Examination of Observed Chlorophyll Concentration and Temperature in Chesapeake Bay and Tributaries

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Executive Summary

This report examines surface chlorophyll concentration as a function of temperature observed at multiple sites in Chesapeake Bay and tributaries. Data bases examined include the Chesapeake Bay Program monitoring data, the Maryland DNR “Eyes on the Bay” program and the “Virginia Estuarine Coastal Observing System.” The investigation is conducted to provide guidance in assigning algal growth parameters for predictive models employed in climate-change scenarios. In particular, the investigation is aimed at determining whether algal production rate should be extended indefinitely as a function of temperature or if there is a maximum temperature above which algal production declines.

Part I of this report is a visual examination of observations. Various behaviors are observed at the large number of stations examined. The predominant behavior, however, indicates chlorophyll concentration reaches a maximum at 31C^{o} – 32C^{o} and levels off or declines thereafter. There is no indication that chlorophyll concentration increases indefinitely and universally as temperature increases.

Part II of this report applies a statistical analysis to observations at twenty stations with sufficient data for the analysis. Quantile regression, rather than ordinary least-squares regression, is employed to examine chlorophyll concentration as a function of temperature. Quantile regression can be employed to examine extreme behavior in observations rather than average behavior, as in least squares regression. In this case, two regressions are conducted. The first considers the median of the dependent variable (chlorophyll) scaled over temperature. The second considers the 90th percentile of chlorophyll scaled over temperature. Observations at each location are divided into two subsets: below 32C^{o} and above 32C^{o}, consistent with the breakpoint recommended in Part I. Two regressions at twenty stations provide forty individual analyses in each subset. Thirty-one of the forty analyses at temperatures below 32C^{o} indicate a positive relationship of chlorophyll to temperature. This is expected behavior. Thirty-one of the forty analyses at temperatures above 32C^{o} indicate that chlorophyll declines or levels off as temperature increases. These analyses reinforce the conclusion from Part I that chlorophyll observations do not increase indefinitely and universally as temperature increases.

Part I – Observed Chlorophyll Concentrations vs. Temperature

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Introduction

Eutrophication models commonly require a set of parameters which relate algal production to temperature. The parameters and their values depend on the specific formulations employed in each model. Parameter values are usually obtained by fitting the model results to observed primary production rates and chlorophyll concentrations. The 2017 version of the Chesapeake Bay Environmental Model Package (CBEMP, Cerco and Noel, 2019) employs a relationship (Figure 1) in which production increases up to an optimal temperature and decreases thereafter:

$$f(T) = e^{-KTg1 \cdot (T - Topt)^2} \quad when \quad T \leq Topt$$
$$= e^{-KTg2 \cdot (Topt - T)^2} \quad when \quad T > Topt \qquad (1)$$

where:

T = temperature (°C)
Topt = optimal temperature for algal production (°C)
KTg1 = effect of temperature below Topt on production ($°C^{-2}$)
KTg2 = effect of temperature above Topt on production ($°C^{-2}$)

The original model parameter set employed a value of 25°C as the optimal temperature for the dominant summer algal group. Production was held at a constant value for temperatures above 25°C. During the model application, the need to apply the model to climate-change scenarios became apparent. The climate-change scenarios involved temperatures up to ≈32°C. Consequently, the original parameter set was replaced with a set which extrapolated the original production vs. temperature relationship so that production increased at temperatures beyond the previous optimal temperatures of 25°C to 29°C (Figure 2).

The revised parameter set was controversial, largely because of the parameter values which were required to obtain a smooth transition from the original production vs. temperature relationship to the revised relationship. The present transition to a new generation of Bay models (Hood et al., 2019) provides the opportunity to revisit the parameterization of the production vs. temperature relationship, especially at higher temperatures. The effort described here involves the examination of existing chlorophyll and temperature data for insight into model parameterization at extreme temperatures exceeding 30°C.

Data Bases

Maryland "Eyes on the Bay"

The "Eyes on the Bay" (EOB) program (Maryland DNR, 2024) is an extensive monitoring program operated by the Maryland Department of Natural Resources (DNR). The program includes continuous monitoring (15-minute intervals) of multiple water quality properties including salinity, temperature, and fluorescence. Numerous stations have been monitored over multi-year periods. Seven locations (Figure 3) were selected for analysis, to provide spatial distribution and a range of conditions. Monitoring periods varied at each station within the interval from 2004 to 2022. Data reported here includes surface chlorophyll (derived from fluorescence) and surface temperature.

Virginia Estuarine and Coastal Observing System (VECOS)

VECOS is a website (VIMS, 2024) intended to distribute water quality data collected from Chesapeake Bay and associated tributaries within Virginia. Available data includes continuous monitoring (15-minute intervals) of water quality taken from fixed, shallow-water monitoring stations. Multiple reported parameters include salinity, chlorophyll (converted from fluorescence), and water temperature. Seven locations (Figure 4) were selected for analysis, to provide spatial distribution and a range of conditions. Observations were available largely from 2006 to 2009. Data reported here includes surface chlorophyll (derived from fluorescence) and surface temperature.

Chesapeake Bay Program (CBP) Water Quality Data

The CBP operates an extensive water quality monitoring program (Chesapeake Bay Program, 1993). The program includes discrete sampling (≈20 per annum) of water quality at multiple stations. Observations analyzed here include surface chlorophyll concentrations and water temperature. Thirteen stations were selected for examination (Figure 5). These were selected to characterize regimes including "tidal freshwater" (TF), "lower estuary" (LE), and "Chesapeake Bay" (CB). Data analyzed covered the interval 1985-2014.

Analysis at Individual Stations

"Eyes on the Bay" Data

EOB data were examined as individual observations, collected at 15-minute intervals, and as daily averages. Plots of chlorophyll vs. temperature are presented here for three stations: Possum Point (Figure 6), Piscataway (Figure 7), and Otter Point (Figure 8). Figures for the remaining stations are presented in the appendix. Discrete chlorophyll observations at both Otter Point and Possum Point indicate concentration declines when temperature exceeds ≈32°C. Discrete chlorophyll observations at Piscataway decline almost uniformly at temperatures above ≈25°C.

Peak daily-average temperature at all stations is less than peak temperature in the discrete observations, suggesting a diurnal temperature cycle. Results at Otter Point and Piscataway echo the discrete data. At Otter Point, daily-average chlorophyll declines when daily-average temperature exceeds ≈32°C. At Piscataway, daily-average chlorophyll declines uniformly for daily-average temperature above ≈25°C. Results at Possum Point are difficult to interpret although daily-average chlorophyll concentrations at the highest temperatures, ≈33°C, are lower than the highest observations at lower temperatures.

