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

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(and others)

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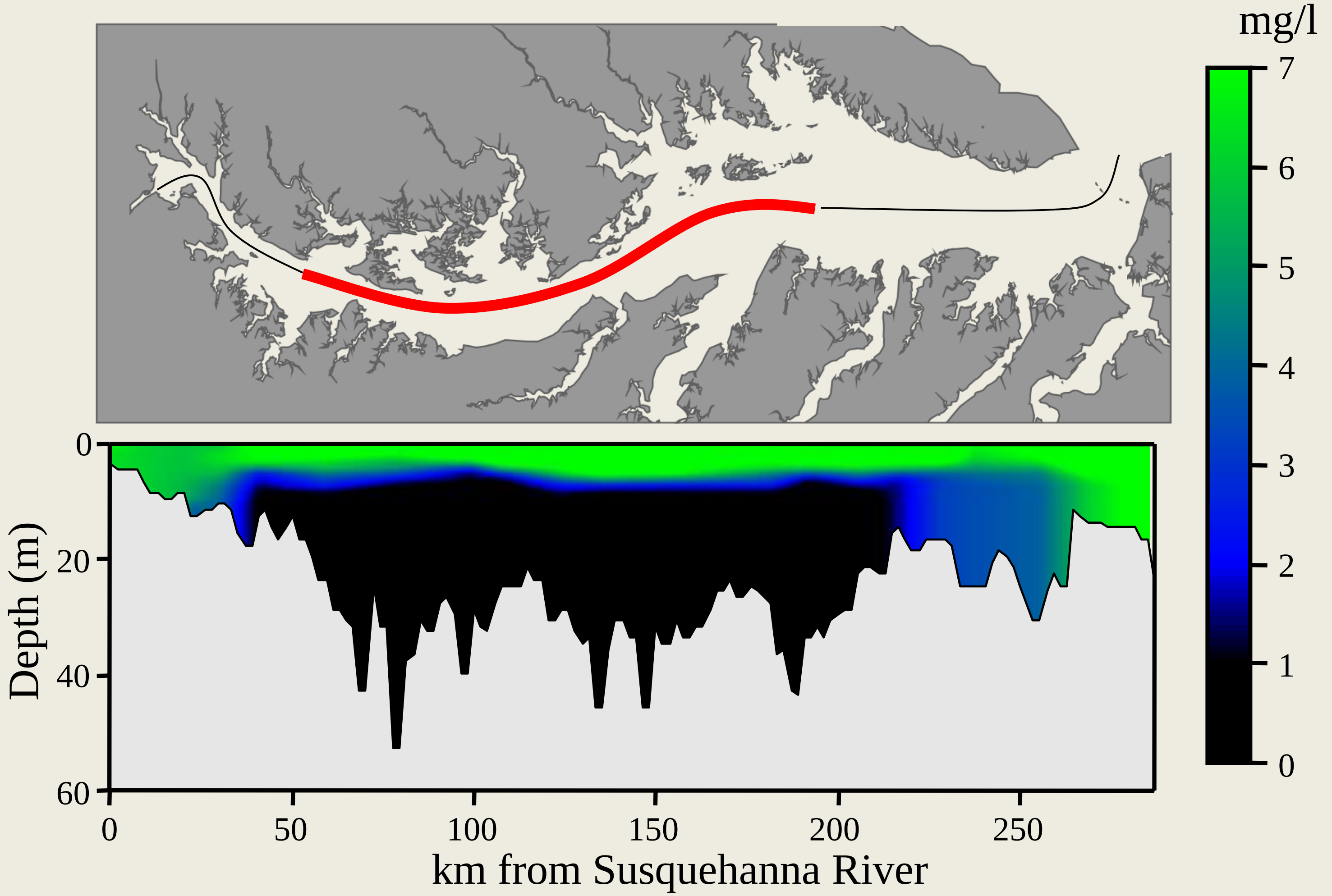
University of Delaware

Funding: National Science Foundation: Cyberinfrastructure for Environmental Observatories (CEO) Program: 2006-2010

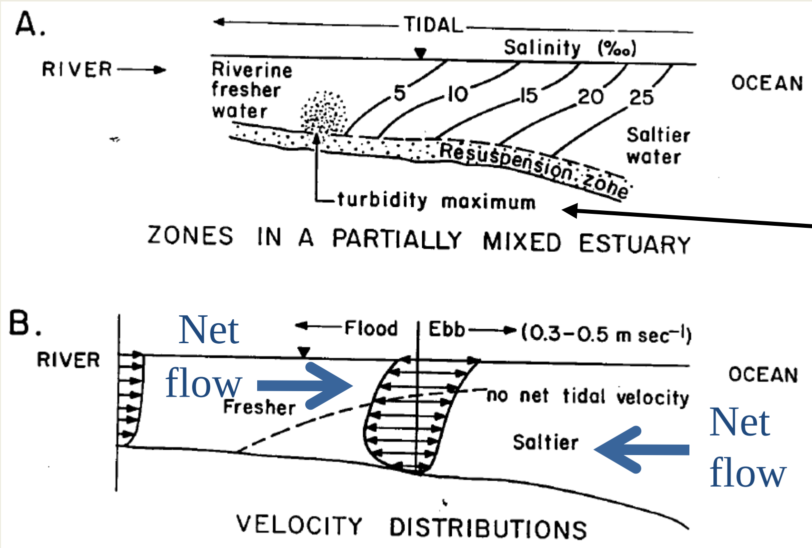
CBEO
Chesapeake Bay Environmental Observatory

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)

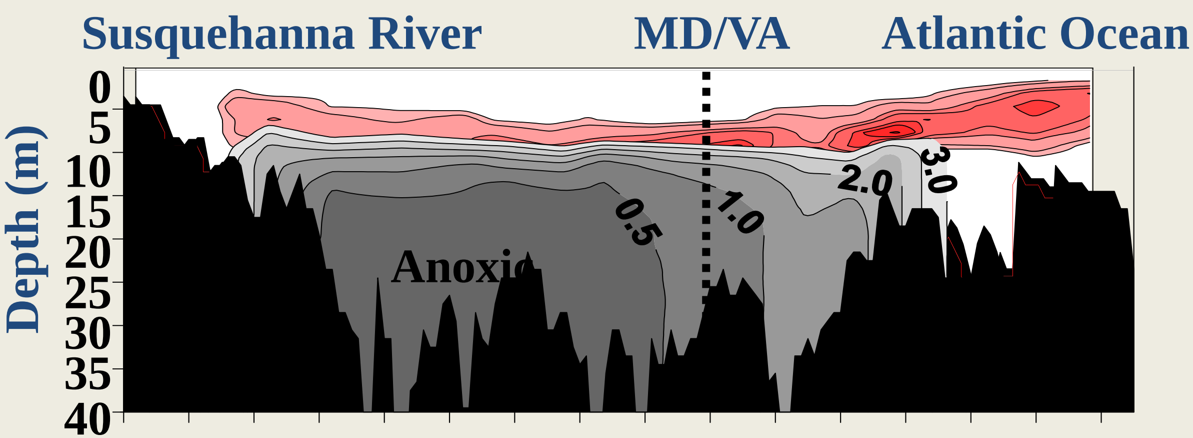
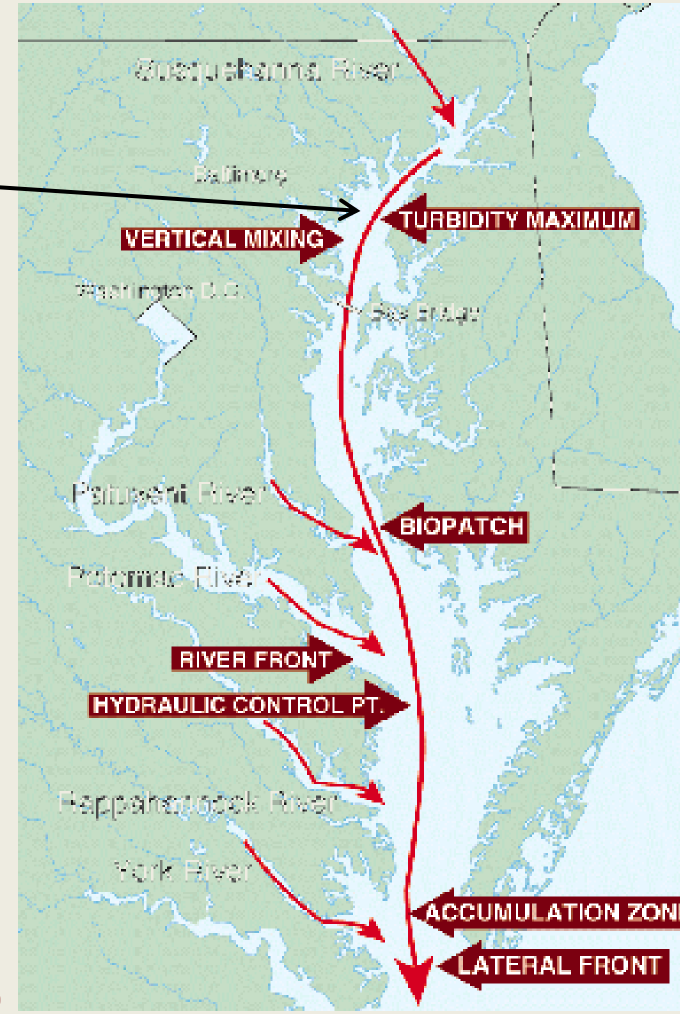


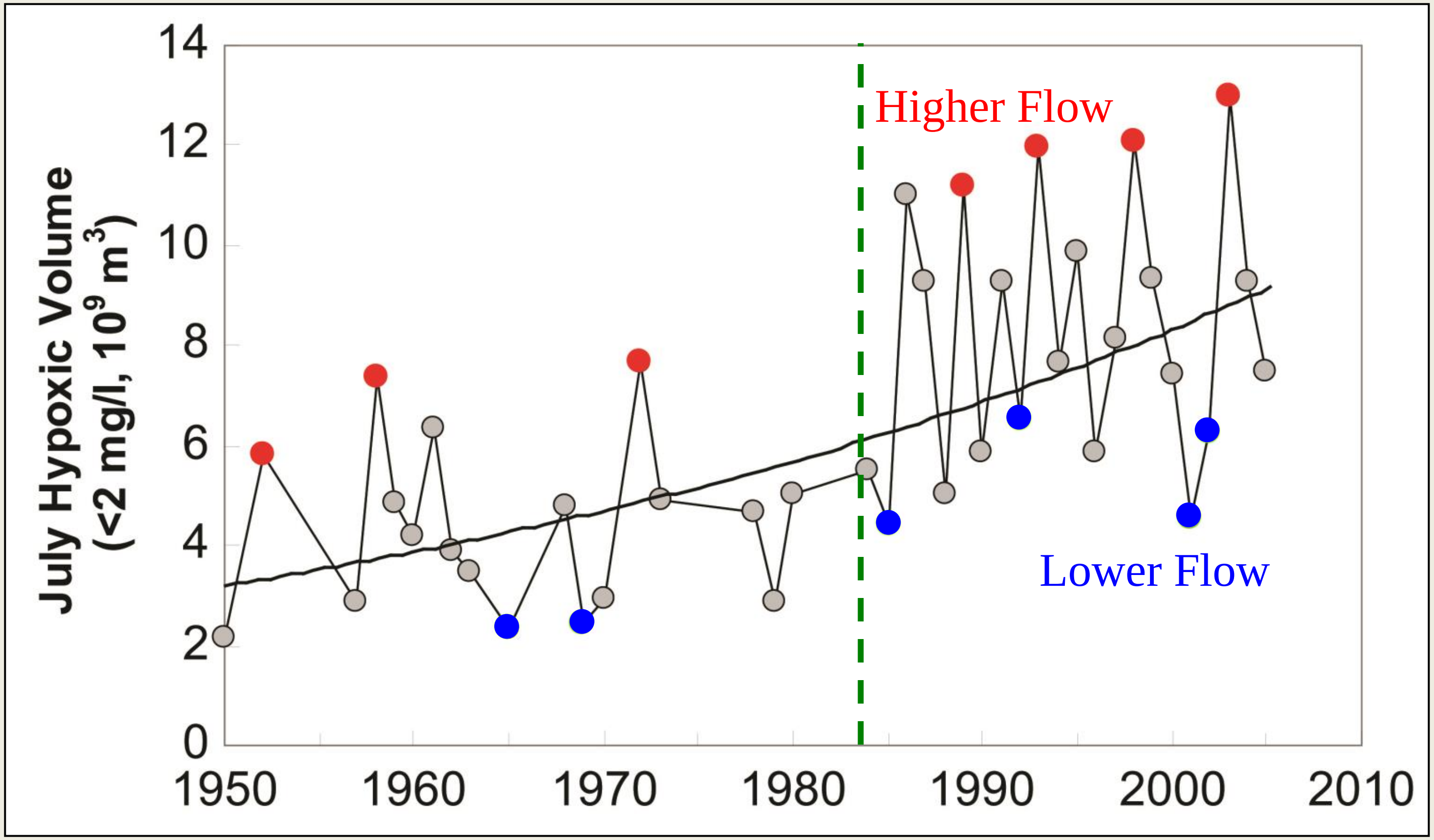
Figure courtesy M. Kemp; from J. Hagy 2002 Thesis, UMd)



(from CBP website)

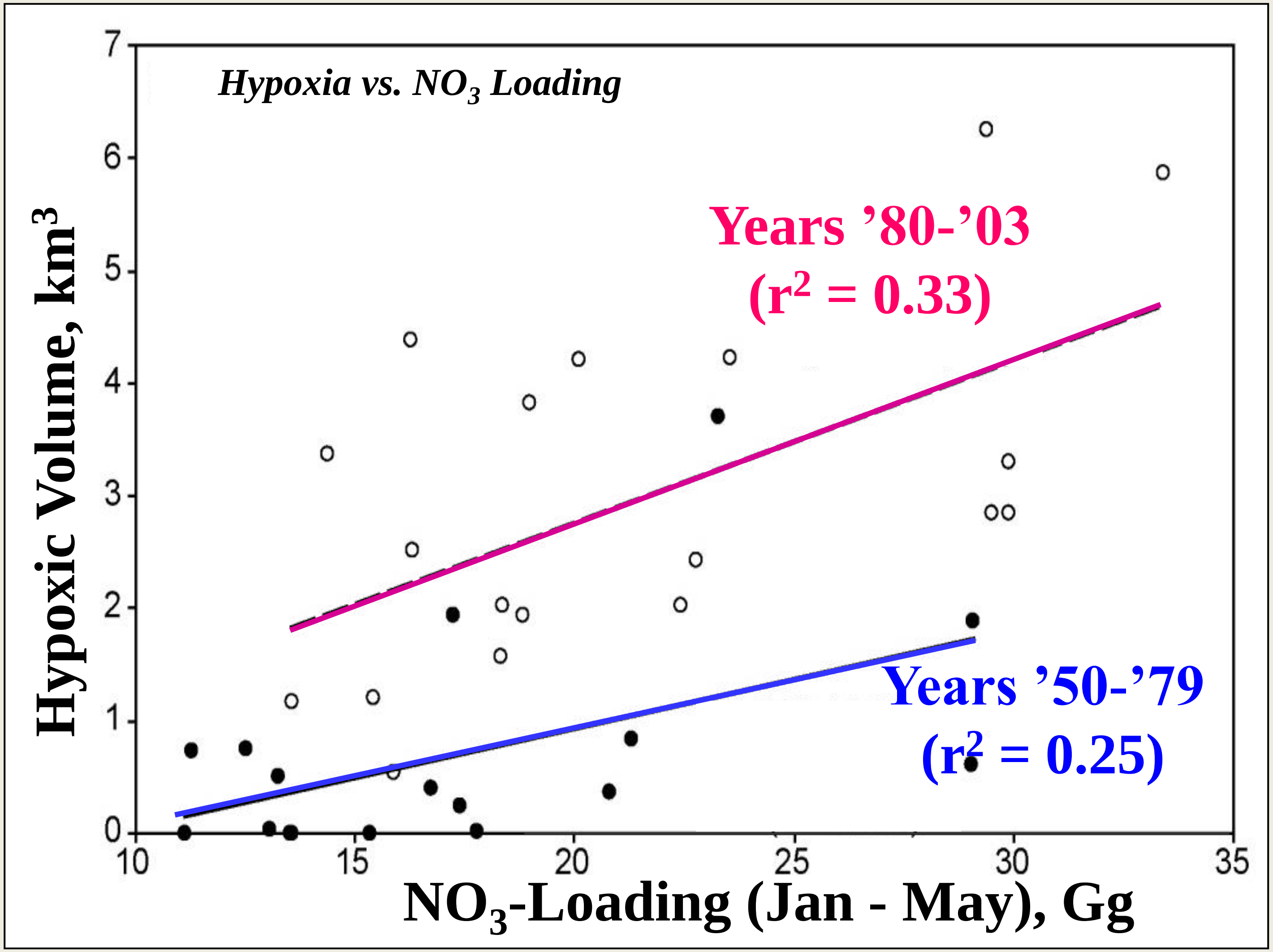
- Settling and decomposing phytoplankton deplete O_2 in deeper water
- Pycnocline controls position of low O_2 water.
- Landward transport replenishes deep O_2 pools (more so near mouth).

