Tributary hypoxia- is it locally initiated or primarily under Bay's Influence?

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Outline

- Background

- Part 1: Initiation of Hypoxia in the Maryland Tributaries (by Isaac Irby)

- Part 2: Overview of Tributary Hypoxia dynamics

  (by Harry Wang)

Part 1

Initiation of Hypoxia in the Maryland Tributaries

Ike Irby, Graduate Student
Marjy Friedrichs, Advisor
Harry Wang
7/24/2013

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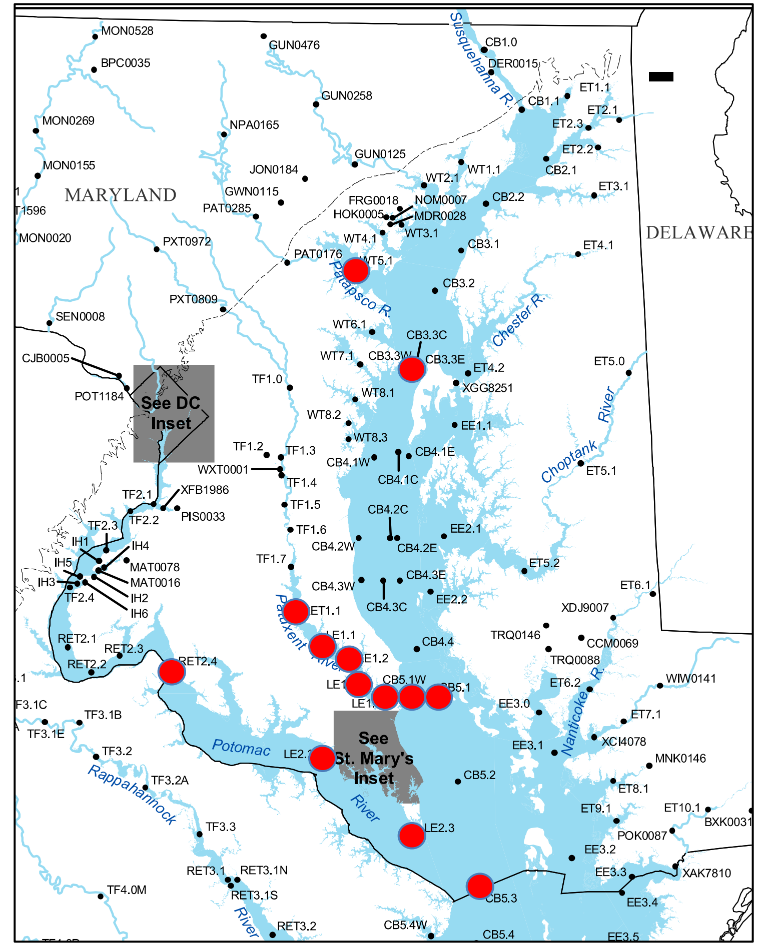
Focus of Project

- Is hypoxia initiated within the individual Maryland tributaries, or is it advected in from the main stem of the Chesapeake Bay?
  - Look at hypoxia initiation date and duration characteristics using CBP WQ monitoring data

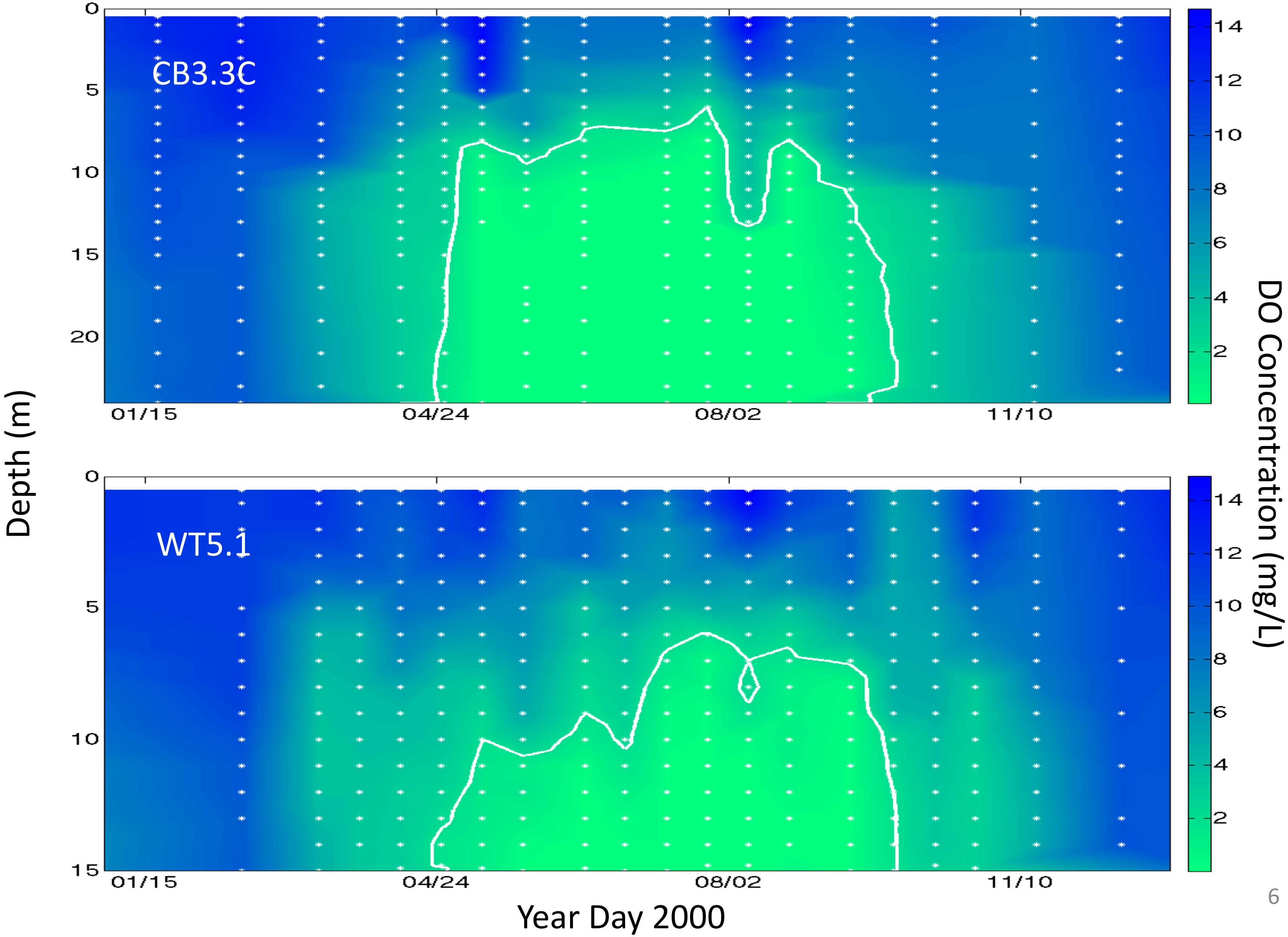
→ **Hypoxia is typically initiated within the individual tributaries.**

Outline

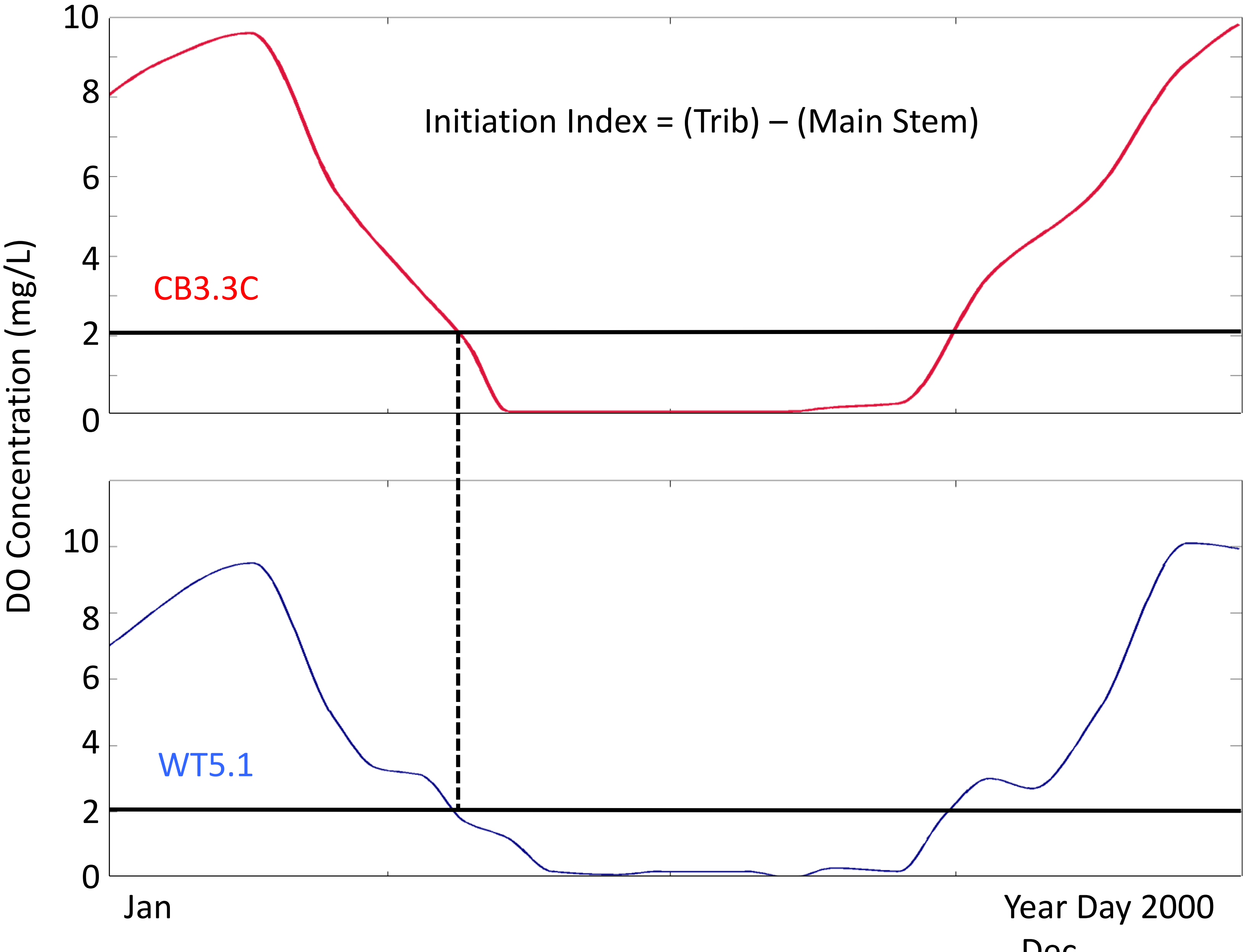
- Time & Space Interpolation
- Initiation Dates
  - Potomac
  - Patuxent
  - Patapsco
- Correlation with Spring River Flow
- Future Modeling Options