"Virginia Estuarine and Coastal Observing System" Data

VECOS data were examined as individual observations, collected at 15-minute intervals, and as daily averages. Plots of chlorophyll vs. temperature are presented here for three stations: Nomini Bay (Figure 9), Osborne Landing (Figure 10), and Ashland (Figure 11). Figures for the remaining stations are presented in the appendix. At Nomini Bay, maximum individual chlorophyll observations occur between ≈25°C to 27°C. Maximum concentrations clearly decline at temperatures above this range. At Osborne Landing, maximum concentrations show two peaks, one at ≈30°C and the second at ≈33°C. Maximum concentrations clearly decline when temperature exceeds ≈33°C. Ashland exhibits maximum chlorophyll concentrations between ≈24°C to 28°C with maximum values trending downwards at higher temperatures.

As with the EOB data, maximum daily-average temperature at each station is less than the maximum individual temperature observations at the same station. When daily averages are taken, all three stations demonstrate an interesting characteristic: minimum daily-average chlorophyll concentrations are greater than individual minima and suggest an apparent continuous increase with temperature above ≈20°C. The increase in minimum concentrations promotes the appearance of indefinite increasing chlorophyll concentration with temperature although examination of maximum daily-average values indicates trends consistent with the individual observations. Maximum concentrations occur at less than maximum temperatures and decline as temperature approaches the maximum value. At Nomini Bay, the greatest daily-average chlorophyll concentrations occur circa 25°C. The temperature of peak chlorophyll concentration is higher, ≈30°C, at Ashland and ≈32°C at Osborne Landing.

Chesapeake Bay Program Water Quality Data

The CBP data was examined as individual observations collected at bi-weekly to monthly intervals. No daily averages could be calculated from these discrete observations. Plots of chlorophyll vs. temperature are presented here for three stations: TF2.3 (Figure 12), LE3.1 (Figure 13), and CB3.3C (Figure 14). Figures for the remaining stations are presented in the appendix. The selected stations illustrate the difficulties encountered in interpreting the Bay Program monitoring data. The intervals between observations are relatively large, and few observations exist at the highest temperatures which might limit algal production.

The tidal fresh stations, as illustrated by TF2.3, are practically the only stations with multiple observations collected at greater than ≈30°C. The observations here suggest a trend in which maximum chlorophyll concentrations occur in the interval 25°C to 29°C and decline as temperature increases but one anomalous concentration, the second greatest in the record, occurs at the greatest observed temperature. Consequently, interpretation at this station is clouded. None of the temperatures in the record at LE3.1 reaches 30°C and no trend at lesser temperatures is apparent. The record at CB3.3C indicates two chlorophyll peaks, one at ≈17°C and the second from ≈25°C to ≈27°C.

Analyses at Grouped Stations

Summaries of the effect of temperature on chlorophyll were created for groups of stations including all EOB, all VECOS, all (five) TF examined, all (five) LE examined, and all (three) CB examined. Box and whisker plots were created for chlorophyll observations grouped in 1°C intervals. Daily-average chlorophyll and temperature were considered for EOB and VECOS stations. Only discrete observations were available for the CBP stations. The plots indicate the range of the chlorophyll observations, the first quartile (25%), the third quartile (75%) and the median of the observations within each temperature interval: (x,y] indicates $x < T \leq y$. Outliers are shown as individual points. The number of observations in each interval is shown across the top of the figure.

EOB Stations

Eliminating outliers, the highest observed chlorophyll concentrations at the EOB stations (Figure 15) occur at extremely low temperatures, ≈4°C to ≈8°C. Thereafter, maximum concentrations, tend to decline until the range ≈22°C to ≈25°C. Maxima are relatively uniform in the range ≈26°C to ≈31°C then drop off at higher temperatures. The behavior of the maxima at the extreme end of the temperature scale is duplicated in the median concentrations which decline at temperatures greater than 32°C.

VECOS Stations

Eliminating outliers, the highest chlorophyll concentrations at VECOS stations (Figure 16) occur in two intervals, ≈12°C to ≈15°C and ≈28°C to ≈32°C. Maximum concentrations drop off above 32°C. Median concentrations increase smoothly from ≈26°C to ≈31°C then drop off sharply.

TF Stations

Trends in maximum chlorophyll concentration at the TF stations (Figure 17) are difficult to visualize. Relatively high concentrations occur in the interval ≈19°C to ≈31°C. The maxima drop off sharply at higher temperatures although observations are scarce in this range. No trend is apparent in the median concentrations. The two greatest medians occur in the intervals 27°C to 28°C and 30°C to 31°C. As with the maxima, the median chlorophyll drops off sharply above 31°C.

LE Stations

The highest chlorophyll concentrations at the LE stations (Figure 18) occur in the range 6°C to 9°C, likely indicative of the spring phytoplankton bloom. Maxima diminish as temperature increases, reaching the lowest values in the record at 20°C to 22°C. At higher temperatures, the greatest maximum is in the interval 22°C to 23°C. Thereafter, no trend is apparent in maximum chlorophyll concentration.

Interpretation of this record is hampered by the paucity of observations at temperatures greater than 30°C and absence of observations at temperatures greater than 31°C. Trends in the EOB, VECOS, and TF observations indicate that chlorophyll concentration drops off as temperatures exceed 31°C to 32°C but there is no data to indicate that behavior is duplicated at the LE stations.

CB Stations

Interpretation of the record at the CB stations (Figure 19) is difficult. Several of the intervals with the greatest maxima occur in the range 15°C to 21°C but an interval with one of the least maxima occurs in this range also. The maxima show a smooth decline from 27°C to 30°C but the single observation in the interval 30°C to 31°C is greater than the maxima of multiple observations in the two preceding intervals. As with the LE stations, data is absent in the temperature range, $T > 31$°C, at which maximum chlorophyll concentration might decline, based on trends in other groups.

Conclusions

The results from discrete observations at individual stations show a great deal of variance. Individual stations can be found which demonstrate different patterns. There is no evidence, however, that chlorophyll concentration increases indefinitely as temperature increases. The predominant behavior is that the maximum chlorophyll concentration drops off when temperature exceeds 31°C to 32°C. The box and whisker plots, which summarize behavior over groups of stations, show this behavior clearly for the EOB, VECOS, and TF stations. Conclusions about the chlorophyll concentration at temperatures greater than 30°C cannot be specified for the LE and CB stations since observations are higher temperatures are sparse or missing. We note, however, that Bay Program climate change scenarios add roughly 2°C to existing temperature so temperature at the LE and CB stations will not exceed 32°C when the model is used in scenario mode.

