TMDL Models and Hypoxic Volume: A Long-term Modeling Approach

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Modeling Quarterly Review

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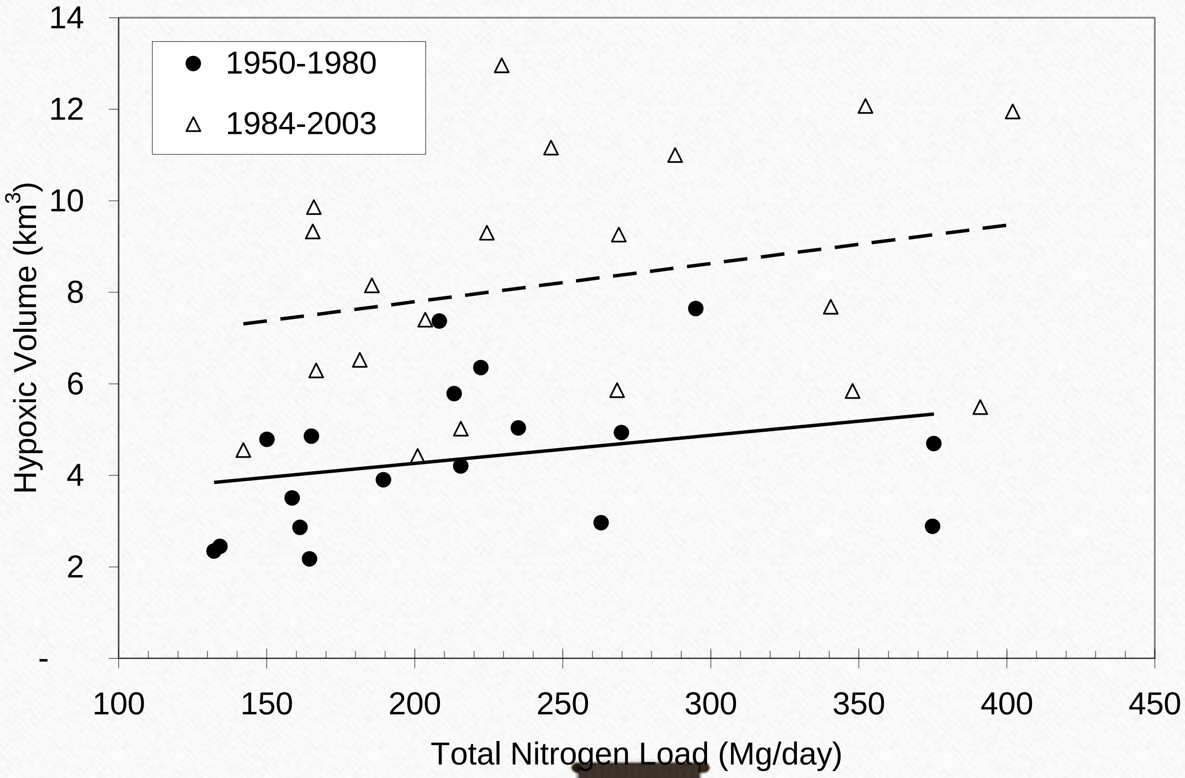
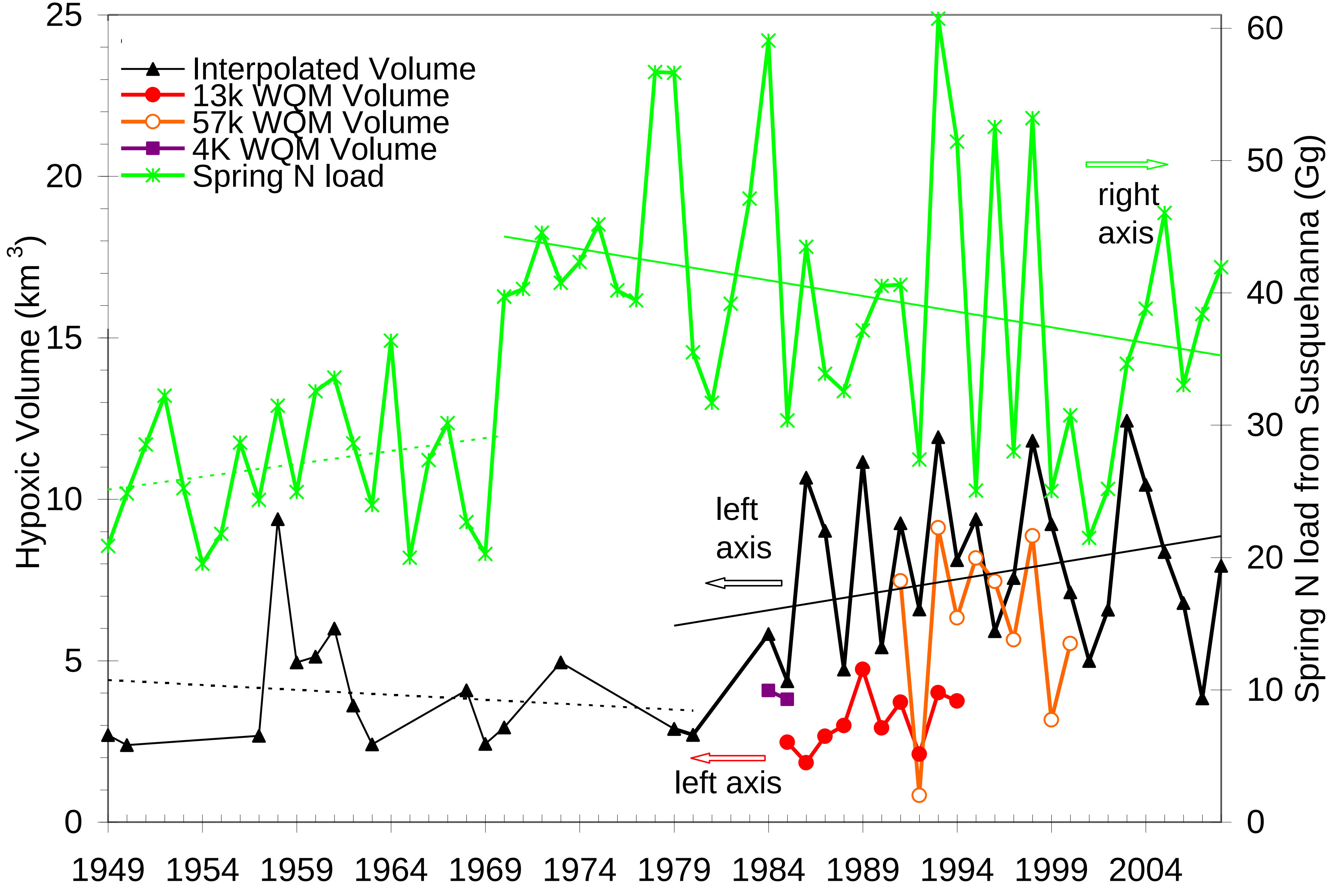
The PLOT (Hagy et al 2004)




Interpolated Volume
13k WQM Volume
57k WQM Volume
4K WQM Volume
Spring N load
Hypoxic Volume (km3)
Spring N load from Susquehanna (Gg)
right axis
left axis
left axis
25
20
15
10
5
0
60
50
40
30
20
10
0
1949
1954
1959
1964
1969
1974
1979
1984
1989
1994
1999
2004

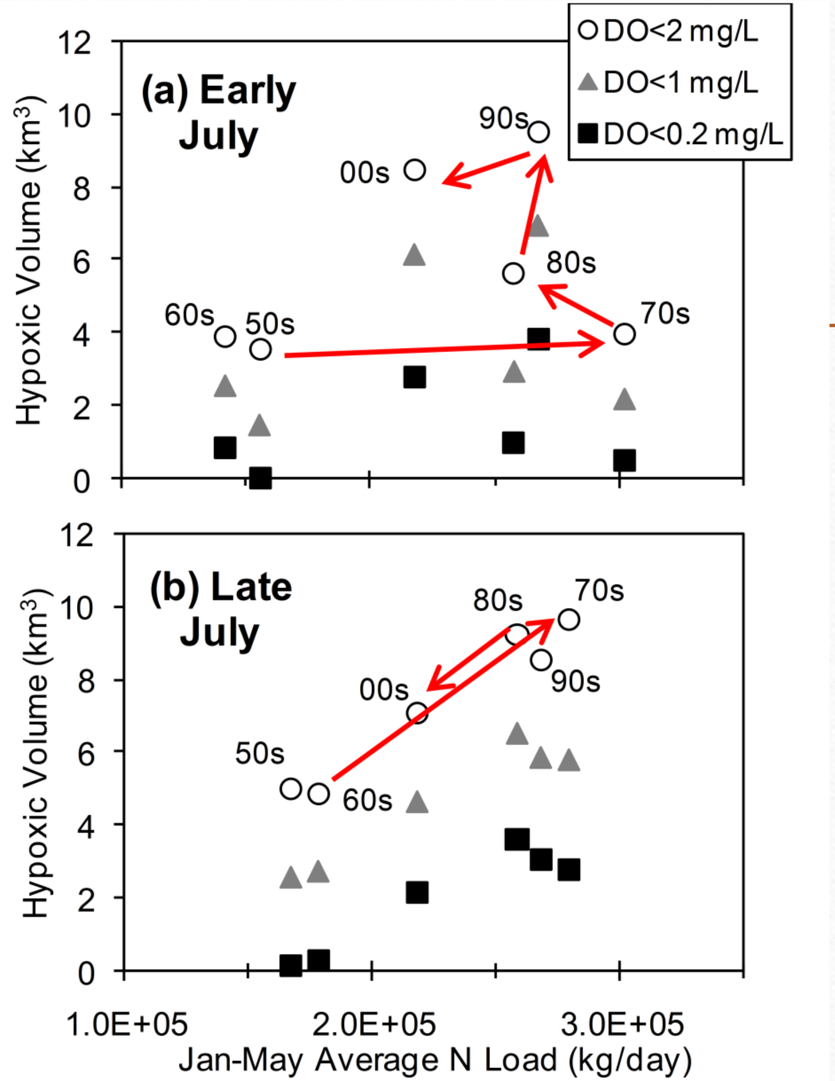
Regime Shift

- Water Environment Research Federation grant
  - Investigate some potential causes and determine what dynamics may or may not be missing from TMDL models
    - Sediments and estuarine memory
    - Use a long term nutrient loading record and the relatively simple 4K CBEMP model to simulate 1950-2010
  - CAVEAT: We were interested in biogeochemistry/nutrient loading and had a limited ability to manipulate hydrodynamics (more to follow)

Scully Hypothesis

"The model demonstrates that the interaction between wind-driven lateral circulation and enhanced vertical mixing over shoal regions is a dominant mechanism for providing oxygen to hypoxic sub-pycnocline waters"

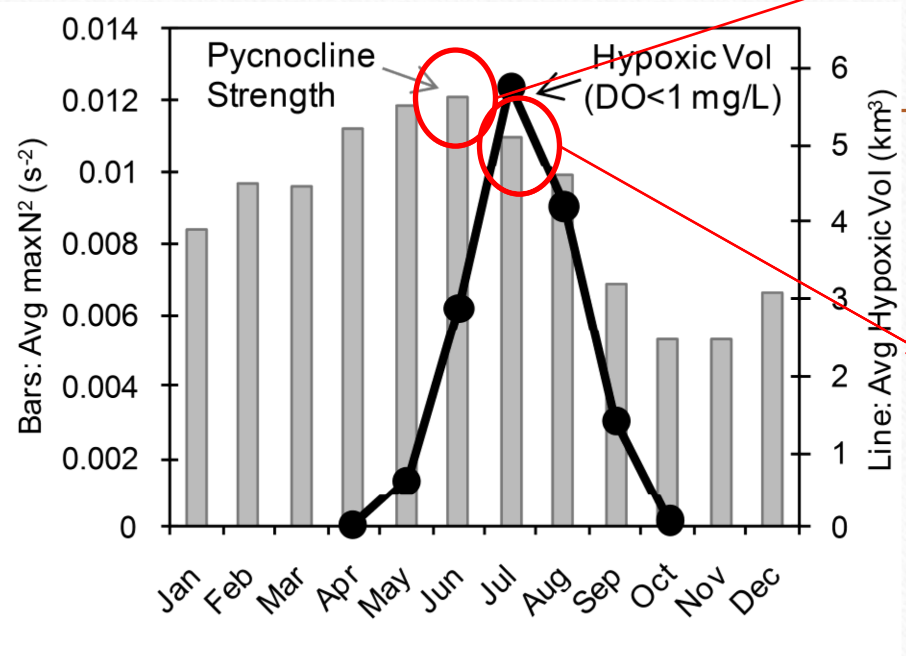
"Beginning around 1980, the surface pressure associated with the summer Bermuda High has weakened, favoring winds from a more westerly direction, the direction most correlated with observed hypoxia."

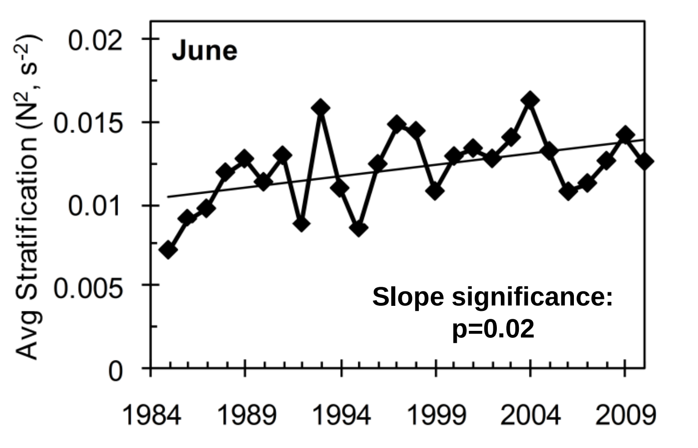


Decadal average hypoxic volume vs. TN

Figure derived from: Murphy, Kemp, and Ball. 2011. Long-Term Trends in Chesapeake Bay Seasonal Hypoxia, Stratification, and Nutrient Loading. *Estuaries and Coasts*