Trend in Chesapeake Bay Average July Hypoxic Volume



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

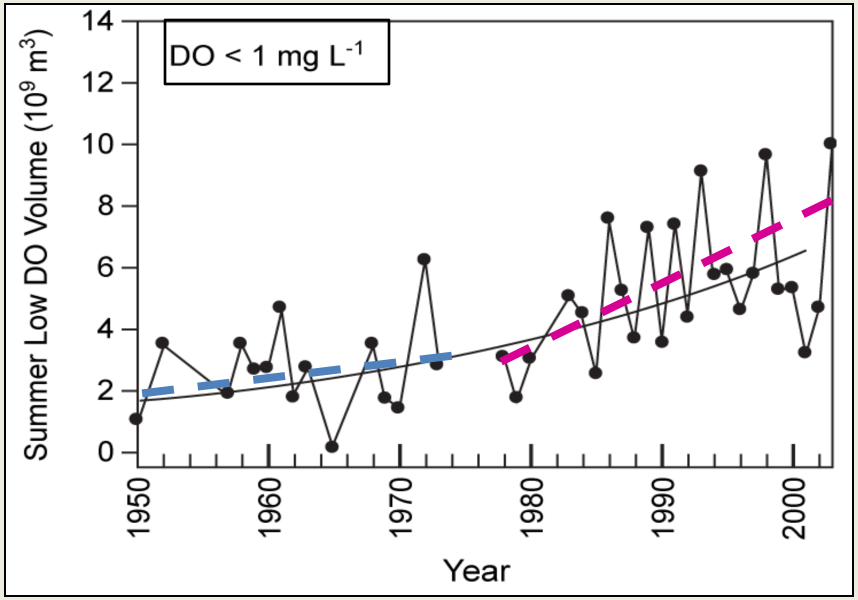
Trend in Chesapeake Bay Average July Hypoxic Volume



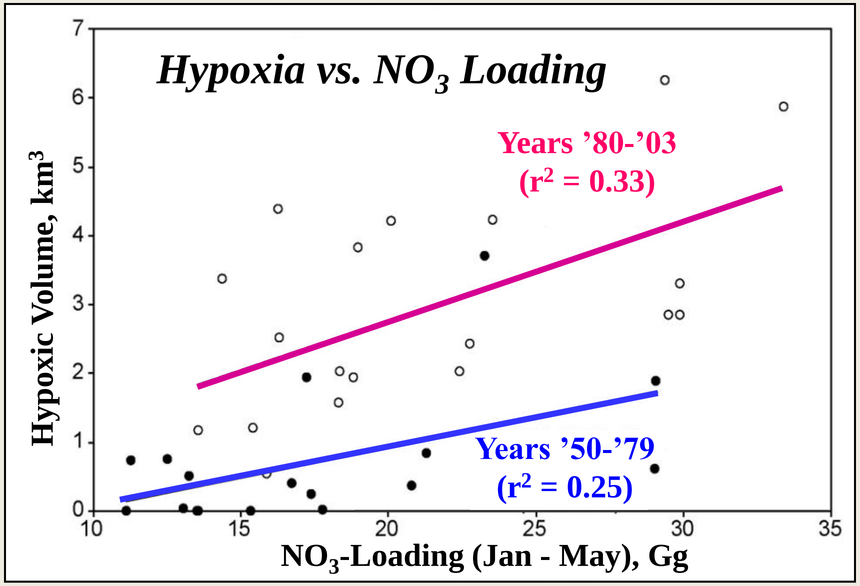
(Hagy et al. *Estuaries* 2004 ;
Kemp et al. *Marine Ecology Progress Series*. 2005)

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

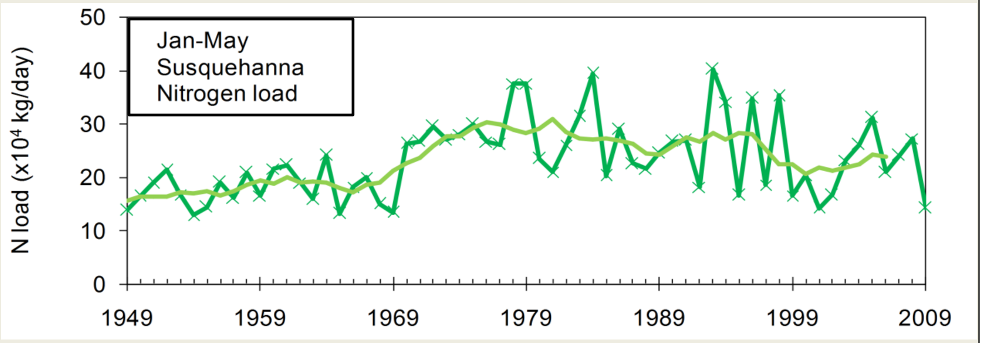
- **Increase in slope of hypoxia-nitrate relation for 1980-2003 relative to 1950-1979**
- **1980-2009 : Average July hypoxia rising despite level or decreasing nitrate loading. Why?**
-



(Hagy et al. *Estuaries* 2004)

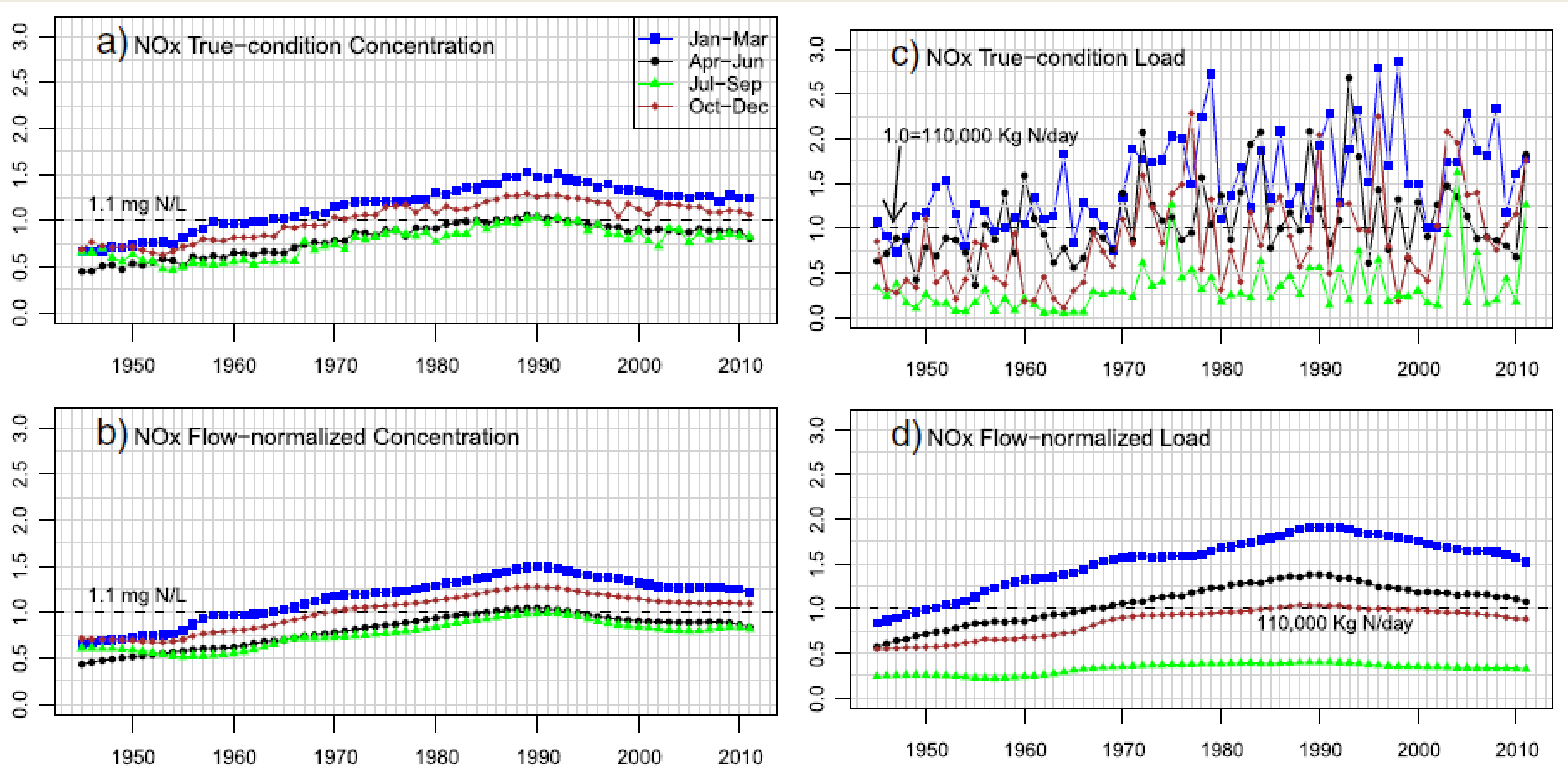


(Hagy et al. *Estuaries* 2004 ;
Kemp et al. *Marine Ecology Progress Series*. 2005)



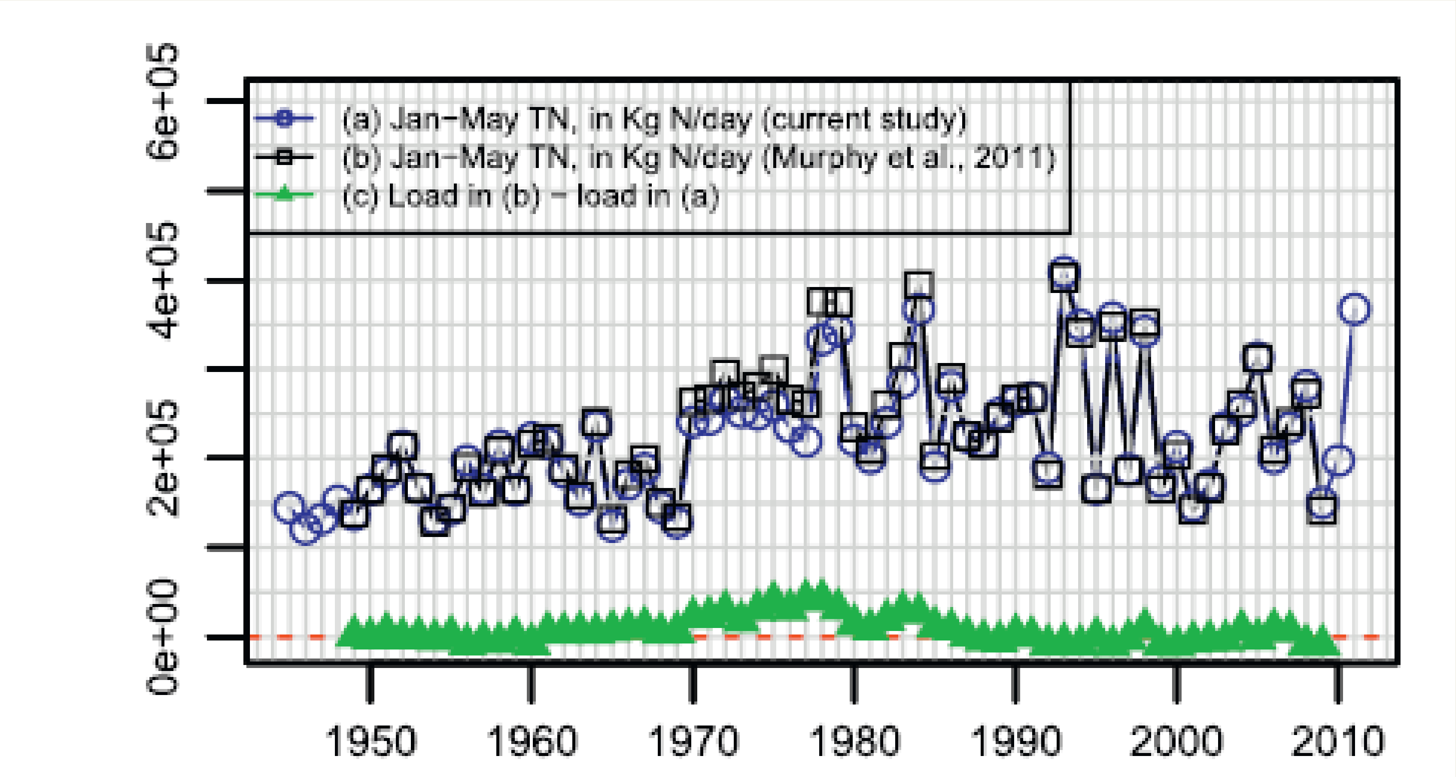
(Murphy et al. *Estuaries and Coasts* 2010)

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

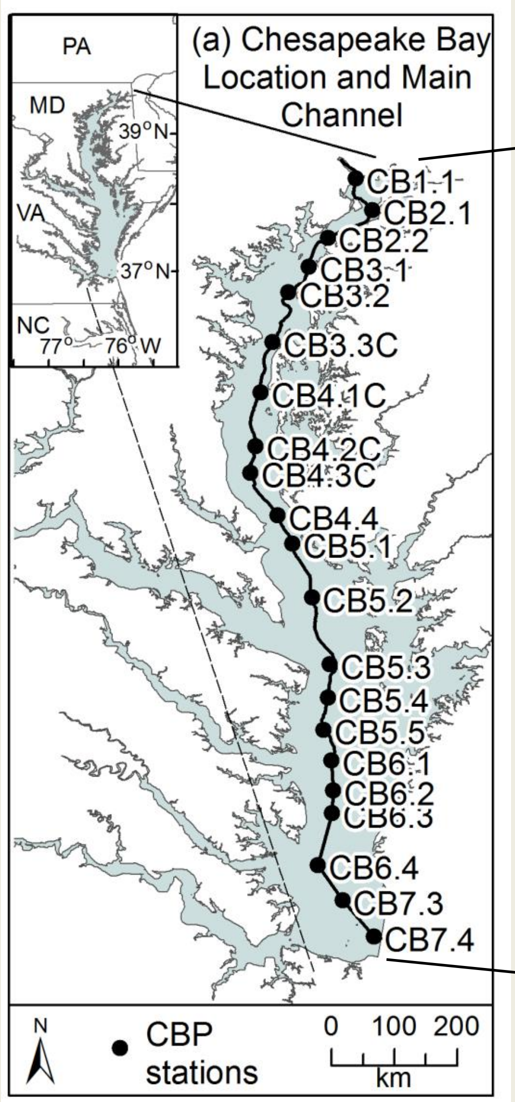
(Rebecca Murphy Ph.D. Dissertation, 2010)

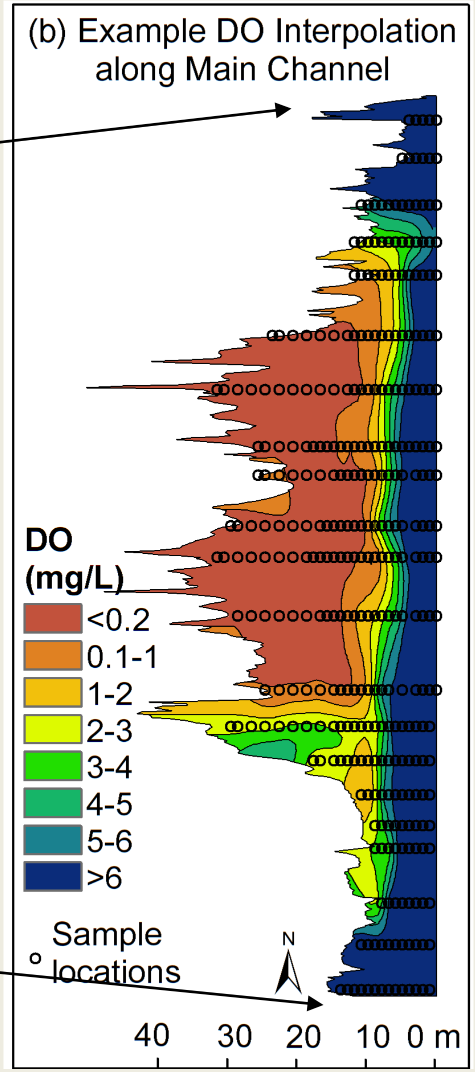
1. Identify DO data collected by CBP (1984-2010) and CBI (1949-1980)

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

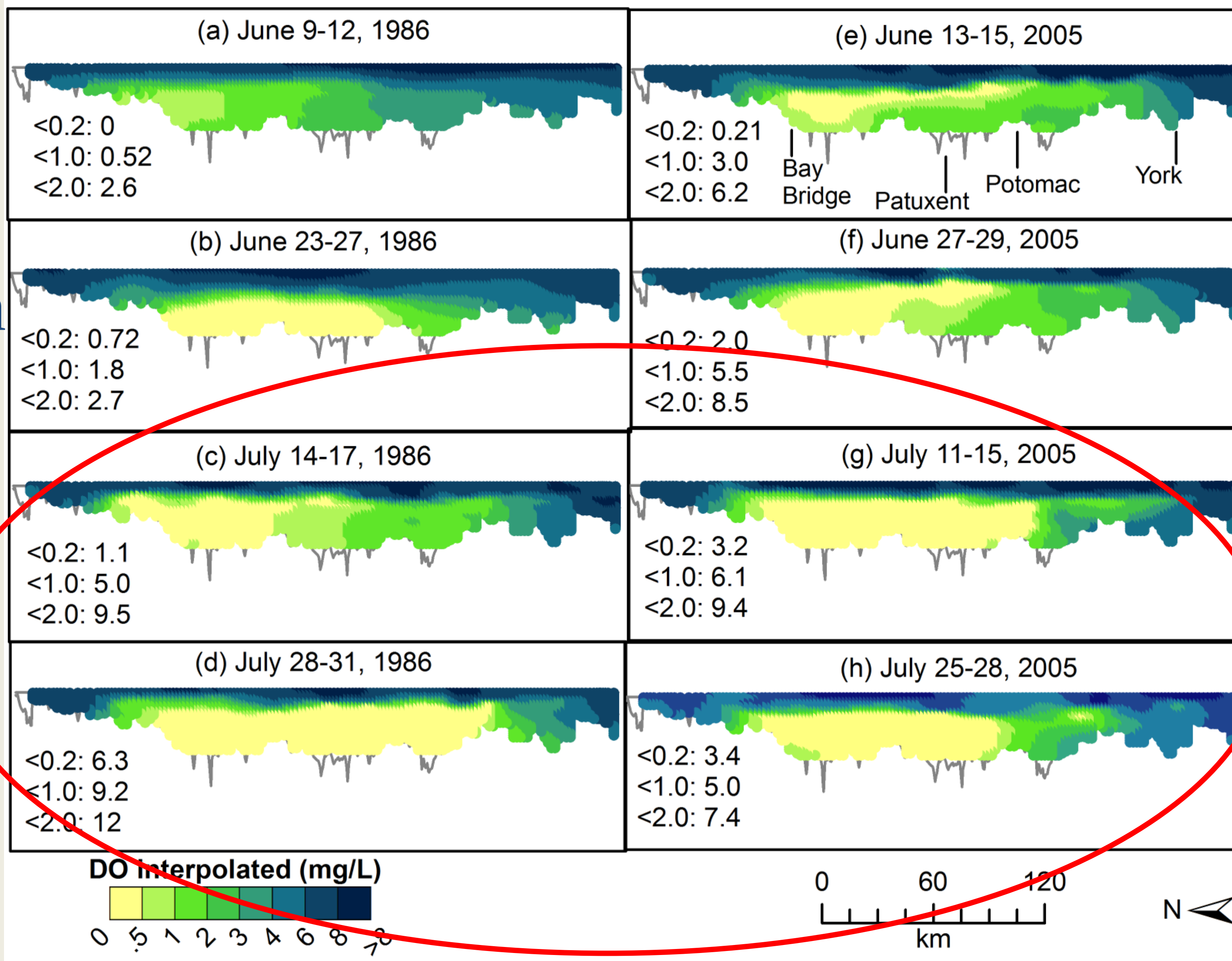
4. Used tabulated cross section volumes (Cronin and Pritchard 1975) calculate volume of water below cutoffs