Recommendations

The observed chlorophyll concentrations represent a standing stock. The standing stock can be related to the net production, growth minus respiration. The evidence suggests that net production conforms to Equation 1 with Topt ≈32°C (Figure 1). The phytoplankton model considers growth and respiration as individual functions with individual parameter sets. These parameters should be specified so that maximum growth (no light or nutrient limitations) less respiration follows the pattern of Equation 1 with Topt ≈32°C.

References

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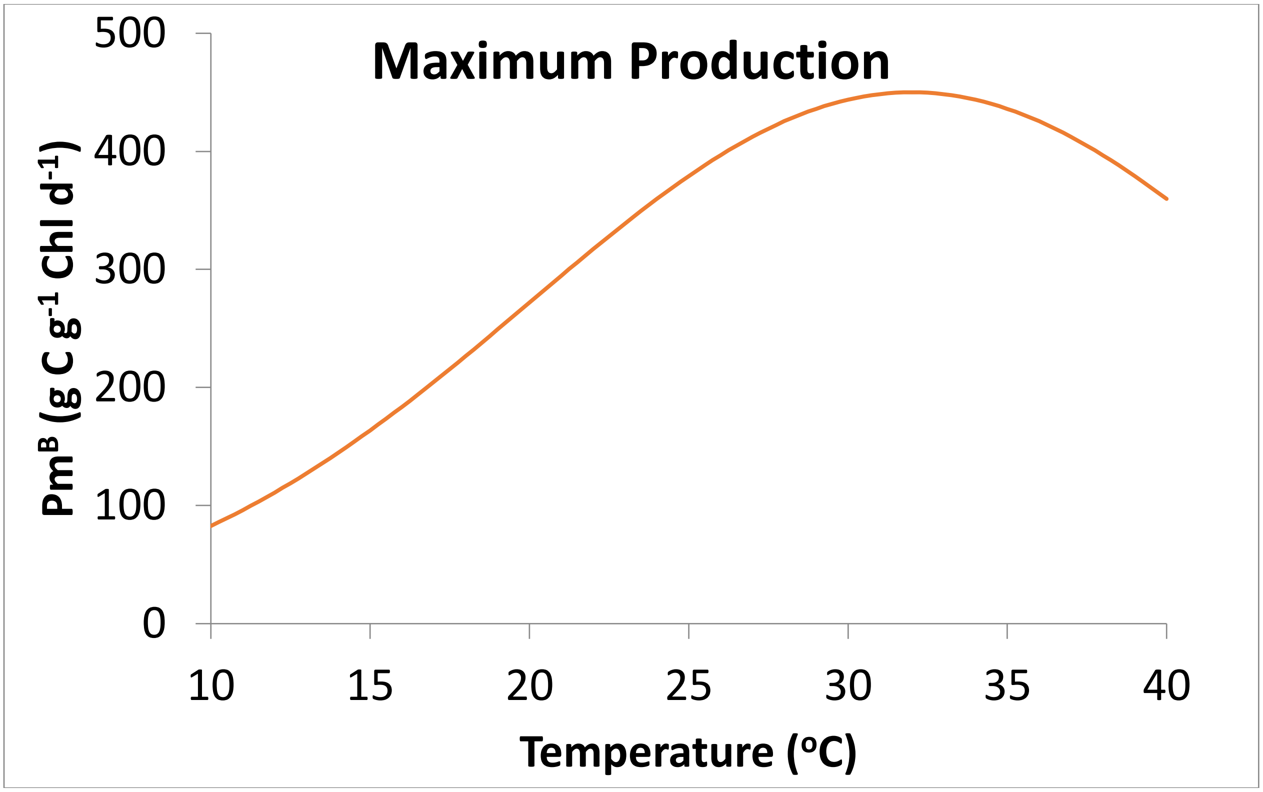

Figure 1. Example model production vs. temperature relationship. For this example, Pm^B = 450, Topt = 32°C, Ktg1 = 0.0035, Ktg2 = 0.0035.

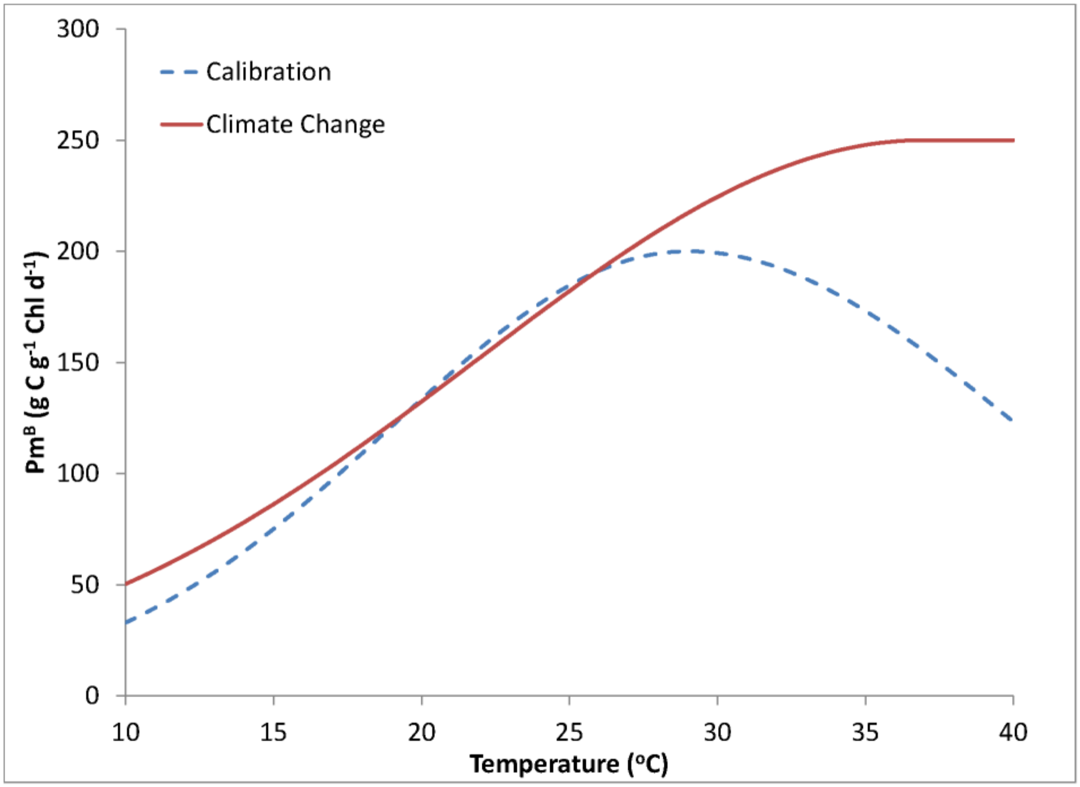

Figure 2. Algal photosynthetic rate versus temperature for Group 1 algae with calibration and climate-change parameter sets. Topt = 29°C for calibration, Topt = 37°C for Climate Change.