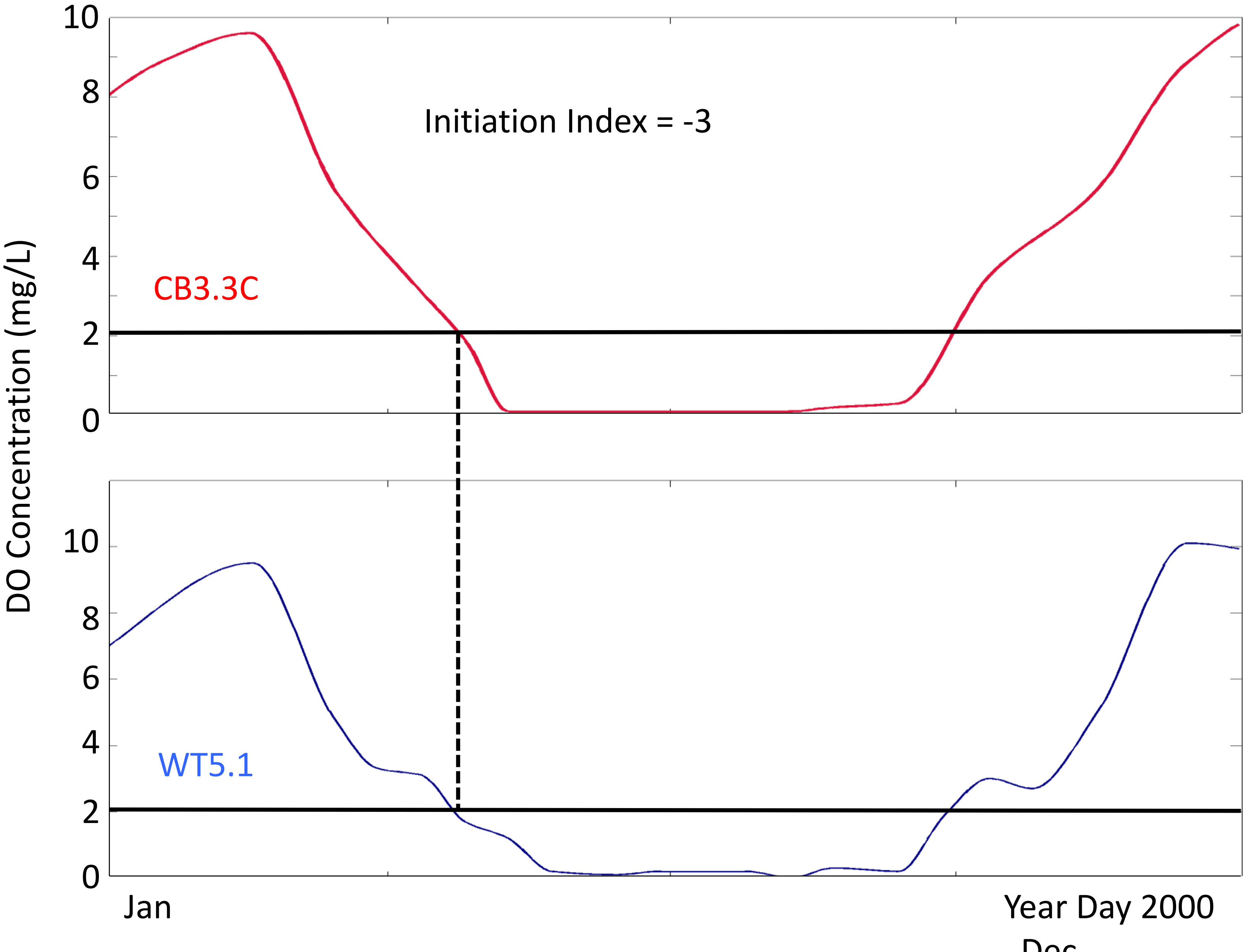
Interpolation: Duration Characteristics



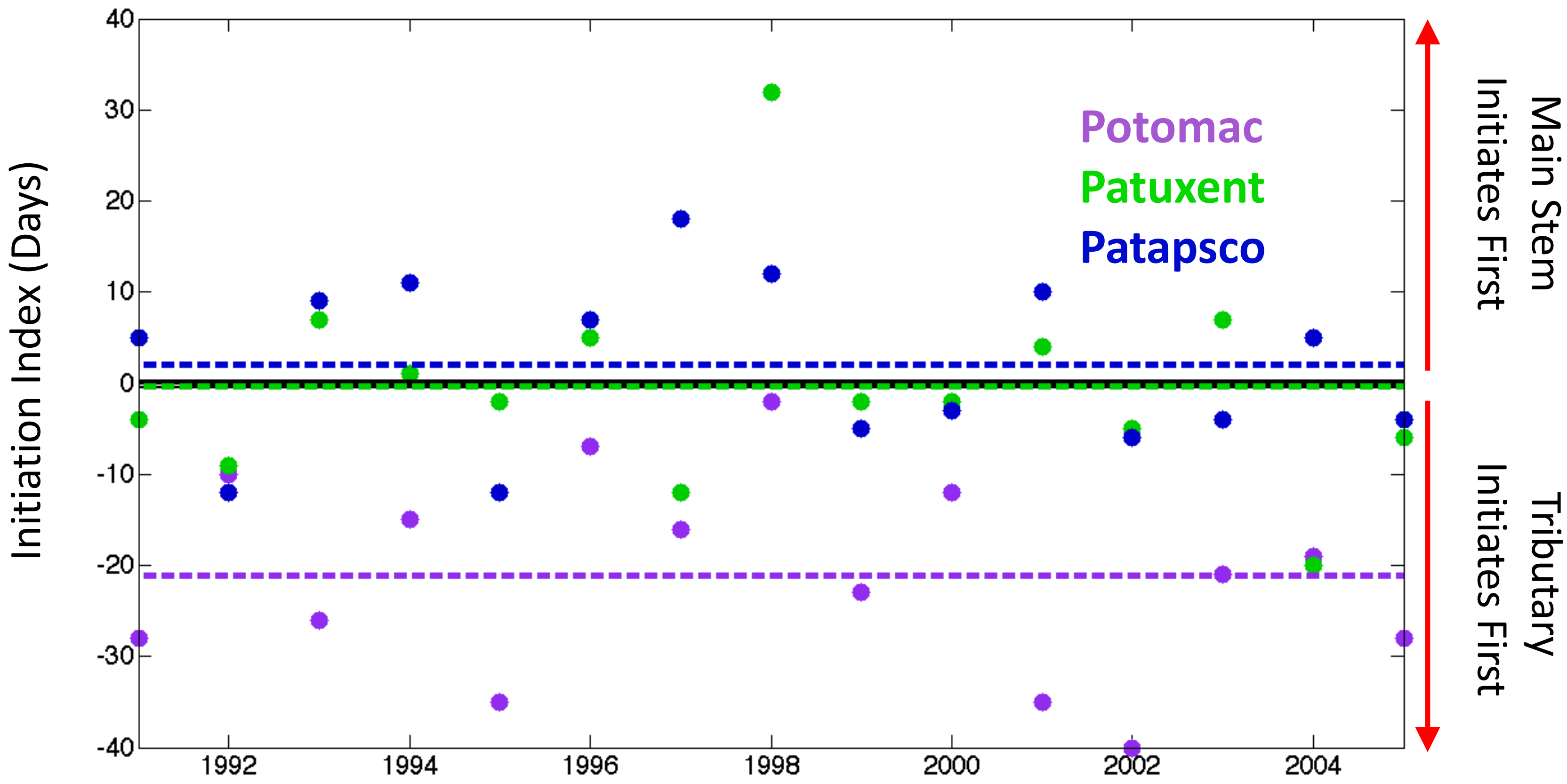
Interpolation: Initiation Date



Interpolation: Initiation Date

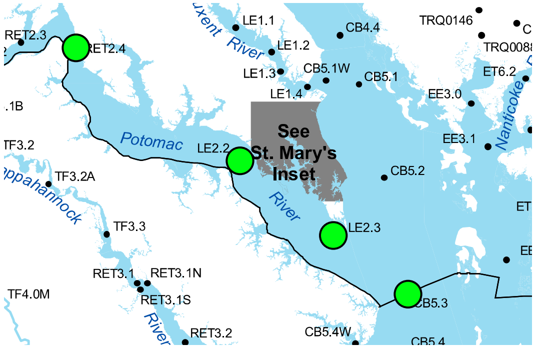


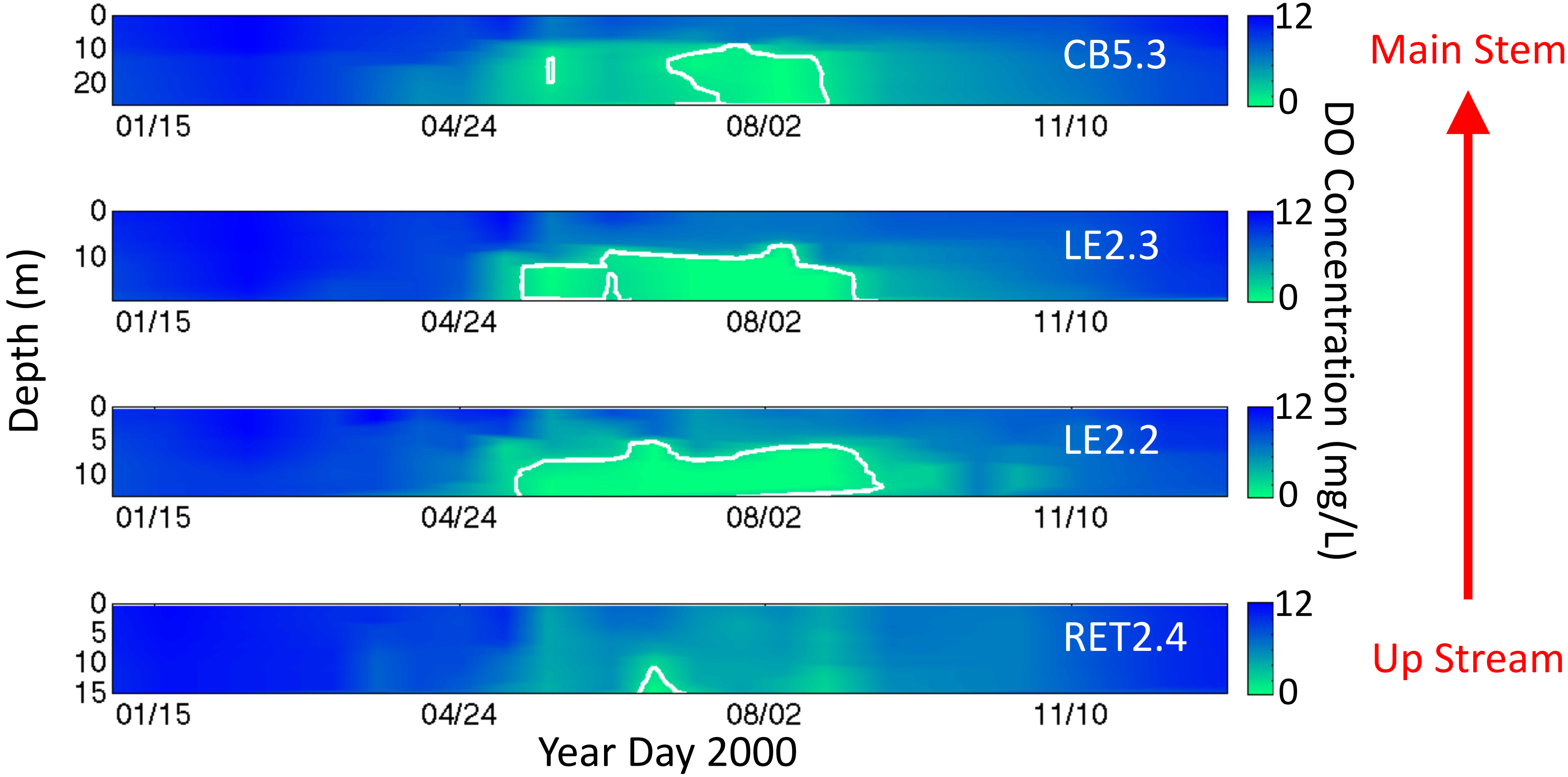
Initiation Indices



- Patapsco and Patuxent initiate at about the same time as main stem on average. Potomac consistently initiates earlier than main stem.

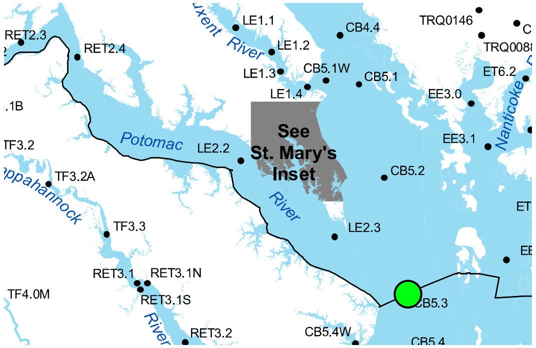
Potomac

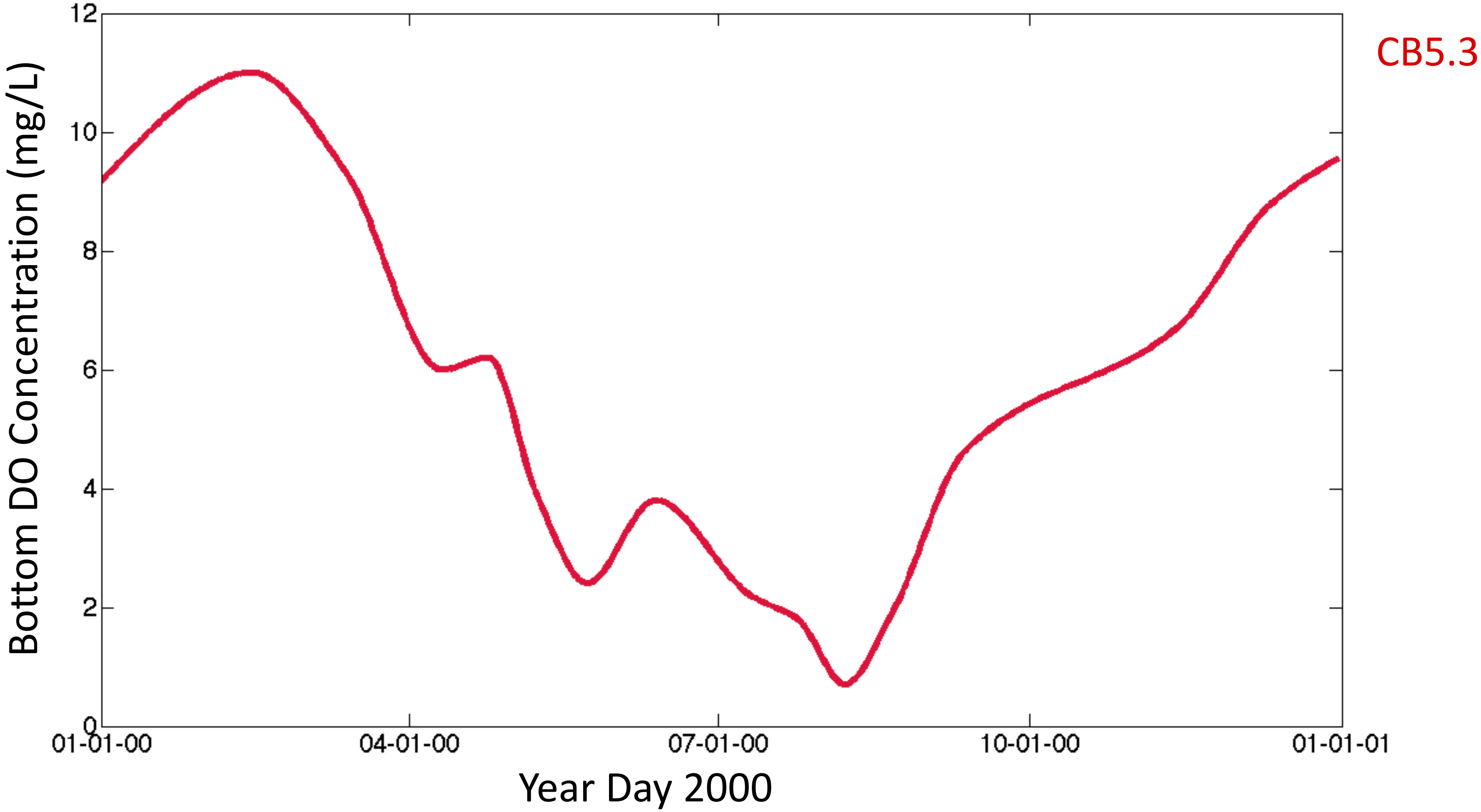




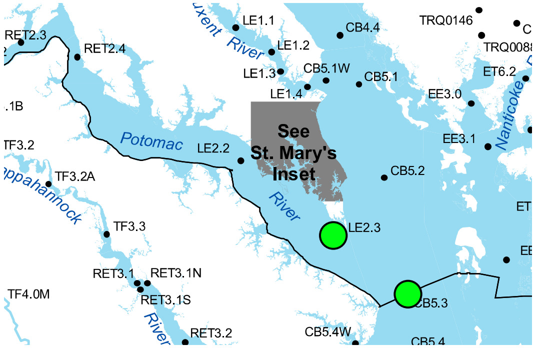
- Duration characteristics of LE2.3/LE2.2 are more similar to each other than to CB5.3

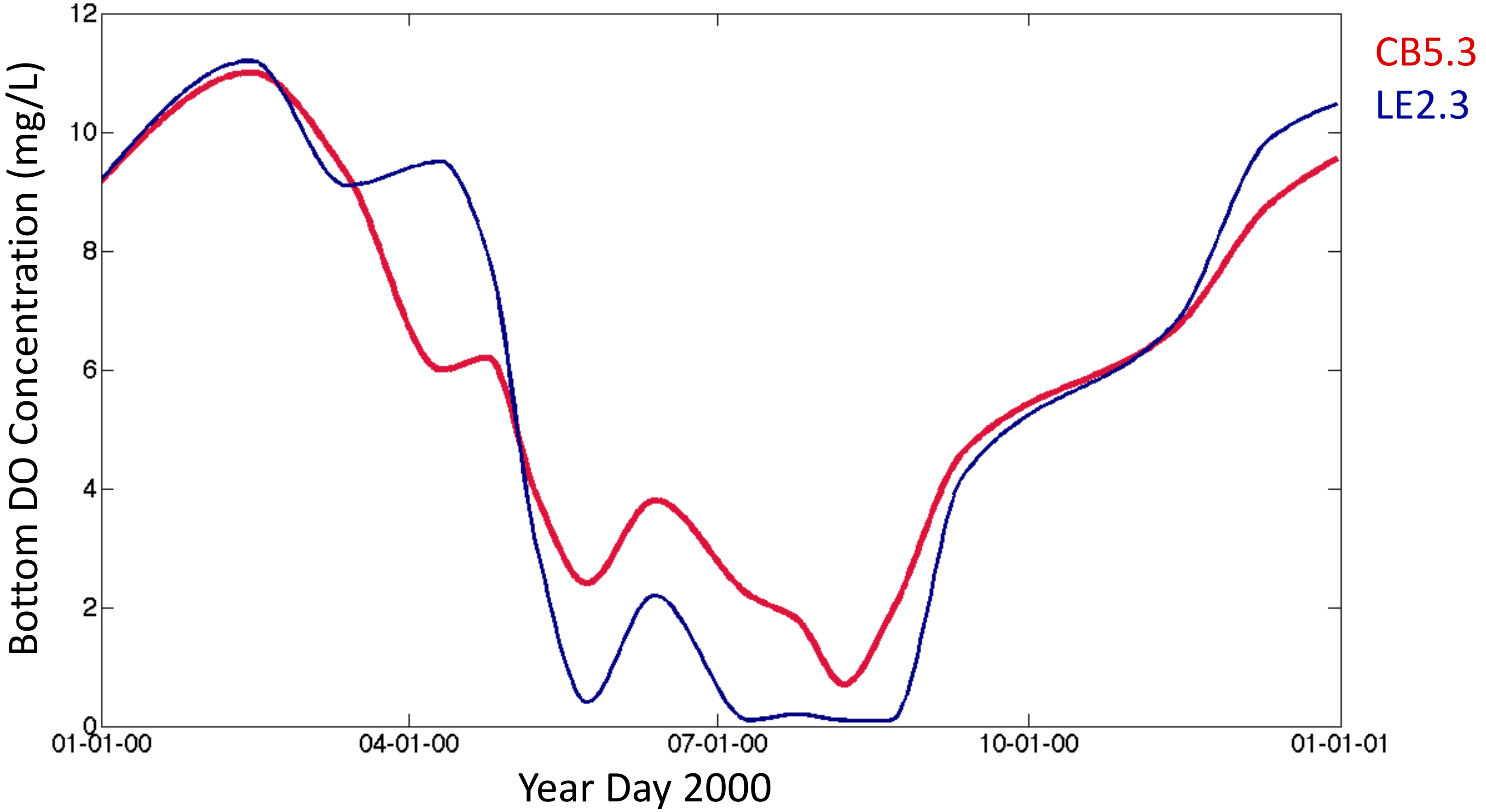
Potomac


Potomac
River
See
St. Mary's
Inset
CB5.3

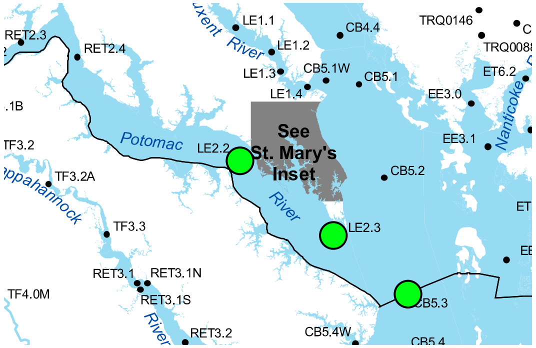

CB5.3
Bottom DO Concentration (mg/L)
Year Day 2000
0
2
4
6
8
10
12
01-01-00
04-01-00
07-01-00
10-01-00
01-01-01

