

Understanding patterns in Chesapeake Bay water clarity: the importance of measurement, location, and physical versus biological controls.

Carl Friedrichs and the CBP-STAC Water Clarity Trends Workshop Team,
with major contributions from Jeni Keisman, Rebecca Murphy, Jeremy Testa,
Slava Lyubchich and Qian Zhang

(Fincham, 2008. Photo credits: M. Eversmier (left) and N. Caloyianis (right))



Choptank River, 1979



Mainstem Bay, Dominion Reef, 2008

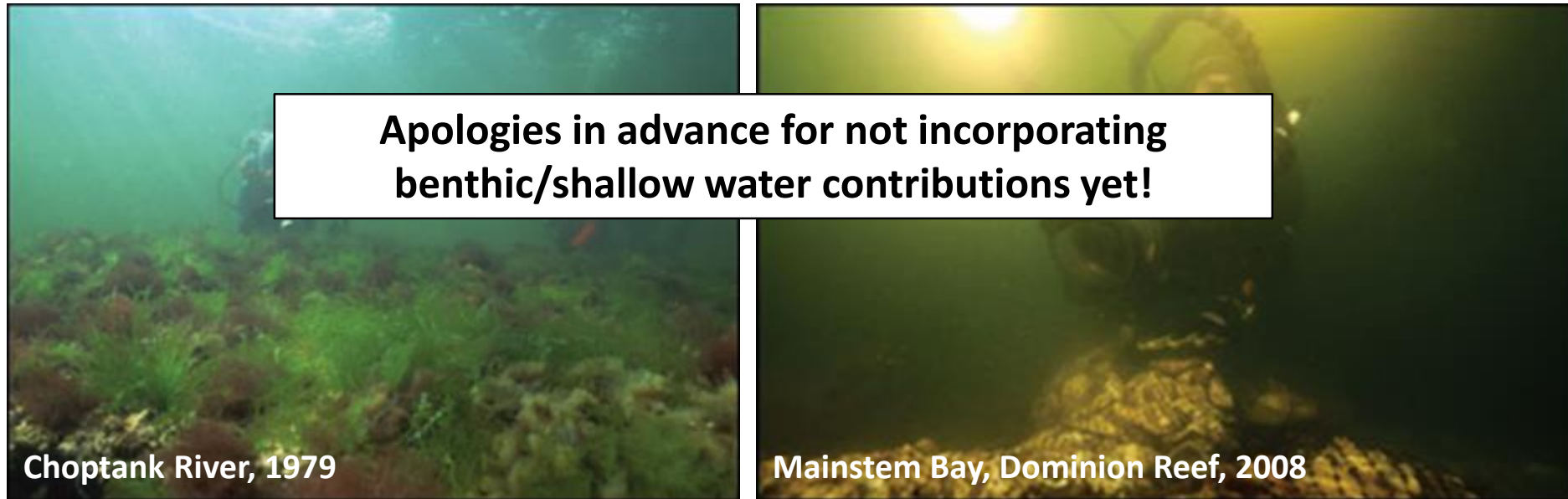
Motivation for better understanding of CB water clarity – e.g.,

- Indicator of health and trophic state of aquatic ecosystem.
- Sufficient shallow water clarity is needed for SAV and benthic algae.
- Deep water clarity affects ecology of phytoplankton, zooplankton and fish.
- Aesthetic value of water bodies, effecting recreation and property values.

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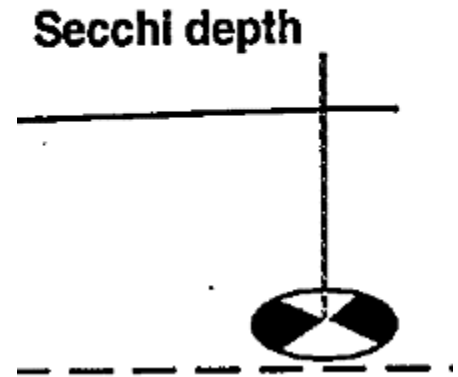
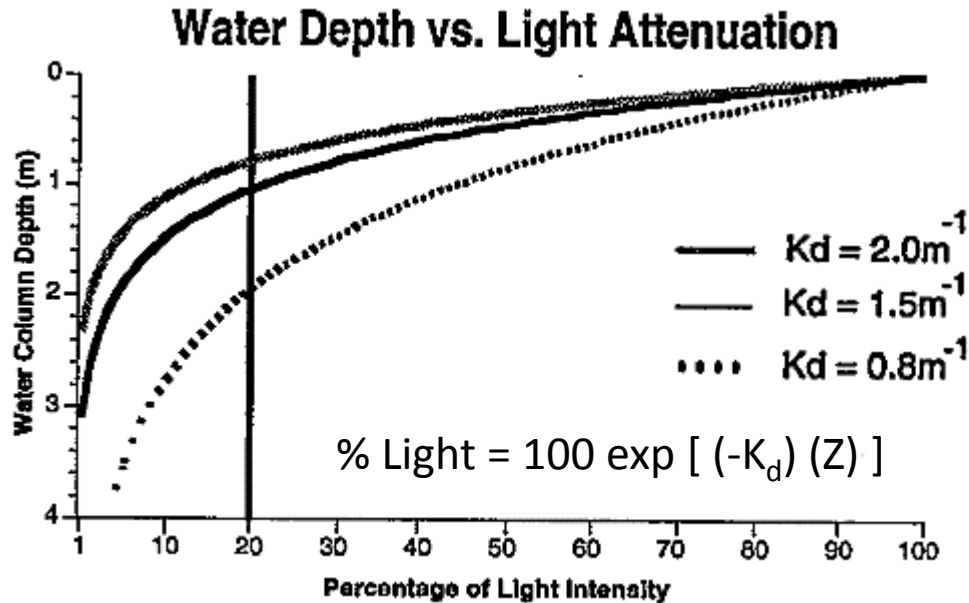
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- Aesthetic value of water bodies, effecting recreation and property values.

Why are we witnessing declining trends or no trends in water clarity against the backdrop of decades of BMP implementation and dramatic reductions in wastewater and atmospheric deposition loads?

What has happened in the past decade that has lead to the widespread increases in water clarity particularly in the mainstem Bay?

Motivation for the synthesis – *Rich Batiuk (EPA-CBPO)*

Question 1: How is Bay water clarity measured/defined? How should improving or degrading water clarity be defined?



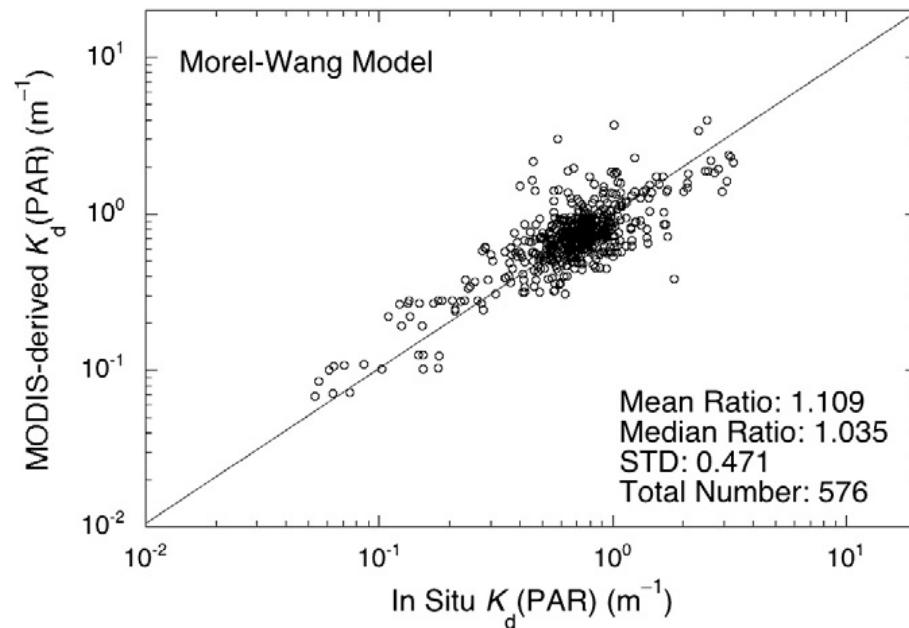
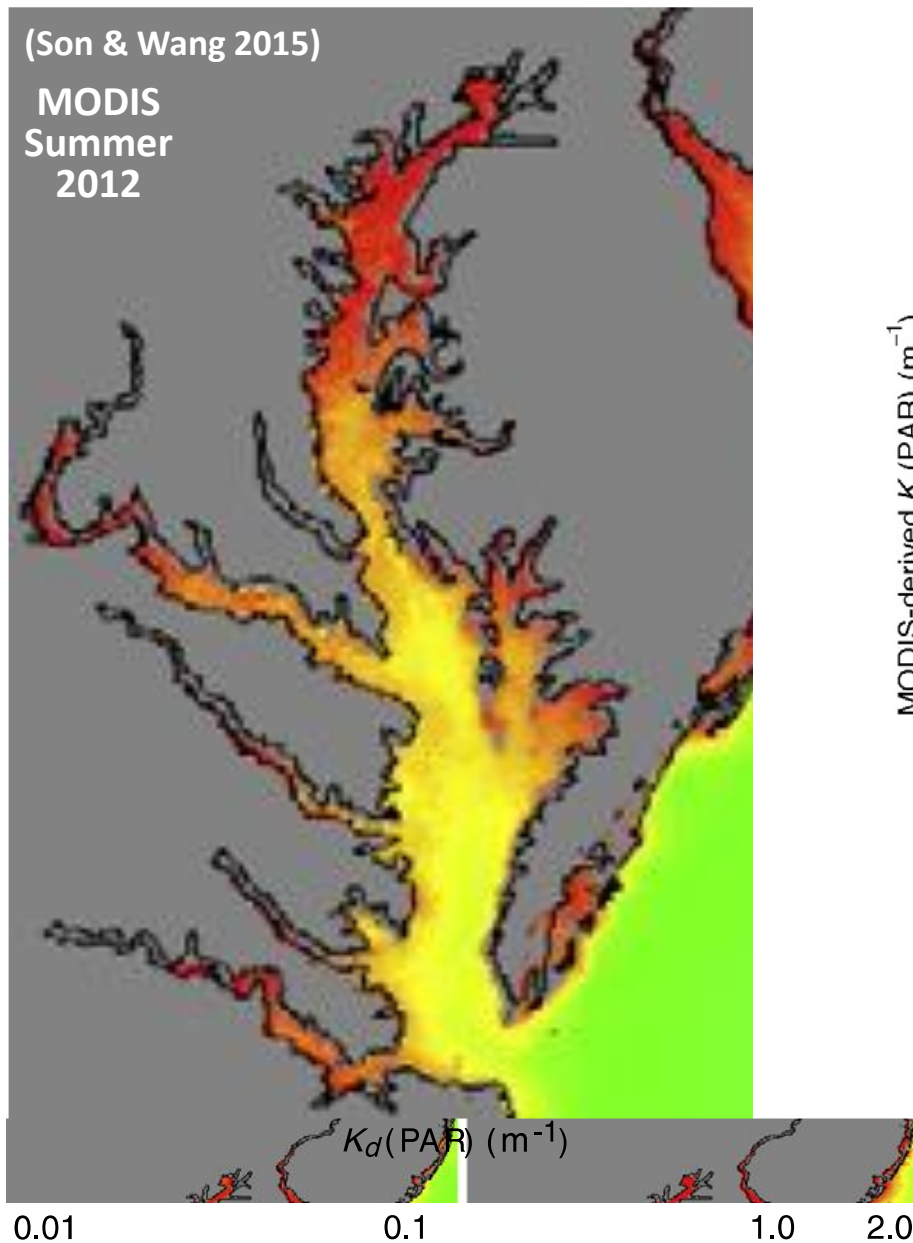
(Batiuk et al. 1992)

Attenuation (via K_d) and transparency (via Secchi depth) measure different light properties. Both are important! Attenuation limits photosynthesis; transparency is how we see clarity.

Unambiguously improving (or degrading) clarity should mean both K_d and Secchi are improving (or degrading).

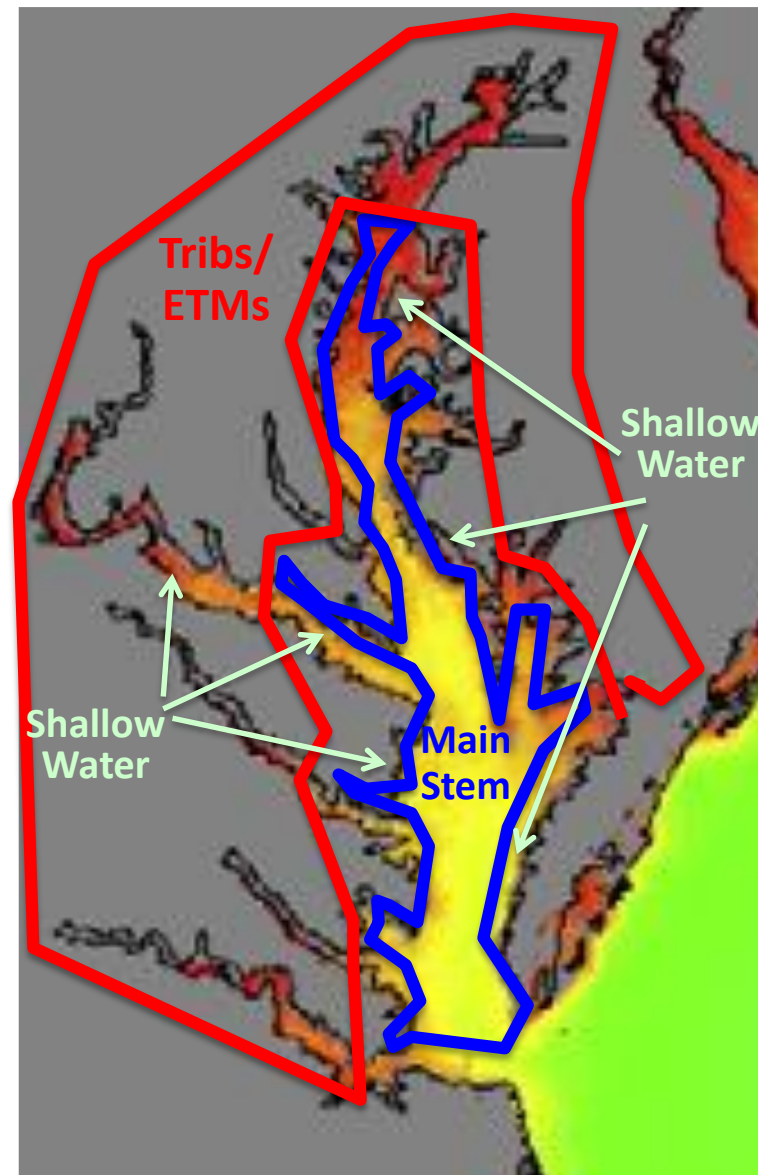
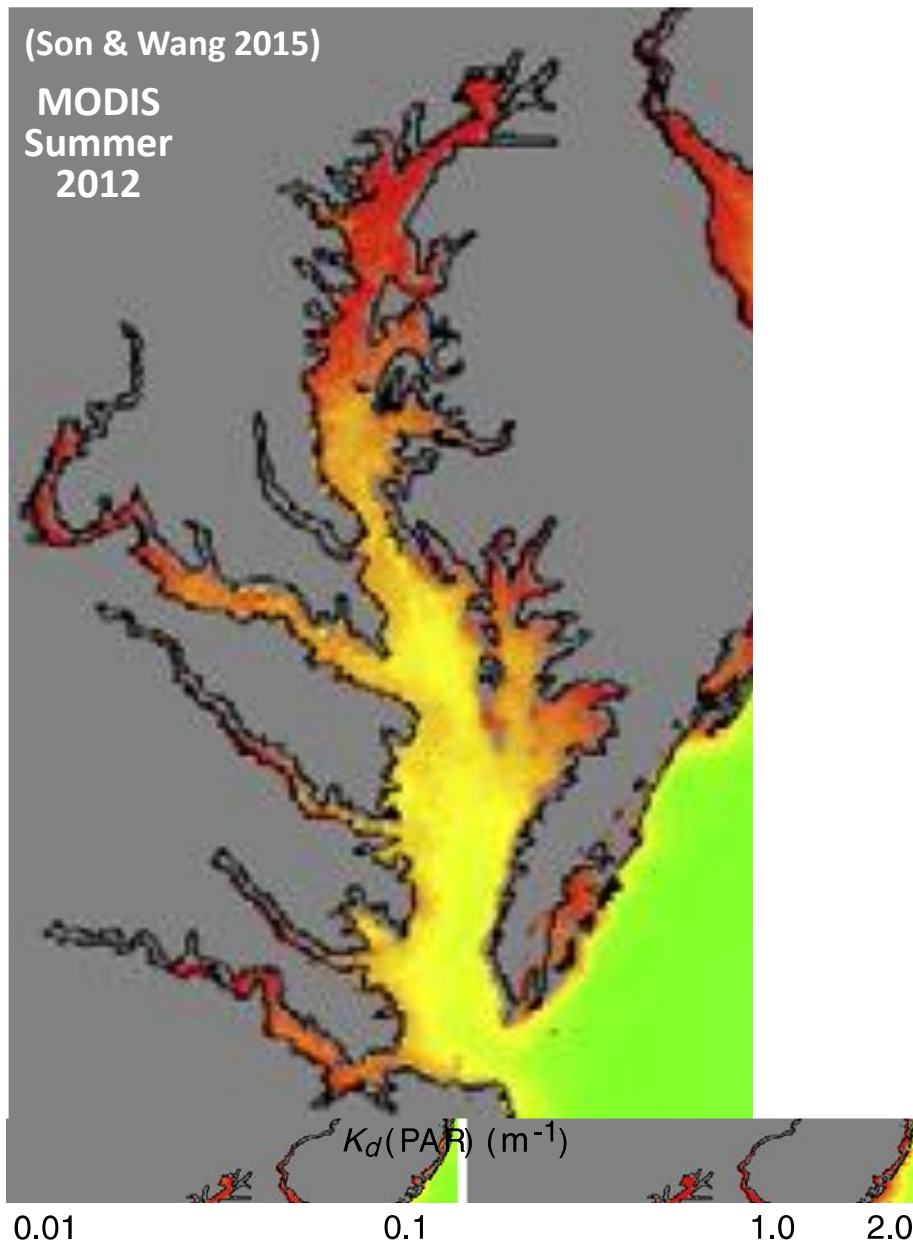
(Clearer water means that K_d gets smaller and Secchi depth get larger. $K_d \sim 1/\text{Secchi}$)

Question 2: What are the largest scale spatial patterns in Bay water clarity?



(Son & Wang 2015)

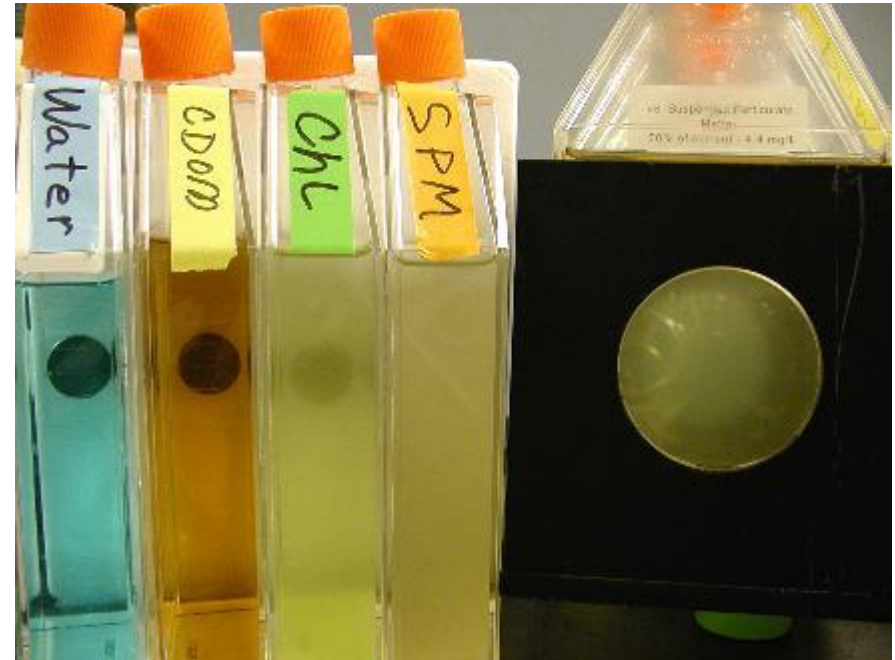
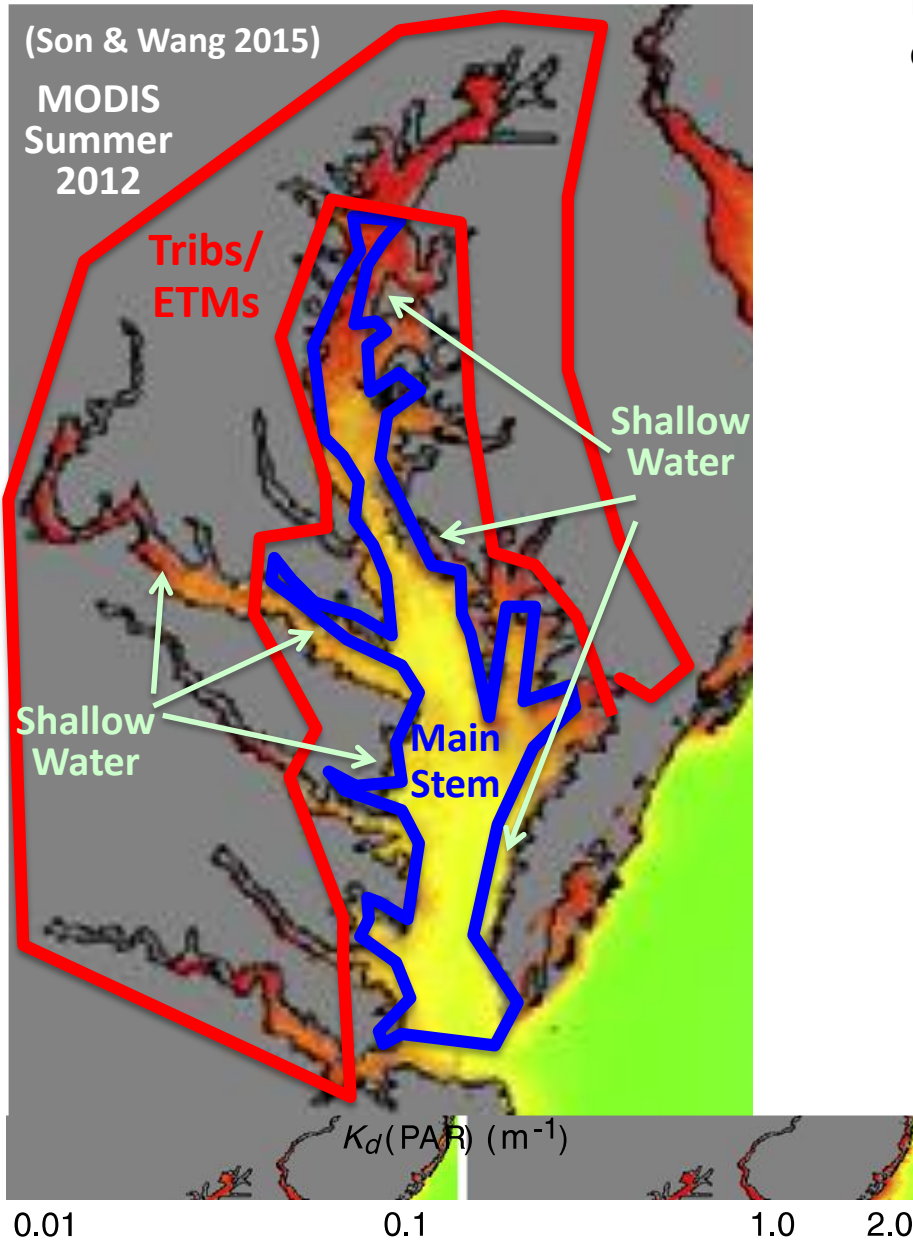
Water is generally clearer in the open waters of the Main Stem than in shallow water or in the Tidal Tribs/Estuarine Turbidity Maxima



What is driving these spatial differences in clarity?

