Thresholds in Degradation and Recovery of Hypoxic Coastal Ecosystems

W. M. Kemp

University of Maryland CES,
HPL, Cambridge, MD

(*Collaborators*: W. Boynton, J. Testa, R. Murphy, J. Hagy, Y. Li, M. Li)

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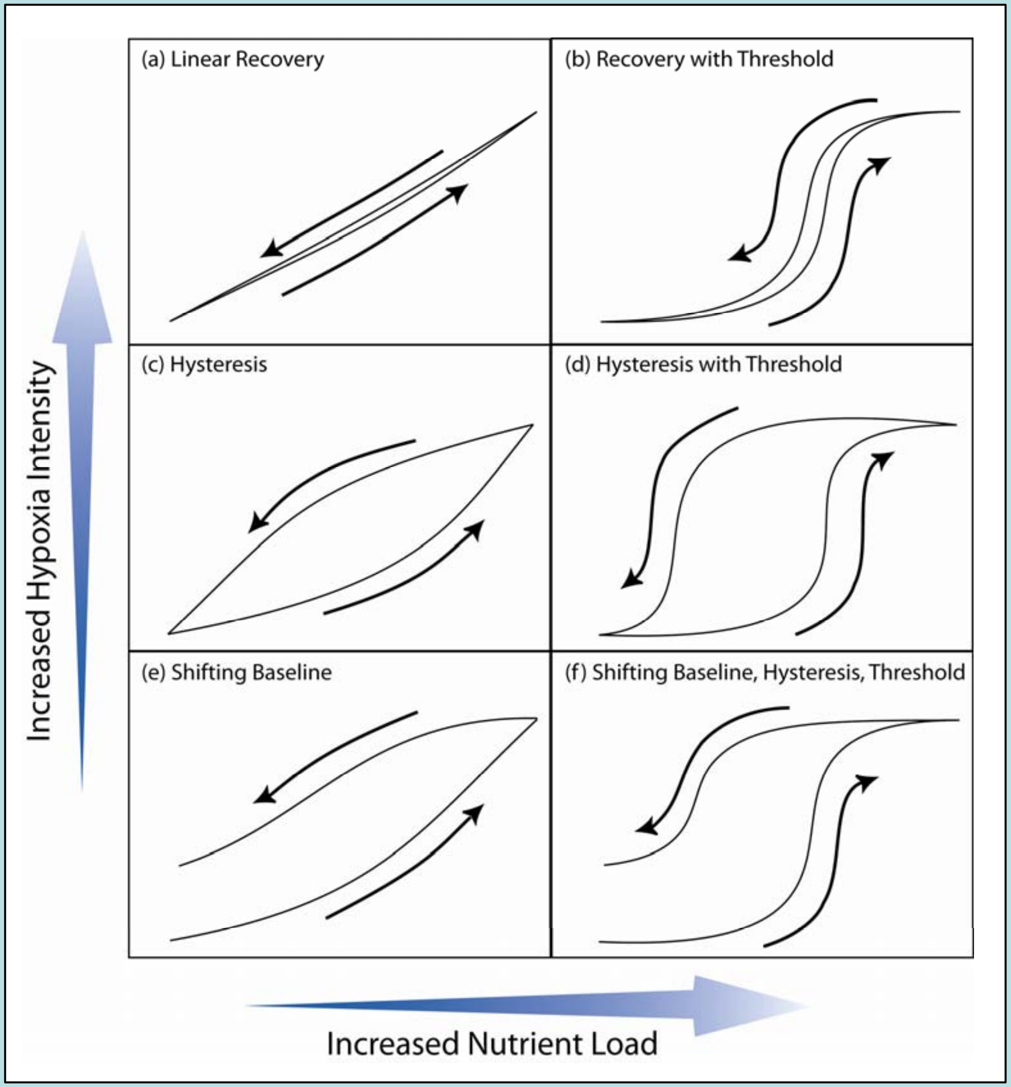
Potential Trajectories of Hypoxia Response to Remediation



- **Before investing in efforts to remediate hypoxia by reducing inputs of nutrient and organic wastes, we need clear sense of expected responses over time.**

- **Many potential alternatives**
  - **--Linear dose-response**
  - **--Threshold response**
  - **--Hysteresis parallel tracks**
  - **--Baseline shift**