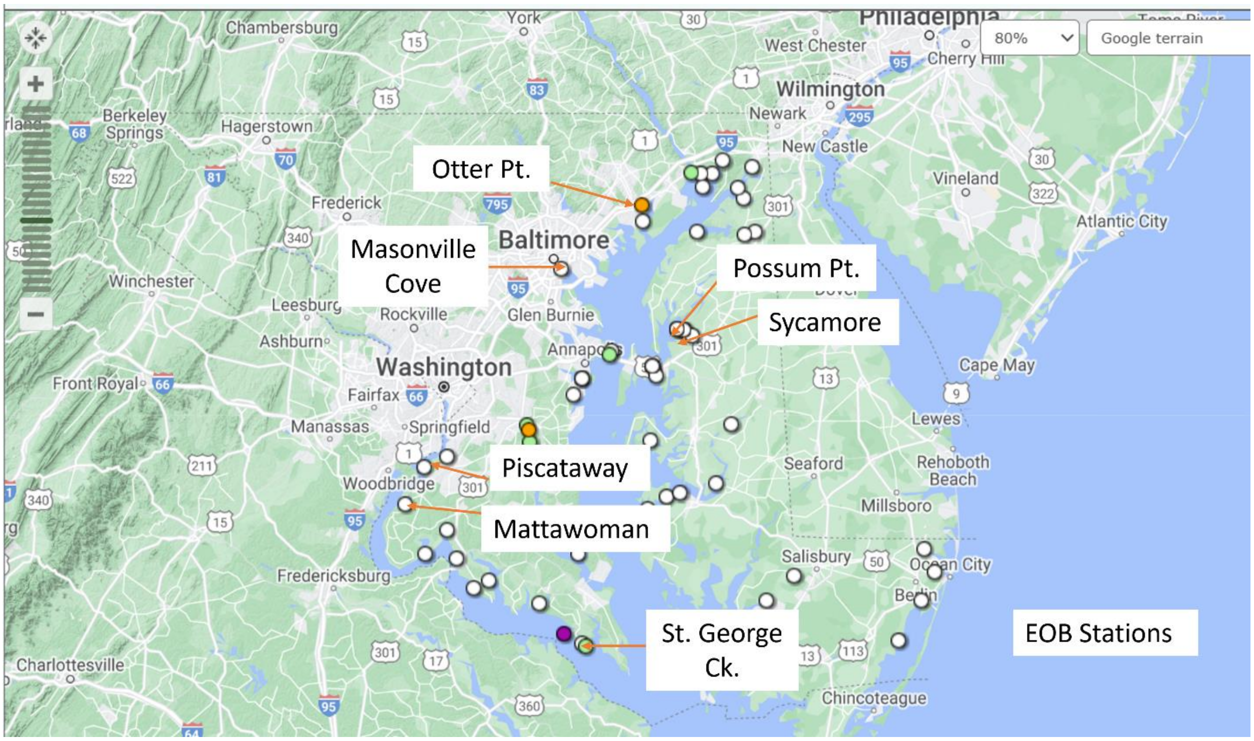

Figure 3. EOB stations used in analysis.

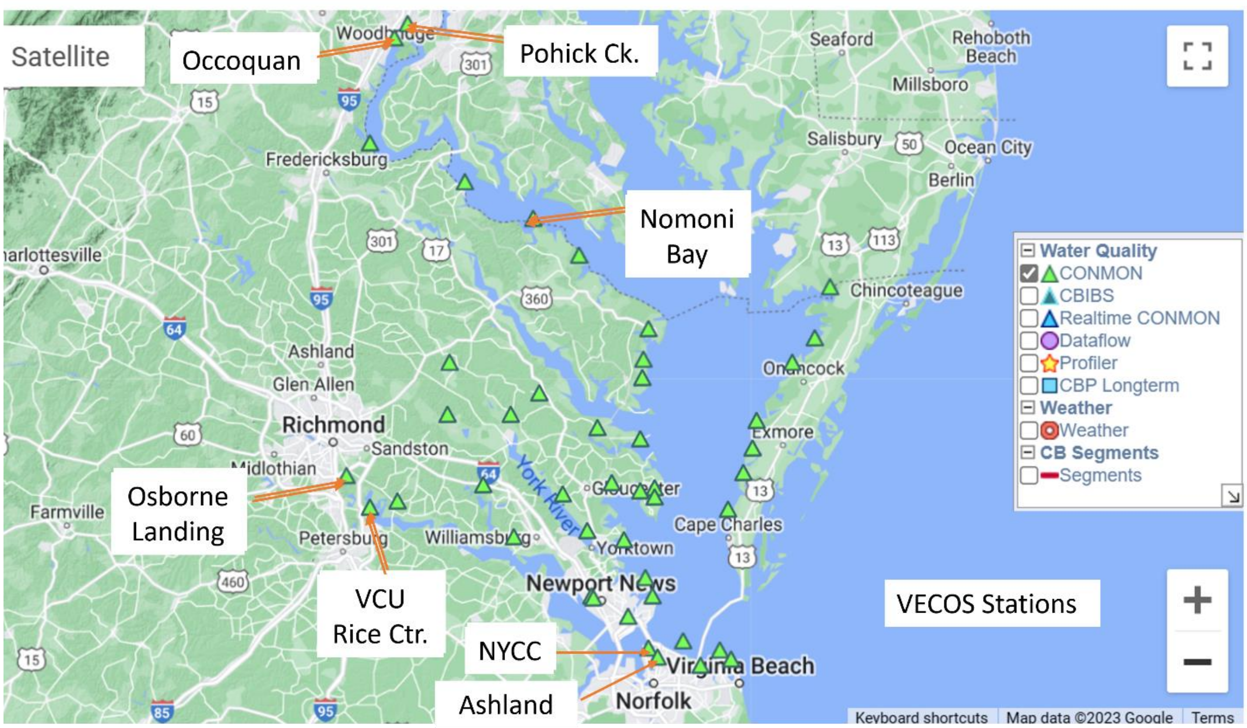

Figure 4. VECOS stations used in analysis.