According to optical models, we expect four main factors to contribute to scattering and absorption of light in Bay waters:

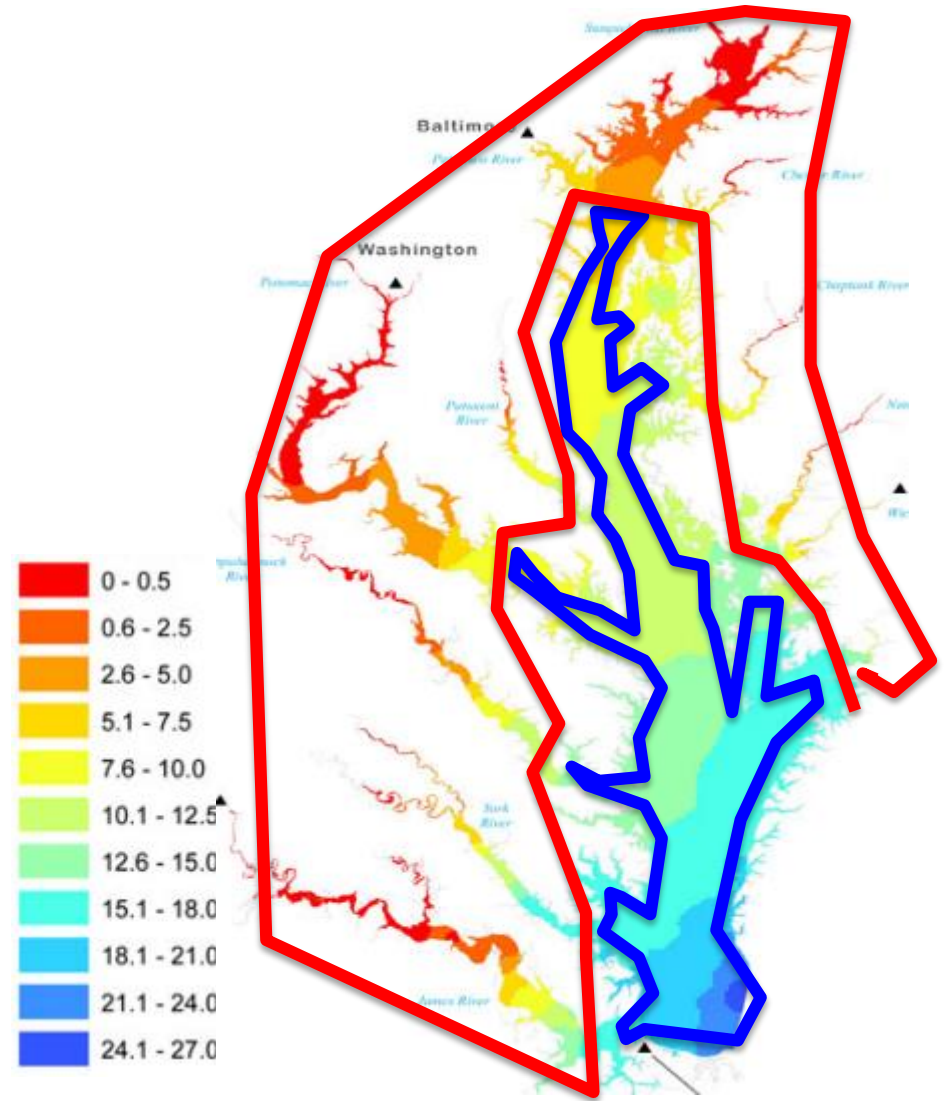
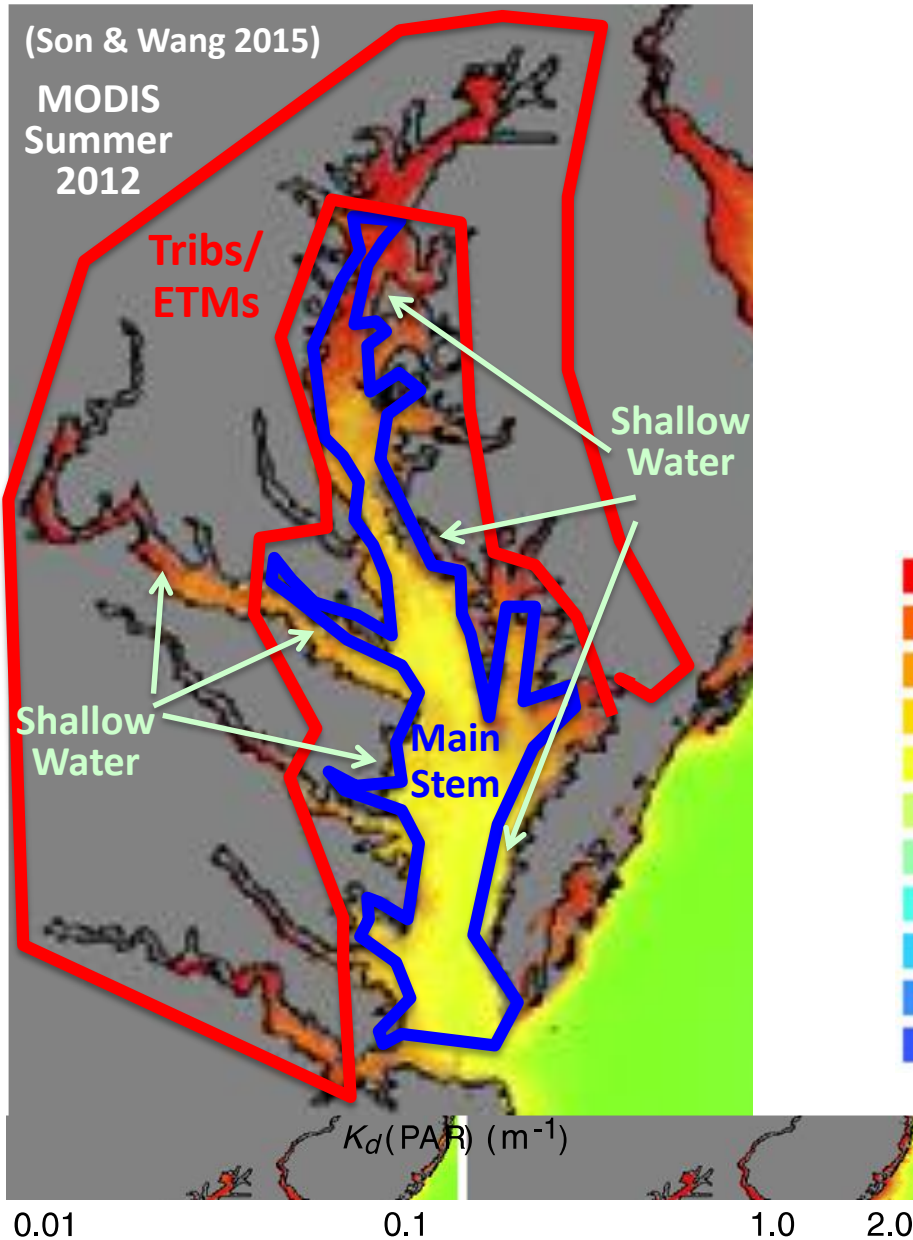
(Gallegos 2005)



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

Salinity is often used as an inverse proxy for CDOM

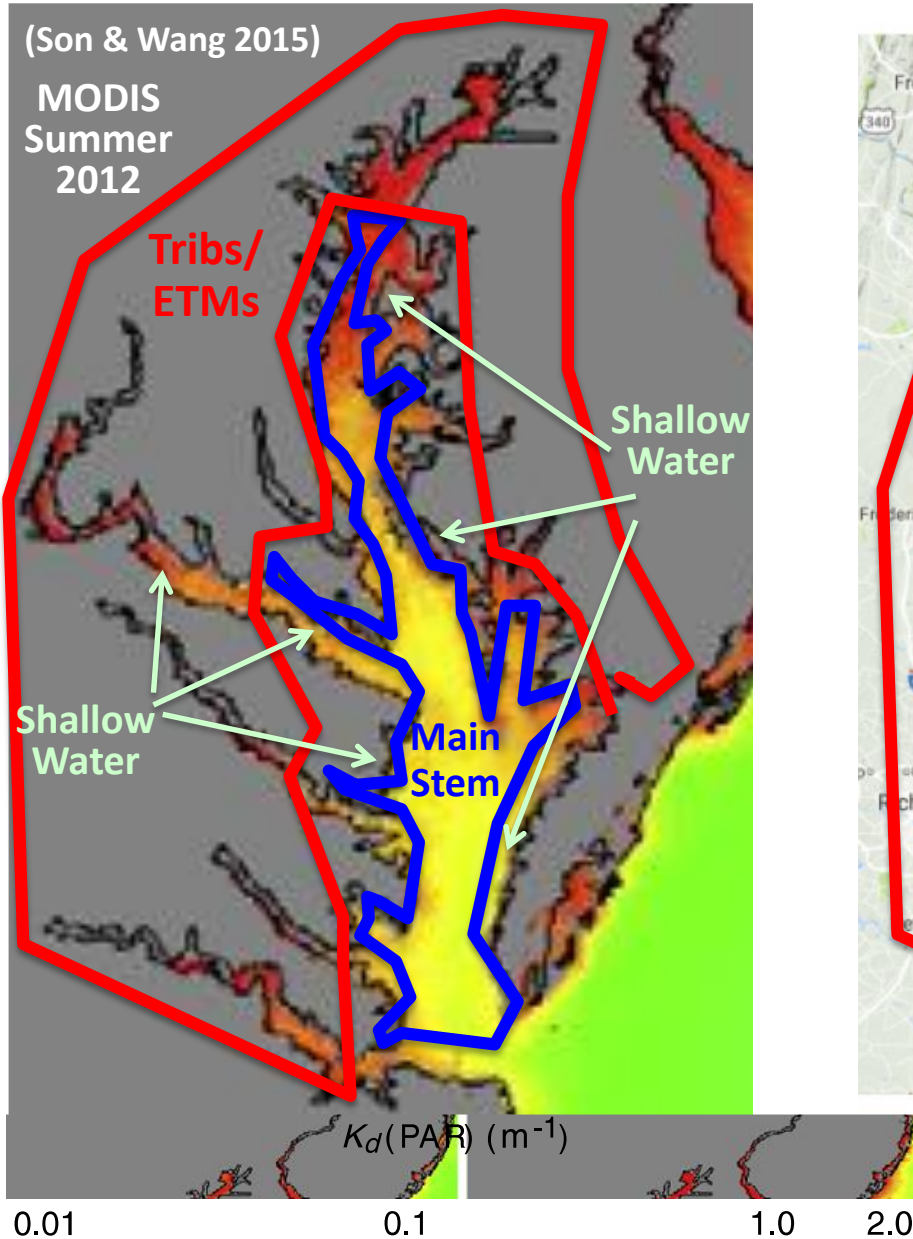
Satellite K_d is inversely correlated to salinity in space with lower K_d in the saltier Main Stem



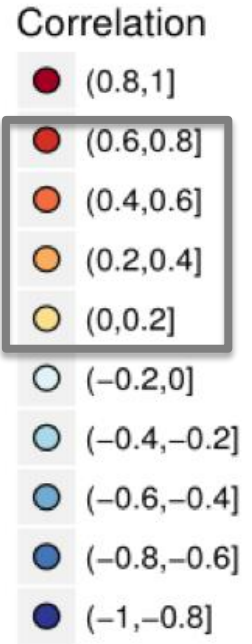
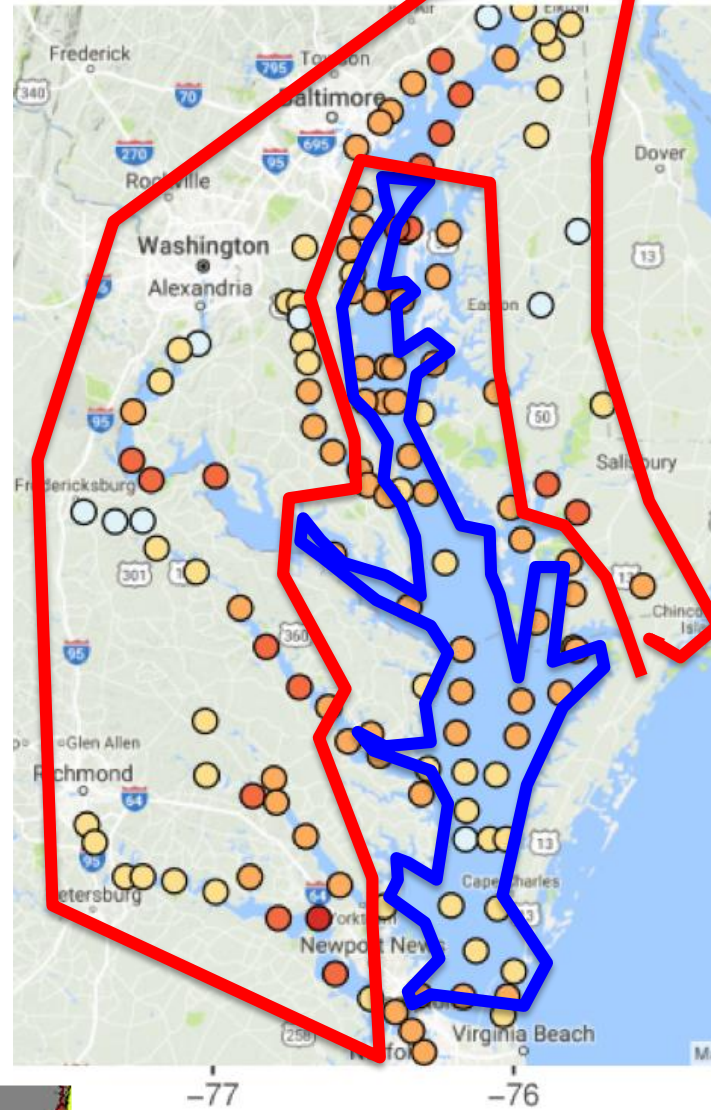
Mean spring surface salinity (1985-2006)

(chesapeake.net)

Secchi depth is positively correlated to salinity in time nearly everywhere.



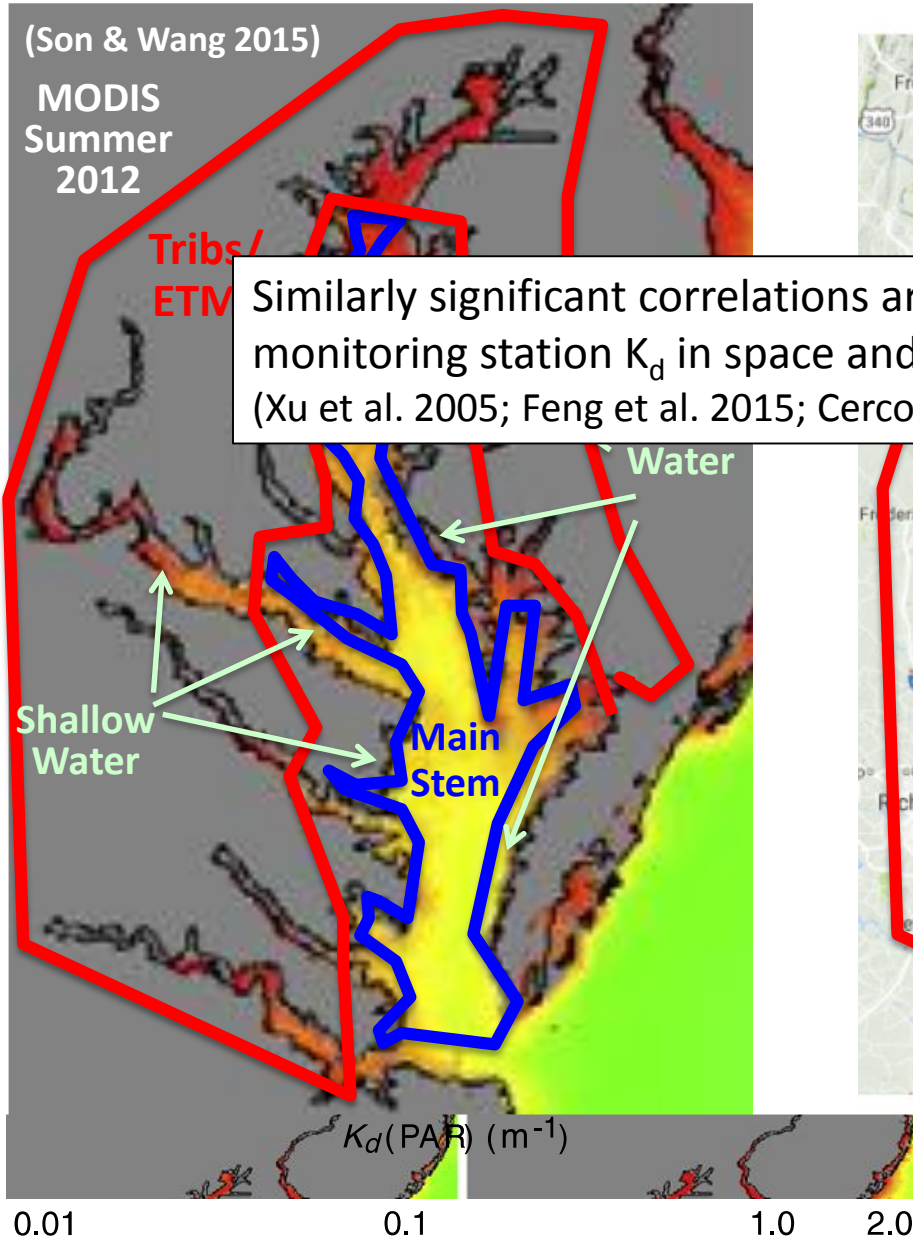
resid. Secchi vs. resid. Salinity



133 stations
~16/year
since 1984

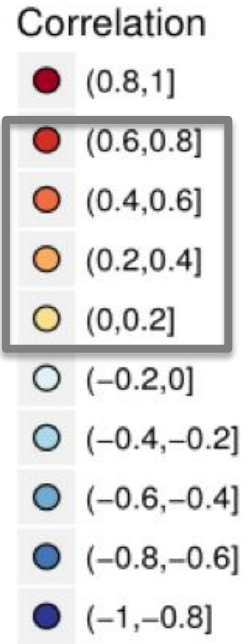
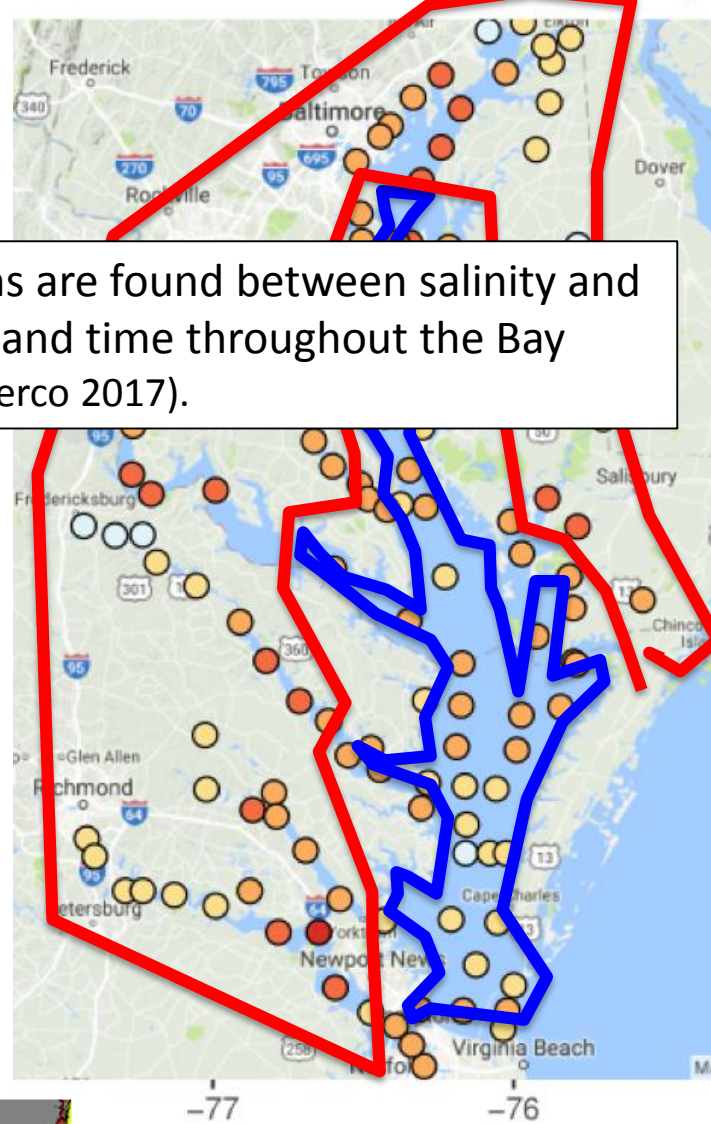
(Testa, Lyubchich, Zhang 2017)

Secchi depth is positively correlated to salinity in time nearly everywhere.



Similarly significant correlations are found between salinity and monitoring station K_d in space and time throughout the Bay (Xu et al. 2005; Feng et al. 2015; Cerco 2017).

resid. Secchi vs. resid. Salinity



133 stations
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since 1984

(Testa, Lyubchich, Zhang 2017)

BUT there is little evidence for a direct correlation of K_d with DOC except in some Tribs.