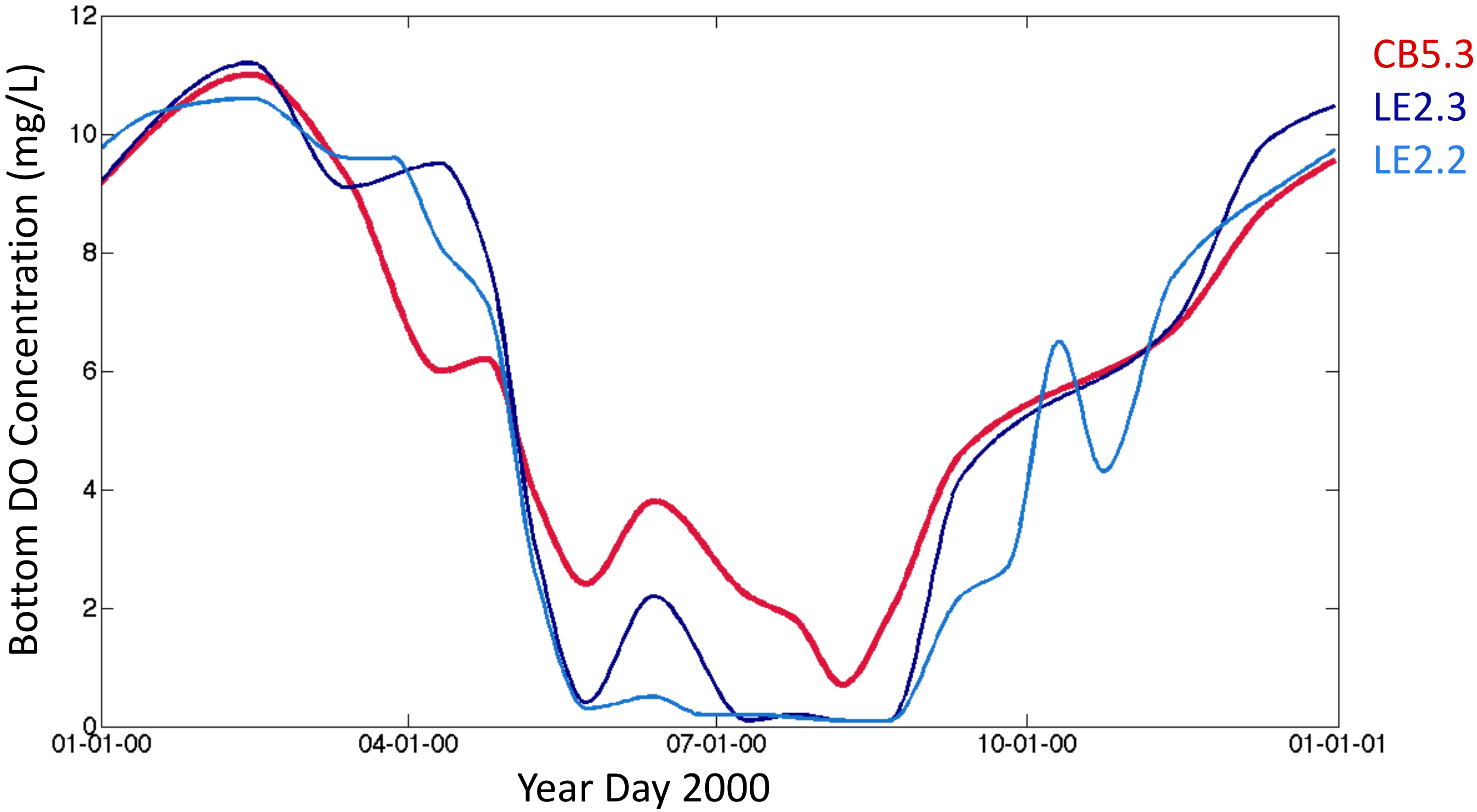
Potomac



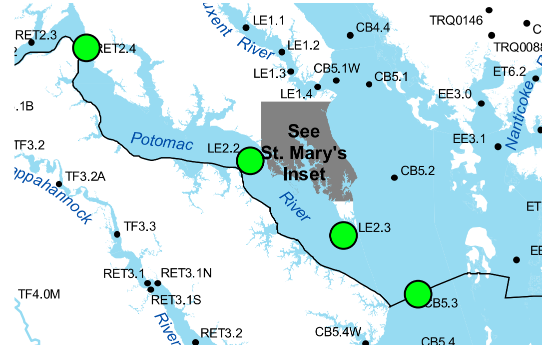

CB5.3
LE2.3
Bottom DO Concentration (mg/L)
Year Day 2000
01-01-00
04-01-00
07-01-00
10-01-00
01-01-01

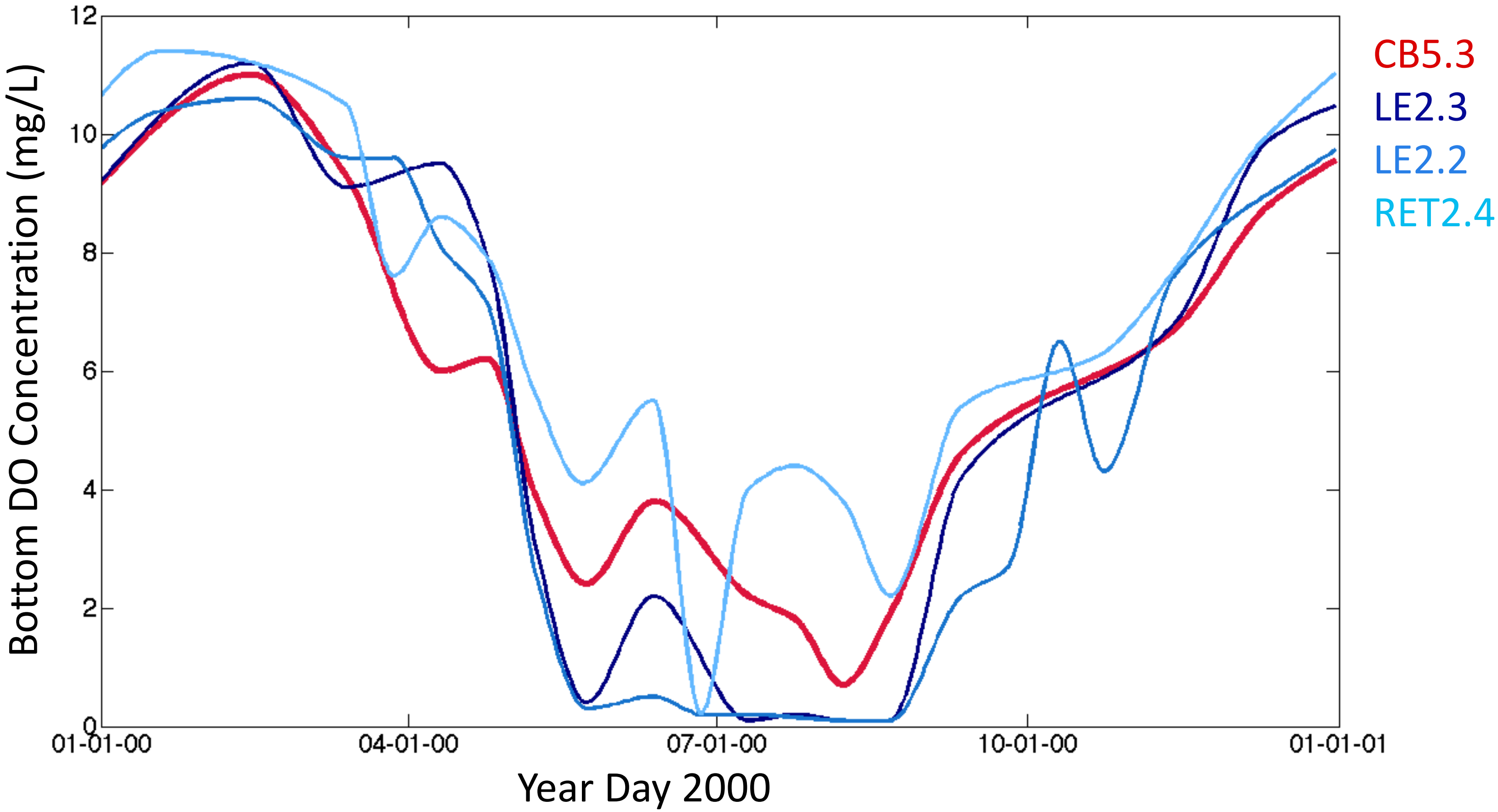
Potomac


See
St. Mary's
Inset
Potomac
River
LE2.2
LE2.3
CB5.3


Bottom DO Concentration (mg/L)
Year Day 2000
01-01-00
04-01-00
07-01-00
10-01-00
01-01-01
0
2
4
6
8
10
12
CB5.3
LE2.3
LE2.2

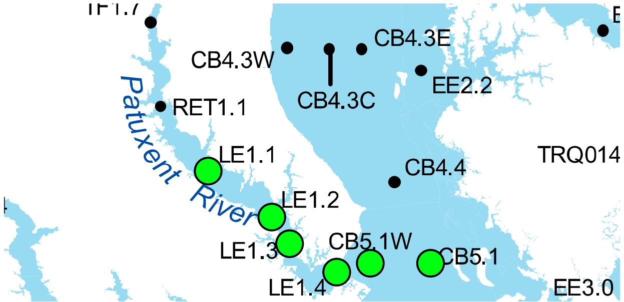
Potomac

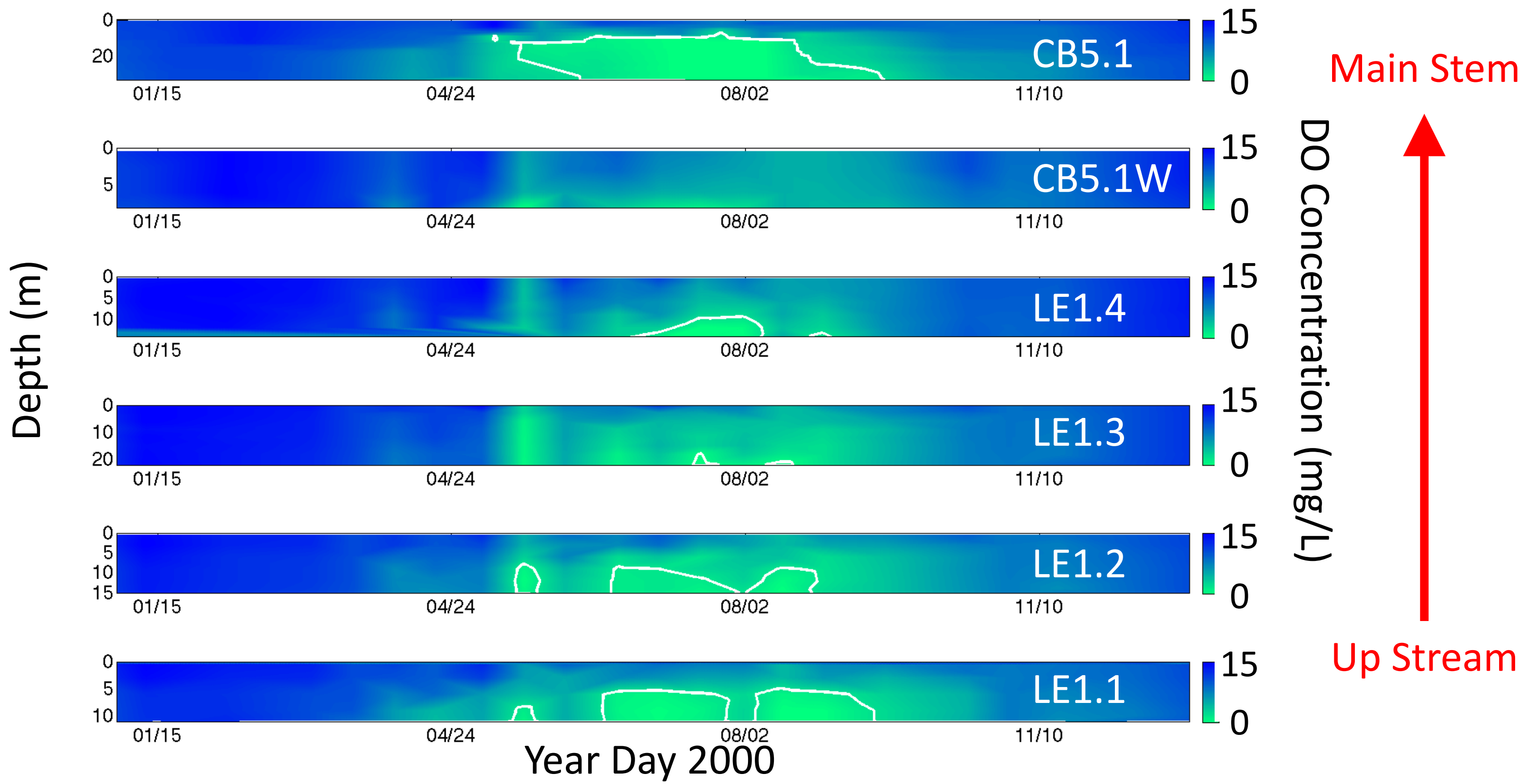




- Tributary stations initiate before main stem.

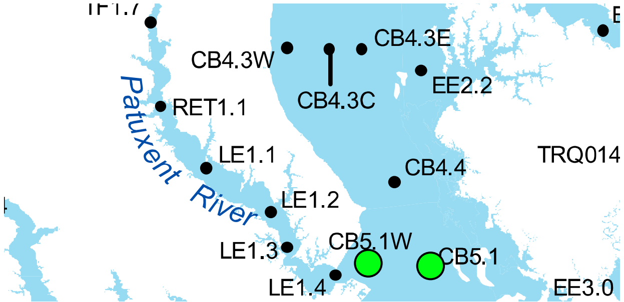
Patuxent



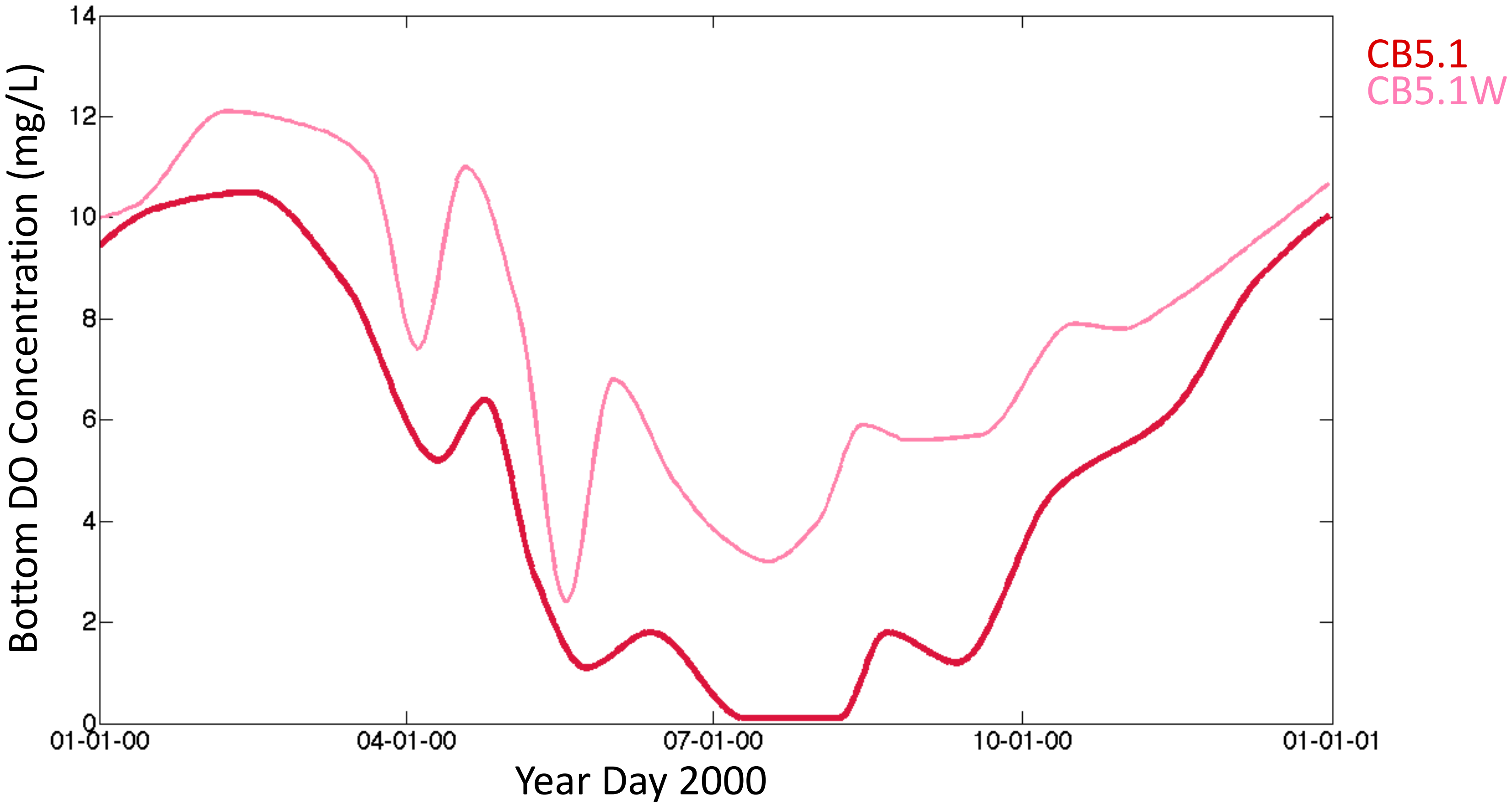


- Duration characteristics of the tributary stations are more similar to each other than to CB5.3