Stratification trends





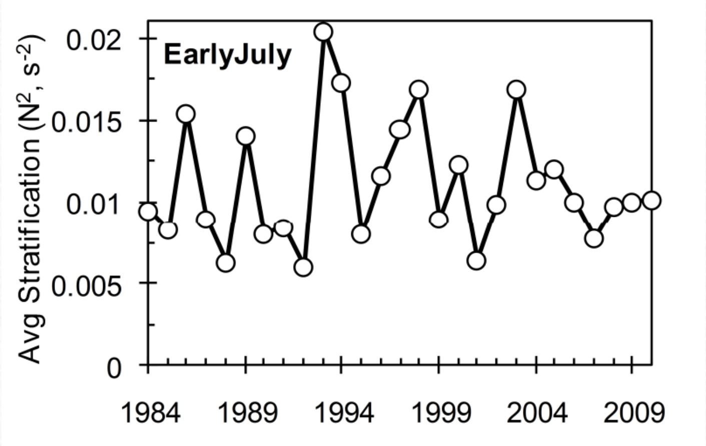
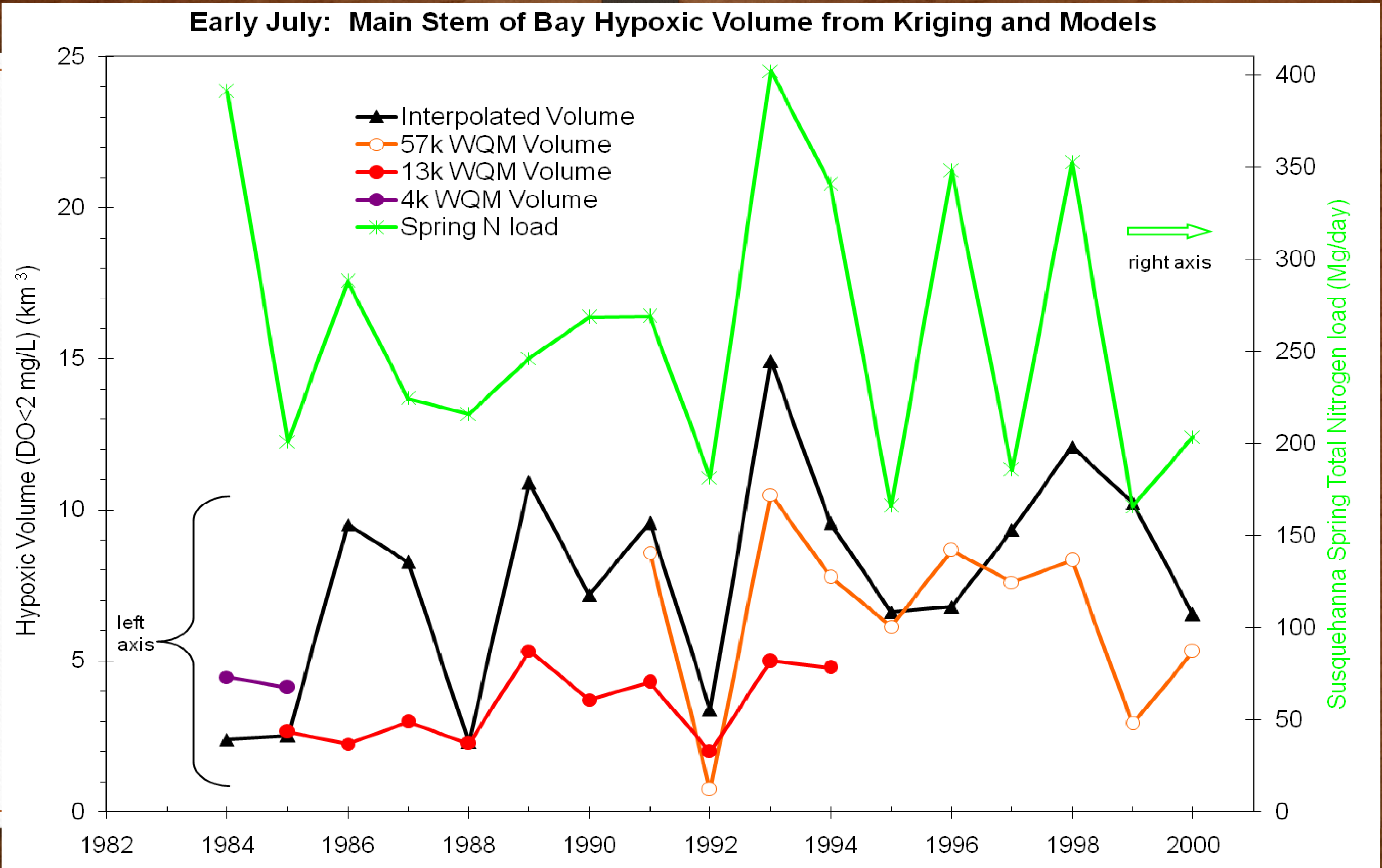
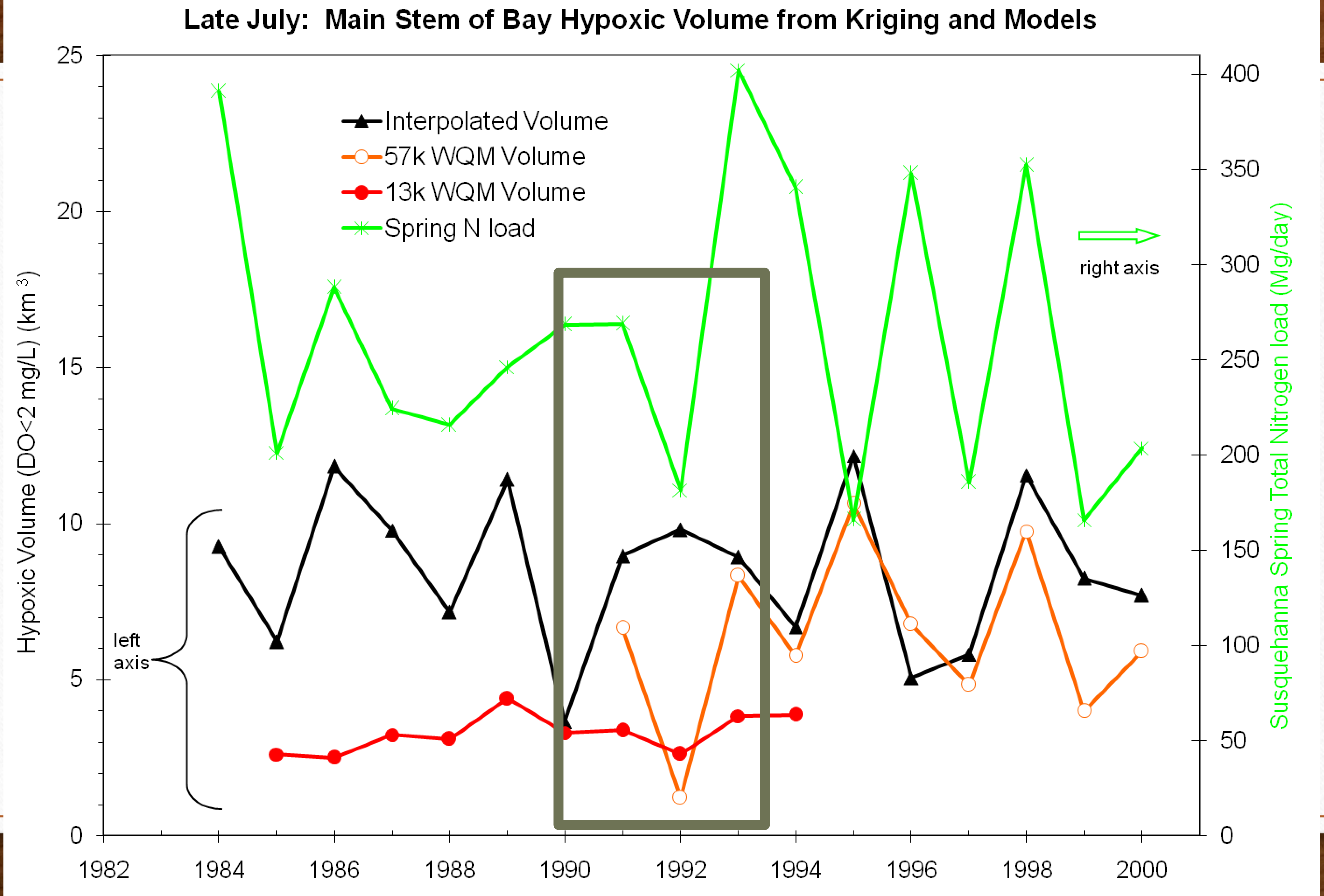


Figure from: Murphy, Kemp, and Ball. 2011. Long-Term Trends in Chesapeake Bay Seasonal Hypoxia, Stratification, and Nutrient Loading. *Estuaries and Coasts*



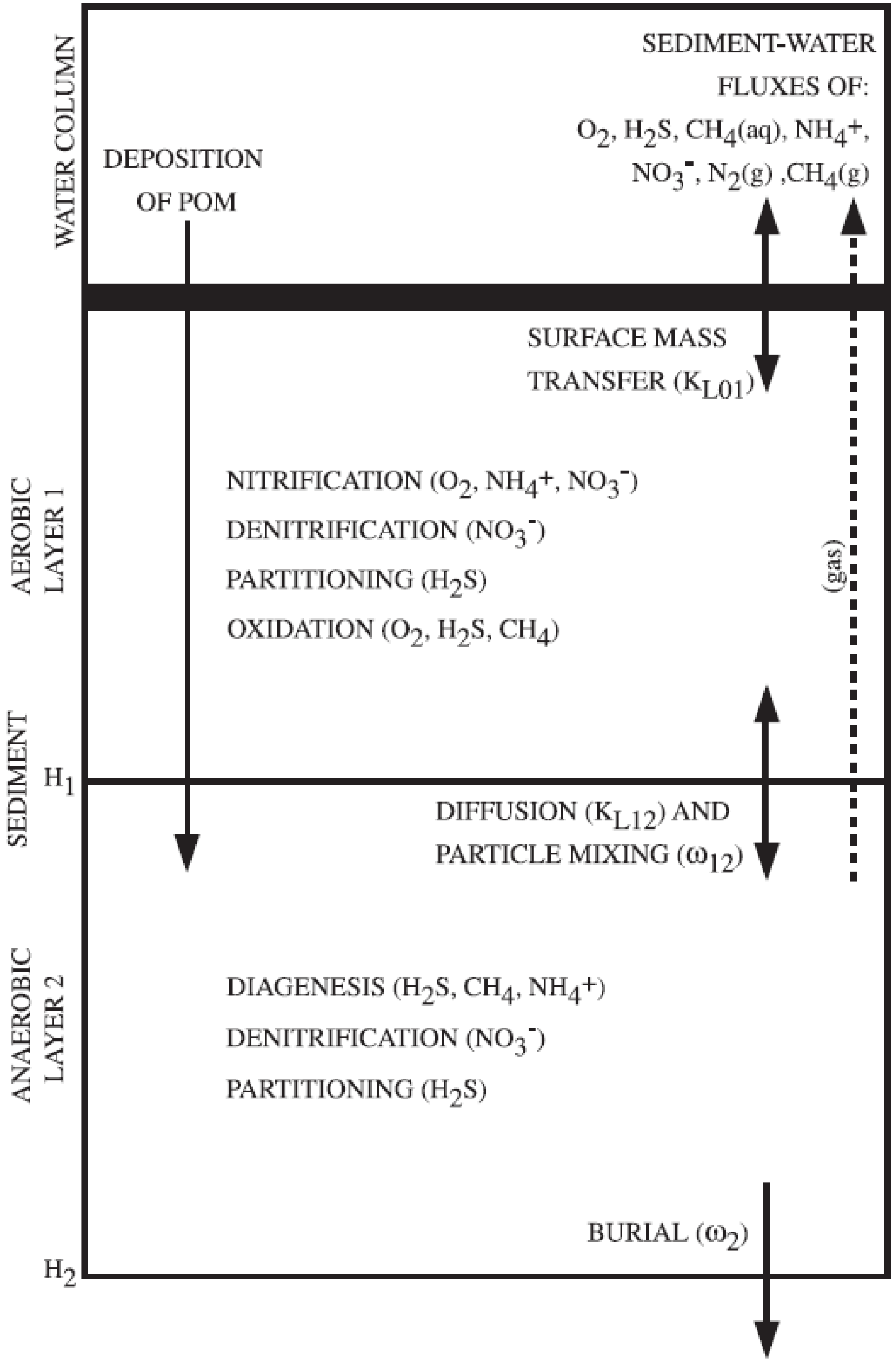
Early July: Main Stem of Bay Hypoxic Volume from Kriging and Models
Interpolated Volume
57k WQM Volume
13k WQM Volume
4k WQM Volume
Spring N load
right axis
left axis
Hypoxic Volume (DO<2 mg/L) (km ^{3})
Susquehanna Spring Total Nitrogen load (Mg/day)
0
5
10
15
20
25
0
50
100
150
200
250
300
350
400
1982
1984
1986
1988
1990
1992
1994
1996
1998
2000



Late July: Main Stem of Bay Hypoxic Volume from Kriging and Models
Interpolated Volume
57k WQM Volume
13k WQM Volume
Spring N load
right axis
left axis
Hypoxic Volume (DO<2 mg/L) (km 3)
Susquehanna Spring Total Nitrogen load (Mg/day)
0
5
10
15
20
25
0
50
100
150
200
250
300
350
400
1982
1984
1986
1988
1990
1992
1994
1996
1998
2000

Sediments

- **Non-linear responses associated with Sediment could also play a role**
  - Storage of organic matter from one season…diagenesis in another season
  - A little hypoxia can decouple nitrification from denitrification…increase nutrient recycling efficiency…keep more and more nutrients in the system
  - Fluxzilla (Sediment Oxygen and Nutrient Exchange Database) has an unprecedented amount of sediment flux data and perhaps it was time to revisit the Sediment Flux Model in CBEMP
  - Calibration and comparison to data sources unavailable during model development
  - See Brady et al and Testa et al for comparisons of sulfate reduction, ammonia porewater, denitrification rates



Stand-alone Sediment Flux Model

- Brady et al 2013
- Testa et al 2013

J[PON]

Back Calculate Deposition from Ammonia Flux

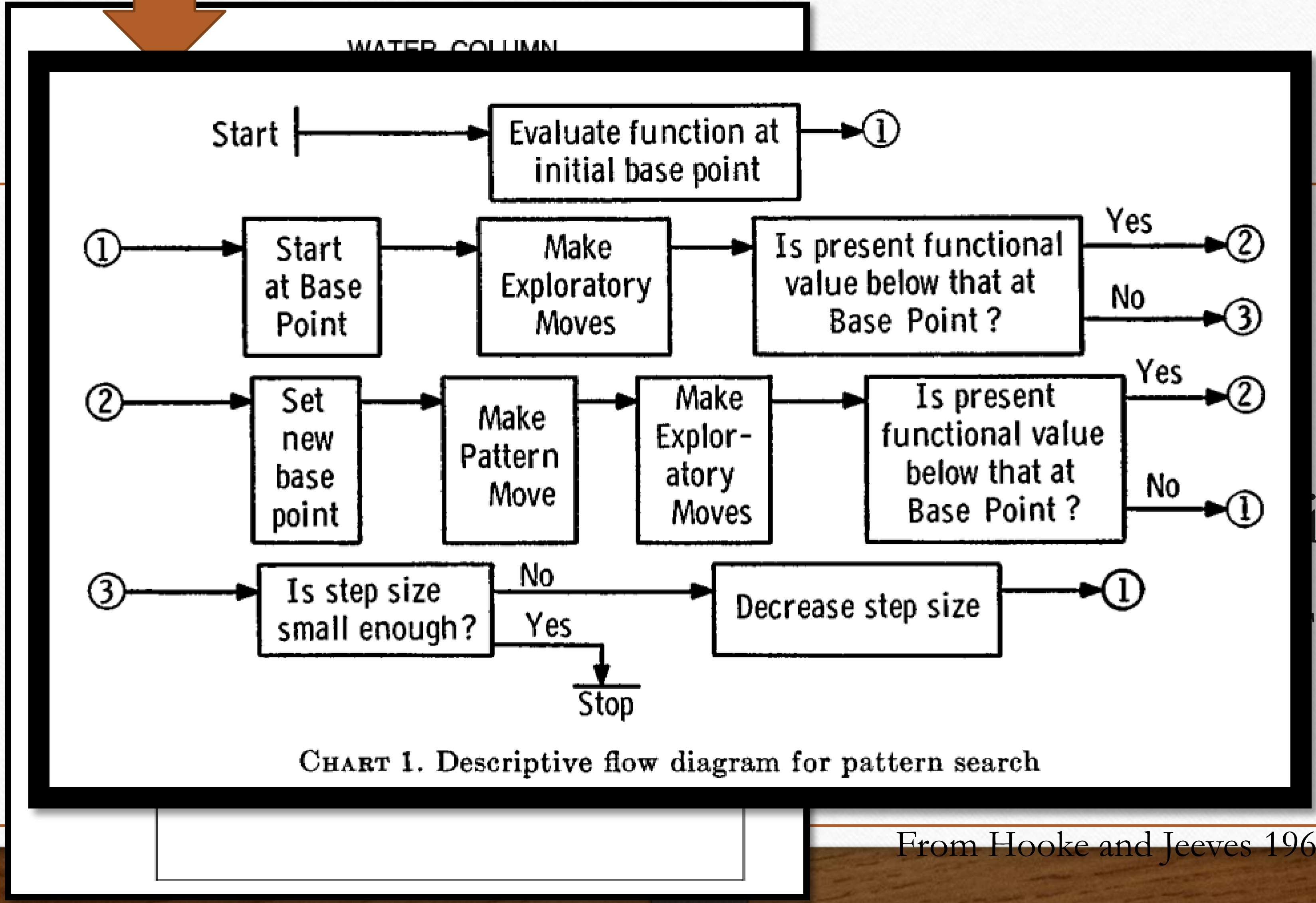
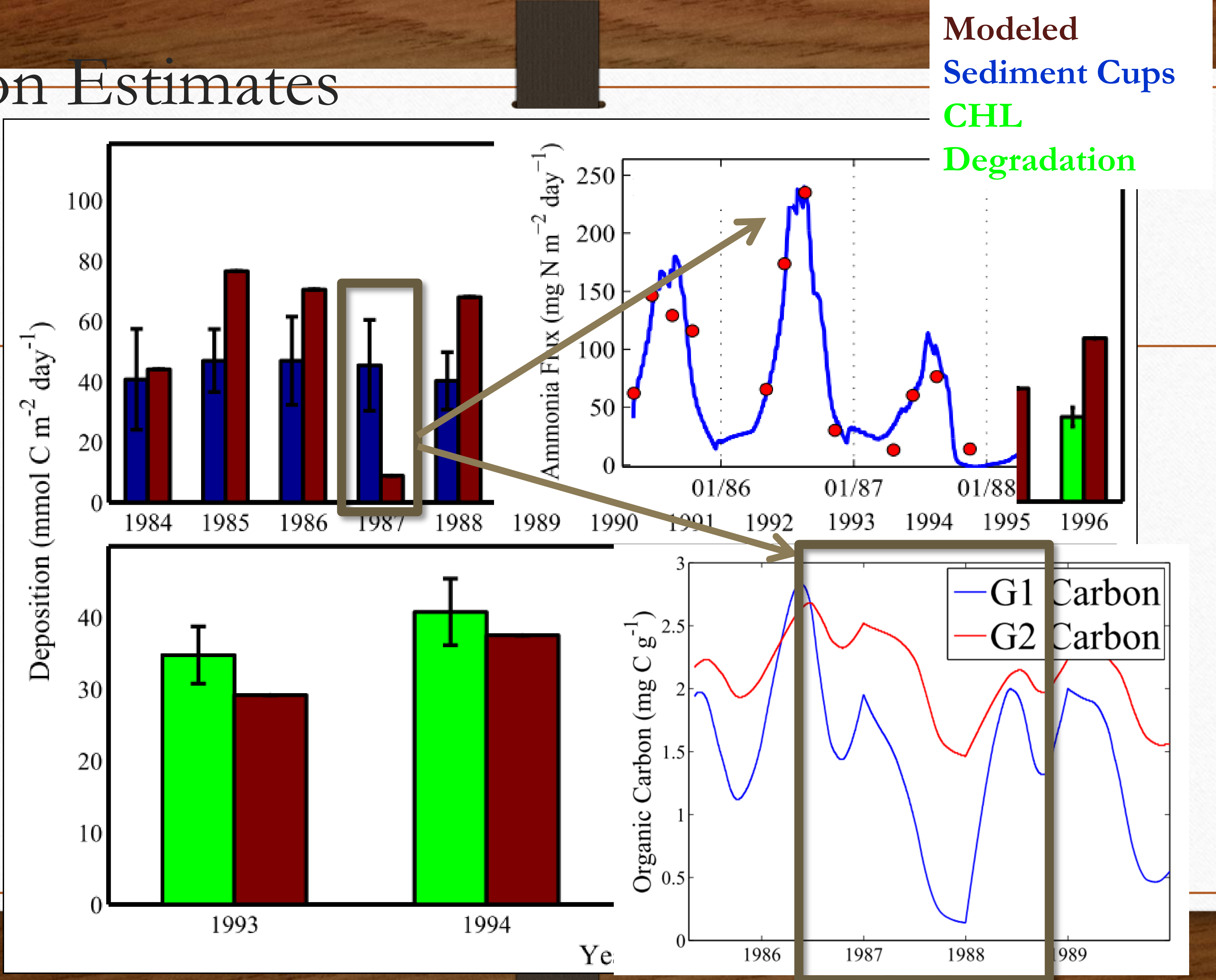