Multiple regression coefficients from Gallegos & Moore (2000). (ns) = not significant

$$K_d = K_0 + k_{\text{DOC}} [C_{\text{DOC}}] + k_{\text{CHL}} [C_{\text{CHL}}] + k_{\text{TSS}} [C_{\text{TSS}}]$$

Station	Coefficient of Determination	Degrees of Freedom	Intercept	Dissolved Organic Carbon (m^2g^{-1})	Phytoplankton Chlorophyll (m^2mg^{-1})	Total Suspended Solids (m^2g^{-1})
Mainstem Chesapeake Bay						
CB1.1	0.569	104	0.581	0.1015 ns	0.0022 ns	0.101
CB2.2	0.528	117	1.143	-0.0100 ns	-0.0082 ns	0.074
CB3.3C	0.453	129	0.610	0.0142 ns	-0.0012 ns	0.076
CB4.3C	0.148	121	0.533	-0.0091 ns	0.0192	0.041
CB5.2	0.271	121	0.393	0.0209 ns	0.0105	0.042
Tidal Tributaries						
MET5.1	0.208	96	3.227	0.1960	-0.0236	0.033
MET5.2	0.378	80	0.605	0.0931	0.0170	0.013
MWT5.1	0.530	78	1.581	-0.0493 ns	0.0108	-0.001 ns
PXT0402	0.109	104	2.833	0.3065 ns	-0.0113 ns	0.043
XDA1177	0.338	42	1.327	0.0695 ns	-0.0153 ns	0.047
XDE5339	0.219	100	0.807	0.0409 ns	0.0048 ns	0.042
XEA6596	0.321	47	1.271	0.0074 ns	0.0020 ns	0.064
XED4892	0.463	71	2.096	0.1225 ns	-0.0461	0.058

k_{DOC} →

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Also, K_d is more strongly related to TSS than to Chlorophyll (c.f. Xu et al. 2005; Feng et al. 2015; Cerco 2017)

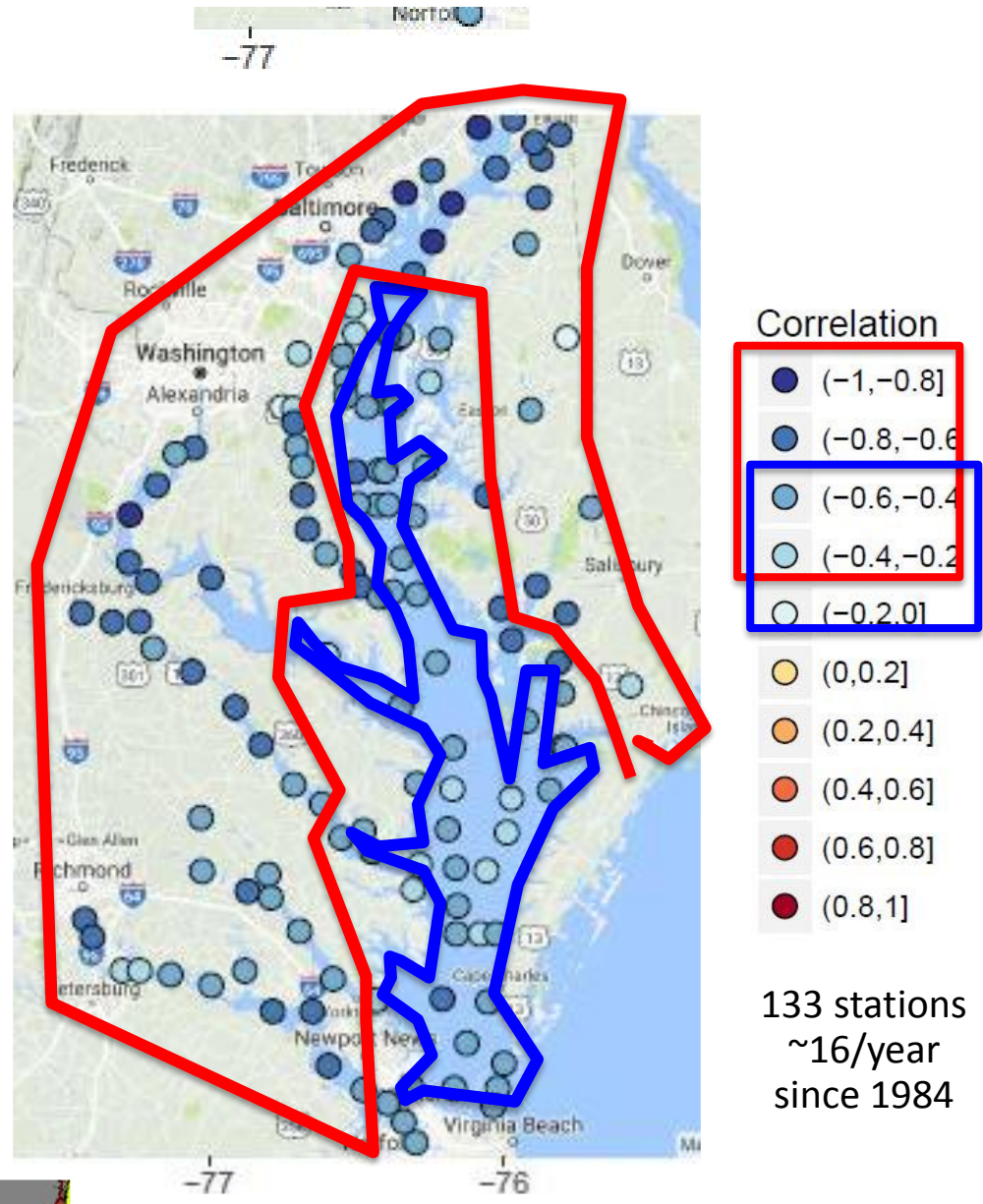
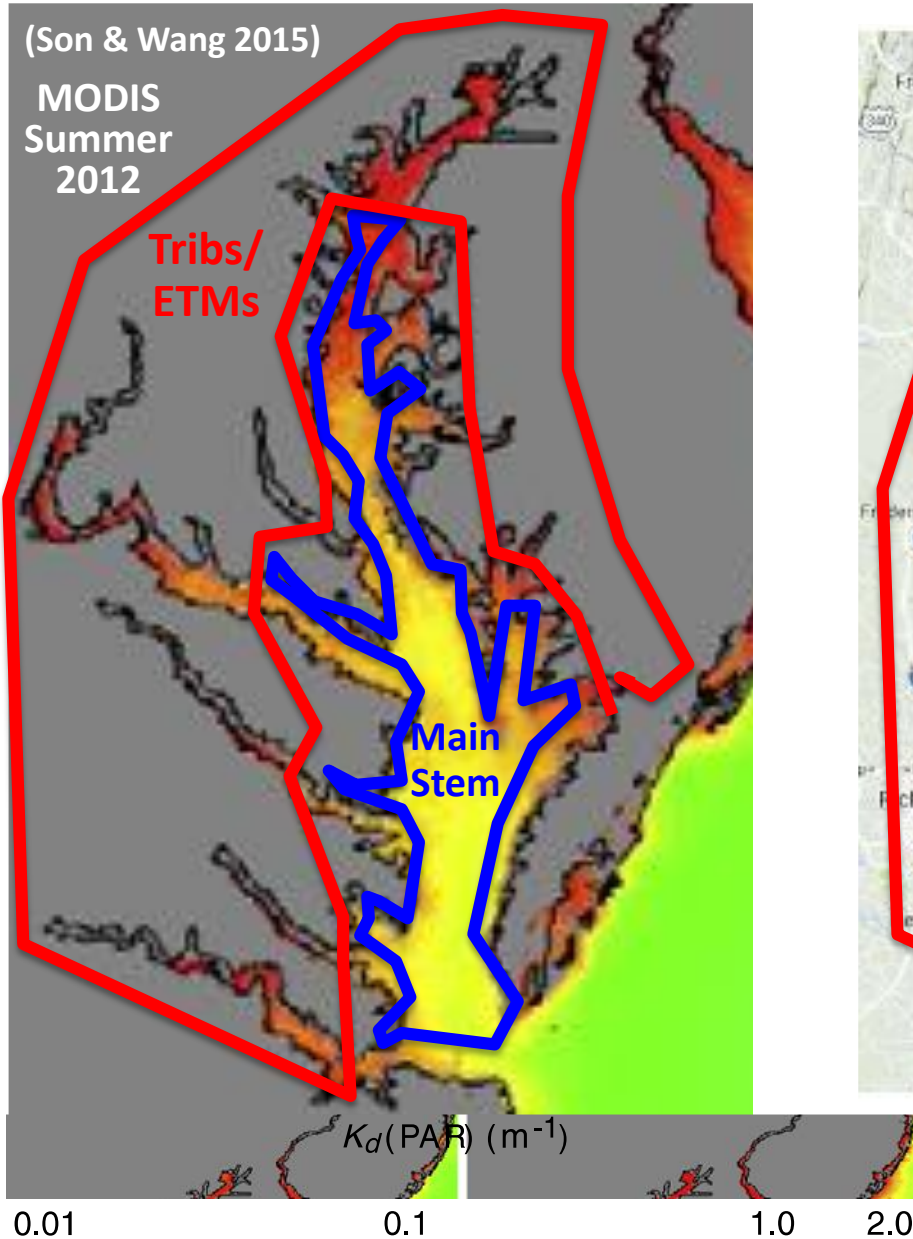
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k_{DOC} →

k_{CHL}

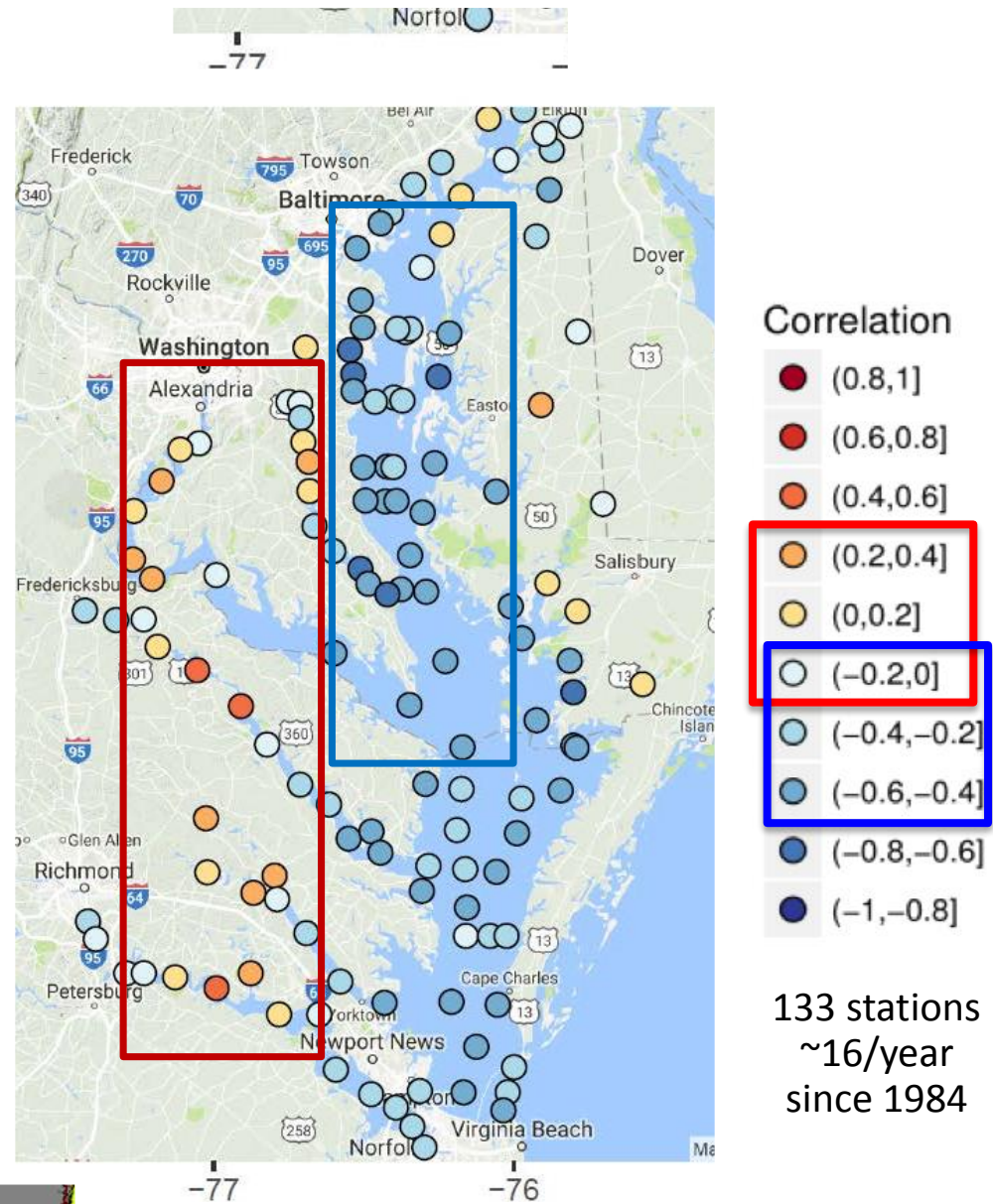
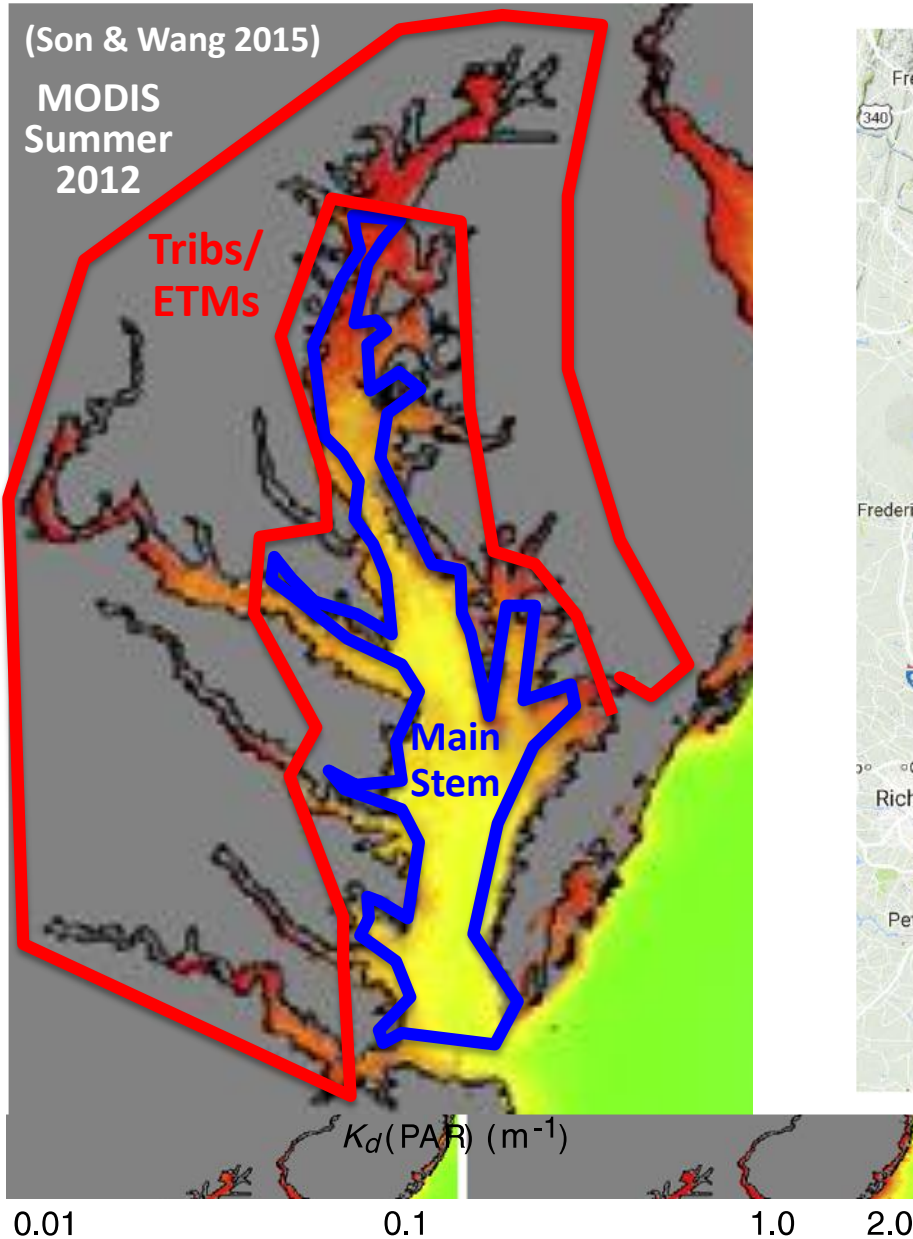
k_{TSS}

Correlation of Secchi with TSS is negative everywhere. Most negative in Tribs/ETM.



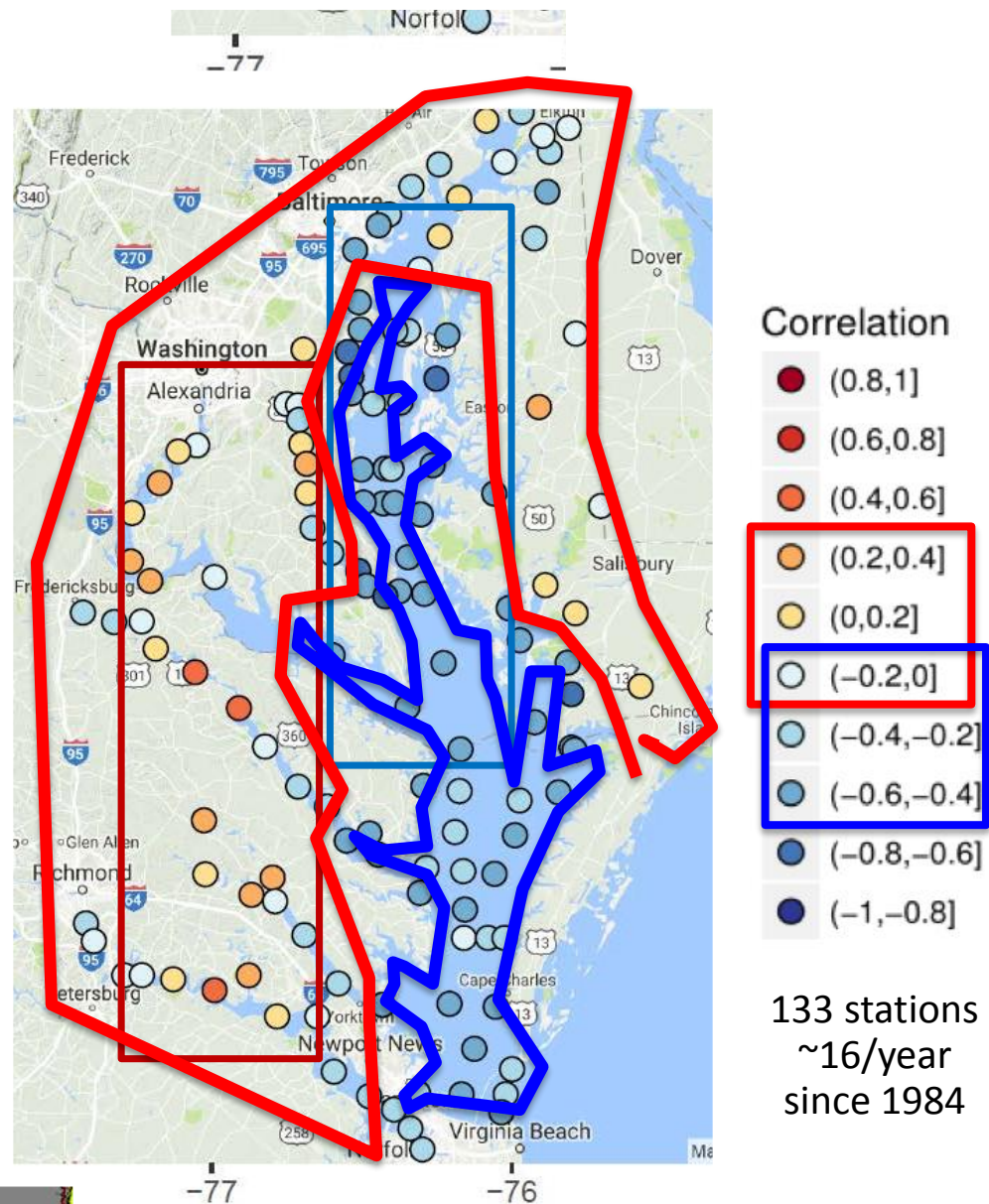
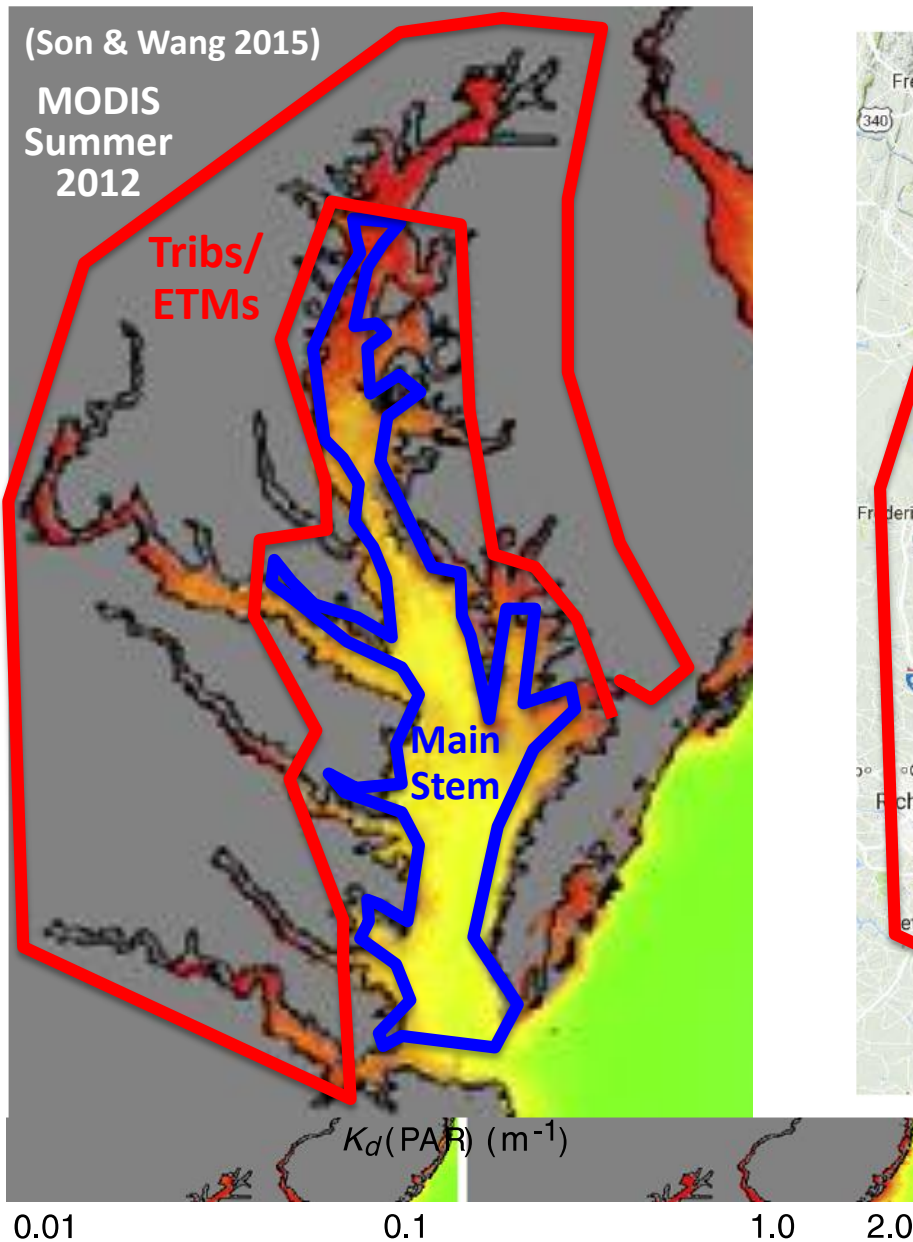
(Testa, Lyubchich, Zhang 2017; c.f. Wang et al. 2013)

Correlation of Secchi with Chlorophyll is negative in main stem and more positive in Tribs/ETM. Light limitation occurs in tribs/ETM. Negative correlations may be more complicated...



