

Synthesis: Understanding of Chesapeake Bay Water Clarity Patterns

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with figures from (lead authors)

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Tango, M. Trice, J. Turner, M. Wang, P. Wang, H. Weinberg, J. Xu

STAC Water Clarity Trends Workshop, 2/6/2017

Synthesis: Understanding of Chesapeake Bay Water Clarity Patterns

OUTLINE

1. Why is K_d the key variable for quantifying water clarity in Chesapeake Bay? What is the main water constituent determining K_d Bay-wide?
2. What are other quick-to-measure proxies for K_d ? How do they compare to K_d ?
3. What are the main components of TSS? On a Bay-wide scale, what drives their spatial distribution?
4. In lower energy areas, what drives their temporal distribution? How do they affect water clarity?
5. How do K_d and Secchi theoretically respond to components of TSS?
6. How has clarity been changing over decadal time scales based on observed Secchi depth?
7. How has clarity been changing over decadal time scales based on observed K_d ?
8. Can Secchi depths be used to represent changes in K_d over shorter time-scales?

Need to know Percent Light through Water (PLW) directly drives need to know K_d

$$PLW = 100 \exp [(-K_d)(Z)].$$

Light intensity diminishes approximately exponentially with depth in water, so that

$$I(Z) = I(0) \text{EXP}(-K_d Z)$$

The light attenuation coefficient was calculated from Eq. 1 as:

$$K_d = \frac{\ln(I_1/I_2)}{(Z_2 - Z_1)}$$

(Kemp et al. 2004; Xu et al. 2005)

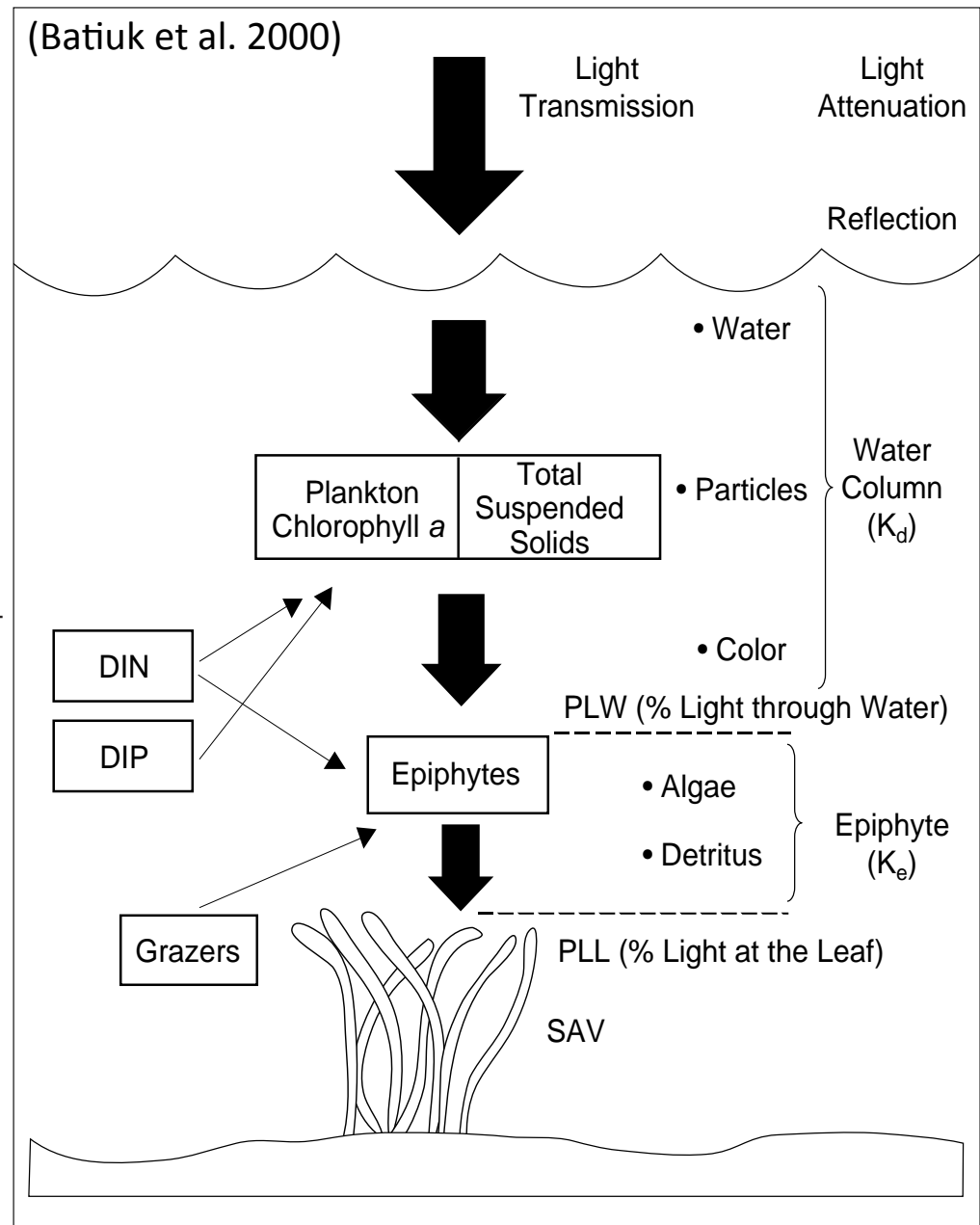


FIGURE II-1. Conceptual Model of Light/Nutrient Effects on SAV Habitat. Availability of light for SAV is influenced by water column and at the leaf surface light attenuation processes. DIN = dissolved inorganic nitrogen and DIP = dissolved inorganic nitrogen.

TABLE 2. Statistically-derived water quality thresholds beyond which submerged aquatic vegetation (SAV) are not present

Salinity Regime ^b	Growing Season ^c	Light Required at SAV Leaf (%), PLL_{min}	Light Required through Water (%), PLW_{min}
Tidal Freshwater	April–October	>9	>13
Oligohaline	April–October	>9	>13
Mesohaline	April–October	>15	>22
Polyhaline	March–May September–November	>15	>22

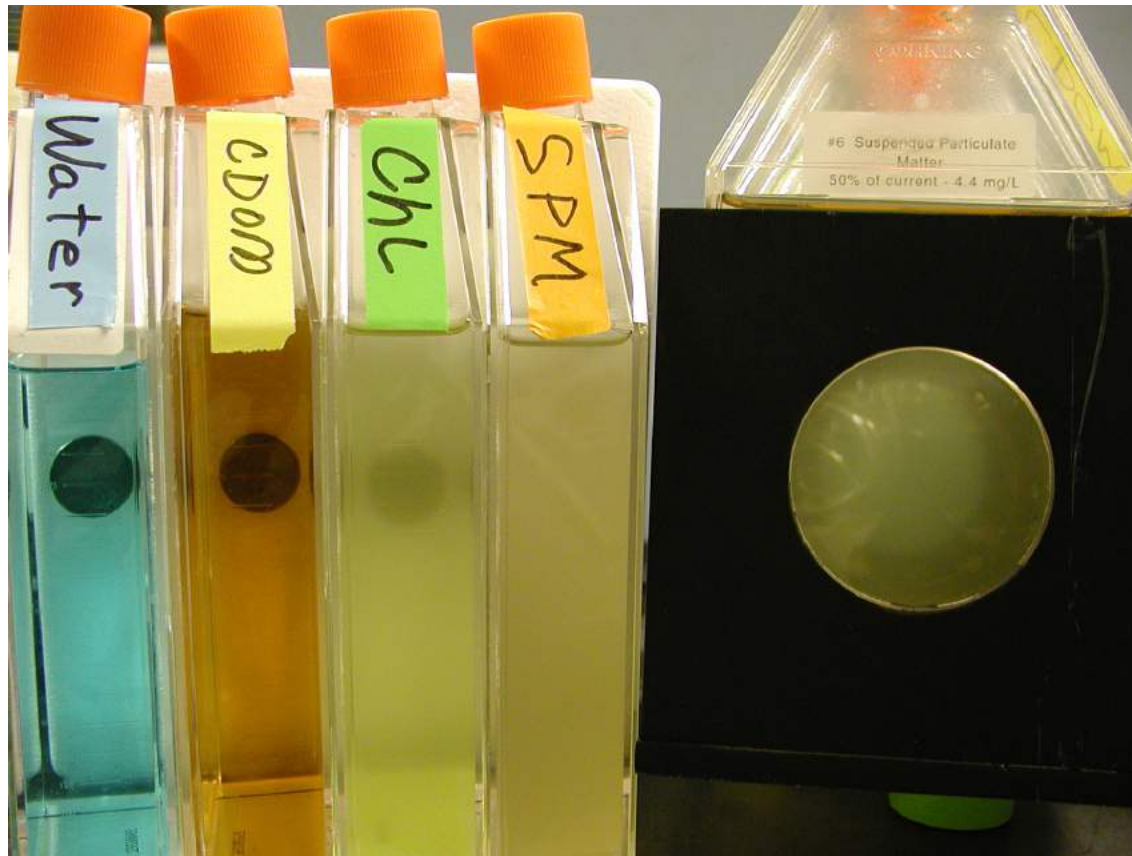
(Kemp et al. 2004)

$$PLW = 100 \exp [(-K_d)(Z)].$$

Salinity Regime	Water Clarity Criteria as Percent Light through Water	Water Clarity Criteria Application Depths (meters)			
		0.5	1.0	1.5	2.0
		Kd (1/m) Equivalents for Criteria Application Depth			
Tidal Fresh & Oligohaline	13%	Kd<4.08	Kd< 2.04	Kd<1.36	Kd<1.02
Mesohaline & Polyhaline	22%	Kd< 3.03	Kd< 1.51	Kd<1.01	Kd<0.76

(Wang & Tian 2015)

Four Factors Contribute to Water-column Light Attenuation



1. Water
2. Colored dissolved organic matter
3. Chlorophyll
4. Suspended particulate matter (a.k.a., Total Suspended Solids)

(Gallegos 2005)

What constituent of water statistically explains the most Bay-wide variance in K_d ?

The linear representation of K_d can then be written as

$$K_d(\text{PAR}) = K_w' + K_c[\text{CHL}] + K_t[\text{TSS}] + K_s[\text{Sal}] \quad (4)$$

TABLE 1. The coefficient, p value, and partial R^2 for each term in Eq. 6. K_c and K_t are the specific attenuation coefficients of chl a and total suspended solids, respectively. K_s is a function of specific attenuation coefficients of CDOM in relation to salinity. K_w' is the attenuation coefficient due to pure water and CDOM in freshwater.

Variables	K_w'	K_c	K_t	K_s
Value	1.932	-0.004765	0.059	-0.0867
p	< 0.001	0.0275	< 0.001	< 0.001
Partial R^2	na	0.001	0.585	0.138

- Bay-wide, TSS statistically accounts for ~ 60% of all variability in K_d .
- Chlorophyll's role (at ~ 0.1%) is ambiguous
- But remember, TSS = solids, not sediment.

(Xu et al. 2005)

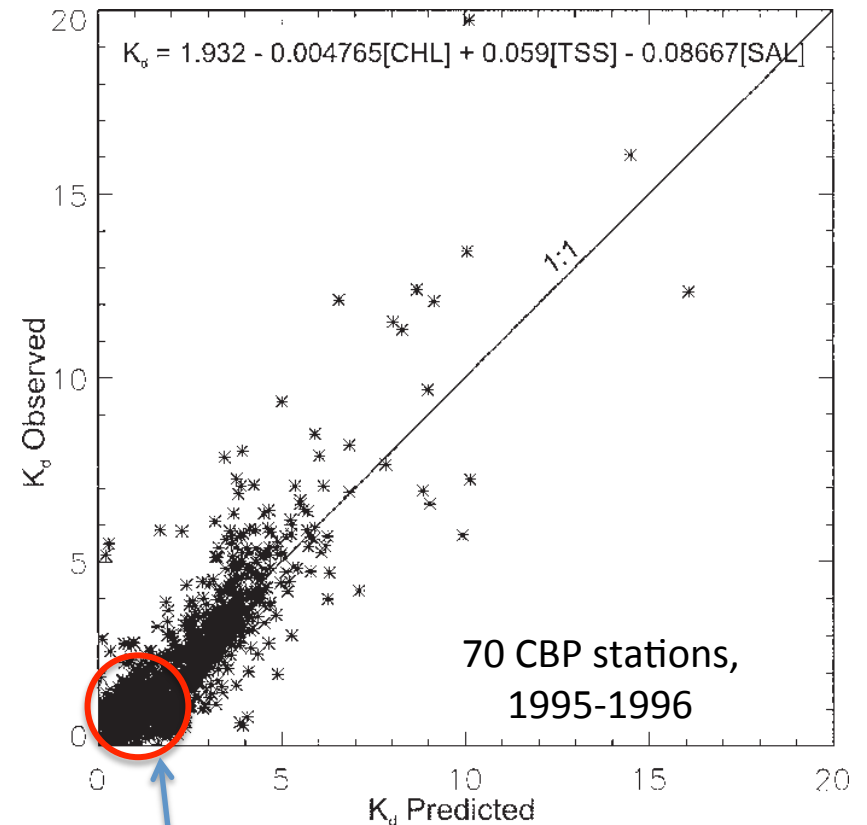


Fig. 2. Vertical light attenuation coefficient (K_d) (m^{-1}) derived from direct light measurements versus K_d obtained from the uniform linear regression relation (shown in the figure).

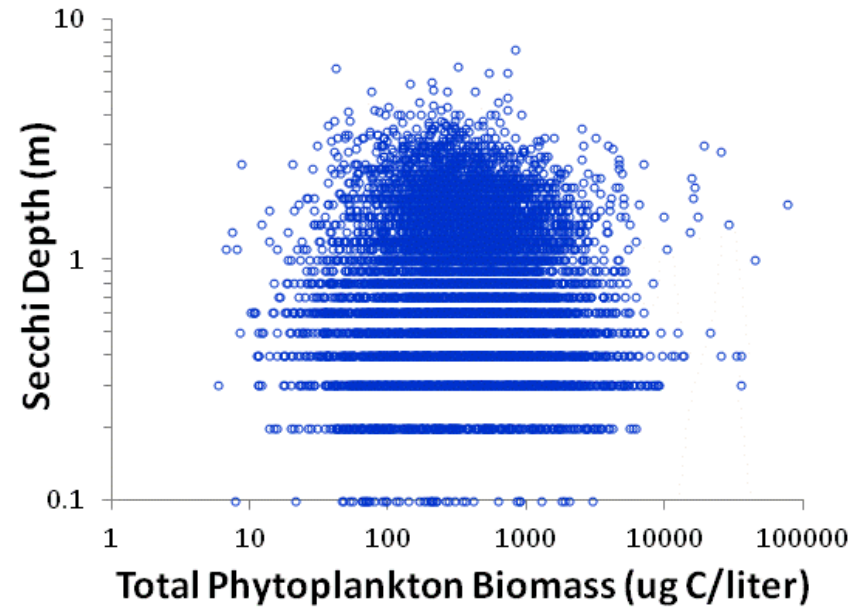
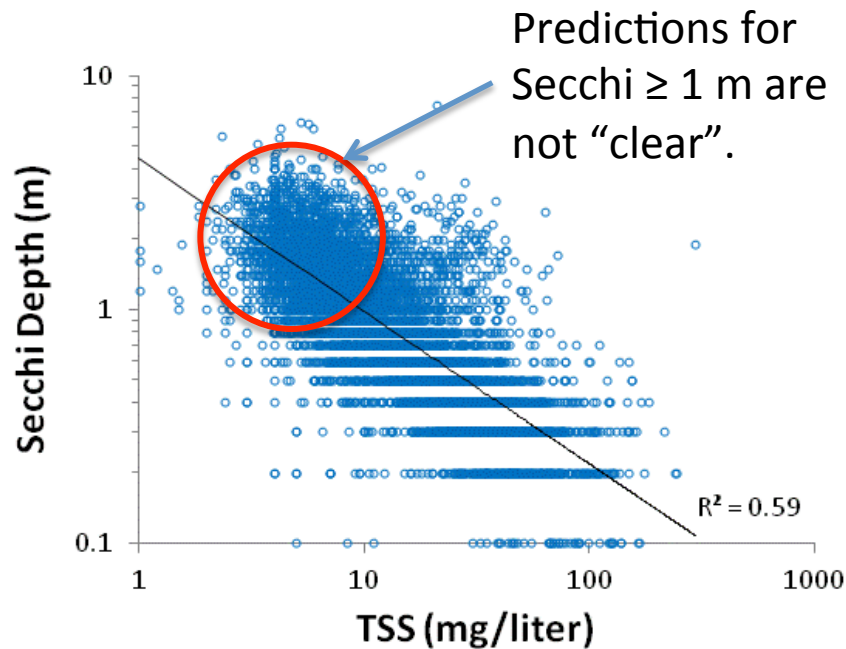
- Also, predictions for $K_d \leq \sim 2 \text{ m}^{-1}$ are less clear.

Synthesis: Understanding of Chesapeake Bay Water Clarity Patterns

OUTLINE

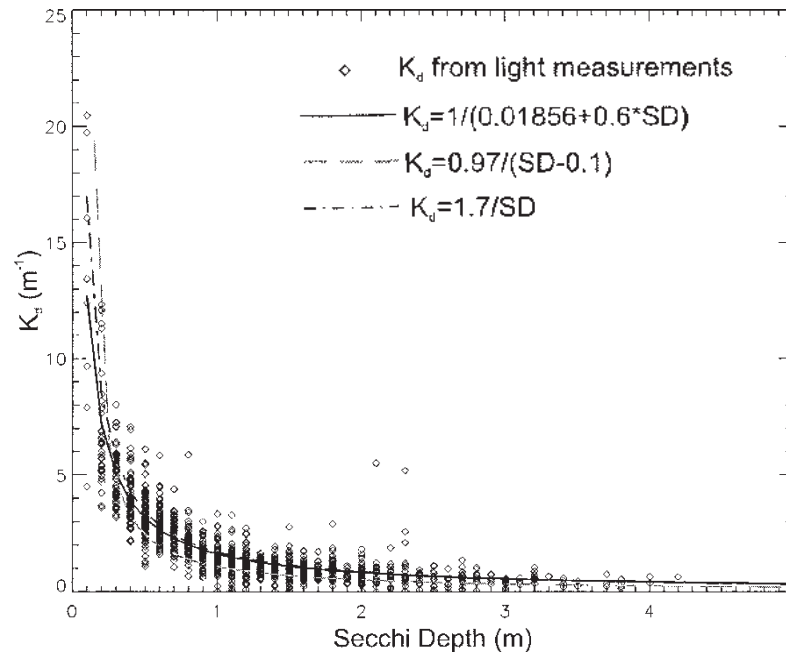
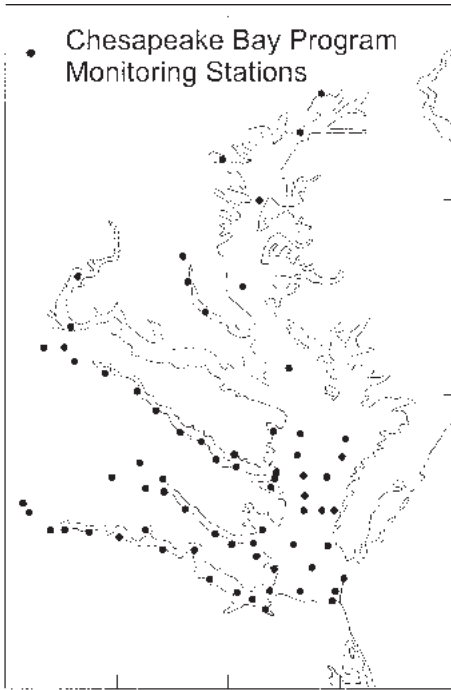
1. Why is K_d the key variable for quantifying water clarity in Chesapeake Bay? (Ans: PLW)
What is the main water constituent determining K_d Bay-wide? (Ans: TSS)
2. What are other quick-to-measure proxies for K_d ? How do they compare to K_d ?
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Data from all CBP phytoplankton monitoring stations, all seasons, 1984-2010



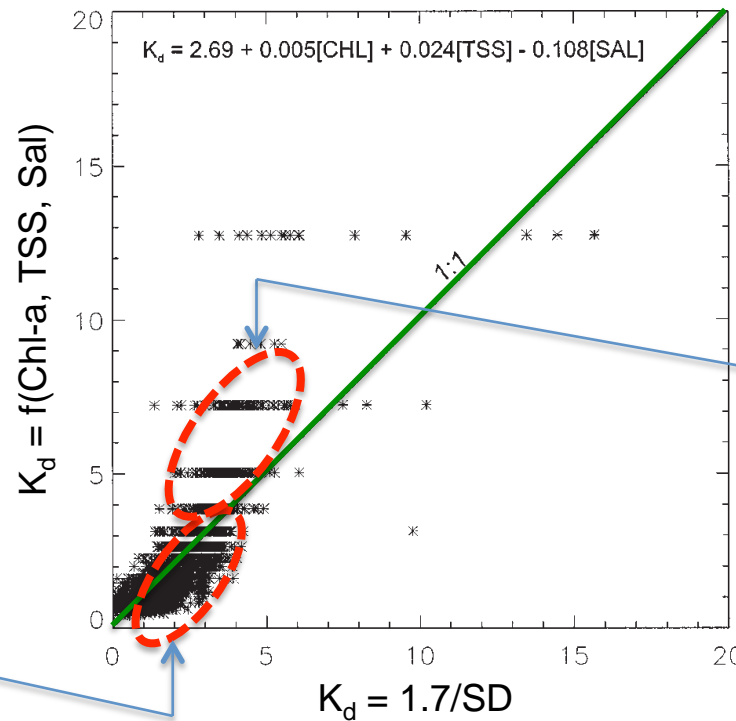
- Secchi depth is a simple, quick measure of clarity that is more widely available.
- Bay-wide, TSS likewise accounts for $\sim 60\%$ variance in Secchi depth.
- Similarly, the relationship of phytoplankton to Secchi depth is ambiguous.
- How do Secchi measurements compare to K_d ?