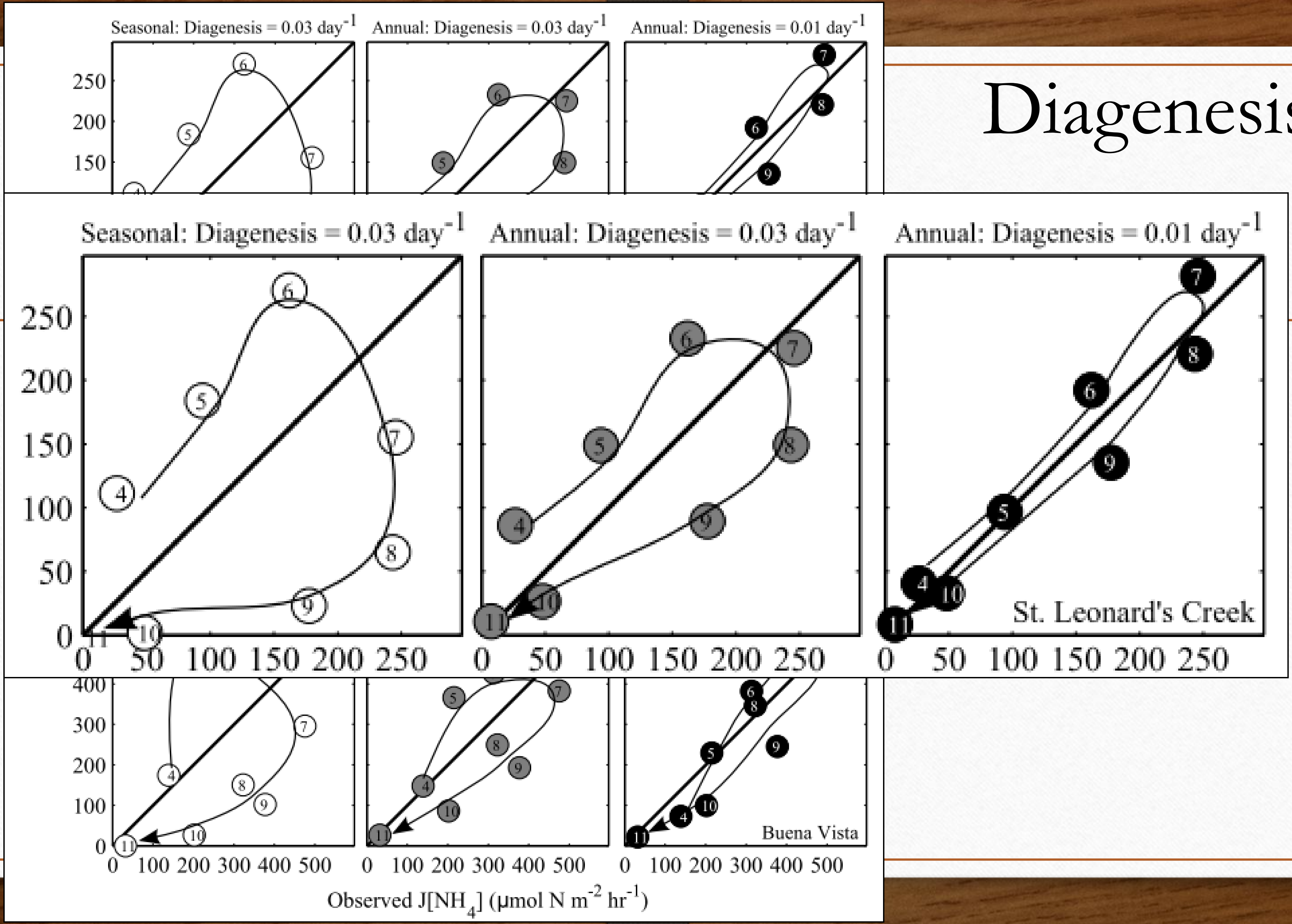
CHART 1. Descriptive flow diagram for pattern search

From Hooke and Jeeves 1960

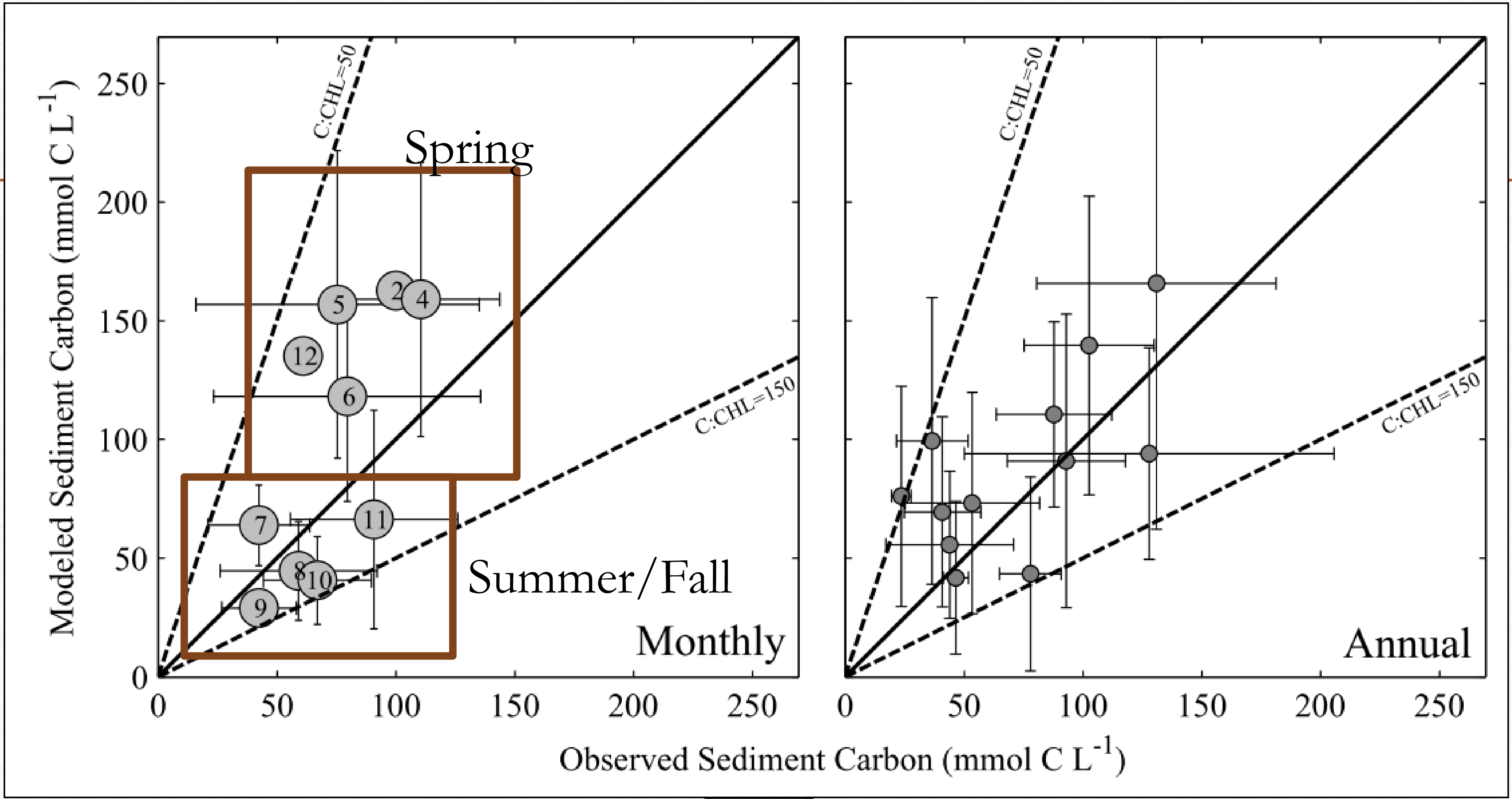
Deposition Estimates



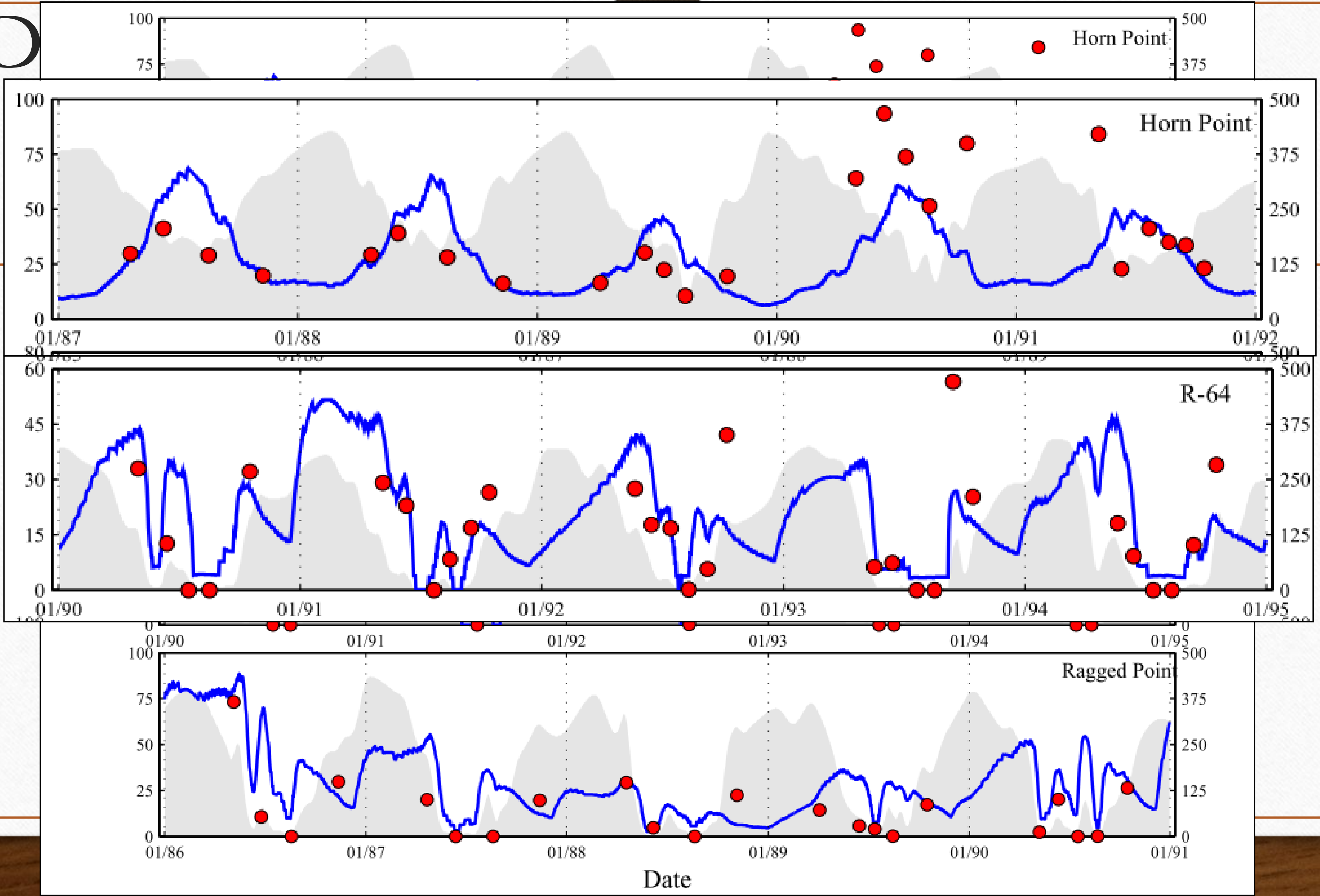
Diagenesis



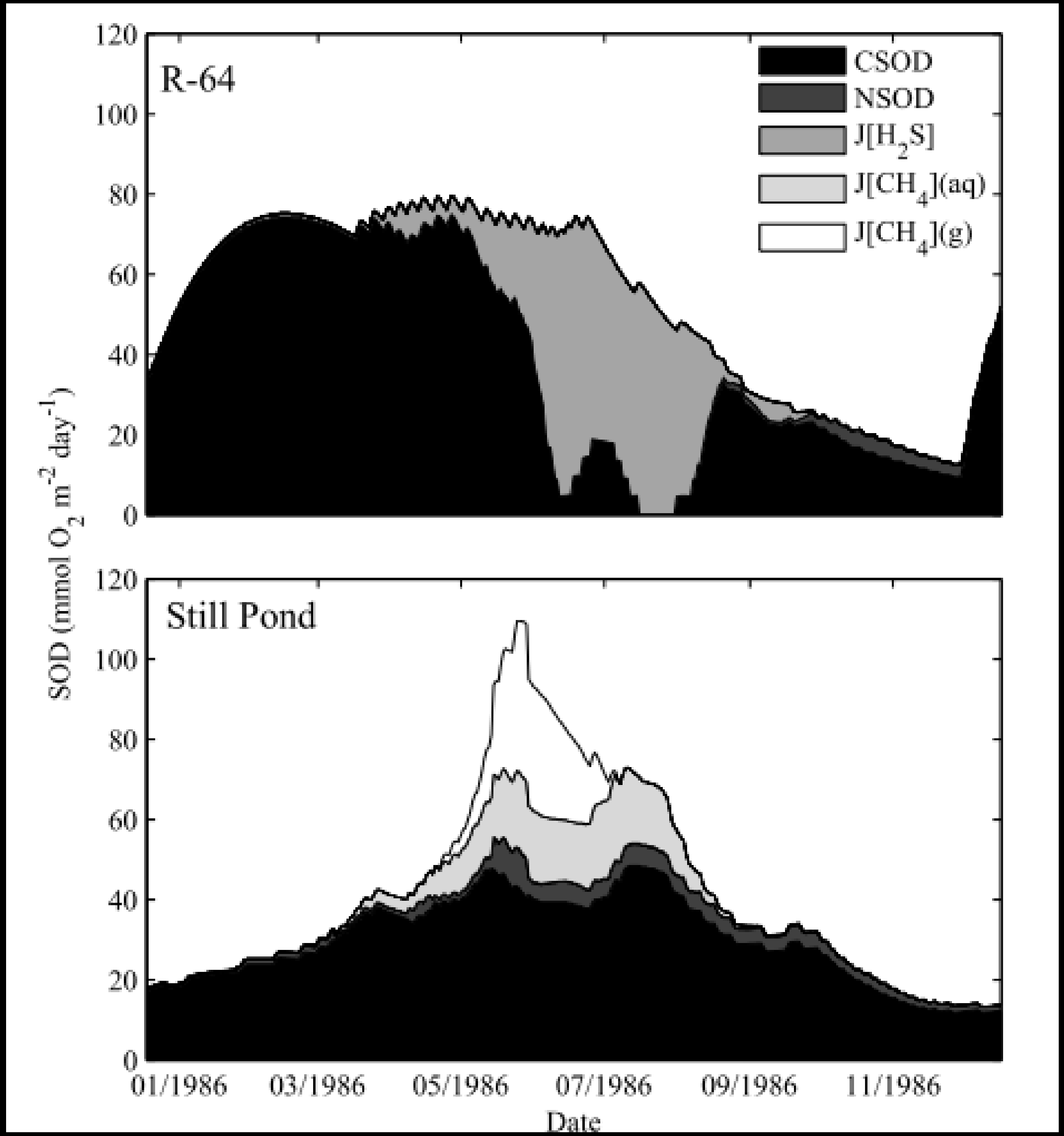
Seasonal: Diagenesis = 0.03 day^{-1}
Annual: Diagenesis = 0.03 day^{-1}
Annual: Diagenesis = 0.01 day^{-1}
St. Leonard's Creek
Buena Vista
Observed J[NH$_4$] (μmol N m^{-2} hr^{-1})


Modeled Sediment Carbon (mmol C L-1)
Observed Sediment Carbon (mmol C L-1)
C:CHL=50
C:CHL=150
Spring
Summer/Fall
Monthly
Annual
0
50
100
150
200
250
1
2
4
5
6
7
8
9
10
11
12