(Testa, Lyubchich, Zhang 2017; c.f. Wang et al. 2013)

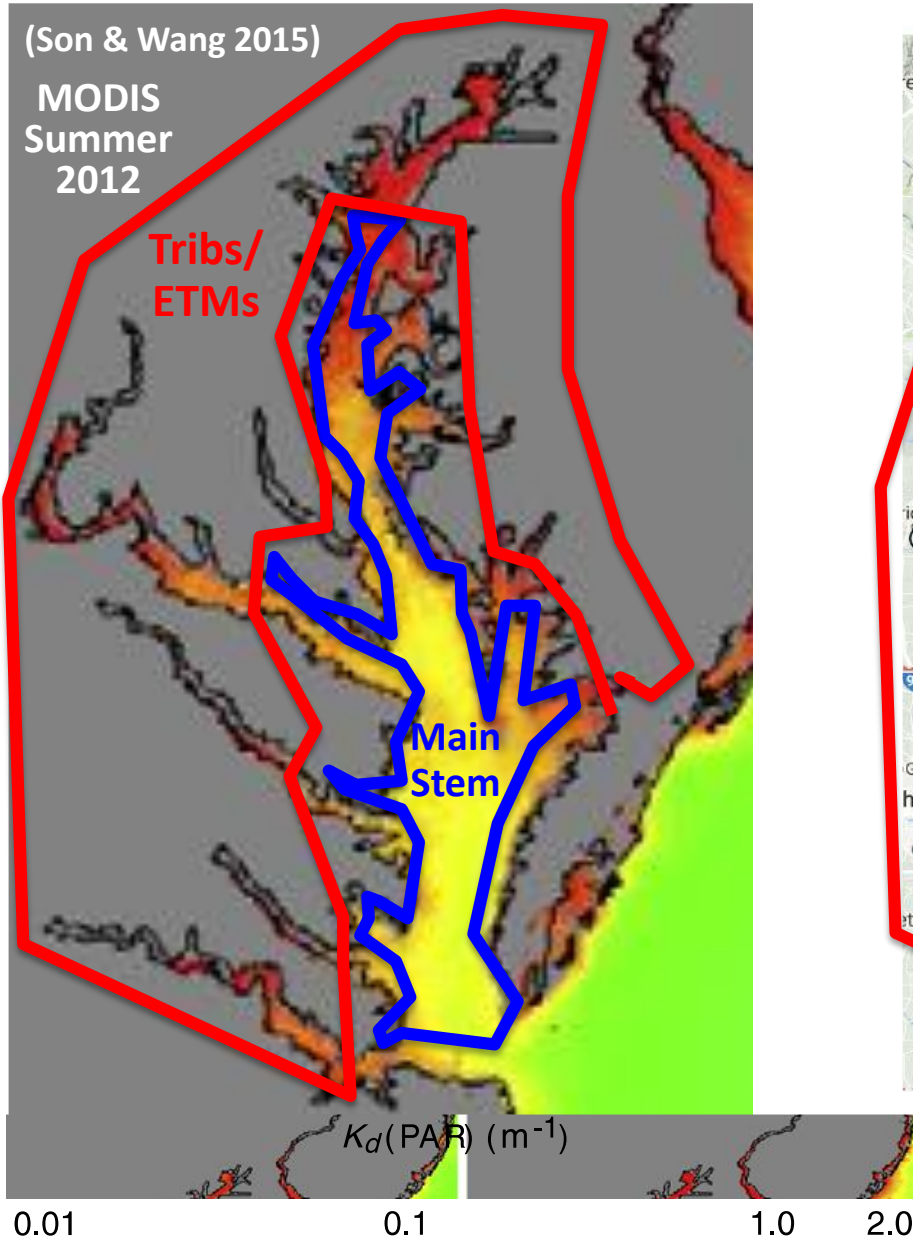
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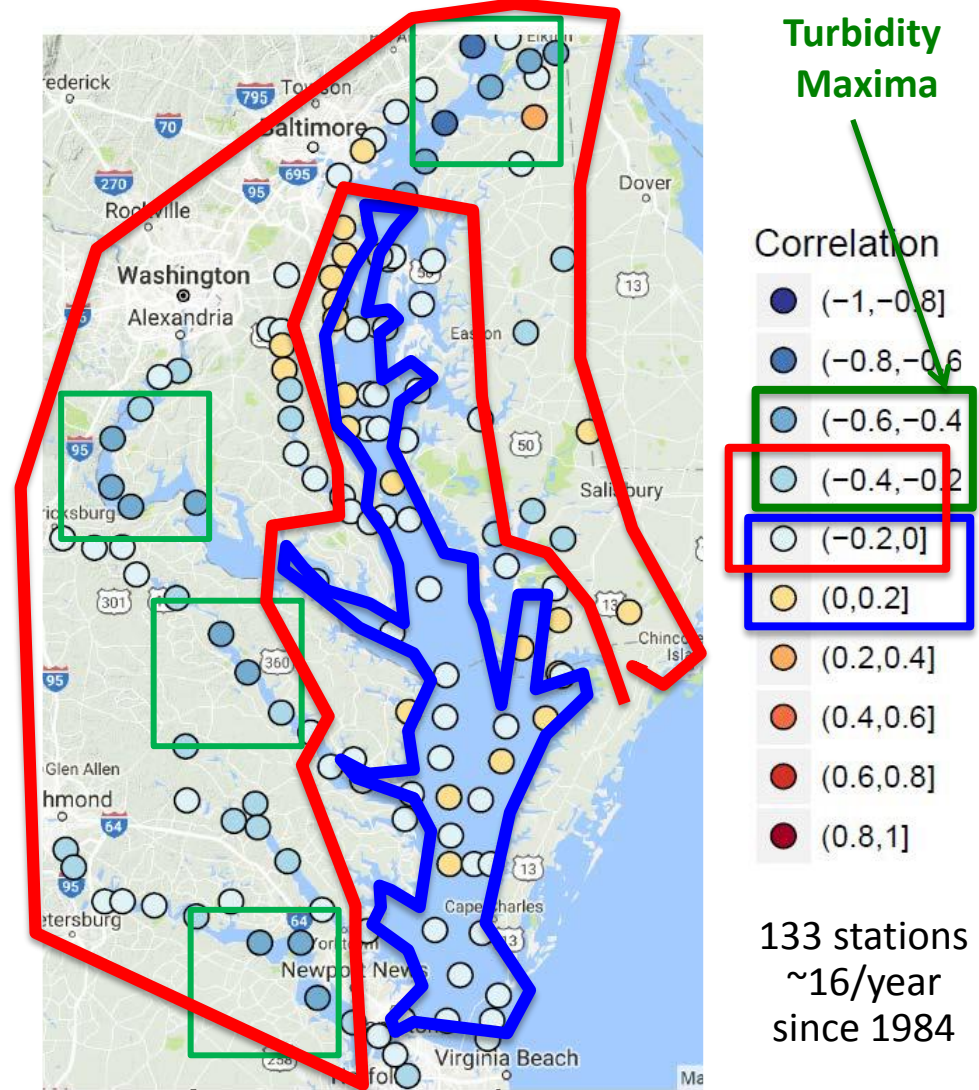
(Testa, Lyubchich, Zhang 2017; c.f. Wang et al. 2013)

Secchi is negatively correlated to riverine sediment load in ETM regions.

Weak negative correlation broadly present in Tribs. No correlation in Main Stem.



Secchi vs. loadSS

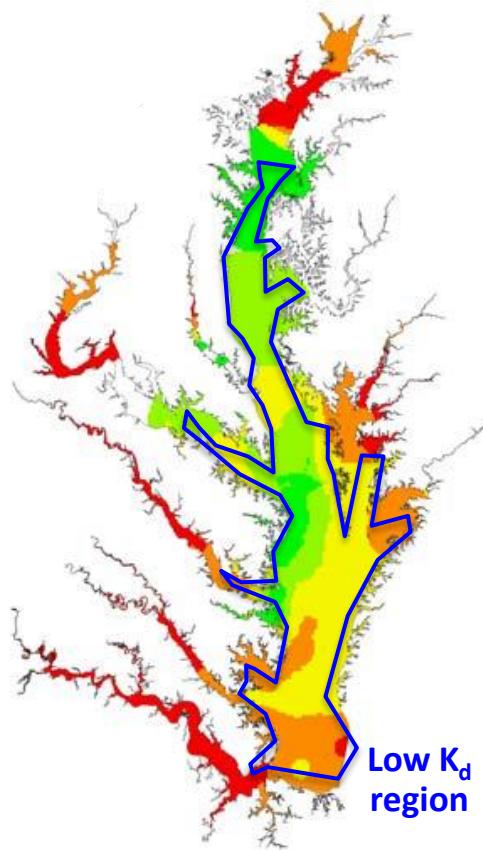


(Testa, Lyubchich, Zhang 2017)

Why are clarity correlations different in the ETMs/upper tribs?

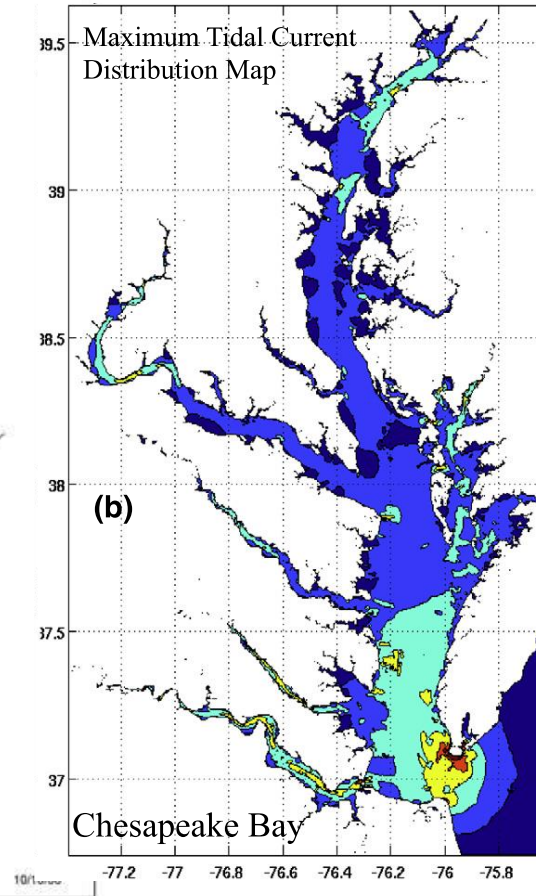
Ans.: Inorganic Suspended Solids (ISS) fraction is much high in the ETMs/upper tribs. Except for tidal resuspension near Bay Mouth, ISS fraction is low in Main Stem.

Observed % ISS



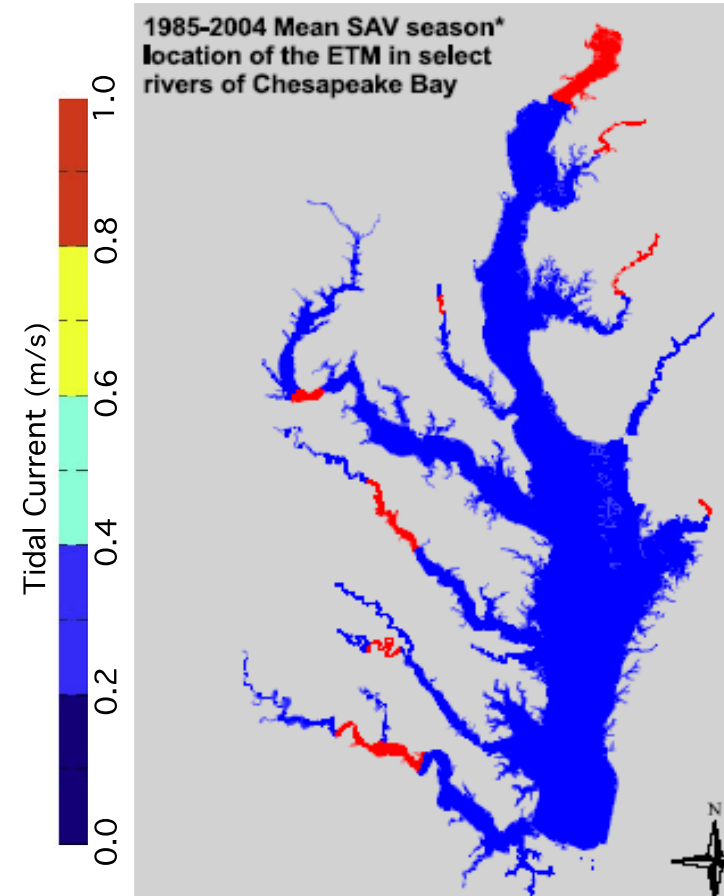
Curry et al. (2007)

Max Tidal Current



Shi et al. (2013)

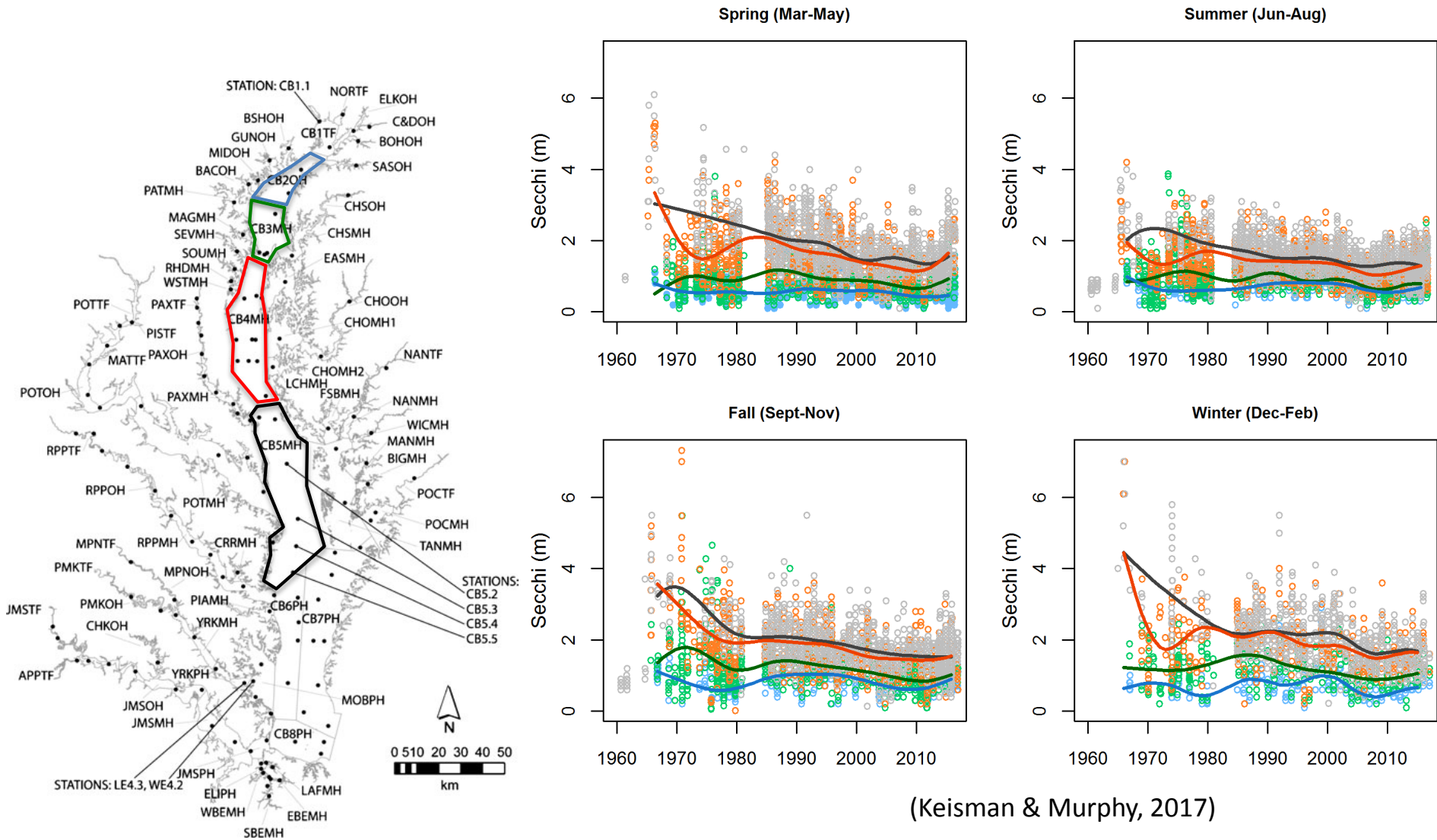
Mean ETM location



Curry et al. (2007)

Question 3: What long-term trends in Bay water clarity have been observed?

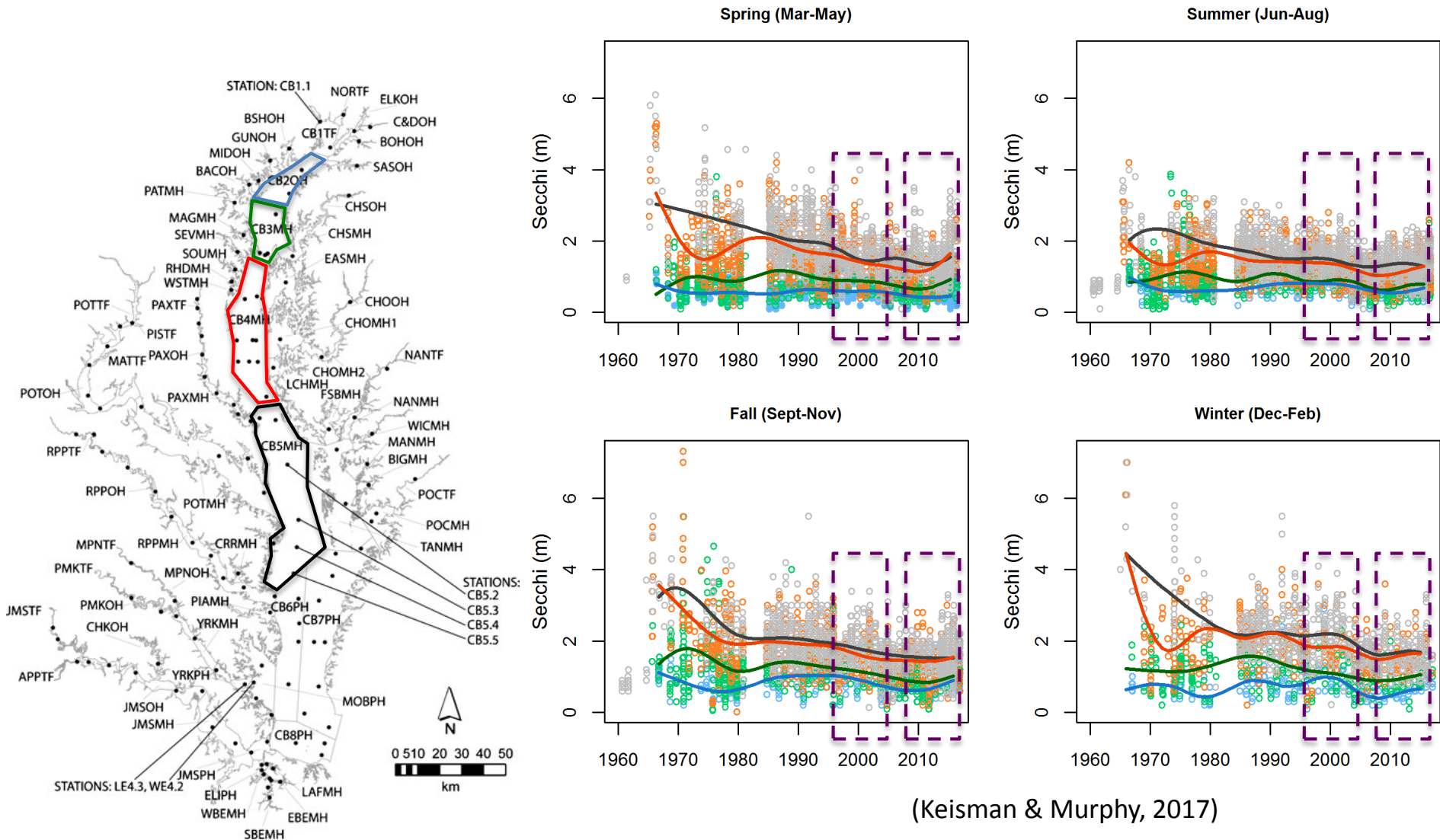
Trends in Secchi Depth, 1960 - 2016



(Williams et al. 2010)

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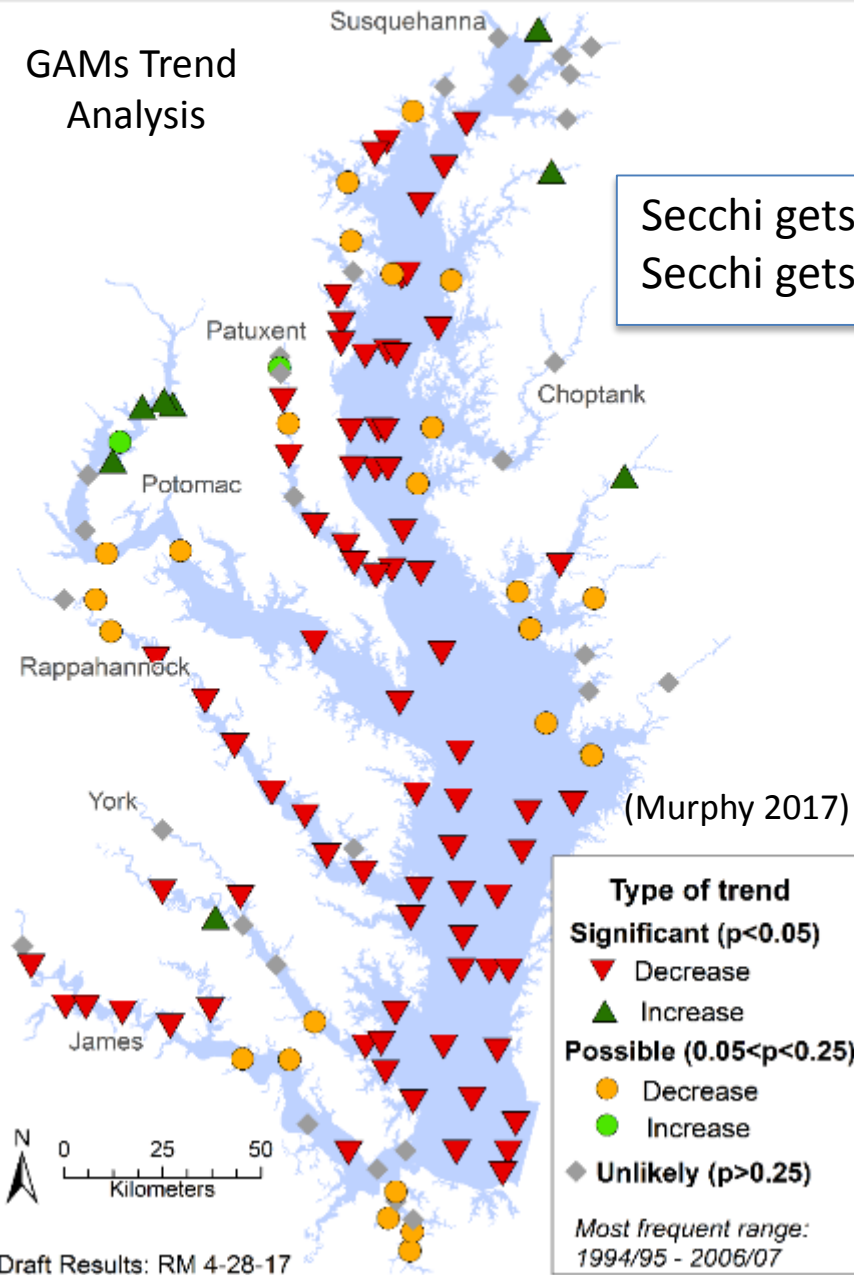