(Xu et al. 2005)



How do Secchi measurements compare to K_d ?

$K_d = \text{Const.}/\text{Secchi}$
overestimates K_d
when water is relatively clear.



$K_d = \text{Const.}/\text{Secchi}$
underestimates K_d
when water is very turbid.

Dataflow equations for K_d as funct. of Turbidity (NTUs), Chl-a and Salinity

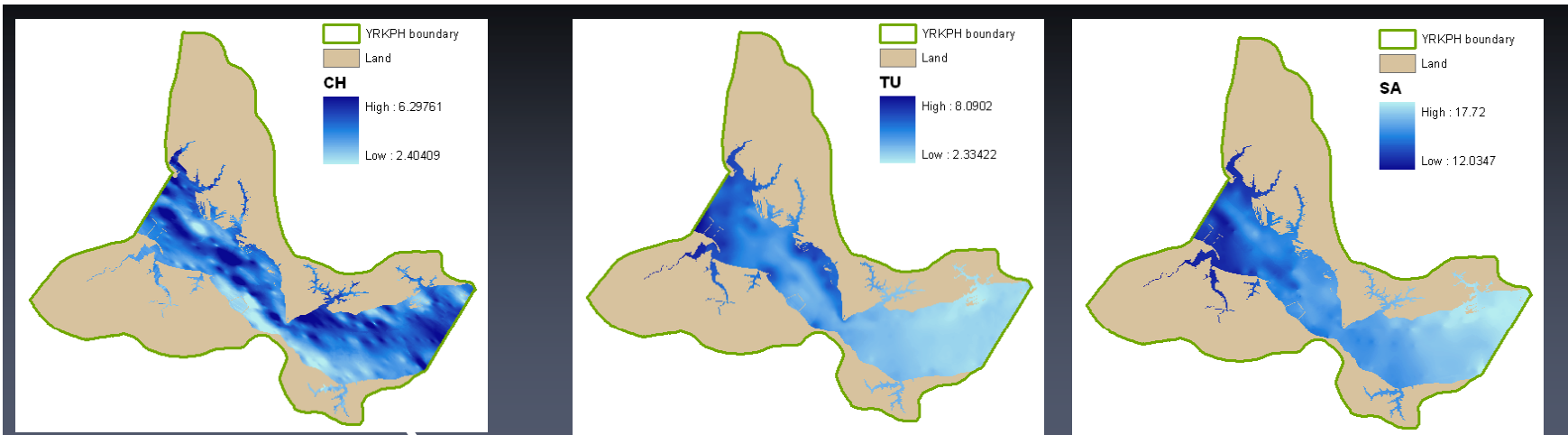
Table IV-2. Regional K_d regression equations.

(Tango et al. 2008)

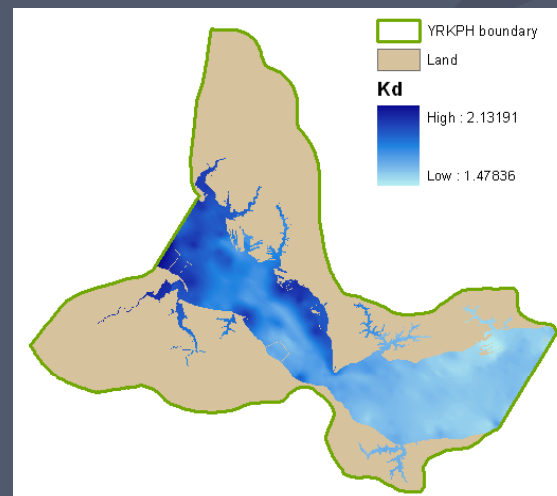
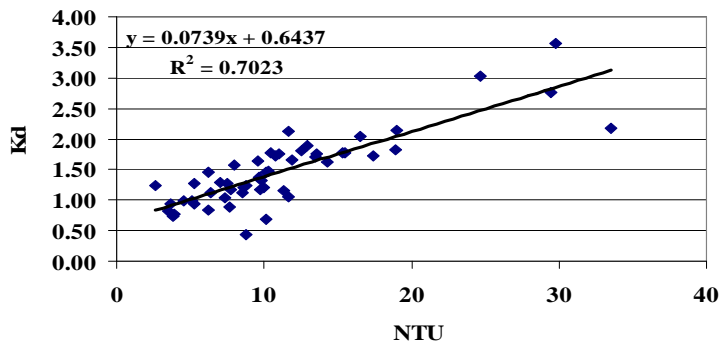
State-River segment Group	Regional K_d equation
MARYLAND GROUP 1 Bush River BSHOH, Gunpowder River GUNOH, Magothy River MAGOH, Middle River MIDOH, St. Mary's River ¹	$K_d = 0.5545 + 0.3172 * \text{Turbidity}^{(1/1.5)} + 0.0160 * \text{Chlorophyll } a - 0.0138 * \text{Salinity}$
MARYLAND GROUP 2 Eastern Bay-EASMH Lower Patuxent River-PAXMH Lower Potomac River-POTMH West/Rhode Rivers-WSTMH/RHDMH	$K_d = -0.1247 + 0.2820 * \text{Turbidity}^{(1/1.5)} + 0.0207 * \text{Chlorophyll } a + 0.0515 * \text{Salinity}$
MARYLAND GROUP 3 Fishing Bay/Chicamacomico River-FSHMH, Severn River-SEVMH South River-SOUMH	$K_d = 1.0895 + 0.4160 * \text{Turbidity}^{(1/1.5)} + 0.0140 * \text{Chlorophyll } a - 0.0950 * \text{Salinity}$
MARYLAND GROUP 4 Little Choptank River-LCHMH Miles/Wye Rivers-EASMH	$K_d = -0.8991 + 0.4338 * \text{Turbidity}^{(1/1.5)} + 0.0180 * \text{Chlorophyll } a + 0.0912 * \text{Salinity}$
MARYLAND GROUP 5 Upper and Middle Patuxent River-PAXOH/PAXTF	$K_d = 0.8191 + 0.2691 * \text{Turbidity}^{(1/1.5)} - 0.0084 * \text{Chlorophyll } a + 0.0384 * \text{Salinity}$

- $K_d \sim \text{Turbidity}^{(1/1.5)}$ indicates turbidity responds more to high K_d than to low K_d .
- Large variation in other coefficients (even sign) as a function of river segment.

Similar to Secchi, K_d derived from Turbidity is often not improved by including Chl-a



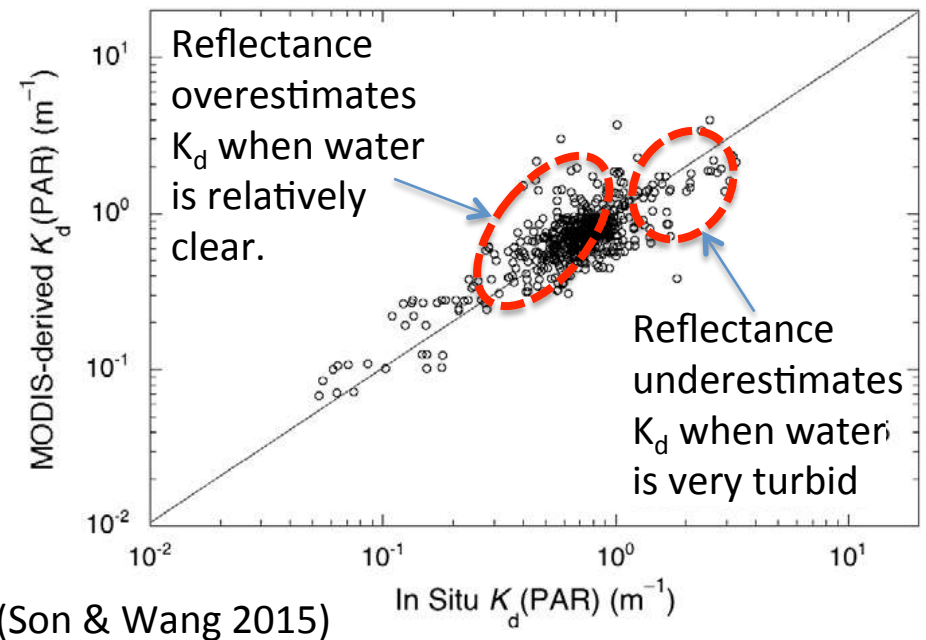
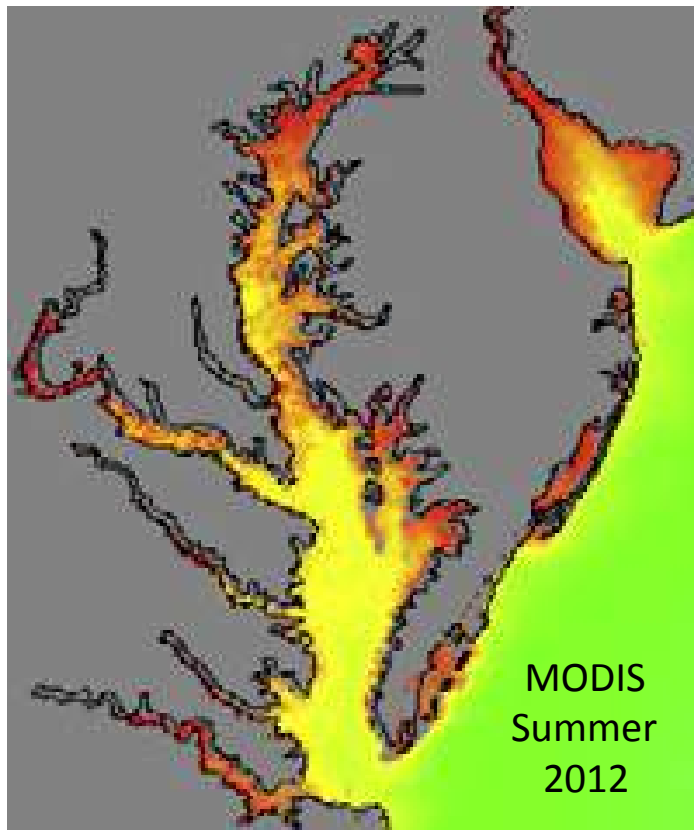
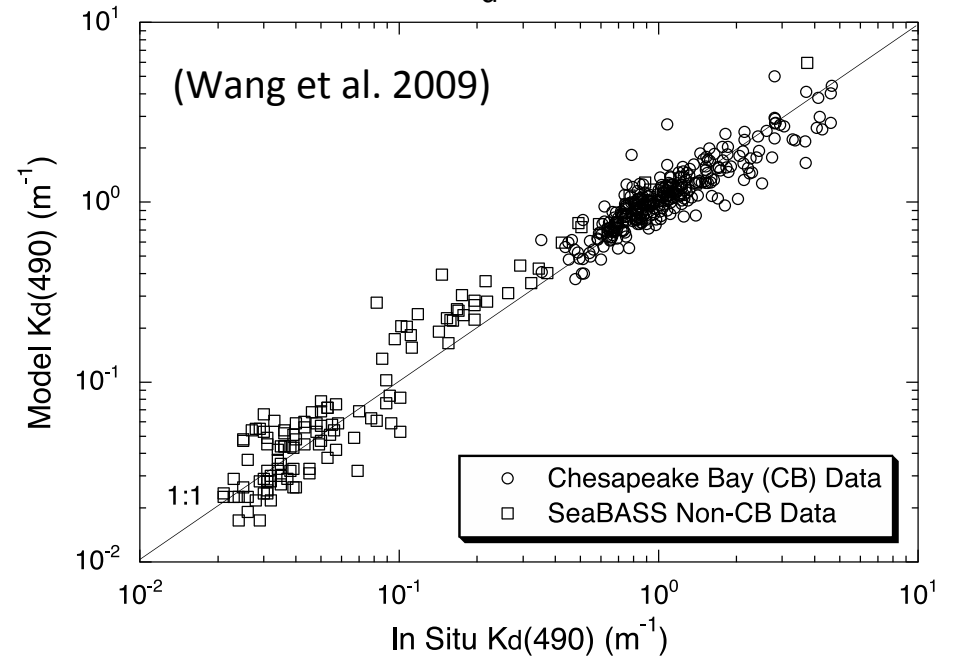
$$Kd = 0.5275793536 + 0.3193475331 \times \sqrt[1.5]{TU} + 0.0176700982 \times SA + 0.0271723238 \times CH$$



(Moore 2012)

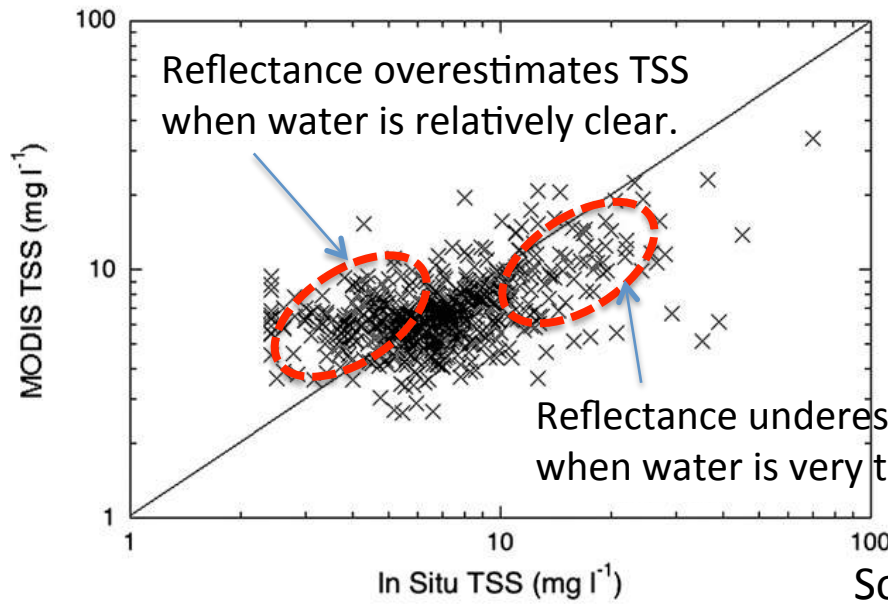
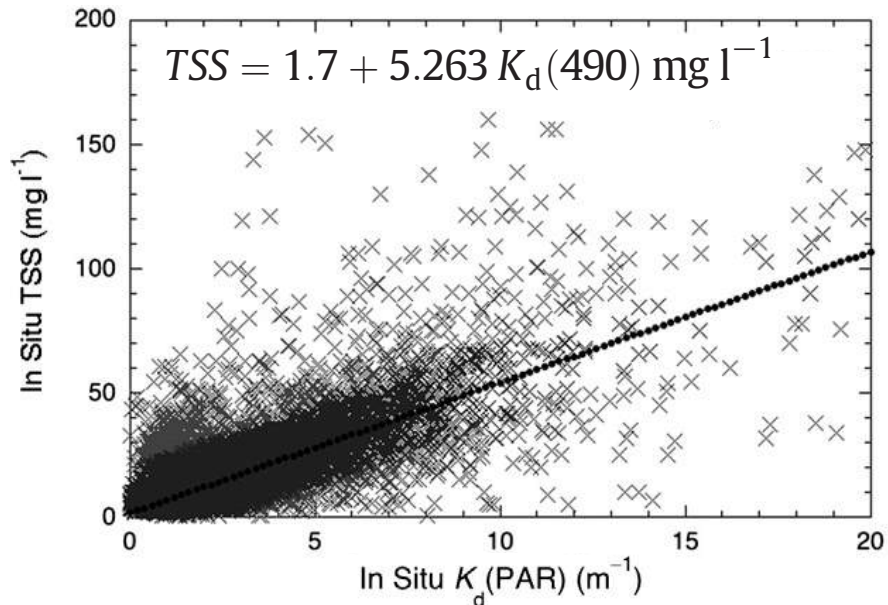
Reflectance of incident light measured by satellites calibrates to K_d

$$K_d(490) = \frac{2.697 \times 10^{-4}}{R(488)} + 1.045 \frac{R(667)}{R(488)} + 4.18 [7 \times 10^{-4} + 2.7135R(667)] \cdot \left\{ 1 - 0.52 \exp \left[-\frac{2.533 \times 10^{-3}}{R(488)} - 9.817 \frac{R(667)}{R(488)} \right] \right\},$$

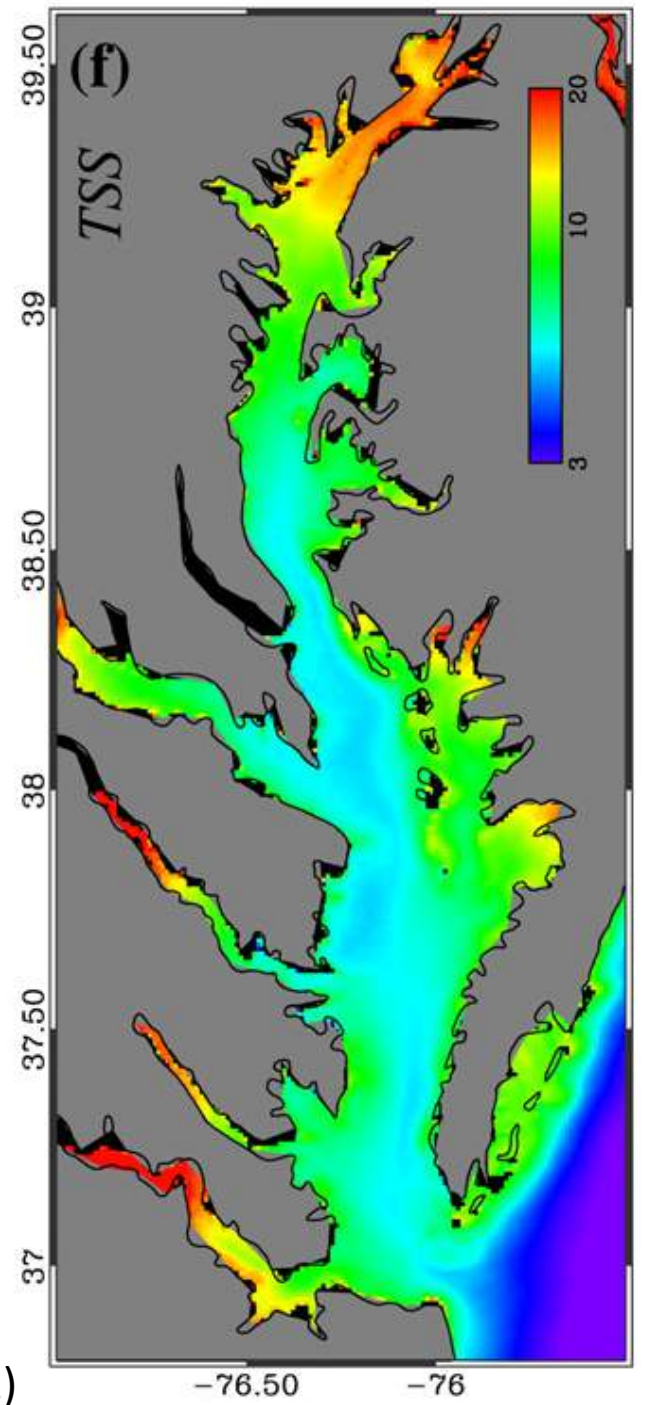


0.01 0.1 1.0 2.0

Satellite TSS from in situ linear fit to applied to Satellite K_d



Son & Wang (2012)



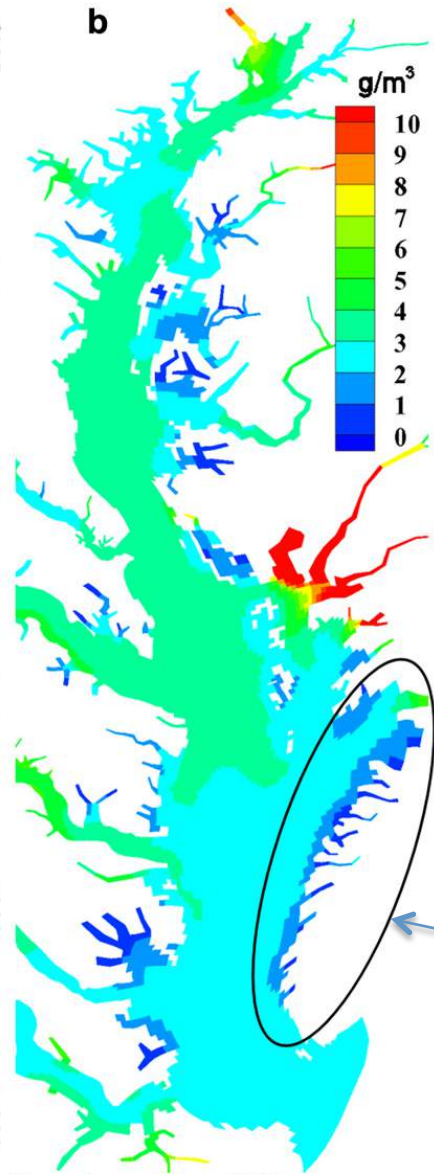
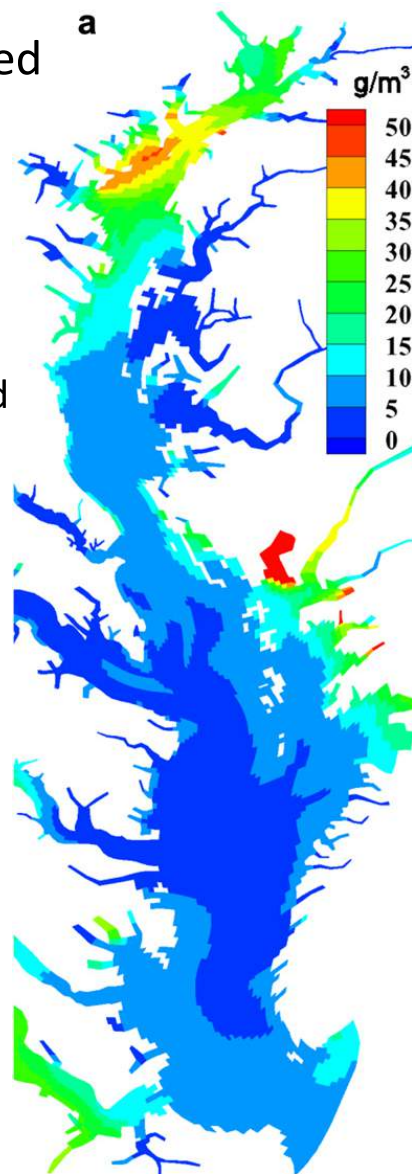
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Inorganic and Organic Suspended Solids in Surface Water in Chesapeake Bay Program Estuarine Water Quality Model

Inorganic Suspended Solids (ISS) mass concentration



Organic Suspended Solids (OSS) mass concentration

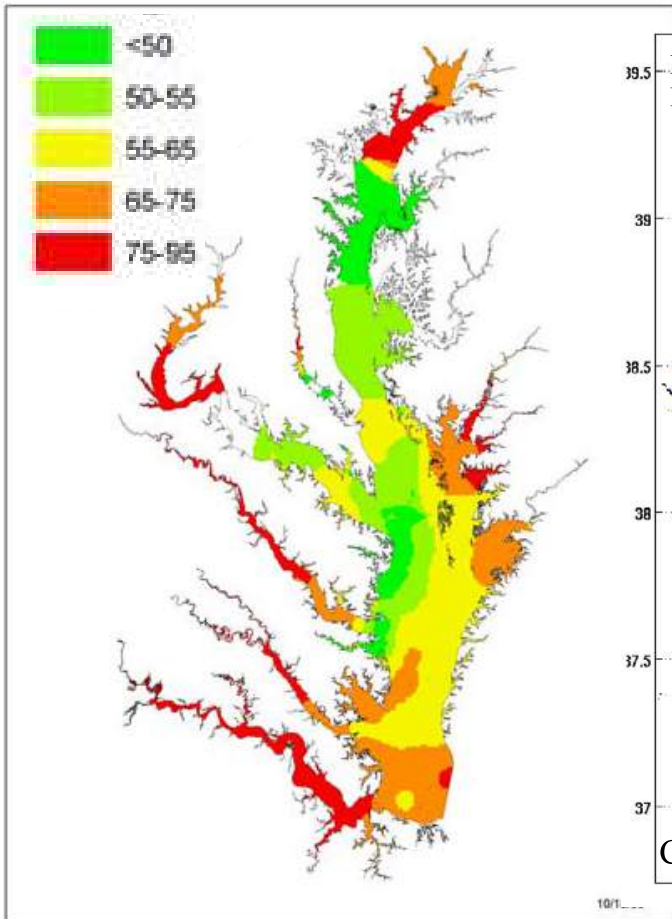
- OSS is of the same magnitude as ISS over of much the Bay.
- OSS settling speed is the same as fine clay, so the ratio of OSS to ISS remains stable in areas with relatively low turbidity.