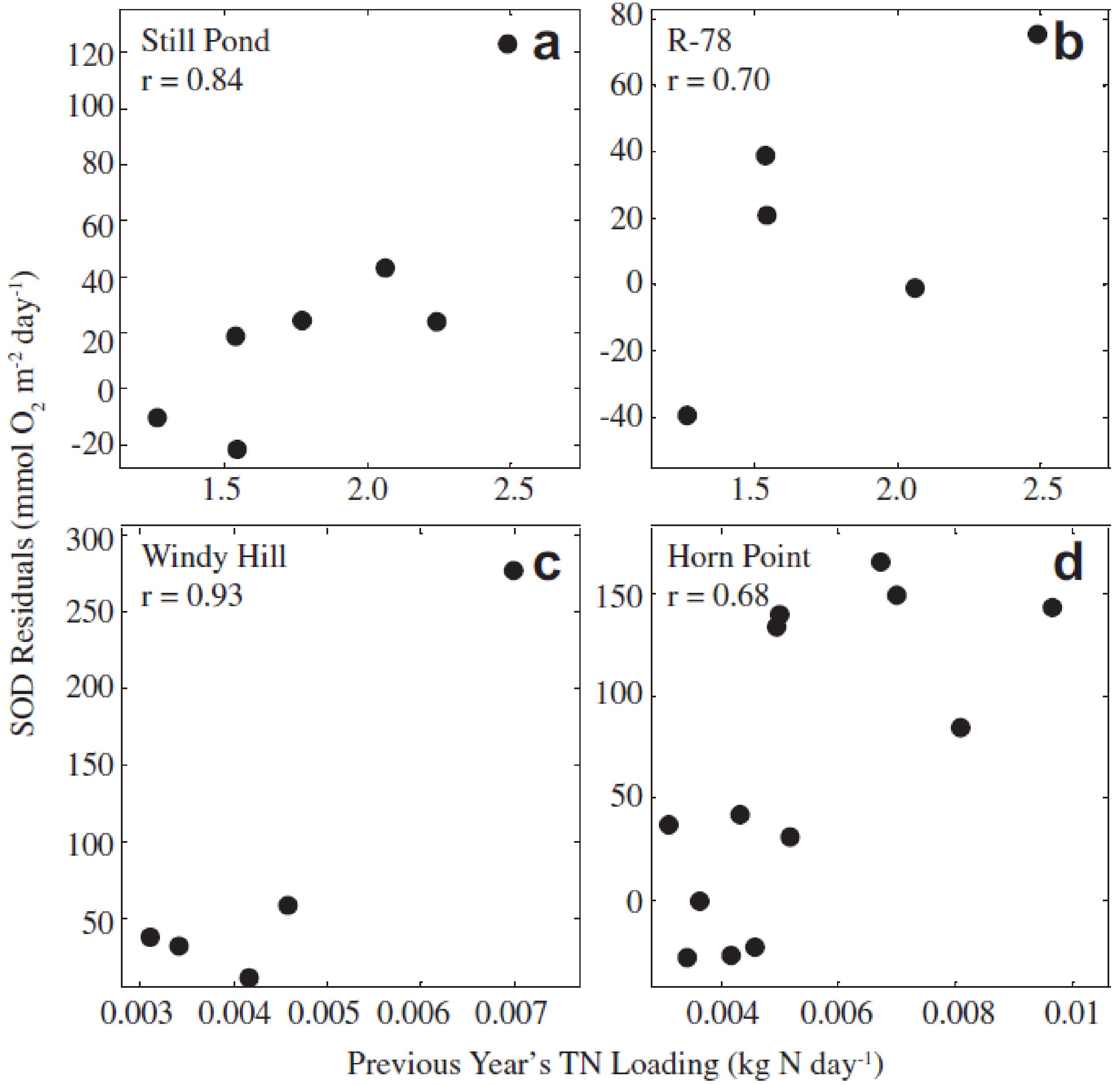
SOD



Horn Point
100
75
50
25
0
500
375
250
125
0
01/87
01/88
01/89
01/90
01/91
01/92
R-64
60
45
30
15
0
01/90
01/91
01/92
01/93
01/94
01/95
Ragged Point
01/86
Date

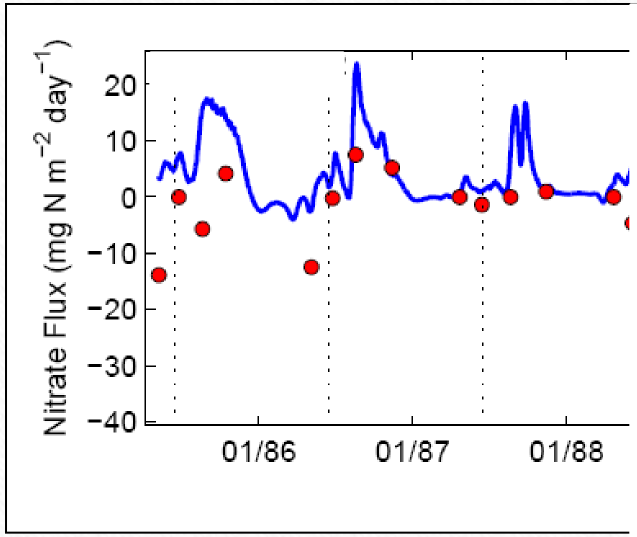


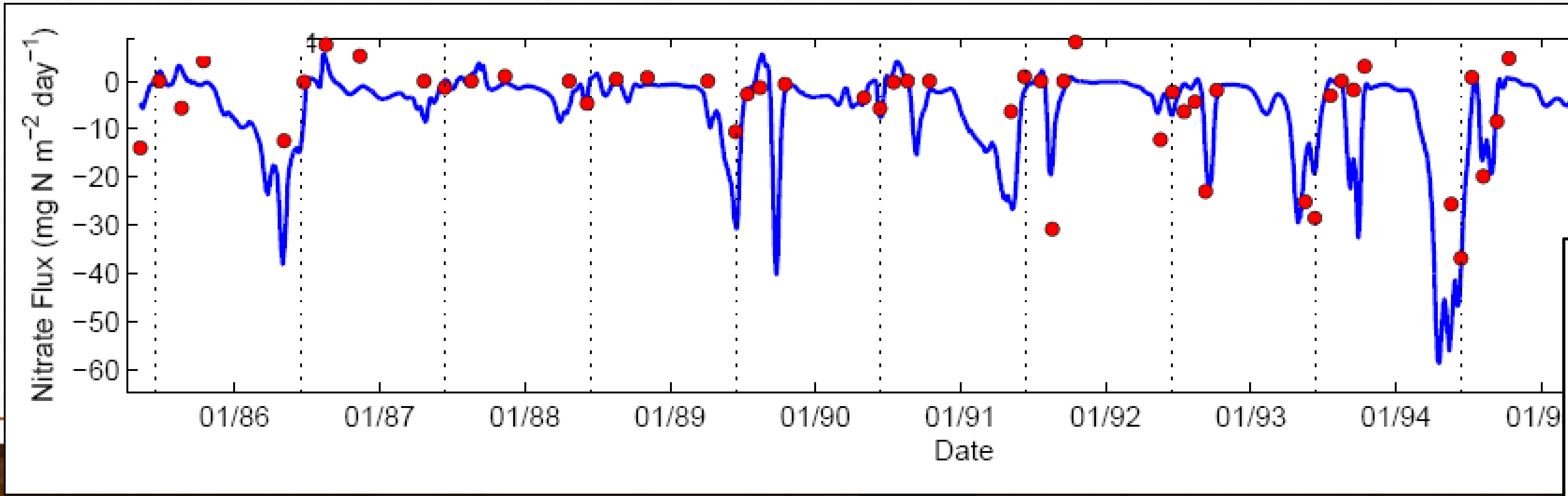
R-64
CSOD
NSOD
J[H2S]
J[CH4](aq)
J[CH4](g)
Still Pond
SOD (mmol O2 m-2 day-1)
0
20
40
60
80
100
120
01/1986
03/1986
05/1986
07/1986
09/1986
11/1986
Date



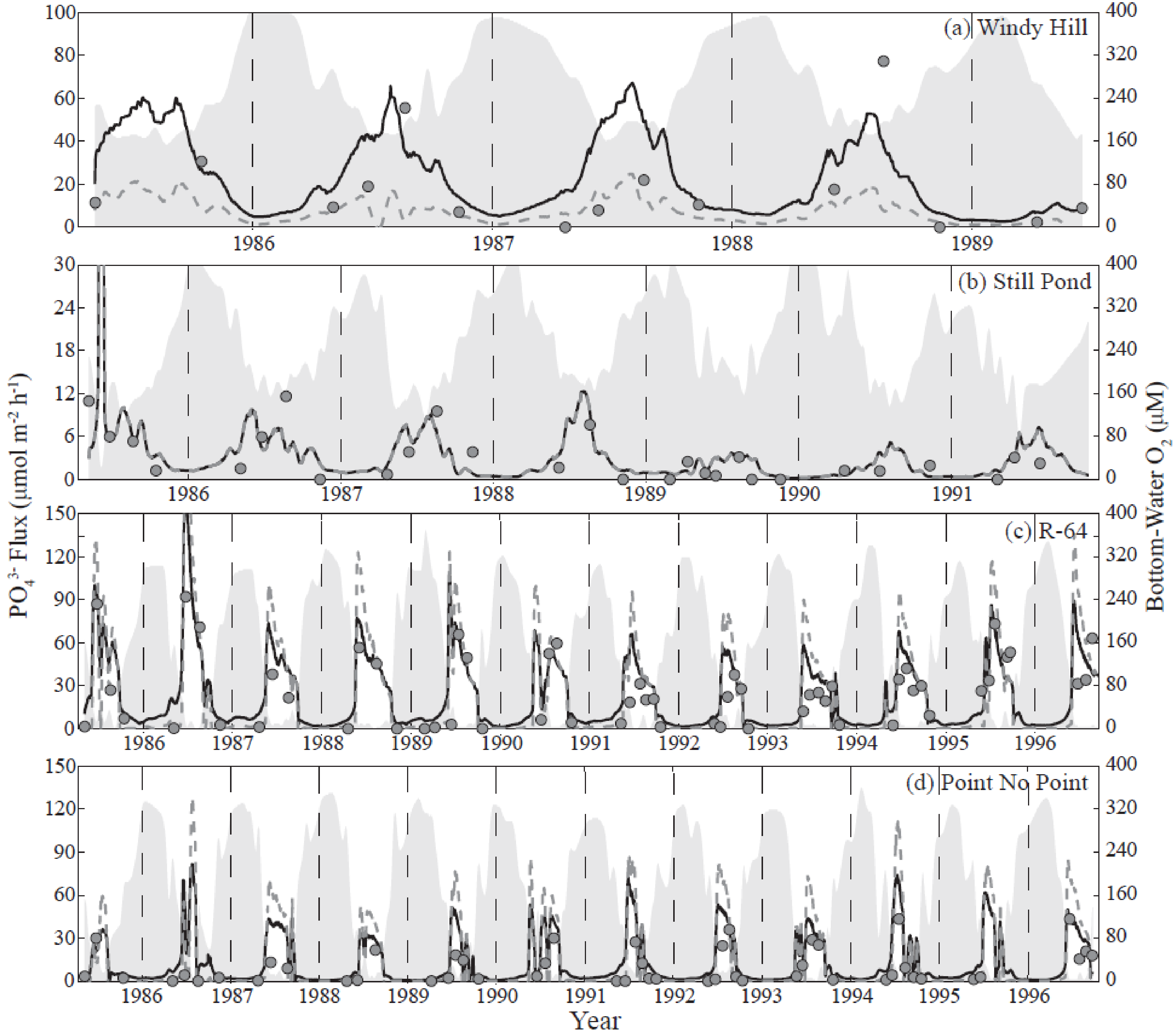
Allochthonous Carbon?

Elevated Aerobic Layer Denitrification Improves Nitrate Model





$K_{NO3,1} = 0.3$
$J_{N2} = 90\text{-}150$
$\mu mol\ m^{-2}\ h^{-1}$

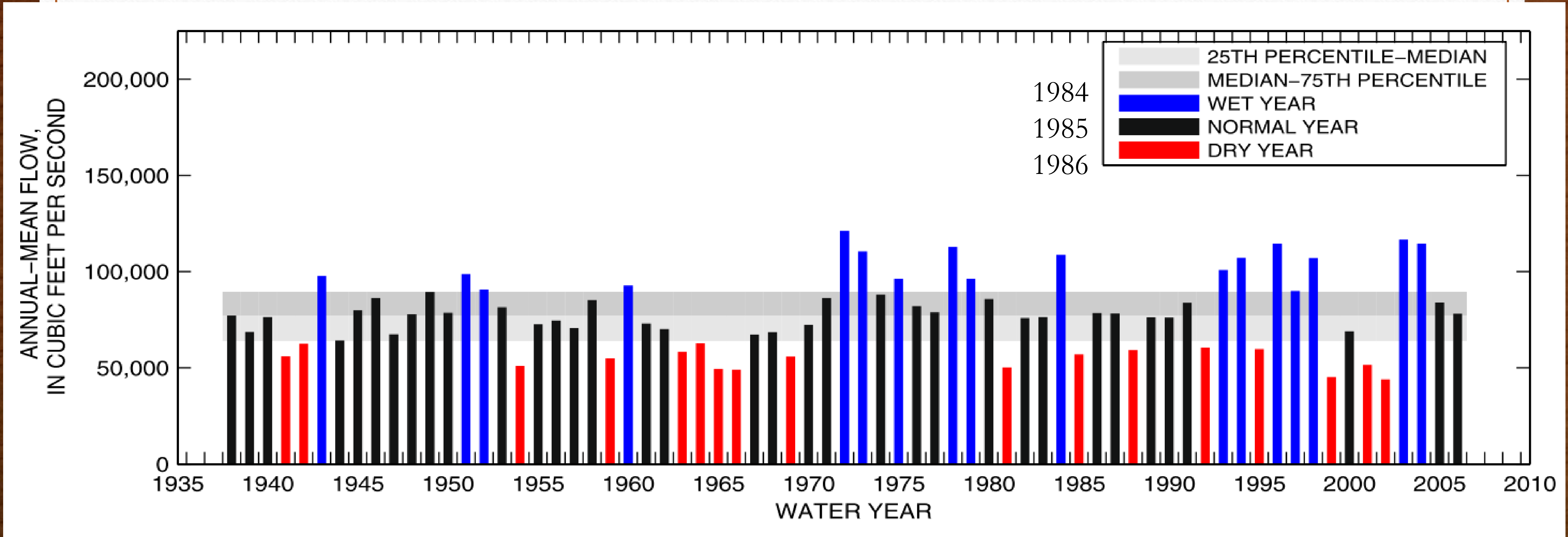


(a) Windy Hill
(b) Still Pond
(c) R-64
(d) Point No Point
PO4 3- Flux (µmol m-2 h-1)
Bottom-Water O2 (µM)
Year
1985
1986
1987
1988
1989
1990
1991
1992
1993
1994
1995
1996

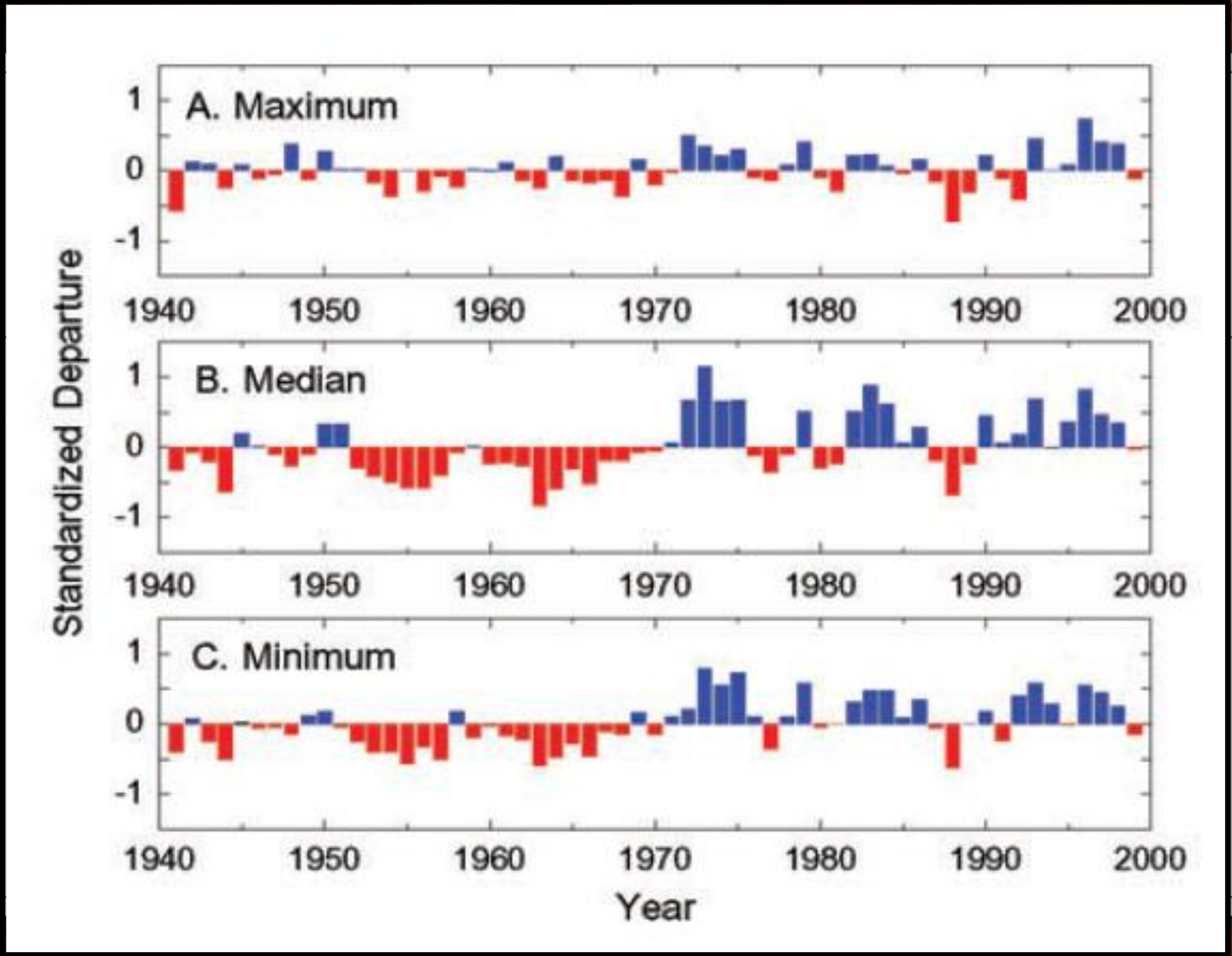
Improvements

- Take home: the model is very robust…there are indications of memory but not past one year
- Reduction in sediment diagenesis rate for labile carbon
- (1) the need for an aerobic-layer denitrification formulation to account for NO_3^- reduction in this zone
- (2) regional variability in denitrification that depends on oxygen levels in the overlying water
- (3) a regionally-dependent solid-solute PO_4^{3-} partitioning that accounts for patterns in Fe availability
- (4) a simplified model formulation for DSi, including limited sorption of DSi onto iron oxyhydroxides.