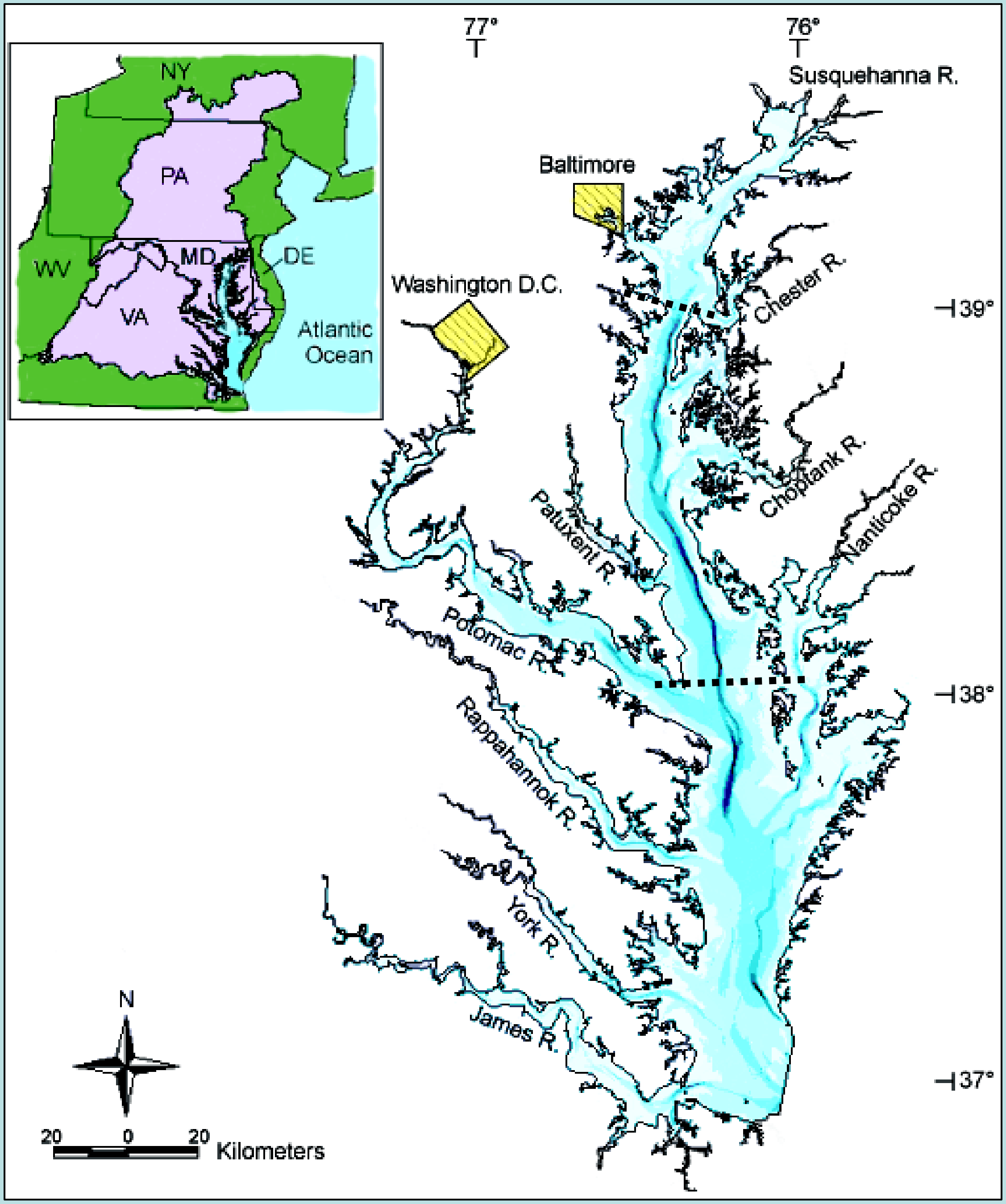
- **Unfortunately, few clear documented case studies have been published**

- **More exist, but data are hard to obtain**

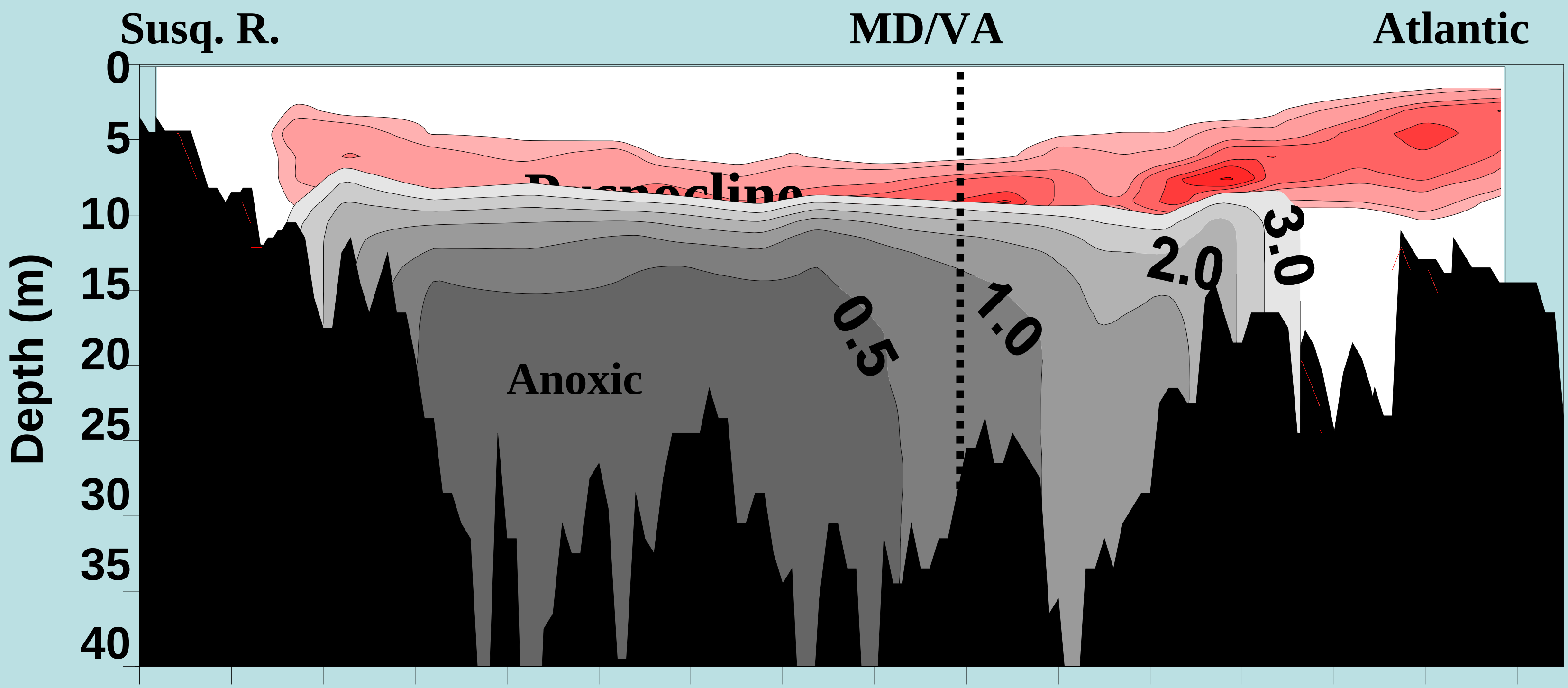
Chesapeake Bay Hypoxia Case:

Key Physical Features

- **Large ratio of watershed to estuarine area (~ 14:1)**
- **Deep channel is seasonally *stratified***
- **Broad shallows flank channel (mean Z = 6.5m)**
- **Relatively long water residence time (~ 6 mo)**



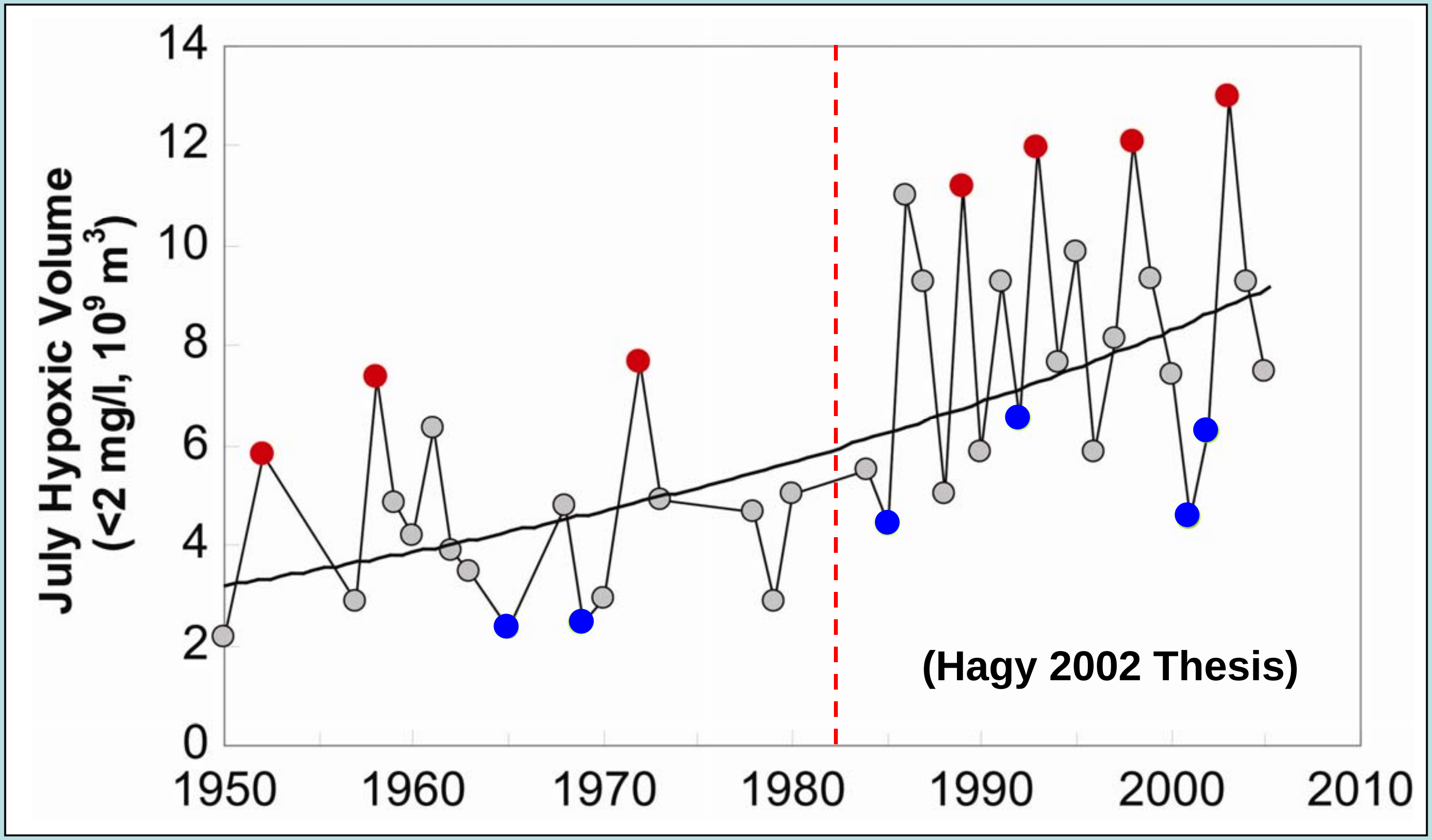
Stratification Control of Hypoxia



- Pynocline strength (red) controls position & intensity of hypoxia (gray)
- Vertical mixing & landward transport replenish deep O_2 pools in summer.

(Hagy 2002 Univ. of MD Thesis)

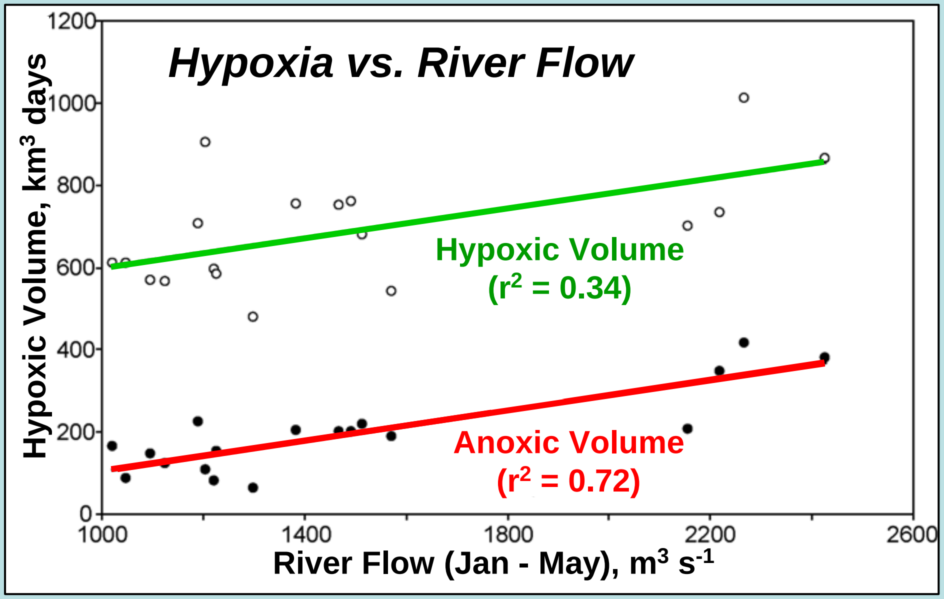
Trend in Bay Summer Hypoxia Volume (1950-2004)