Example of SAV feedback reducing suspended solids

Particle setting velocity in microns/sec	ISS				OSS
	Fine clay	Clay	Silt	Sand	Organic solids
	12	30	100	1000	11.6

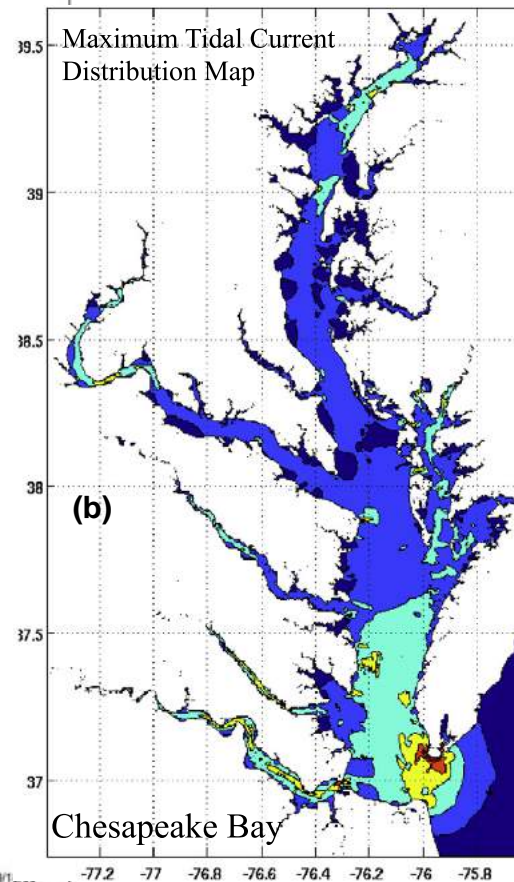
At Bay-wide scales, Inorganic Suspended Solids (ISS) fraction is high where tidal currents are strong and/or density-driven Estuarine Turbidity Maximum (ETM) is present

Observed % ISS



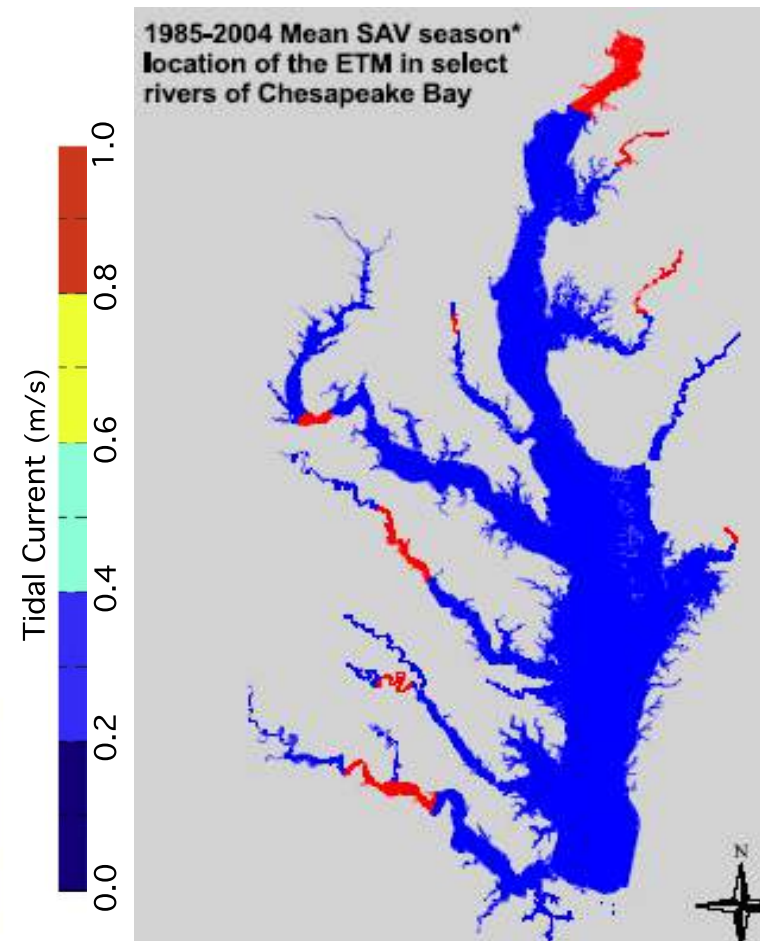
Curry et al. (2007)

Max Tidal Current

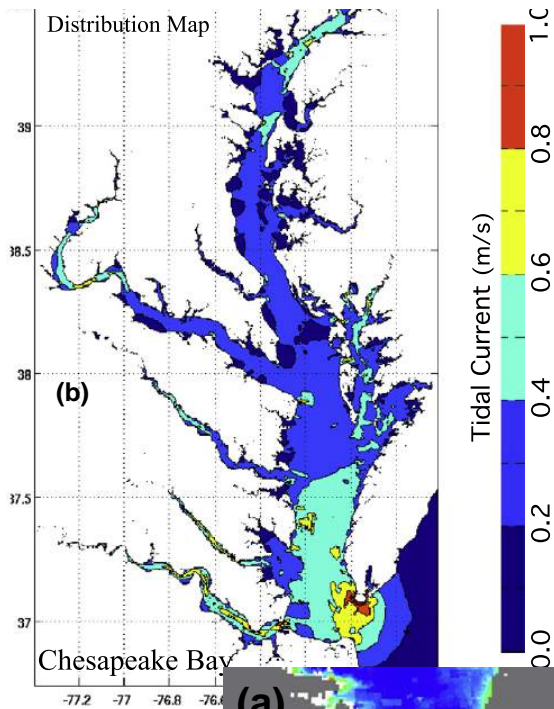


Shi et al. (2013)

Mean ETM location



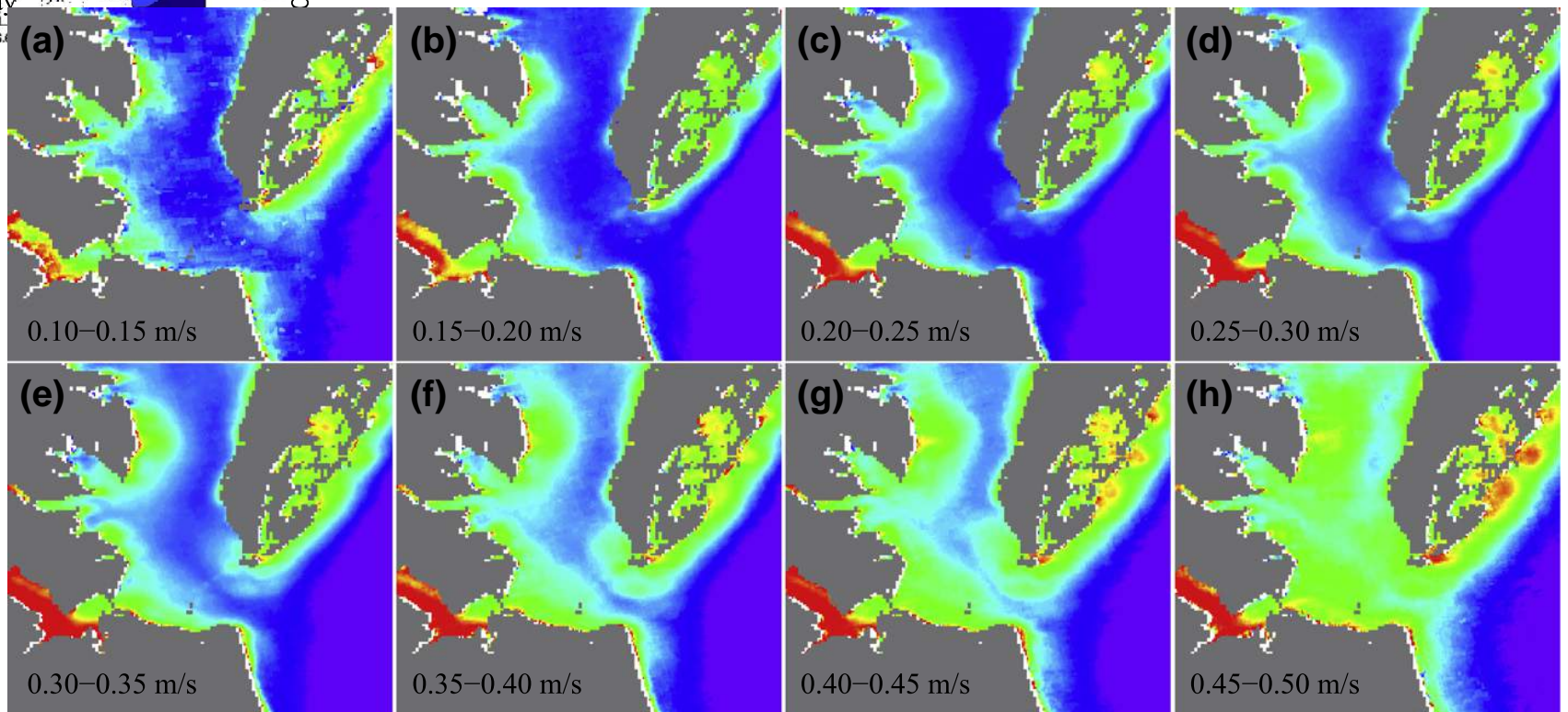
Curry et al. (2007)



Where tidal currents are strong, resuspension of inorganic suspended solids dominates K_d

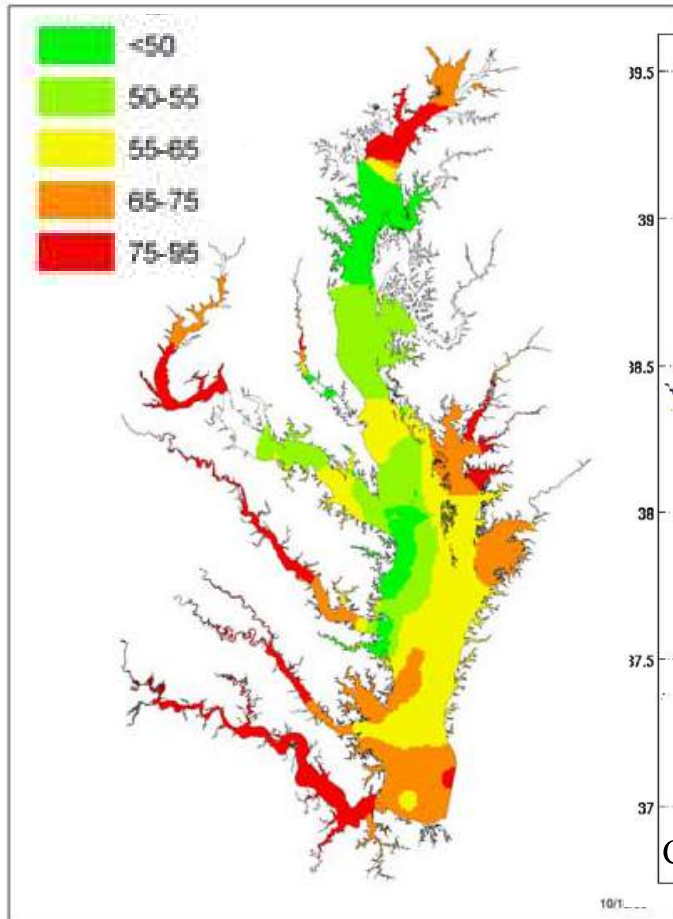
Tidal Current Effect on $K_d(490)$ in Lower Chesapeake Bay

Shi Wang Jiang
(2013)



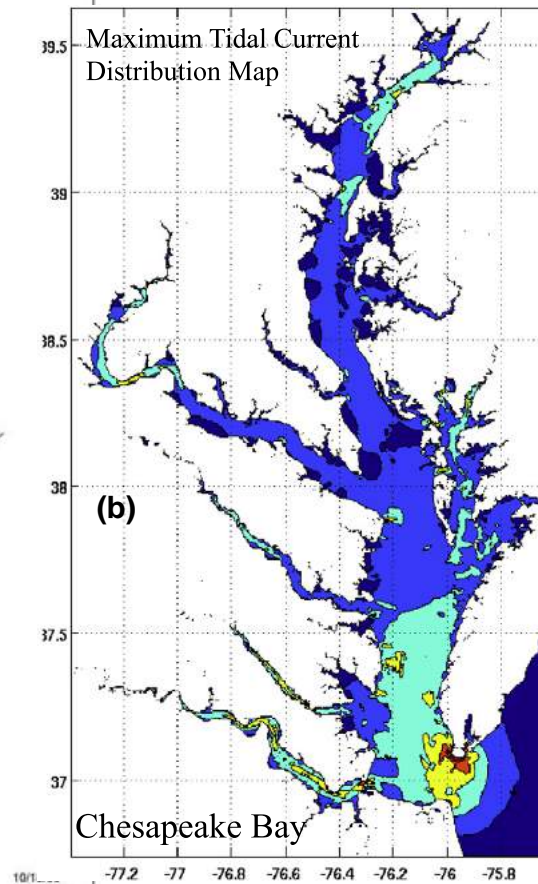
Persistently high K_d occurs in most regions where ISS dominates OSS
(Lowermost Bay is an exception)

SAV growing season
Mean observed % ISS



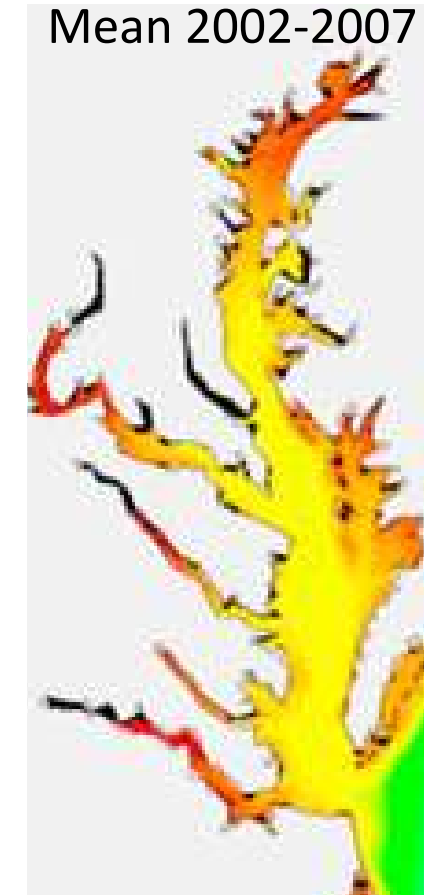
Curry et al. (2007)

Max Tidal Current



Shi et al. (2013)

Satellite derived K_d



Wang et al. (2009)

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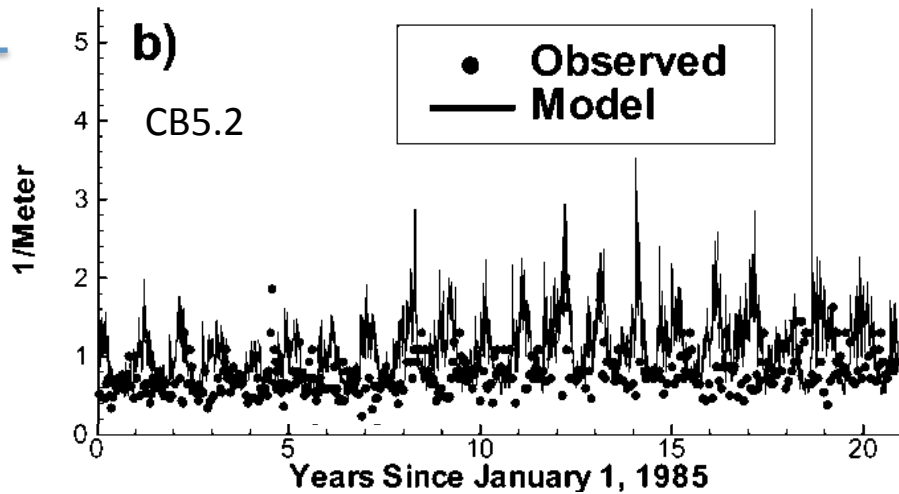
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3. What are the main components of TSS? (Ans: ISS, OSS) On a Bay-wide scale, what drives their spatial distribution? (Ans: ISS = strong current or ETM, OSS = everywhere else)
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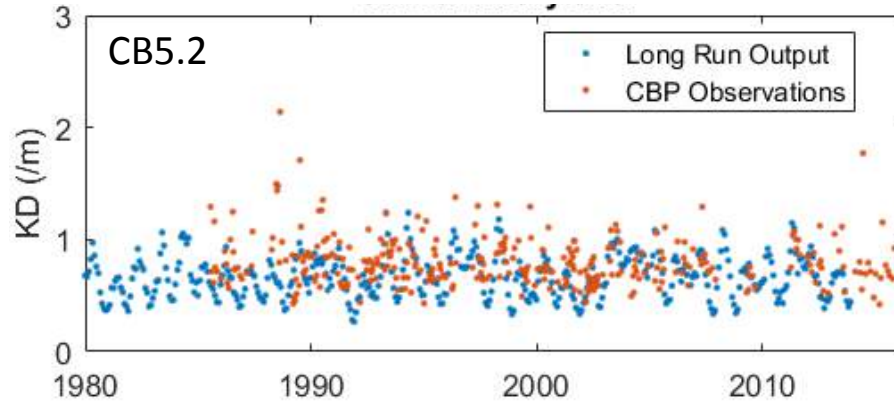
Light Attenuation Time-Series at Mid-Bay, Main Channel Station

Models' light attenuation peaks each spring in conjunction with spring phytoplankton bloom

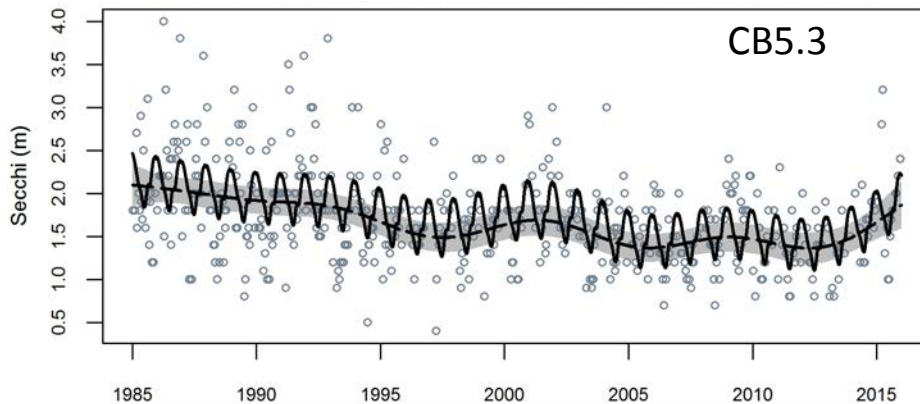
Observed attenuation peaks each summer well after spring phytoplankton bloom



Cerco et al. (2013)
CE-QUAL-ICM
Observed: $K_d = 1.4/\text{Secchi}$
Model: K_d from look up table $f(\text{ISS}, \text{OSS}, \text{CDOM}, \text{Chl-a})$
based on optical model from Gallegos et al. (2011)