Patuxent

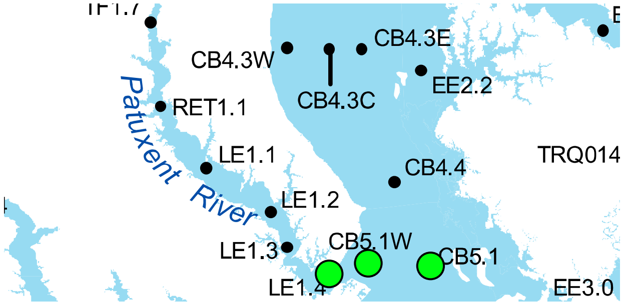


CB4.3W
CB4.3E
CB4.3C
EE2.2
RET1.1
Patuxent River
LE1.1
CB4.4
TRQ014
LE1.2
LE1.3
CB5.1W
CB5.1
LE1.4
EE3.0



Bottom DO Concentration (mg/L)
0
2
4
6
8
10
12
14
01-01-00
04-01-00
07-01-00
10-01-00
01-01-01
Year Day 2000
CB5.1
CB5.1W

Patuxent


CB4.3W
CB4.3E
CB4.3C
EE2.2
RET1.1
Patuxent River
LE1.1
CB4.4
TRQ014
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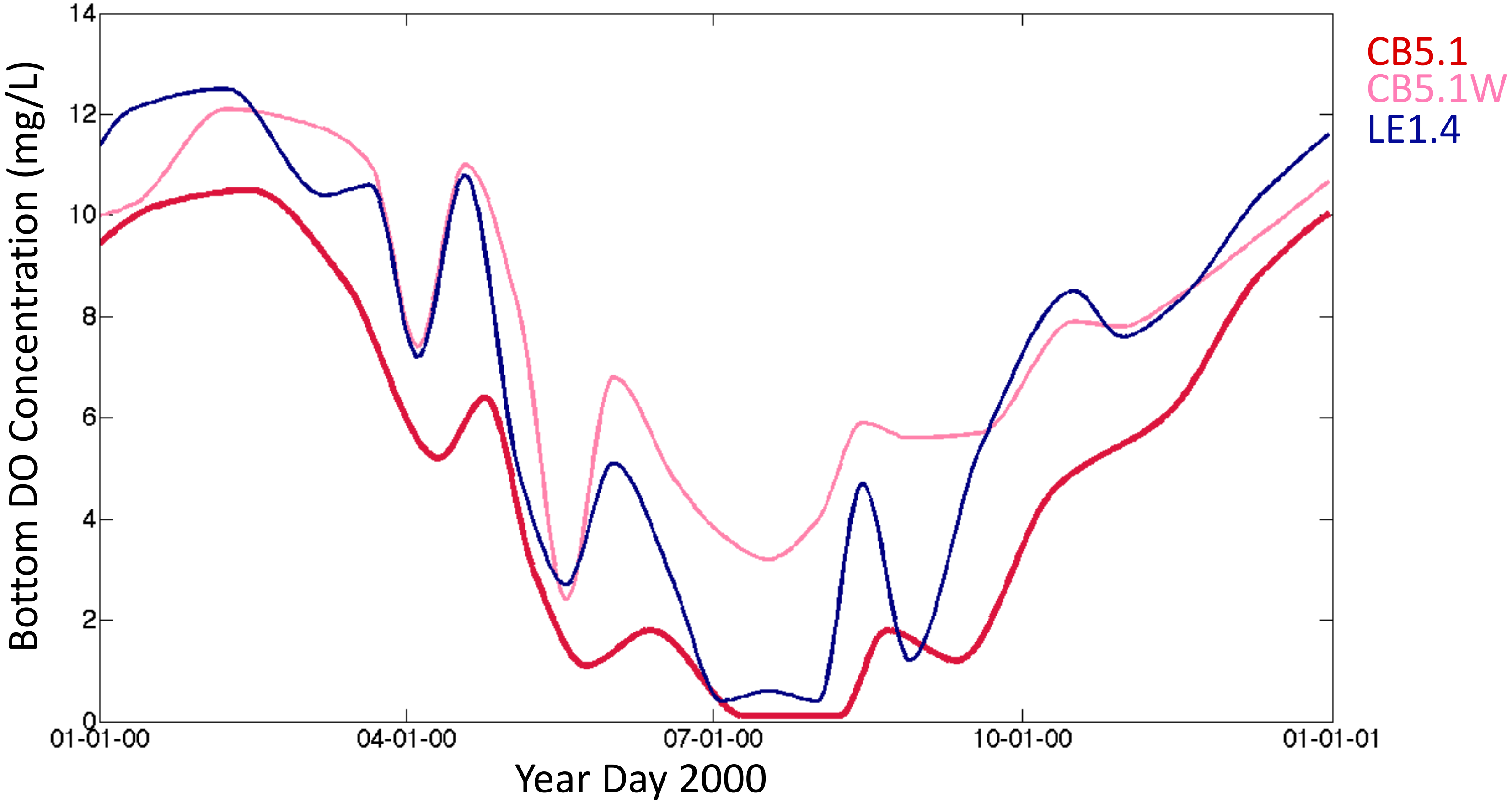
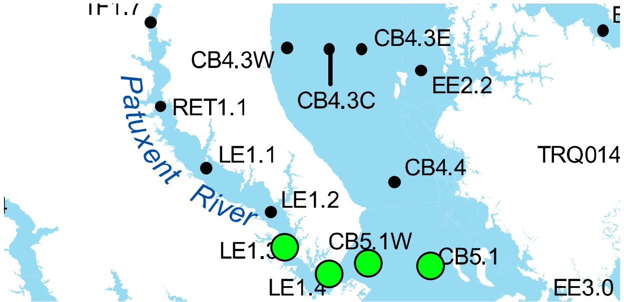
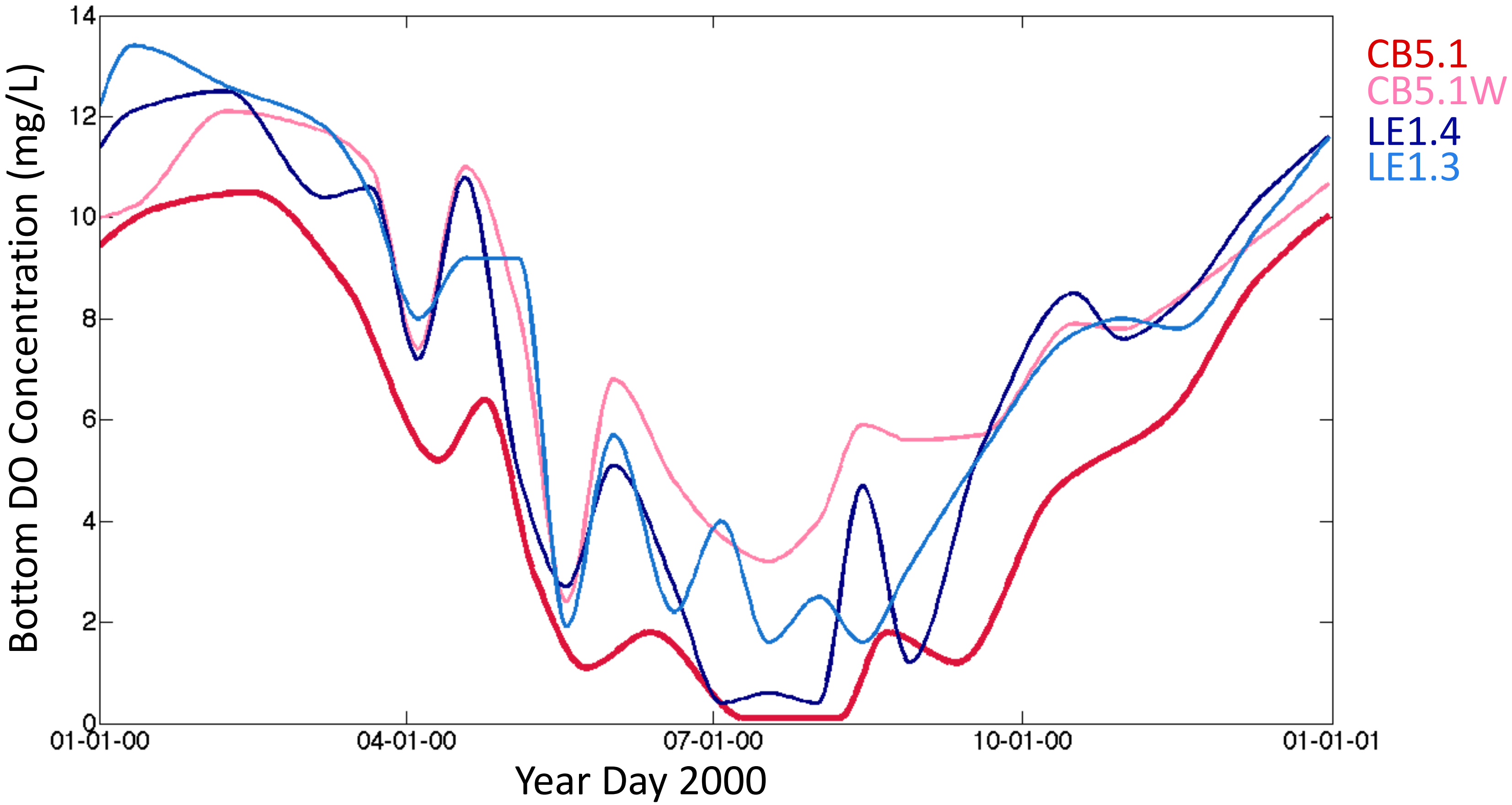
LE1.3
CB5.1W
CB5.1
LE1.4
EE3.0

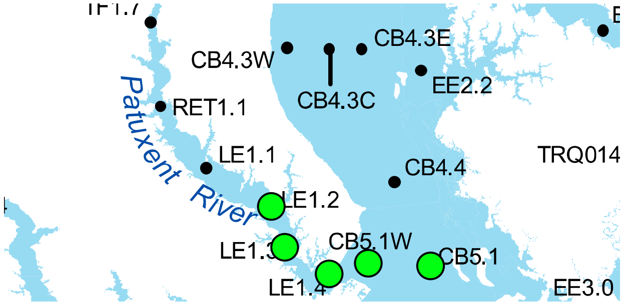

Bottom DO Concentration (mg/L)
0
2
4
6
8
10
12
14
01-01-00
04-01-00
07-01-00
10-01-00
01-01-01
Year Day 2000
CB5.1
CB5.1W
LE1.4

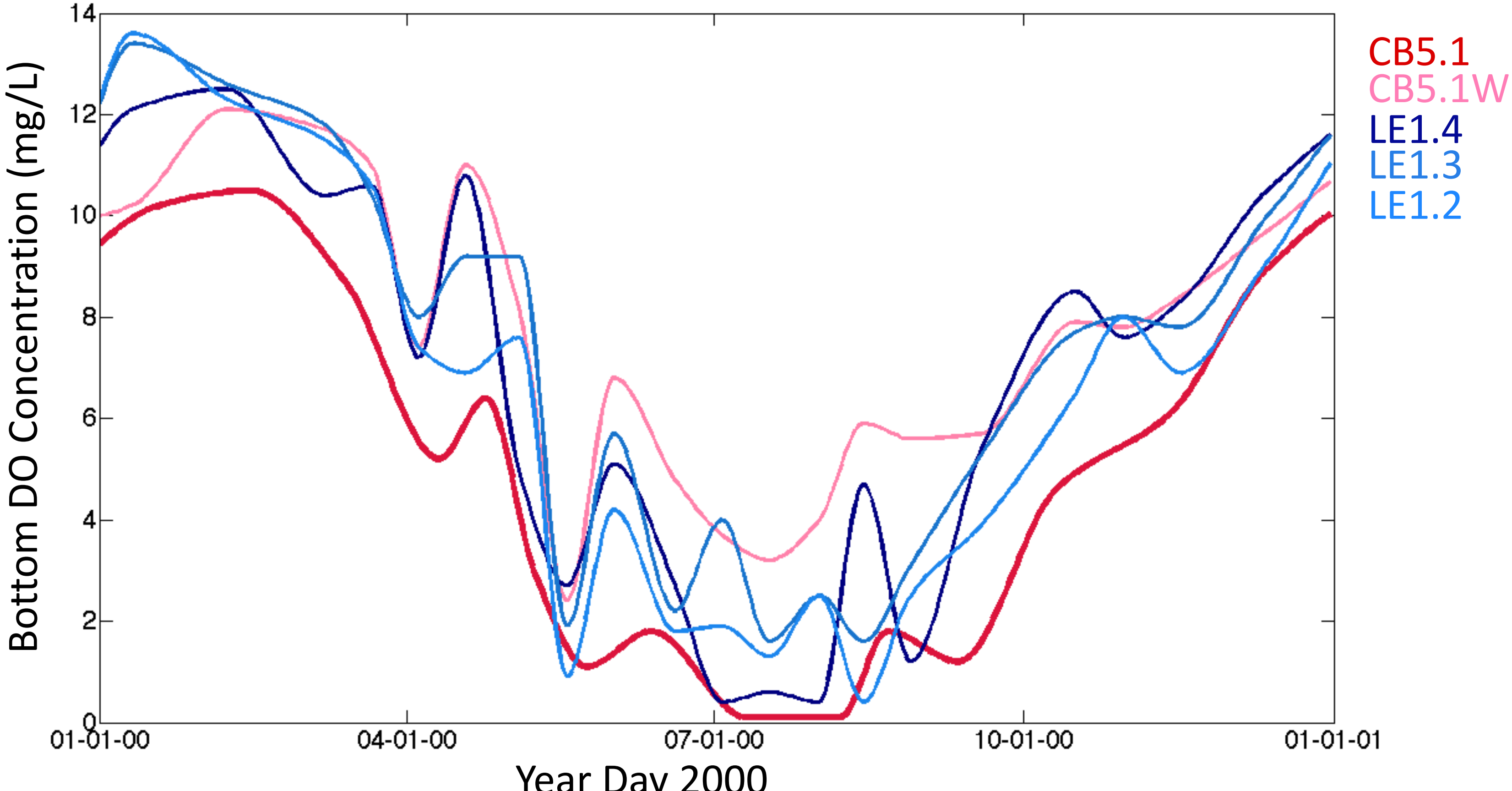
Patuxent


CB4.3W
CB4.3E
CB4.3C
EE2.2
RET1.1
Patuxent River
LE1.1
CB4.4
TRQ014
LE1.2
CB5.1W
CB5.1
LE1.4
EE3.0


Bottom DO Concentration (mg/L)
0
2
4
6
8
10
12
14
01-01-00
04-01-00
07-01-00
10-01-00
01-01-01
Year Day 2000
CB5.1
CB5.1W
LE1.4
LE1.3

