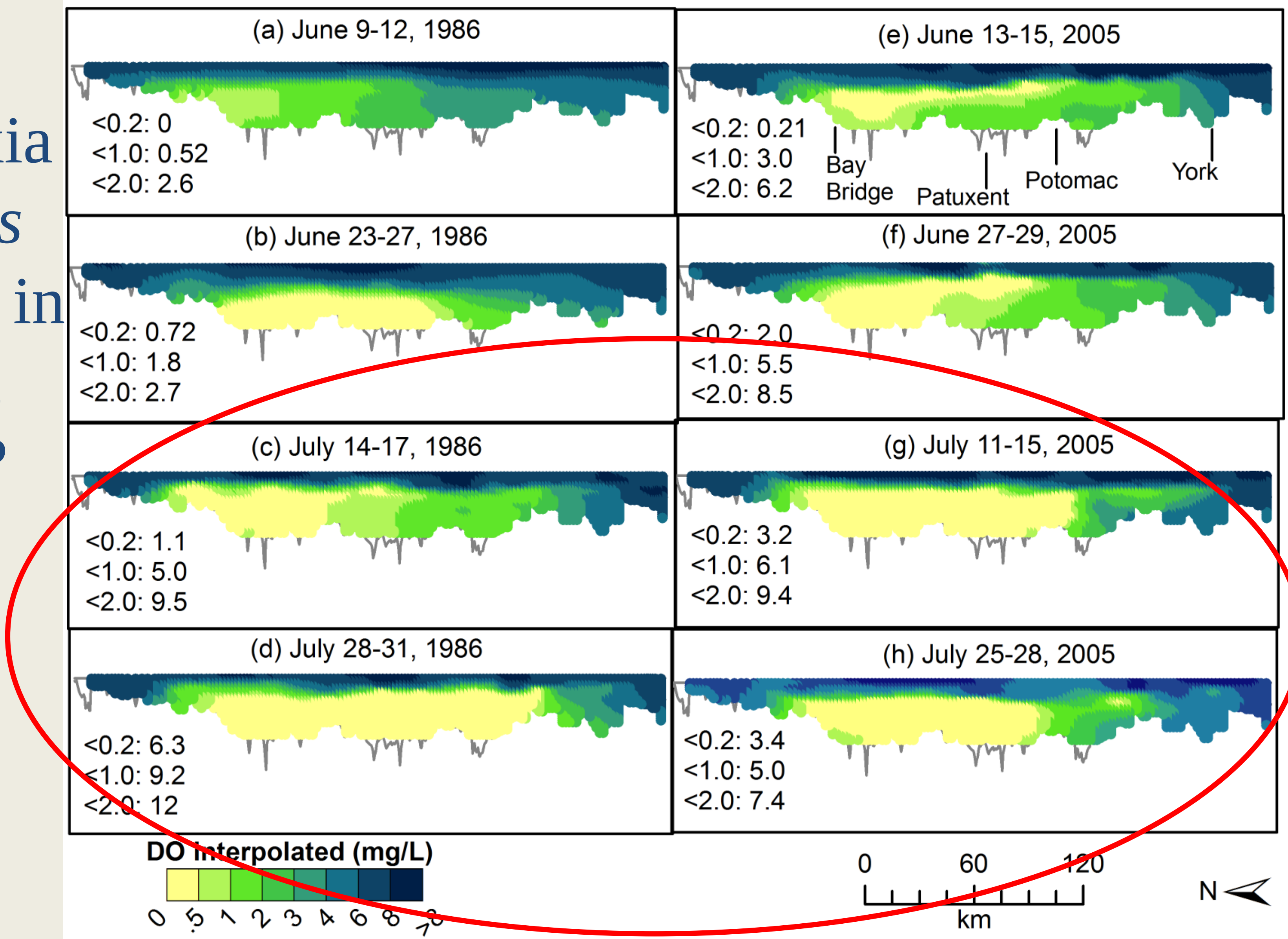
3. Assume depth profile of DO is constant to the east and west across the Bay