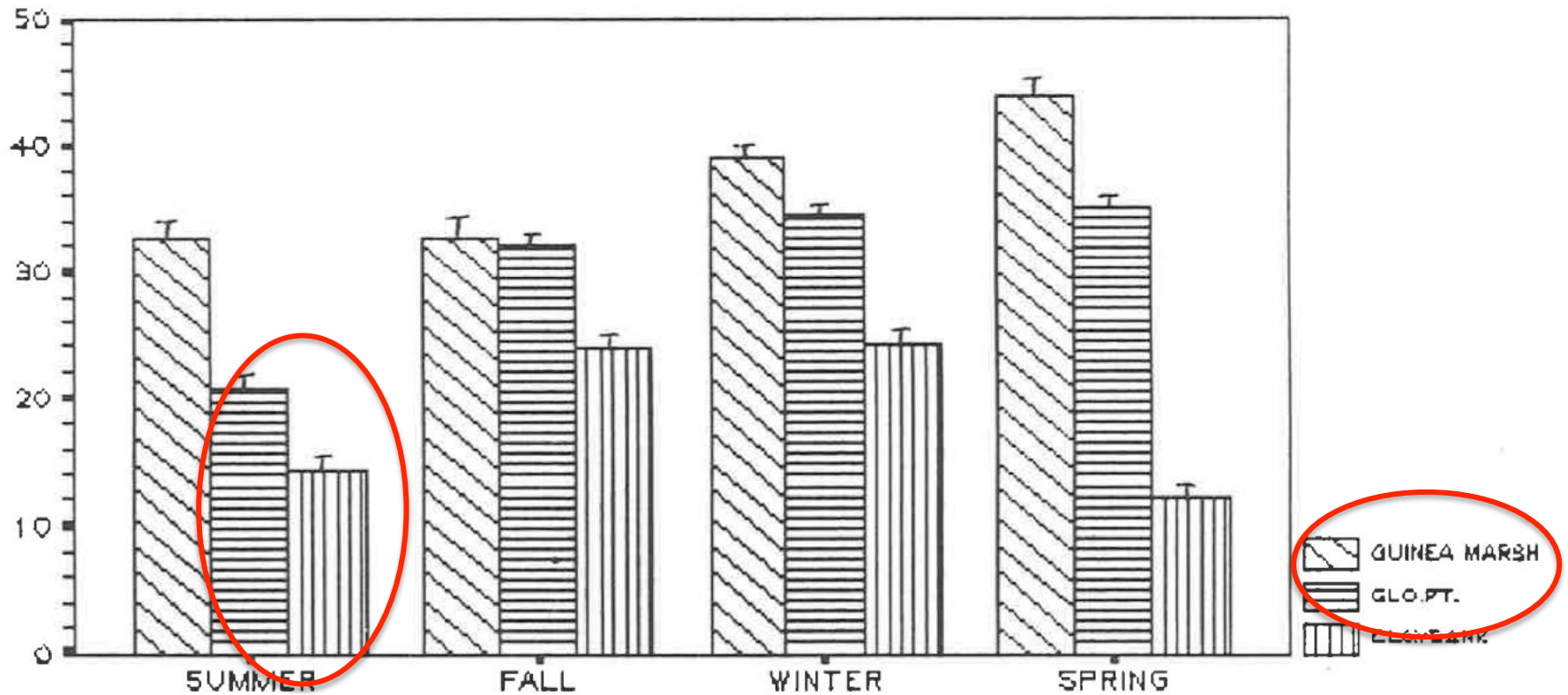
M.Friedrichs & Turner (2017)
ChesROMS-ECB
Observed = in situ K_d
Model: $K_d = \text{Const.} \times \text{OSS}$



Murphy (2016)
Observed = Secchi
Model fit = GAMs
seasonal and interannual components

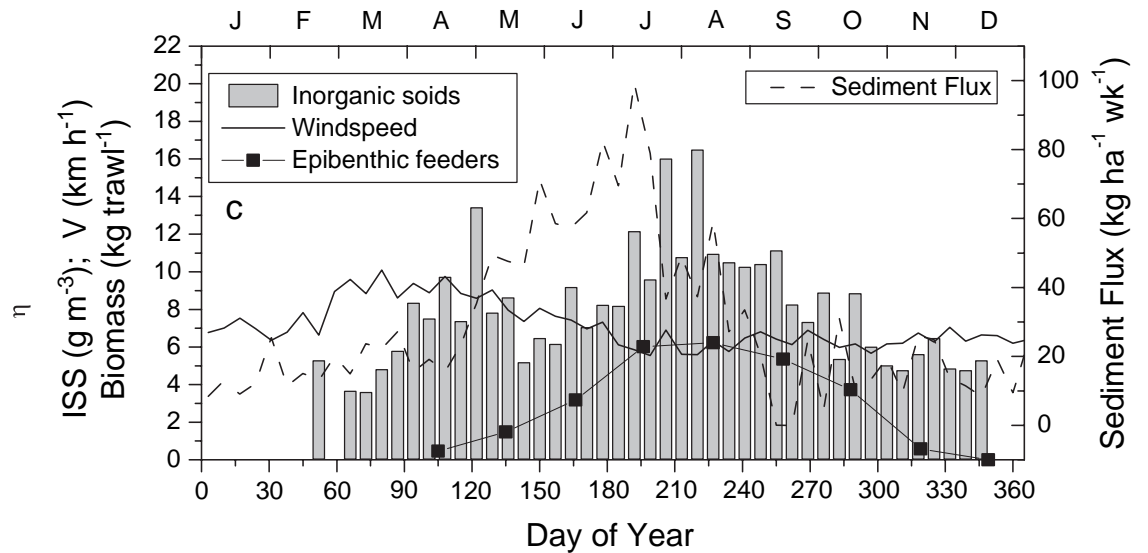
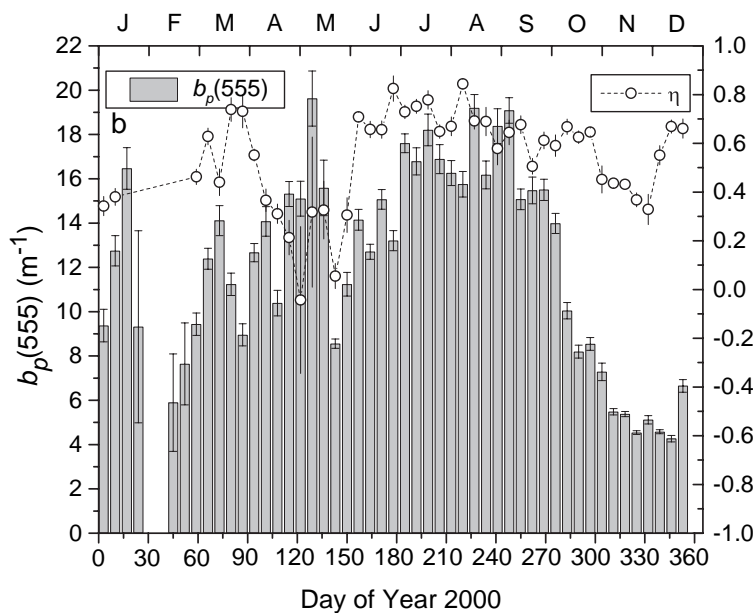
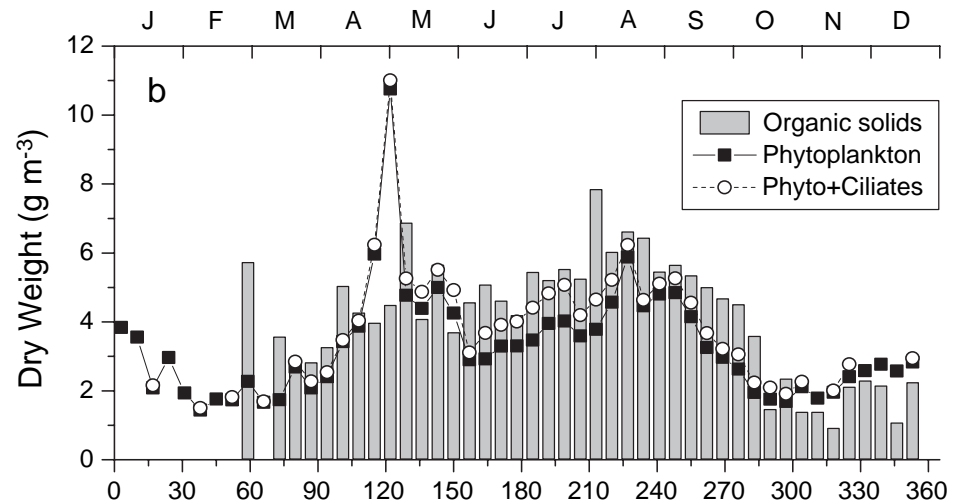
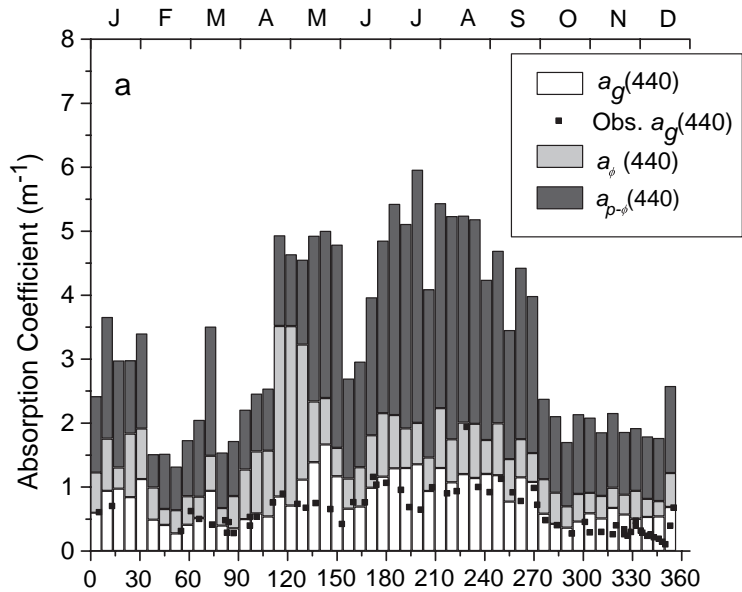
At mouth of York, percent light penetration is least in summer, following biological activity

YORK RIVER — 1984—1989 SEASONAL LIGHT PENETRATION (1.0M MSL)



(Moore, 1991)

In Rhode River, attenuation, scattering, OSS and ISS increase together after spring bloom, peaking in summer in phase with biologic activity and increased ease of bed resuspension.

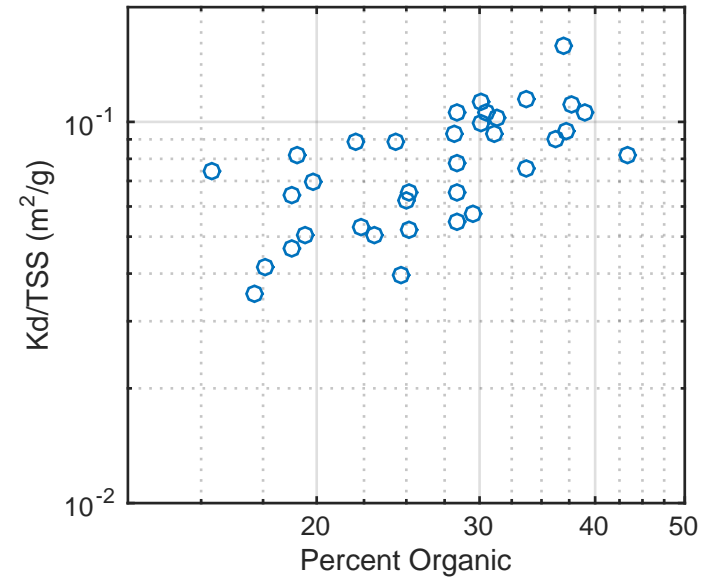
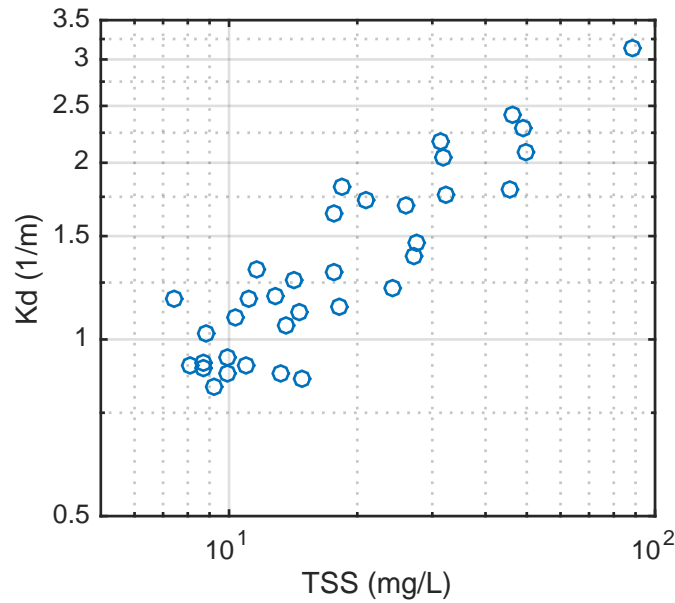


(Gallegos et al. 2005)

Properties of near-surface suspended solids along York River, collected fall 2014 and fall 2015

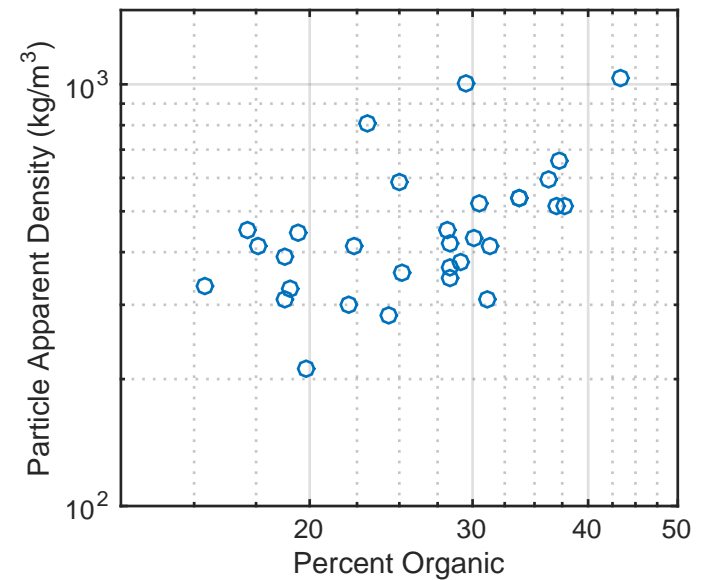
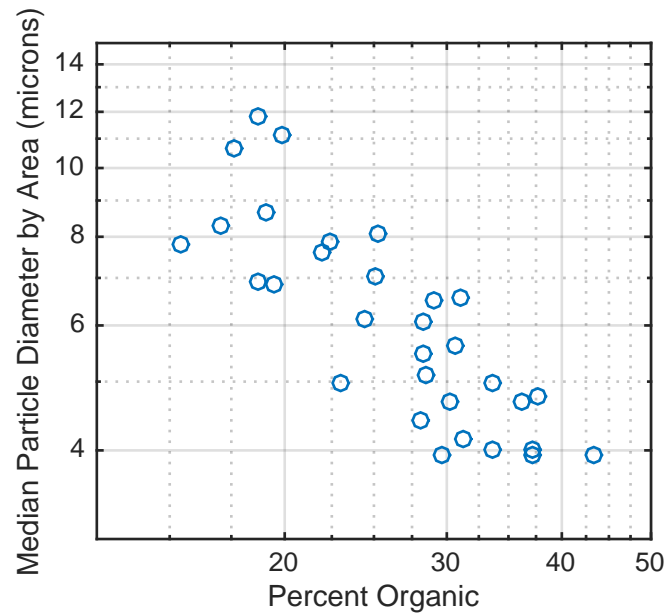
In York River, organic-rich near-surface suspended solids increase K_d more effectively than inorganic rich sediment.

(Fall & C.Friedrichs 2017)

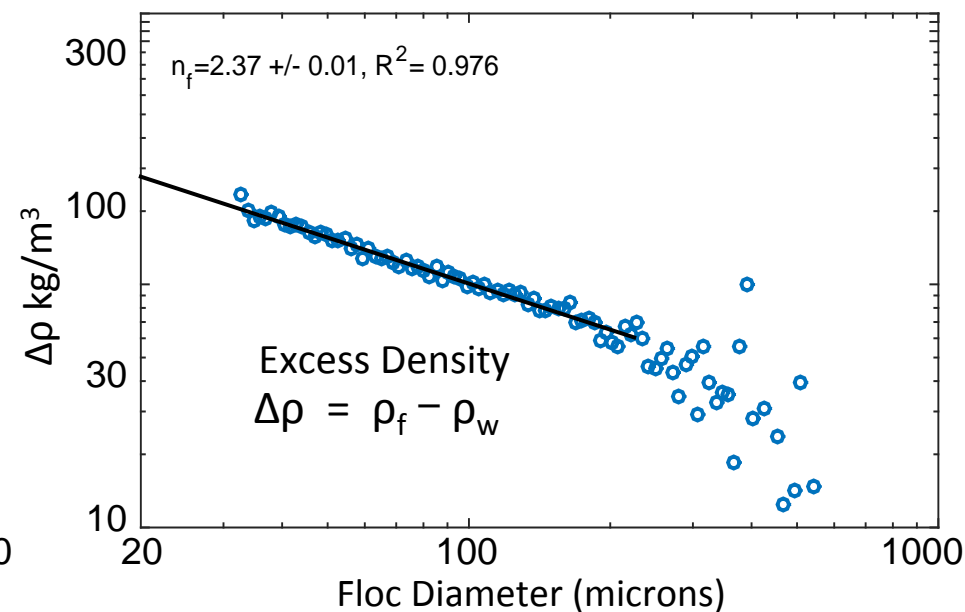
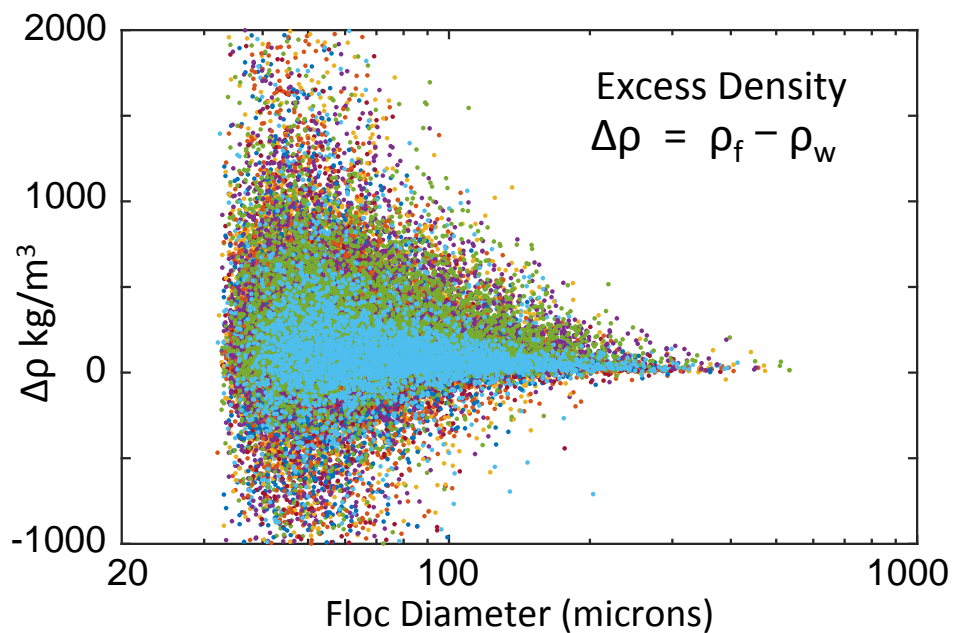
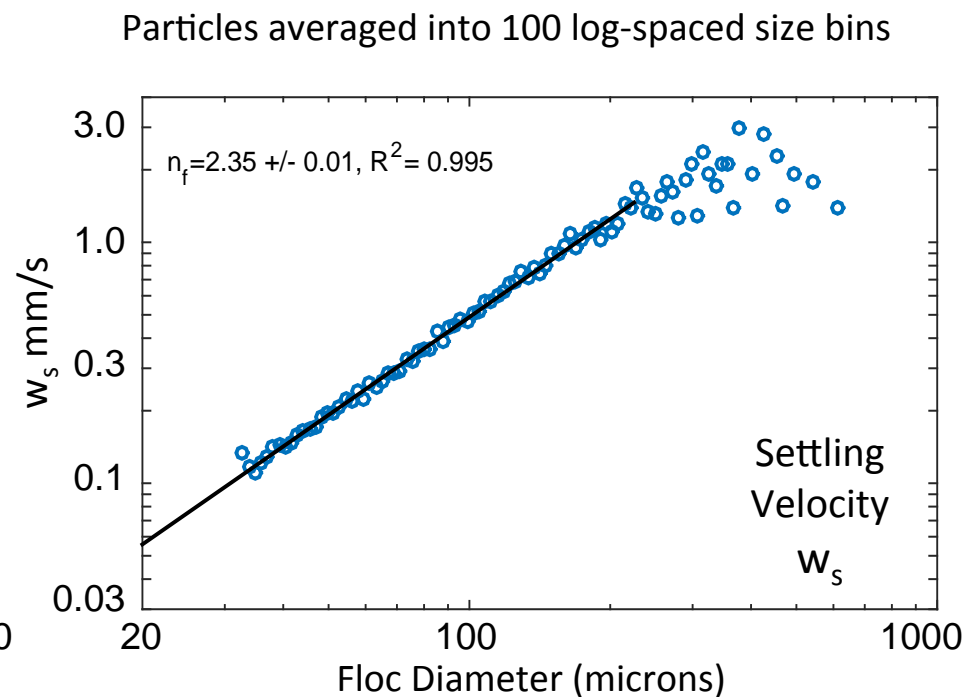
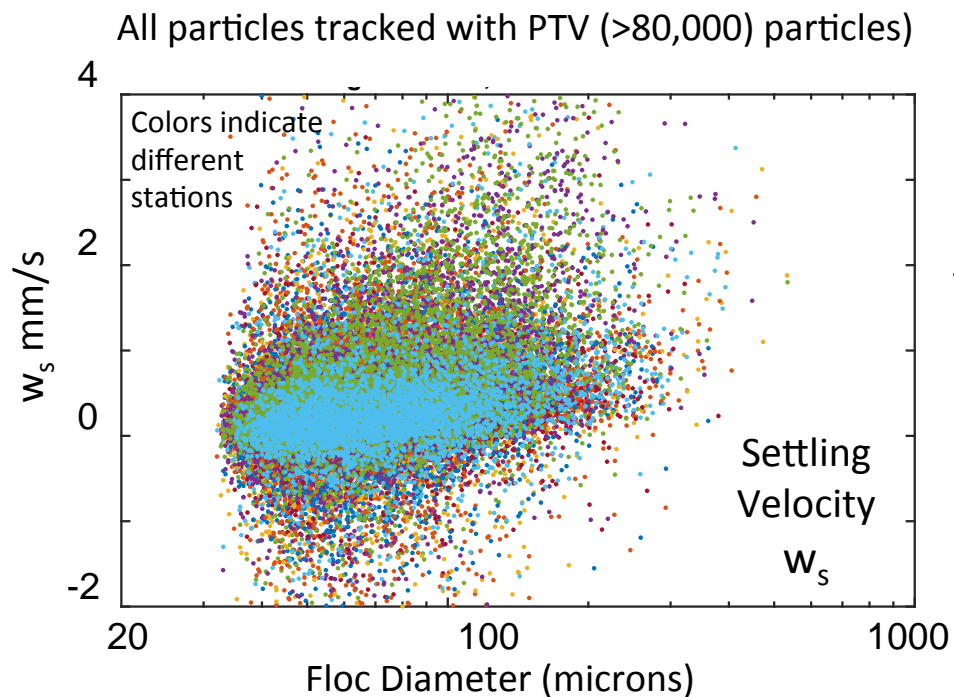


Organic-rich near-surface suspended solids have smaller particle size than inorganic rich solids.