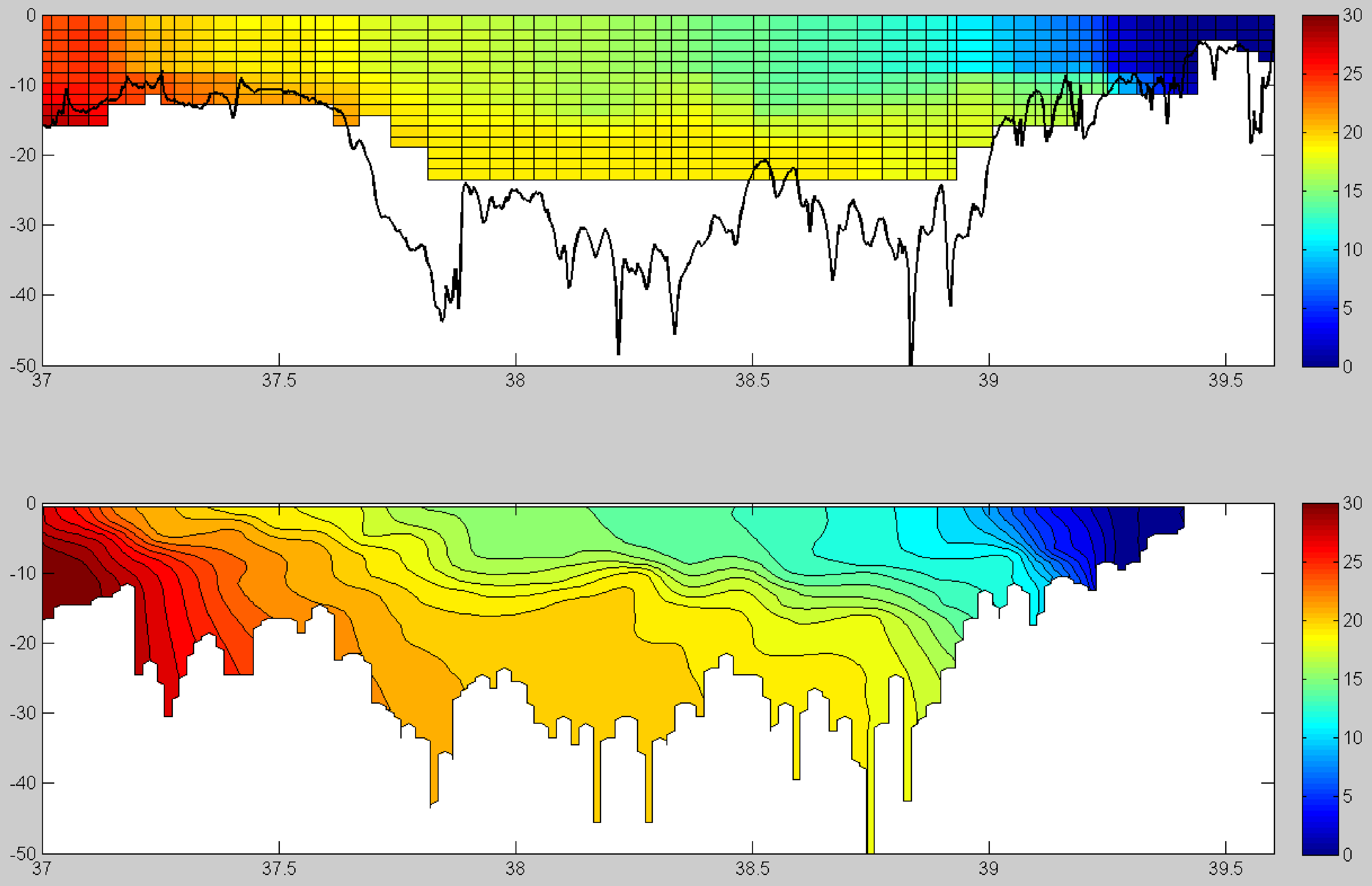
50 Year Simulation: Hydrodynamics

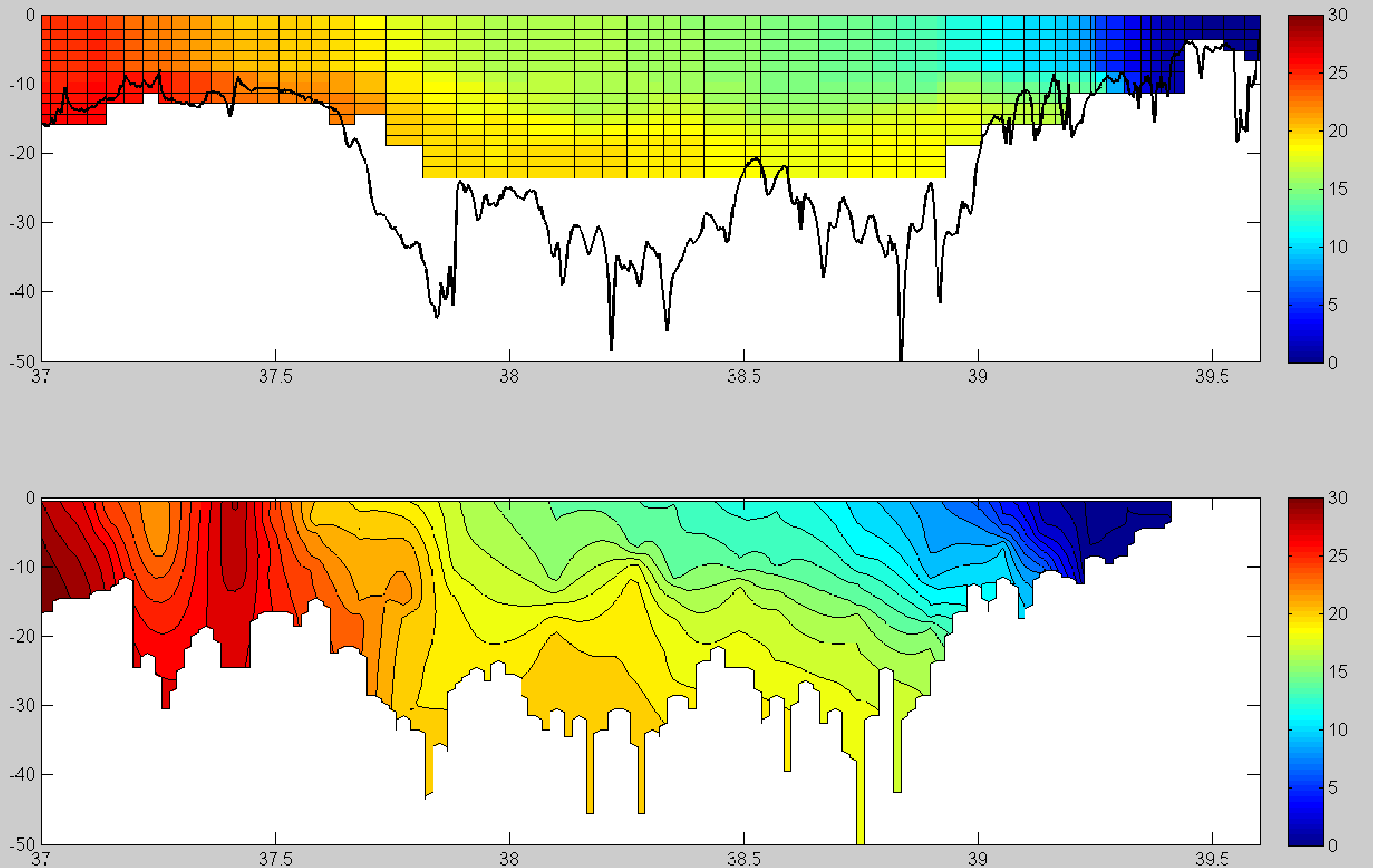


McCabe and Wolock 2001

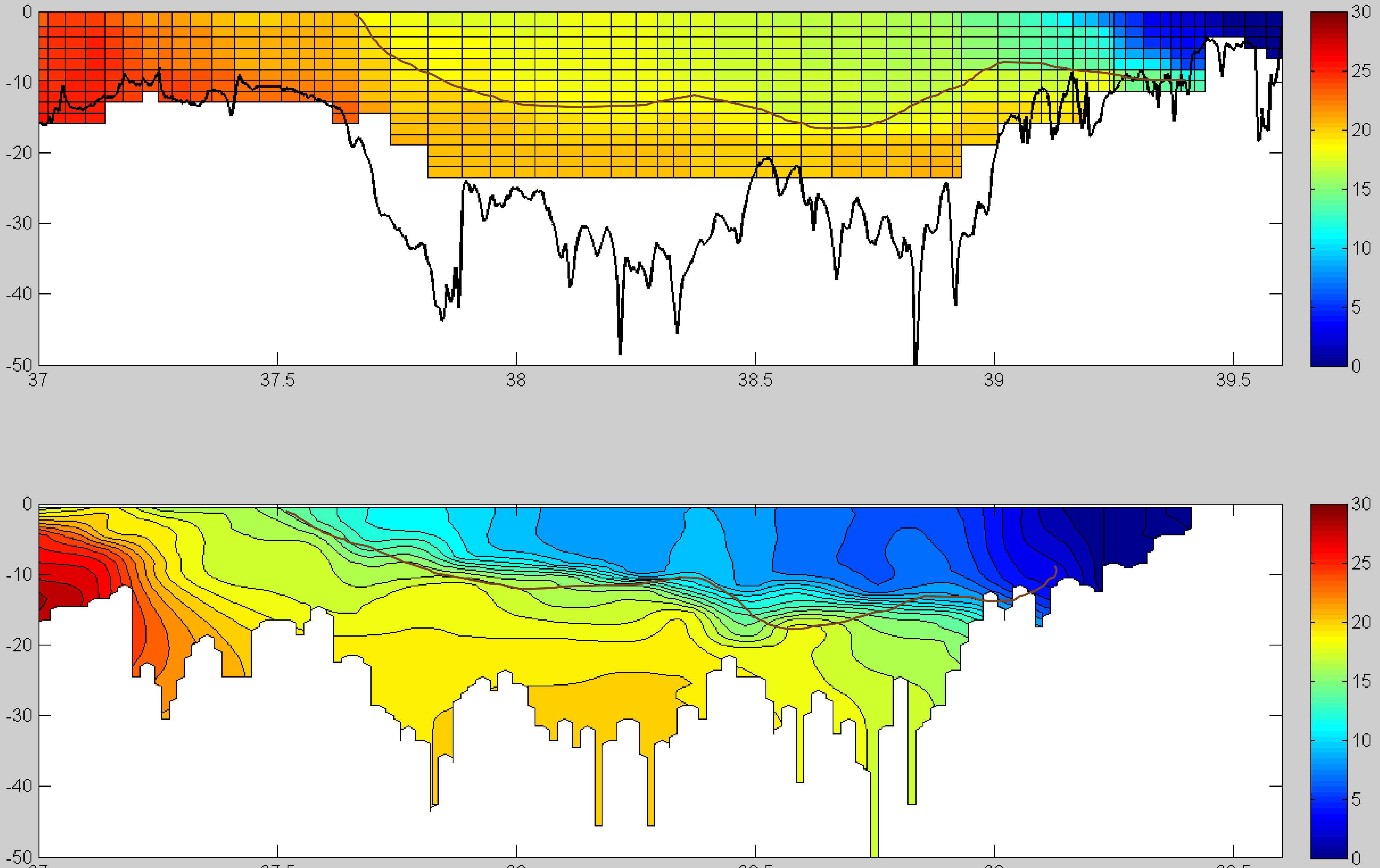


1985 dry

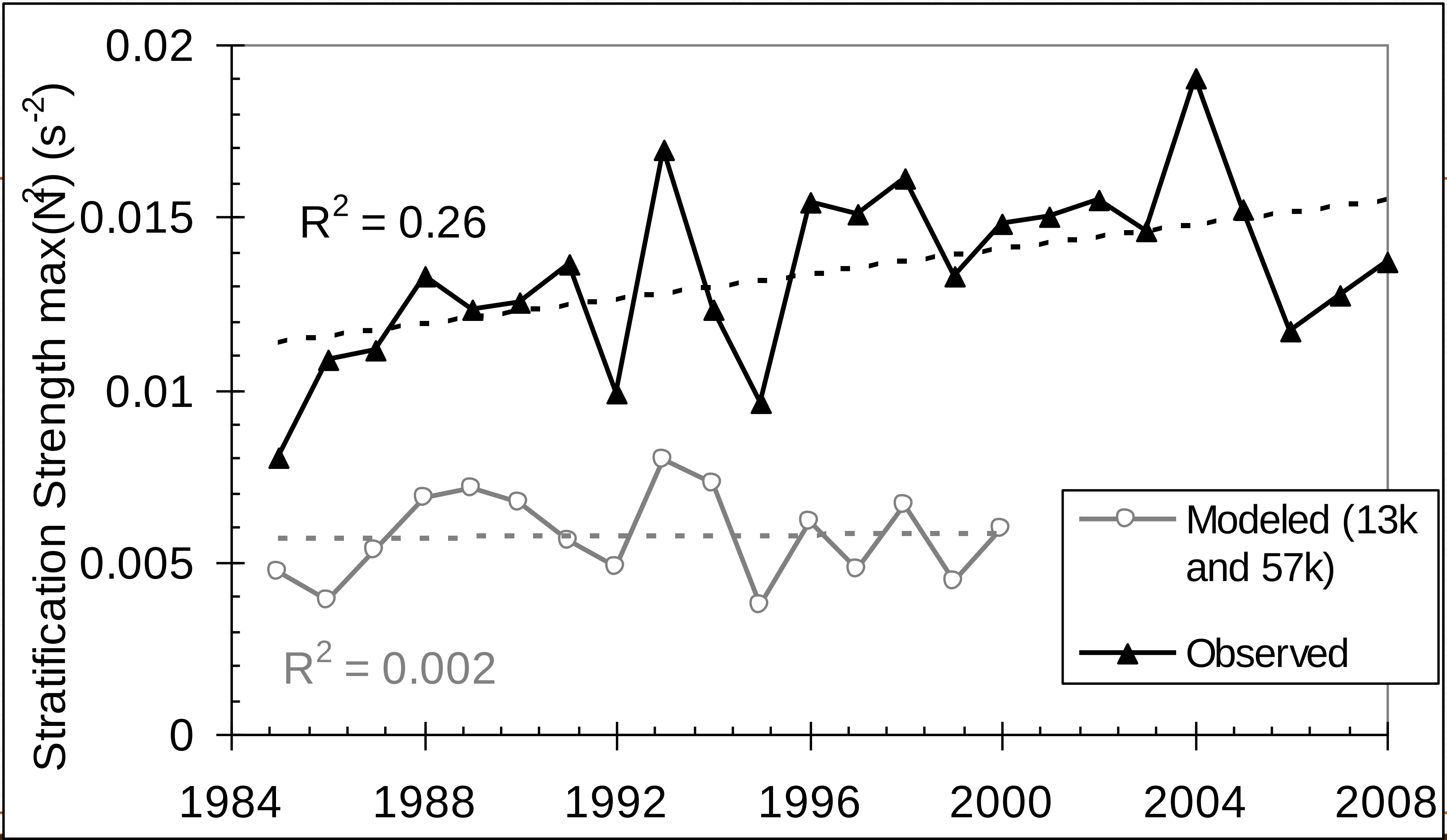




1986 Normal



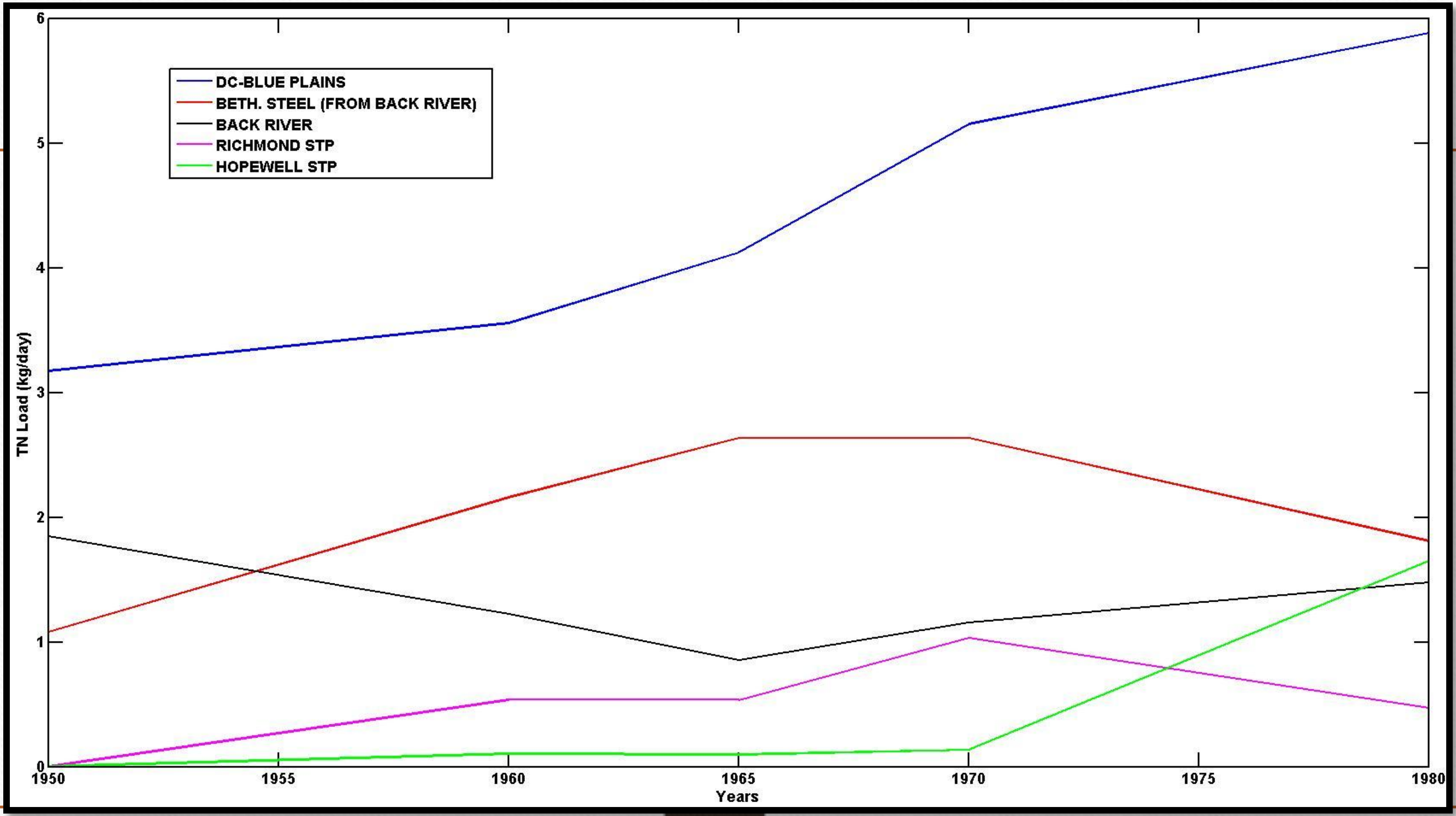
1996 wet


Stratification Strength max(N^2) (s^{-2})
0.02
0.015
0.01
0.005
0
1984
1988
1992
1996
2000
2004
2008
R^2 = 0.26
R^2 = 0.002
Modeled (13k and 57k)
Observed

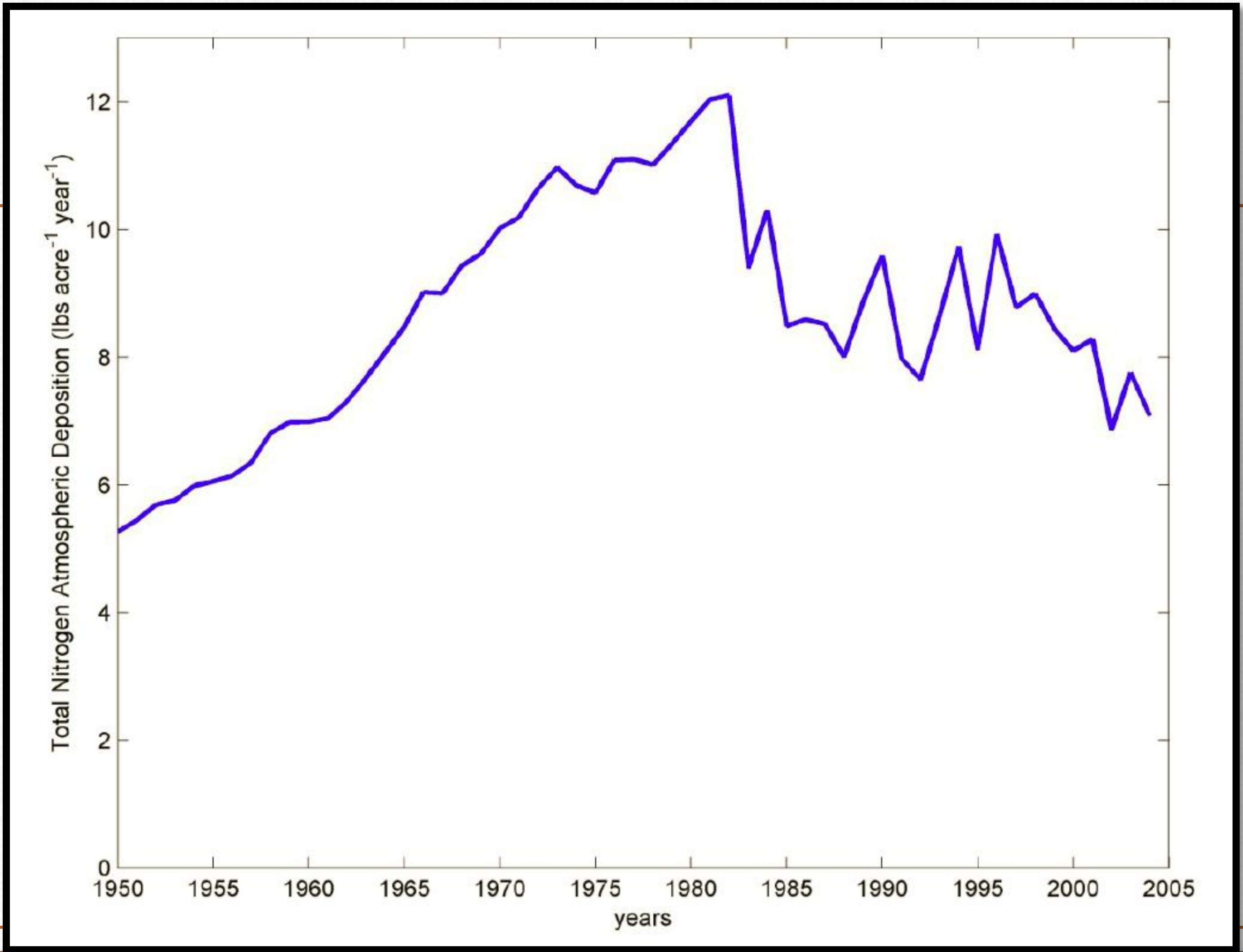
River Matching

Tributary Pair	Measure of Correlation					Match
	daily flow	daily TN concentration	daily TN load	flow-normalized daily TN concentration	flow-normalized daily TN load	
Appomattox & Susquehanna	0.42	-0.31	0.39	-0.4	0.86	
Appomattox & Potomac	0.62	-0.25	0.56	-0.67	0.88	Potomac
Appomattox & Patuxent	0.53	0.16	0.54	0.35	0.69	
Choptank & Susquehanna	0.4	0.25	0.41	0.3	0.87	
Choptank & Potomac	0.54	0.22	0.5	0.36	0.88	Patuxent
Choptank & Patuxent	0.7	-0.5	0.67	-0.57	0.69	
James & Susquehanna	0.5	0.31	0.38	0.56	0.73	
James & Potomac	0.78	0.65	0.71	0.58	0.84	Potomac
James & Patuxent	0.62	0.096	0.55	0.63	0.65	
Mattaponi & Susquehanna	0.5	-0.095	0.48	-0.21	0.91	
Mattaponi & Potomac	0.65	0.078	0.56	-0.04	0.87	Potomac
Mattaponi & Patuxent	0.49	-0.025	0.55	-0.064	0.71	
Pamunkey & Susquehanna	0.47	-0.41	0.45	-0.62	0.86	
Pamunkey & Potomac	0.71	-0.022	0.64	-0.38	0.89	Potomac
Pamunkey & Patuxent	0.56	-0.32	0.59	-0.32	0.67	
Rappahannock & Susquehanı	0.39	0.45	0.33	0.78	0.7	Potomac
Rappahannock & Potomac	0.66	0.8	0.58	0.87	0.78	or
Rappahannock & Patuxent	0.72	-0.17	0.66	0.18	0.64	Patuxent
Patuxent & Susquehanna	0.42	0.19	0.45	0.31	0.74	
Patuxent & Potomac	0.61	-0.073	0.57	0.15	0.72	
Susquehanna & Potomac	0.68	0.64	0.62	0.9	0.91	