- Exponential increase, w/ strongest change since 1980
- Interannual variability driven by **high** and **low** river flow

Volume of Summer Hypoxia Related to River Flow and N Loading: Regime Shift in Early 1980s

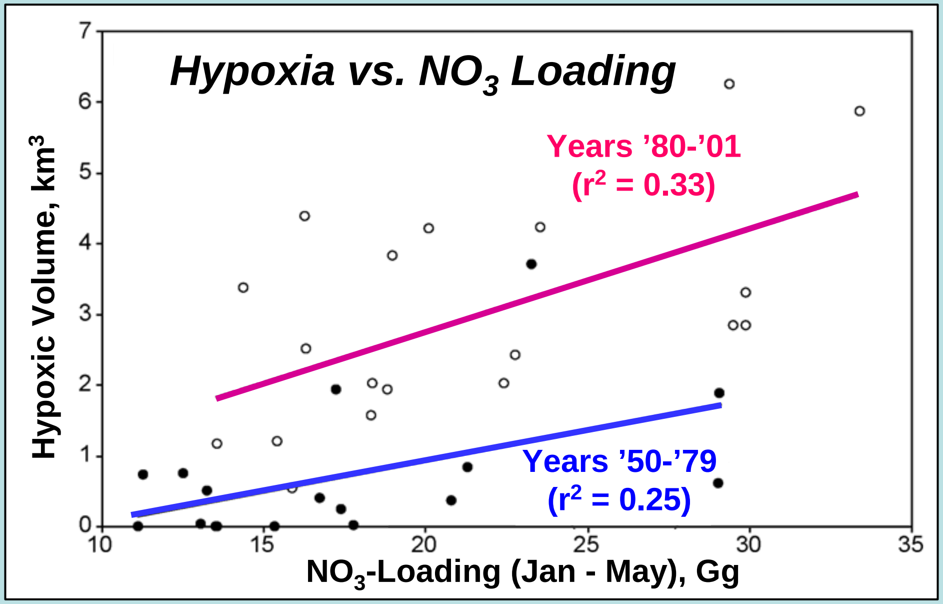
- Volumes of summer hypoxia (< 1 mg/L) and anoxia (< 0.5 mg/L) related to winter-spring river flow.



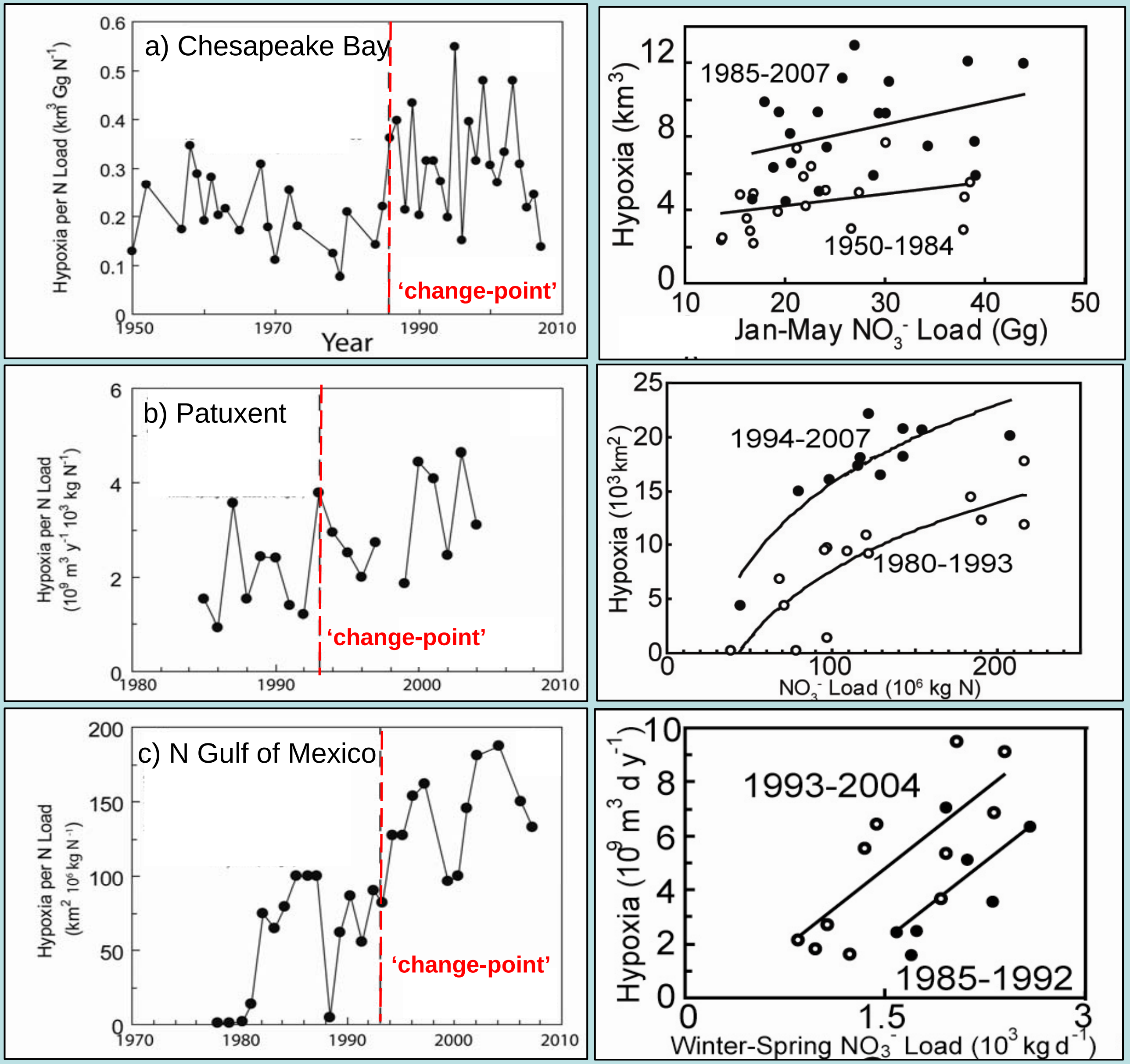
- Abrupt increase in slope of hypoxia-nitrate relation for 1950-1980 and 1980-2003 (hypoxia per NO_3 Load)

- What factors drive this abrupt regime shift?