(Keisman & Murphy, 2017)

(Williams et al. 2010)

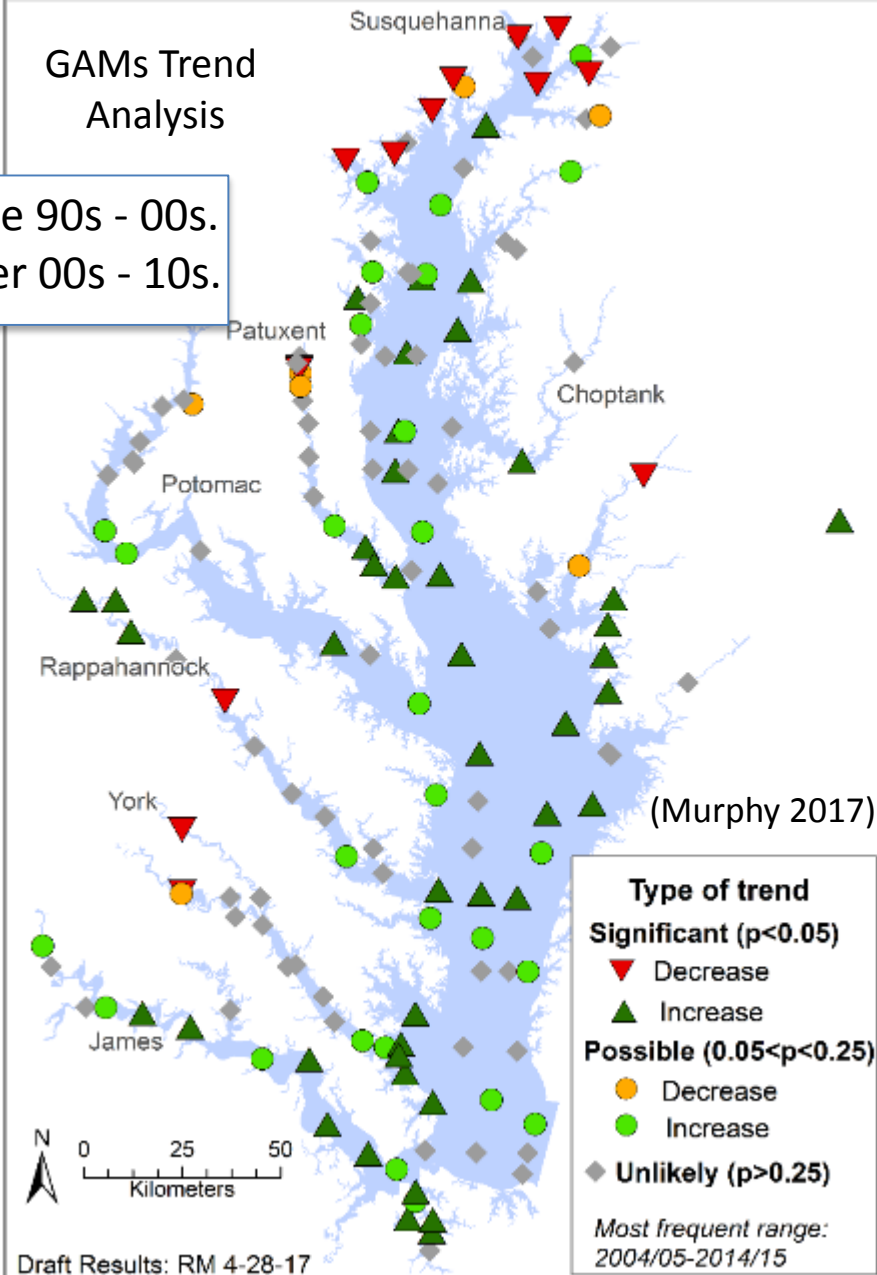
Apr-Oct: Trends for Secchi where sampled in ~10 years from mid-1990s to mid-2000s

GAMs Trend Analysis



Apr-Oct: Trends for Secchi where sampled in recent ~10 years from mid-2000s to mid-2010s

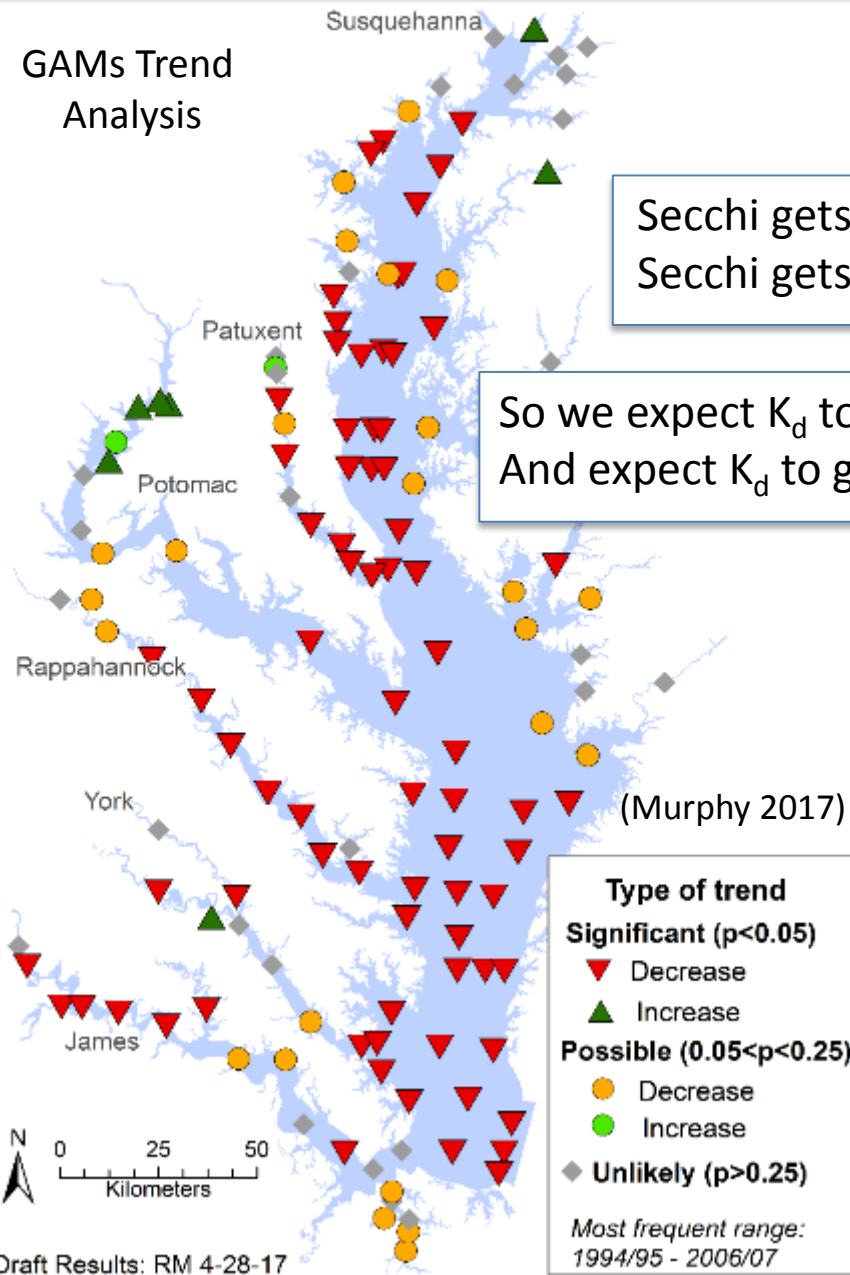
GAMs Trend Analysis



Secchi gets worse 90s - 00s.
 Secchi gets better 00s - 10s.

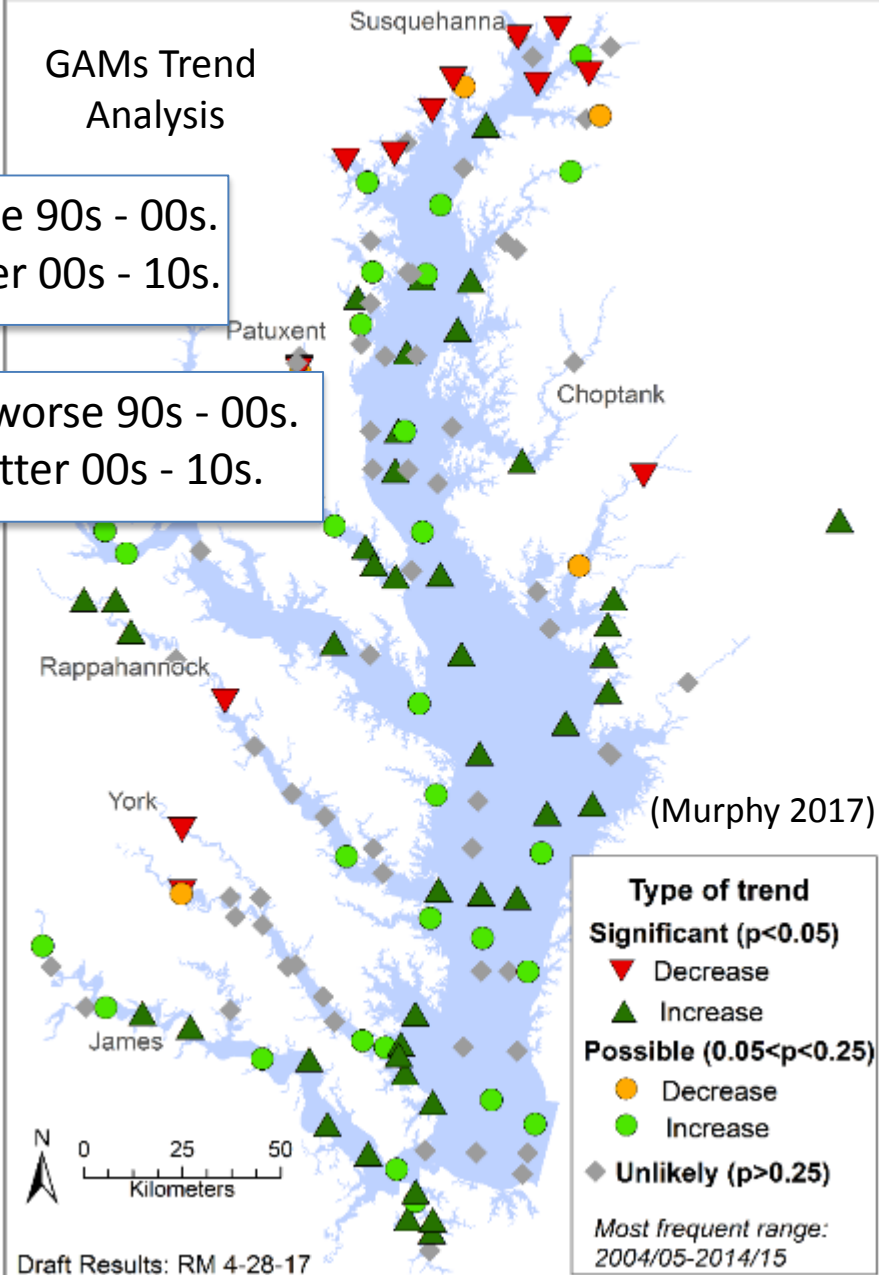
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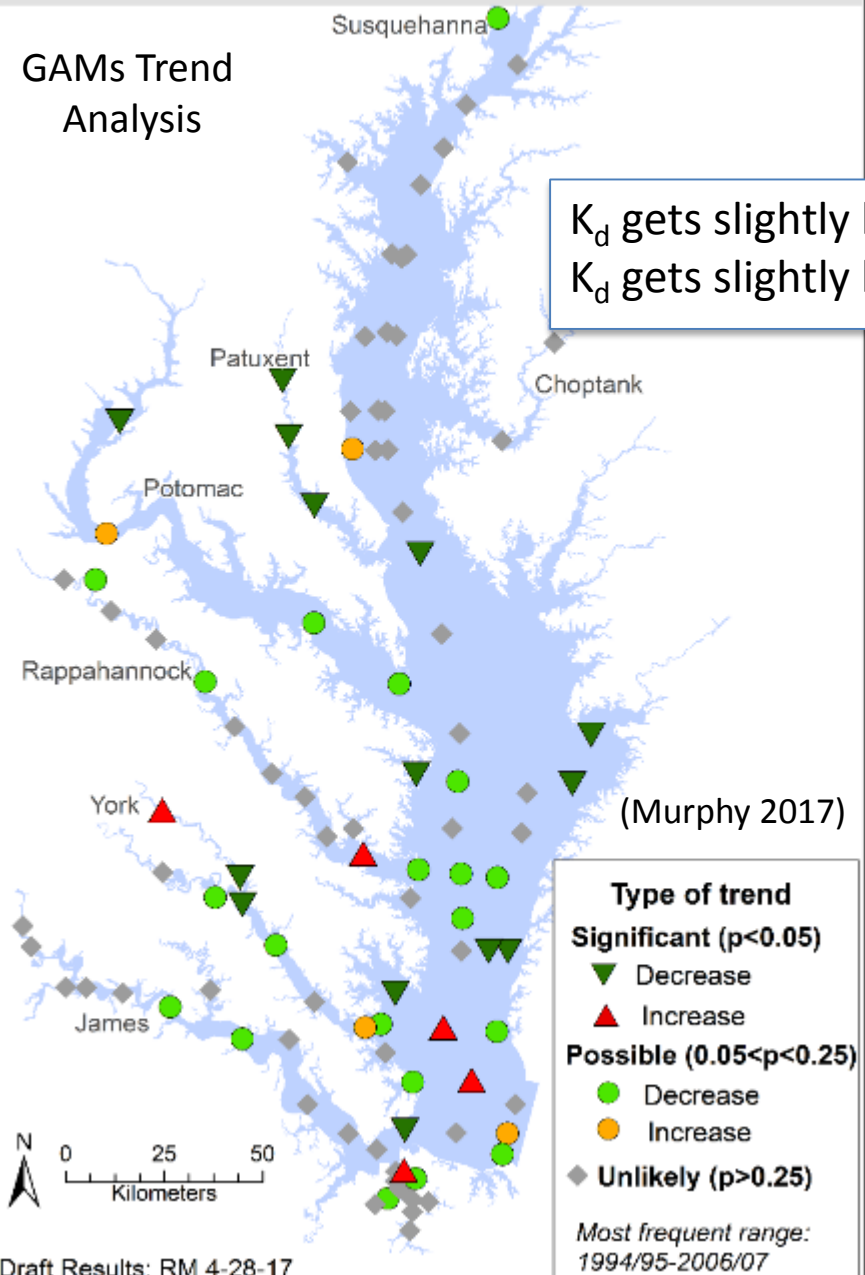
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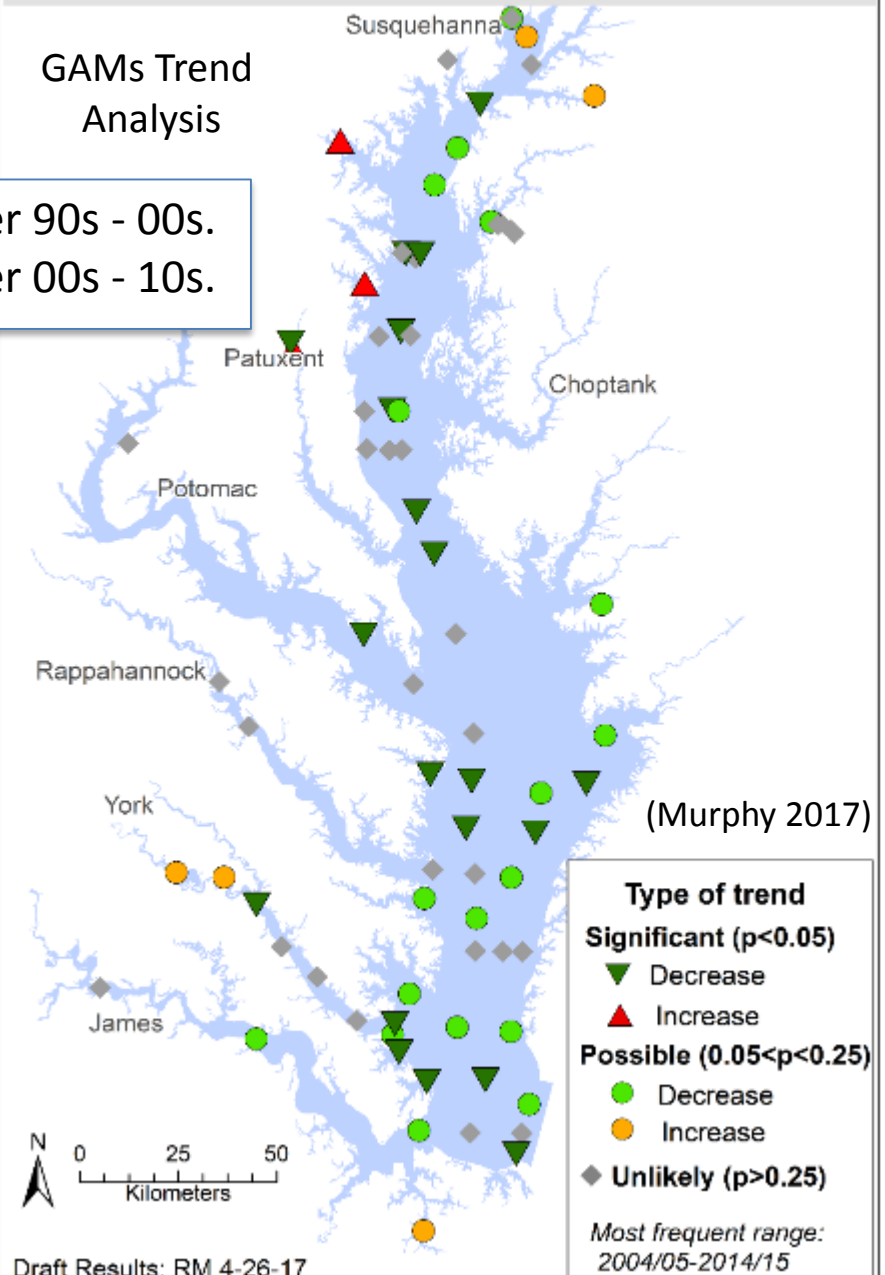
**Apr-Oct: Trends for kd where sampled
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**GAMs Trend
Analysis**



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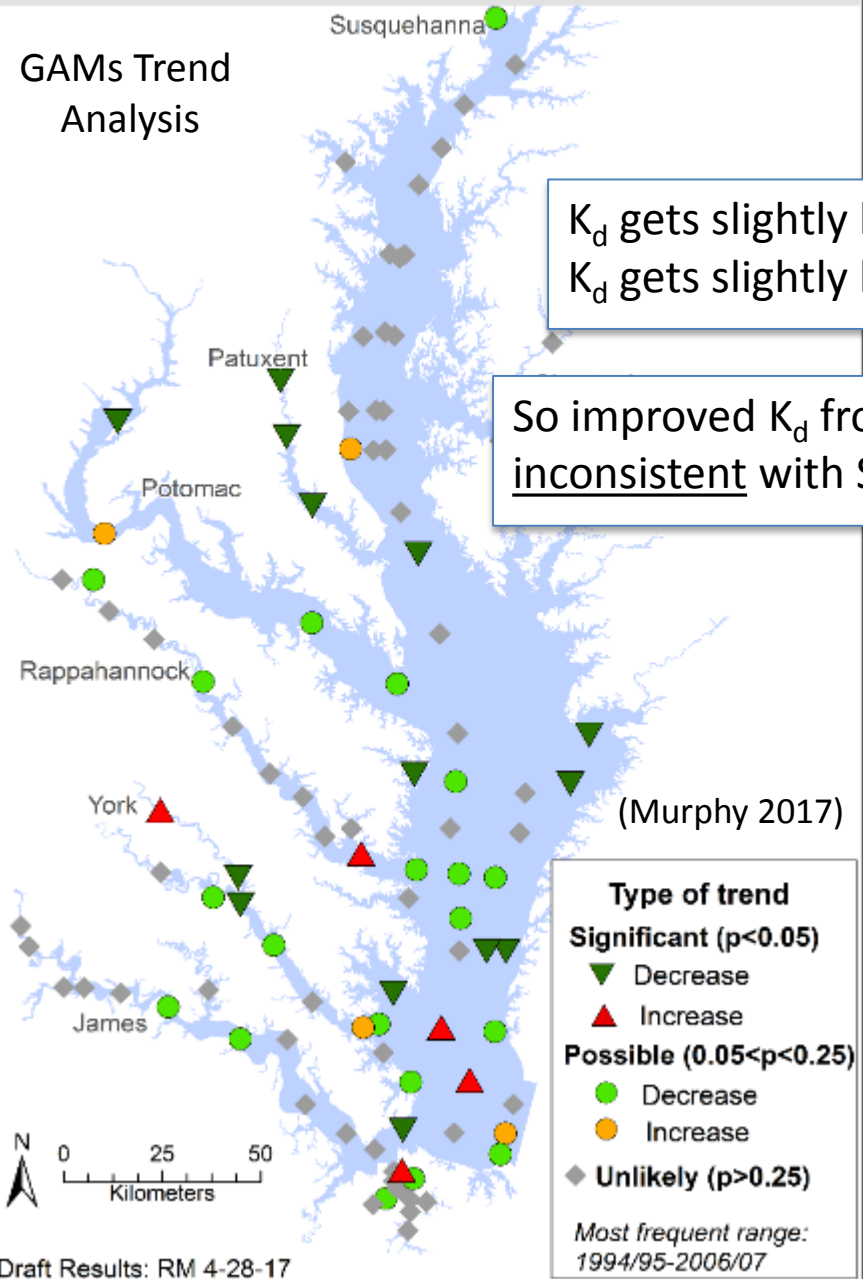
**GAMs Trend
Analysis**



K_d gets slightly better 90s - 00s.
 K_d gets slightly better 00s - 10s.