4. Used tabulated cross section volumes (Cronin and Pritchard 1975) calculate volume of water below cutoffs



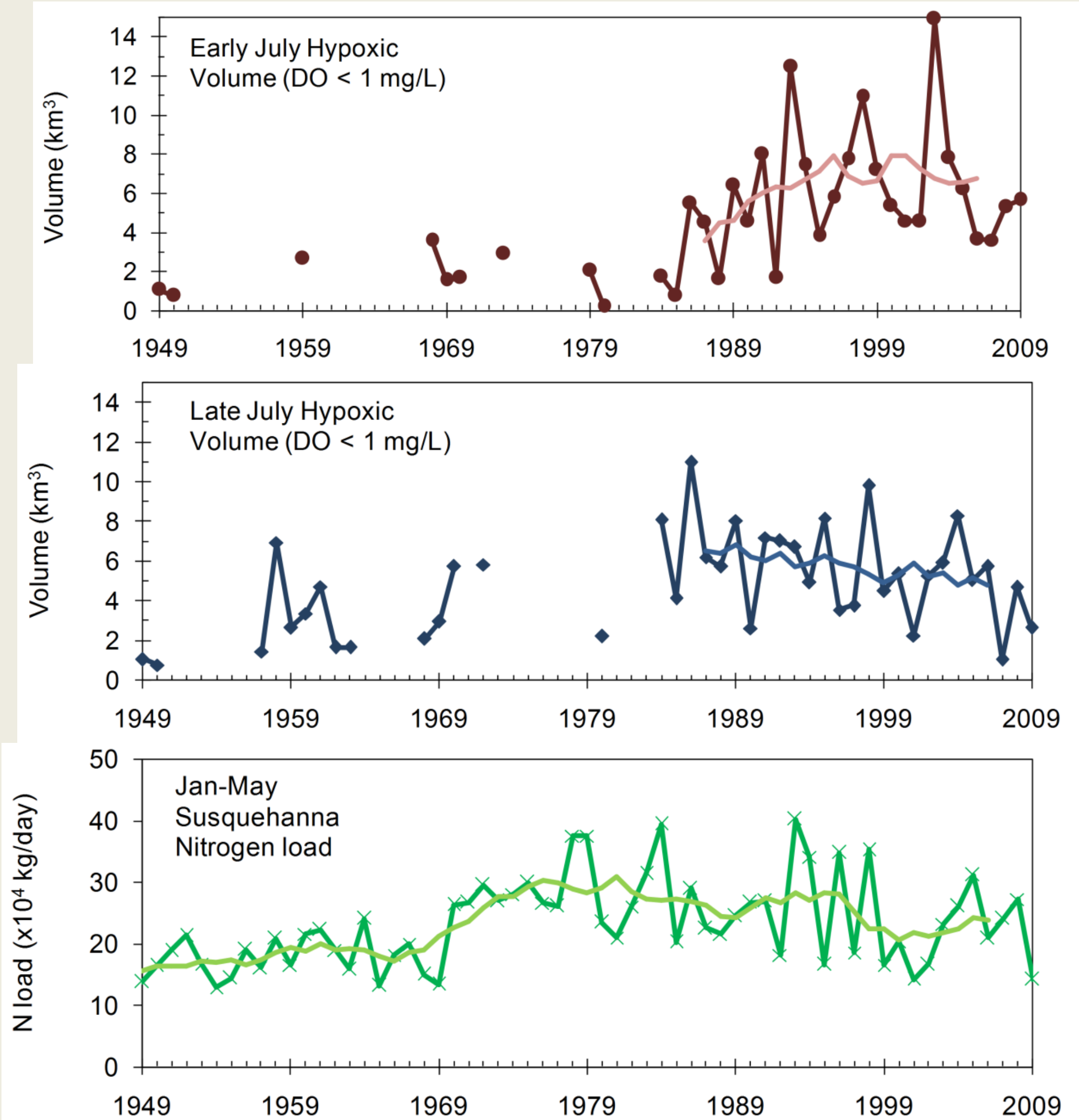

Early July 2005

# But is hypoxia *always* worse in recent years?




Murphy, et al. 2011. Long-Term Trends in Chesapeake Bay Seasonal Hypoxia, Stratification, and Nutrient Loading. *Estuaries and Coasts* 34:1293-1309.

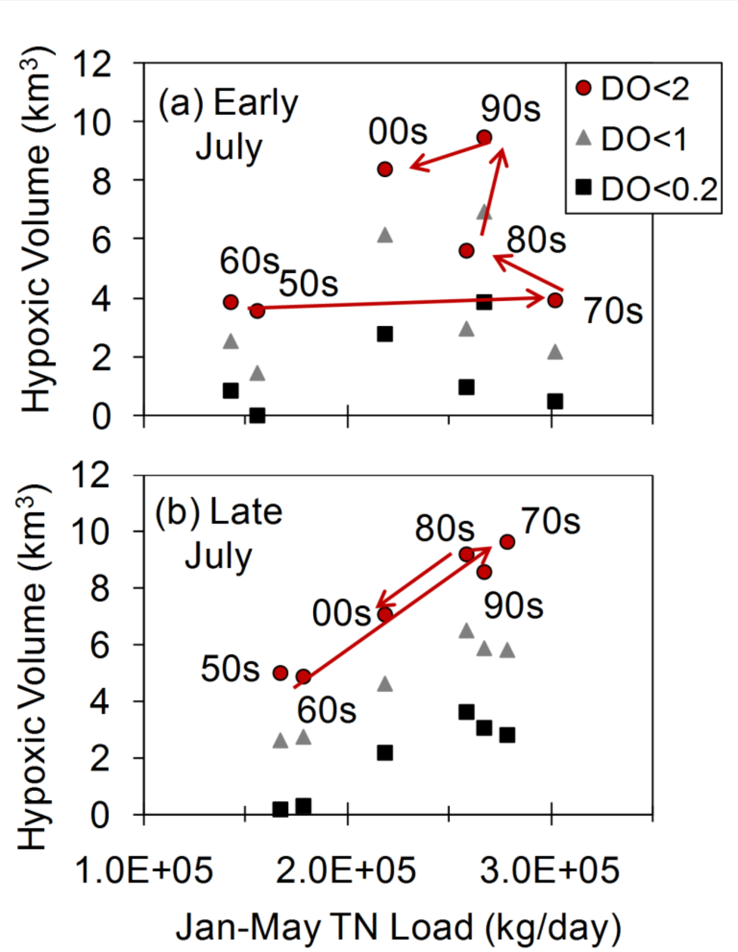
# Early- and late-July hypoxic volumes




- Early July volumes have increased through the 80s and 90s
- Late July volumes followed the long-term trends expected from winter/spring TN loads