(Hagy et al. 2004. Estuar. & Coasts, Kemp et al. 2005. MEPS)



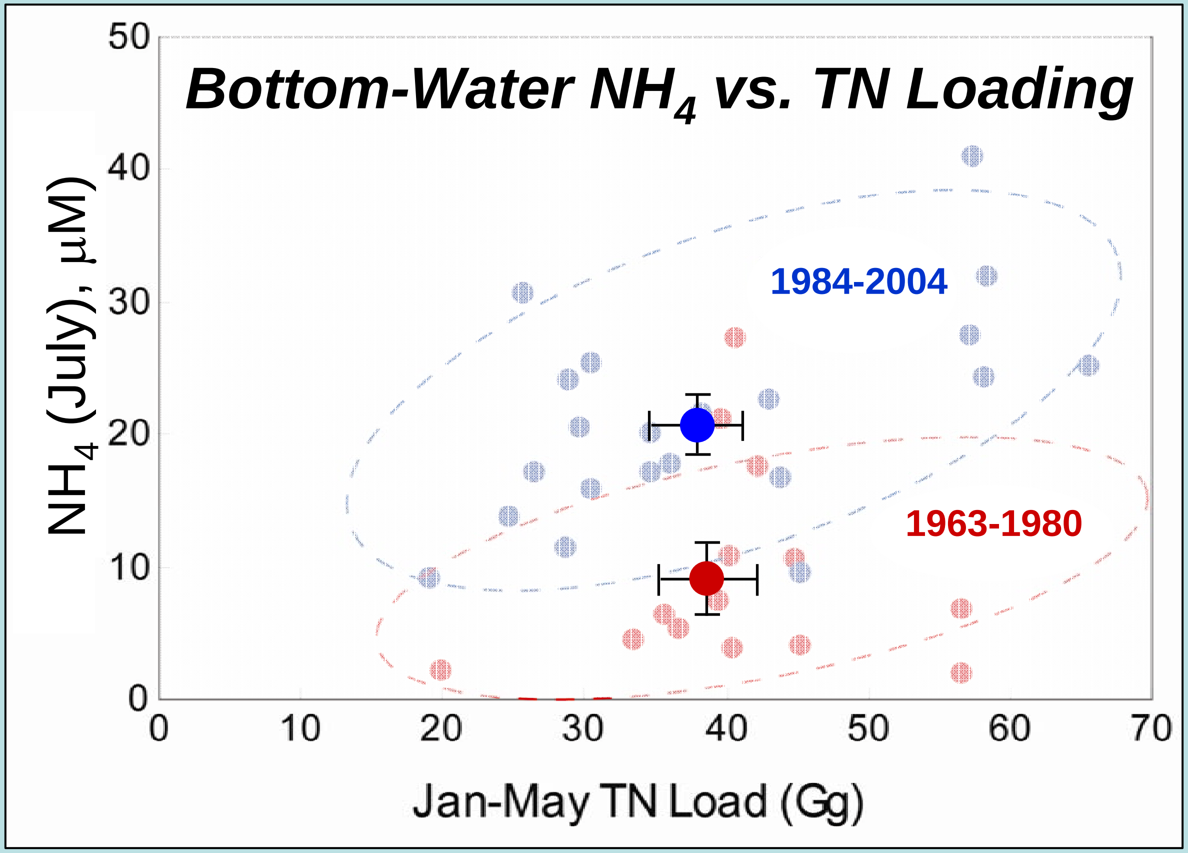
Is Chesapeake Hypoxia Regime Shift Unique?



- Examples (there are others) of abrupt shifts in hypoxia per N-Load
- Change-point analysis used to detect shifts.
- Explanations differ but unexpected increase deters efforts to remediate hypoxia

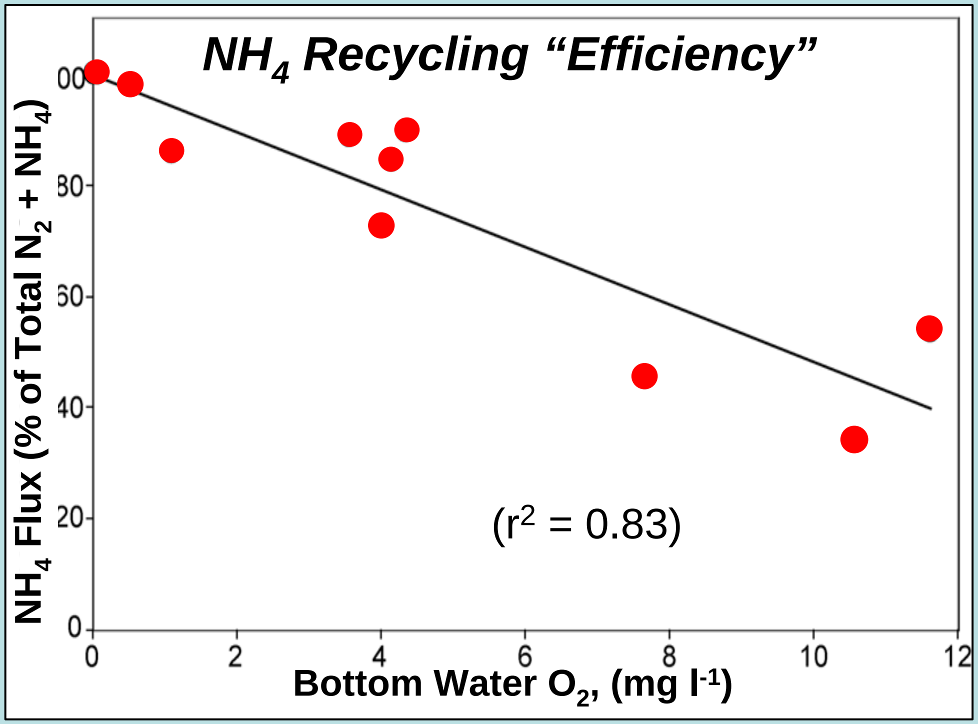
(Kemp et al. 2009. BG)