Patuxent

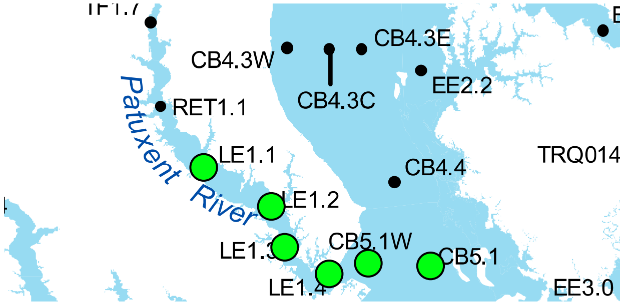


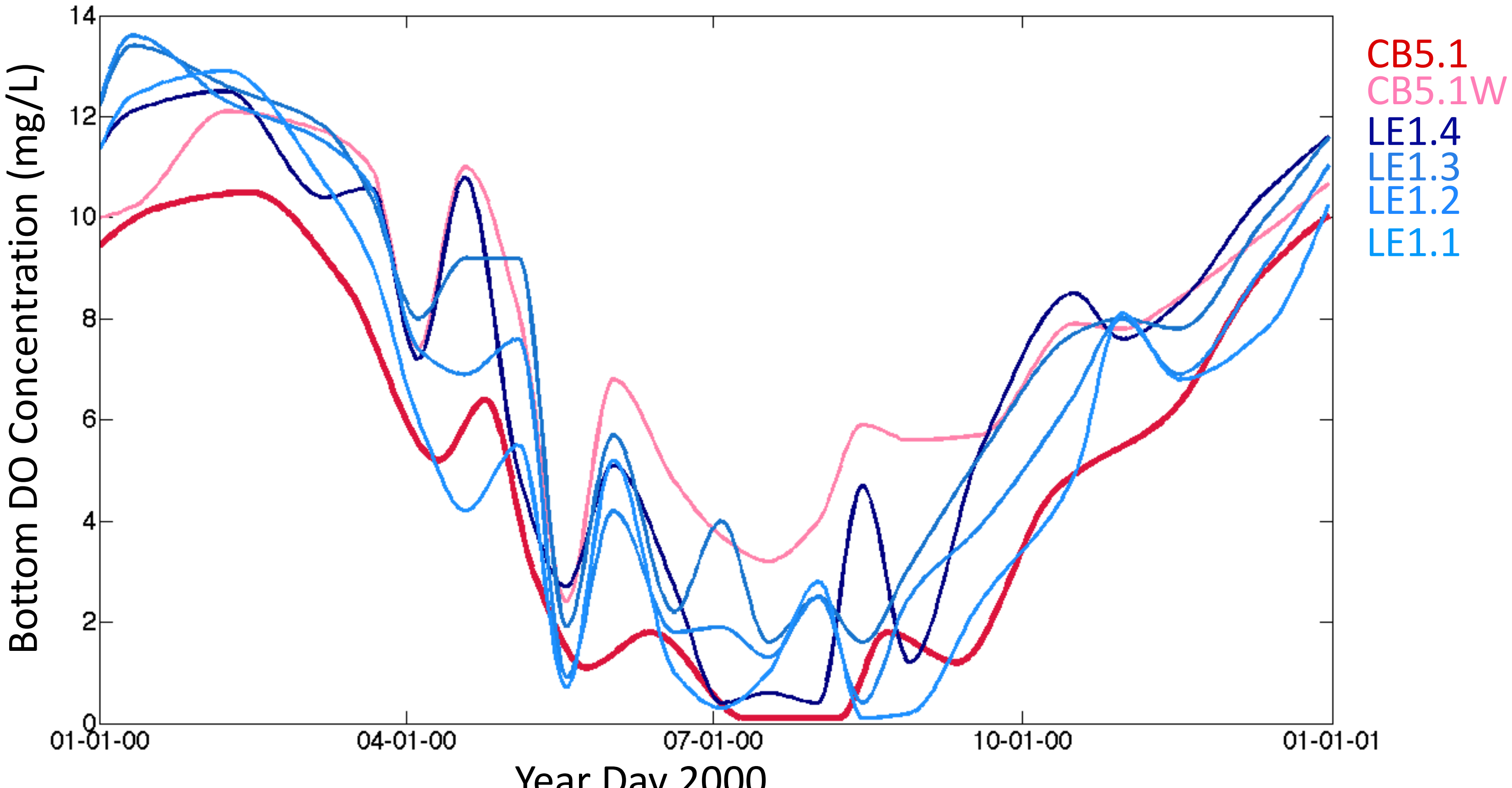


-Mid-tributary stations are first to initiate

-Spatial separation from main stem

Patuxent

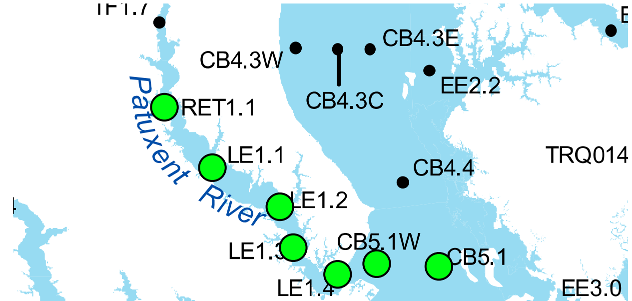


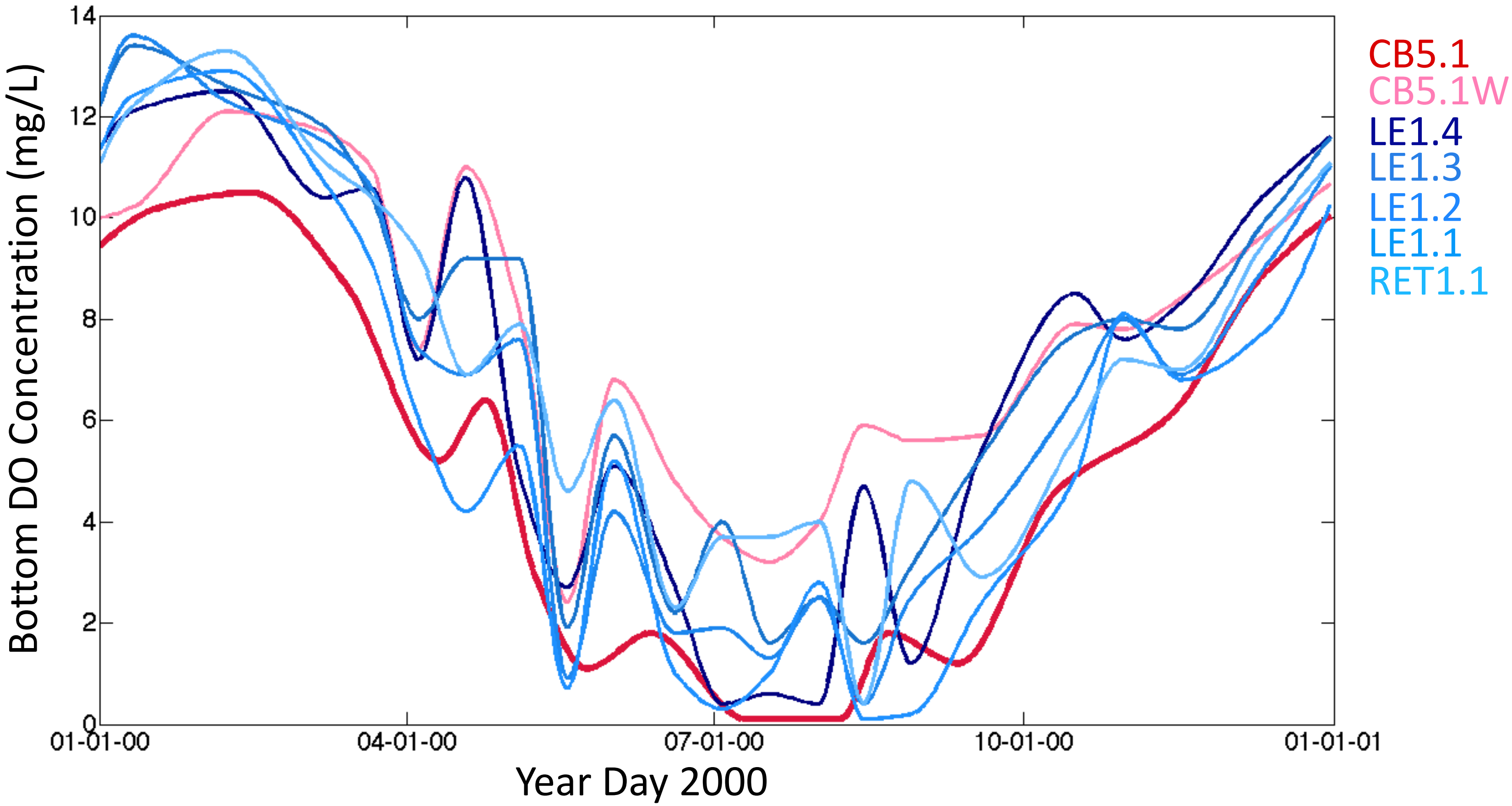


-Mid-tributary stations are first to initiate

-Spatial separation from main stem

Patuxent

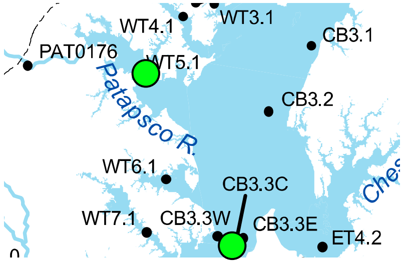


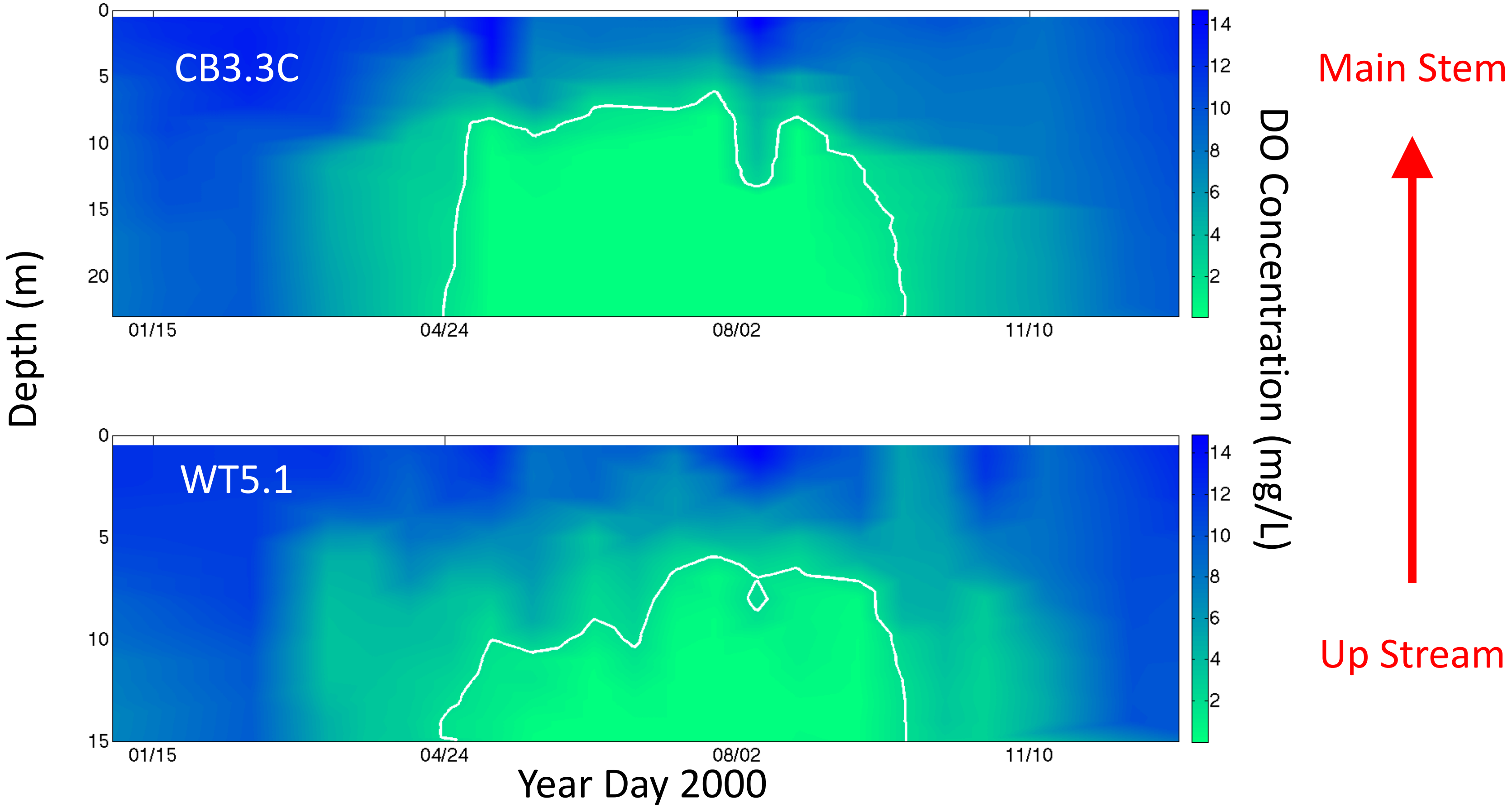


-Mid-tributary stations are first to initiate

-Spatial separation from main stem

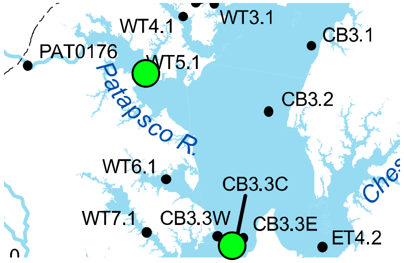
Patapsco

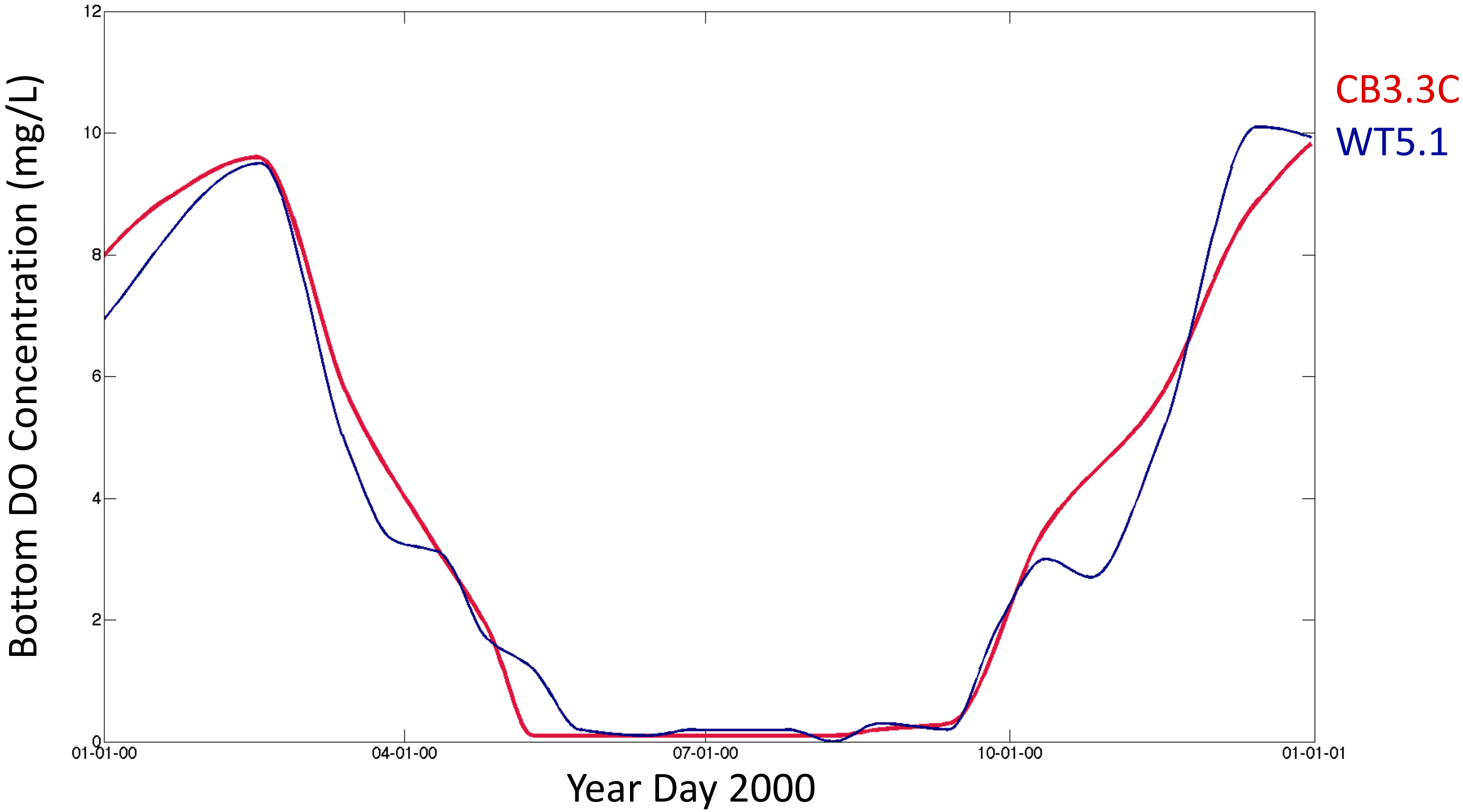




-Patapsco tends to exhibit a close relationship with the main stem.