Smaller, organic-rich solids are also denser, consistent with fractal floc properties.



Settling velocity (w_s) and excess density ($\Delta\rho$) measured by video settling tube. (Fall & C.Friedrichs 2017)



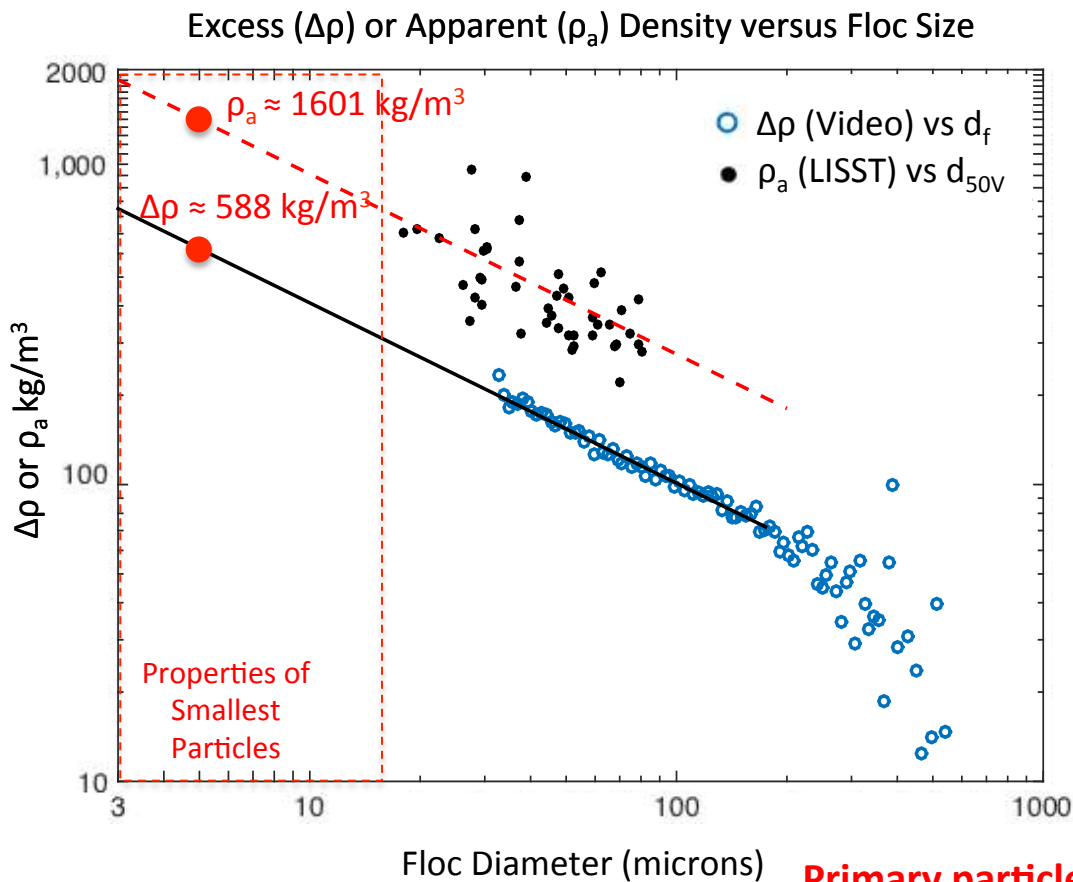
Fractal Properties derived from two independent measurements of floc density ($\Delta\rho$ vs ρ_a)

Determine Primary Particle Size (d_p) and Density (ρ_p) for flocs from $\rho_a - \Delta\rho$

M_p : Mass of Primary particles
 M_w : Mass of Water
 V_p : Volume of Primary Particles
 V_w : Volume of Water
 ρ_f : Floc density
 ρ_w : Density of water

$$1. \Delta\rho = \rho_f - \rho_w = \frac{M_p + M_w}{V_p + V_w} - \frac{M_w}{V_w} \quad \text{From Video and Stokes Law}$$

$$2. \rho_a = \frac{\text{Dry Mass (TSS filters)}}{\text{Floc Volume (VC}_T)} = \frac{M_p}{V_p + V_w} \quad \text{From Pump Samples and Integrated LISST}$$



Solve for difference between ρ_a and $\Delta\rho$:

$$3. \rho_a - \Delta\rho = \frac{M_w}{V_w} - \frac{M_w}{V_p + V_w}$$

For primary particles ($V_w \ll V_p$):

$$\rho_a - \Delta\rho \approx \frac{M_w}{V_w} \approx \rho_w$$

To estimate d_p and $\rho_p = \rho_a$,
determine when $\rho_a - \Delta\rho \approx \rho_w \approx 1013 \text{ kg/m}^3$

Surface waters of the York:
 $d_p \approx 5.1 \mu\text{m}$ and $\rho_p \approx 1601 \text{ kg/m}^3$

Primary particles w/ $\sim 50\%$ OSS, 50% ISS have $\rho_p \approx 1600 \text{ kg/m}^3$

Synthesis: Understanding of Chesapeake Bay Water Clarity Patterns

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Theory

Equation for diffuse attenuation coefficient*

$$K_d = \frac{1}{\mu_0} \sqrt{a^2 + G(\mu_0) ab}$$

a = absorption coefficient, b = scattering coefficient

μ_0 = cosine of refracted solar angle of incidence

$G(\mu_0)$ = function that scales scattering/absorption interaction

Note: This is a non-linear equation, so $K_d \neq K_{d \text{ water}} + K_{d \text{ CDOM}} + K_{d \text{ chl}a} + K_{d \text{ solids}}$

*Kirk, J. T. O. 1984. Dependence of relationship between apparent and inherent optical properties of water on solar altitude. *Limnology and Oceanography* **29**:350-356.

$$K_d = \frac{1}{\mu_0} \sqrt{a^2 + G(\mu_0)ab}$$

$$a = a_{water} + a_{CDOM} + a_{Chla} + a_{solids}$$

$$b = b_{water} + b_{solids}$$

$$a_{solids} = a_{small\ organic} + a_{small\ inorganic} + a_{large\ flocs} + \dots$$

$$b_{solids} = b_{small\ organic} + b_{small\ inorganic} + b_{large\ flocs} + \dots$$

All else being equal:

-- $a \sim A_{tot}$ and $b \sim A_{tot}$, where A_{tot} = total particle surface area. If volume conc. is constant, then $A_{tot} \uparrow$ as particle diameter $d \downarrow$. So a & b & $K_d \uparrow$ as $d \downarrow$

-- So if a larger fraction of particles have small d , then $K_d/TSS \uparrow$

-- In surface waters, as $d \downarrow$ % organic \uparrow . So $K_d/TSS \uparrow$ as organic \uparrow

Gallegos (2009)

Theory: K_d x Secchi Depth (Z_{SD})

$K_d \cdot Z_{SD}$ Product

$$K_d Z_{SD} = \frac{\Gamma\left(1 + G(\mu_0) \left(\frac{b}{a}\right)^{1/2}\right)}{\left(1 + G(\mu_0) \left(\frac{b}{a}\right)^{1/2}\right) + \mu_0 \left(1 + \left(\frac{b}{a}\right)\right)}$$

Bottom line: $K_d \cdot Z_{SD}$ is a function of the scattering-to-absorption ratio, and a few other parameters.

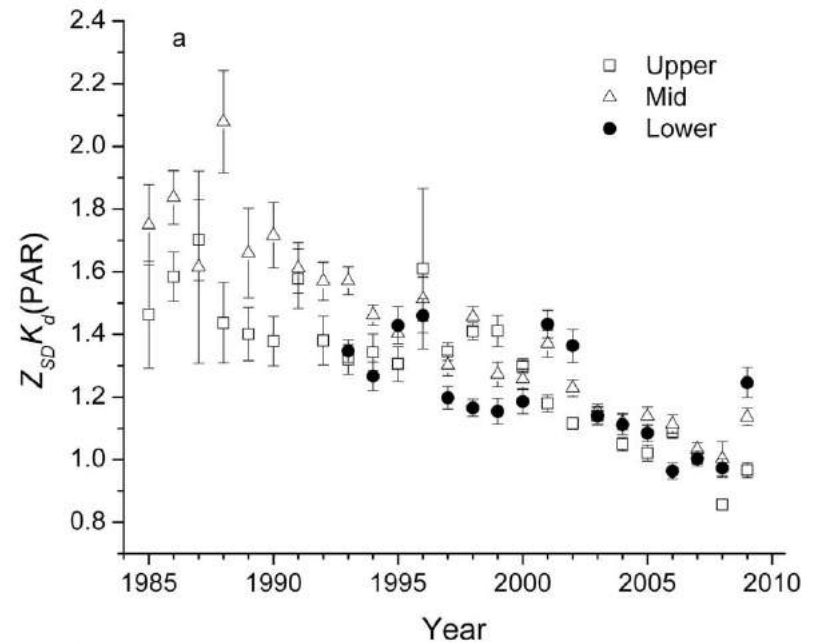
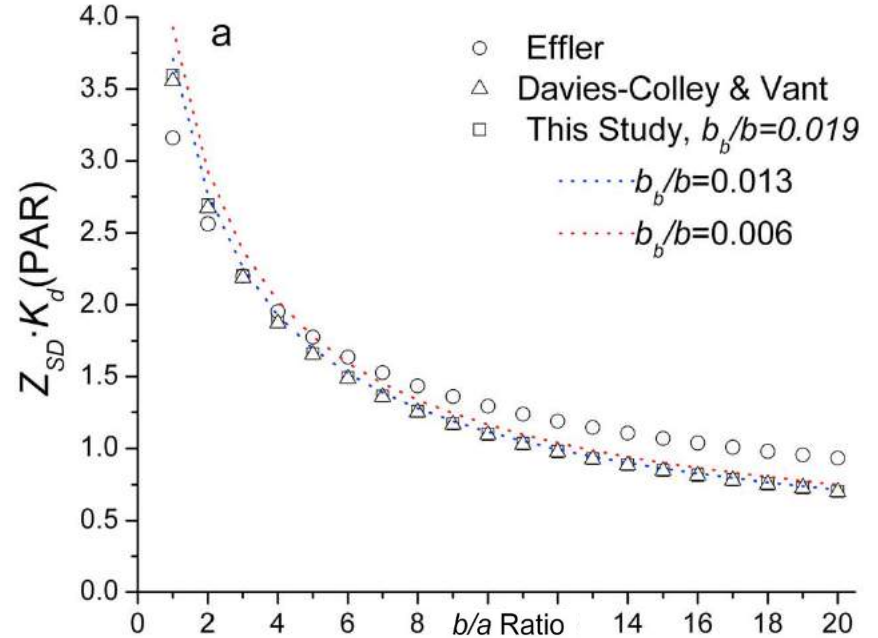
Small organic particles have larger scattering to attenuation (b/a), which decreases $Z_{SD} \cdot K_d$

Gallegos (2009), Gallegos et al. (2011)

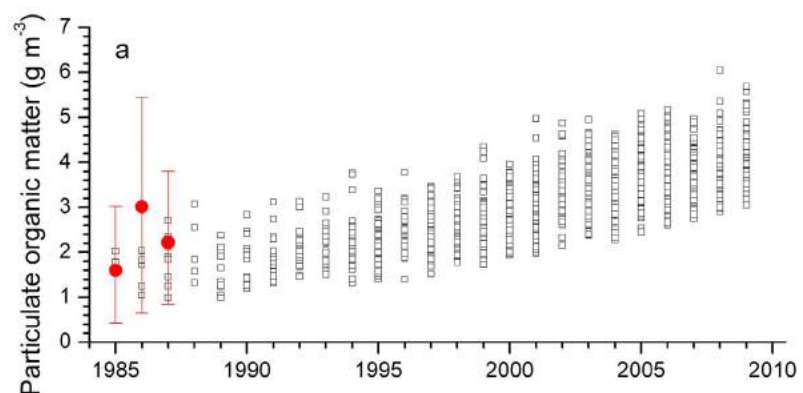
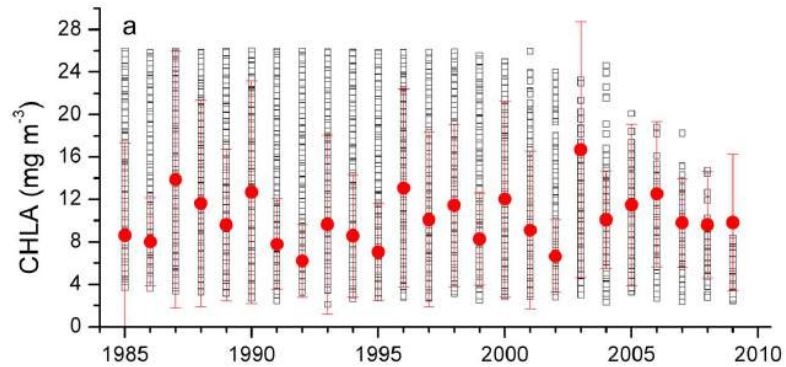
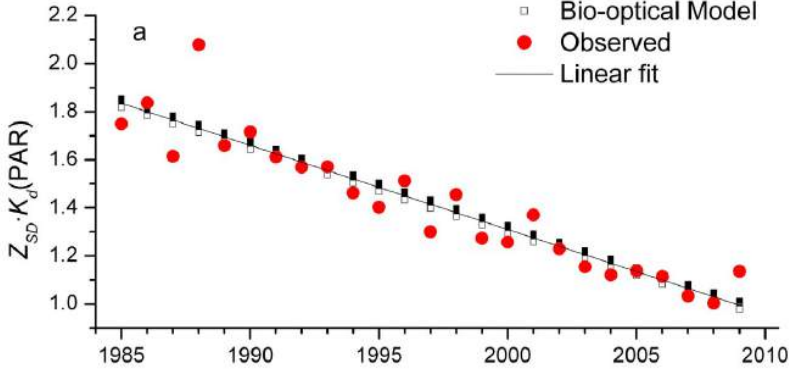
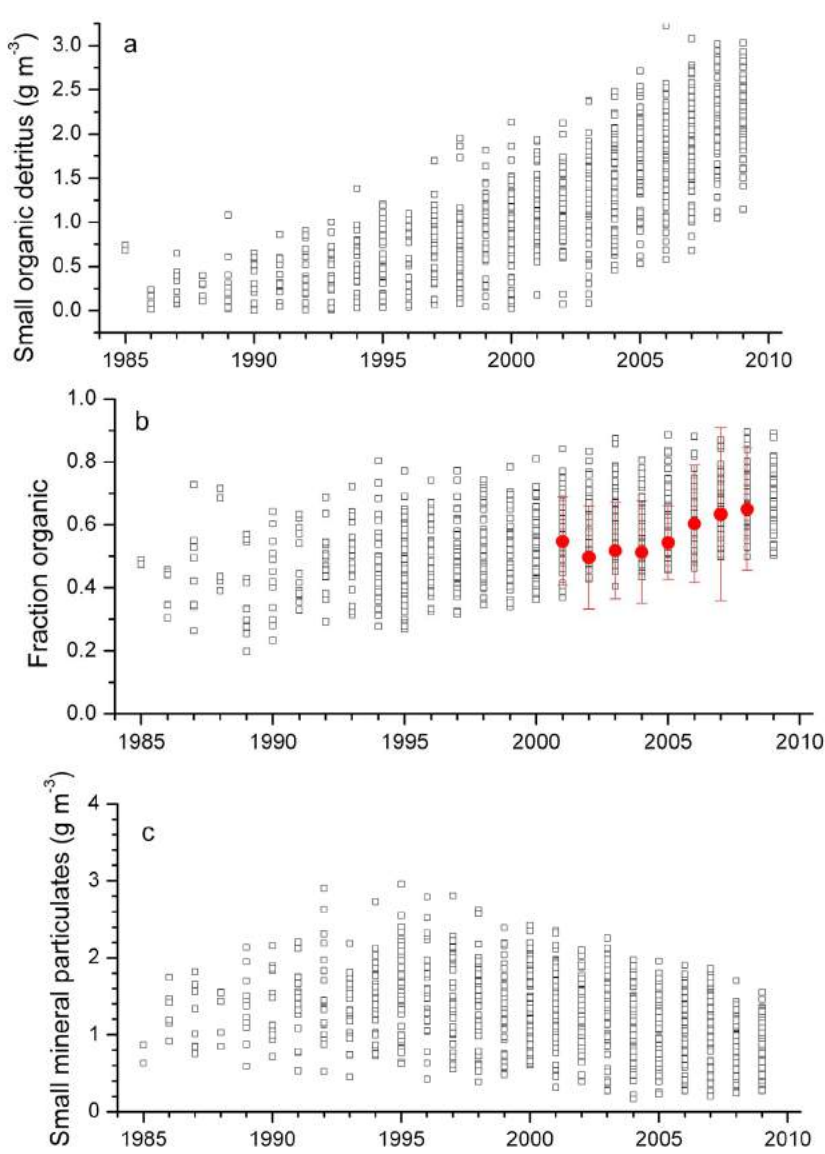
Particle type	b^* m^2g^{-1}	a^* m^2g^{-1}	b/a
Small organics	1.4	0.106	13
Clays	0.35	0.05	7
Fine Silt	0.15	0.025	6

* = per unit mass of solids

- $K_d/TSS \uparrow$ as small organics \uparrow
- $b/a \uparrow$ as small organics \uparrow
- $Z_{SD} \cdot K_d \downarrow$ as small organics \uparrow
- So (normalized by TSS),
 $Z_{SD} \downarrow \downarrow \downarrow$ as small organics \uparrow



Monte Carlo optical model simulations suggest that an increase in small organic particles are a likely explanation for the observed decrease in $Z_{SD} \cdot K_d$



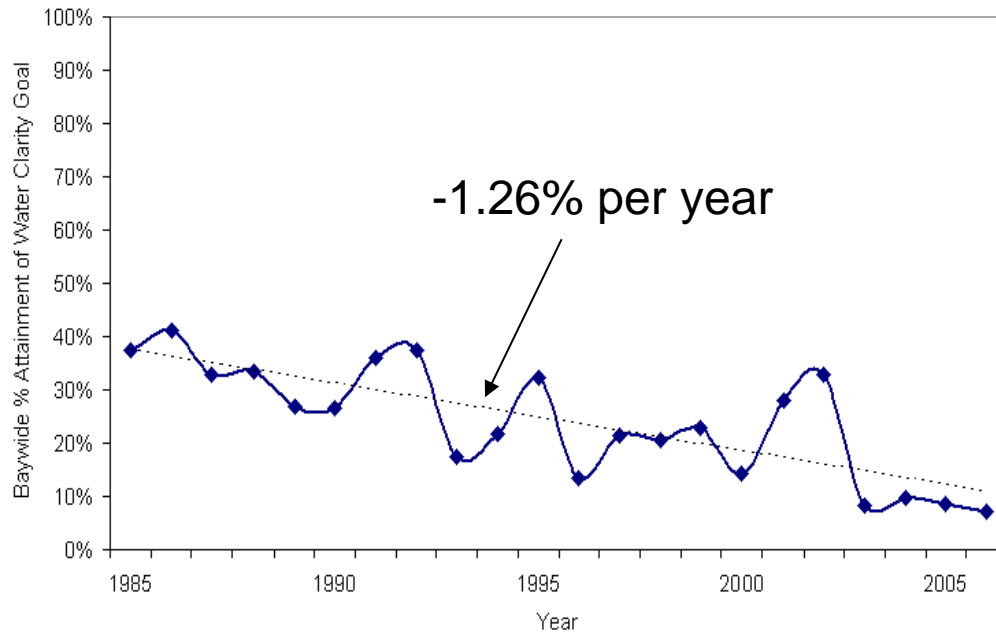
Gallegos et al. (2011)