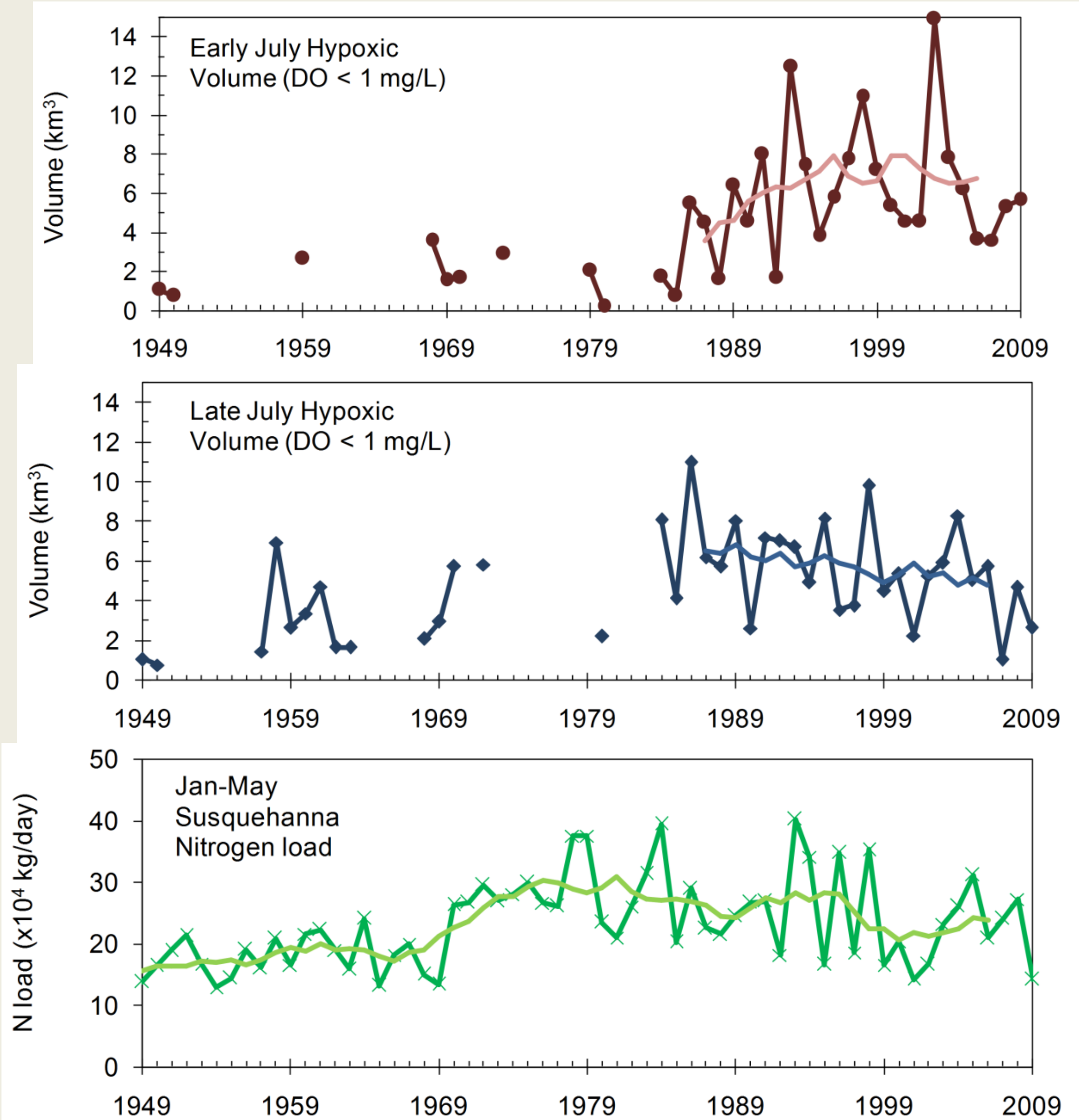
Early July 2005

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.

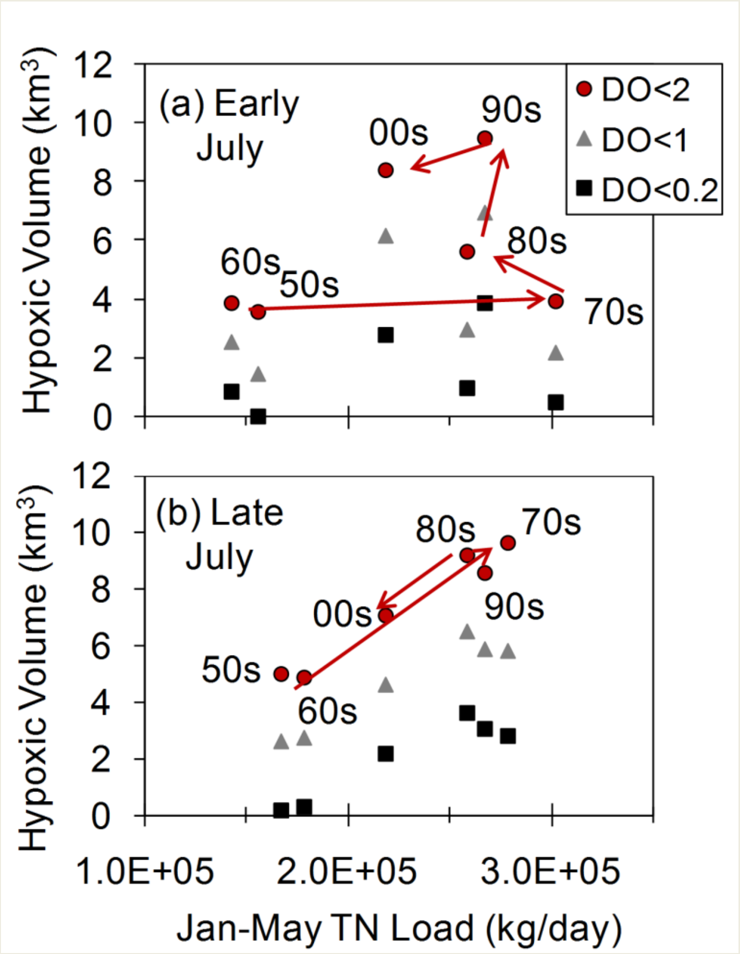
Early- and late-July hypoxic volumes



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

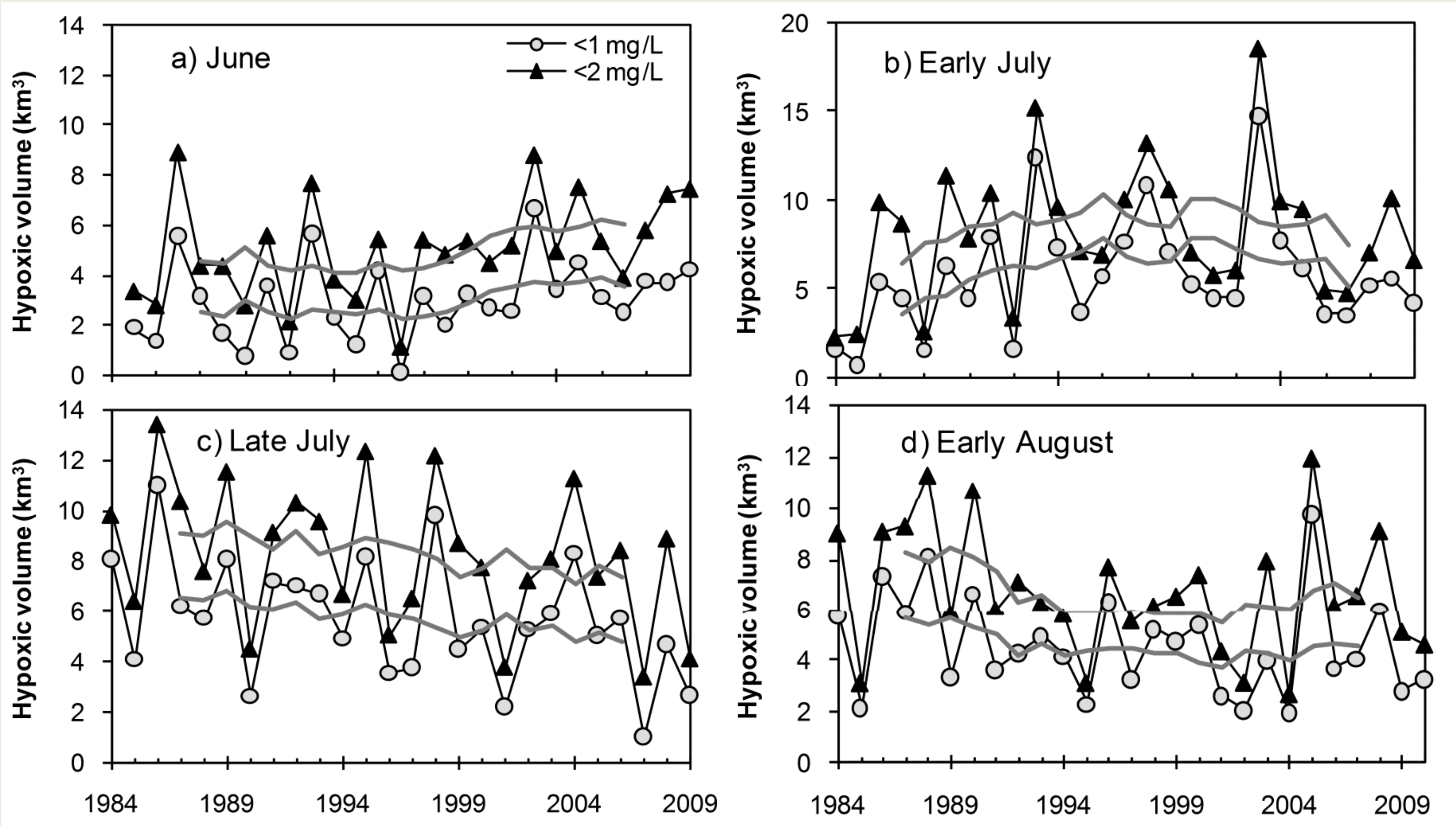
(Murphy et al., *Estuaries and Coasts*, 2011)

Decadal Shifts in Hypoxic Volume vs. TN Load



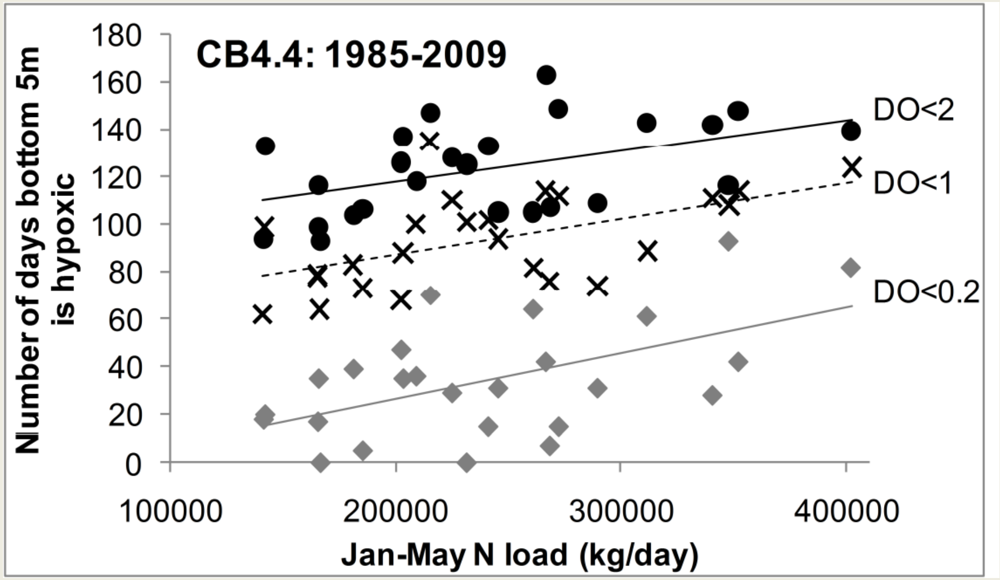
(Murphy et al. *Estuaries and Coasts* 2011).

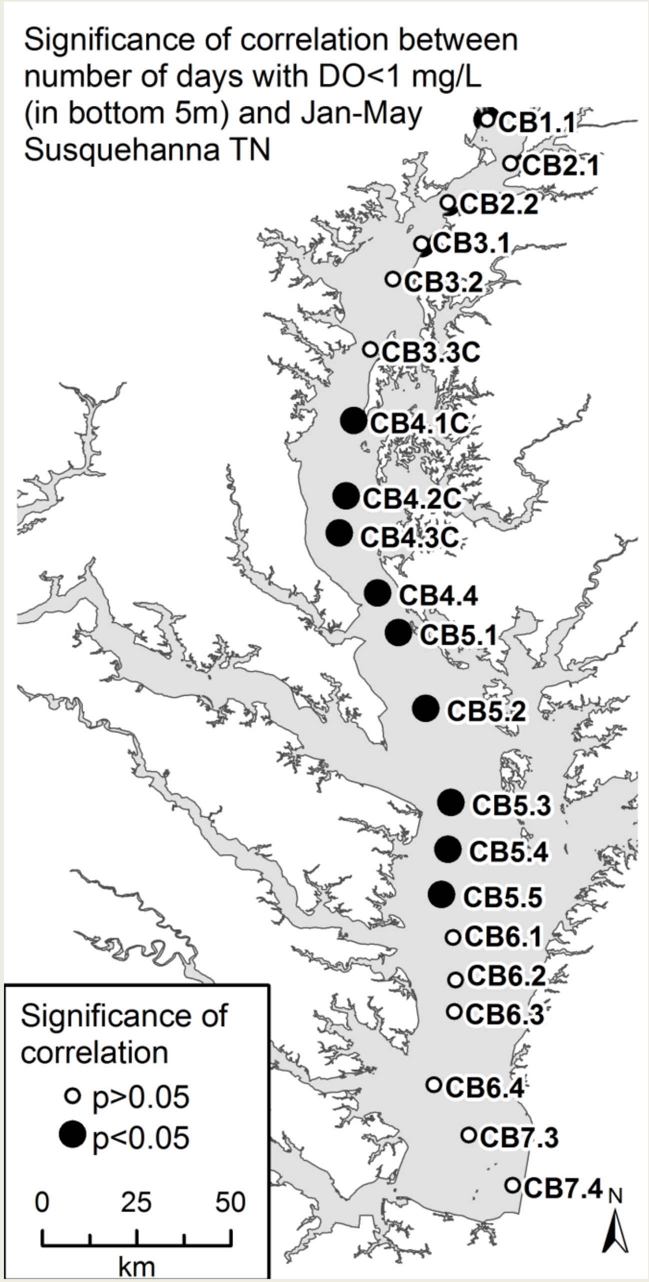
1984-2010 Early- vs. Late-Summer



Hypoxia Duration

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





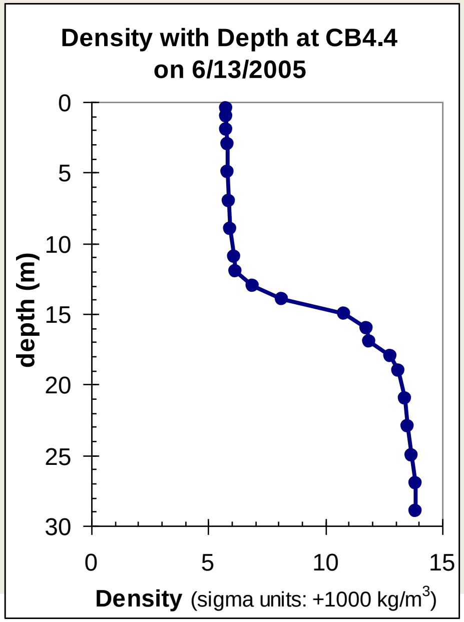
Hypoxia in Chesapeake Bay

- **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

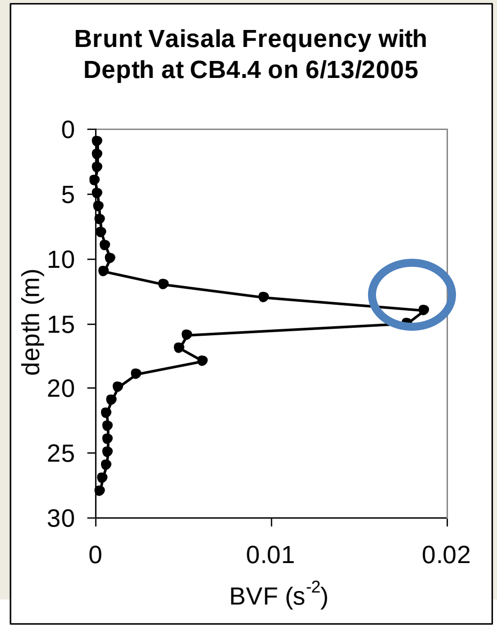
  - Artifact? Shift in how observational metrics relate to reality?
  - Chemical mechanisms? Decadal-scale shifts in limiting nutrient?
  - Biological mechanisms? Enhanced benthic nutrient recycling?
  - Physical mechanisms? Long-term shifts in stratification?
- **Conclusions and Implications**
- **Future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