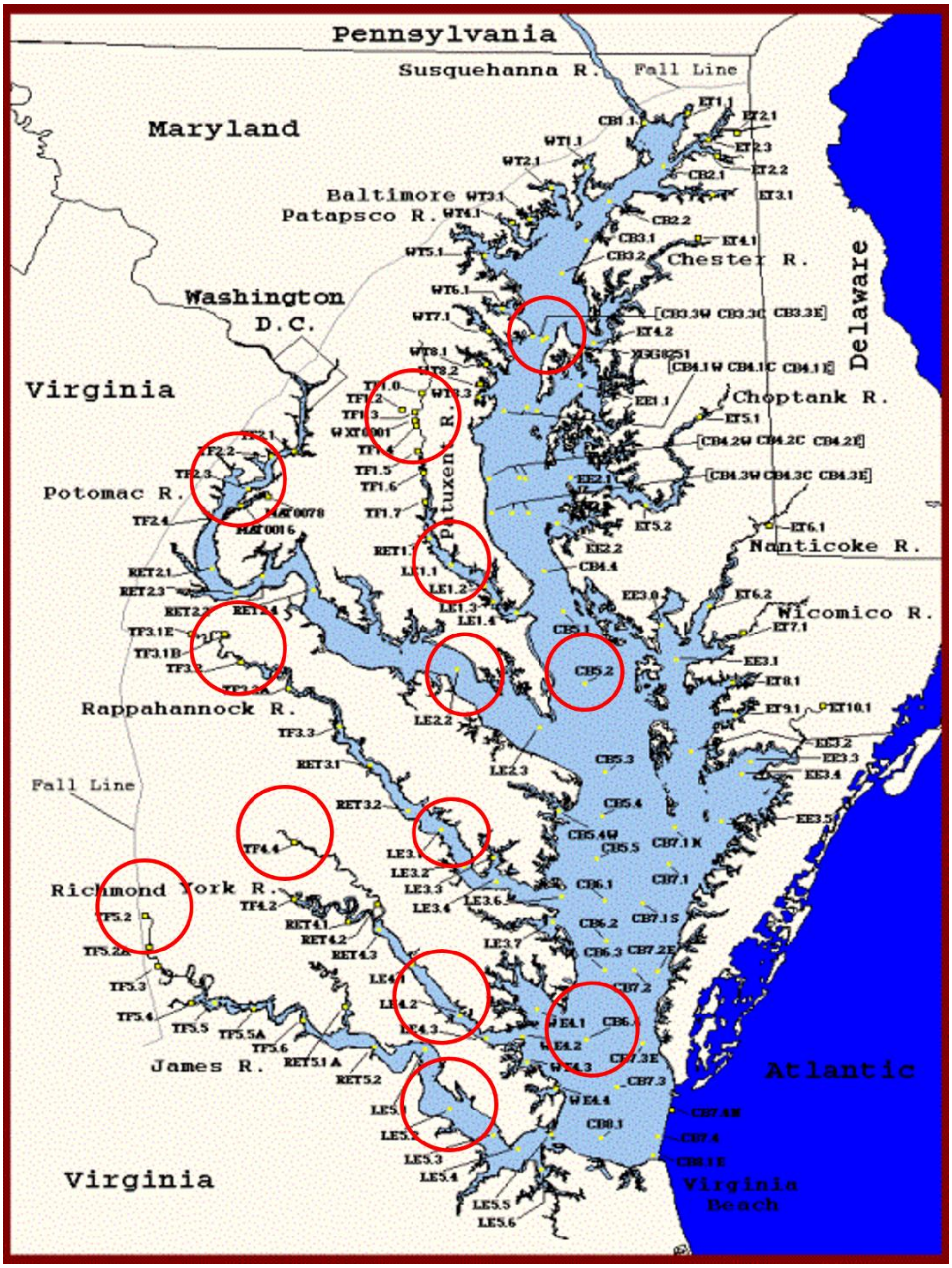

Figure 5. CBP Monitoring Program stations used in analysis.

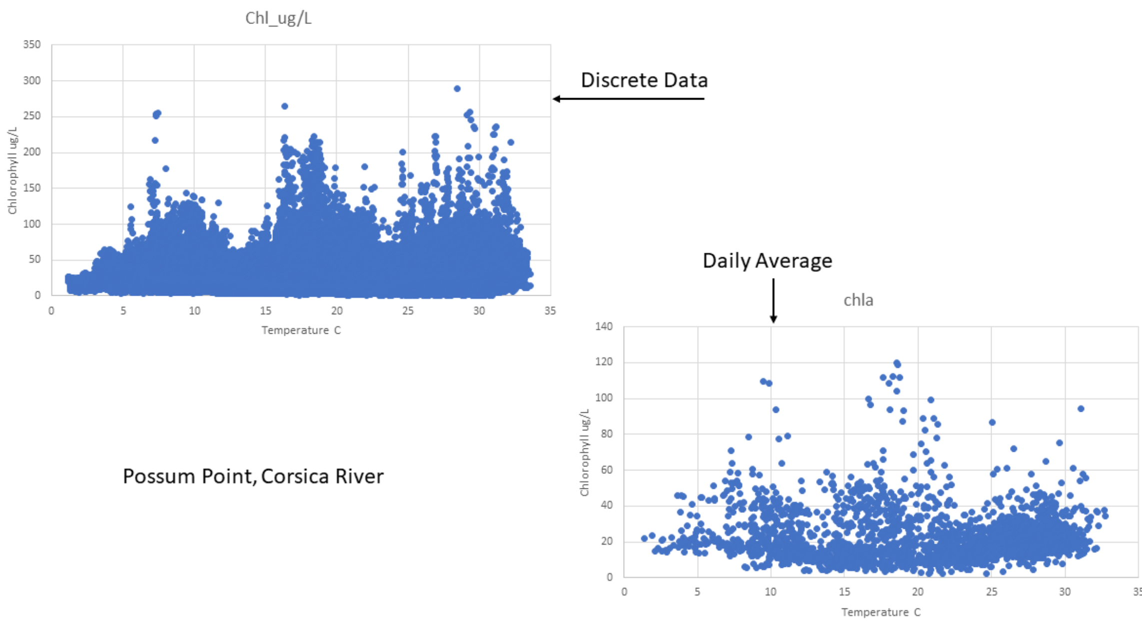

Figure 6. Chlorophyll vs. temperature observations at Possum Point.