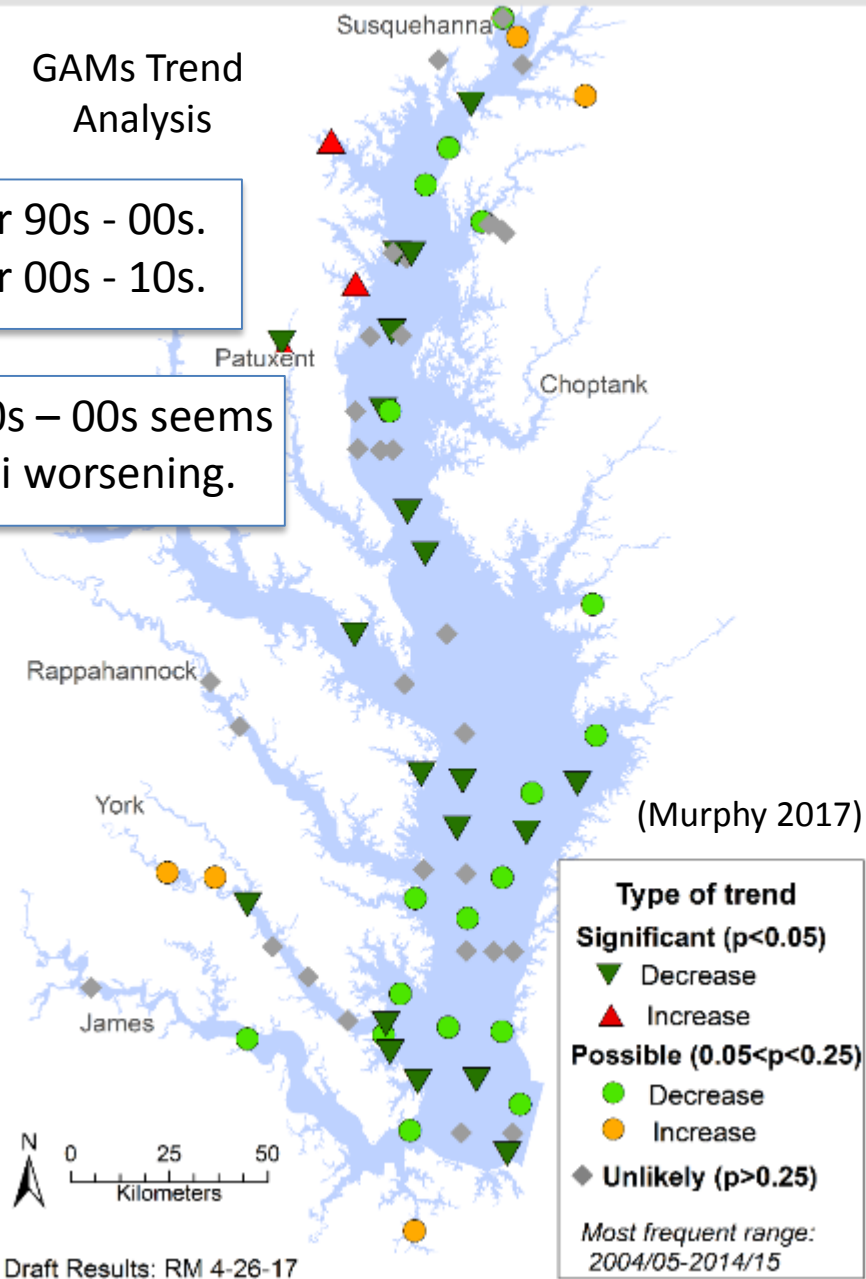
Apr-Oct: Trends for K_d where sampled in ~10 years from mid-1990s to mid-2000s

GAMs Trend Analysis



Apr-Oct: Trends for K_d where sampled in recent ~10 years from mid-2000s to mid-2010s

GAMs Trend Analysis



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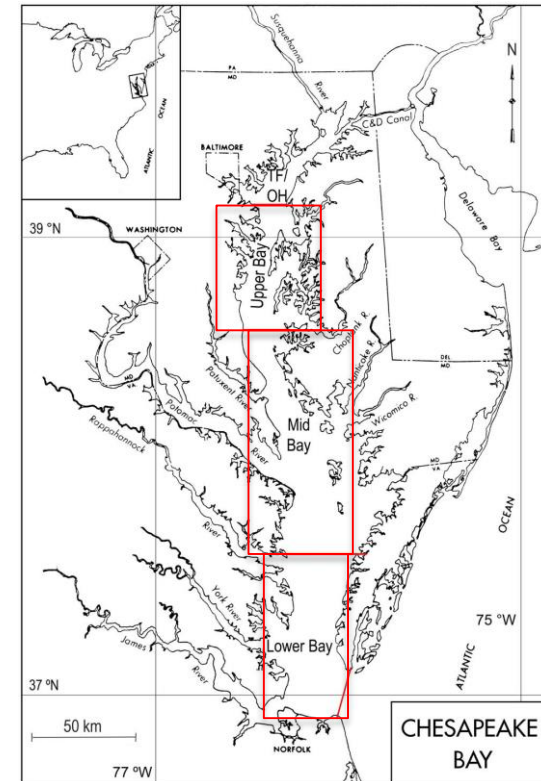
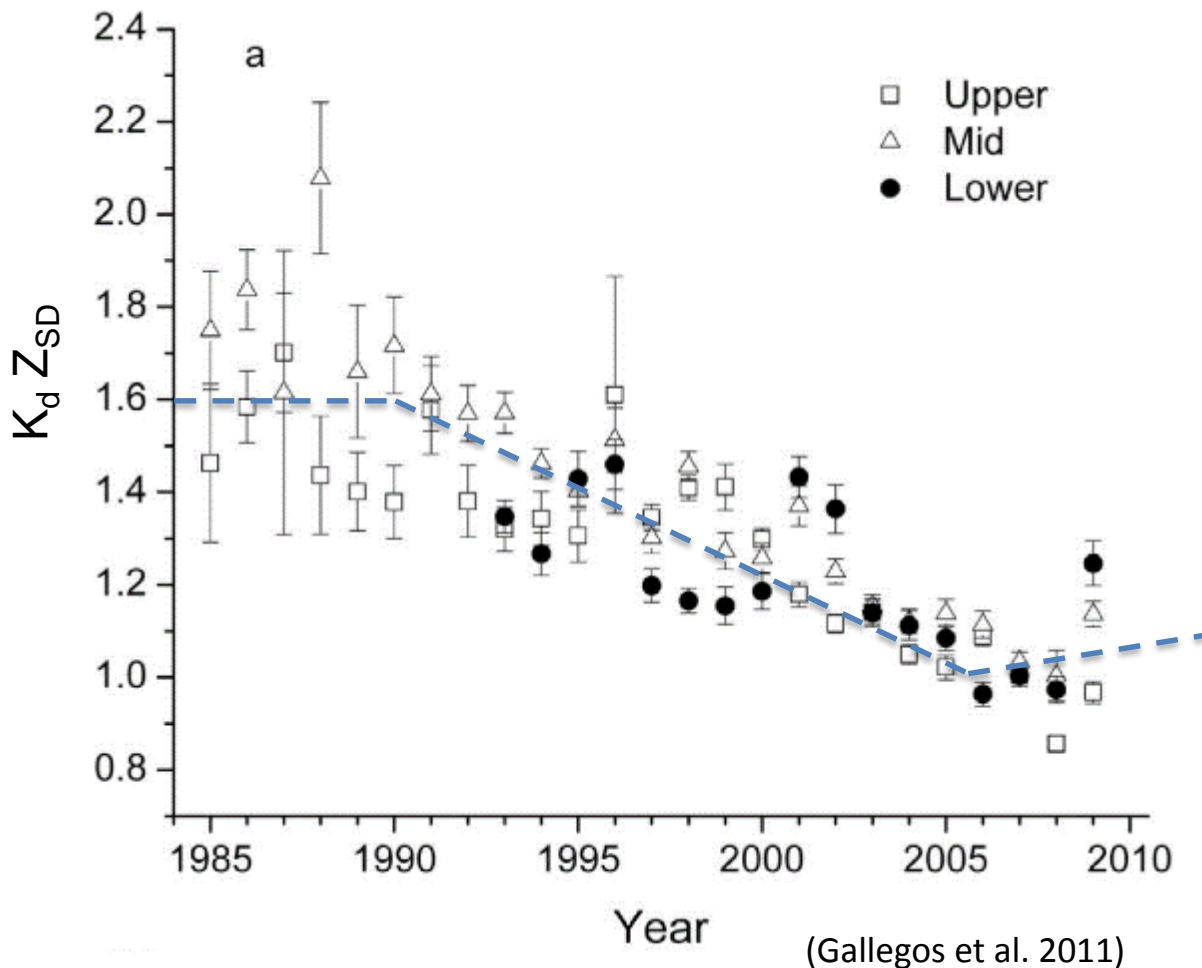
So improved K_d from 90s - 00s seems inconsistent with Secchi worsening.

The product of K_d times Secchi depth (i.e., $K_d Z_{SD}$) decreased from 1990-2005 (Gallegos et al. 2011). This is optically consistent with an increased abundance of small organic particles and fewer small inorganic particles.

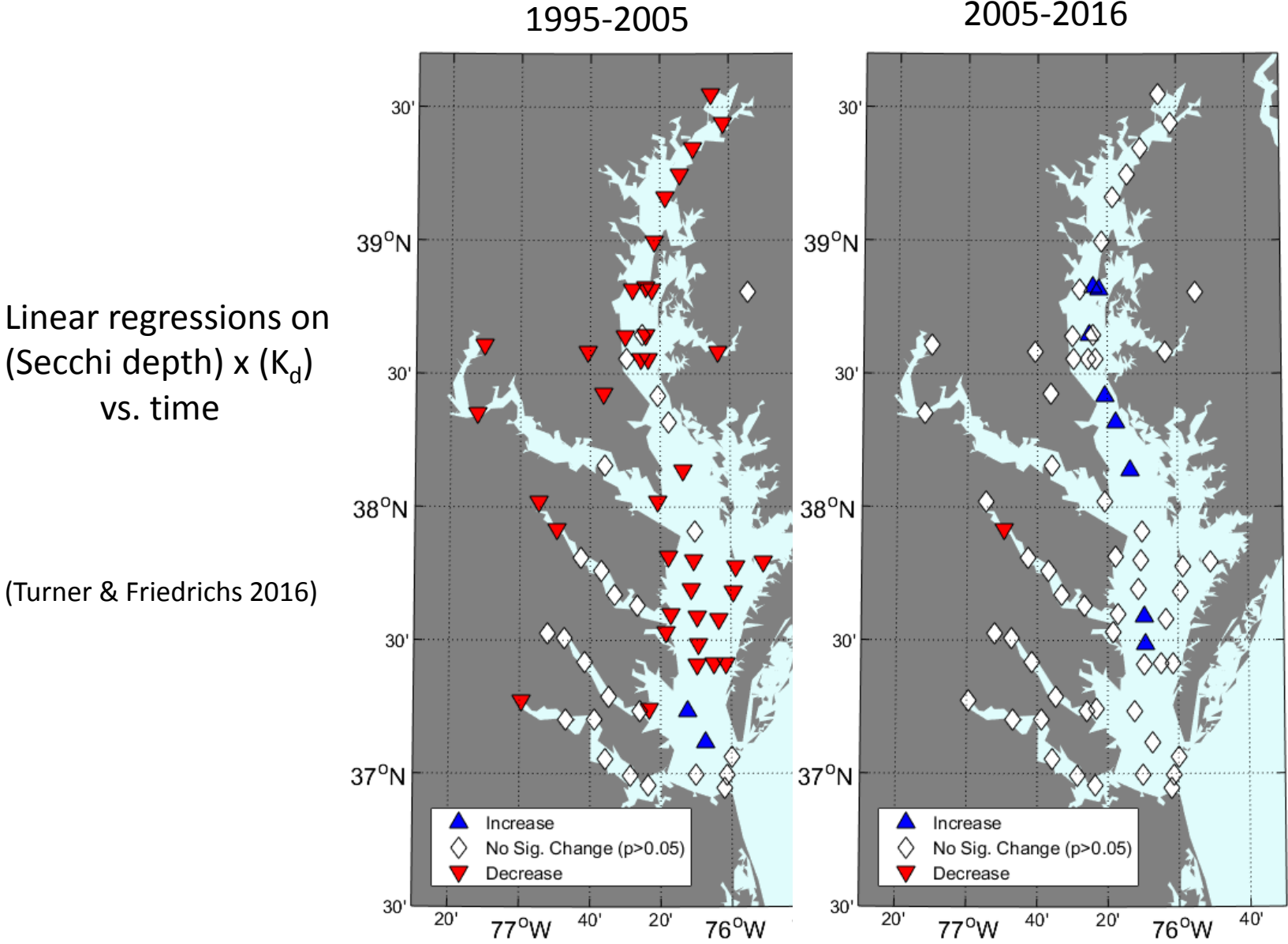
From ~ 1985 to 1990 $K_d Z_{SD}$ fluctuated around ~ 1.6

From ~ 1990 to 2005 $K_d Z_{SD}$ decreased from ~ 1.6 to ~1.1

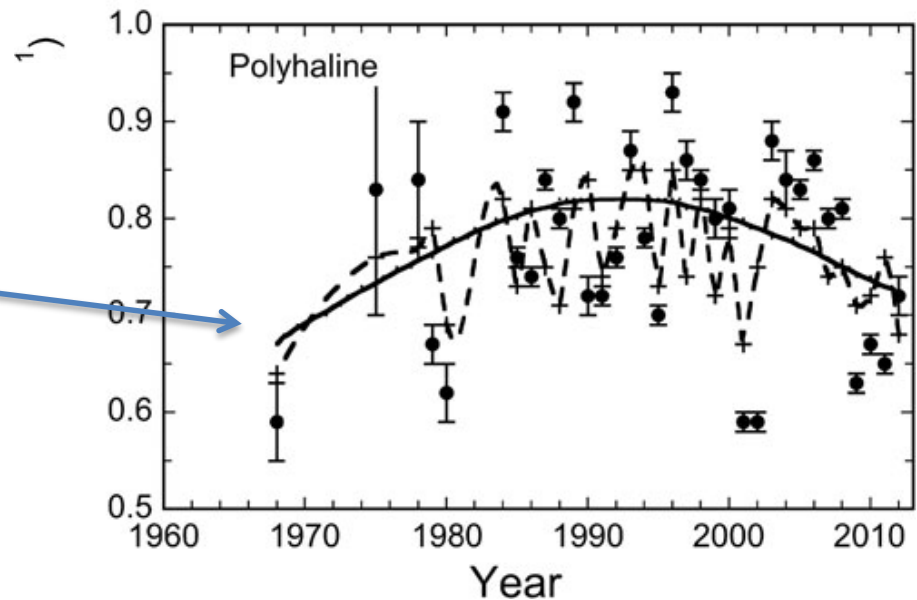
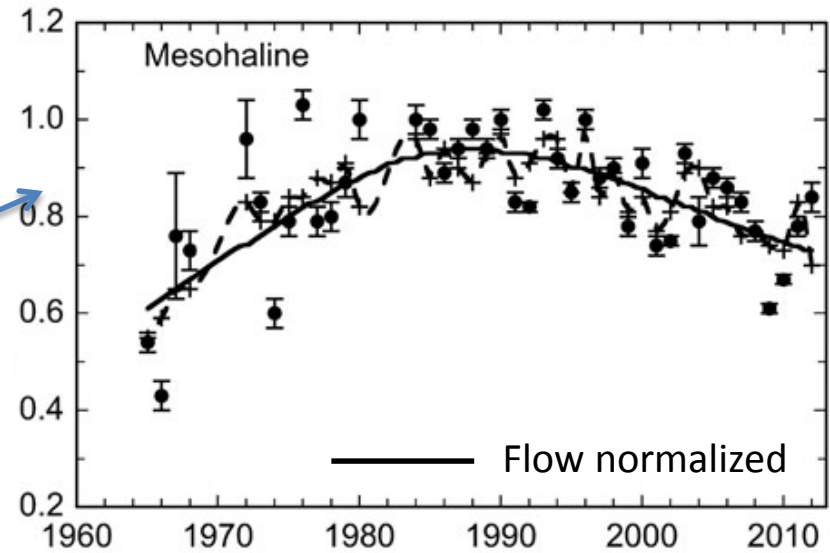
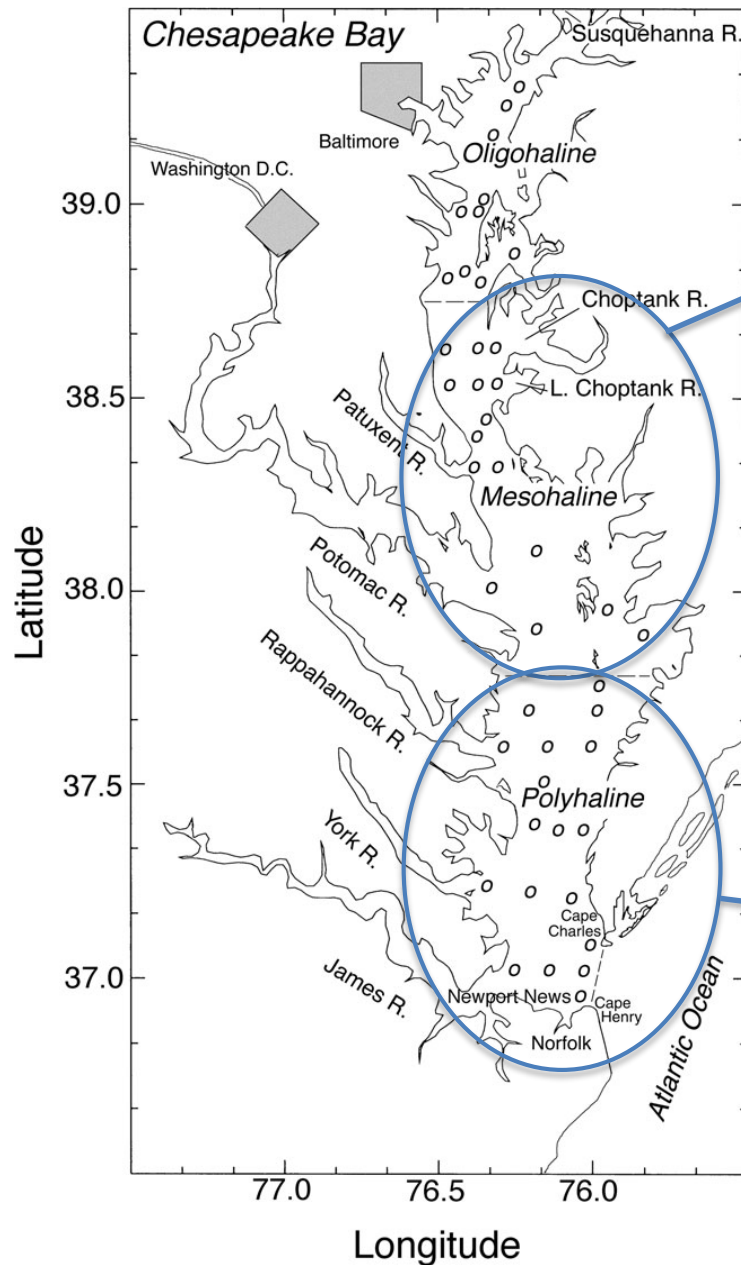
From ~ 2005 to today $K_d Z_{SD}$ has increased slightly



Results of linear regressions in time applied to (Secchi depth) x (K_d) data suggest that the trend in (Secchi depth) x (K_d) changed around 2005



Harding et al. (2016) used the trend in $K_d Z_{SD}$ from Gallegos (2011) to estimate changes in K_d in time:

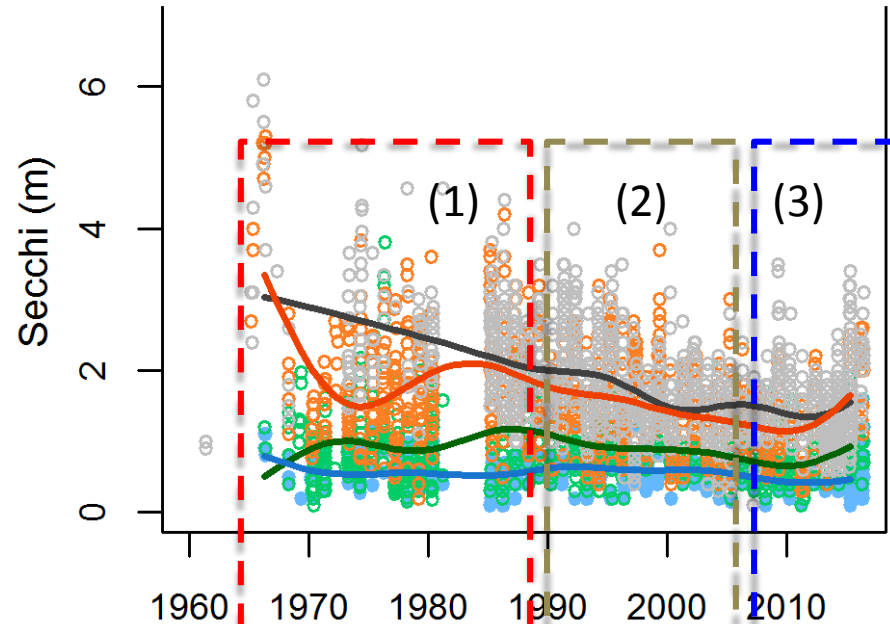


Long-term trends in Main Stem clarity in terms of (a) Secchi depth and (b) K_d

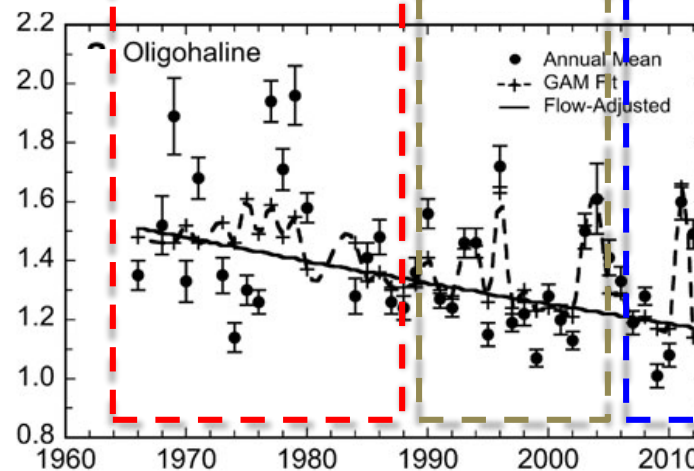
(1) Clarity degrading
(Secchi worse, K_d worse)

(2) Clarity changing
(Secchi worse, K_d better)

(3) Clarity improving
(Secchi better, K_d better)



(Keisman & Murphy 2017)