Historical Point Sources

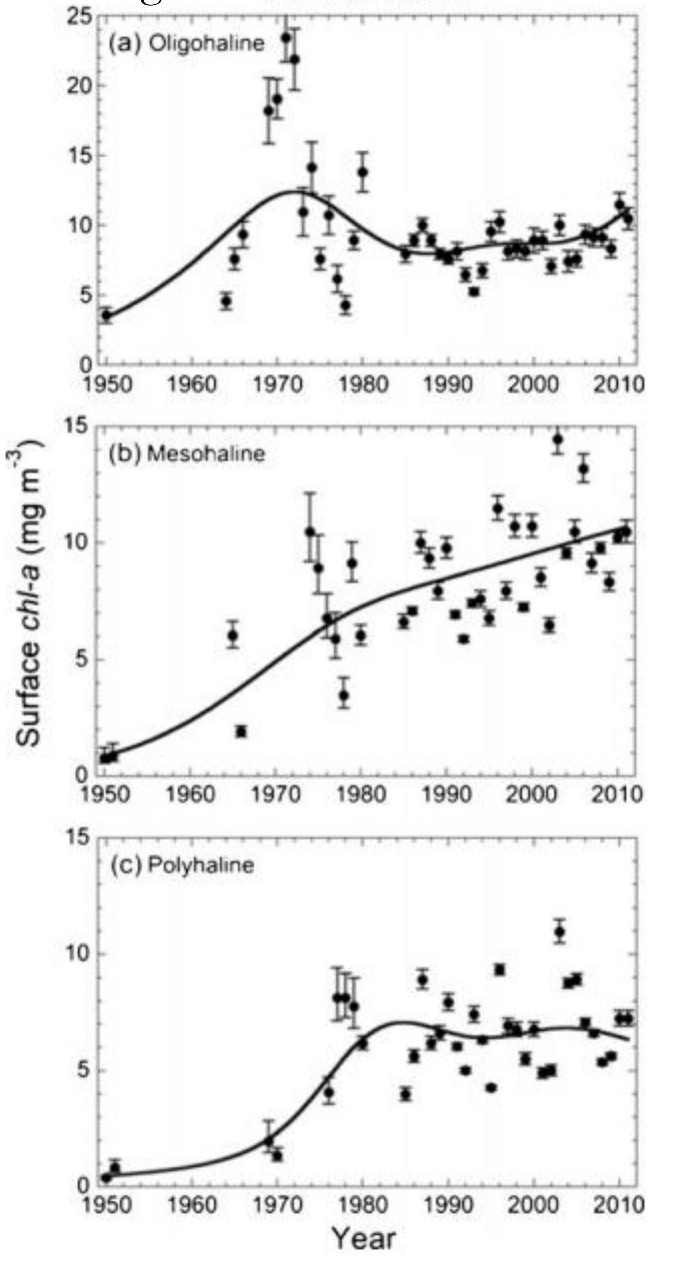


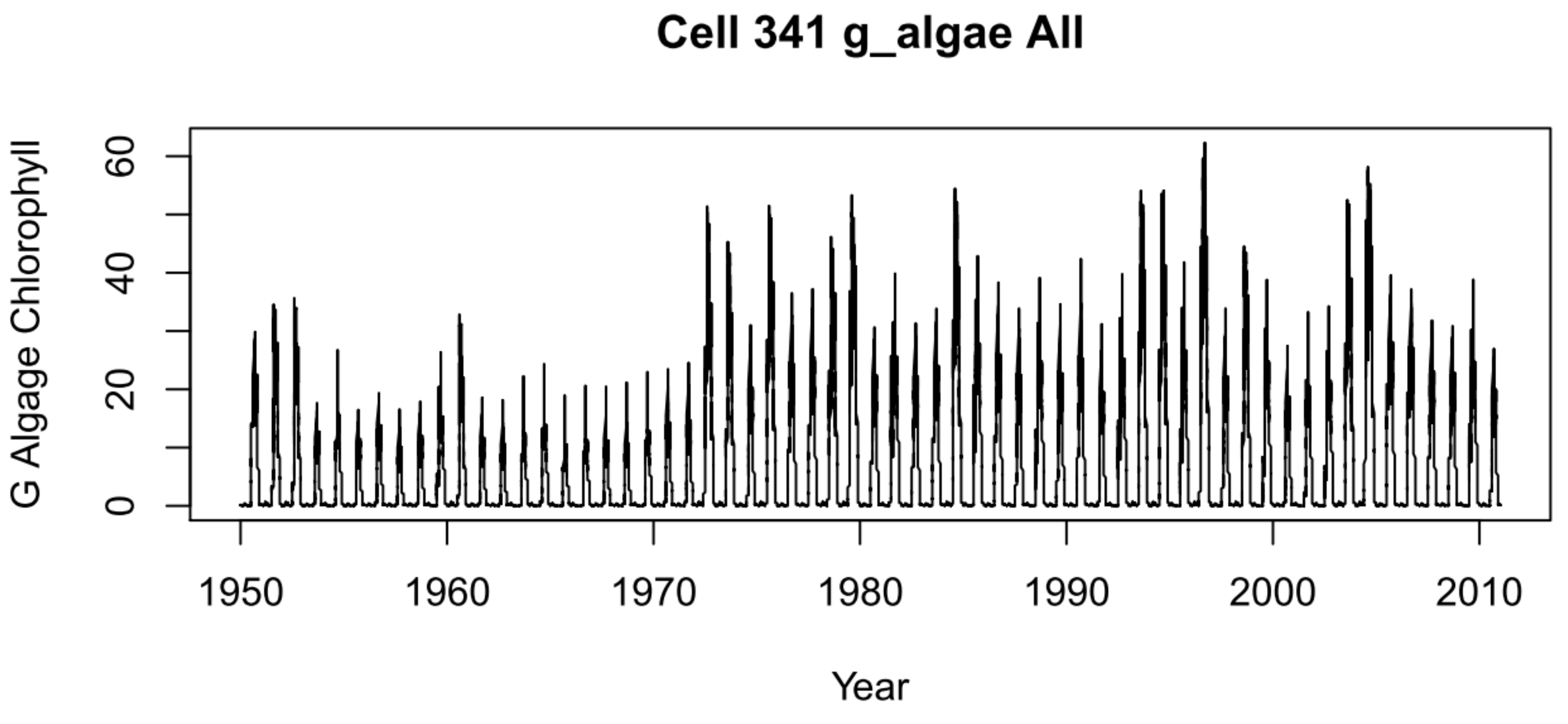
Atmospheric Deposition



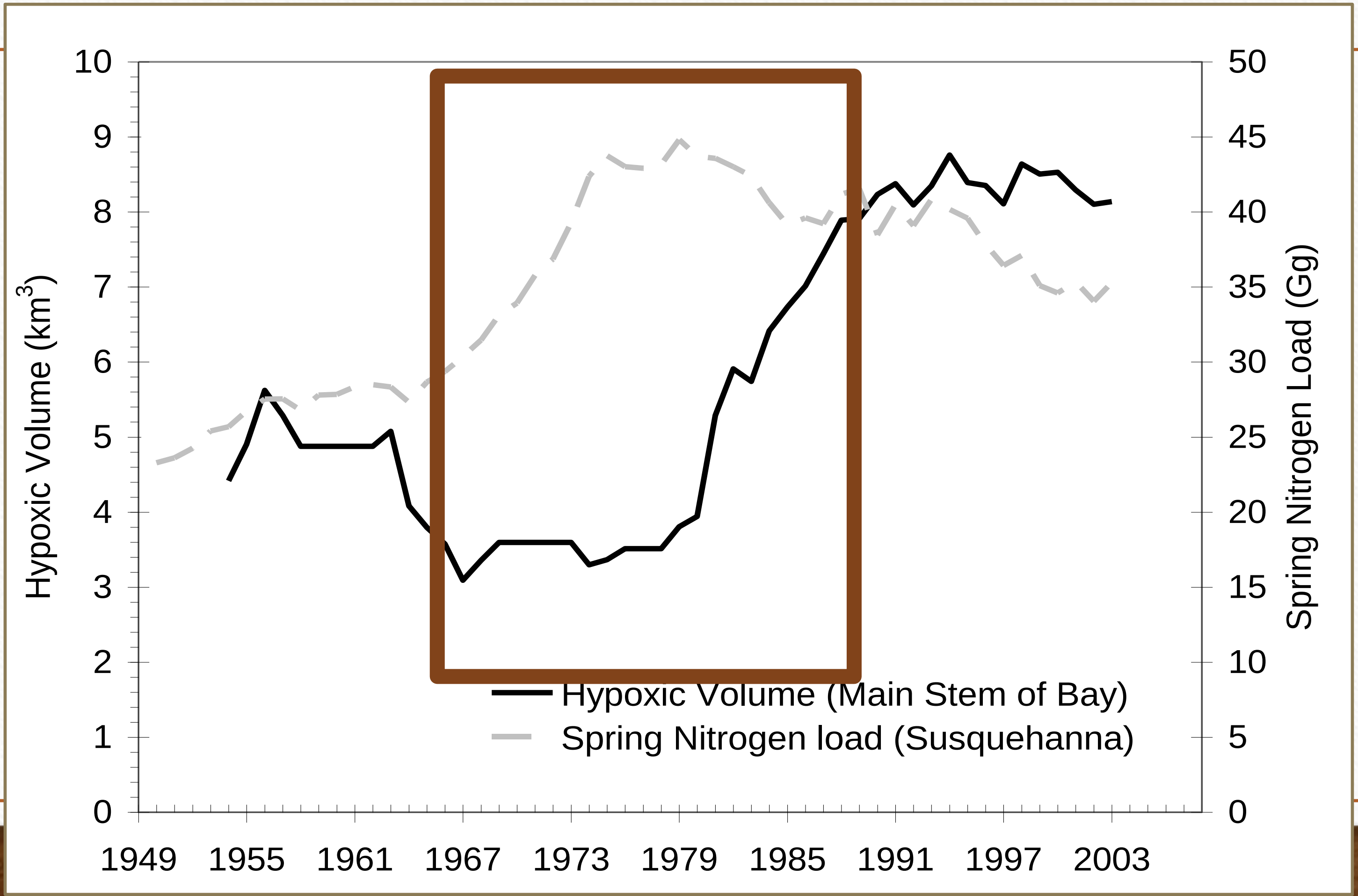
Surface CHL

Harding et al

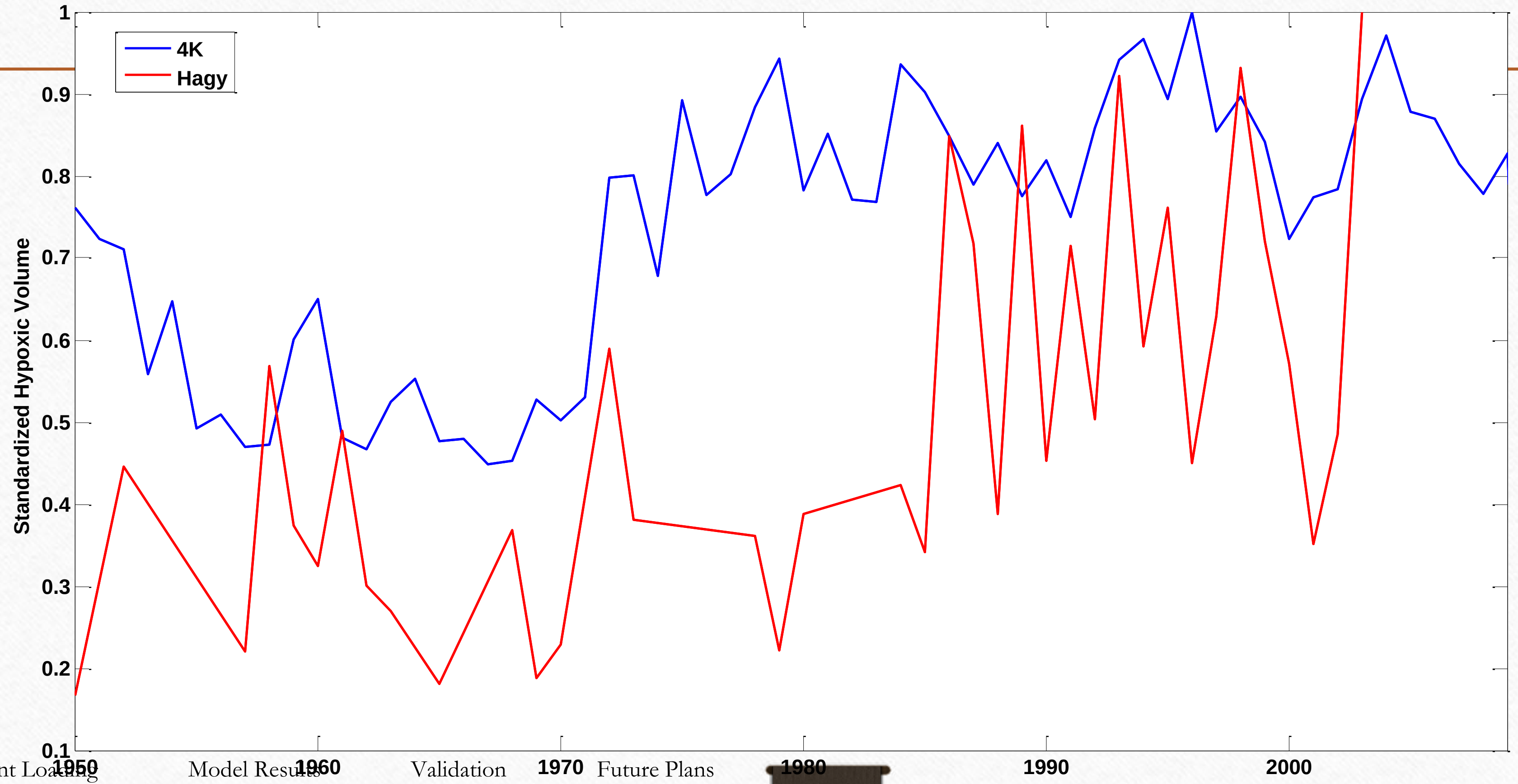




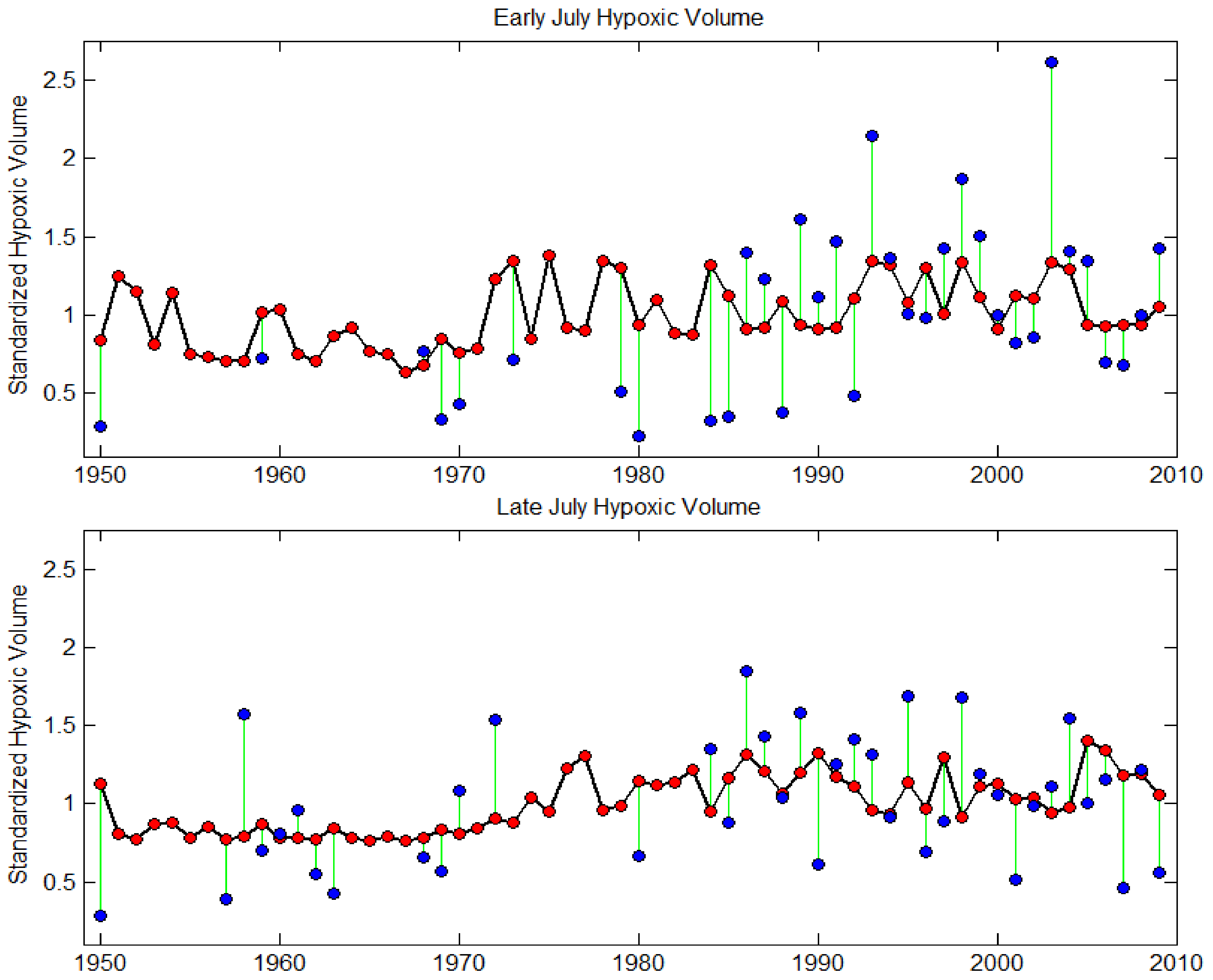
Moving Average

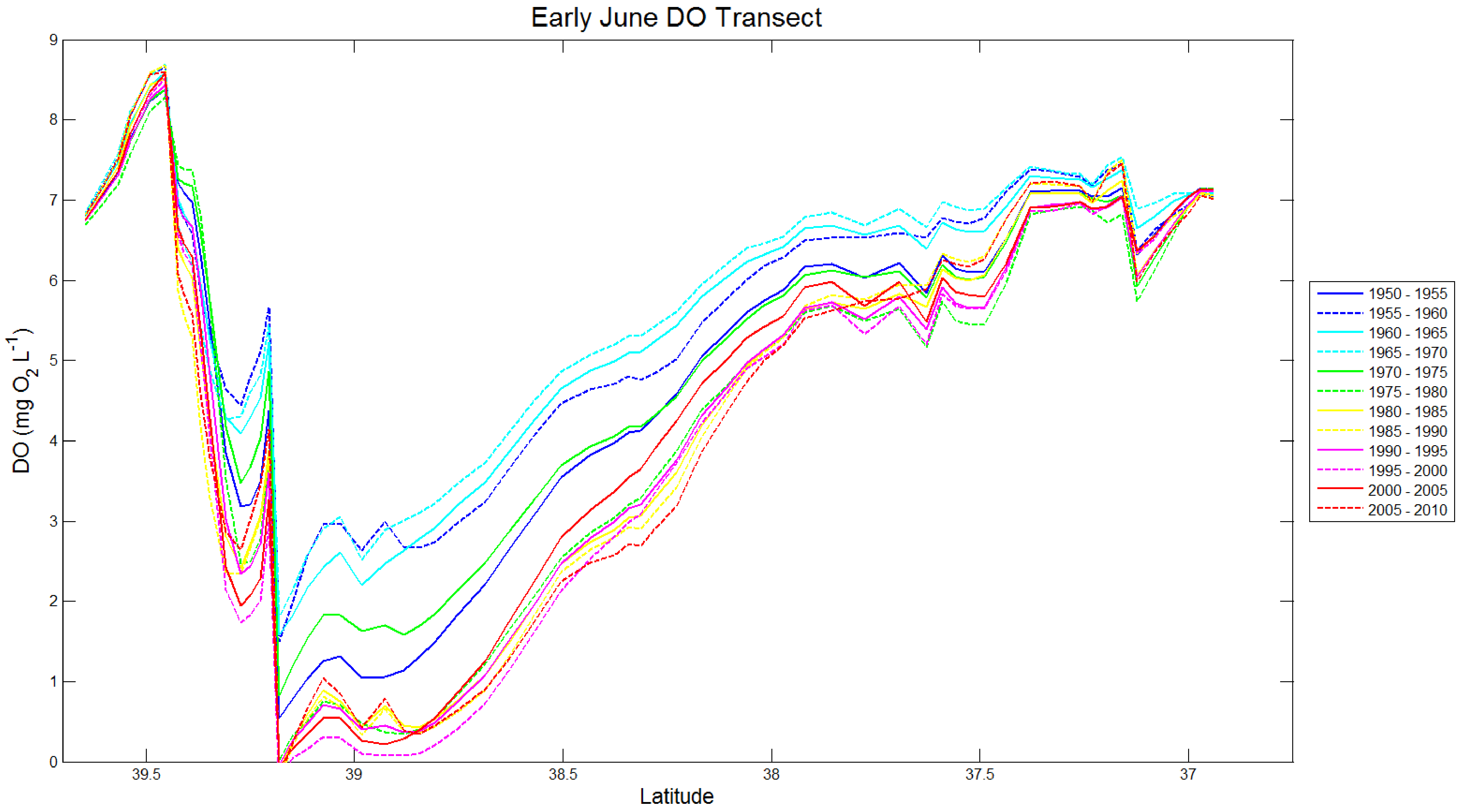


Standardized Hypoxic Volume

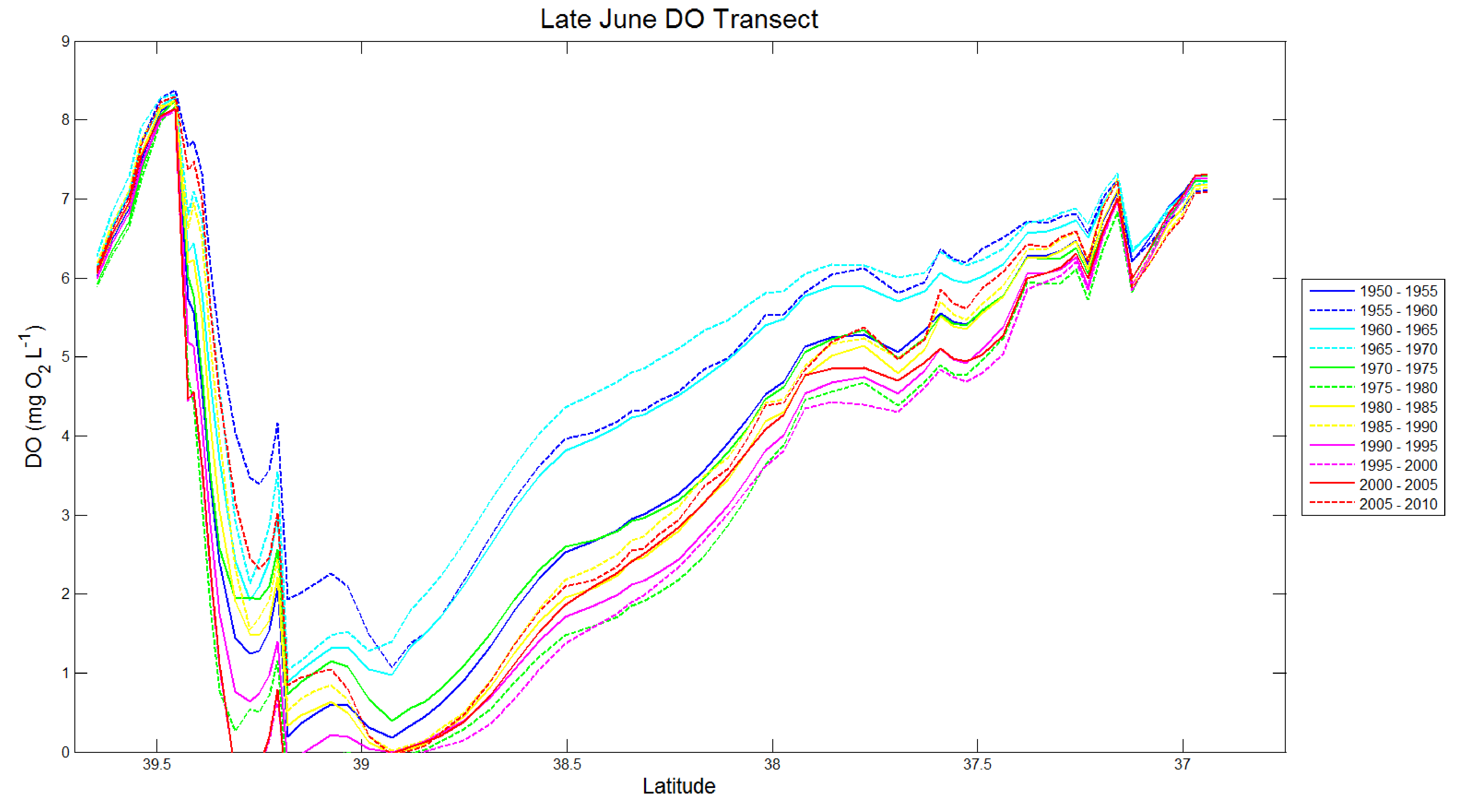


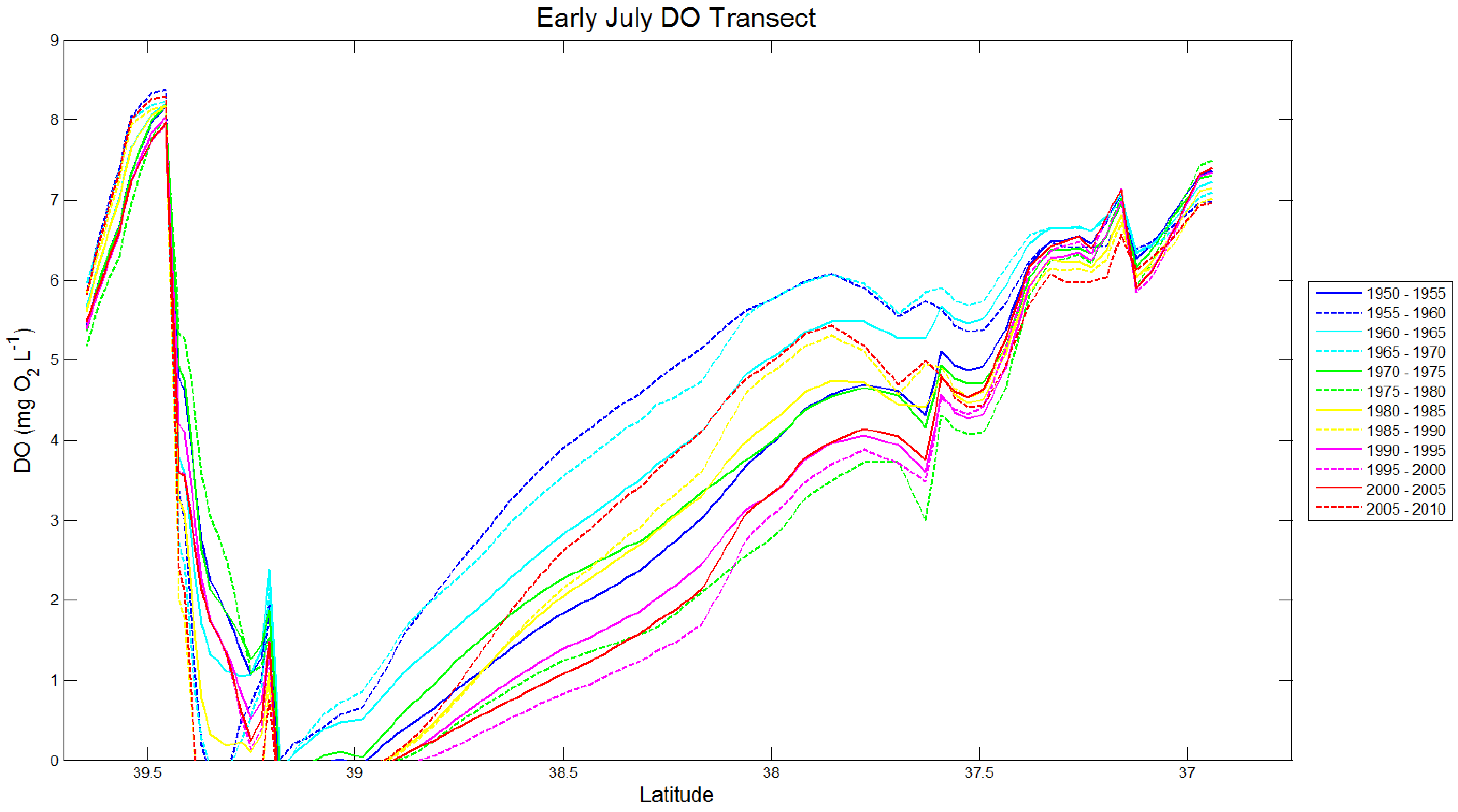
Nutrient Loading Model Results Validation Future Plans


Early July Hypoxic Volume
Standardized Hypoxic Volume
2.5
2
1.5
1
0.5
1950
1960
1970
1980
1990
2000
2010
Late July Hypoxic Volume
Standardized Hypoxic Volume
2.5
2
1.5
1
0.5
1950
1960
1970
1980
1990
2000
2010

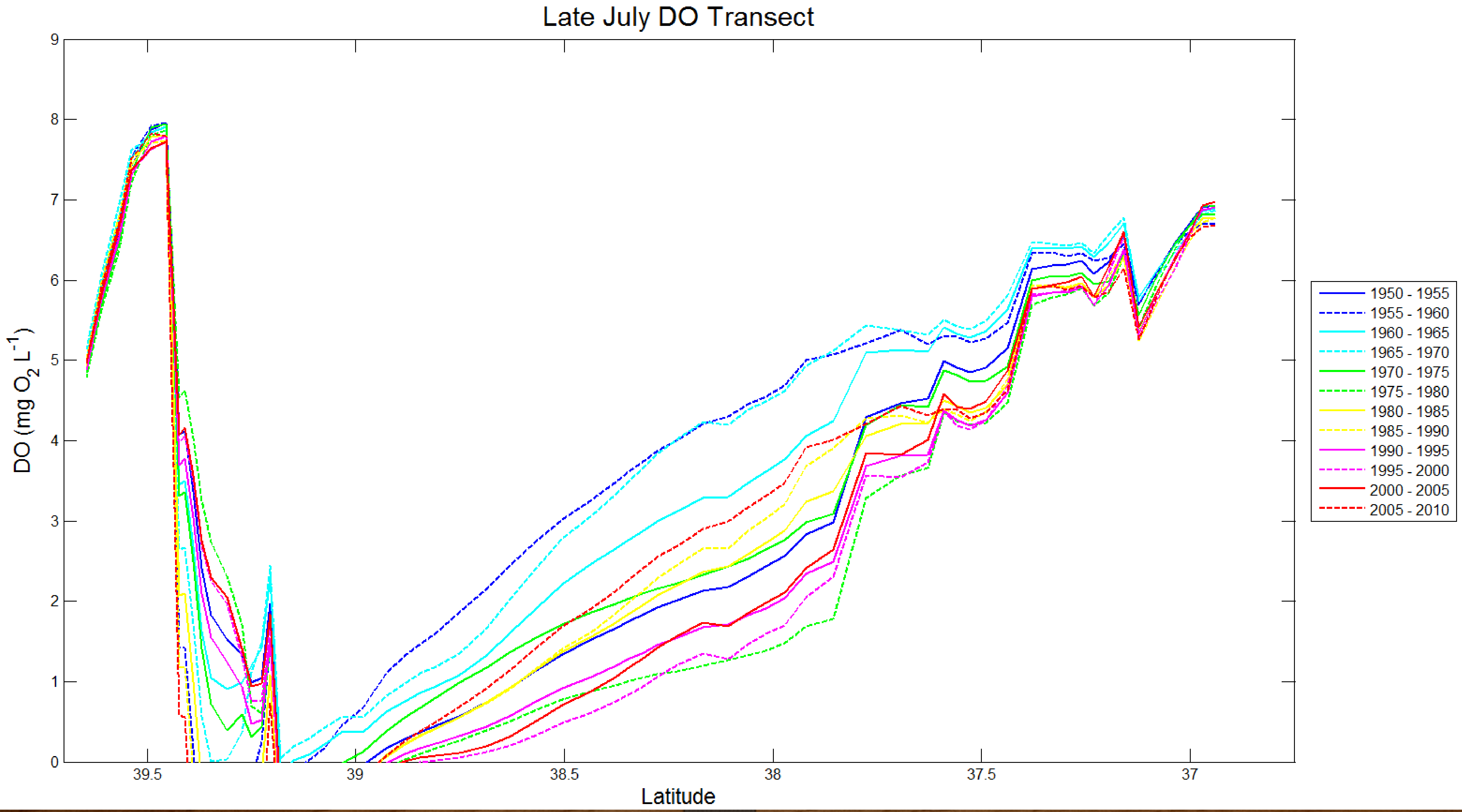