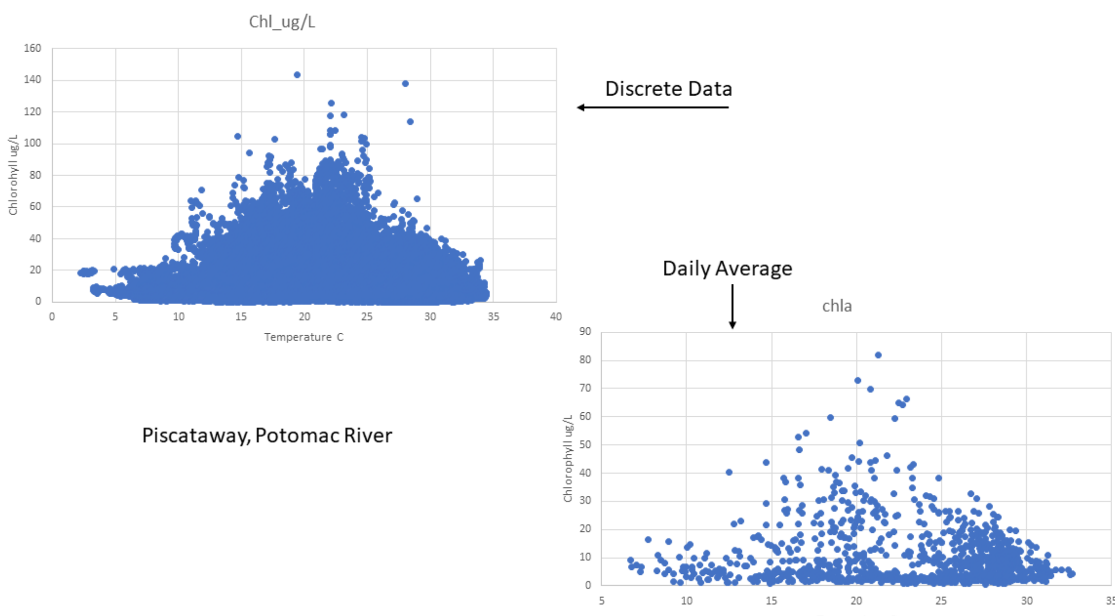

Figure 7. Chlorophyll vs. temperature observations at Piscataway.

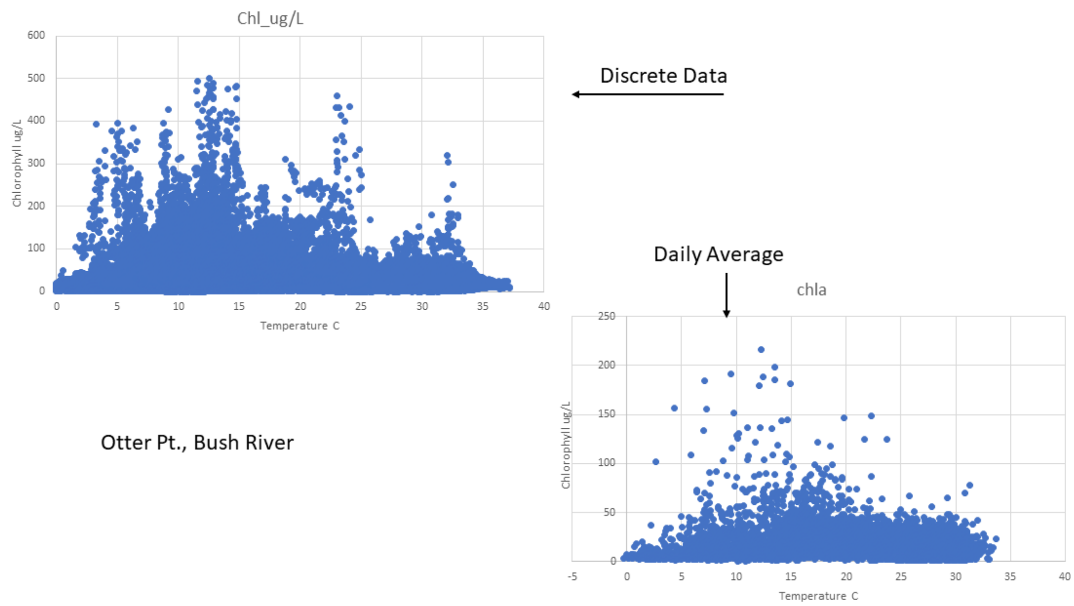

Figure 8. Chlorophyll vs. temperature observations at Otter Point.

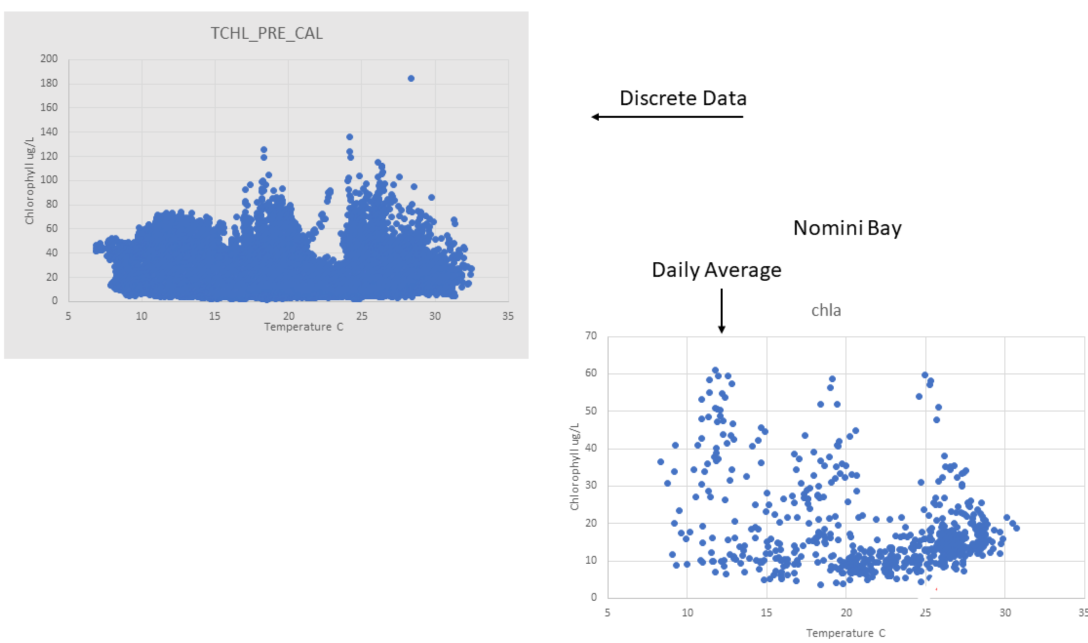

Figure 9. Chlorophyll vs. temperature observations at Nomini Bay.