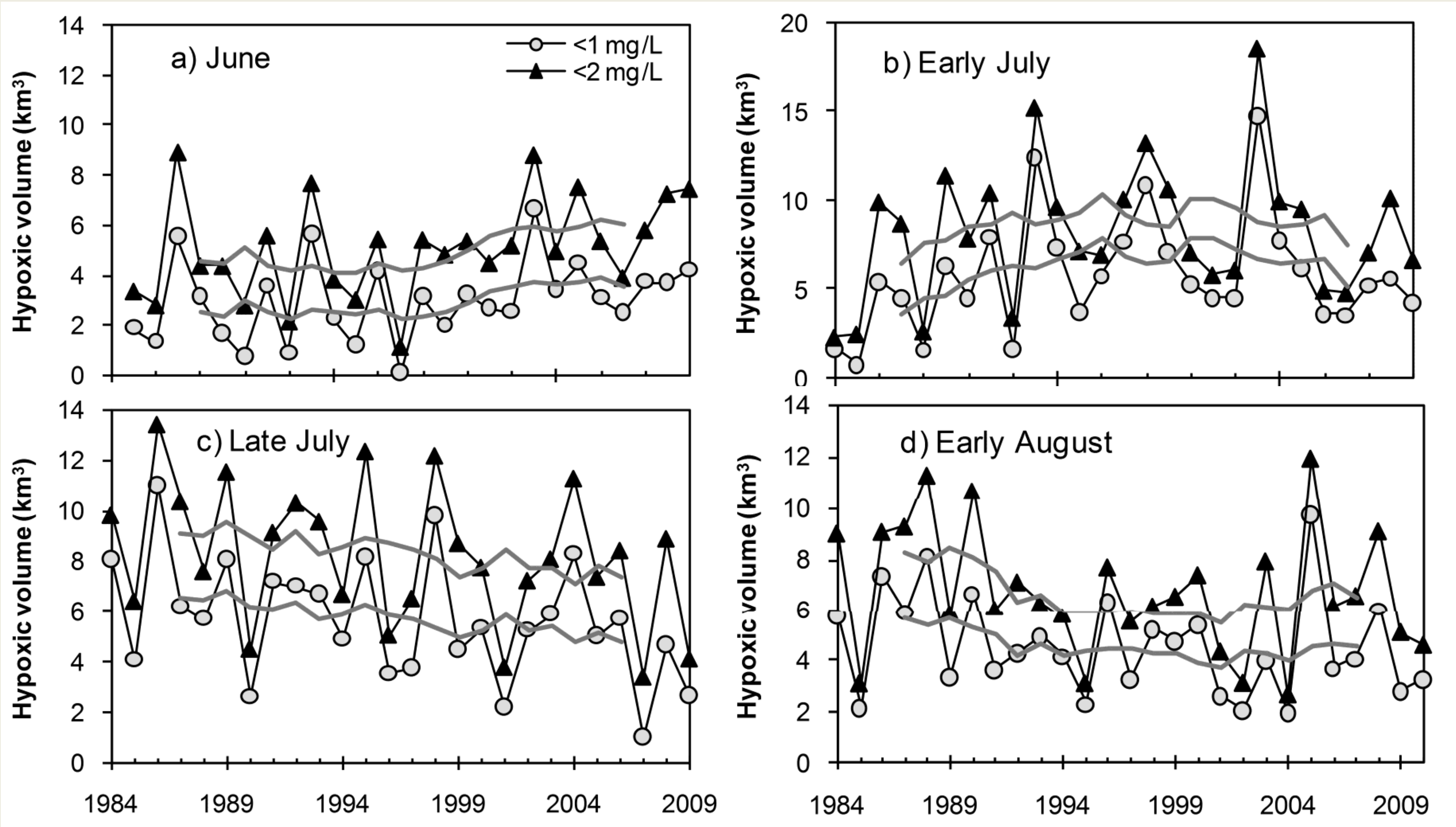
(Murphy et al., *Estuaries and Coasts*, 2011)

# Decadal Shifts in Hypoxic Volume vs. TN Load



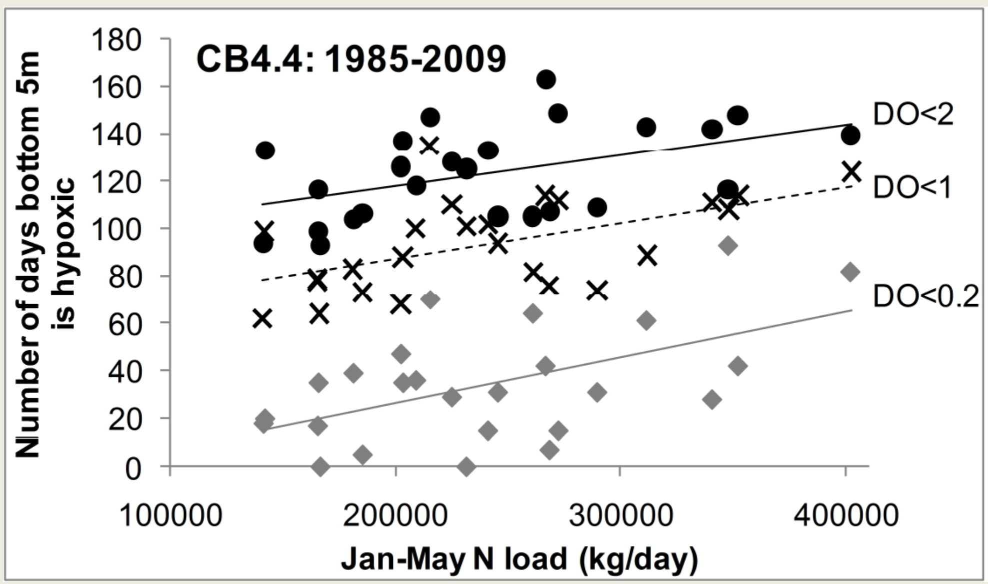

(Murphy et al. *Estuaries and Coasts* 2011).