Calculation of Stratification Strength

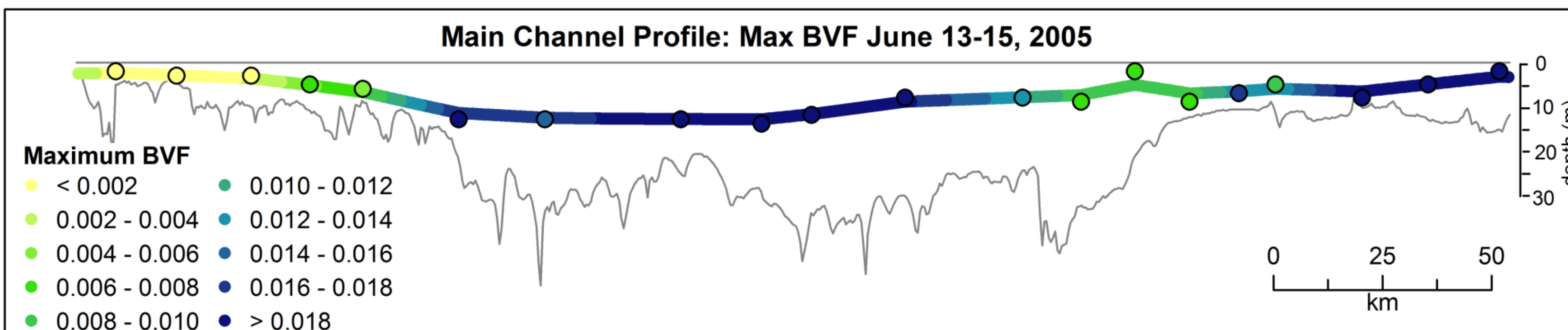


1. Calculate Brunt Väisälä Frequency

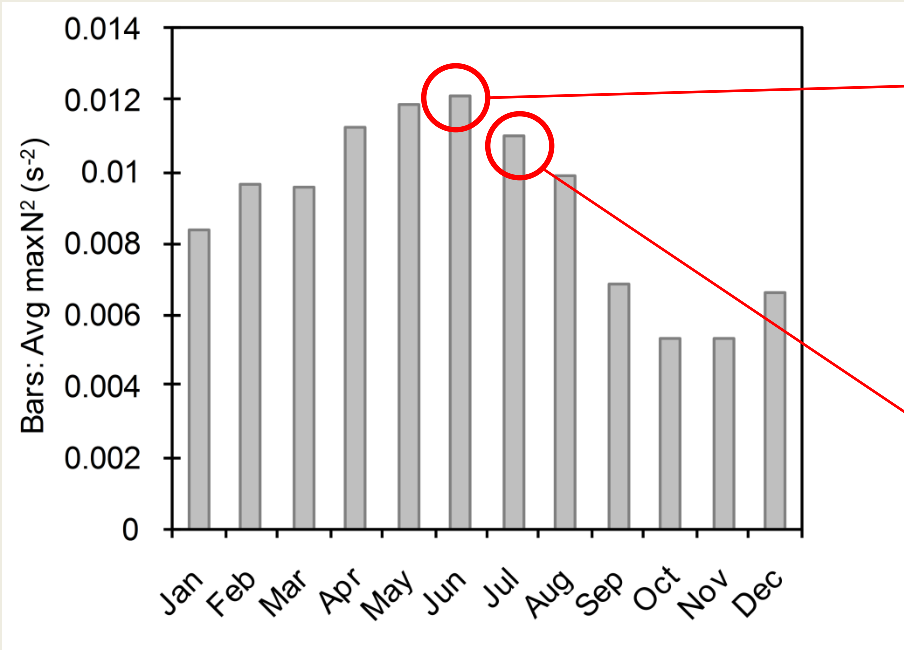
$$BVF = \frac{g}{\rho}\frac{\partial \rho}{\partial z}$$

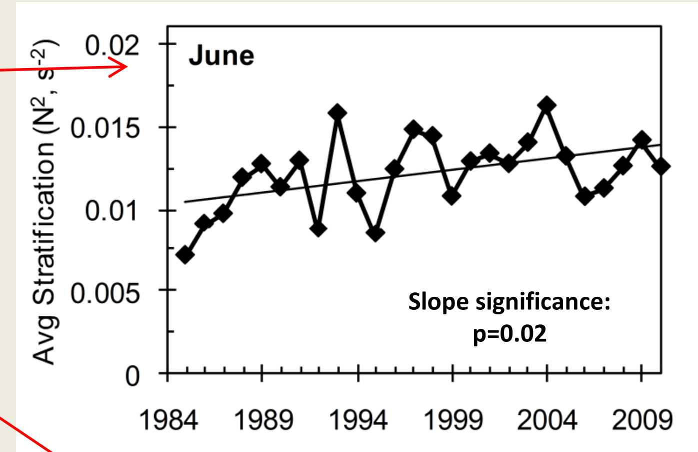


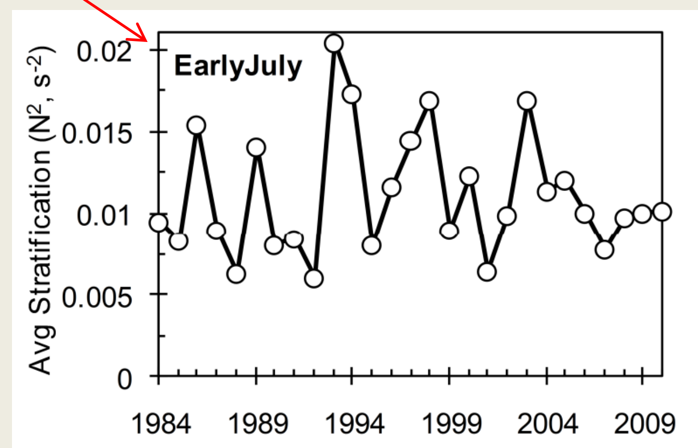
2. Interpolate maximum Brunt Väisälä Frequency (BVF)



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

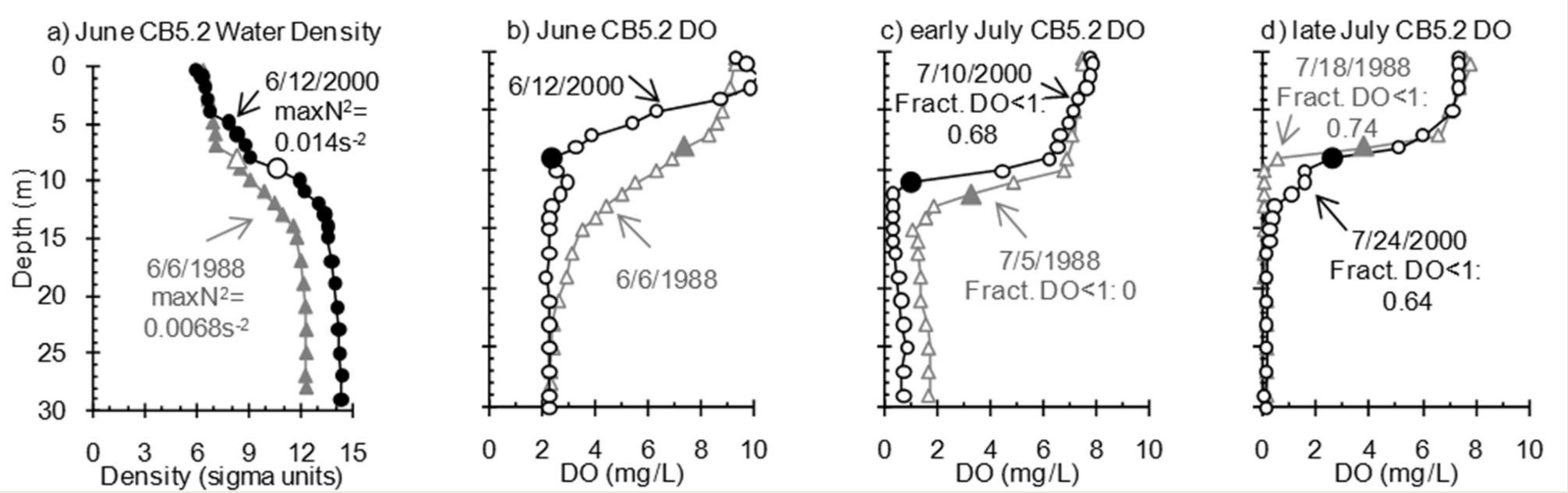
(Munk and Anderson 1948)

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

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

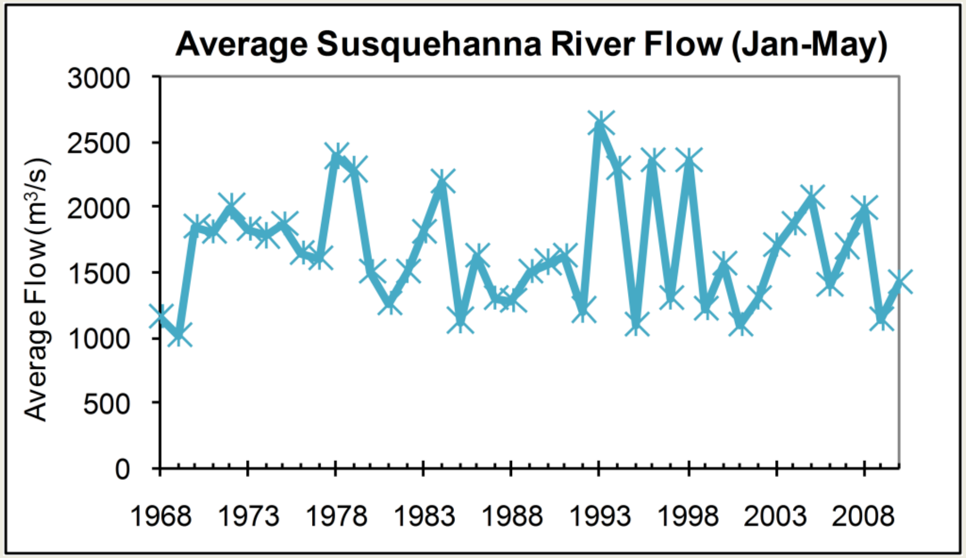
a,b = coefficients

Stratification: Effect on hypoxia



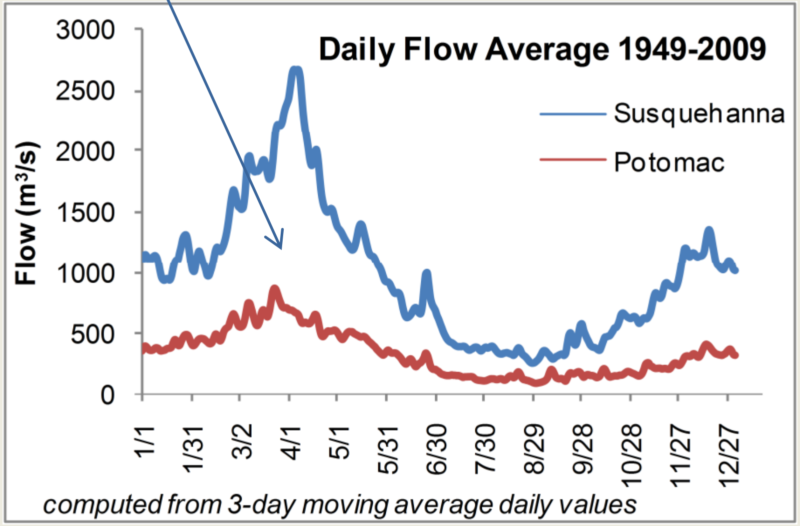
But *why* has June stratification increased?

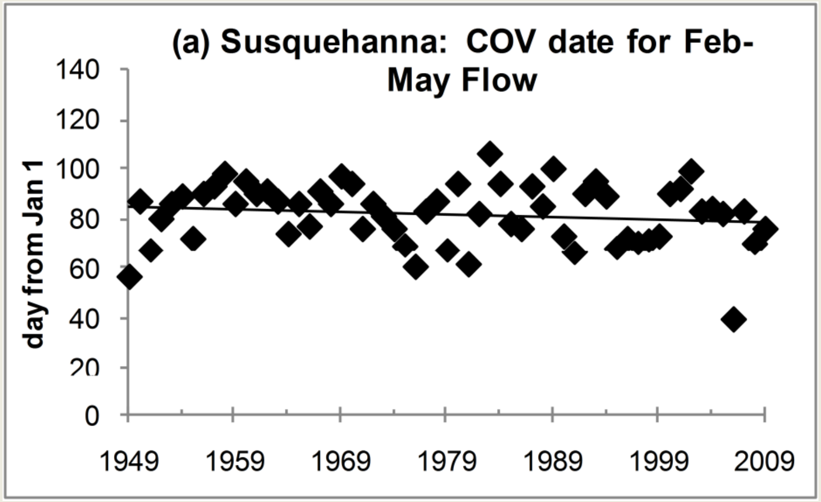
- Increase in average spring flow? *[no]*



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

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

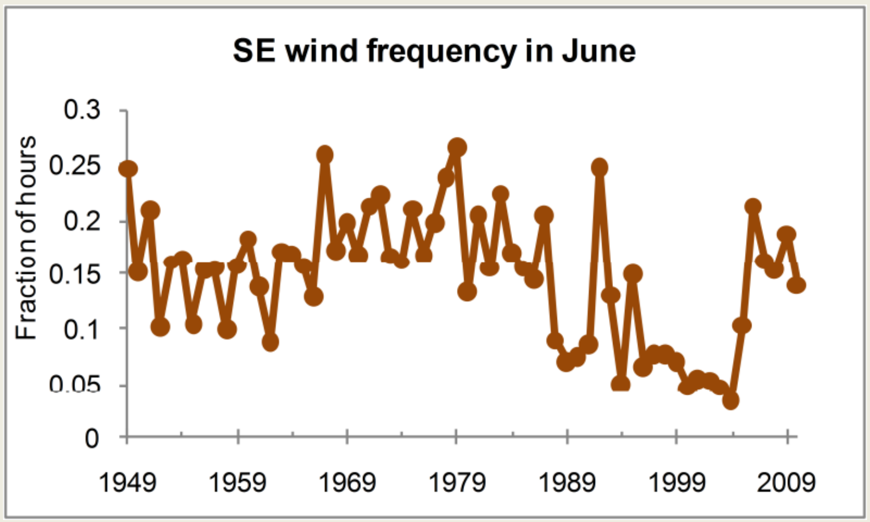




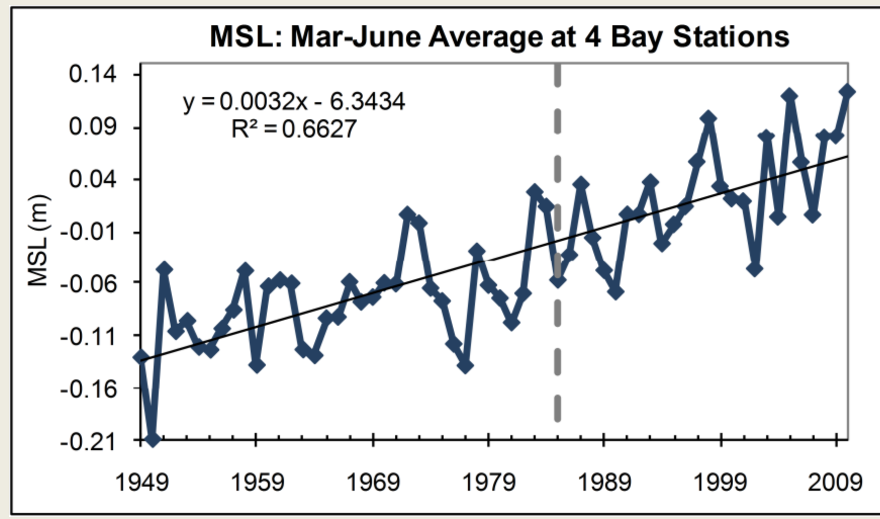
COV=center of volume

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]*

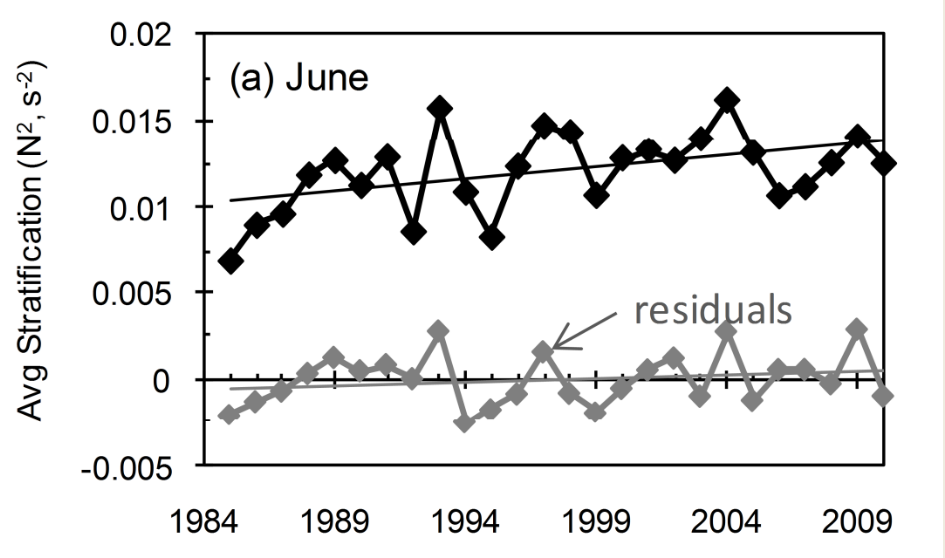


Wind effects
(NOAA data ; figure from R. Murphy [unpublished] based on shift identified by M.E. Scully (*Estuaries and Coasts*, 2010)