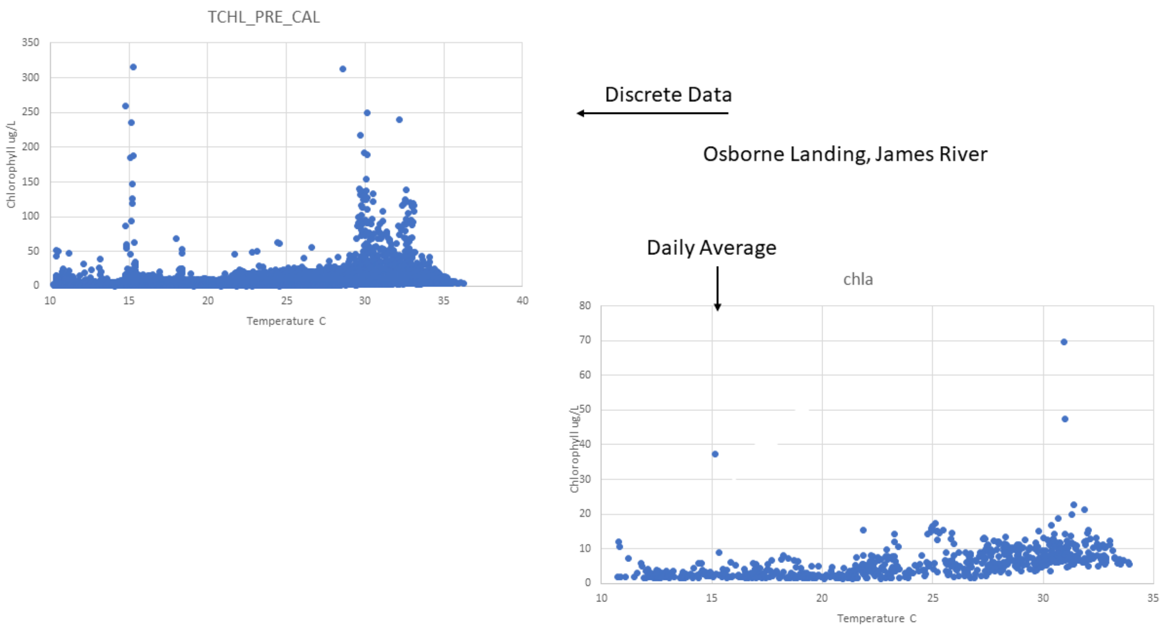

Figure 10. Chlorophyll vs. temperature observations at Osborne Landing.

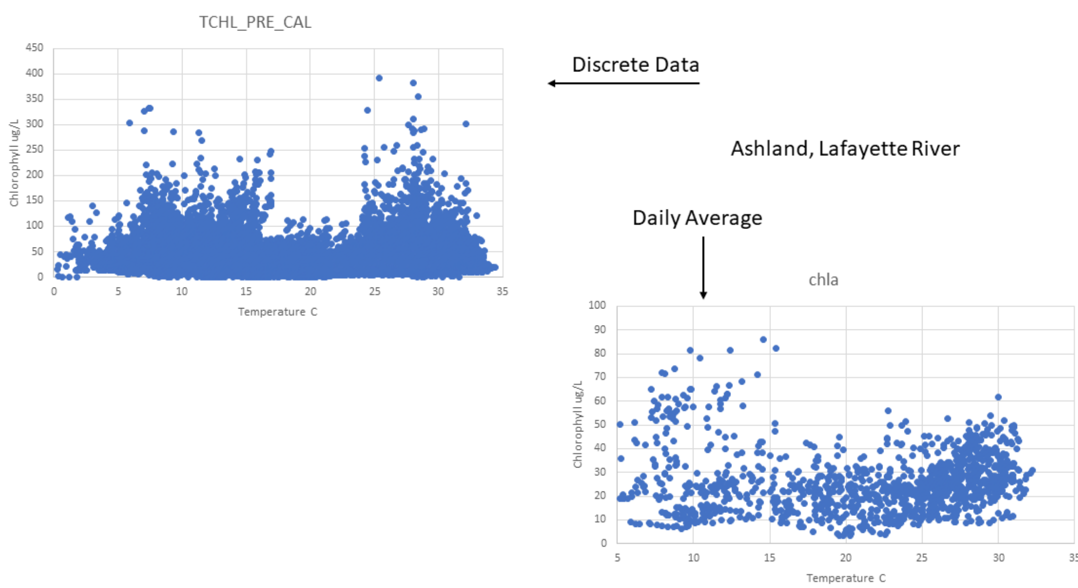

Figure 11. Chlorophyll vs. temperature observations at Ashland.

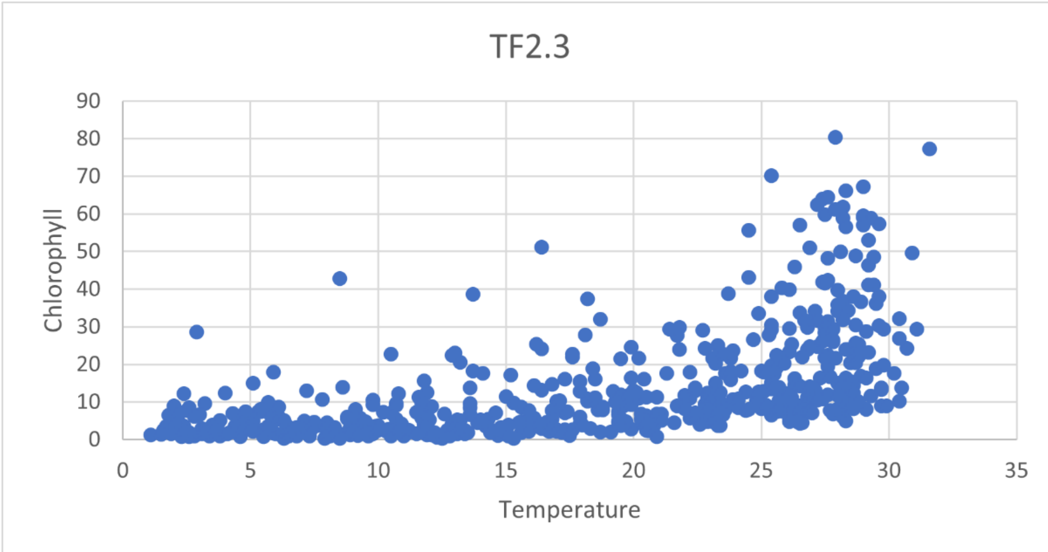

Figure 12. Surface chlorophyll vs. temperature observations at TF2.3.