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 → benthic fauna loss → denitrification loss → more NH_4 recycling → more algae → more hypoxia)

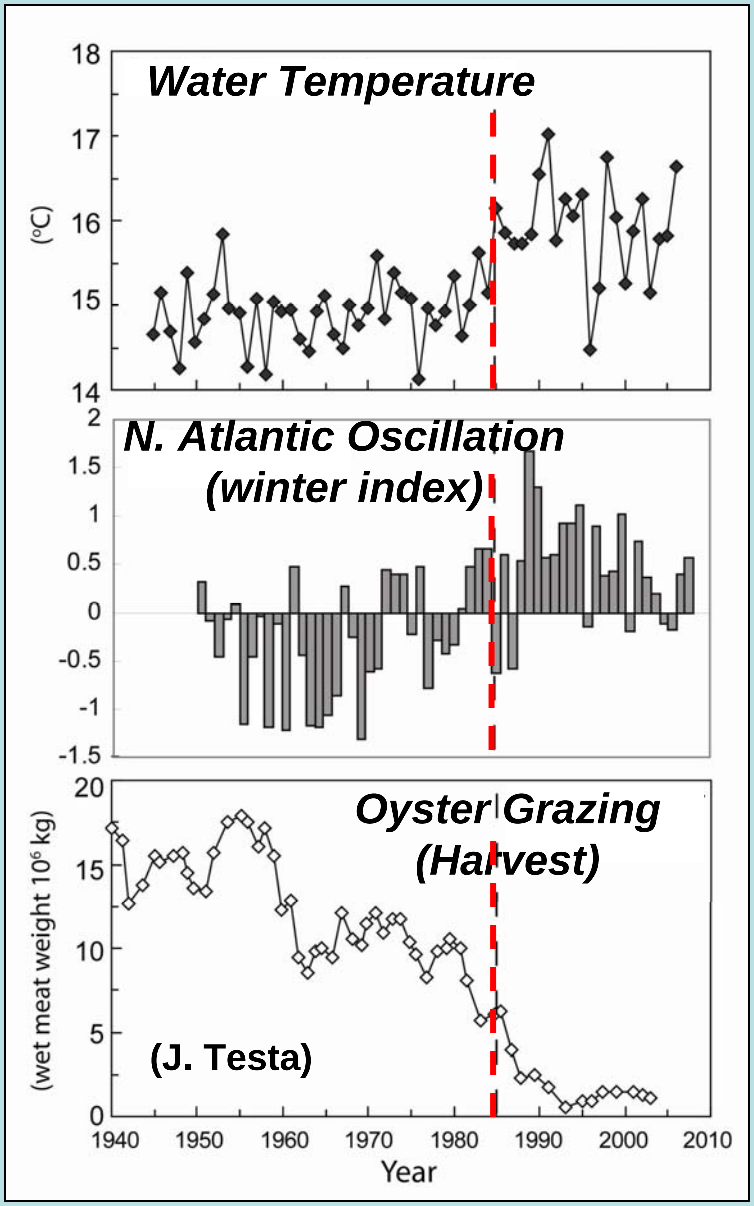
Hypoxia Enhancement of Benthic Nutrient (NH_4^+) Recycling Efficiency



(J. Cornwell data in Kemp et al. '05 MEPS)

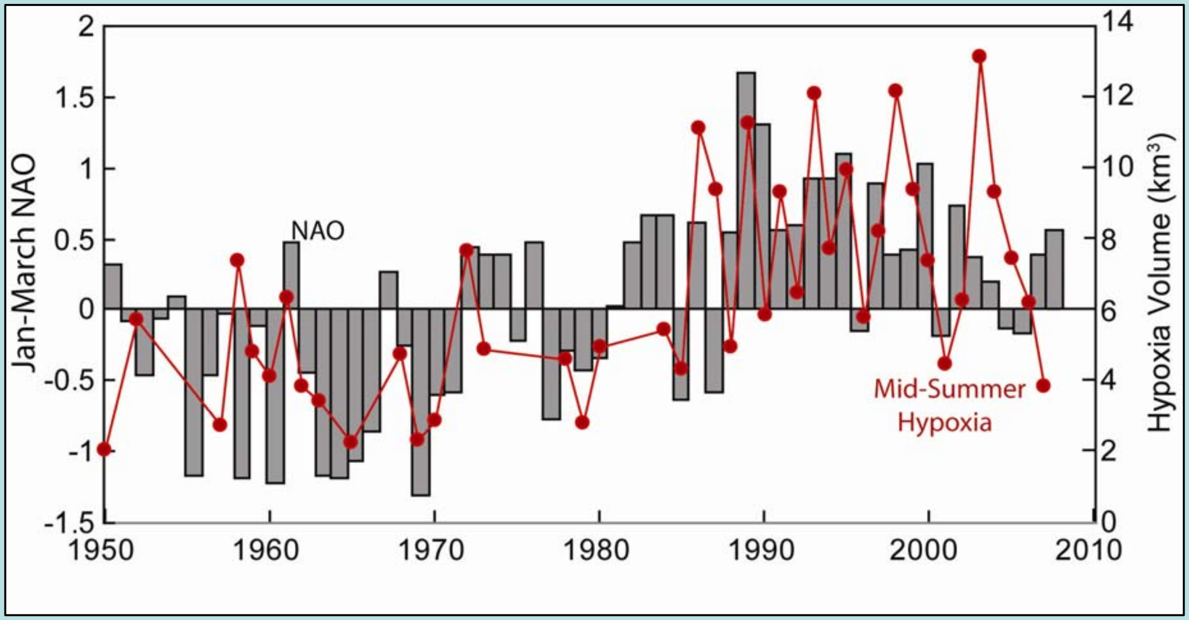
- NH_4 'Recycling Efficiency' (*NRE*) is flux ratio (NH_4 /(NH_4 + N_2))
- *NRE* increases w/ decreasing O_2 as nitrification-denitrification is inhibited (NH_4 shunted & lost to N_2)
- Increased *NRE* with hypoxia further driven by loss of benthic animals
- Thus, NH_4 recycling is higher under hypoxic conditions.
- Higher NH_4 recycling → More algae → More hypoxia → More recycling
- Is increased *NRE* a result or a cause of hypoxia intensification? Or both?