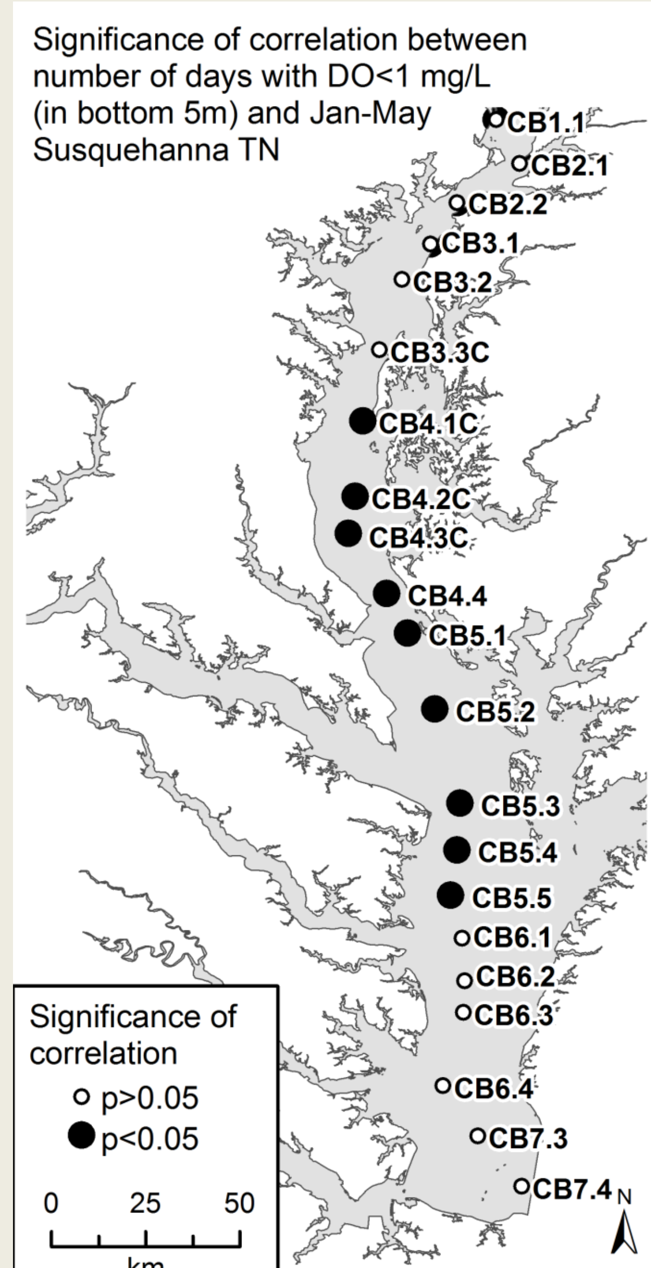
# 1984-2010 Early- vs. Late-Summer



# Hypoxia Duration

The number of summertime days with bottom-water hypoxia in the mid-Bay is significantly correlated to TN load



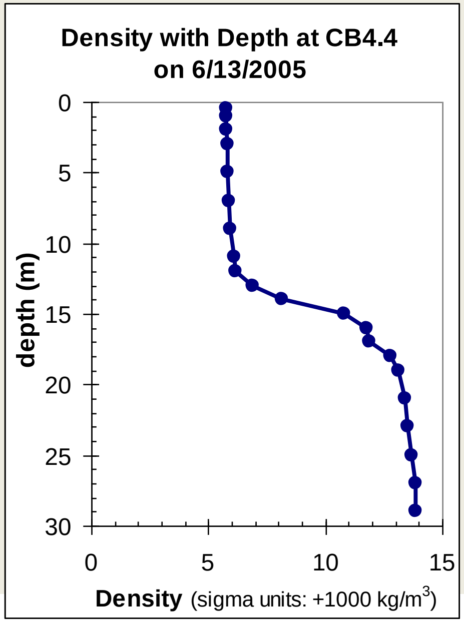



# Hypoxia in Chesapeake Bay

- **Motivation**: The CBEO "science question":
  Why has the relationship between Chesapeake Bay hypoxia and nutrient loadings "shifted" in recent decades?
  - me
- Exploration of alternative hypotheses
  ….using *improved access to data* and *improved analysis* of the observations

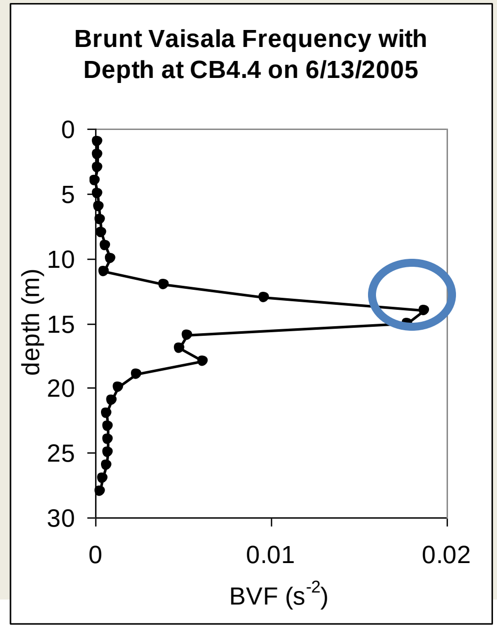
  - Artifact? Shift in how observational metrics relate to reality?
  - Chemical mechanisms? Decadal-scale shifts in limiting nutrient?
  - Biological mechanisms? Enhanced benthic nutrient recycling?
  - Physical mechanisms? Long-term shifts in stratification?
- **Conclusions and Implications**
- **Future work**