Patapsco





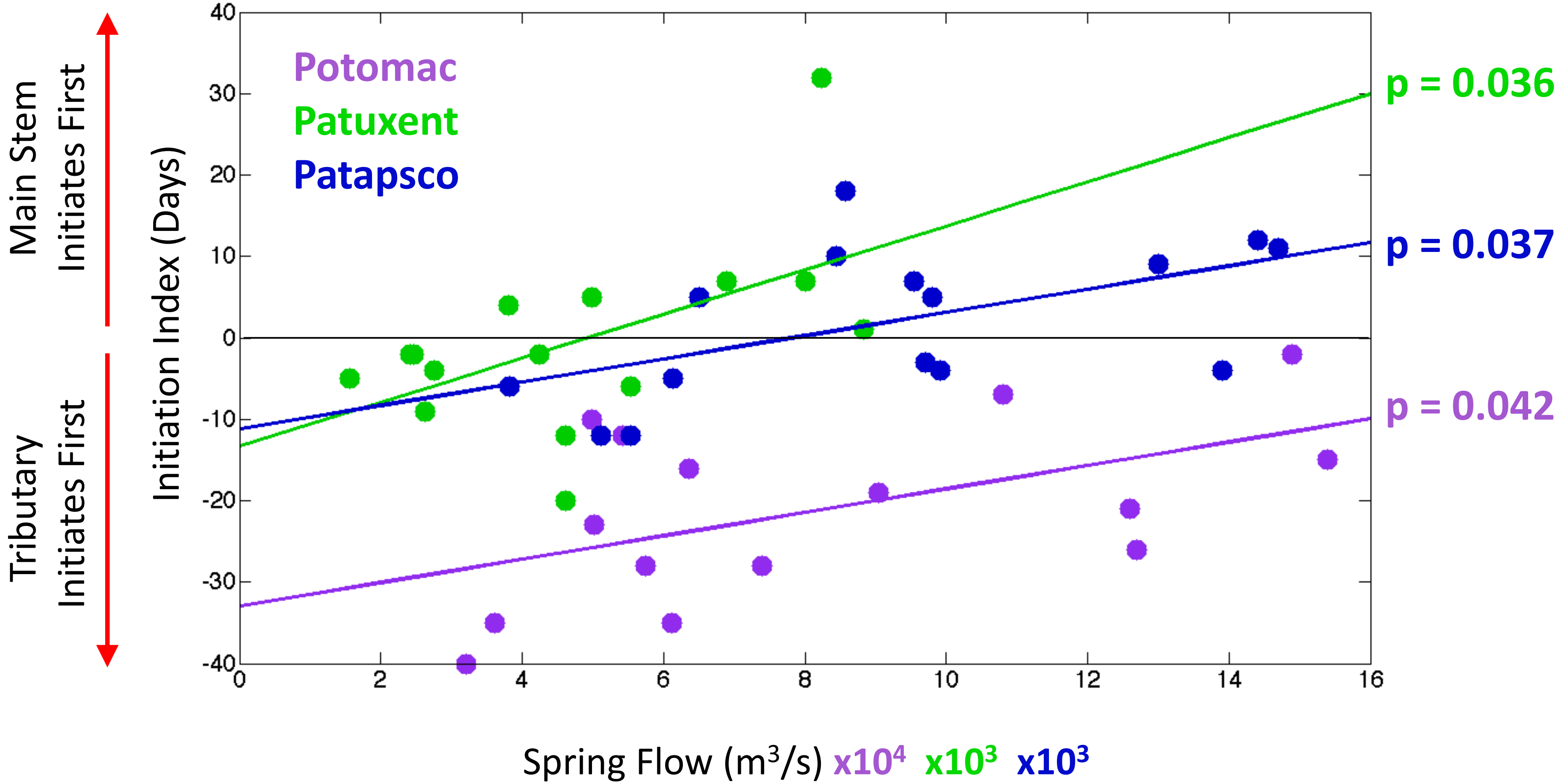
-Trajectories for both stations are consistently similar.

Local Initiation Summary

- Potomac initiates before main stem
  - Evidence for post-initiation advection
- Patuxent and Patapsco initiate at the same time as their associated main stem station
  - Patuxent exhibits duration characteristics that are distinct from the main stem
  - Patapsco exhibits duration characteristics that are similar to the main stem

Correlation with Spring River Flow

-Spring defined as Feb-May
-Patapsco contains flow south of Susquehanna, north of Patuxent



Conclusions (Part 1)

- Hypoxia is initiated locally in the tributaries
- High spring flow tends toward earlier relative main stem initiation
  - High flow may cause early initiation in main stem
    - Nutrients
    - Stratification
  - Does advection from the main stem play a larger role in high flow years?

Future Modeling Options

- Perform model scenario runs to determine the influence of the main stem on tributary hypoxia
  - Full model run
  - Turn off biological attributes in the tributaries
  - Turn off biological attributes in the main stem
  - Compare the simulations to better understand the influence of low DO main stem waters on DO in the tributaries.

Part 2

Overview of Tributary hypoxia dynamics

- Primarily controlled by bottom water movement of the estuarine gravitational circulation (Kuo and Neilson, 1987; Boicourt, 1992)

- Primarily controlled by Local pelagic and benthic processes in the middle estuary (Testa and Kemp, 2008).

- Internal respiration is sufficient to drive tributary hypoxia, but exchange of OM between Bay and tributaries is significant and cannot be discounted (Samuel Lake, 2013, and Lake and Brush, 2013)

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Hypoxia and Salinity in Virginia Estuaries[1]

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School of Marine Science
College of William and Mary
Gloucester Point, Virginia 23062

ABSTRACT: Hypoxia, periods of reduced dissolved oxygen concentrations, has been observed not only in the Chesapeake Bay but also in the deeper waters of the Virginia estuaries that are tributaries to the Chesapeake Bay. When water temperature exceeded 20 °C, minimum oxygen concentrations were observed to be <50% of saturation concentrations in 75%, 50% and 2% of the surveys in the estuaries of the Rappahannock, York and James rivers, respectively. The observation that hypoxia rarely occurred in the James River is surprising, given the fact that it receives the greatest amount of wastewater. Analysis of the oxygen budgets in these estuaries indicates that the variations in the frequency, duration, and severity of hypoxia are related to the net movement of bottom waters. This relationship has significant implications for the management of water quality and marine fisheries.

Introduction

Aquatic organisms are stressed by oxygen deficiency; the risk of damage to aquatic populations increases as concentrations of dissolved oxygen (DO) deviate from saturation values. Thus, there is concern when oxygen supplies are deficient (hypoxia) and greater concern when no dissolved oxygen (anoxia) is available to the biota. Problems of hypoxia and anoxia in estuarine and coastal waters have received increased attention in recent years (Schroeder 1985). Anoxia, which has been observed in Chesapeake Bay since the 1930's (Newcombe and Horne 1938), has become more widespread and of longer duration during recent times (Flemer et al. 1983). It continues to be observed and appears to have had significant ecological effects (Seliger et al. 1985).

In Virginia, hypoxia has been observed repeatedly in deep waters of the lowest reaches of the Rappahannock and York rivers, but rarely in the James River (Fig. 1). These western shore tributaries of Chesapeake Bay are partially-mixed, coastal plain estuaries. The depth along the river axes is generally 5 to 10 m, but near the mouth of each river there are natural deep areas or "holes" of more than 20 m depth. In the James River a second hole about 15 km from the mouth is connected to the one at the mouth by a dredged navigation channel 14 m deep. In these deep waters, DO concentration below 5 mg l^{-1} typically first appear in May or June when water temperatures exceed 20 °C. The hypoxia usually is most pronounced in August when water temperatures are the highest and dissipates in September or October as temperatures decrease. Superimposed on this seasonal cycle is a fortnightly cycle related to spring tide destratification events (Haas 1977; Webb and D'Elia 1980; D'Elia et al. 1981).

Although the hole at the mouth of the James River is quite deep (~25 m) and wastewater loadings to that river are much larger than those in the other tributaries, hypoxia rarely is observed there. Examination of available data also reveals that hypoxia is more severe and of longer duration in the Rappahannock River than in the York River. In this paper the DO and salinity distributions in the lower reaches of these three tributary estuaries are examined and a conceptual model utilized to determine those mechanisms which control the oxygen budgets of the deep waters.

Observations

Since 1971 the Virginia Institute of Marine Science has been conducting slack water surveys in these three major estuaries. The surveys were made monthly except in the winter and early spring. *In situ* measurements and water samples were taken at designated stations while following a given phase of tidal wave as it propagated upstream from the river mouth. The phase of tide was either slack tide before ebb or slack tide before flood. No effort was made to keep phase with spring-neap tidal cycle, thus the surveys were distributed randomly over the fortnightly cycle. All sampling stations were located at the middle of navigation channels. At each station, temperature, conductivity, and salinity were sampled at every 2 m from surface to

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[1] Contribution number 1424 of the Virginia Institute of Marine Science, College of William and Mary.

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"Analysis of the oxygen budgets in these estuaries (James, York, and Rappahannock) indicates that the variation in the frequency, duration , and severity of hypoxia are related to the net movement of bottom waters"

Table

Estuary	Dissolved Oxygen <5 mg l^{-1} June, July, August (a)	Dissolved Oxygen <5 mg l^{-1} All Surveys With T > 20 °C (b)
Rappahannock	37 (38)	55 (58)
York	37 (41)	49 (65)
James	2 (39)	4 (60)

Estuary	Salinity Difference Longitudinal (c)	Salinity Difference Vertical (d)	Salinity Difference Vertical (e)	U_* cm/sec (f)
Rappahannock	1.7	2.4	1.5	6.2
York	3.8	2.5	1.7	7.8
James	7.8	4.2	4.3	16

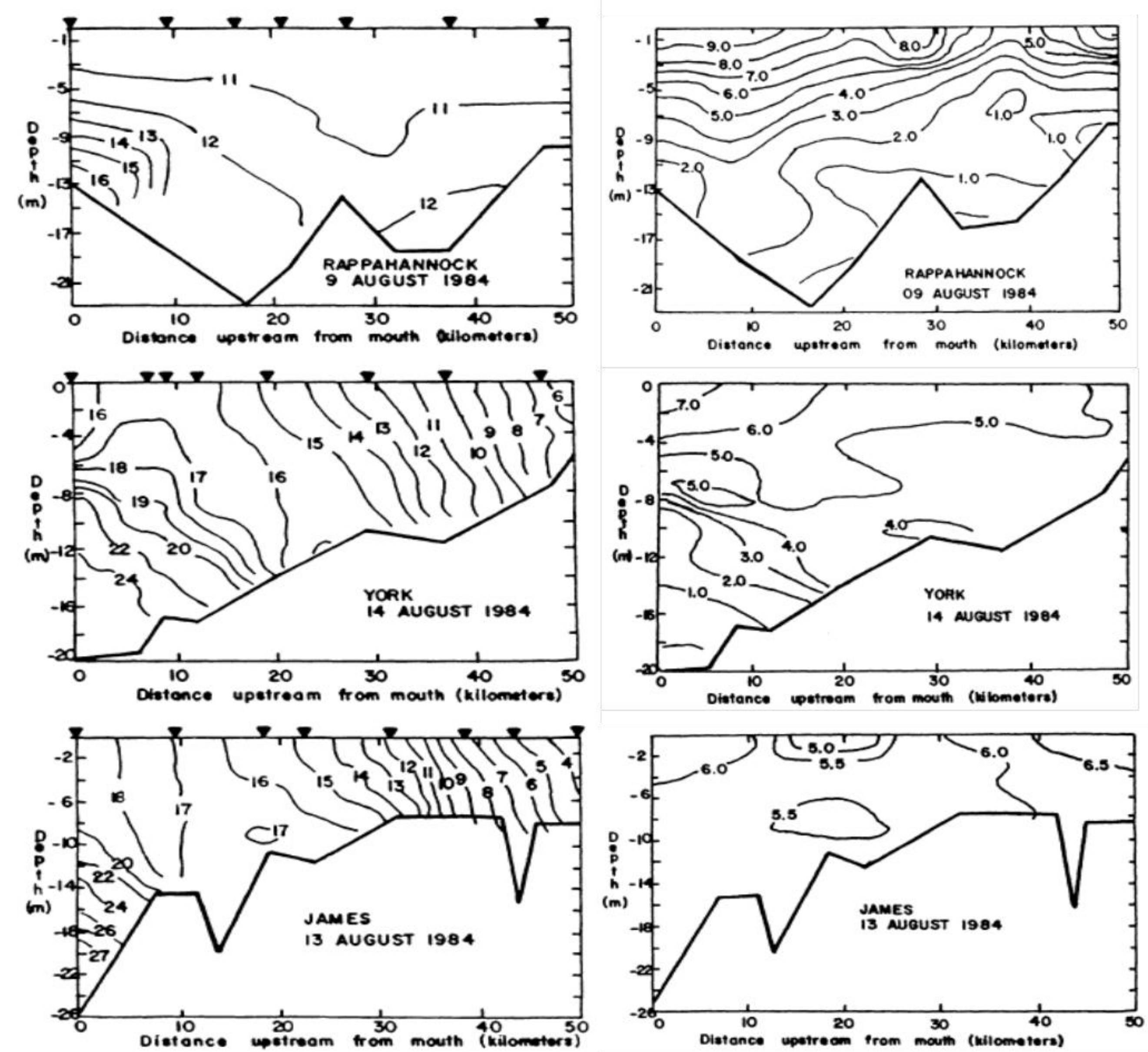

Figure: Salinity (left panel) and oxygen (right panel) in the Virginia tributaries during August, 1984 (from Kuo and Neilson, 1987)

$$\Delta V \frac{dc}{dt} = -B_{SOD}\Delta A - k_c M \Delta V + k_z \frac{c_s - c}{d} + Q_1 c_1 - Q_2 c - Q_v c$$

$$Q_1 = Q_2 + Q_v$$

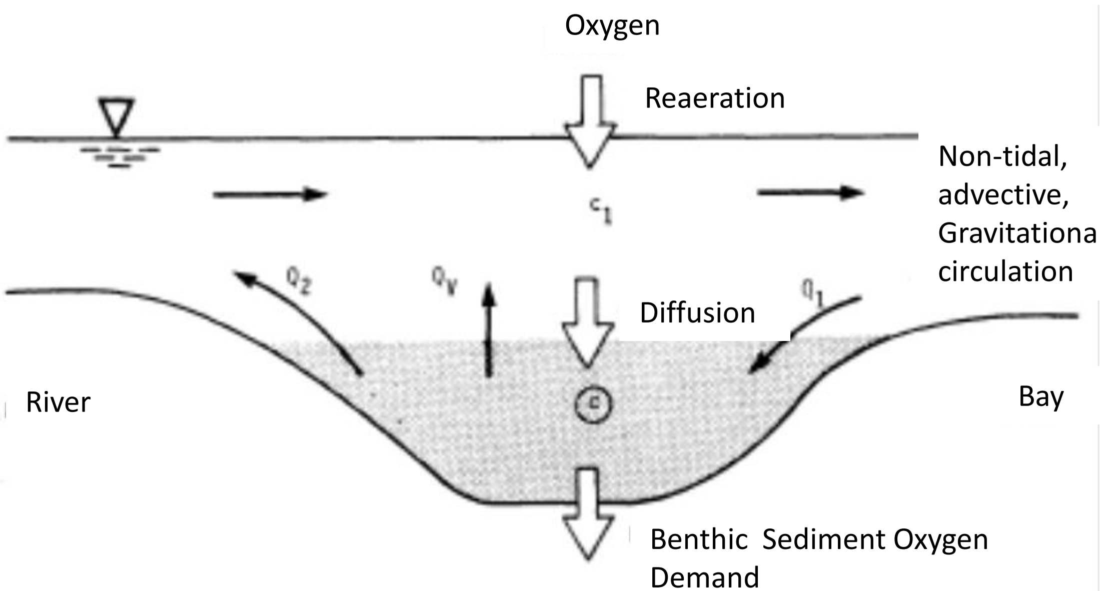

Fig. 6. A conceptual model of the dissolved oxygen budget in the deep hole of a partially mixed estuary. c and c_1 are the mean DO concentrations in the hypoxic and overlying waters, respectively; Q_1, Q_2, and Q_V are the flow rates due to gravitational circulation.

Q =flow
C_s =surface DO
C is bottom layer DO
K_c is decay coefficient
M is organic matters (mg/l)
SOD = sediment oxygen demand (g-O_2/m2/day)

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Variability of biogeochemical processes and physical transport in a partially stratified estuary: a box-modeling analysis

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ABSTRACT: Regional, seasonal, and interannual variations of freshwater inputs, biogeochemical transformations, and pelagic–benthic interactions were examined in the Patuxent River estuary. Monthly rates of net biogeochemical production (or consumption) and physical transport of carbon, oxygen, and nutrients were calculated for 6 estuarine regions using data-constrained salt- and water-balance computations (box model) with hydrologic and water quality data. Assuming fixed stoichiometry for O_2, carbon, and silicate, we derived estimates of particulate organic carbon (POC) sinking and net diatom growth. Our results indicate that nutrients delivered from the watershed to the estuary during winter and spring supported >100% of the spring phytoplankton bloom. The spring bloom, which subsequently sinks across the pycnocline to the bottom layer, was decomposed in May–September to support 50 to 90% of annual bottom-layer NH_4^+, PO_4^{3-}, and silicate regeneration. Sinking POC from surface waters accounted for 50 to 100% of bottom-layer respiration in the middle estuary, with deficits partially compensated by organic carbon delivered in landward flowing bottom water. Lateral transport of POC to the central channel from adjacent shallow waters was required to meet bottom water respiratory demands. Bottom-layer regeneration and subsequent upward transport of nutrients were sufficient to support 70 to 80% of summer rates of net organic production in surface layers. Pelagic and benthic processes were most tightly linked in the middle estuary, which is highly productive and does not interact strongly with adjacent waters. Elevated nutrient inputs to the estuary associated with high freshwater flow enhanced chlorophyll *a*, net O_2 production, and net DIN uptake in surface layers; however, muted effects of flow on bottom-layer processes suggest that much of the increased organic production in surface layers during high flow is transported to seaward regions.