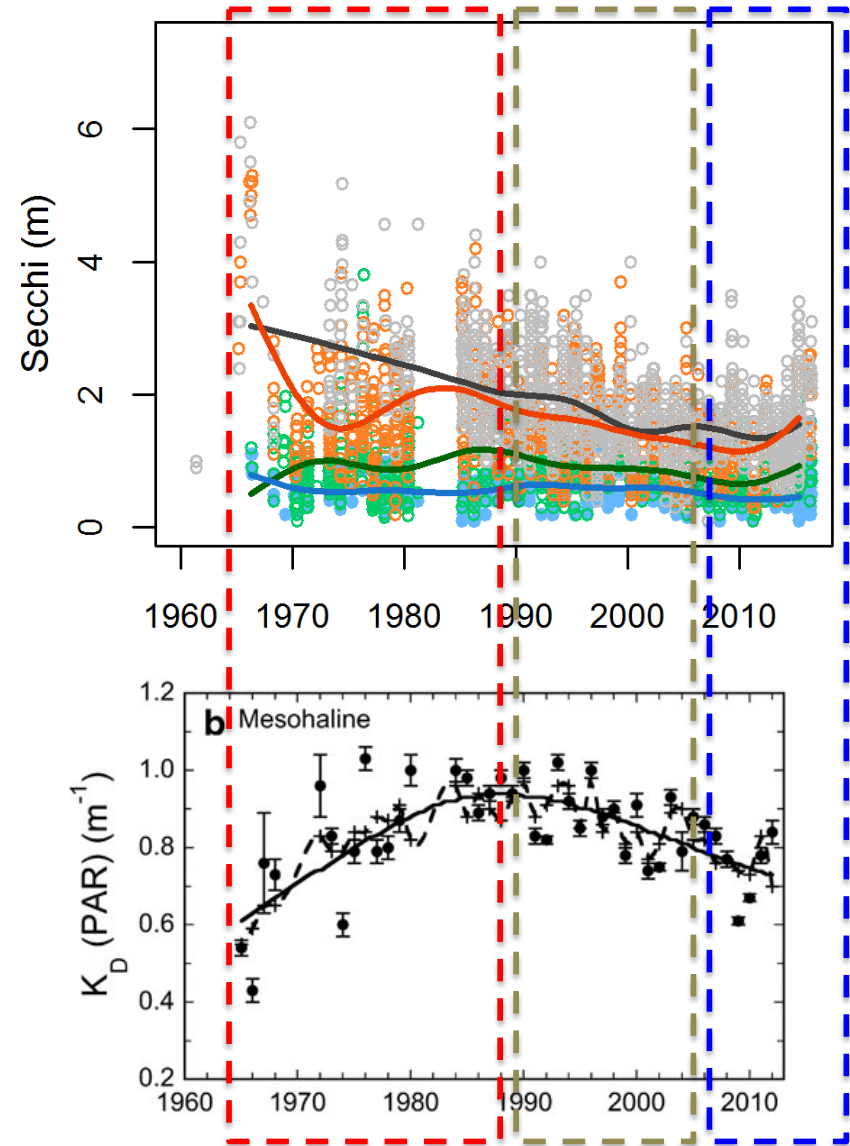
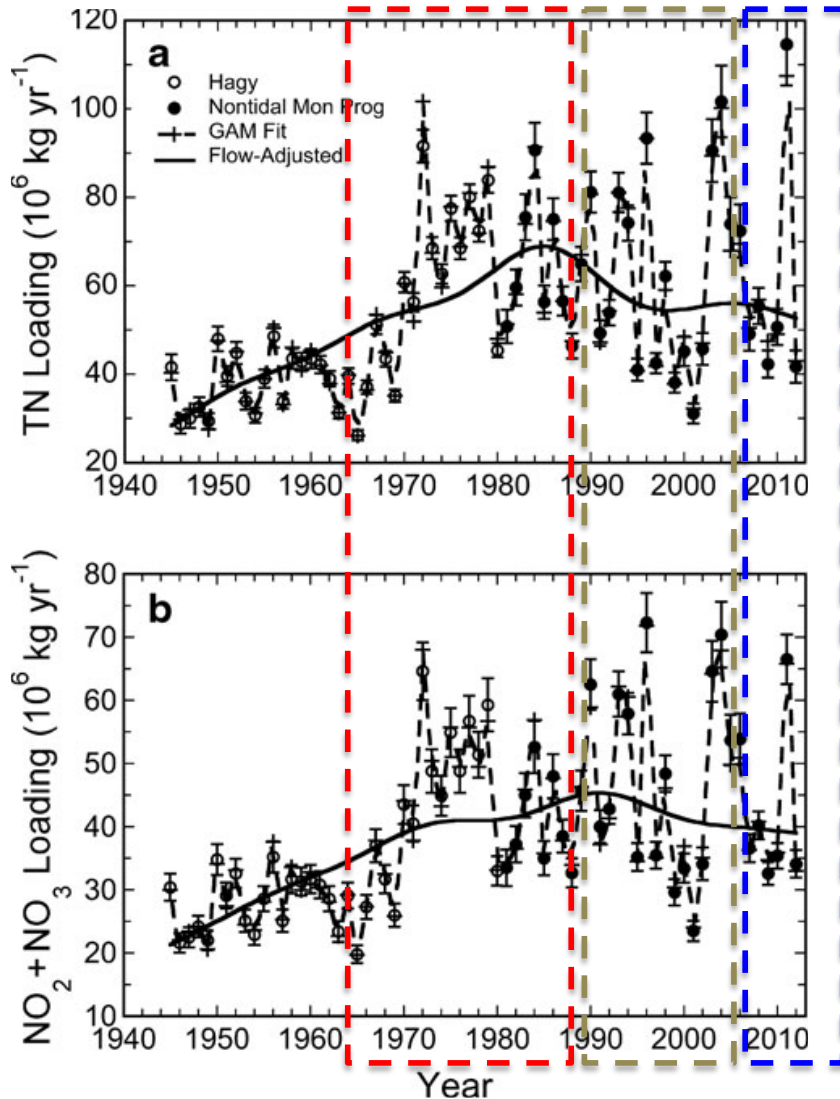


(Harding et al. 2016)

Question 4: What caused these long-term trends in water clarity?

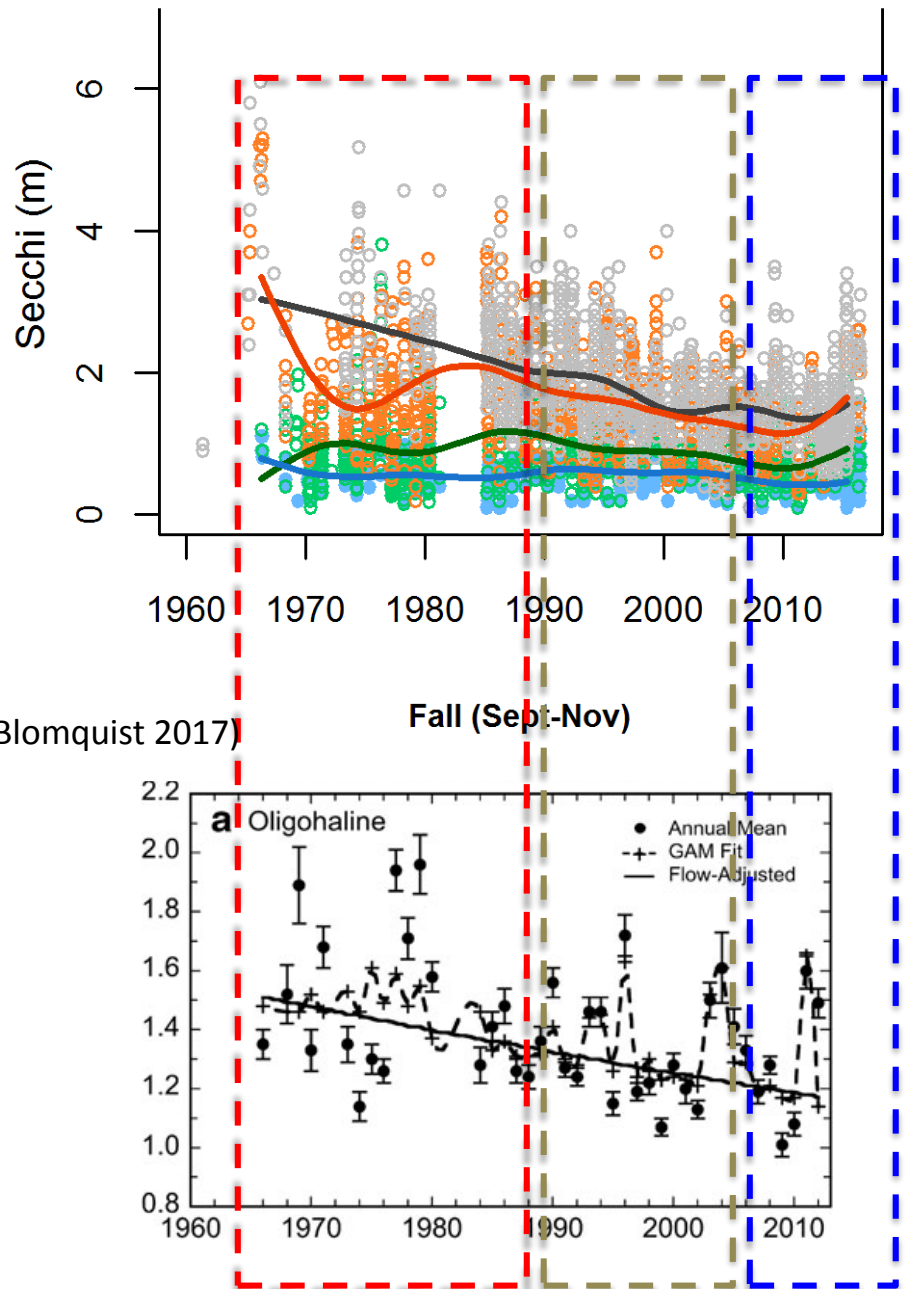
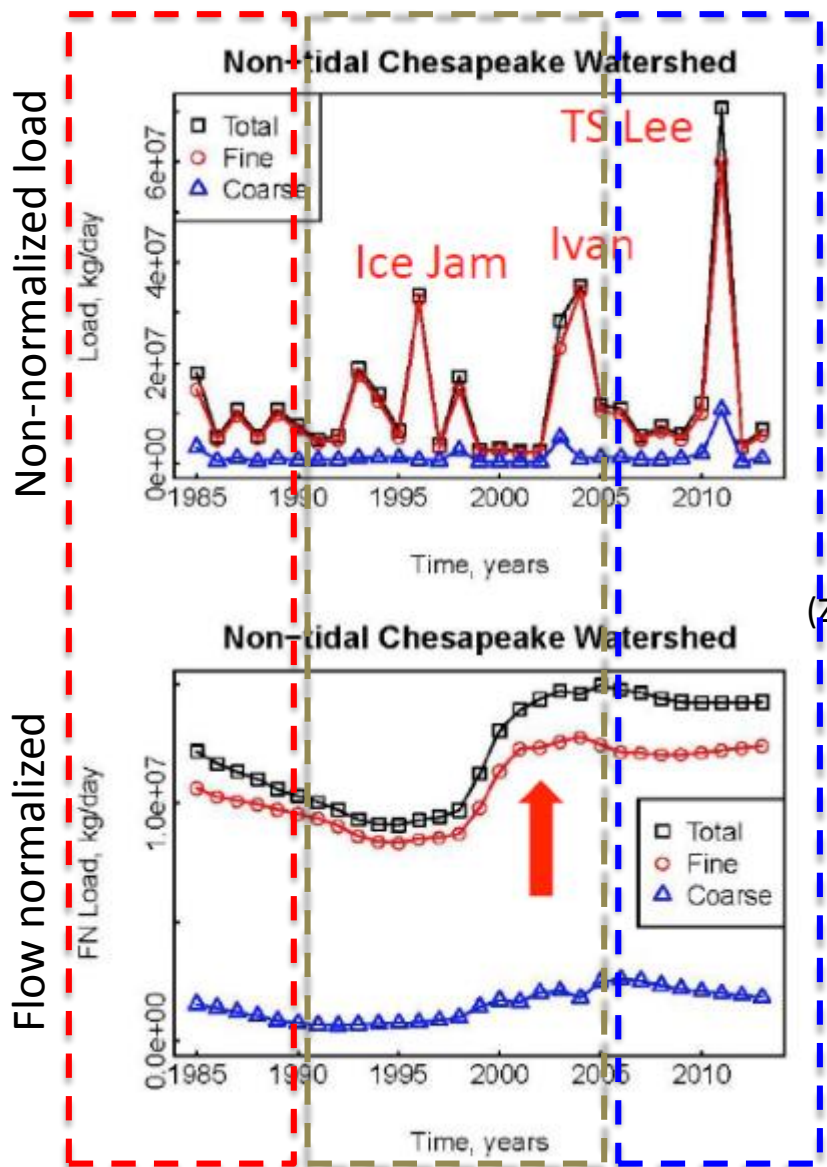
Are nitrogen trends an obvious driver of Bay-wide clarity?

Spring (Mar-May)



Degrading Secchi and K_D follow nitrogen loading through 1990. Pattern after that is complicated.

Are trends in river sediment loading an obvious driver of Bay-wide clarity?

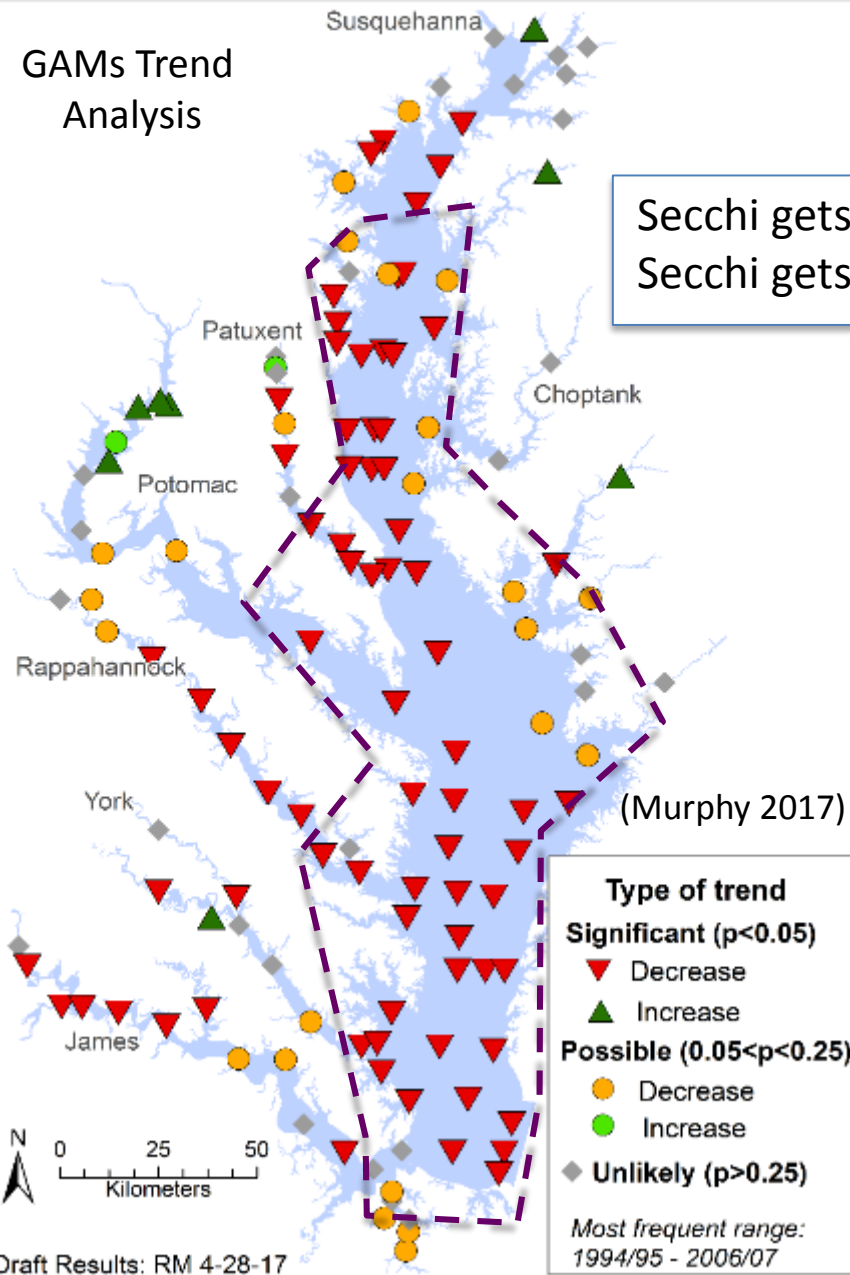


(Zhang & Blomquist 2017)

Water quality trends are opposite to that expected from the flow normalized trends in suspended sediment load from the Susquehanna (and from all rivers if combined).

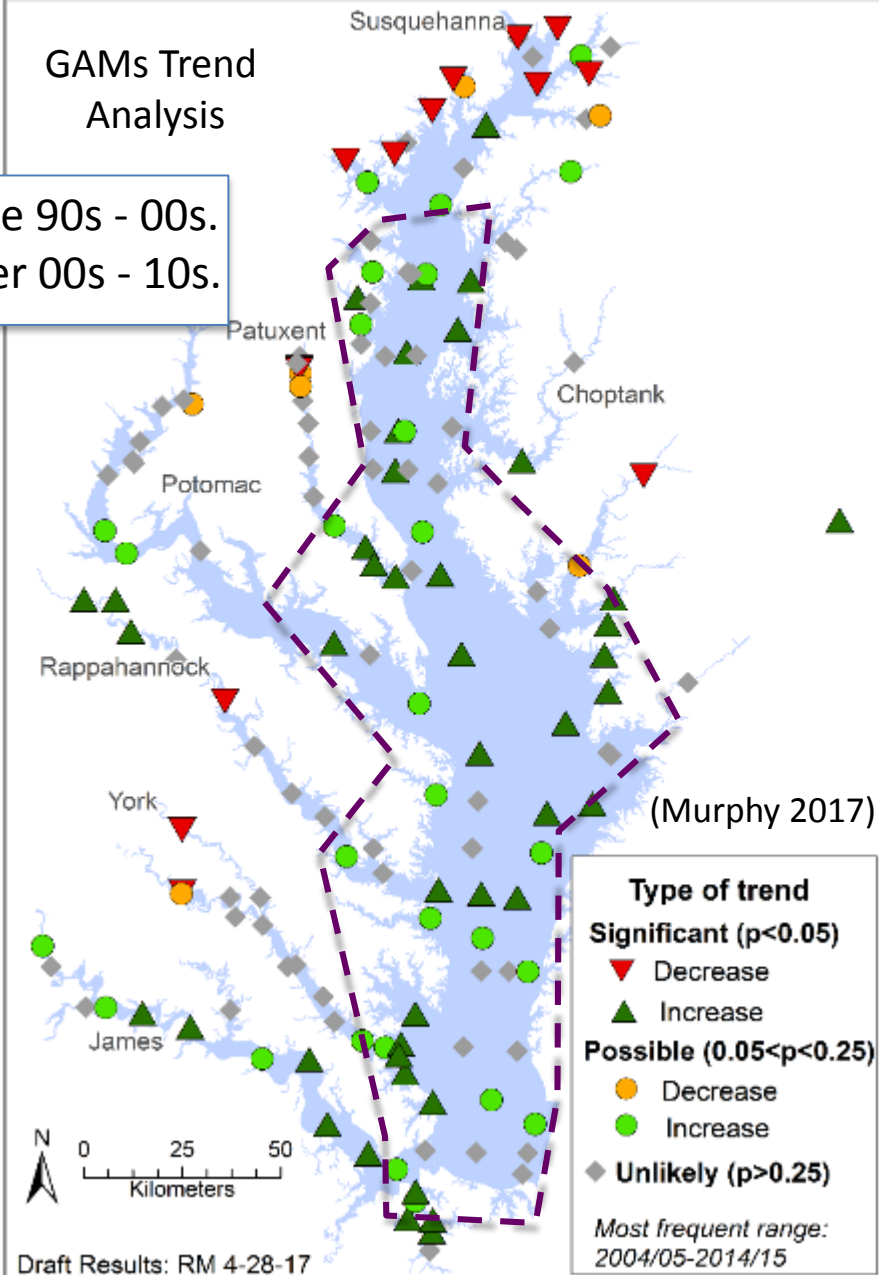
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GAMs Trend Analysis



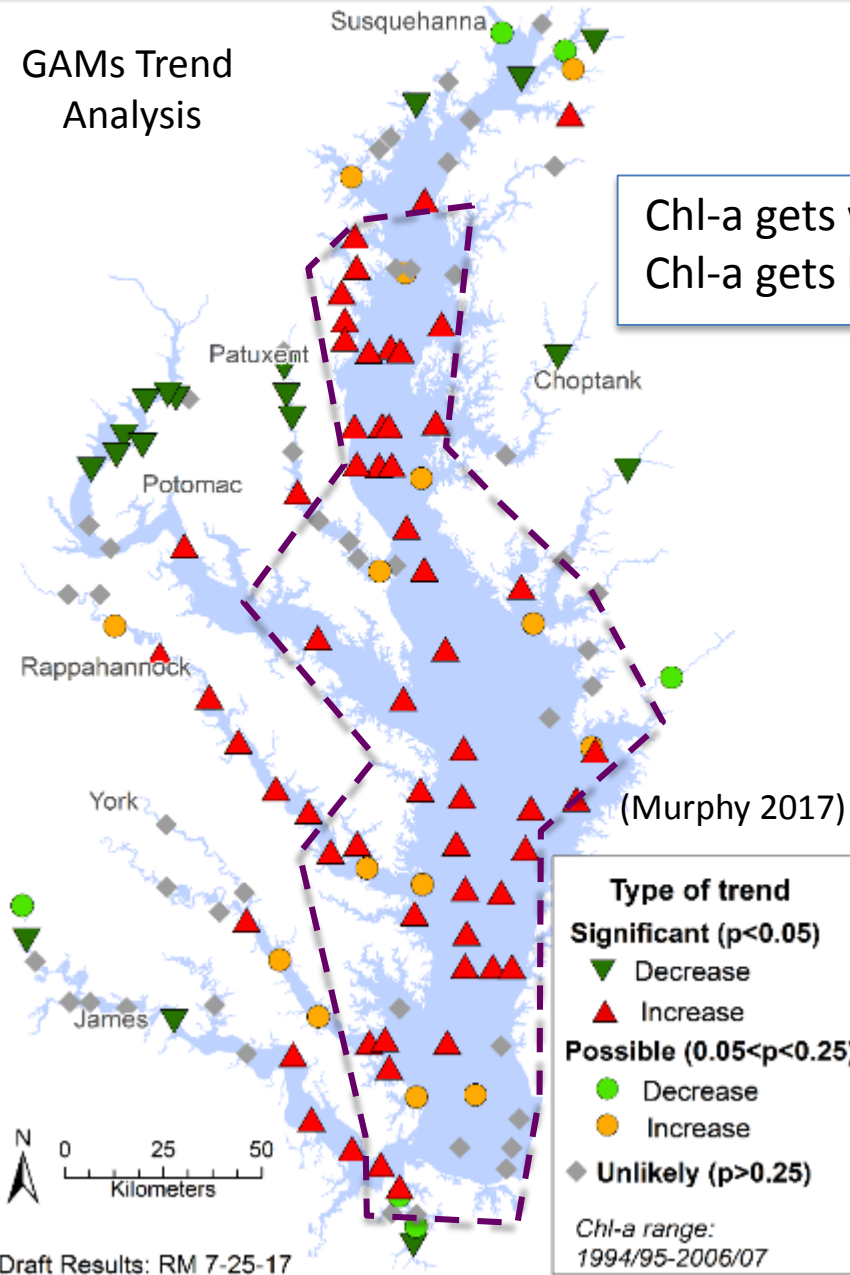
Apr-Oct: Trends for Secchi where sampled in recent ~10 years from mid-2000s to mid-2010s