# Calculation of Stratification Strength

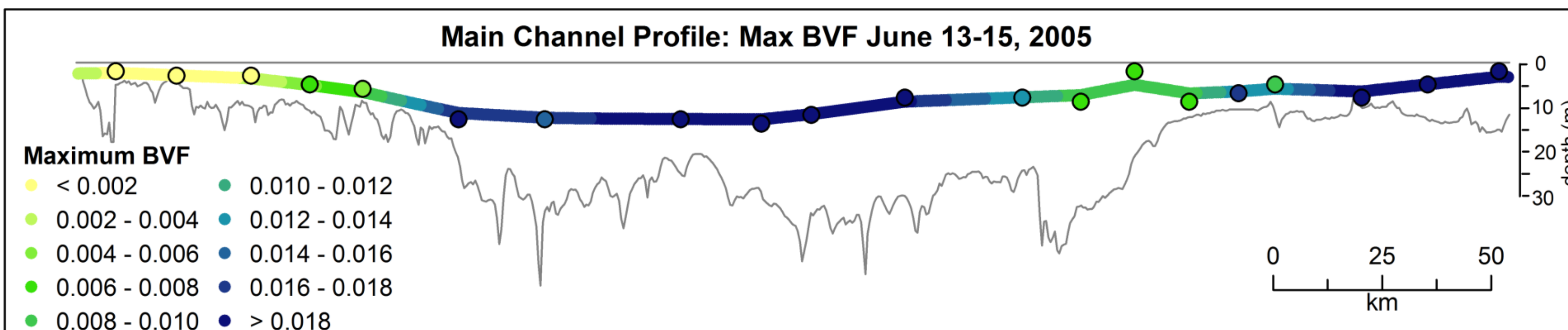



1. Calculate Brunt Väisälä Frequency

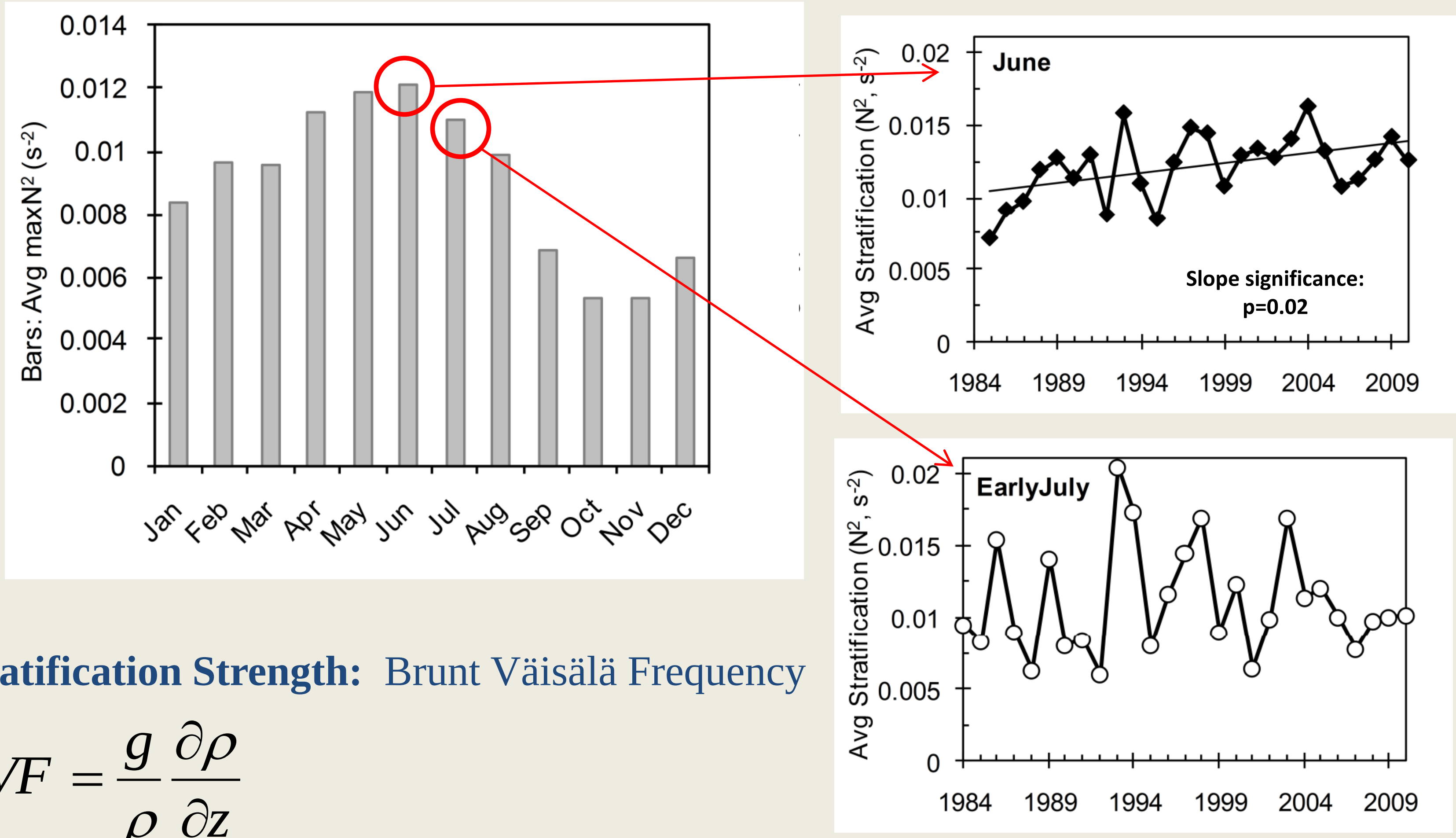
$$BVF = \frac{g}{\rho}\frac{\partial \rho}{\partial z}$$