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, β_0	River flow dependence (Feb-May), β_1	SE wind[a] dependence (Jun), β_2	MSL[b] dependence (Jul-Jun), β_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.**

Hypoxia in Chesapeake Bay

- **Motivation**: The CBEO "science question": Why has the relationship between Chesapeake Bay hypoxia and nutrient loadings "shifted" in recent decades?
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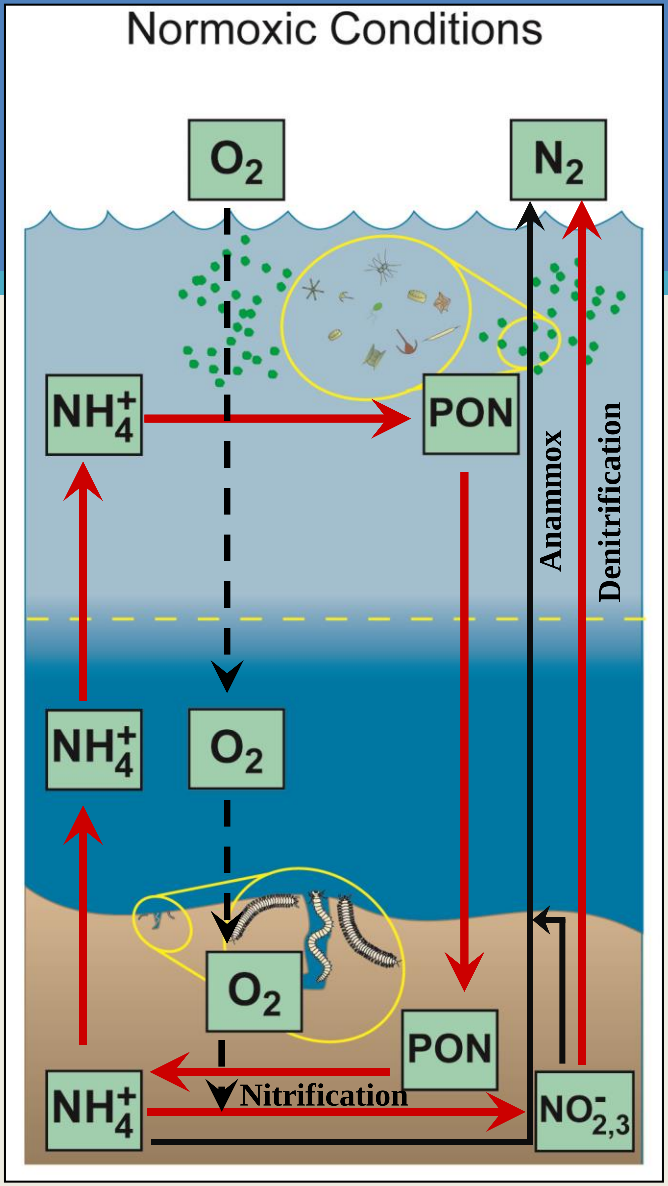
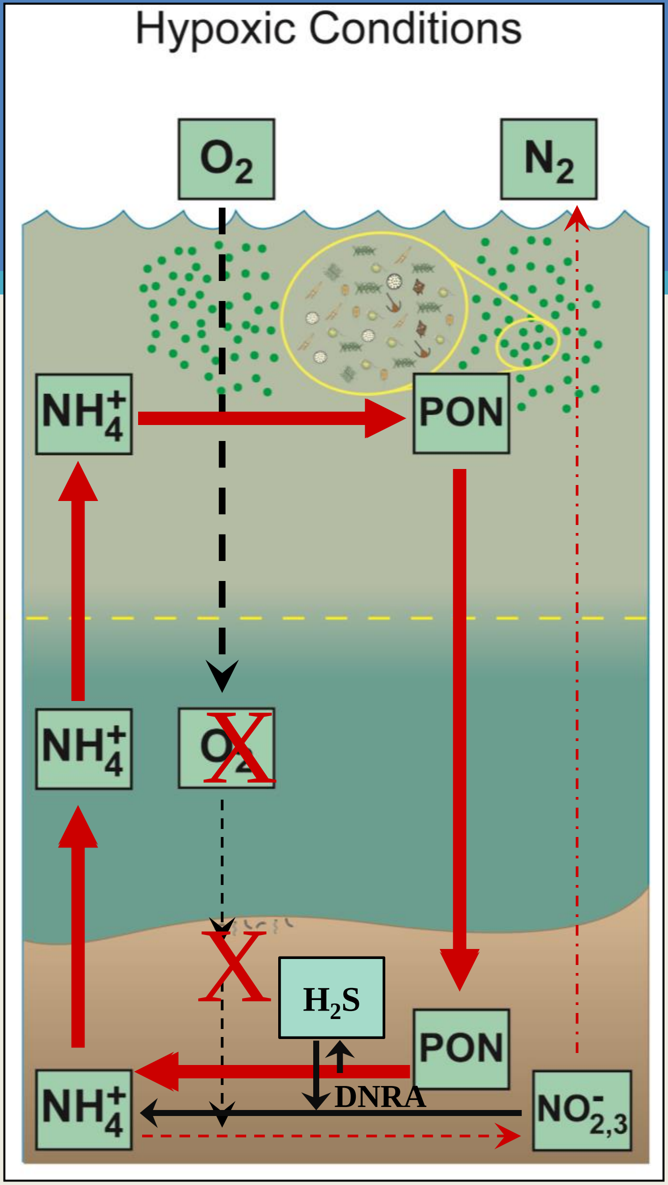
Conceptual Model of O_2 Interactions with N-Cycle

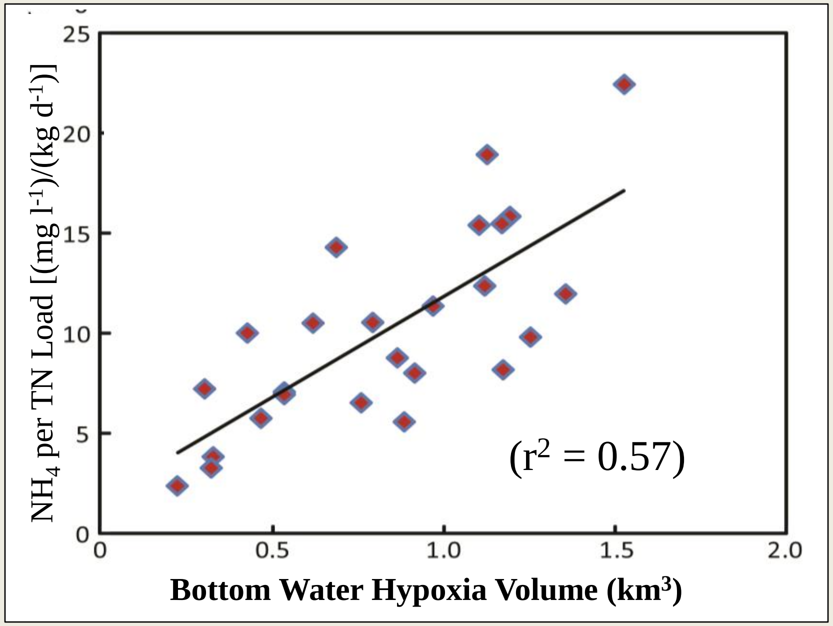




(J.Testa 2011, unpublished)

Biological Mechanism:
Redox-Induced Increase in Nutrient Recycling Efficiency

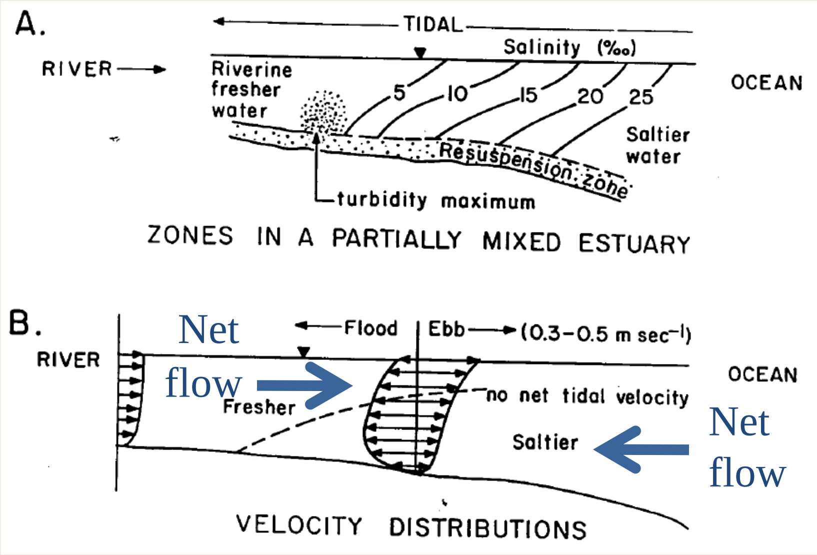
Bottom water NH_4 pool per unit TN Load
[mg/L NH_4 per average spring TN loading [kg/day]



(Testa et al., 2012)

- Hypoxia affects nutrient fluxes from the sediment through mechanisms of enhanced recycling of sediment N.
- Observations confirm that "Nutrient Pool per TN Load" has indeed increased during times of greater hypoxia
- This positive feedback <u>reinforces</u> (<u>but does not cause</u>) the observed "shift" in hypoxic response
    - No decadal shift in mechanism
    - Cannot explain lack of response to drop in N loading

Stratification Control of Vertical Location of Hypoxia



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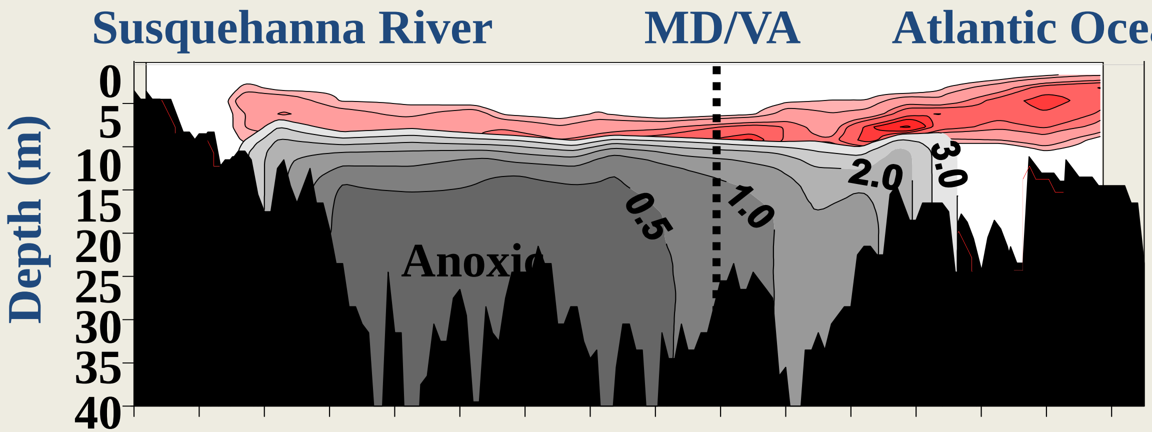
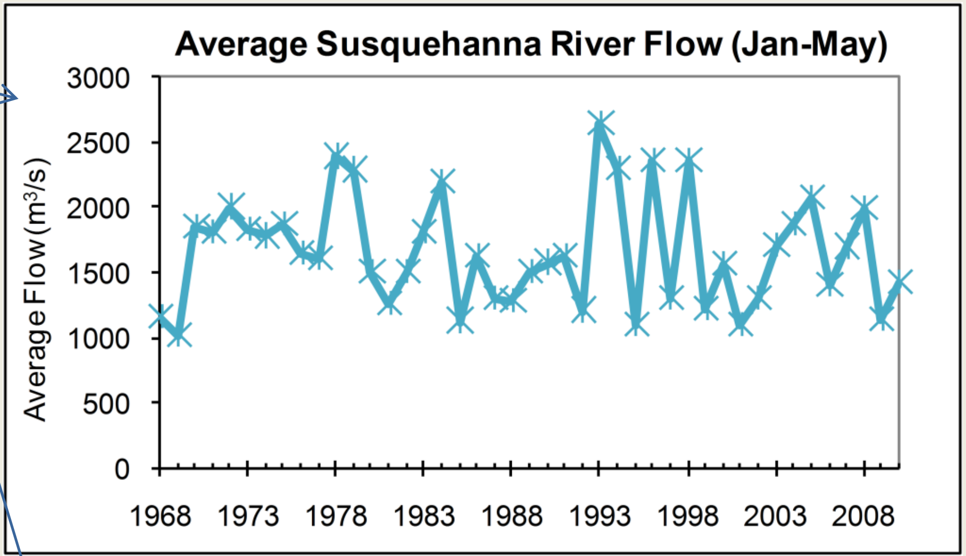


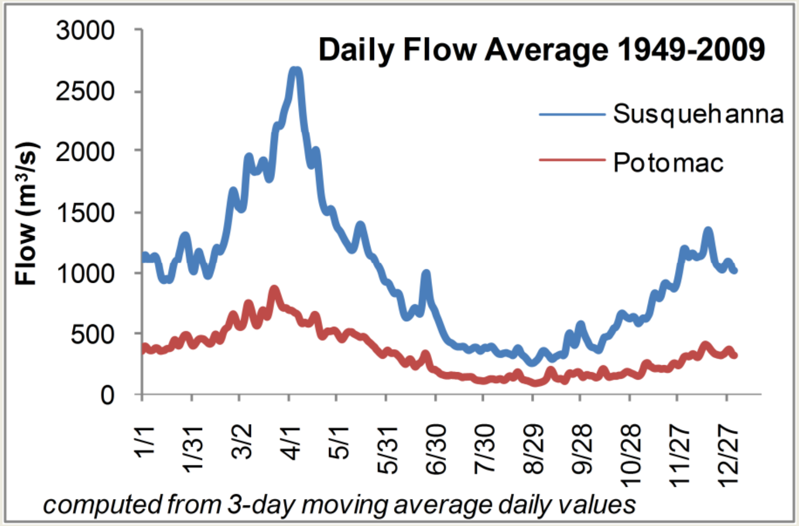
Figure courtesy M. Kemp; from J. Hagy 2002 Thesis, UMd)

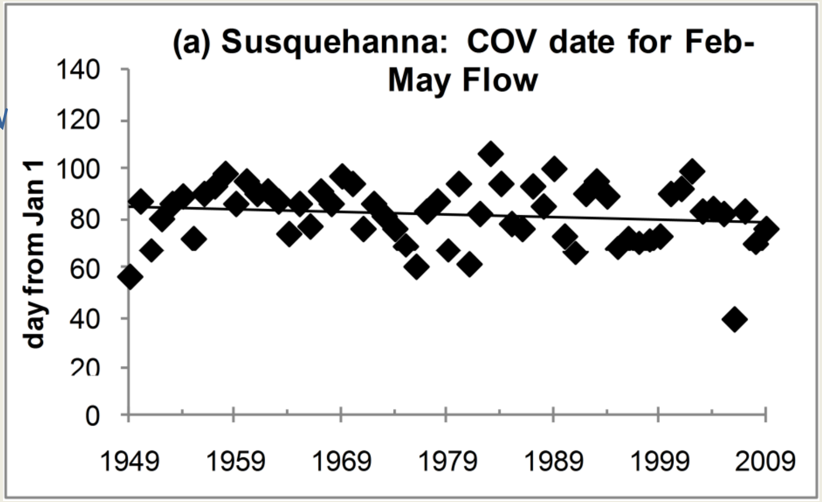
Salinity/temp -controlled pycnocline controls position and extent of low O_2 water.