Synthesis: Understanding of Chesapeake Bay Water Clarity Patterns

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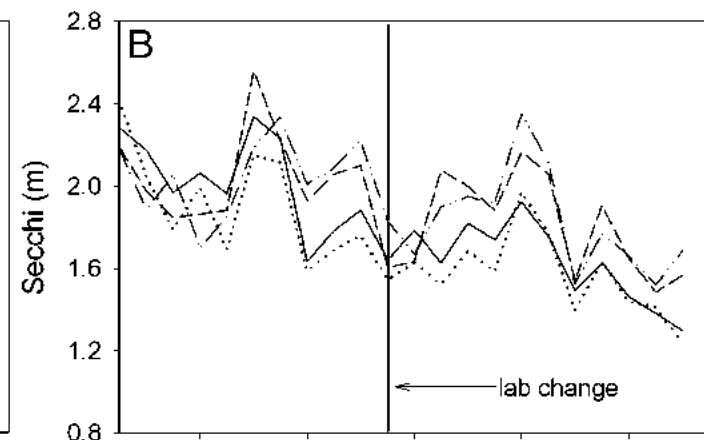
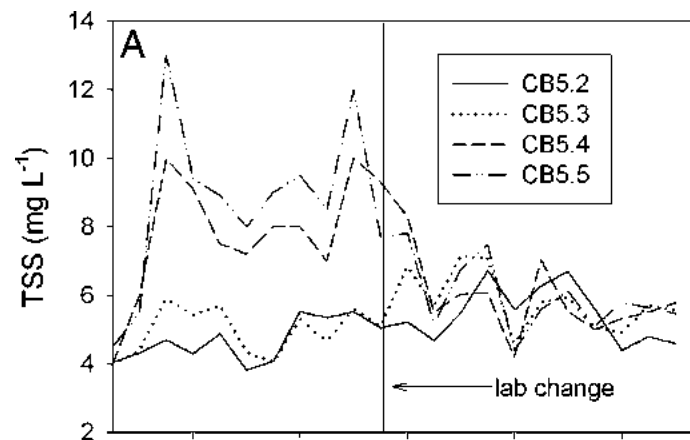
Nearly a decade ago, it was recognized that Secchi depth has been decreasing



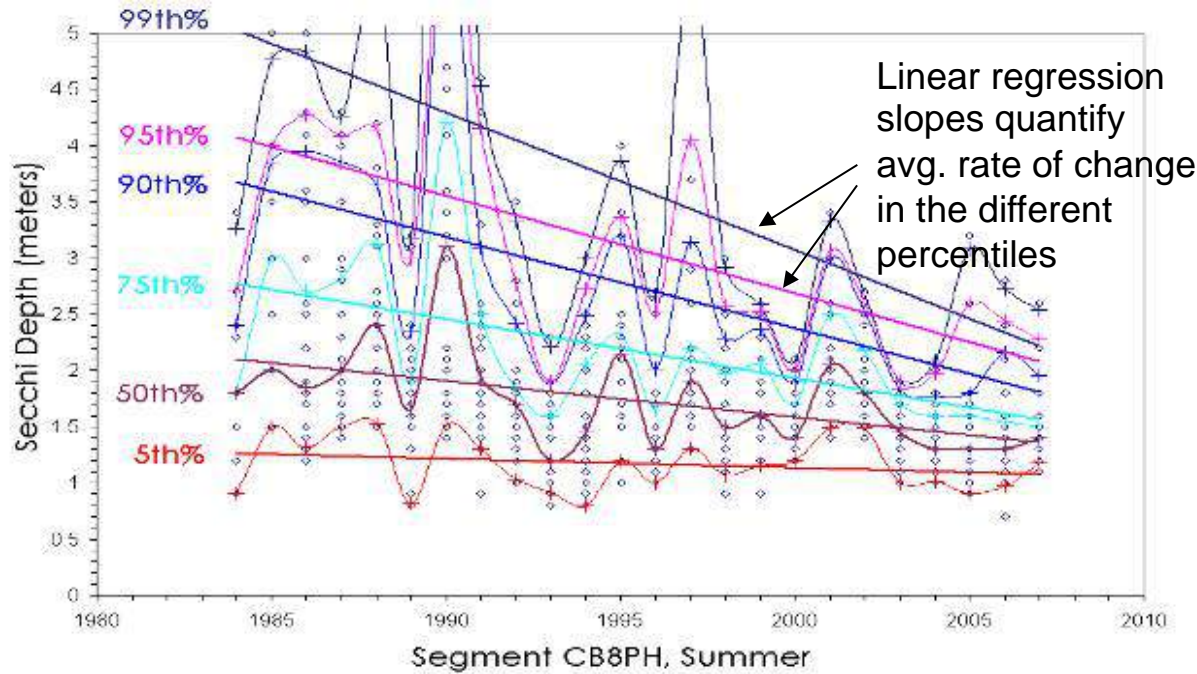
(Tango 2008 TMAW)

This indicator measures the percent of Bay surface waters with Secchi depths greater than specific Secchi thresholds. The water clarity goal is 100% attainment of the Secchi thresholds. The regression slope (- - -) indicates a 1.26% drop in %attainment occurs on average each year baywide.

(Williams et al. 2010)

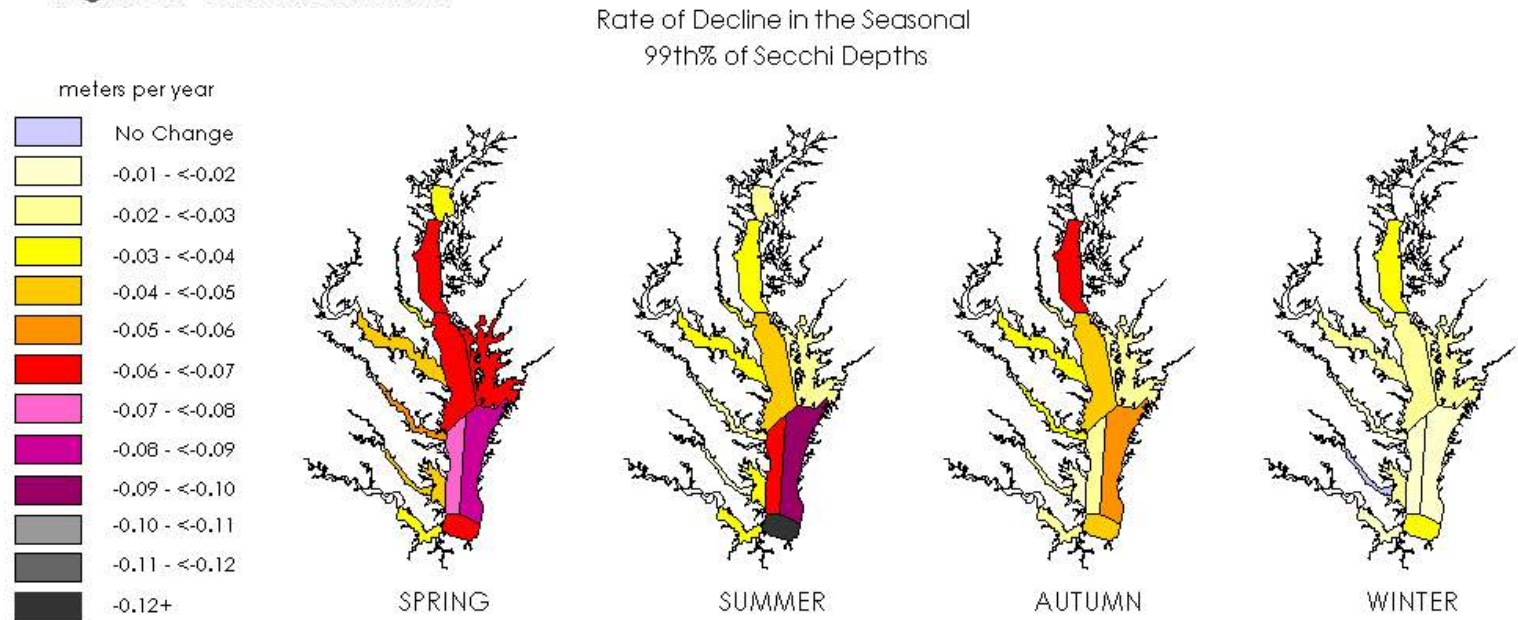


Less cloudy water was getting cloudier faster



(Buchanan & Tango, 2008)

Seasonal differences – greatest decline in spring and summer

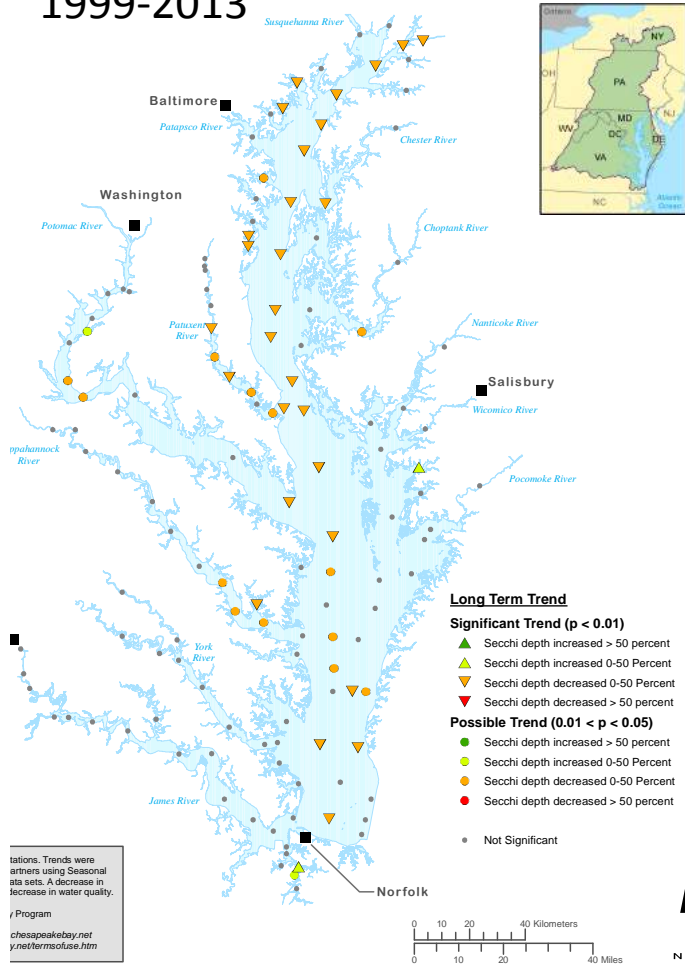


Secchi depth decreasing is clear regardless of statistical method

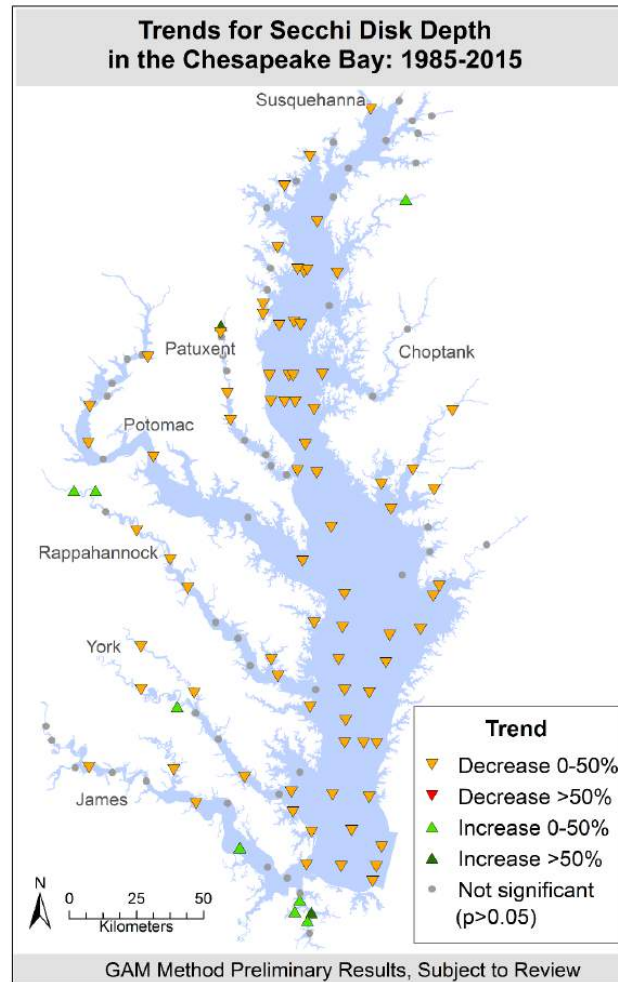
Turner & C.Friedrichs (2016)

Weinberg (2015)

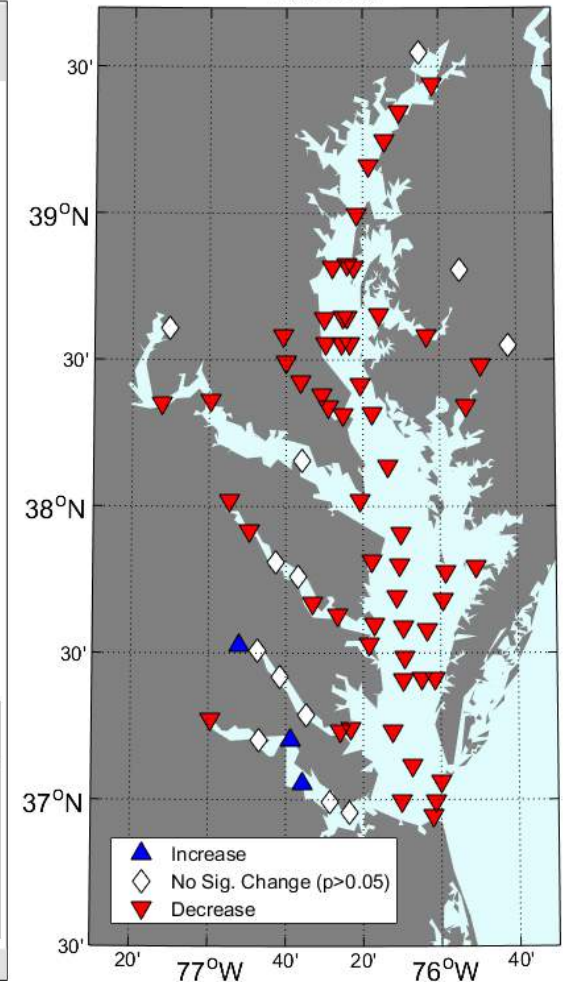
1999-2013



Murphy (2016)



SECCHI 1984-2016

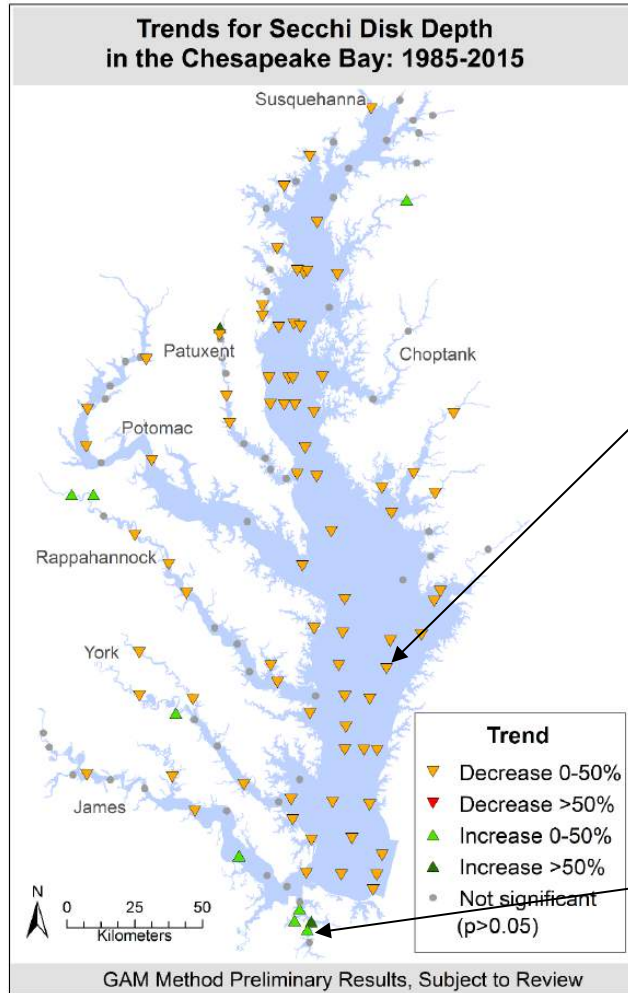


Seasonal Kendall method

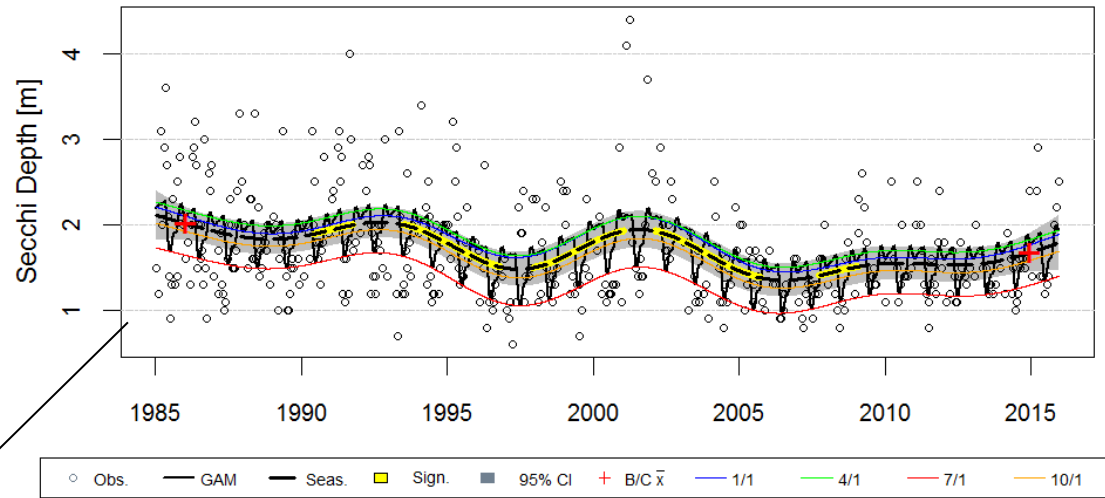
GAMs method

Linear Regression

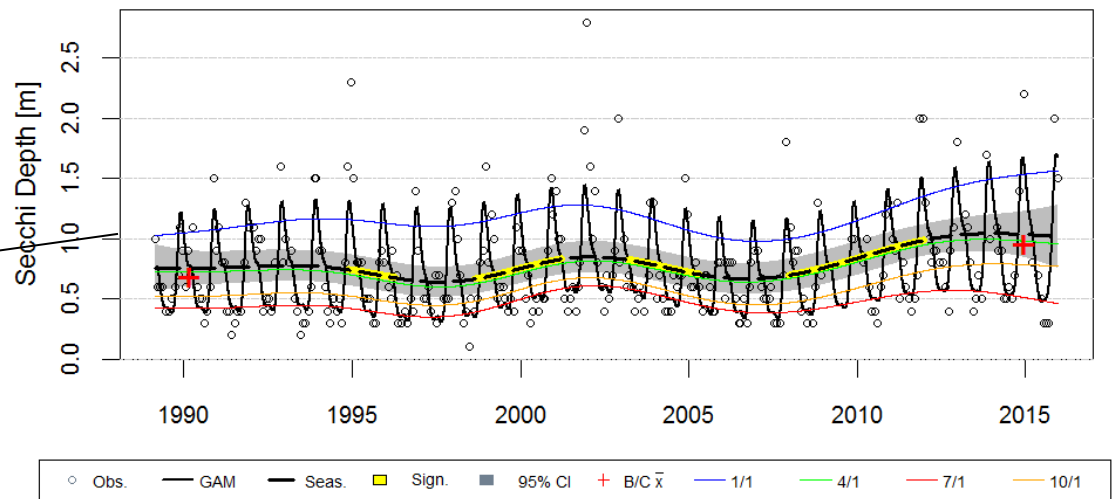
Murphy (2016)



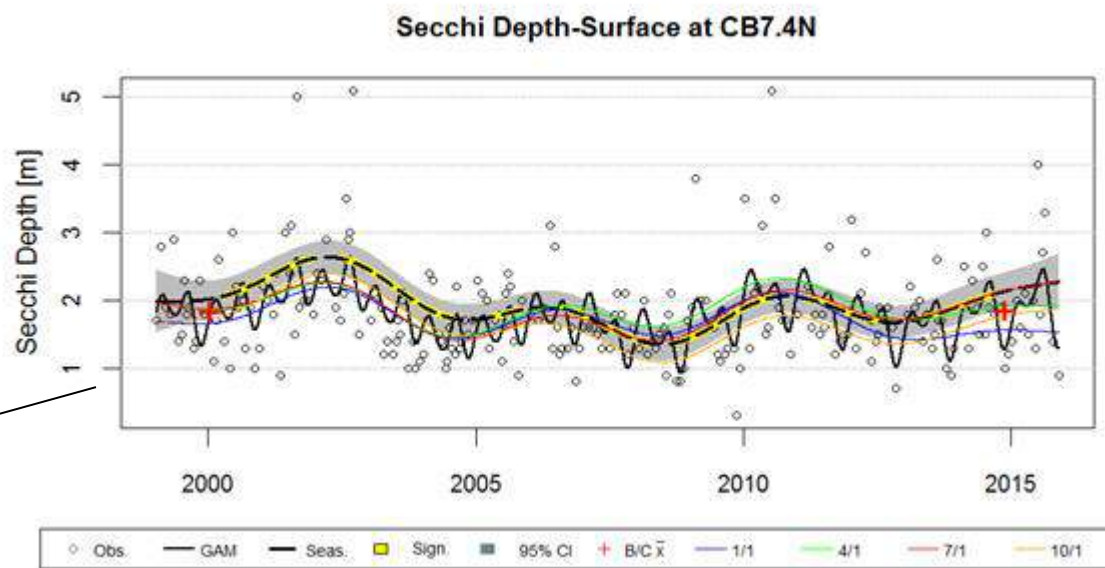
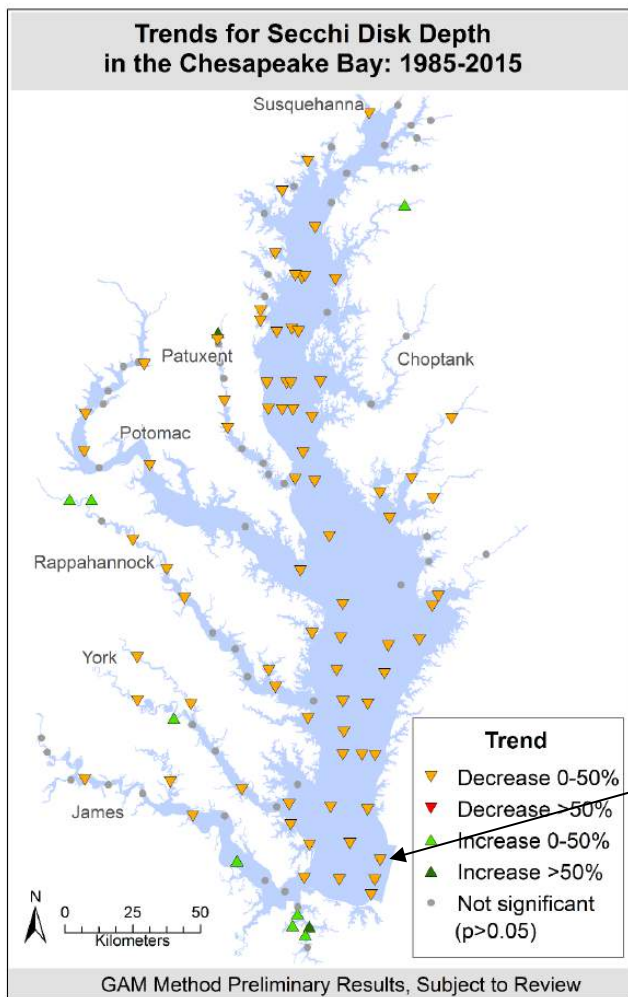
Secchi Depth-Surface at CB7.1