2. Interpolate maximum Brunt Väisälä Frequency (BVF)



# Stratification Trends in Recent Decades




**Stratification Strength:** Brunt Väisälä Frequency

$$BVF = \frac{g}{\rho}\frac{\partial \rho}{\partial z}$$

ρ = density at depth z ($kg/m^3$); g = 9.81 $m/s^2$

Used 2-meter moving average to calculate density gradient

# Mechanisms for stratification effects on hypoxia

- Direct vertical mixing
- Longitudinal replenishment (less DO in southern bottom waters)
- Lateral mixing (less lateral mixing with more stratification)

# Stratification and Vertical Mixing

BVF ➡ Richardson Number, $R_i$

($R_i$: balance between buoyant and shear forces)

$R_i$ > 25: strong stratification, little mixing

$$R_i = \frac{\frac{g}{\rho}\frac{\partial \rho}{\partial z}}{\left(\frac{\partial u}{\partial z}\right)^2}$$

BVF

vertical velocity gradient

$R_i$ ➡ Vertical Diffusivity, $E_z$

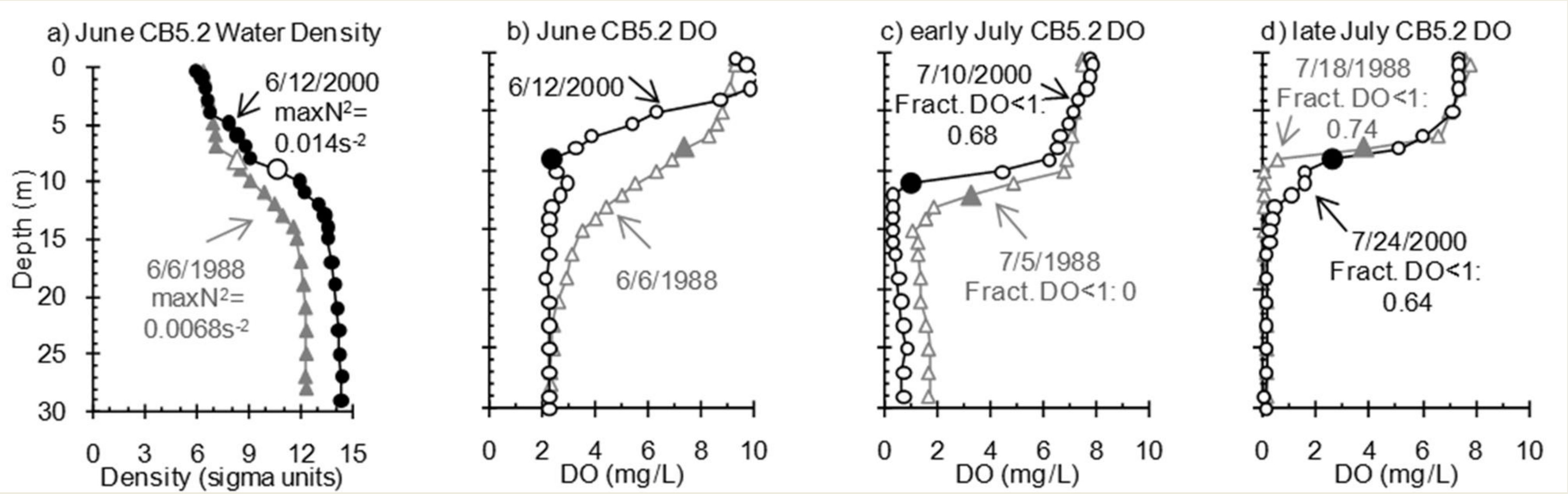
(Munk and Anderson 1948)