KEY WORDS: Estuary · Biogeochemistry · Box model · Water quality · Monitoring · Patuxent River

INTRODUCTION

Estuarine ecosystems form the transition zone between adjacent terrestrial, riverine, and oceanic regions. Biogeochemically reactive materials enter estuaries from the watershed and atmosphere and are processed within estuarine systems prior to being transported to the ocean (Kemp & Boynton 1984). Estuarine processing of anthropogenic and terrestrially derived materials is regulated by a balance between physical transport and biogeochemical uptake and recycling (Kemp & Boynton 1984, Smith et al. 1991, Howarth et al. 1996). Understanding the nature and magnitude of these transformation and transport processes is essential for evaluating and managing estuarine production and nutrient cycling.

Past estuarine ecological research has elucidated regional variation in key biogeochemical processes (e.g. Cloern et al. 1983, Smith et al. 1991, Cowan et al. 1996). In upper regions of estuaries, high organic car-

*Email: jtesta@hpl.umces.edu

"Pelagic and benthic processes were most tightly linked in the middle estuary, which is highly productive and does not interact strongly with adjacent waters".

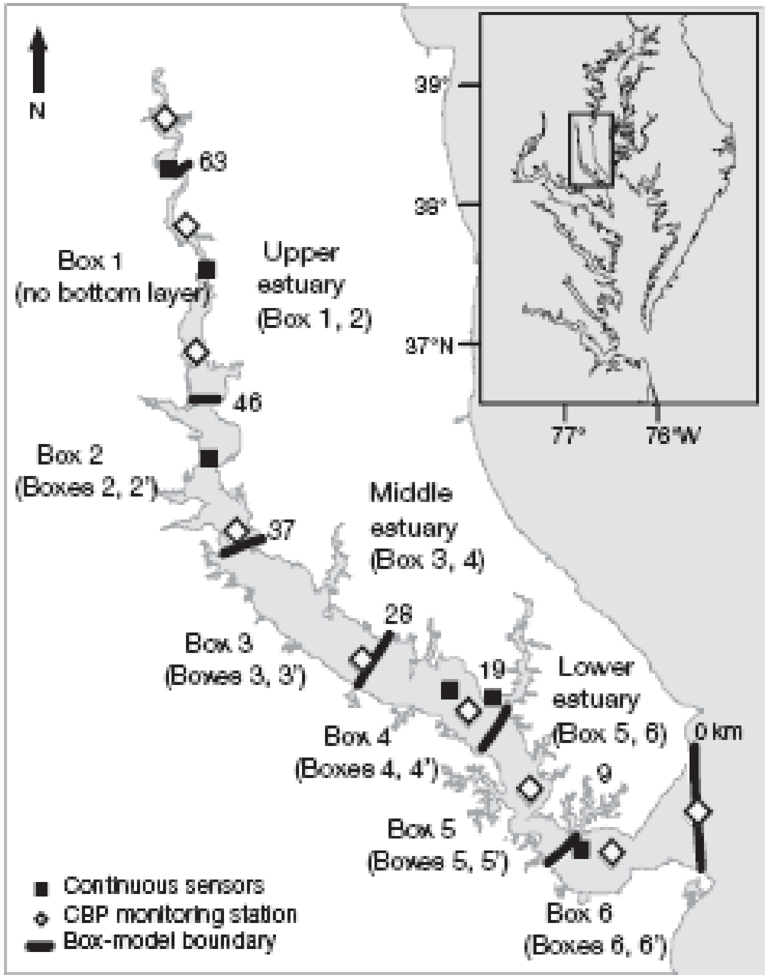


Fig. 1. Patuxent River estuary with Chesapeake Bay (inset), including box-model boundaries (Hagy et al. 2000), water quality monitoring stations, and the location of Maryland Department of Natural Resources' continuous water quality sensors. Numbers to the right of box-model boundaries indicate distance (km) from the mouth of the estuary

$$V_m \frac{ds_m}{dt} = Q_{m-1}s_{m-1} + Q_{vm}s'_m - Q_m s_m + E_{vm}(s'_m - s_m) + E_{m-1,m}(s_{m-1} - s_m) + E_{m,m+1}(s_{m+1} - s_m) \qquad (1)$$

$$\frac{dV_m}{dt} = 0 = Q_m - (Q_{m-1} + Q_{vm} + Q_{tm}) \qquad (2)$$

$$V'_m \frac{ds'_m}{dt} = Q'_{m+1}s'_{m+1} - Q_{vm}s'_m - Q'_m s'_m - E_{vm}(s'_m - s_m) \qquad (3)$$

$$\frac{dV'_m}{dt} = 0 = Q'_m + Q_{vm} - Q'_{m+1} \qquad (4)$$

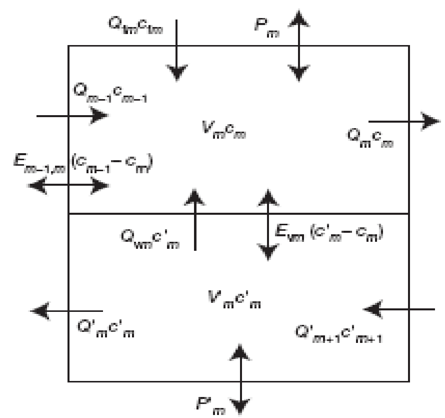


Fig. 2. Two-layer non-conservative box model for Boxes 2–6. Arrows represent advective (Q), non-advective (E), and net production (P) terms for the box. The non-advective exchange, $E_{m,m-1}(c_m - c_{m-1})$, is a term for the calculation in the surface layer of Box 2 only. Atmospheric inputs are included ($Q_{tm}c_{tm}$) for the non-conservative DIN flux. Refer to Hagy et al. (2000) for further details

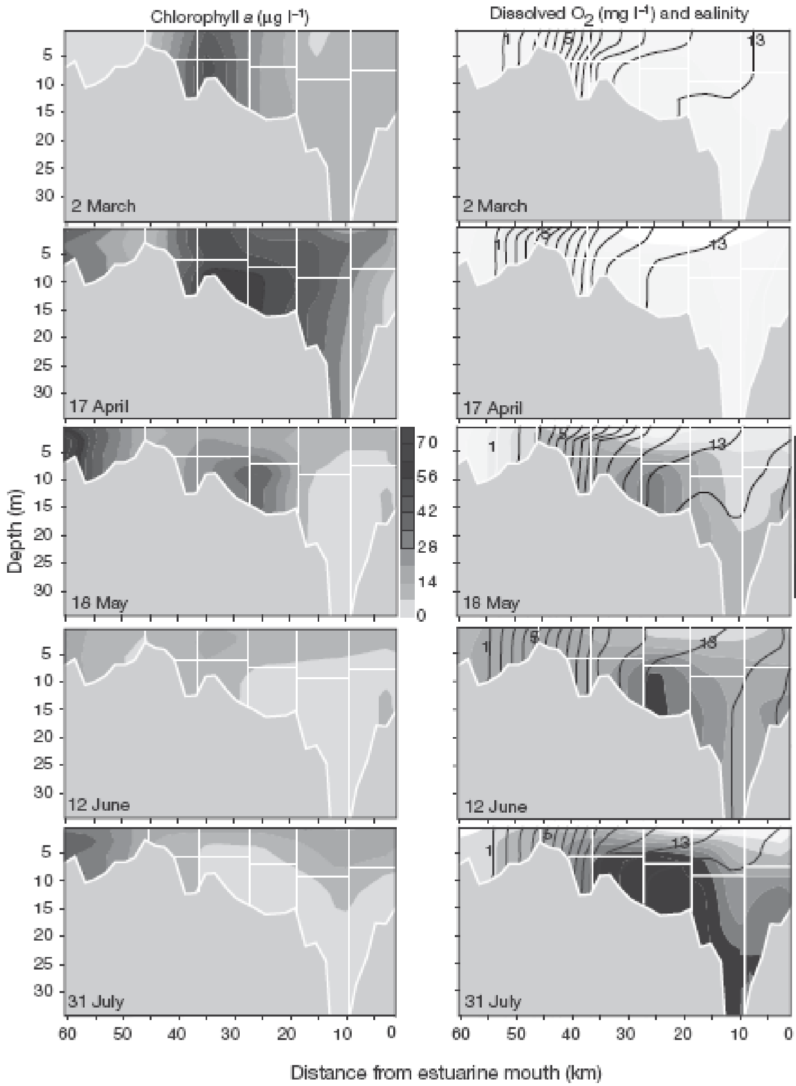
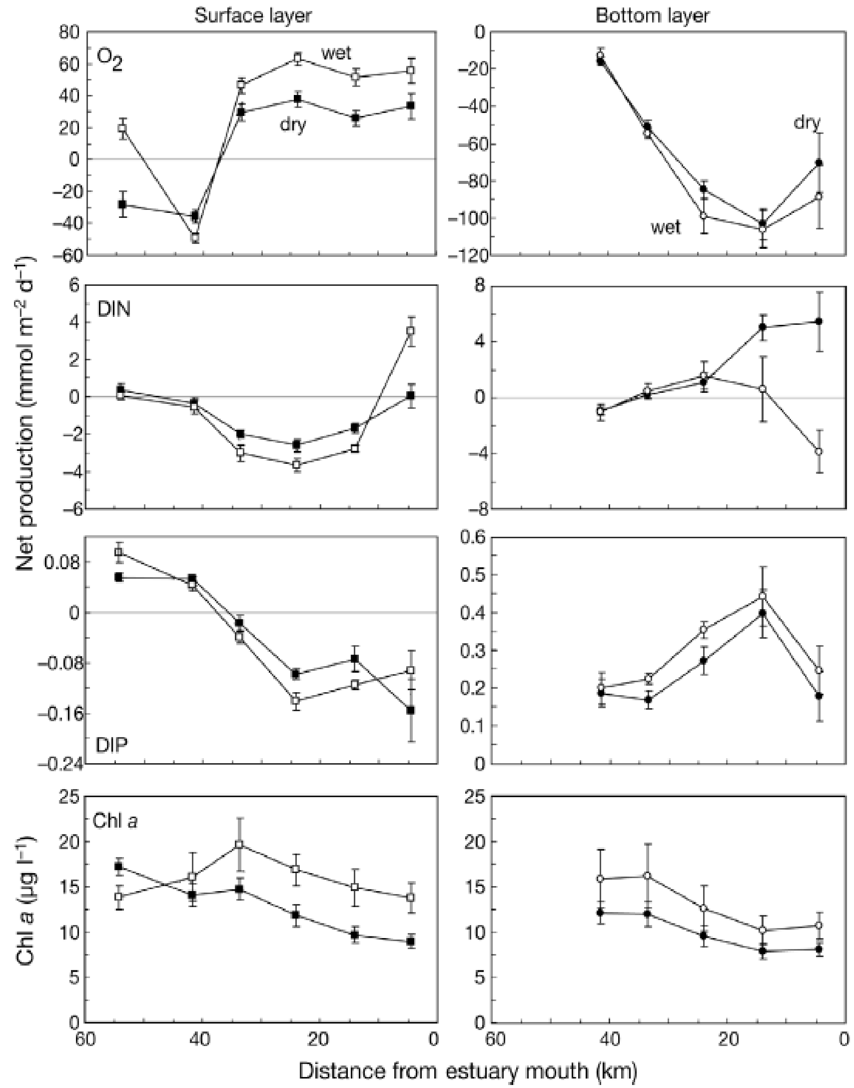


Fig. 3. Contour plots of water quality monitoring data for chl *a* (left-hand panels) and dissolved oxygen/salinity (right-hand panels) in the Patuxent River estuary in the winter, spring, and summer of 1995. White lines: box-model boundaries. O_2/salinity graphs — numbers are salinity-contour values; black areas: hypoxic water (O_2 < 2 mg l^{-1}). Data acquired from www.chesapeakebay.net