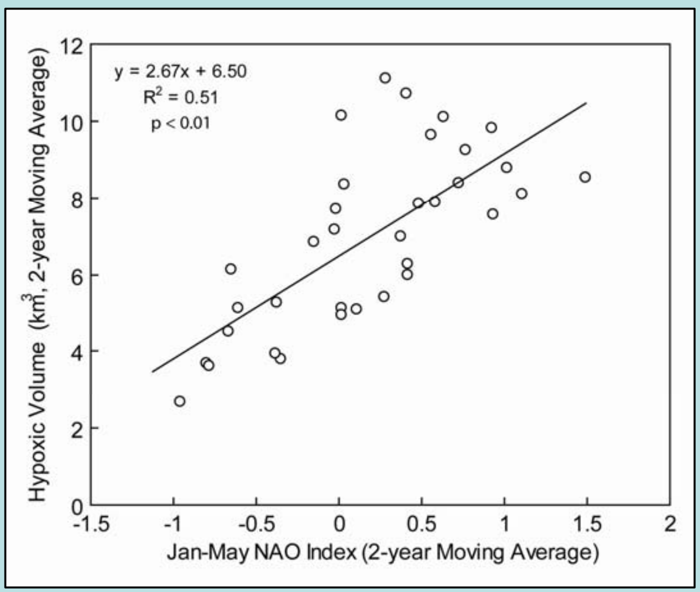
Potential Explanations for 'Regime Shift' in Hypoxia vs. N-Loading



- We considered other explanations
- Increased water temperature tends to decrease respiration and O_2 solubility
- Decadal-scale climate shifts might affect river flow or wind
- Decline of reef-forming shellfish filter feeders would decrease control on plankton algal growth
- Other changes (not shown) include loss of nutrient trapping with degradation of tidal marshes and submersed plant beds

Coherence Between NAO & Hypoxia



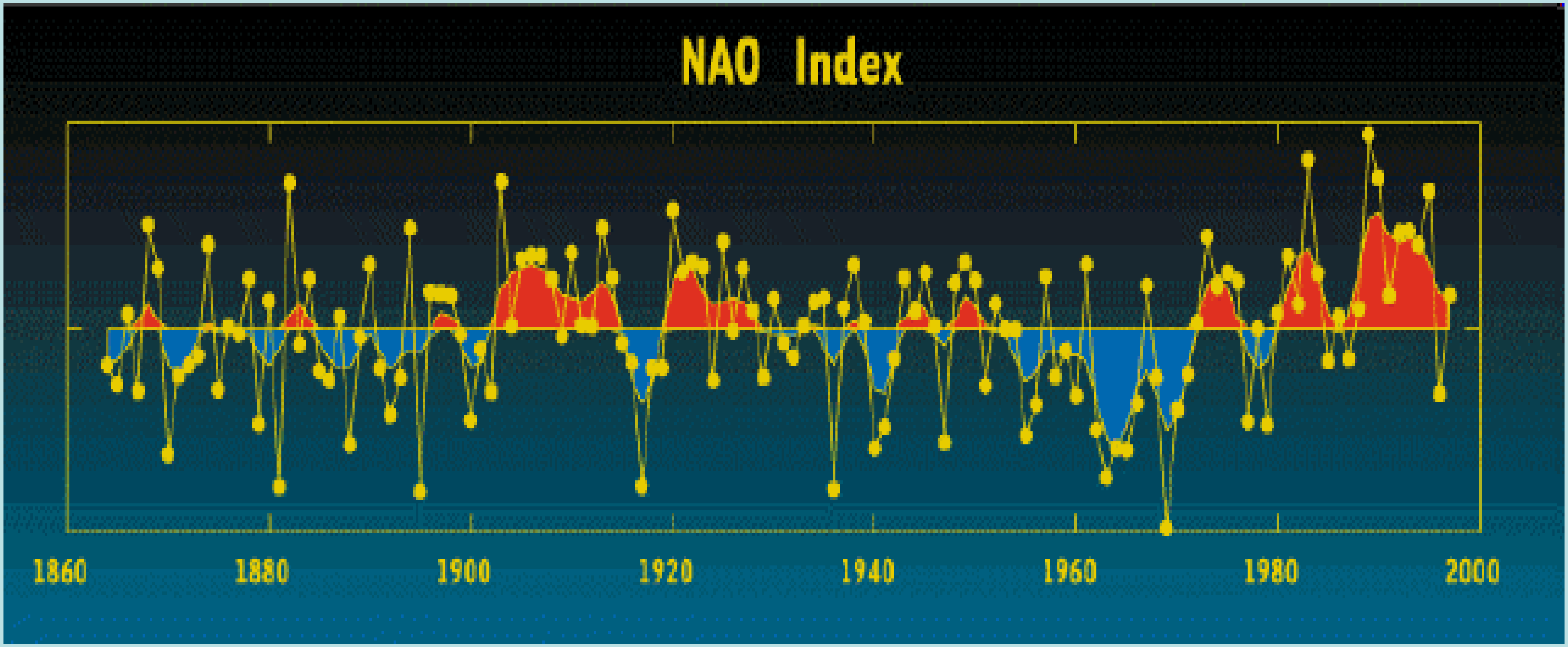


- **Strong correlation and coherence between NAO & hypoxia over time.**

- **NAO indexed to weaker Bermuda High & loss of S winds that cause vertical mixing; also indexed to Gulf Stream position, higher salinity & stratification.**