$$E_z = \frac{E_{z,0}}{[1 + bR_i]^a}$$

$E_{z,0}$ = Eddy diffusivity with no stratification

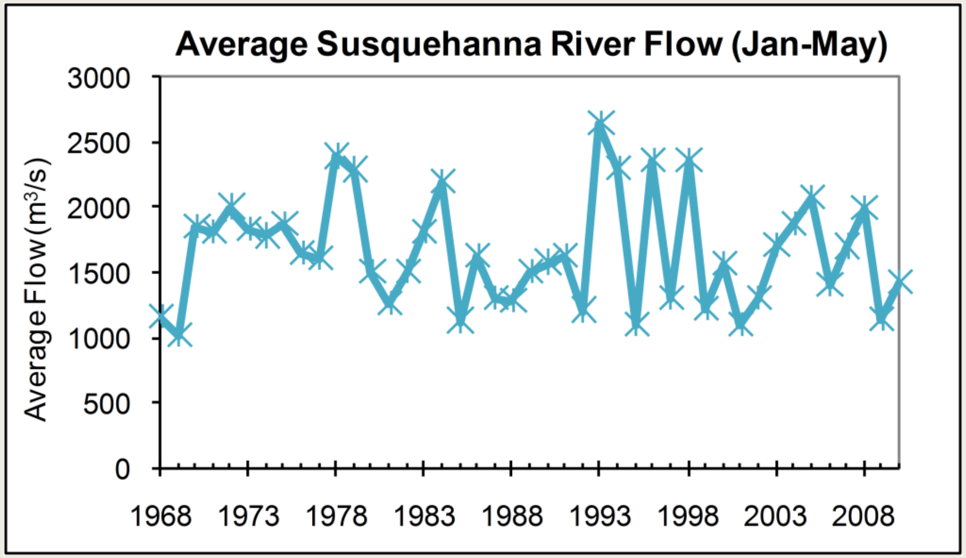
a,b = coefficients

# Stratification: Effect on hypoxia

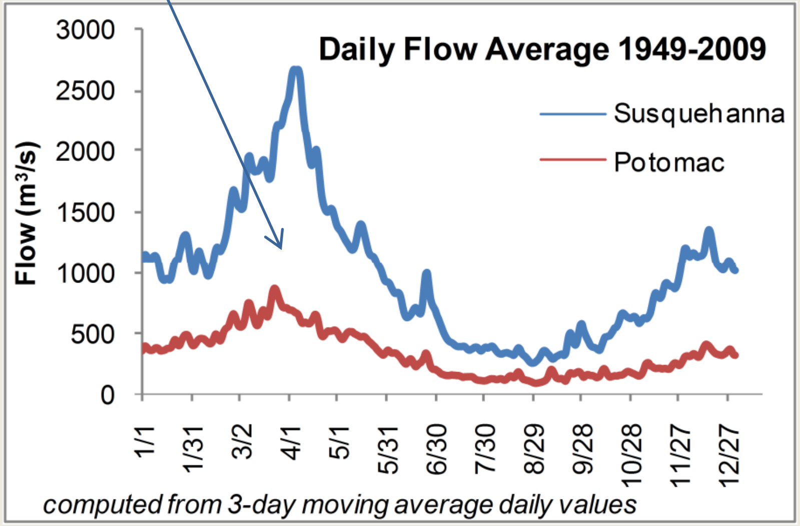


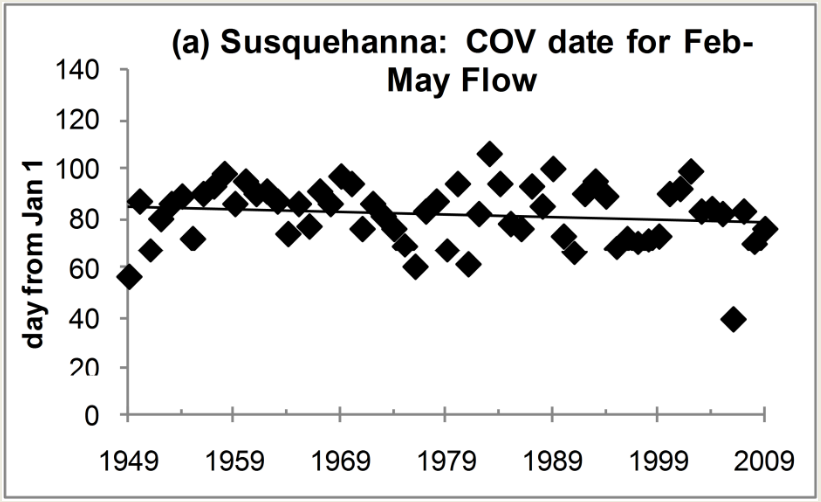
# But *why* has June stratification increased?

- Increase in average spring flow? *[no]*
- Shift in timing of spring flow? *[no]*