MODELING THE FORMATION OF PERIODIC HYPOXIA IN

PARTIALLY MIXED ESTUARIES AND

ITS RESPONSE TO OLIGOTROPHICATION AND CLIMATE CHANGE

A Dissertation

Presented to

The Faculty of the School of Marine Science

The College of William and Mary in Virginia

In Partial Fulfillment

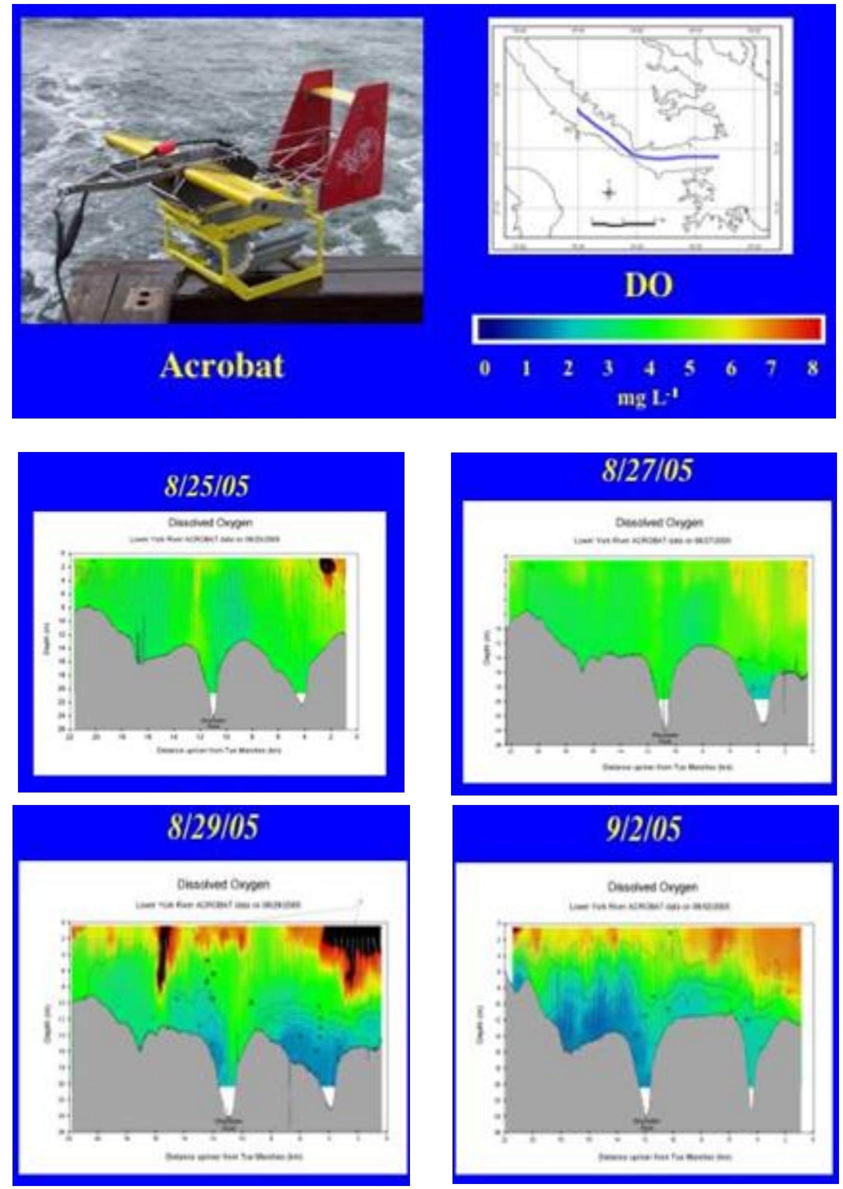
Of the Requirements for the Degree of

Doctor of Philosophy

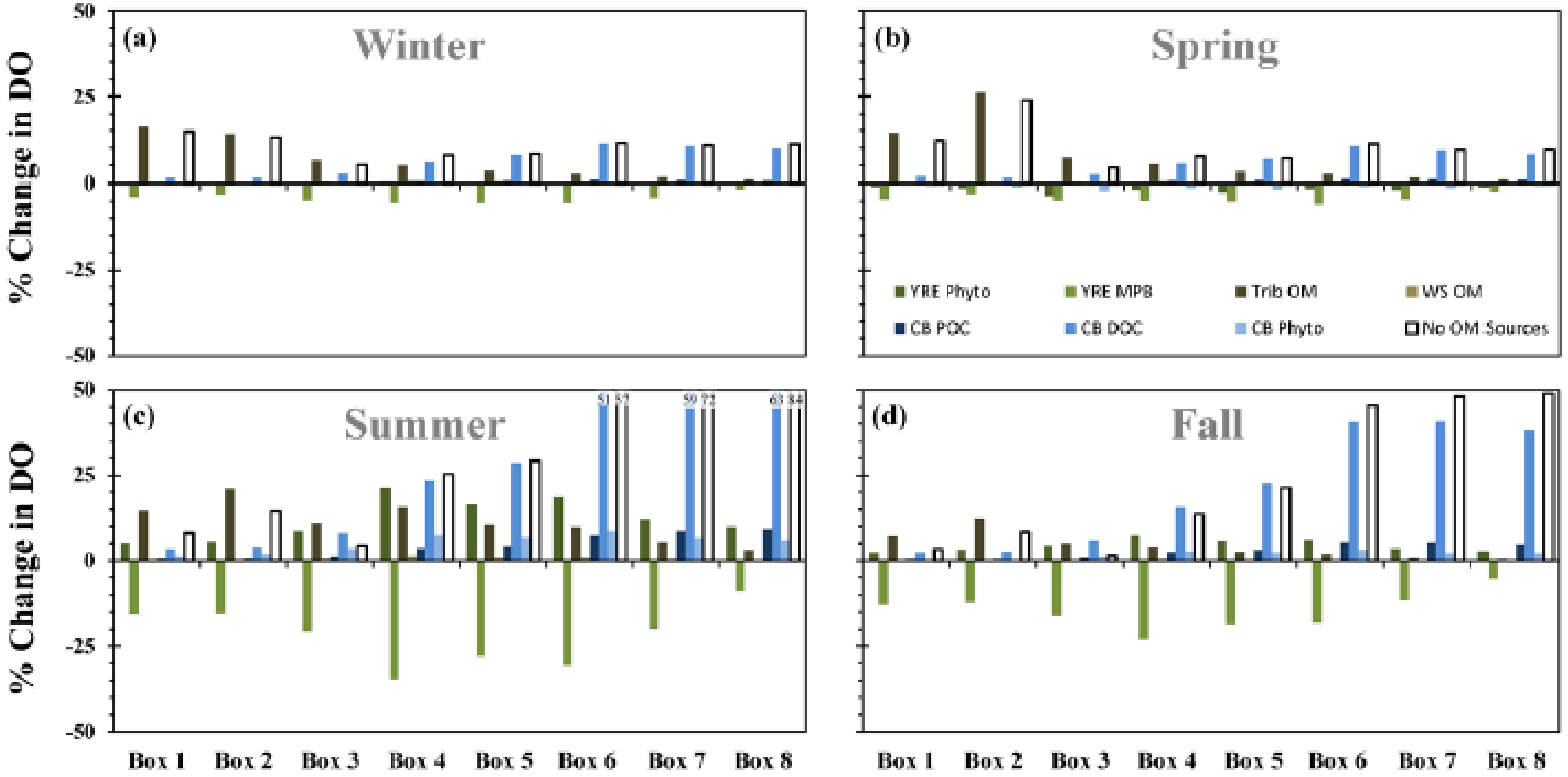
By

Samuel Joseph Lake

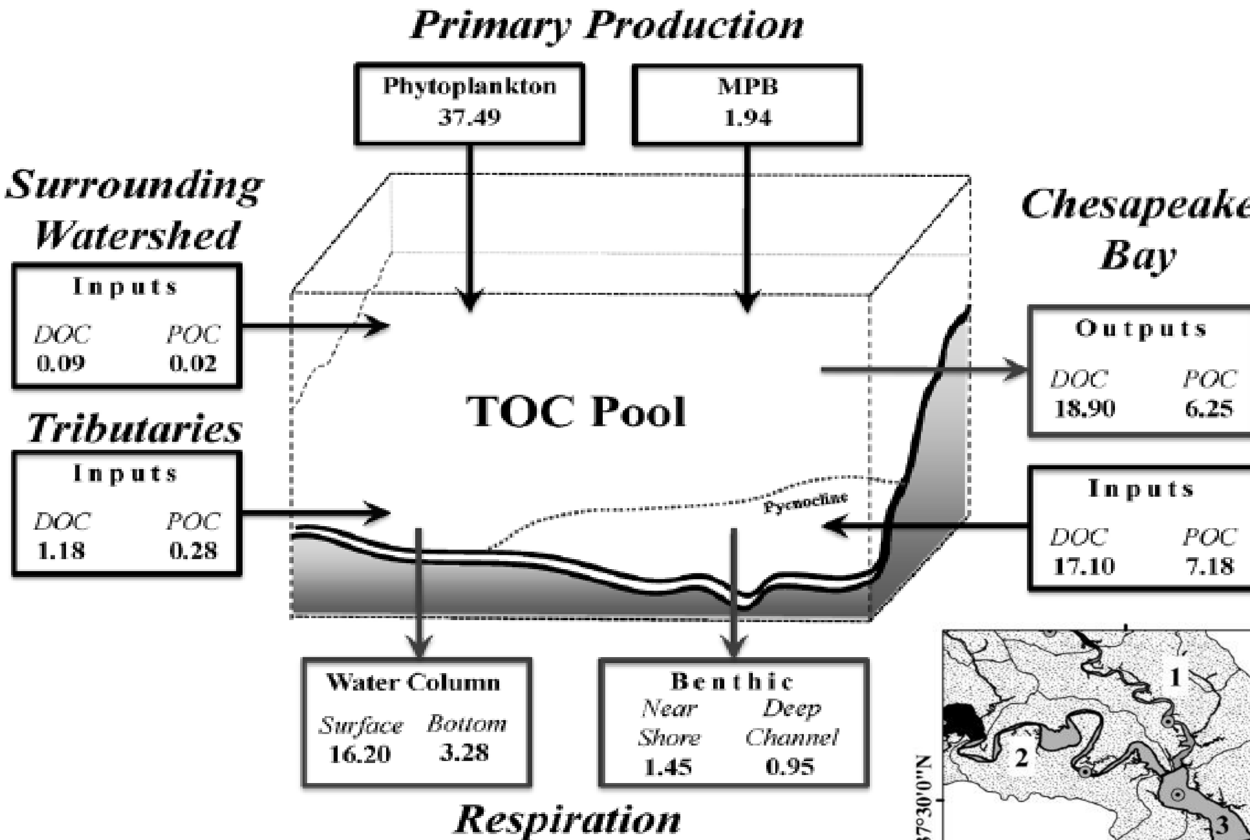
2013

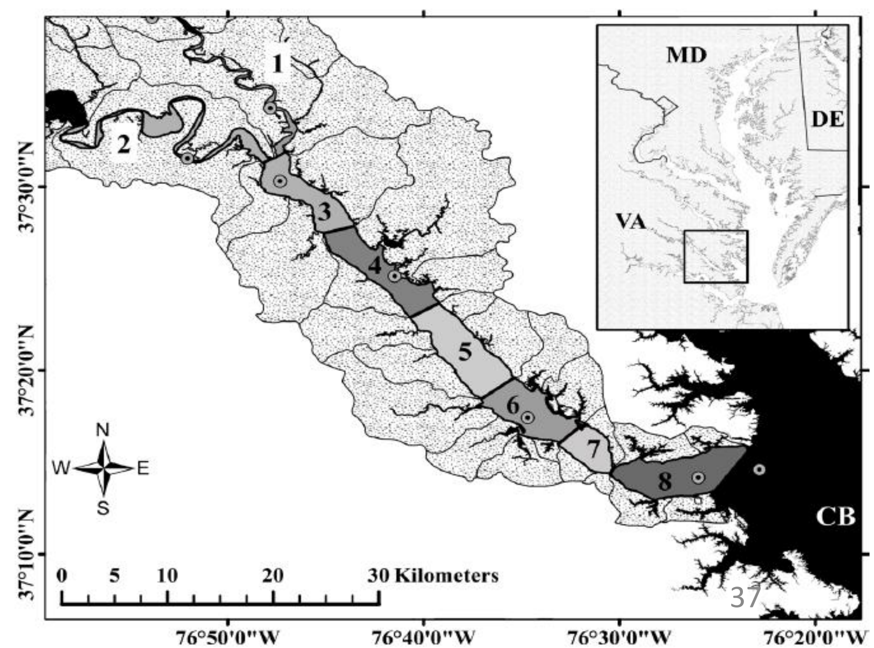


Contribution of OM Sources to Bottom Water DO



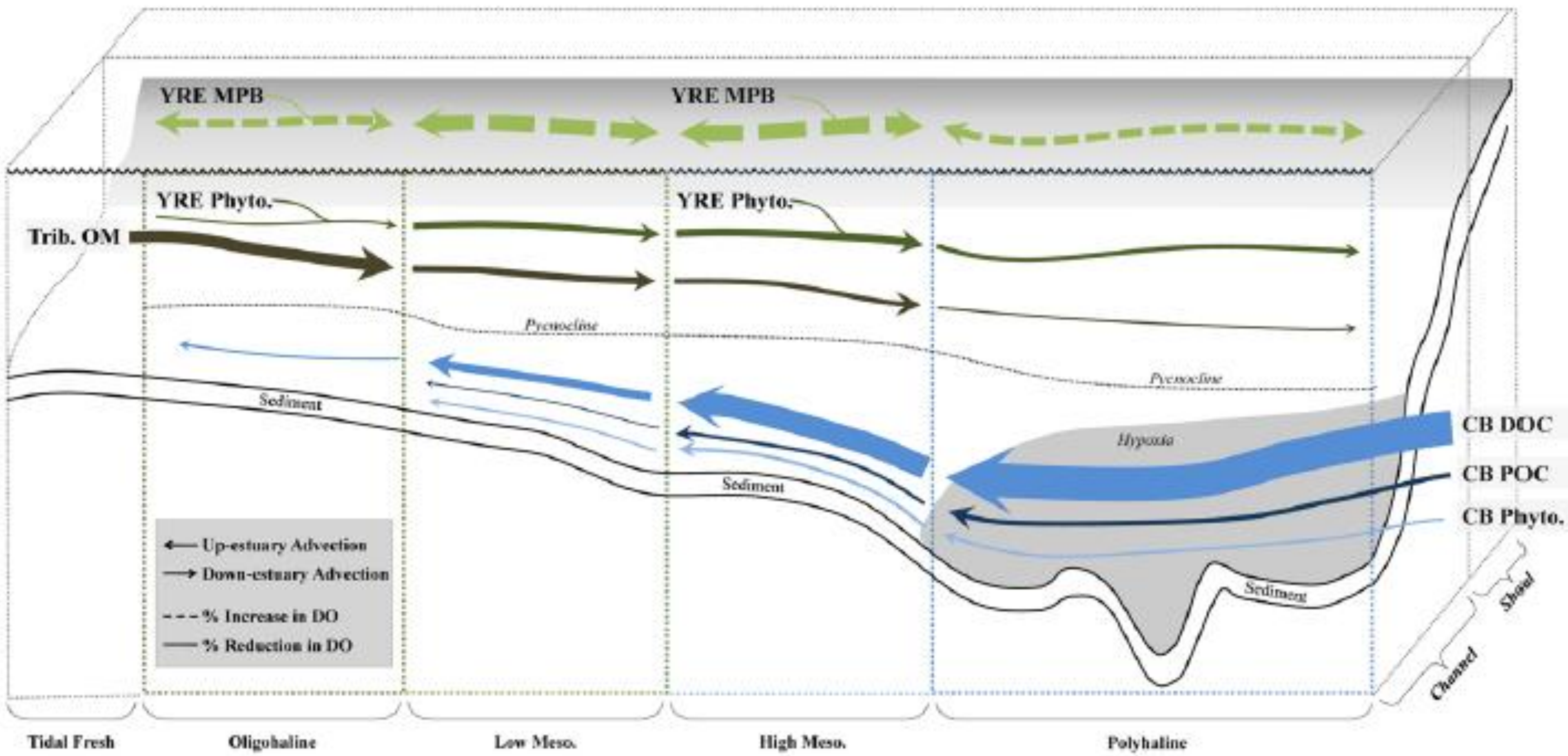
Total Organic Carbon





Organic Matter Sources

Relative Contribution to Bottom Water Oxygen



Analysis from the fundamental equation for DO

$$\frac{\partial DO}{\partial t}+\frac{\partial (uDO)}{\partial x}+\frac{\partial (vDO)}{\partial y}+\frac{\partial (wDO)}{\partial z}=\frac{\partial}{\partial x}\left(K_x\frac{\partial DO}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_y\frac{\partial DO}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_z\frac{\partial DO}{\partial z}\right)+S_c\,........(1)$$

Where
DO= Dissolved oxygen concentration of a water quality state variable
u, v, w = velocity components in the x-, y- and z-directions, respectively
Kx, Ky, Kz = turbulent diffusivities in the x-, y- and z-directions, respectively
Sc = internal and external sources and sinks per unit volume.

$$\begin{aligned}S_c = \frac{\partial DO}{\partial t} &= \sum_{x=c,d,g}\left((1.3-0.3\cdot PN_x)P_x-(1-FCD_x)\frac{DO}{KHR_x+DO}BM_x\right)AOCR\cdot B_x\\ &-AONT\cdot Nit\cdot NH4-AOCR\cdot K_{HR}\cdot DOC-\frac{DO}{KH_{COD}+DO}KCOD\cdot COD\\ &+K_r(DO_s-DO)+\frac{SOD}{\Delta z}+\frac{WDO}{V}\,..(2)\end{aligned}$$

Where
PNx = preference for ammonium uptake by algal group x (0 ≤ PNx ≤ 1)
AONT = mass of DO consumed per unit mass of ammonium nitrogen nitrified (4.33 g O2 per gN)
Px = primary production for species x
AOCR = dissolved oxygen-to-carbon ratio in respiration (2.67 g O2 per g C)
Kr = reaeration coefficient (day-1), applied to the surface layer only
DOs = saturation concentration of dissolved oxygen (g O2 m-3)
SOD =sediment oxygen demand (g O2 m-2 day-1), applied to the bottom layer only;
a direction of positive is towards the water column
WDO = external loads of dissolved oxygen (g O2 day-1)

Transport processes included in Equation (1) are:

(1)-a. local time change
(1)-b. horizontal advection
(1)-c. vertical advection
(1)-d. horizontal turbulent diffusivity
(1)-e. vertical turbulent diffusivity
(1)-f. internal and external source and sink

Kinetic processes Included in Equation (2) are:

(2)-a. algal photosynthesis and respiration
(2)-b. nitrification
(2)-c. heterotrophic respiration of dissolved organic carbon
(2)-d. oxidation of chemical oxygen demand
(2)-e. surface reaeration for the surface layer only
(2)-f. sediment oxygen demand for the bottom layer only
(2)-g. external loads

A. *Kuo and Neilson (1987) emphasize on (1)-b to address observations in James, York, and Rappahannock*

B. *Testa and Kemp (2008) emphasis on (2)-a and (2)-f to address Patuxent River hypoxia dynamics*

C. *Lake and Brush (2013) emphasized on (2)-a , (2)-c, and (1)-b (in particular the transport of OM from the bay to tributaries by bottom water movement) to address York River hypoxia dynamics*

"The fundamental equation that govern the DO in the main stem does not need to be different from that for the tributaries.

Several notable differences on the physical and biological setting between main stem and tributaries, and among tributaries, however, will shift the dominant balance among different processes".

Table

	Maximum depth	*Pelagic and sediment coupling*	*External source of carbon*	*Wind forcing*	*Open boundary condition*
Main stem (deep channel)	*~20 m*	*Less important*	*Sink*	*Important*	*Ocean*
Tributaries	*< 10 m*	*Very important*	*Source*	*Less important*	*Bay*

Recognizing the different setting between main steam and tributaries, a possible interpretation for the conclusion of Part 1:

"High spring flow tends toward earlier relative main stem initiation"

1. *With the high spring flow, overall, more nutrients in the tributaries are flushed out into the main stem Bay, which will cause the speed up for the initiation of the Bay hypoxia*

2. *With the high spring flow, it will cause more stratification in the main stem Bay than that in the tributary because the deeper depth in the channel, which, in turn, will reduce the vertical reaeration from the surface water.*

Conclusion (part II)

- Statistic evidences suggested that tributary Hypoxia in many times are initiated locally in the tributaries
- Since the tributaries are connected to the main stem bay, the bottom water movement of the gravitational circulation will have greater influence on the lower part of the tributaries as it moves upstream of the tributary.
- To what extent and how much is the influence of the bay on the tributaries depends on many factors. The assessment is yet to be conducted and determined in quantitative measure.
- The numerical model could be an effective tool to assess the optimal nutrient control for restoring tributary hypoxia by turning on and off of biological attributes in the tributaries and vice versa in the main stem Bay for comparison.