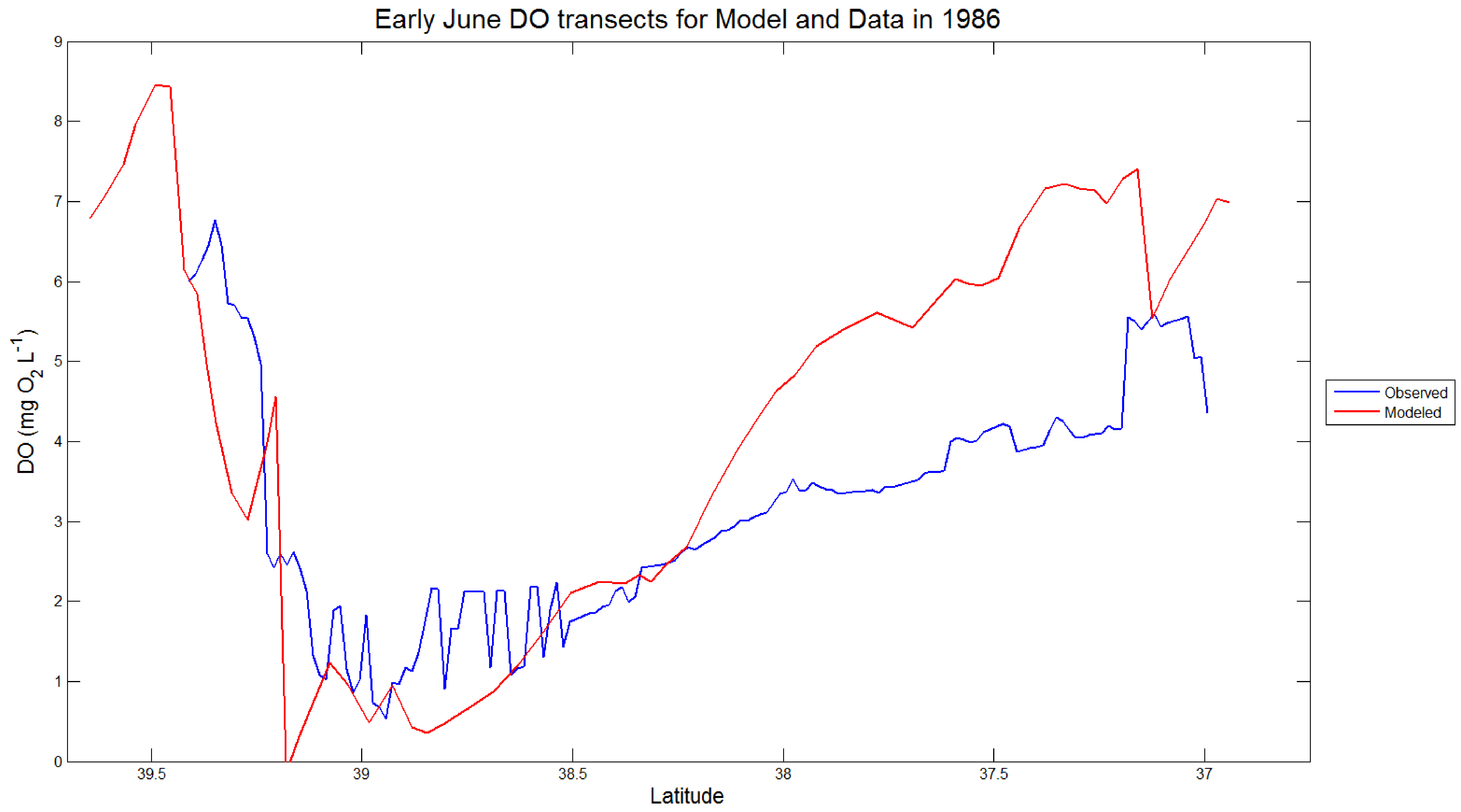
Early June DO Transect
DO (mg O_2 L^{-1})
Latitude
9
8
7
6
5
4
3
2
1
0
39.5
39
38.5
38
37.5
37
1950 - 1955
1955 - 1960
1960 - 1965
1965 - 1970
1970 - 1975
1975 - 1980
1980 - 1985
1985 - 1990
1990 - 1995
1995 - 2000
2000 - 2005
2005 - 2010

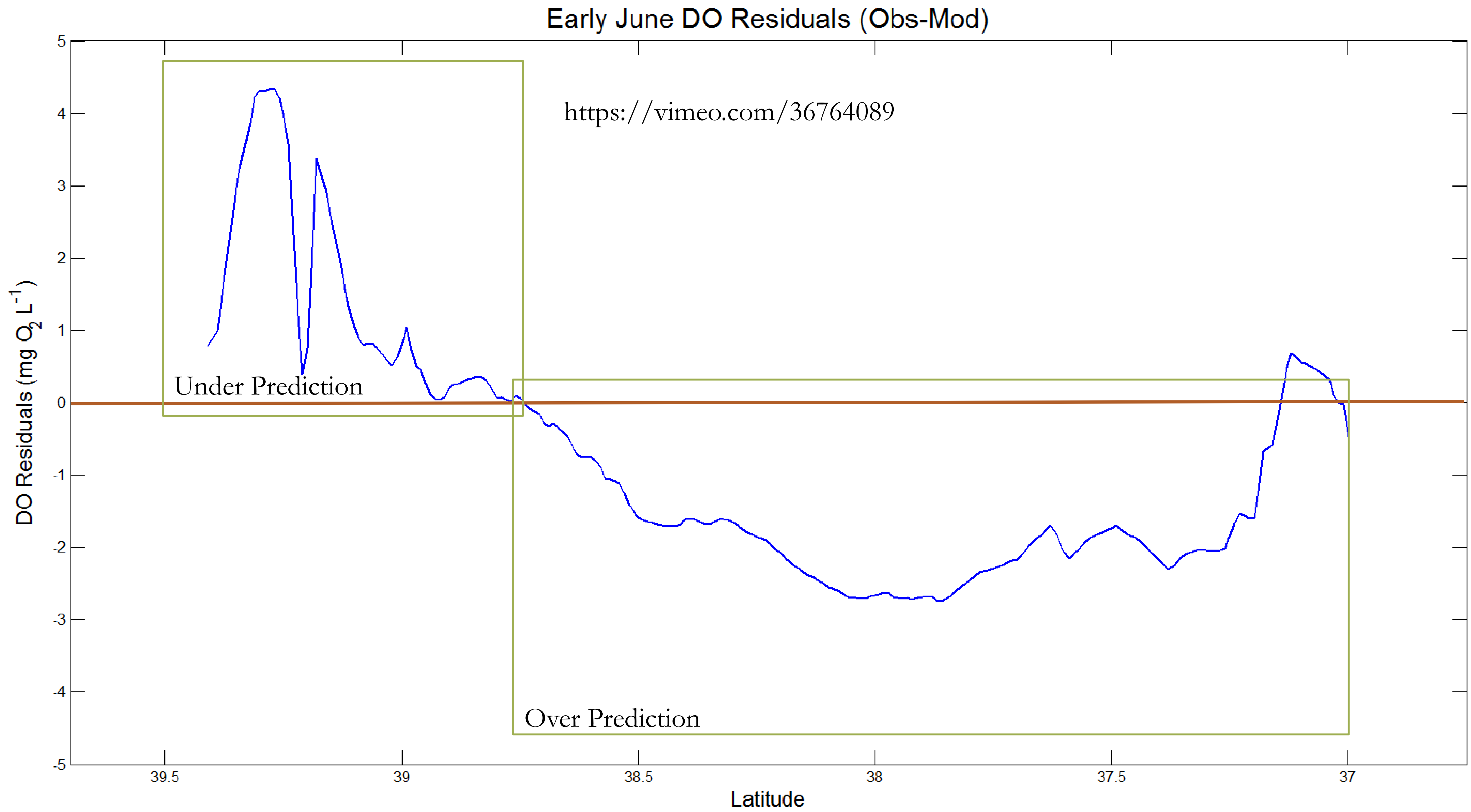

Late June DO Transect
DO (mg O2 L-1)
Latitude
9
8
7
6
5
4
3
2
1
0
39.5
39
38.5
38
37.5
37
1950 - 1955
1955 - 1960
1960 - 1965
1965 - 1970
1970 - 1975
1975 - 1980
1980 - 1985
1985 - 1990
1990 - 1995
1995 - 2000
2000 - 2005
2005 - 2010



Early July DO Transect
DO (mg O_2 L^{-1})
Latitude
9
8
7
6
5
4
3
2
1
0
39.5
39
38.5
38
37.5
37
1950 - 1955
1955 - 1960
1960 - 1965
1965 - 1970
1970 - 1975
1975 - 1980
1980 - 1985
1985 - 1990
1990 - 1995
1995 - 2000
2000 - 2005
2005 - 2010


Late July DO Transect
DO (mg O_2 L^{-1})
9
8
7
6
5
4
3
2
1
0
39.5
39
38.5
38
37.5
37
Latitude
1950 - 1955
1955 - 1960
1960 - 1965
1965 - 1970
1970 - 1975
1975 - 1980
1980 - 1985
1985 - 1990
1990 - 1995
1995 - 2000
2000 - 2005
2005 - 2010


Early June DO transects for Model and Data in 1986
DO (mg O_2 L^{-1})
Latitude
9
8
7
6
5
4
3
2
1
0
39.5
39
38.5
38
37.5
37
Observed
Modeled



Early June DO Residuals (Obs-Mod)
https://vimeo.com/36764089
Under Prediction
Over Prediction
DO Residuals (mg O2 L-1)
Latitude
5
4
3
2
1
0
-1
-2
-3
-4
-5
39.5
39
38.5
38
37.5
37

Thank you

- Many Thanks to NOAA Coastal Hypoxia Research Program
- …and the Water Environment Research Federation (WERF)