Stratification-related hypotheses investigated

- Increase in average spring flow *[no]*
- Shift in timing of spring flow *[no]*
- Increase in water temperature
- Shift in predominant wind direction
- Sea level rise effects via increase in salinity

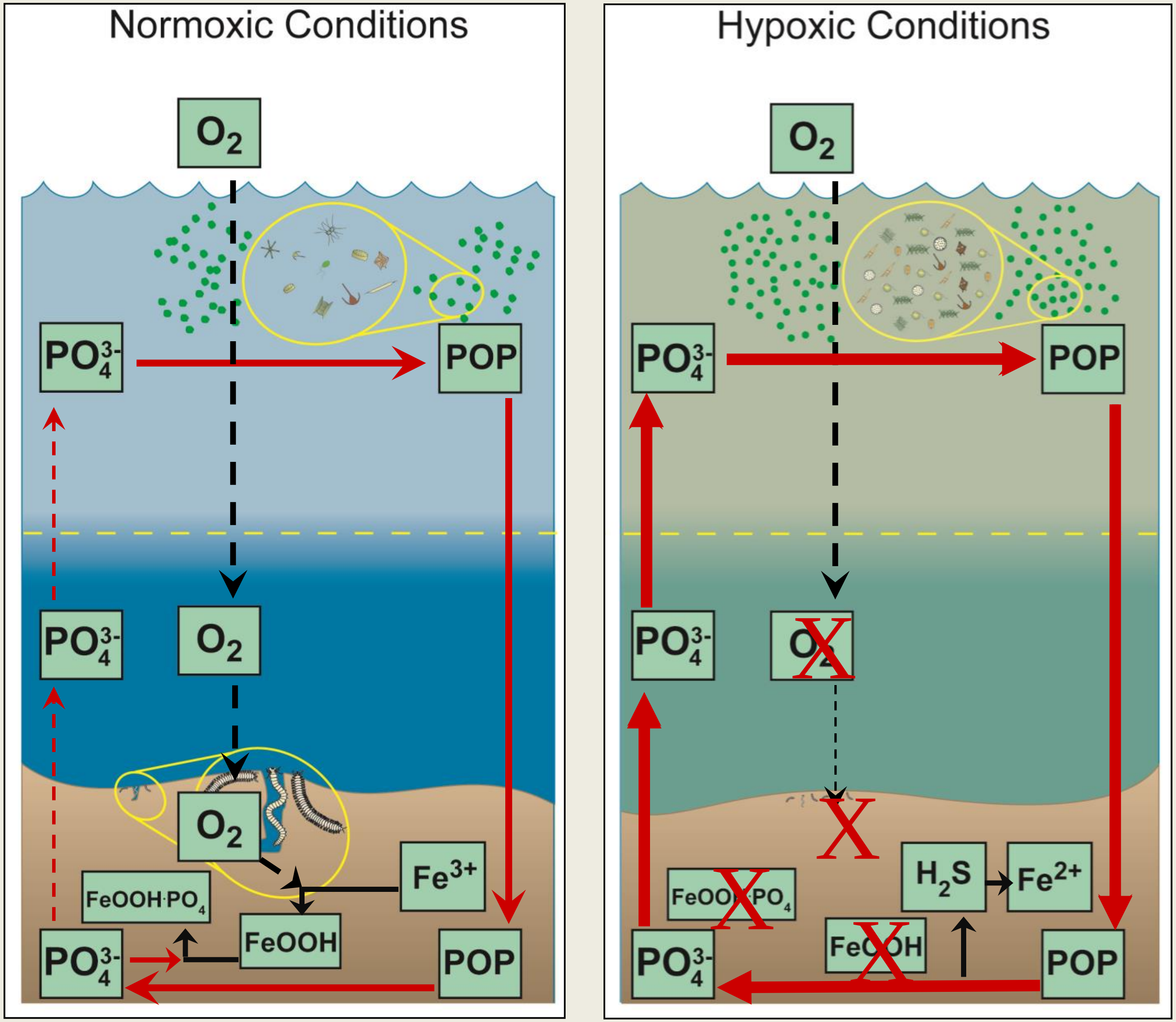






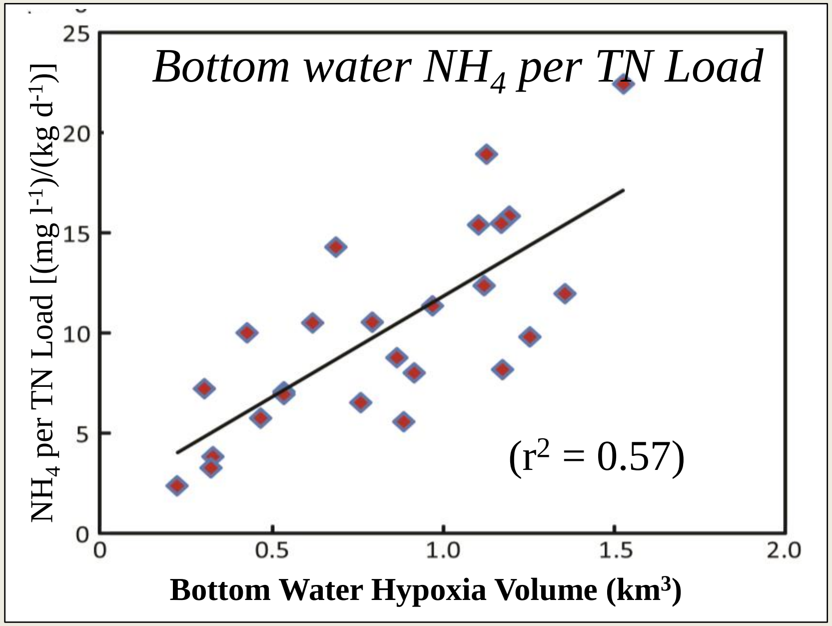
COV=center of volume

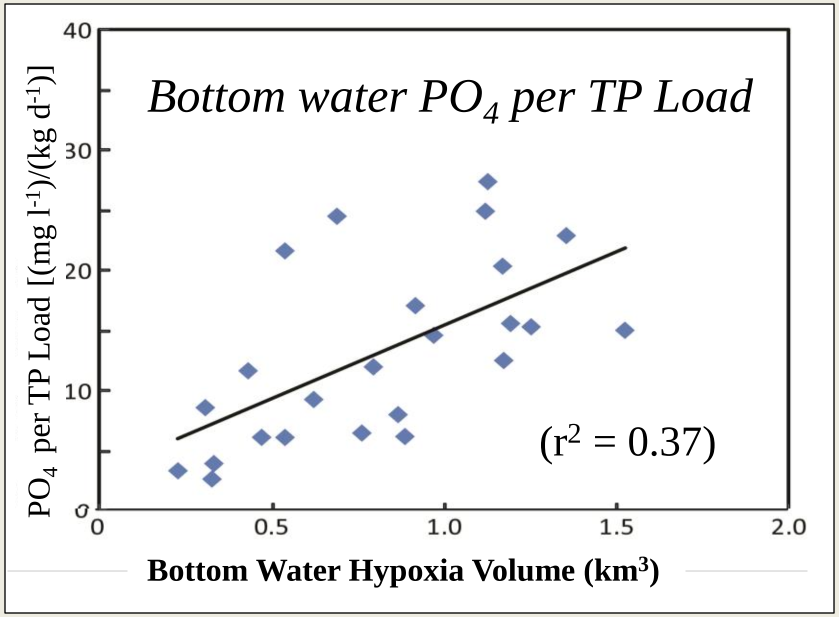
Conceptual Model of O_2 Interactions with P-Cycle



(J.Testa 2011, unpublished)

Nutrient Pools per Load vs. Hypoxic Volume





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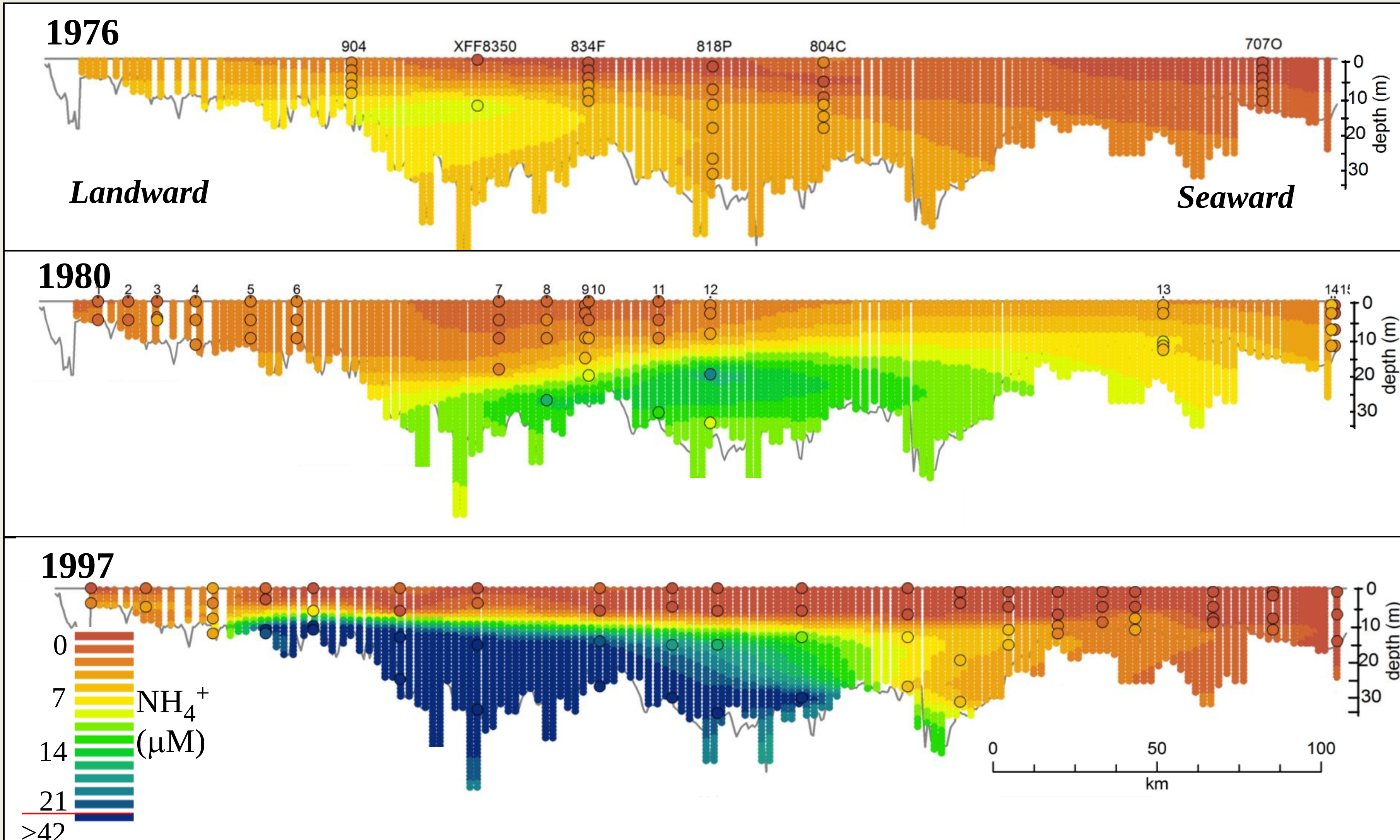
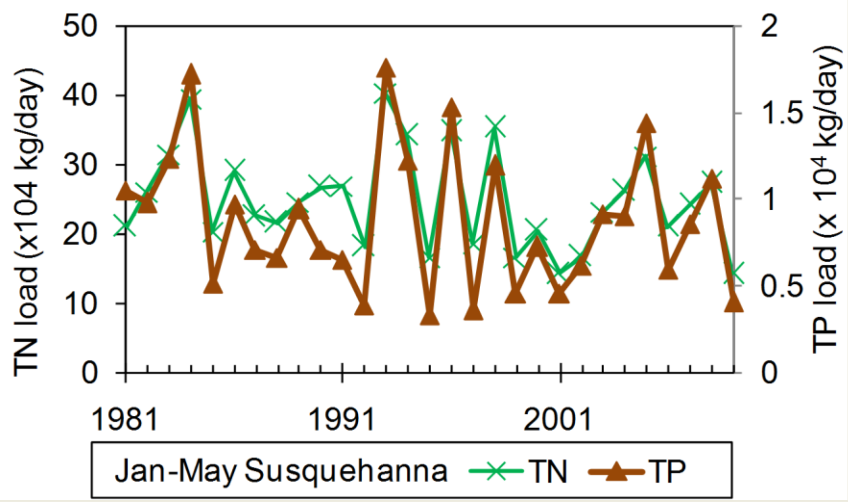
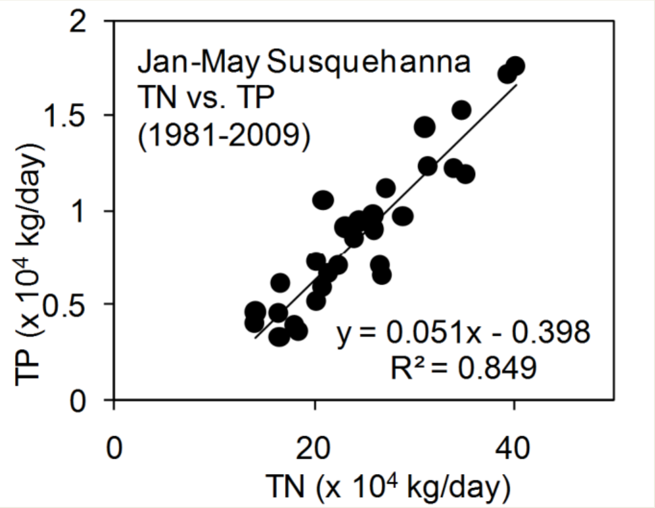
Decadal Change in Bay July [NH4+] Distribution



(Rebecca Murphy, JHU. unpublished)

Could a change in phosphorus load be the cause of the shift?





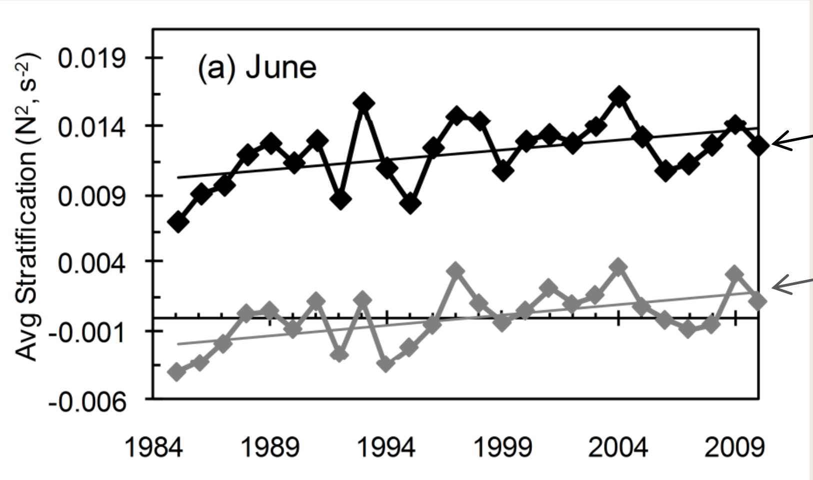
Probably not:

- TP follows the same long-term trend as TN for the years with data
- Most imporantly:
  TN has been well demonstrated to be the limiting nutrient for phytoplankton growth during the summer in mid-Bay

(Fisher et al., *Marine Biology* 1999)

Findings: Stratification trends

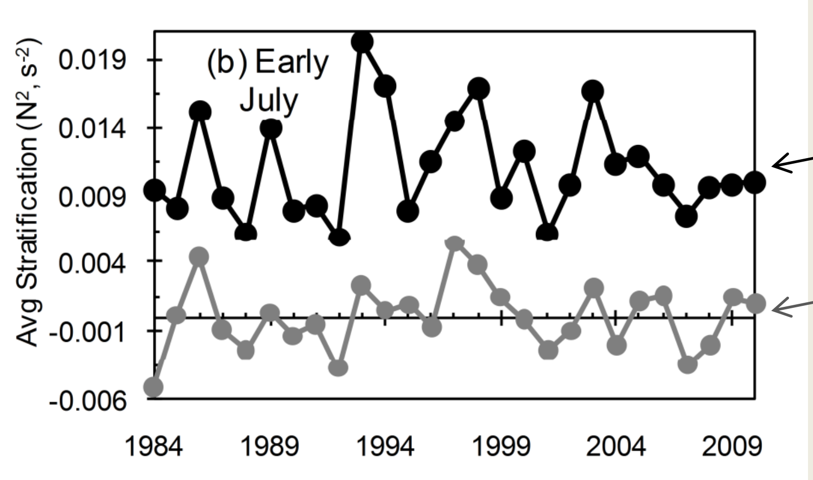
- June stratification increase
  - Increase becomes even more significant after accounting for flow effects
- Rest of summer – no increase