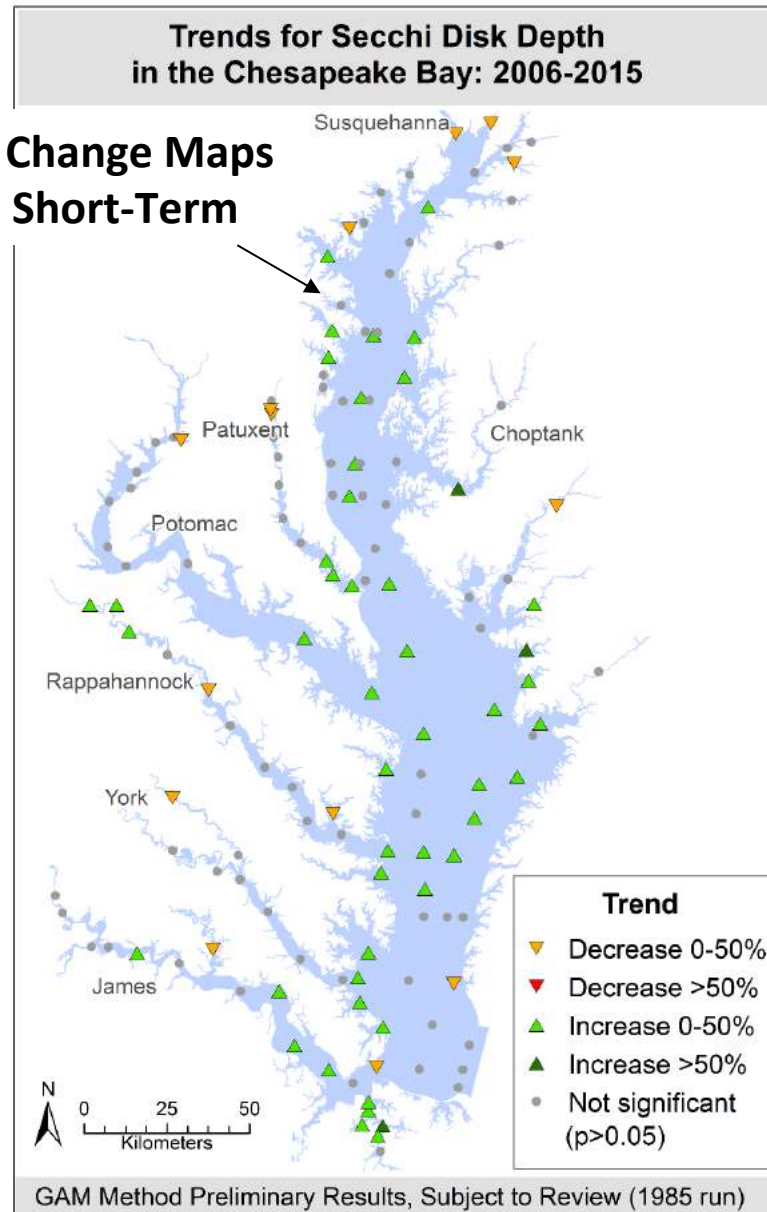
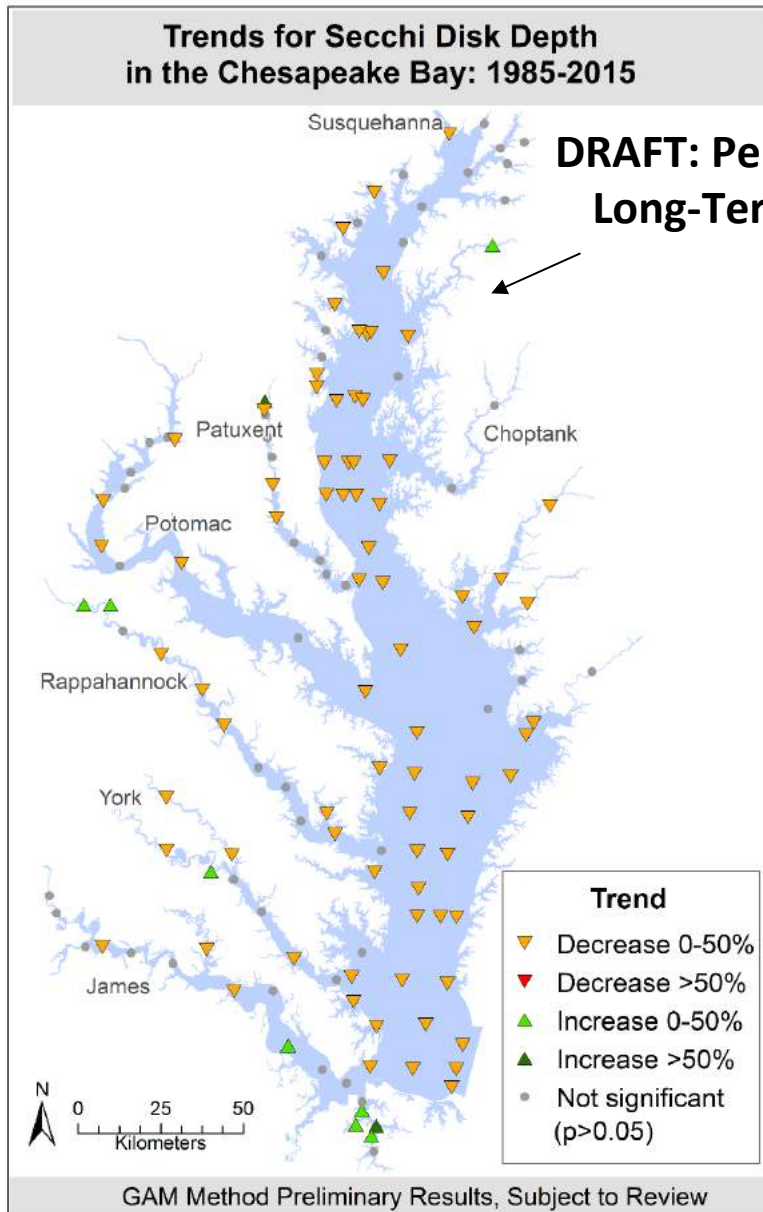


Secchi Depth-Surface at WBE1



Murphy (2016)

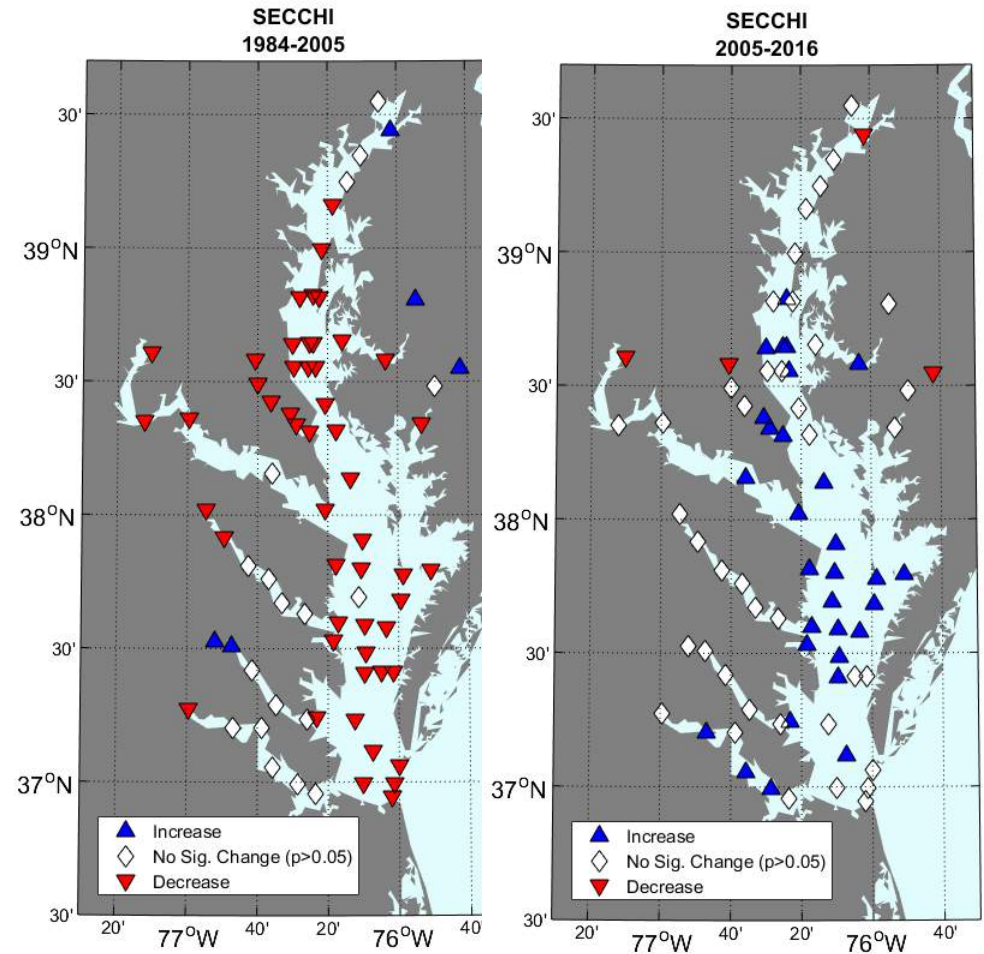
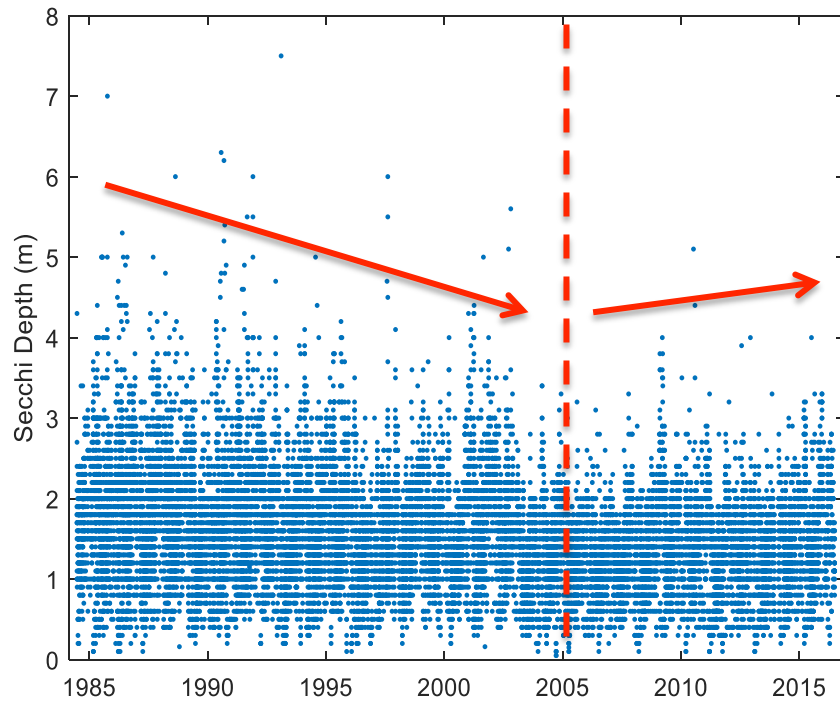




**DRAFT: Percent Change Maps
Long-Term vs. Short-Term**

Turner & C.Friedrichs (2016)

Linear Regressions also show change in temporal trend close to the same time identified by Murphy



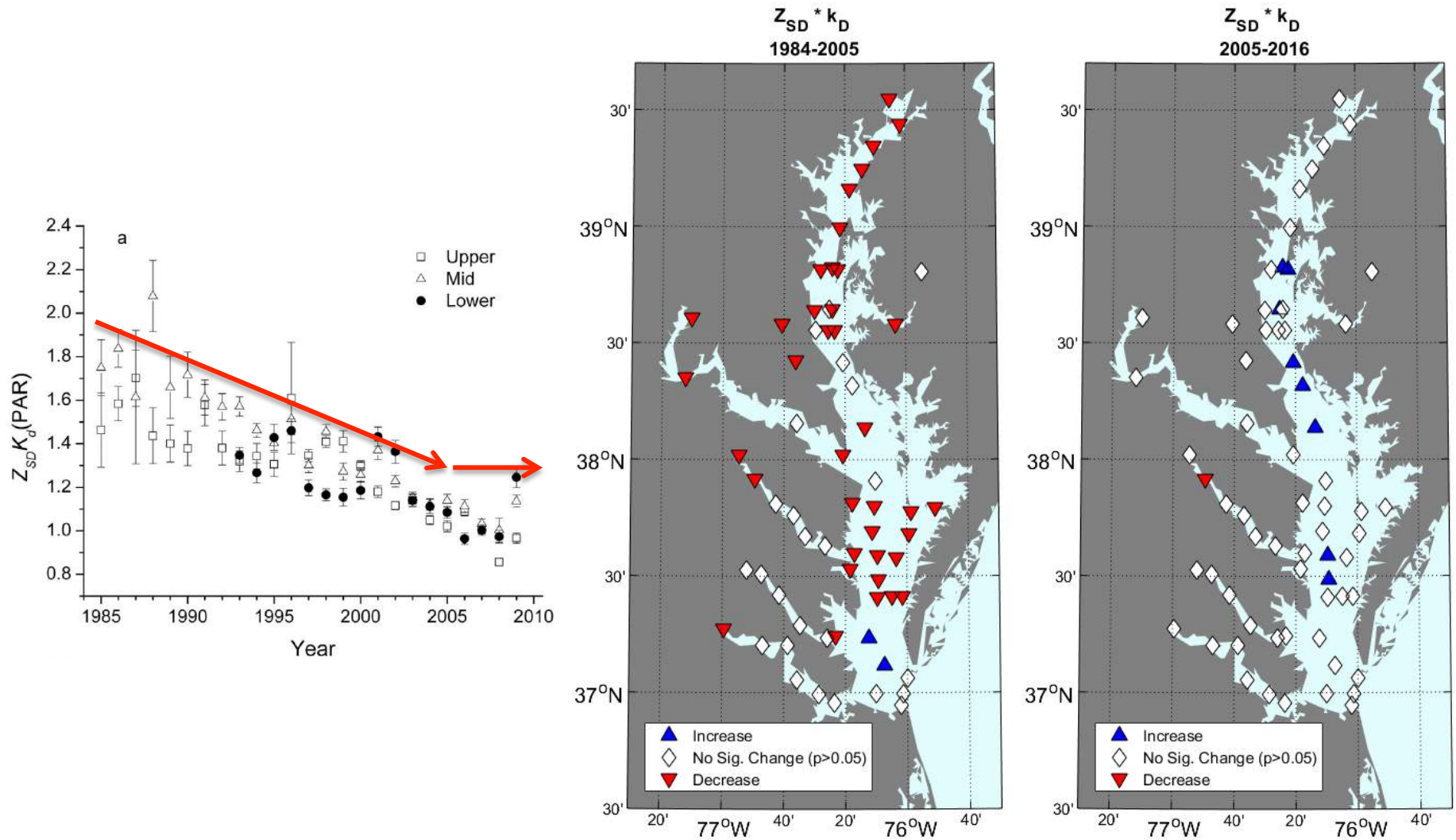
Blue = clearer (less cloudy) water. Red = less clear (more cloudy) water.
Consistent with Murphy.

Synthesis: Understanding of Chesapeake Bay Water Clarity Patterns

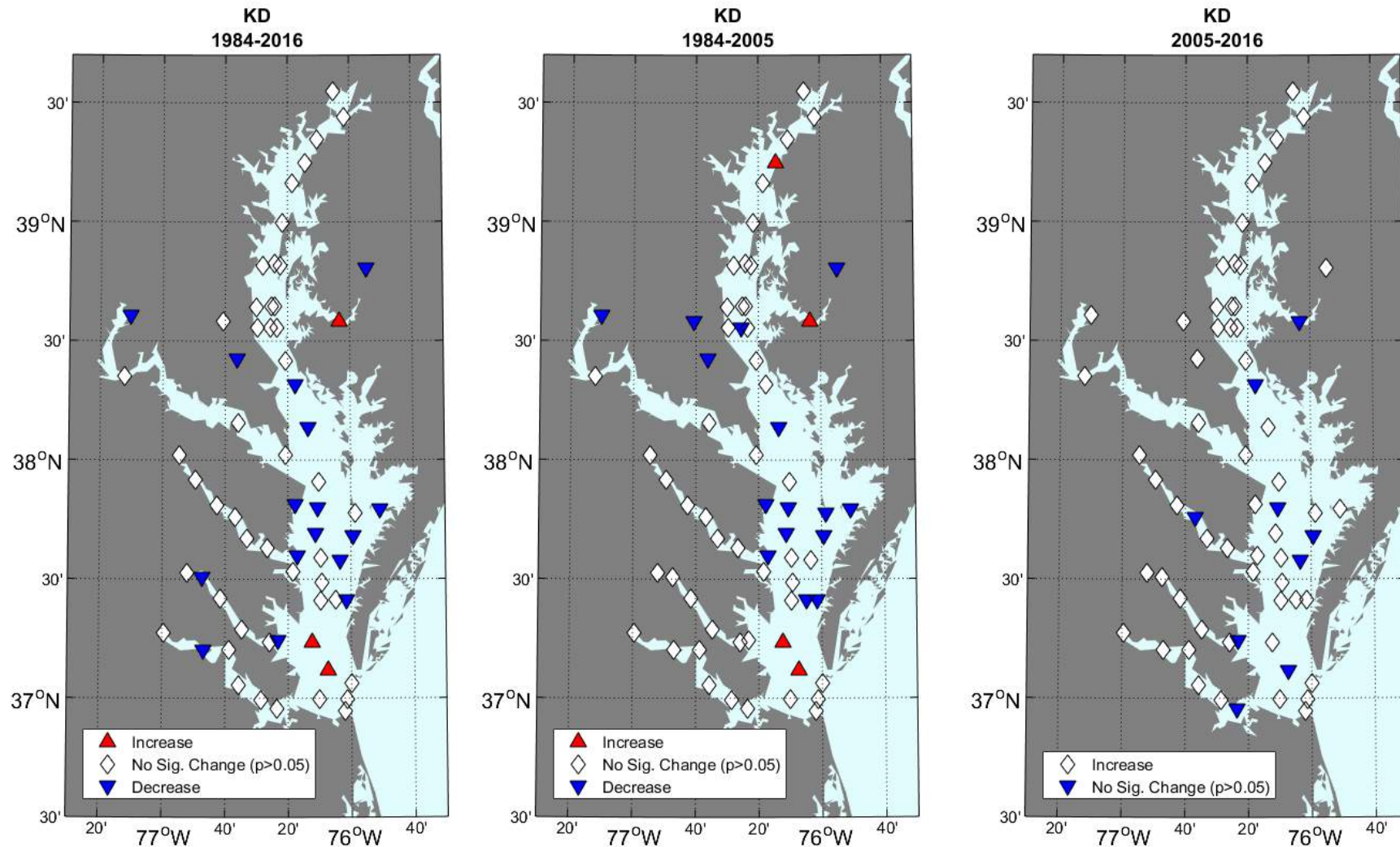
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Results of linear regressions in time applied to (Secchi depth) x (Kd) data suggest trend in (Secchi depth) x (Kd) also may have changed around 2005 ($Z_{SD} = \text{Secchi depth}$)

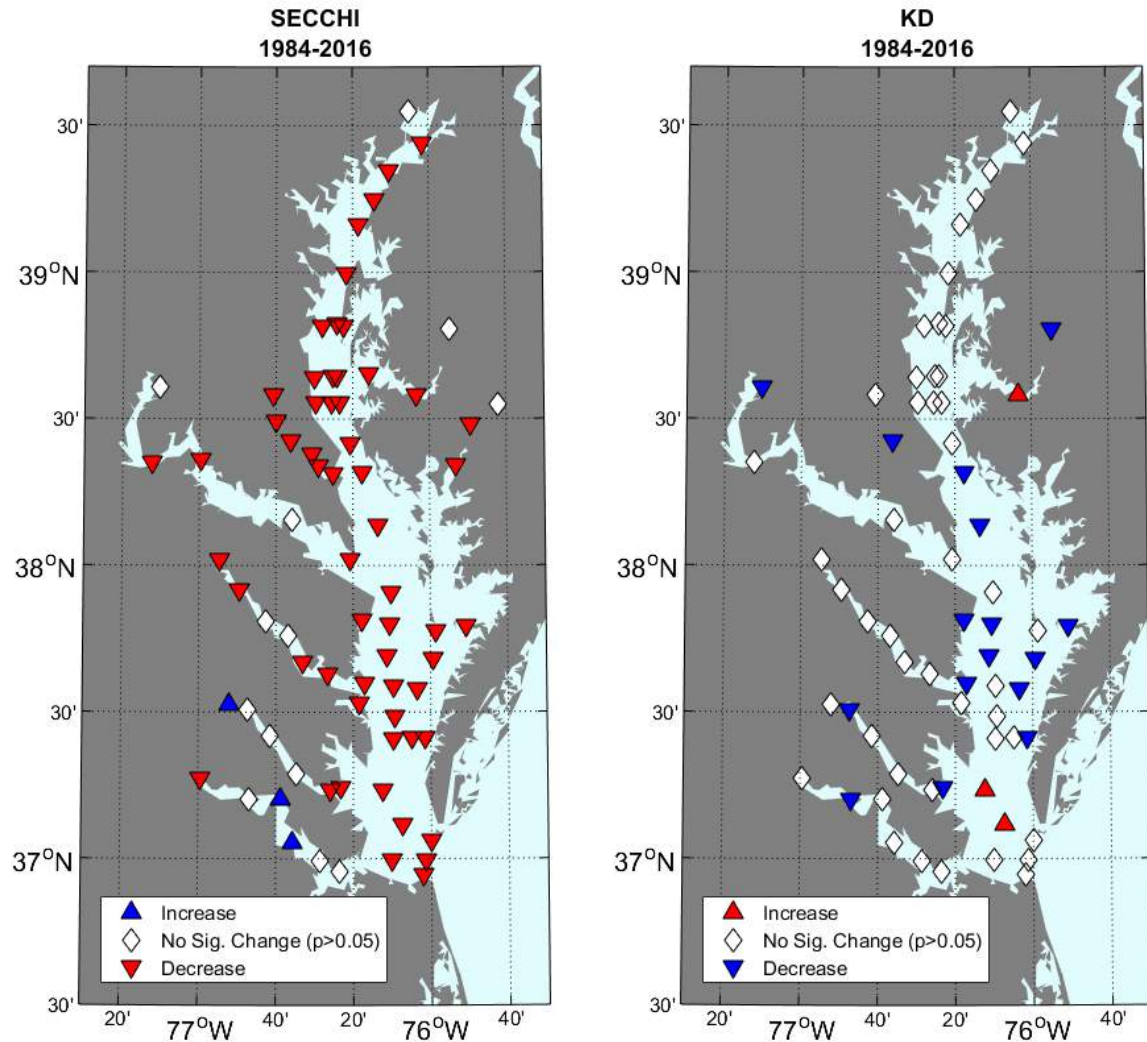


However, trend in K_d with time is not consistent with water clarity trends suggested by Secchi alone. In general, clarity measured by K_d has been improving or staying relatively constant.