GAMs Trend Analysis



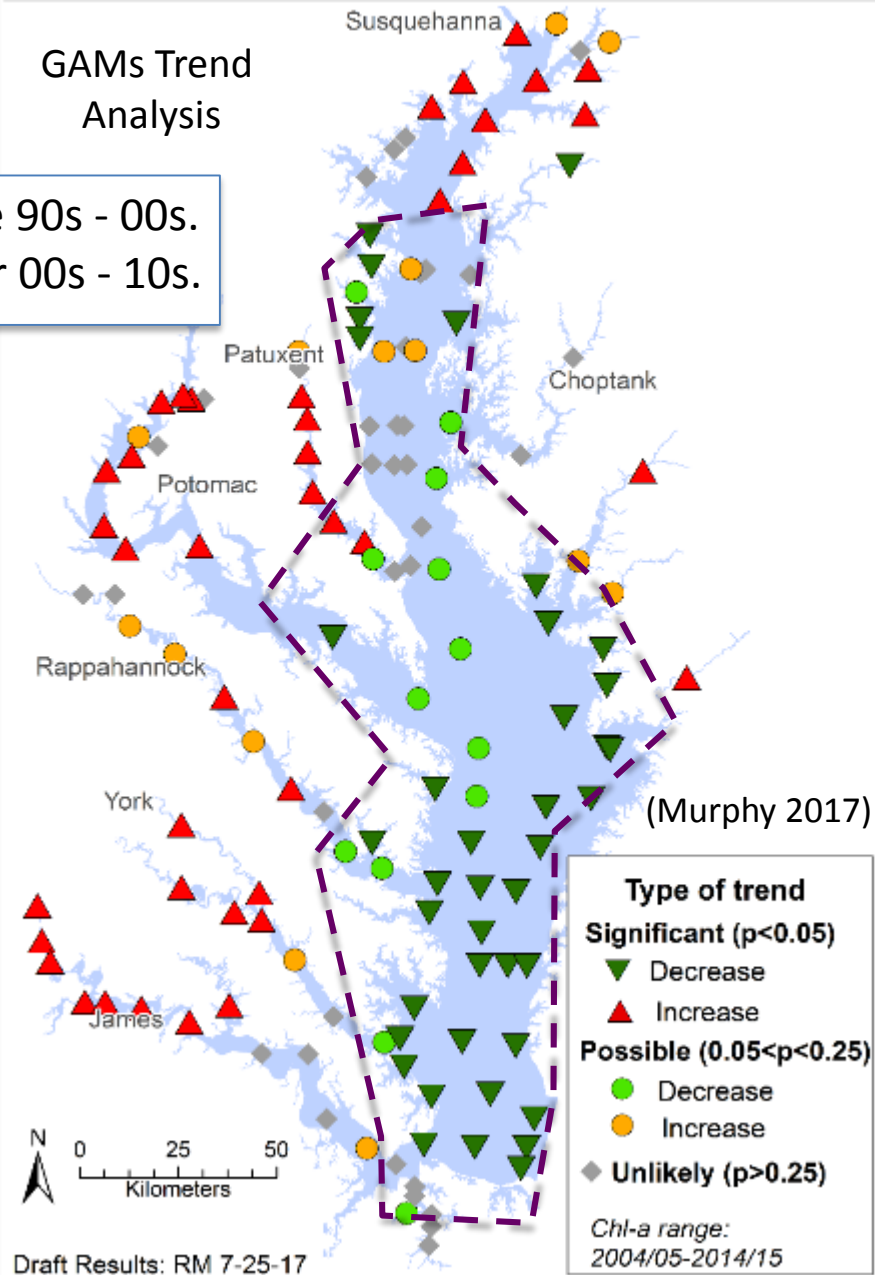
Apr-Oct: Trends for surface Chlorophyll-a in ~10 years from mid-1990s to mid-2000s

GAMs Trend Analysis



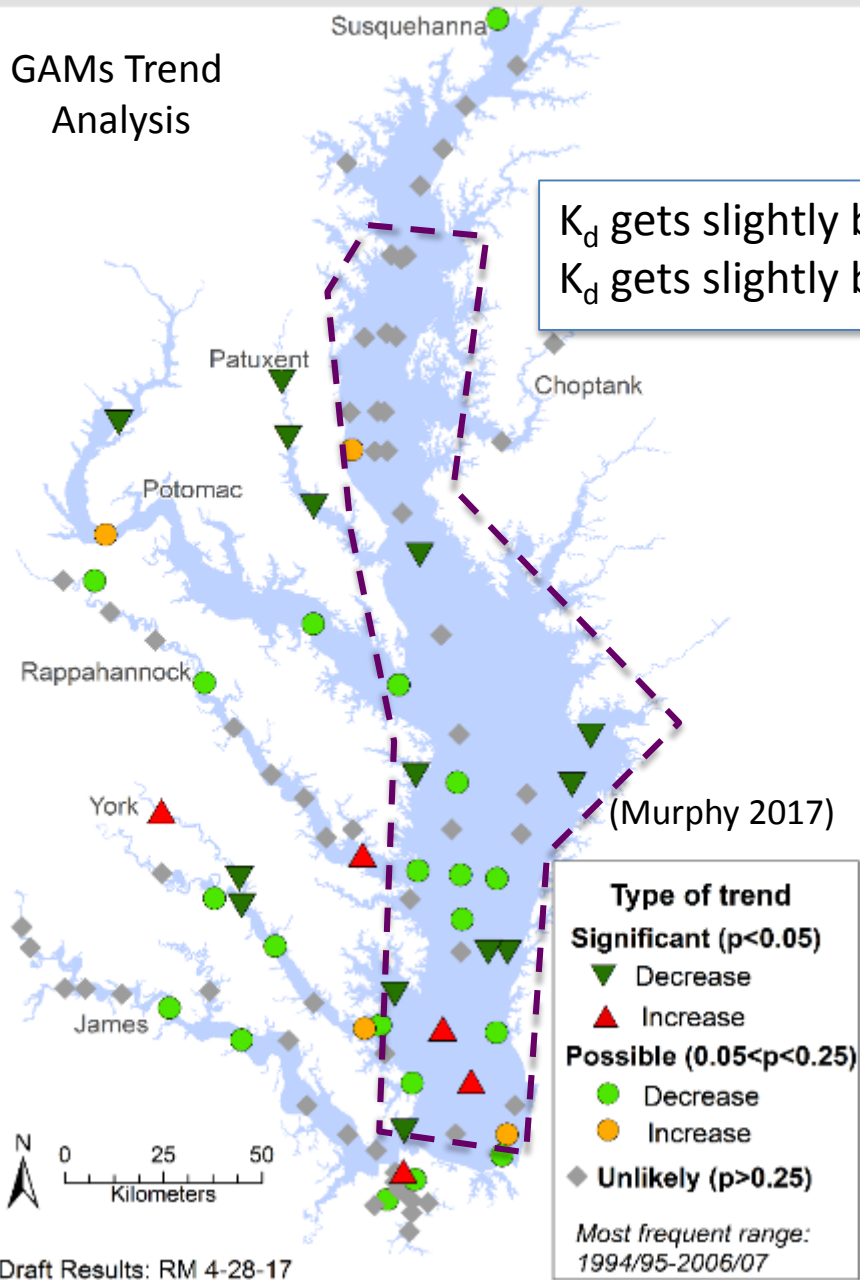
Apr-Oct: Trends for surface Chlorophyll-a in ~10 years from mid-2000s to mid-2010s

GAMs Trend Analysis



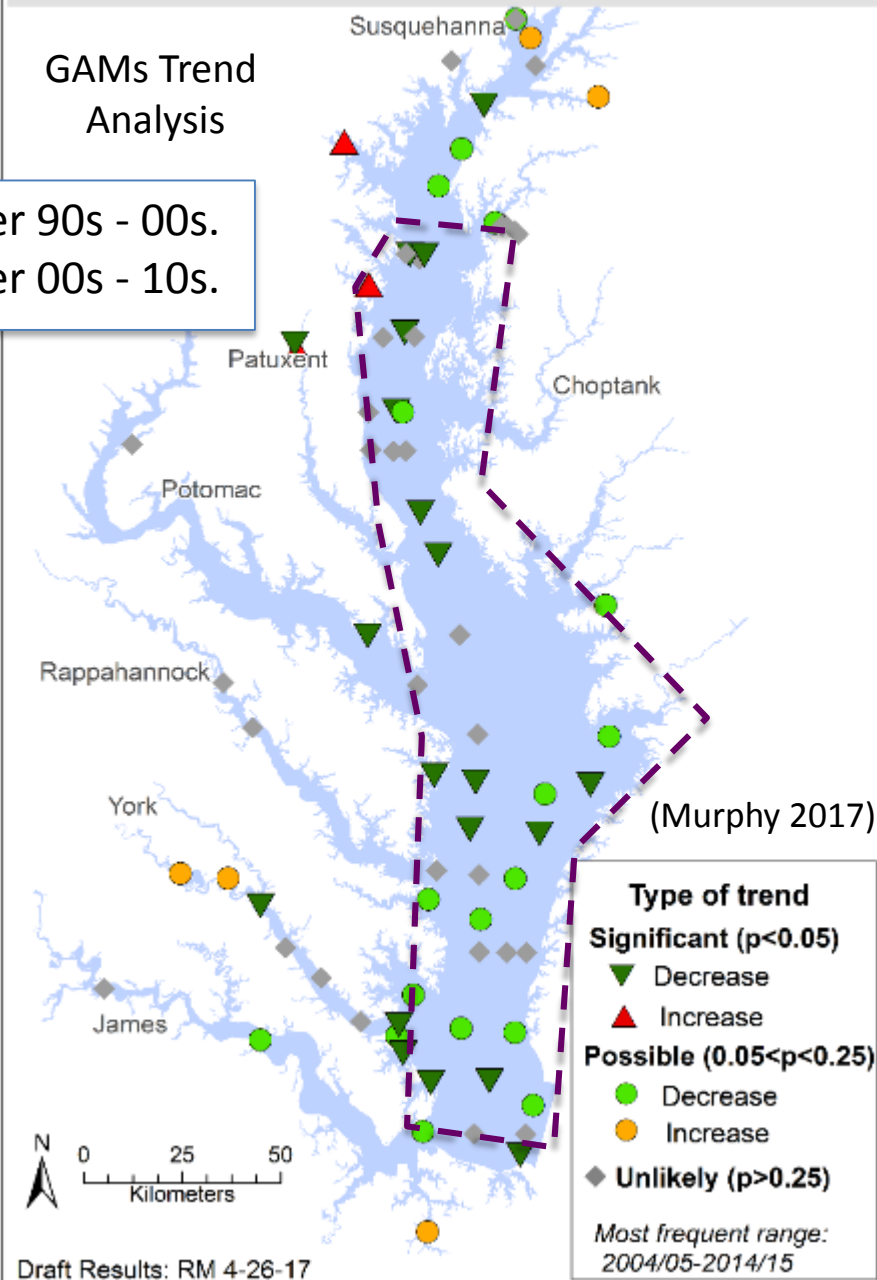
**Apr-Oct: Trends for kd where sampled
in ~10 years from mid-1990s to mid-2000s**

GAMs Trend
Analysis



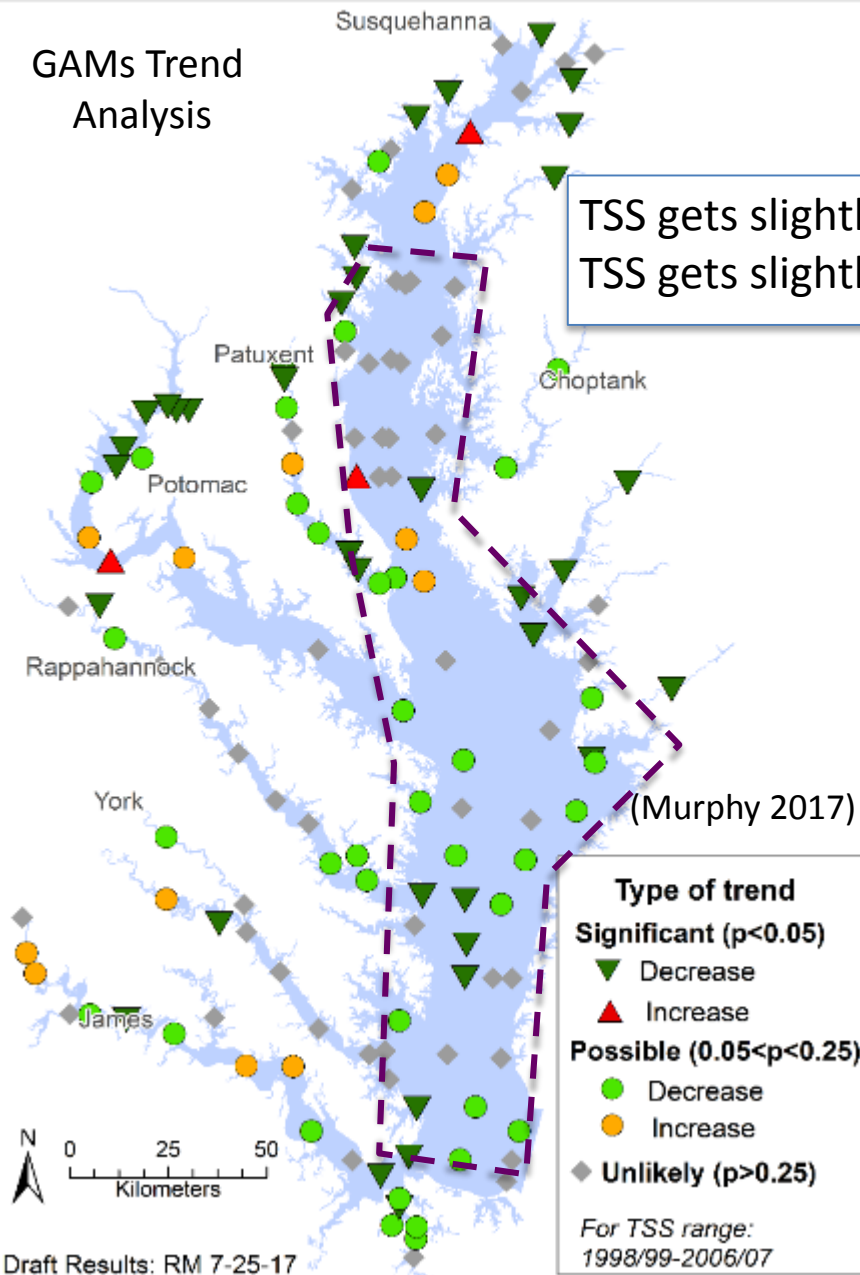
**Apr-Oct: Trends for kd where sampled
in recent ~10 years from mid-2000s to mid-2010s**

GAMs Trend
Analysis



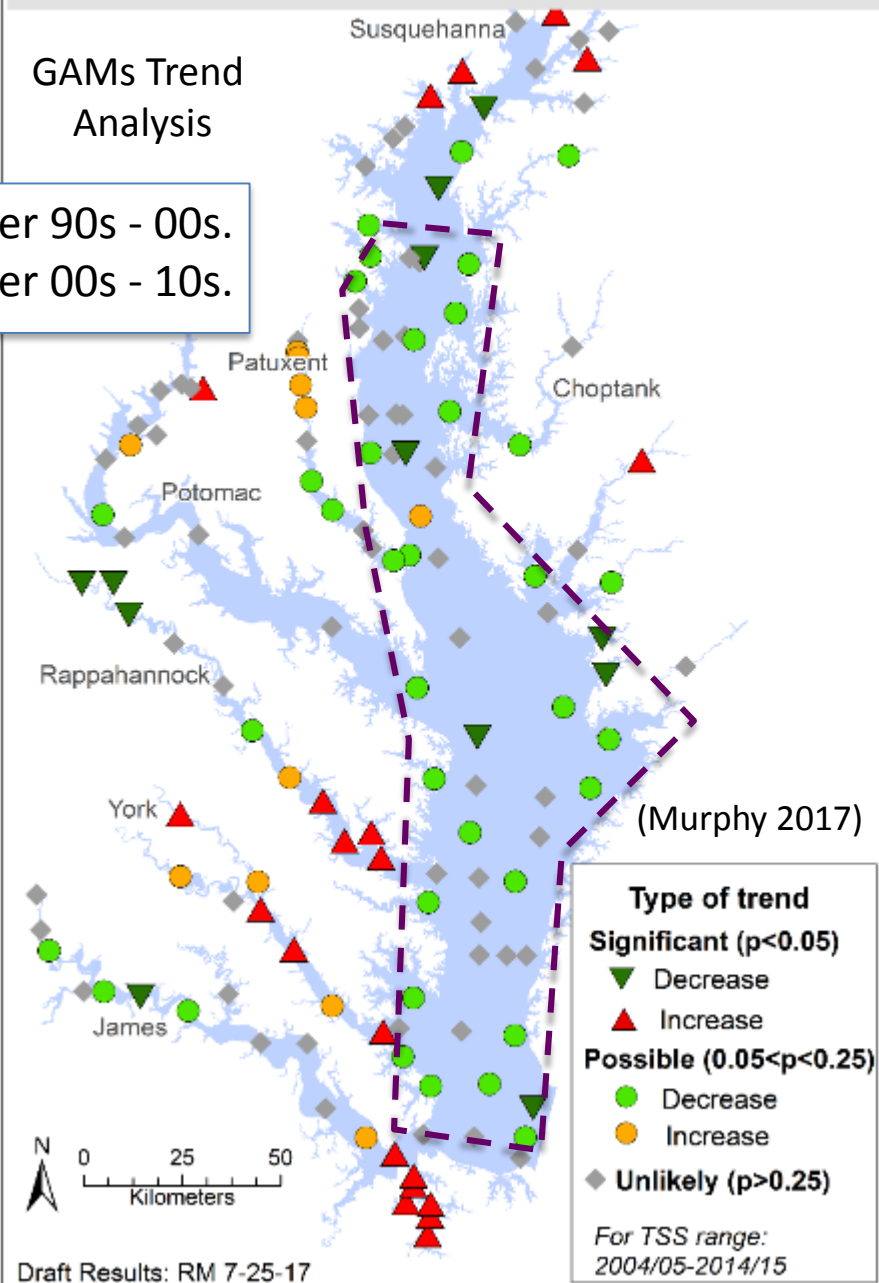
**Apr-Oct: Trends for surface TSS
in ~10 years from late-1990s to mid-2000s**

GAMs Trend
Analysis



**Apr-Oct: Trends for surface TSS
in ~10 years from mid-2000s to mid-2010s**

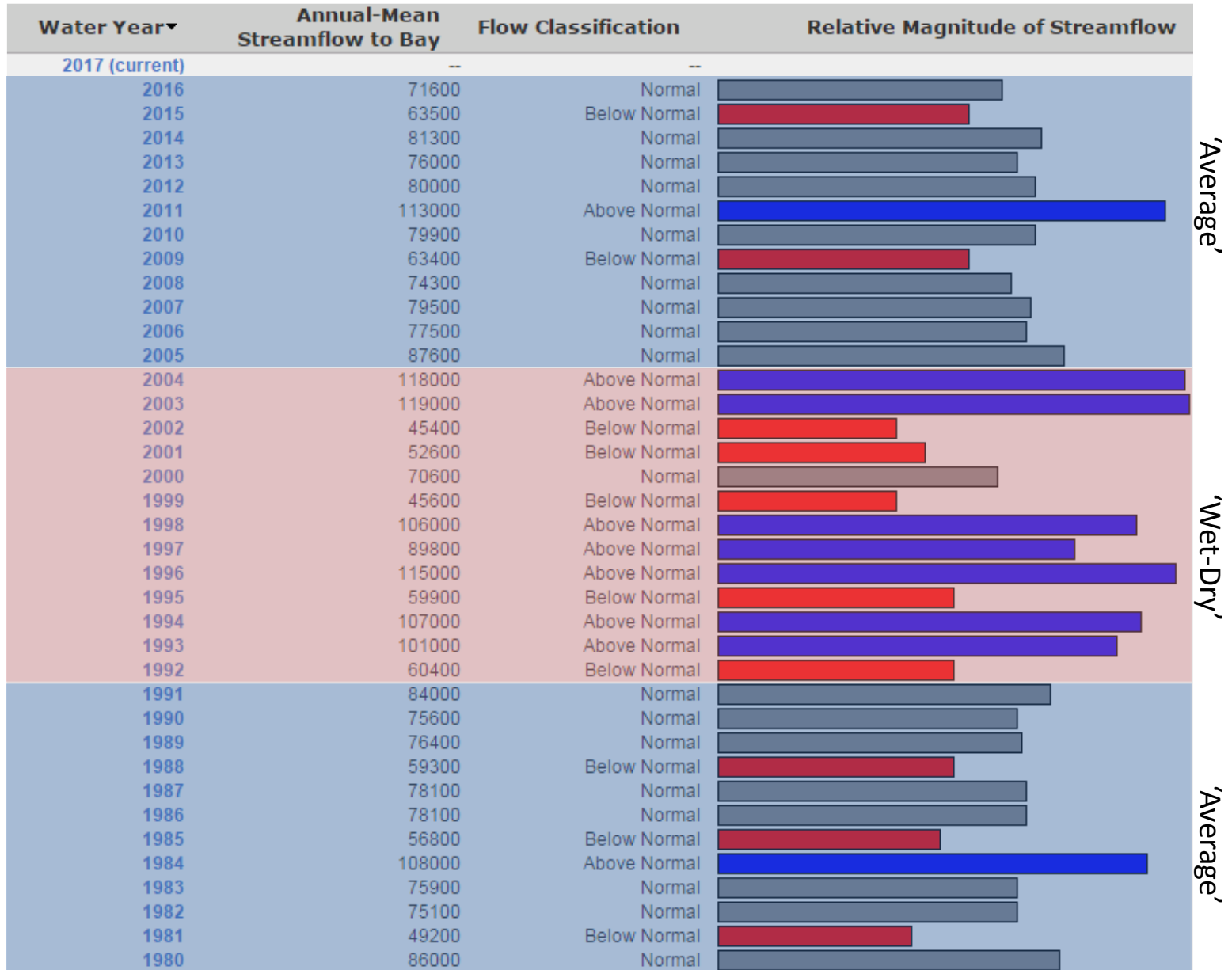
GAMs Trend
Analysis



TSS gets slightly better 90s - 00s.
TSS gets slightly better 00s - 10s.

What's driving recent decadal trends in constituents in water and therefore water clarity?

(Testa 2017)



Some Summary Points: (Apologies again for not incorporating shallow water benthics yet!)

Unambiguously improving (or degrading) clarity should mean both K_d and Secchi are improving (or degrading). Both measures are important.

Increased salinity and lower TSS in time and space are unambiguously associated with clearer water.

Secchi is more sensitive to small organic particles (which, in turn, are correlated to Chl). K_d is more sensitive to overall TSS. But TSS \neq riverine sediment.

Patterns of water clarity are distinctly different in the upper Tidal Tributaries/ETMs relative to the open waters of the Main Stem because of differences in overall inorganic TSS concentration and fraction of organics vs. inorganics.

Riverine sediment loads affect clarity in Tidal Tribs/ETM region, but not in the central/lower main stem.

Some Summary Points:

Water clarity in the main stem degraded from pre-1960 to ~1990 (both K_d and Secchi got worse).

The nature of water clarity changed from ~1990 to ~2005. The water got less transparent (i.e., cloudier, Secchi got worse), but light attenuation decreased (K_d got better).

Optical modeling suggests that a combination of reduced inorganic fine sediment plus increased organic fine sediment are the culprit.

Water clarity has improved since ~ 2005 (both K_d and Secchi have gotten better). This may be because of fewer intensely wet years.

Nutrients associated with land use and wet/dry year frequency have driven Secchi trends in main stem.

But why is TSS decreasing in the main stem? Shoreline armoring? Lots more work to do on water clarity synthesis!!