Trends with year:

stratification p=0.02

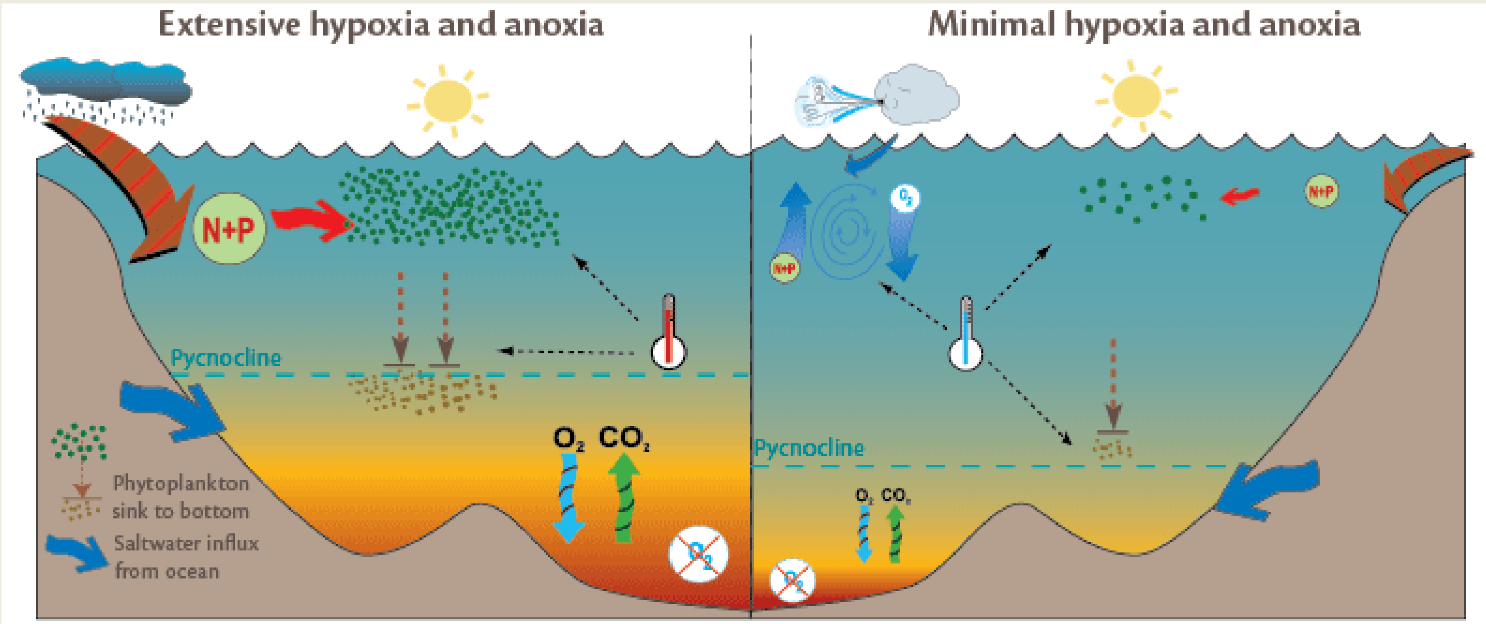
residuals from flow regression p=0.004



stratification

residuals from flow regression

Nutrient Enrichment Effects on Coastal Ecosystems

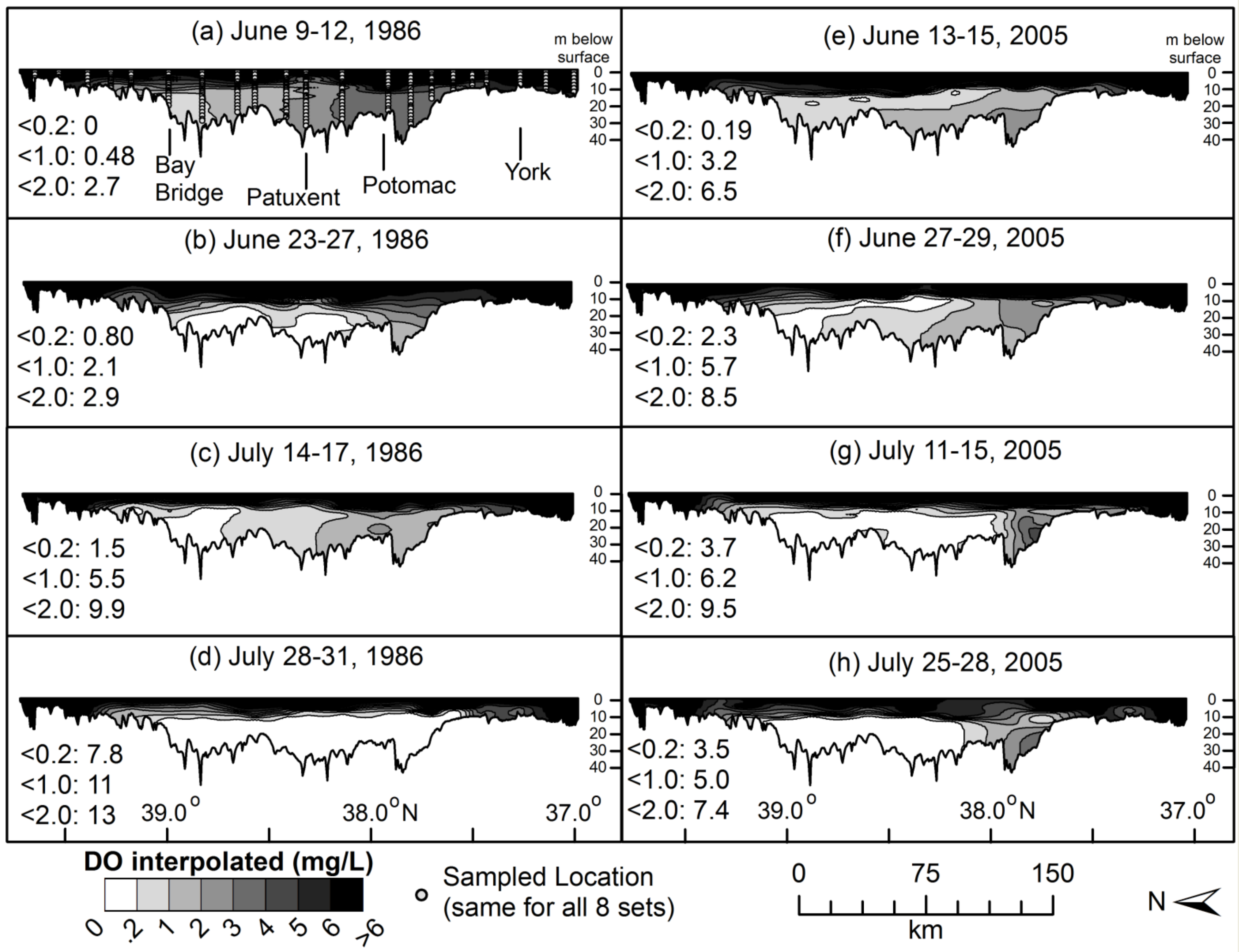


	Loads	Phytoplankton	Decomposition	Temperature	Wind event
Large amount of low dissolved oxygen	Large nitrogen and phosphorus loads	Elevated nutrients cause large phytoplankton blooms	High oxygen consumption by decaying phytoplankton	Warm water a) Stimulates decomposition b) Stratifies water column c) 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

Conceptual diagram detailing the factors that determine the dissolved oxygen content of the tidal waters of Chesapeake Bay

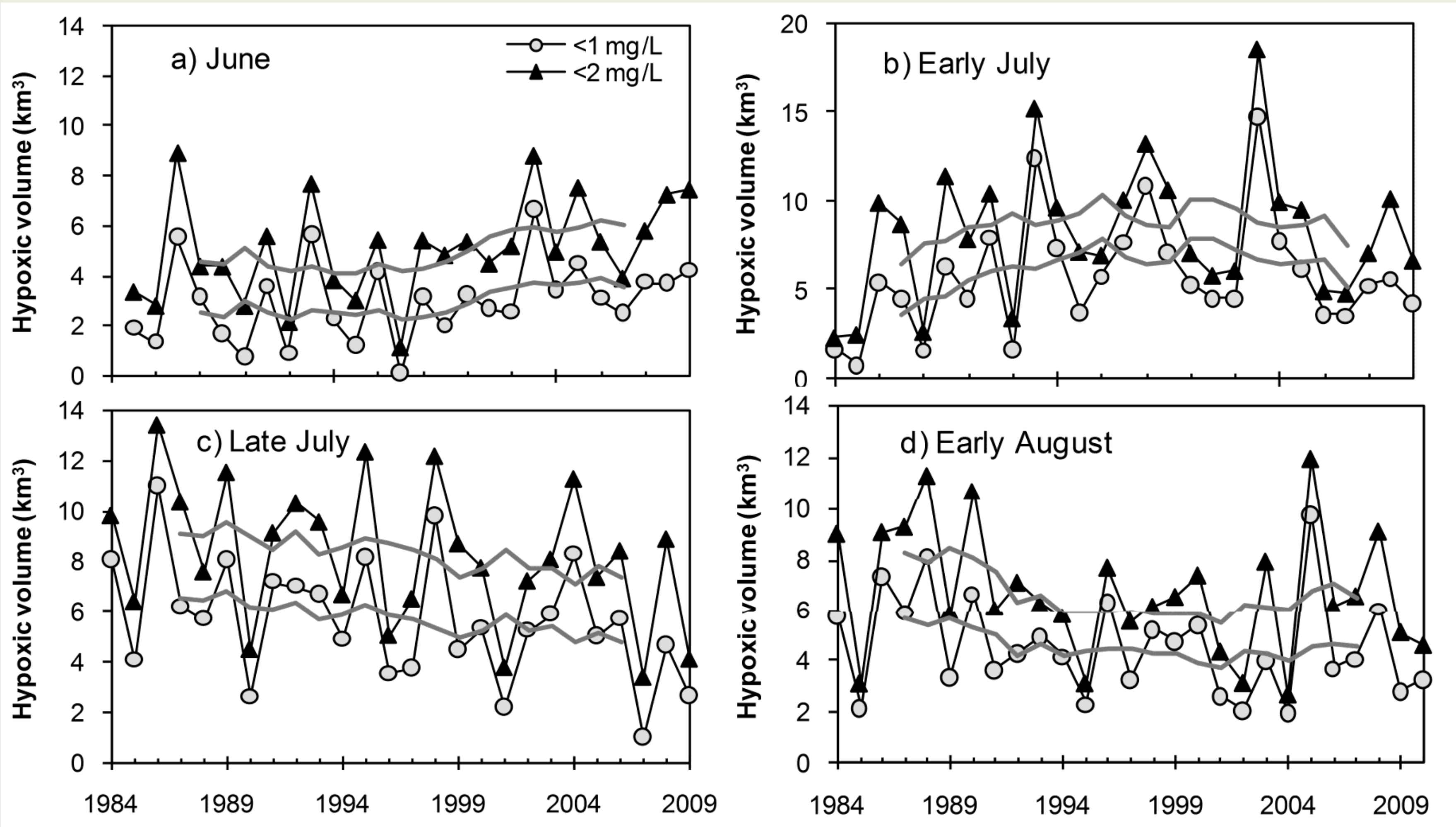
From: Chesapeake Ecocheck (NOAA, UMCES)
http://www.eco-check.org/forecast/chesapeake/2009/indicators/anoxia/#_Methodology

Main channel DO examples



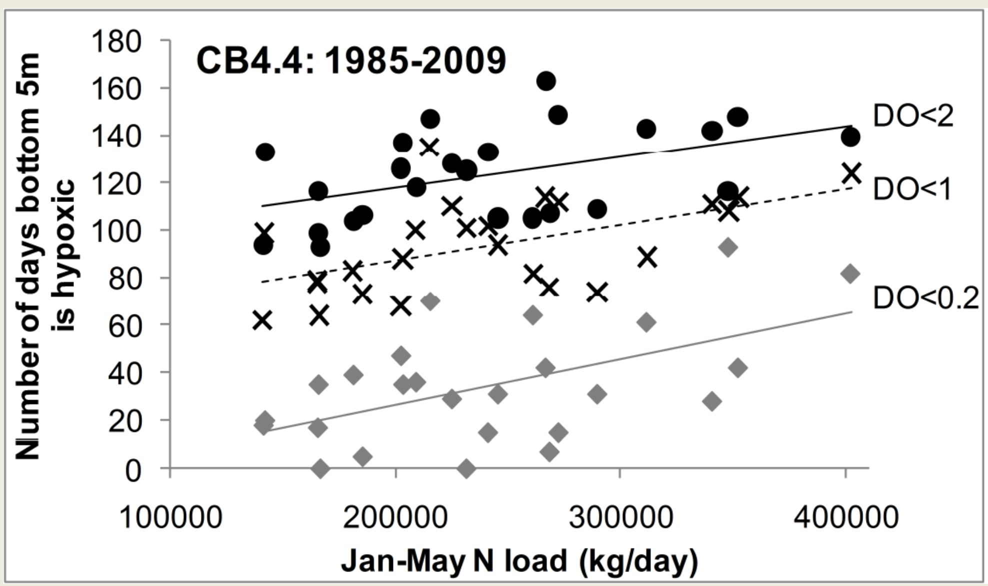
Data Source: CBP

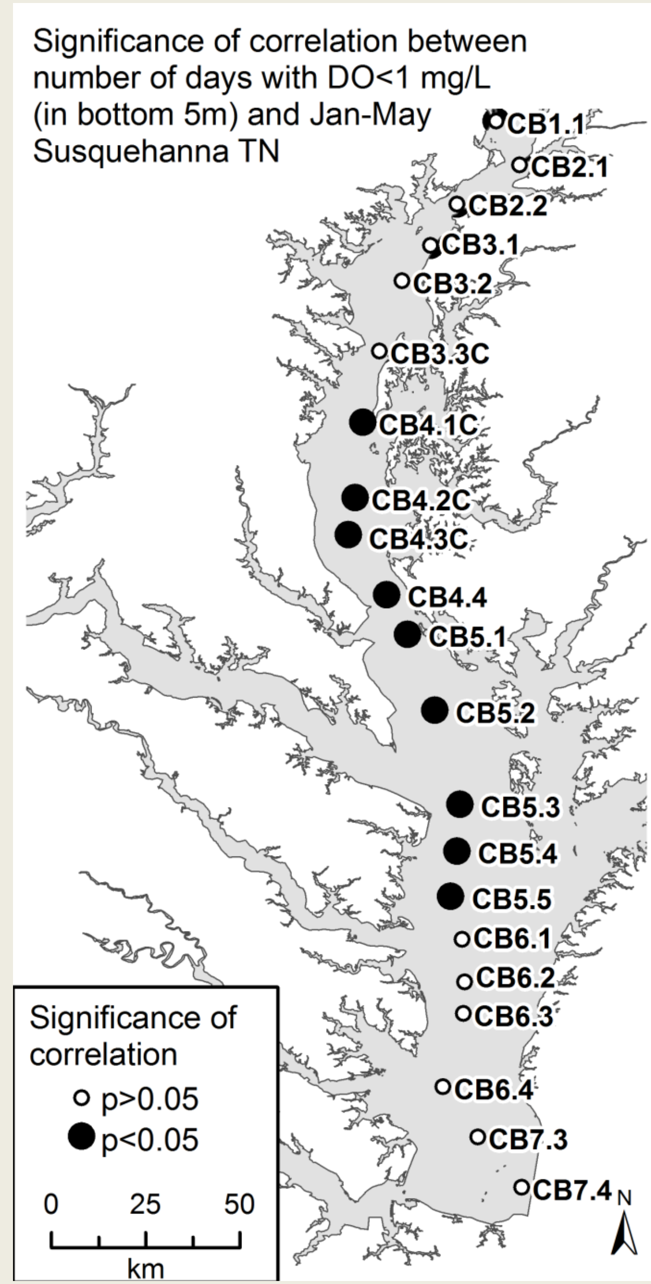
1984-2010 Early- vs. Late-Summer



Findings: Nutrients

- Significant relationship between late July and August hypoxic volume with TN (previous slides)
- Number of summertime days with bottom-water hypoxia is significantly correlated to TN load





Findings: Hypoxic Volume Trends

- **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

Parameters investigated

- Nutrient loads
  - TN, TP
  - All tributaries
  - Effect on duration of summertime hypoxia
- Stratification and factors that effect stratification
  - Flow – temporal changes or shift?
  - Wind
  - Temperature
  - Sea level rise

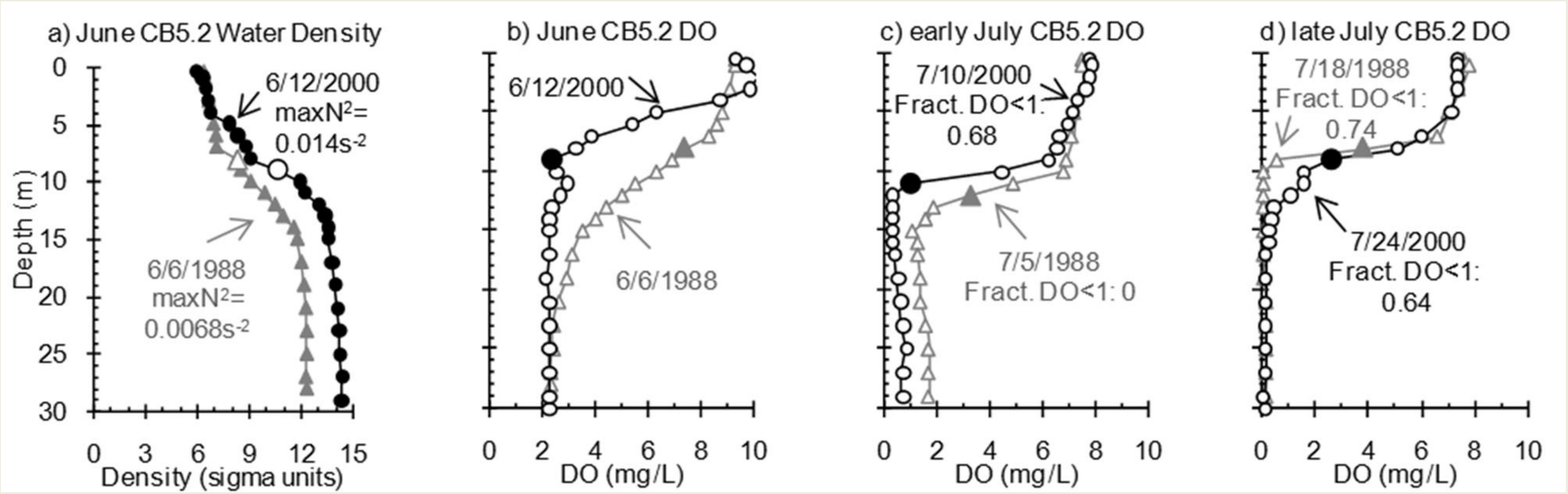
Regression results (1949-2009)