Blue = clearer water (less light attenuation). Red = less clear (more light attenuation).

Turner & C.Friedrichs (2016)



Red = “less clear” water. Blue = “clearer” water.

- Although Secchi depth has decreased (i.e., cloudier water) almost everywhere since 1984, Kd has also decreased (i.e., less overall light attenuation) over much of the Bay during this period.
- Secchi depth trends may not always be a good indicator of long-term (decadal) trends in light quality most relevant to living resources.

Harding et al. (2016)

Pre-1985 Post-2008

Estimated K_D from
observed Secchi
depths based on

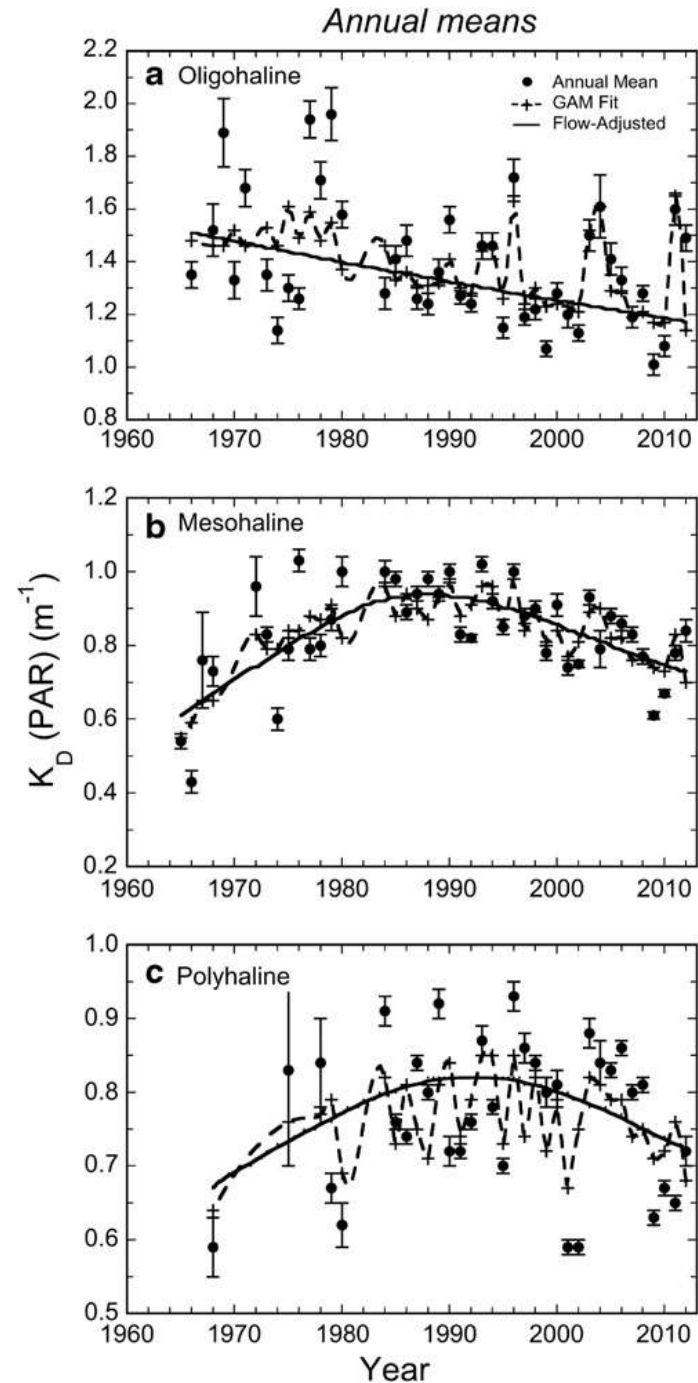
$$K_D(\text{PAR}) = \frac{\Gamma}{Z_{SD}}$$

$\Gamma = 1.61$ $\Gamma = 1.03$

$\Gamma = 1.84$ $\Gamma = 1.16$

$\Gamma = 1.54$ $\Gamma = 1.16$

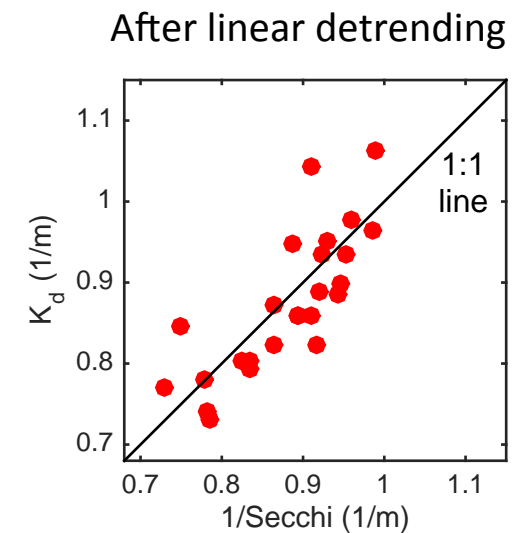
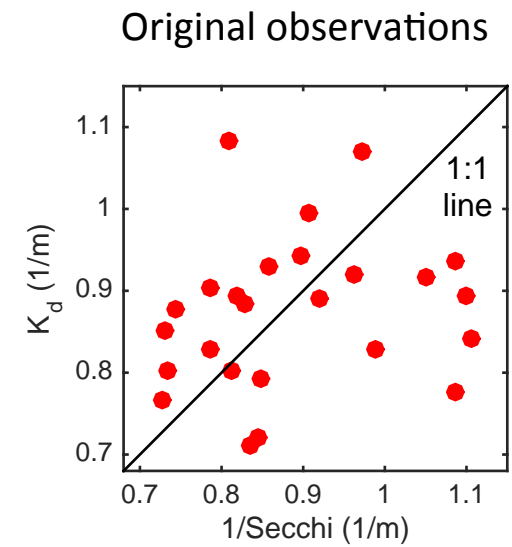
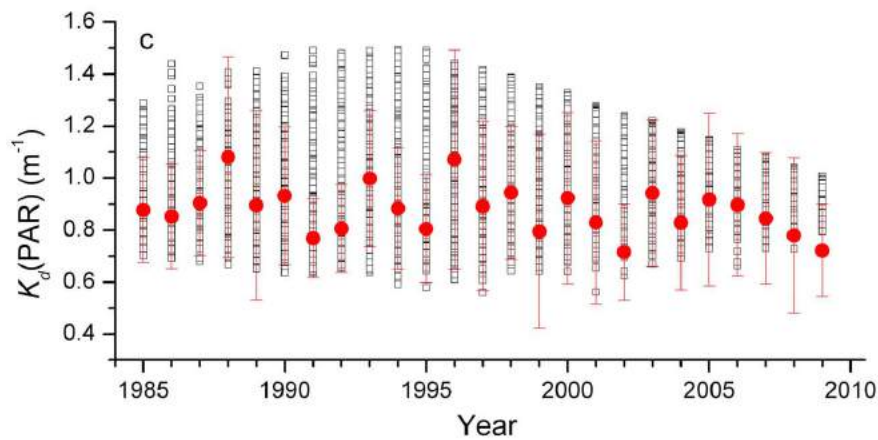
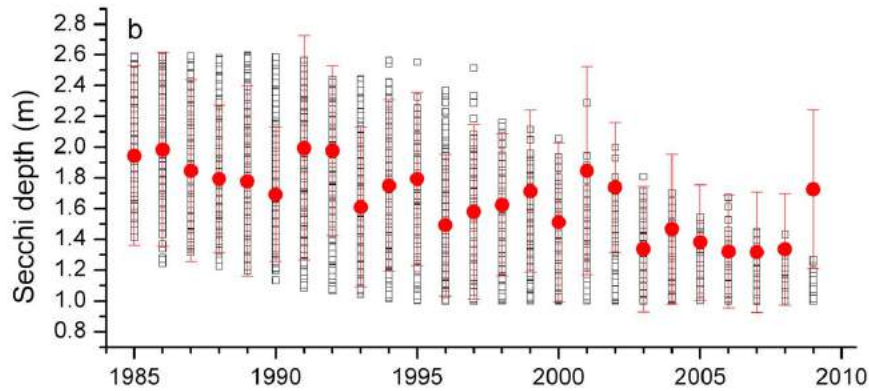
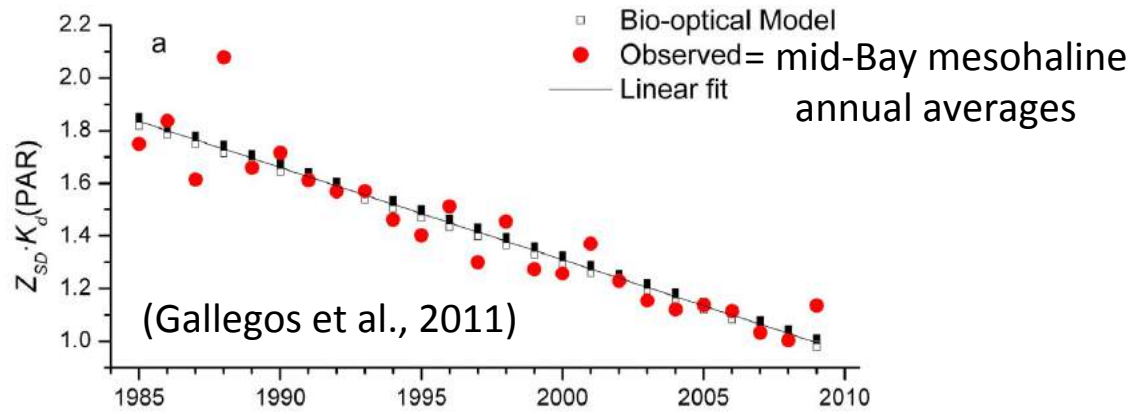
Linear regressions for Γ in time from Gallegos et al. (2011) between 1985 and 2008.



Synthesis: Understanding of Chesapeake Bay Water Clarity Patterns

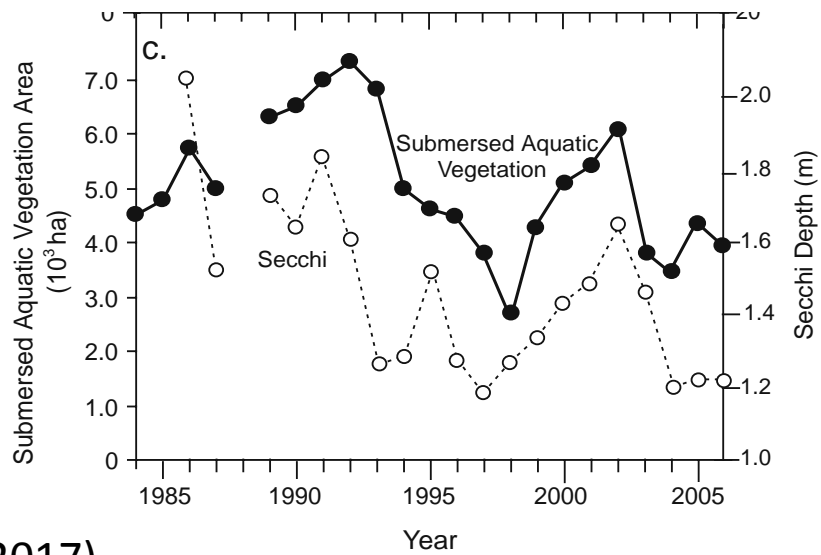
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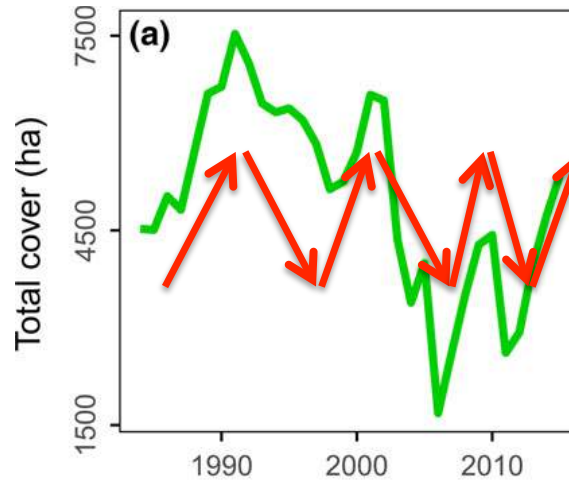
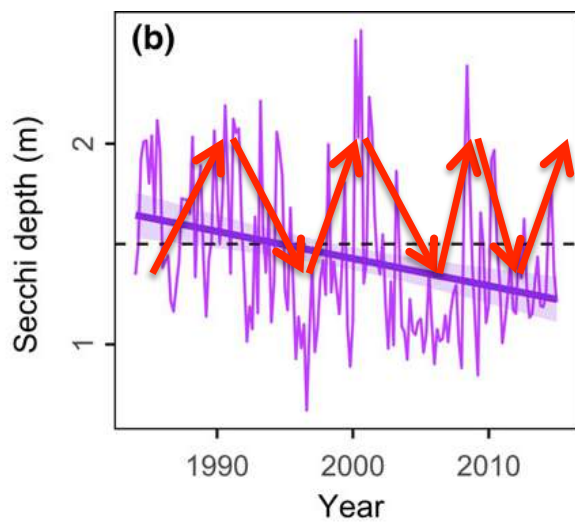
Detrending of Secchi depth long-term drift supports its use as a year-to-year proxy for K_d .

(Orth et al. 2010)



Secchi Depth and SAV Area in Tangier Sound

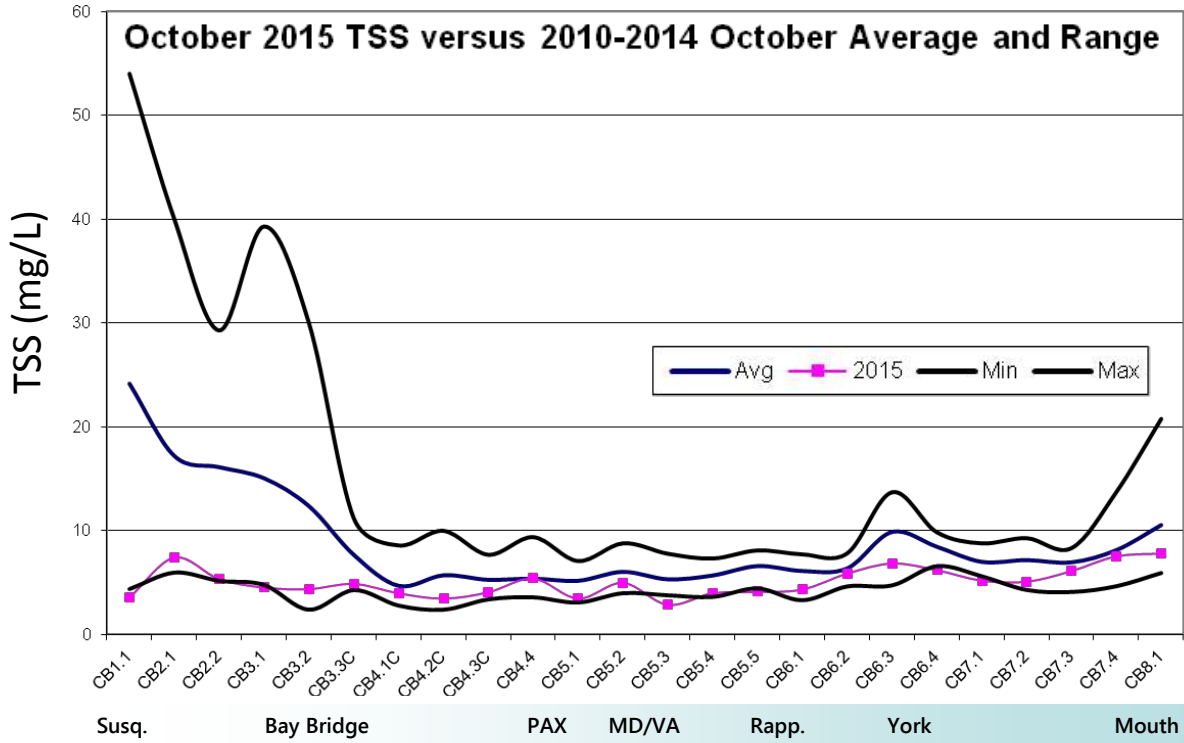
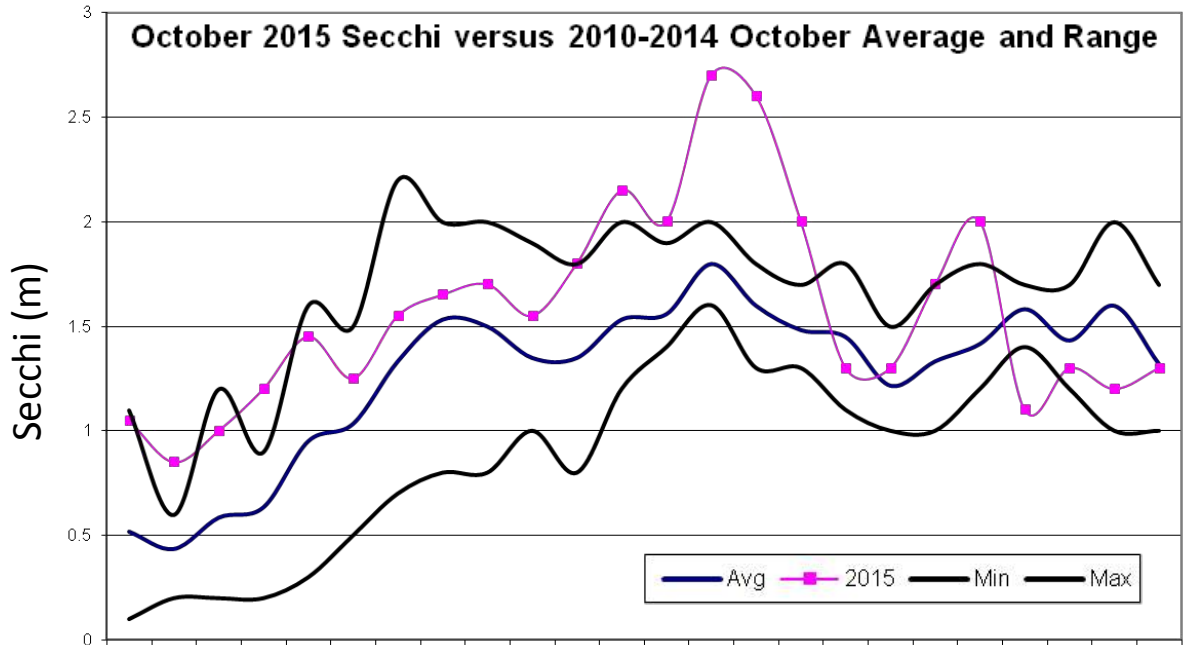
(Lefcheck et al. 2017)



Secchi Depth in Tangier Sound

Increases/decreases in Secchi depth over ~5 years parallel increases/decreases in SAV area.

(Trice et al. 2015)



The Chesapeake Bay is looking strangely clear. But why?

By Dave Mayfield
 The Virginian-Pilot
 Nov 29, 2015



Bill Portlock | Chesapeake Bay Foundation
 The northern tip of Goose Island, north of Tangier Island in the Chesapeake Bay, was photographed Nov. 17, 2015.

In October 2015, Secchi depths and TSS were highly consistent in documenting that most of the main stem of the Bay was significantly clearer than it had been on average in October over the previous four years.

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