Center of Volume (COV) date for Feb-May flow

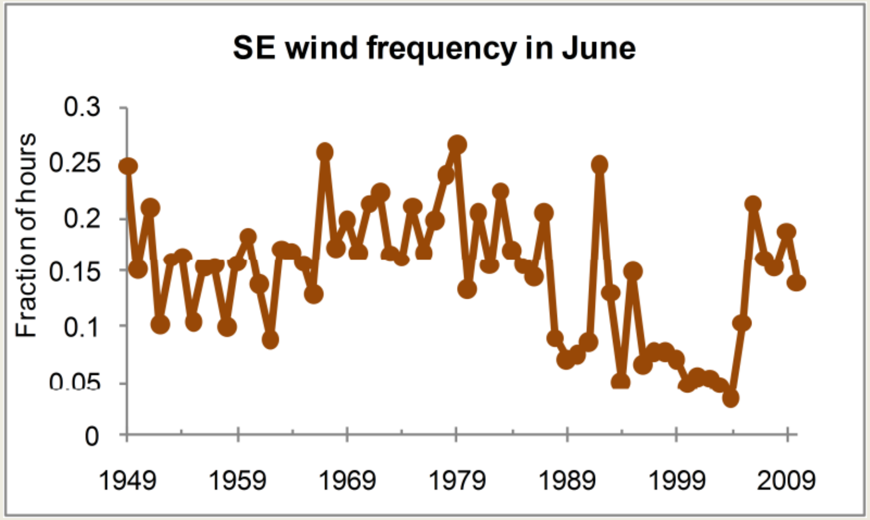


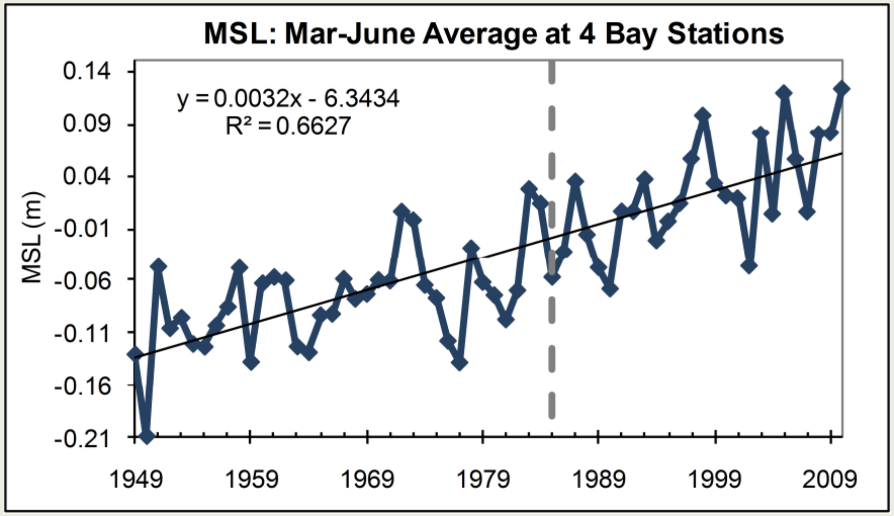

COV=center of volume

# Why has June stratification increased?

- Increase in average spring flow *[no trend observed]*
- Shift in timing of spring flow *[no trend observed]*
- Increase in water temperature *[observed; but too low to cause]*
- Shift in predominant wind direction *[**maybe** : correlations found]*
- Rising sea level via increased salinity *[**maybe**: correlations found]*

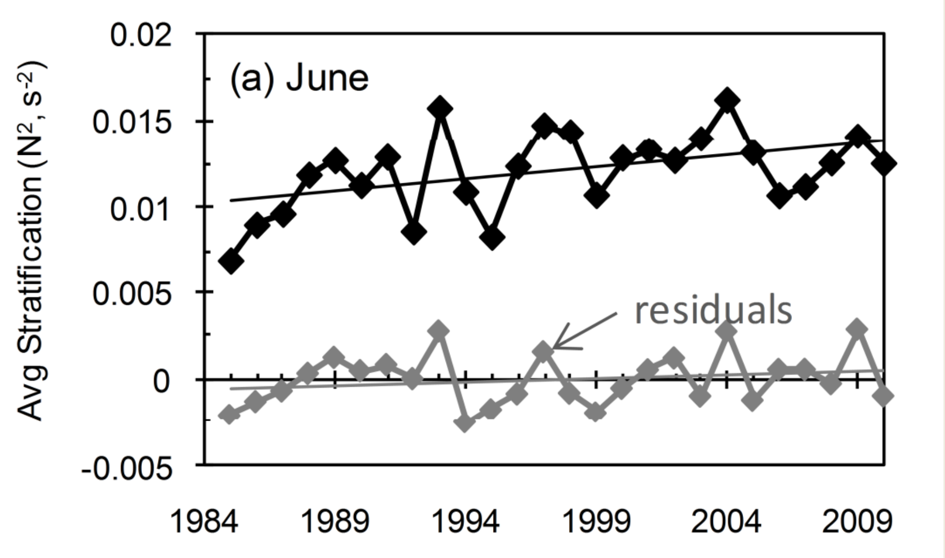



**Wind effects**
(NOAA data ; figure from R. Murphy [unpublished]
based on shift identified by
M.E. Scully (*Estuaries and Coasts*, 2010)




**MSL Rise and Associated Effect on Salinity**
(NOAA data; figure from R. Murphy [unpublished])
(Sea level rise has been linked to increased Bay salinity [Hilton et al., *J. Geophys. Res.* 2008])

# June stratification regression models




| June Stratification Models | | | | | | Residuals regressed with year $R^2$, p-value |
|---|---|---|---|---|---|---|
| Equation | Model Fit: $R^2$, p-value | Intercept, $\beta_0$ | River flow dependence (Feb-May), $\beta_1$ | SE wind[a] dependence (Jun), $\beta_2$ | MSL[b] dependence (Jul-Jun), $\beta_3$ | |
| $maxN^2 = \beta_0 + \beta_1(Flow) + \beta_2(SEwind)$ | 0.36, p=0.006 | 0.012 | 0.0007 (p=0.1) | -0.001 (p=0.03) | -- | 0.35, p=0.001 |
| $maxN^2 = \beta_0 + \beta_1(Flow) + \beta_2(SEwind) + \beta_3(MSL)$ | 0.58, p<0.001 | 0.012 | 0.0004 (p=0.2) | -0.001 (p=0.002) | 0.001 (p=0.002) | 0.05, p=0.3 |

From 1985-2010

# Findings

- **Early summer**: High levels of hypoxia are happening earlier in the summer (June, early July), likely due to an increase in the strength of June stratification, which restricts oxygen replenishment
- **Late summer** long-term hypoxic volume is correlated with decreasing nitrogen loads
- **Duration** of hypoxia is correlated with spring nitrogen loads

# Conclusions

- ***Both*** nutrient loads and physical conditions play a role in development and persistence of hypoxic volume.
  - DO concentrations ***are*** responding to nutrient load reductions from the watershed in significant, positive ways.
    - Late summer hypoxic volume
    - Duration of summer hypoxia
  - However, *an increase in June stratification* has led to higher hypoxic volumes in early summer.

- Higher stratification in June is likely due to a combination of wind, sea level, and other climatic forces.
- **Long-term monitoring and collaborative work can foster new and "transformative" scientific understanding.**