$HypoxicVol = \beta_0 + \beta_1(TN) + \beta_2(year)$

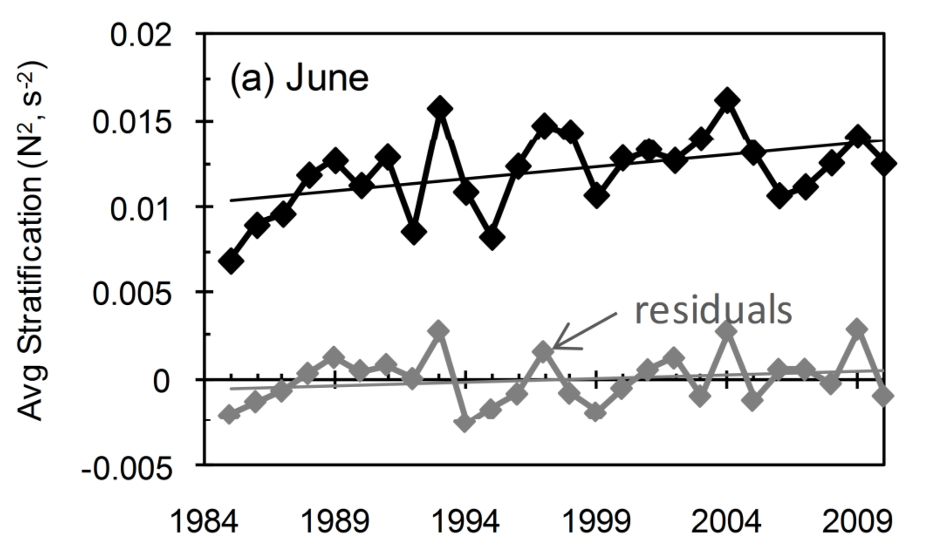
Time period	DO level (mg/L)	Model Fit: R^2 and p-value	Intercept, β_0	TN dependence, β_1 (p-value)	Temporal dependence, β_2 (p-value)
Early July	<0.2	0.44, $p<0.001$	2.2	**0.84 (p=0.005)**	**0.93 (p=0.002)**
	<1	0.37, $p<0.001$	4.7	0.84 (p=0.09)	**1.7 (p=0.001)**
	<2	0.30, $p=0.003$	7.1	0.74 (p=0.2)	**1.9 (p=0.003)**
Late July	<0.2	0.43, $p<0.001$	2.1	**0.98 (p<0.001)**	**0.67 (p=0.02)**
	<1	0.34, $p<0.001$	4.7	**1.2 (p=0.003)**	0.65 (p=0.08)
	<2	0.26, $p=0.004$	7.3	**1.2 (p=0.01)**	0.69 (p=0.1)

Note: Early July does not include the 2010 data

Stratification: Effect on hypoxia



June stratification regression models



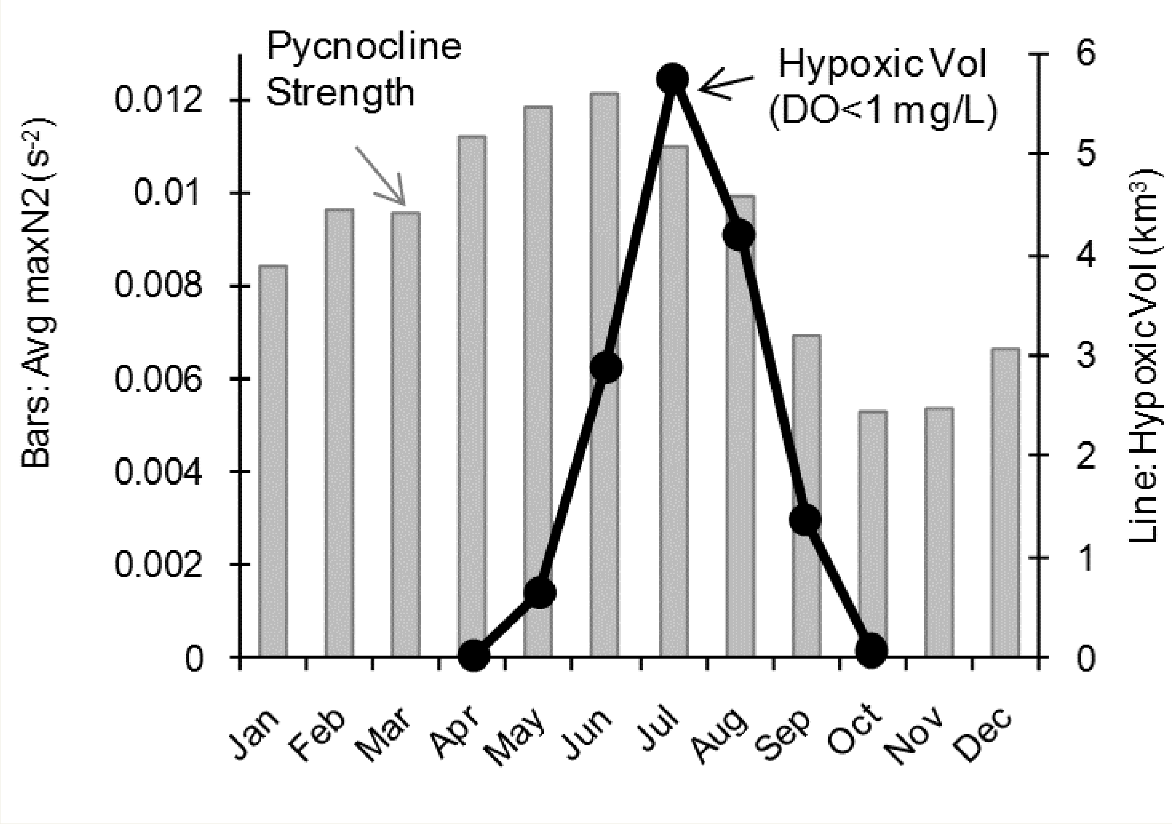
June Stratification Models						Residuals regressed with year R^2, p-value
Equation	Model Fit: R^2, p-value	Intercept, β_0	River flow dependence (Feb-May), β_1	SE wind[a] dependence (Jun), β_2	MSL[b] dependence (Jul-Jun), β_3	
$maxN^2 = \beta_0 + \beta_1(Flow) + \beta_2(SEwind)$	0.36, p=0.006	0.012	0.0007 (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

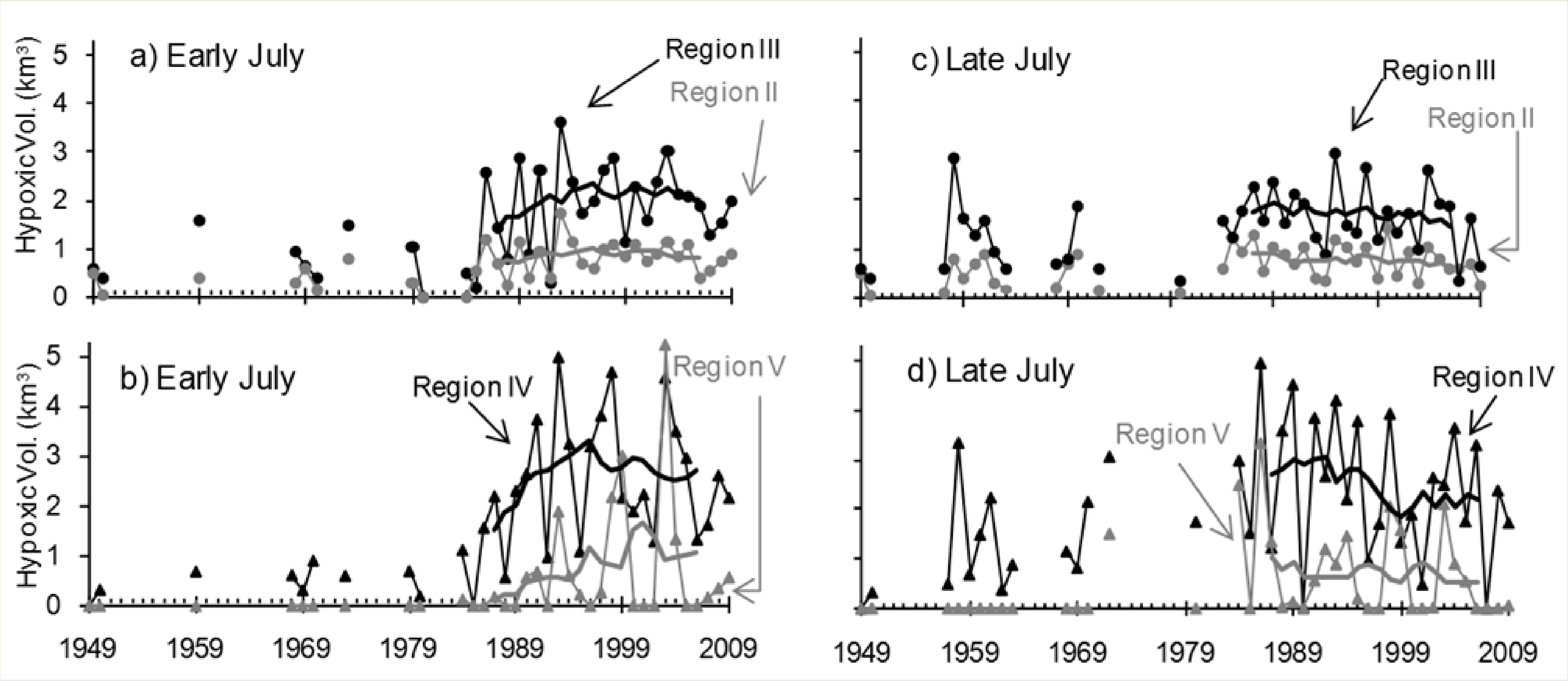
Mechanisms for stratification effect on hypoxia

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

Monthly average hypoxic volume and stratification

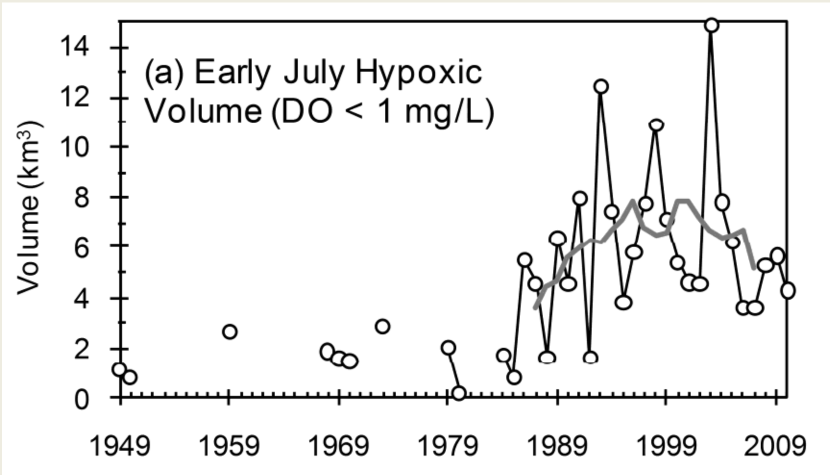


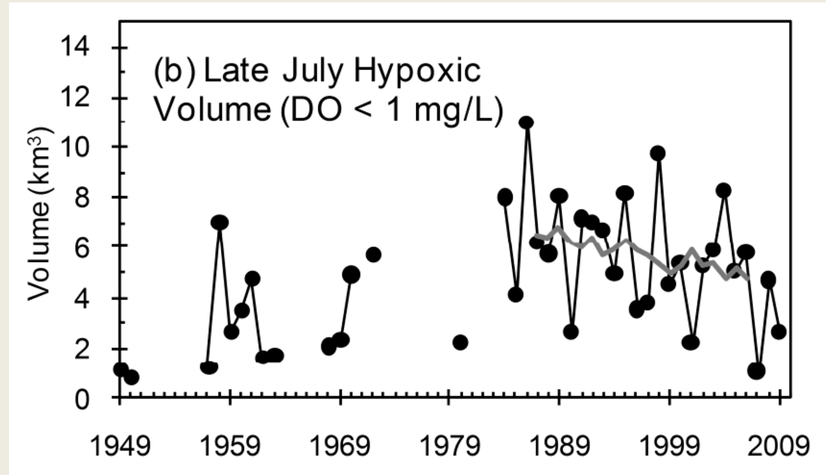
Regional results



Region 1 is north, 6 is furthest south

Hypoxic volume and TN trends



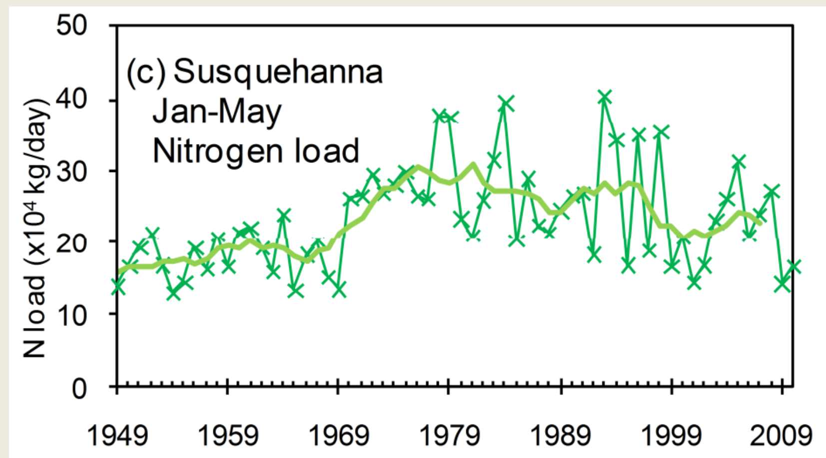


Regressions:

Early July ~ TN: R^2=0.07 p=0.1
Residuals ~ year: p=0.003

Late July ~ TN: R^2=0.28, p<0.001
Residuals ~ year: p=0.1

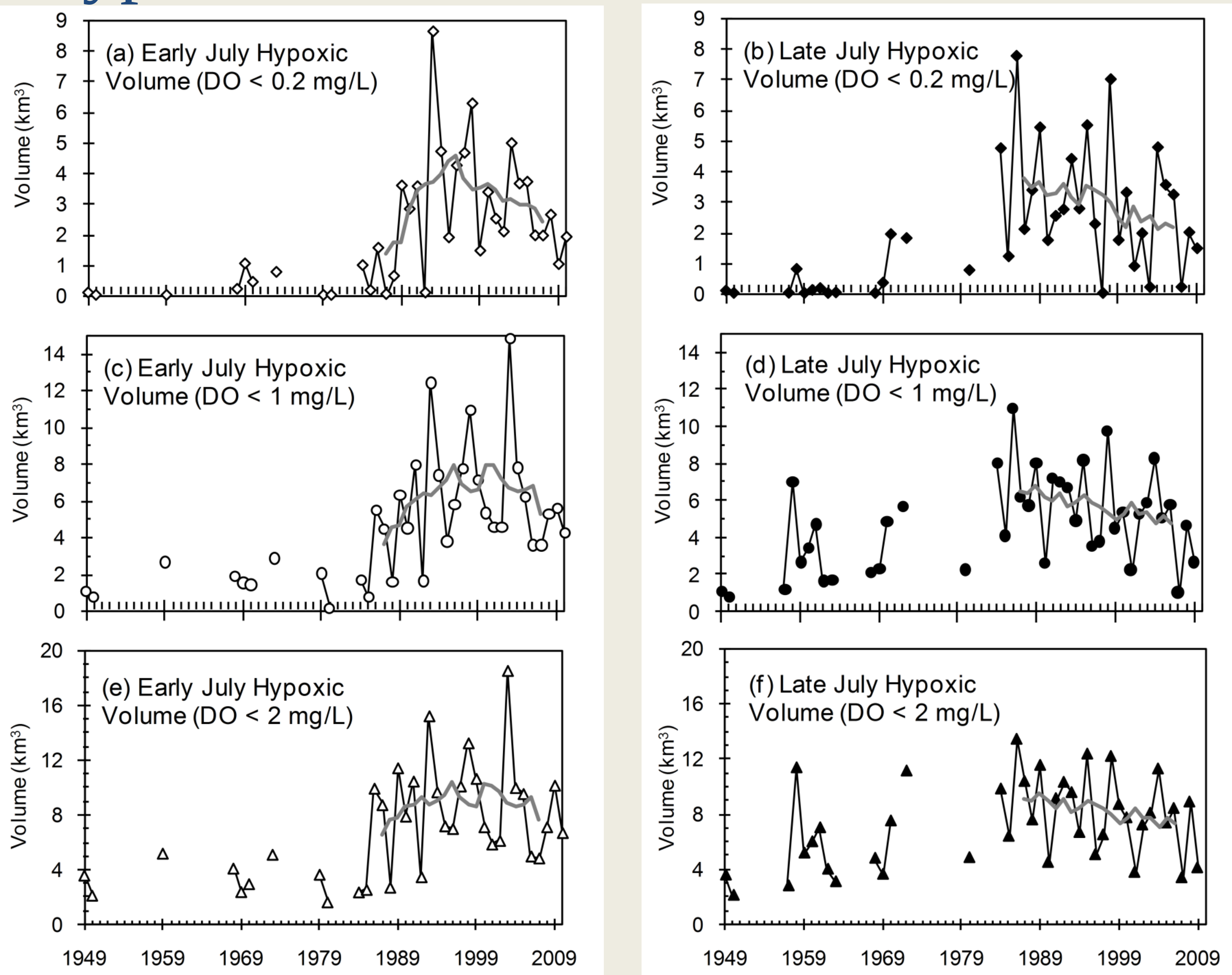
TN ~ year (1970-2010): R^2=0.14, p=0.02



Note: Similar patterns for DO<0.2 and DO<2 mg/L

Data Sources: CBP, CBI, USGS

Hypoxic volume: 3 levels



1984-2010 Early- vs. Late-Summer