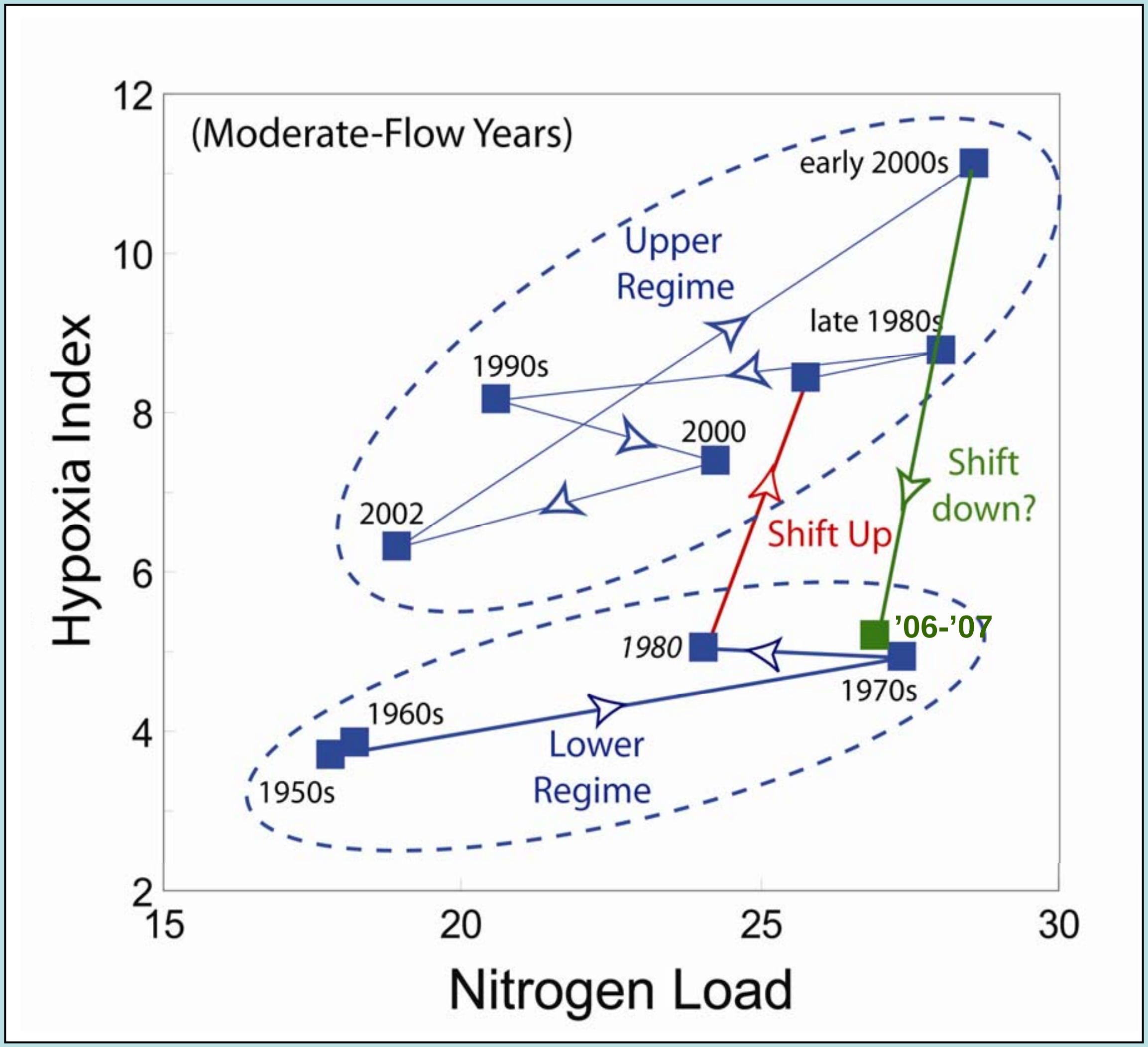
- **Less mixing during positive phase of NAO promotes more hypoxia per N.**

Winter NAO Index: Longer Time-Series



- Longer term trends in Winter NAO index shows variations and periodic (~10-30 yr) shifts between positive and negative phases.
- Last major shift coincides with Bay “regime shift” in hypoxia per N-loading
- Index in recent years suggests a shift back down to negative phase (& possible increase in vertical mixing and weakening of stratification).

Hypoxia Response to Changes in N-Load



- To minimize effects of interannual variations in flow on relation, use mean data from years with intermediate flow.
- Between 1980 - 1985, relation of hypoxia to N-Loading shifted up to higher regime.
- This caused more hypoxia per unit N-loading, frustrating efforts to remediate.
- Recent years show down-shift back to pre-1980 conditions, giving hope for hypoxia controls.

Concluding Comments

• Cost-effective strategies for hypoxia remediation require understanding of expected responses to interventions (e.g., reductions in nutrient load).

• Many physical and biogeochemical processes control hypoxia, and these must be clearly understood before choosing remediation strategy.

• Chesapeake hypoxia has grown with increasing nutrient loading, and an abrupt Increase in hypoxia/N-load occurred in early 1980s.

• It appears that hypoxia-enhanced N-recycling has contributed to this "Regime Shift" and/or Bay recalcitrance to restoration.

• However, abrupt changes in climatic conditions (indexed to winter NAO) coincide with this hypoxia "regime shift," driving physical controls on hypoxia.

• There may be reason for "cautious optimism" for Bay hypoxia recovery; possibly, a "shift-down" to lower regime with less hypoxia per N-load