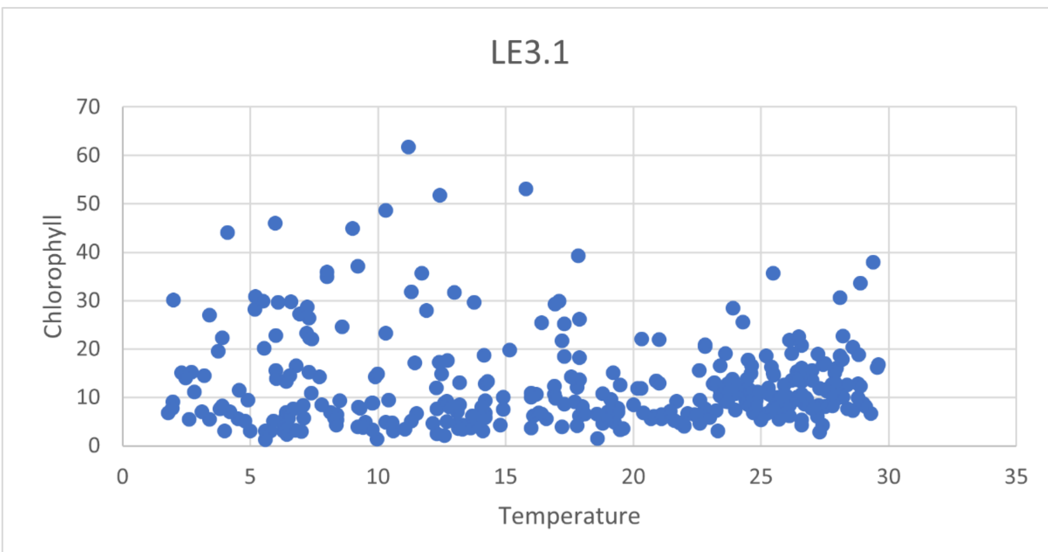

Figure 13. Surface chlorophyll vs. temperature observations at LE3.1.

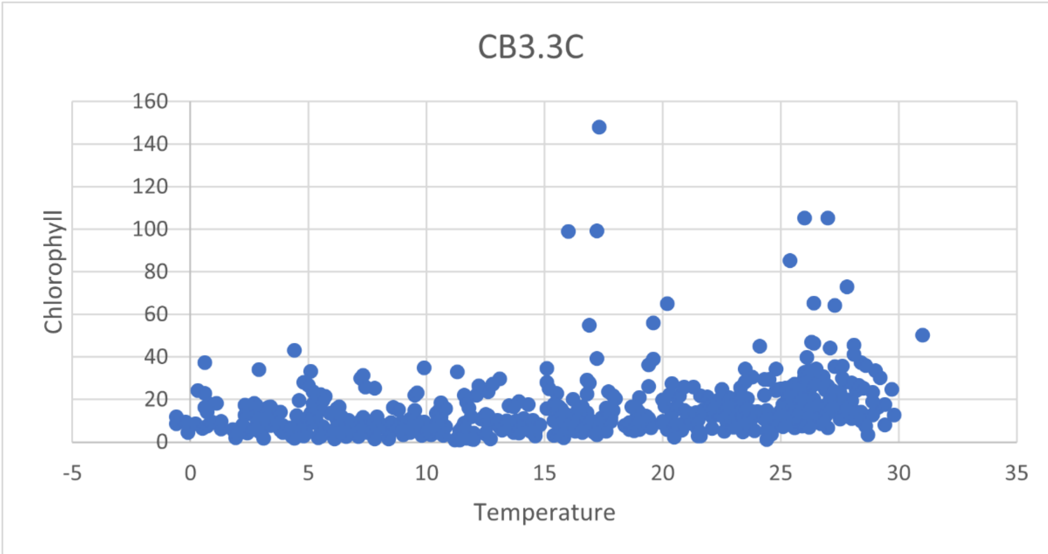

Figure 14. Surface chlorophyll vs. temperature observations at CB3.3C.

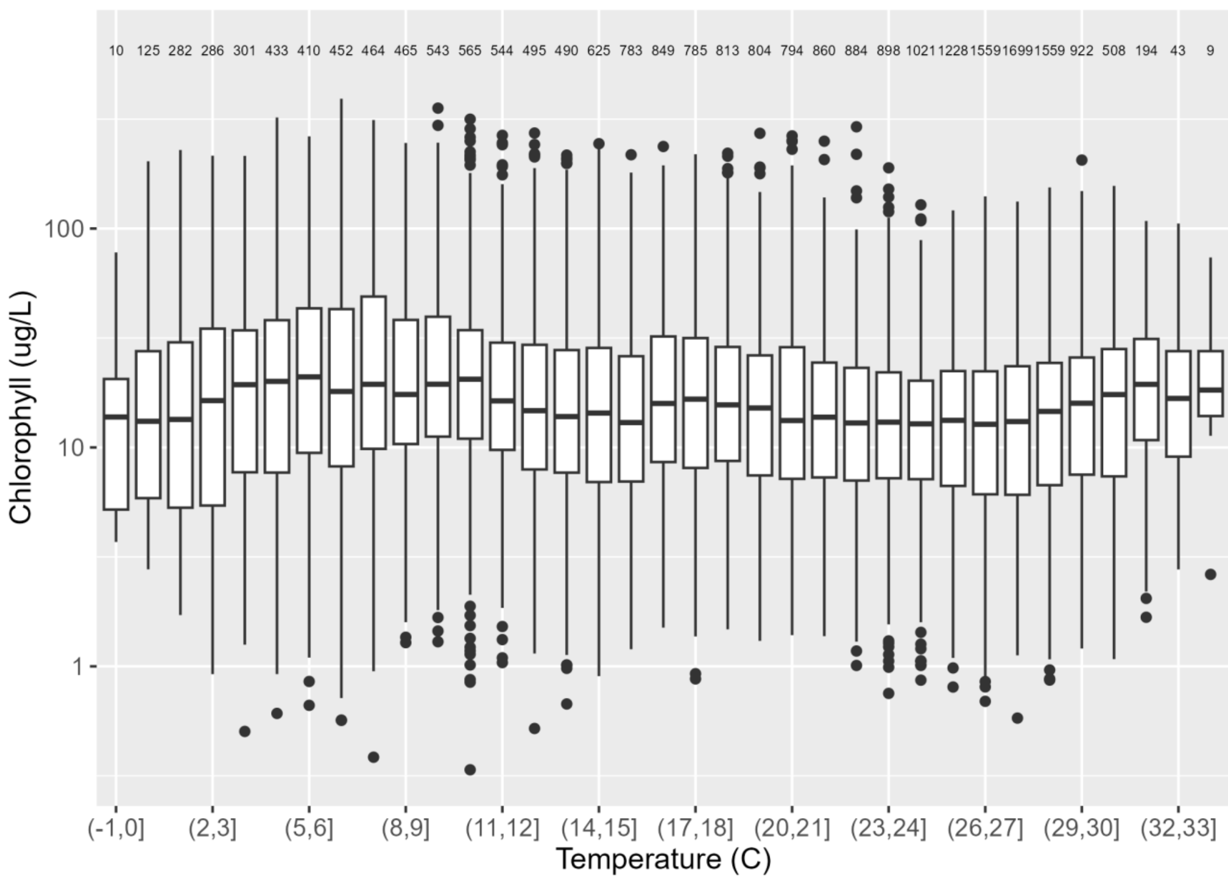

Figure 15. Chlorophyll vs. temperature for pooled data from all EOB stations.

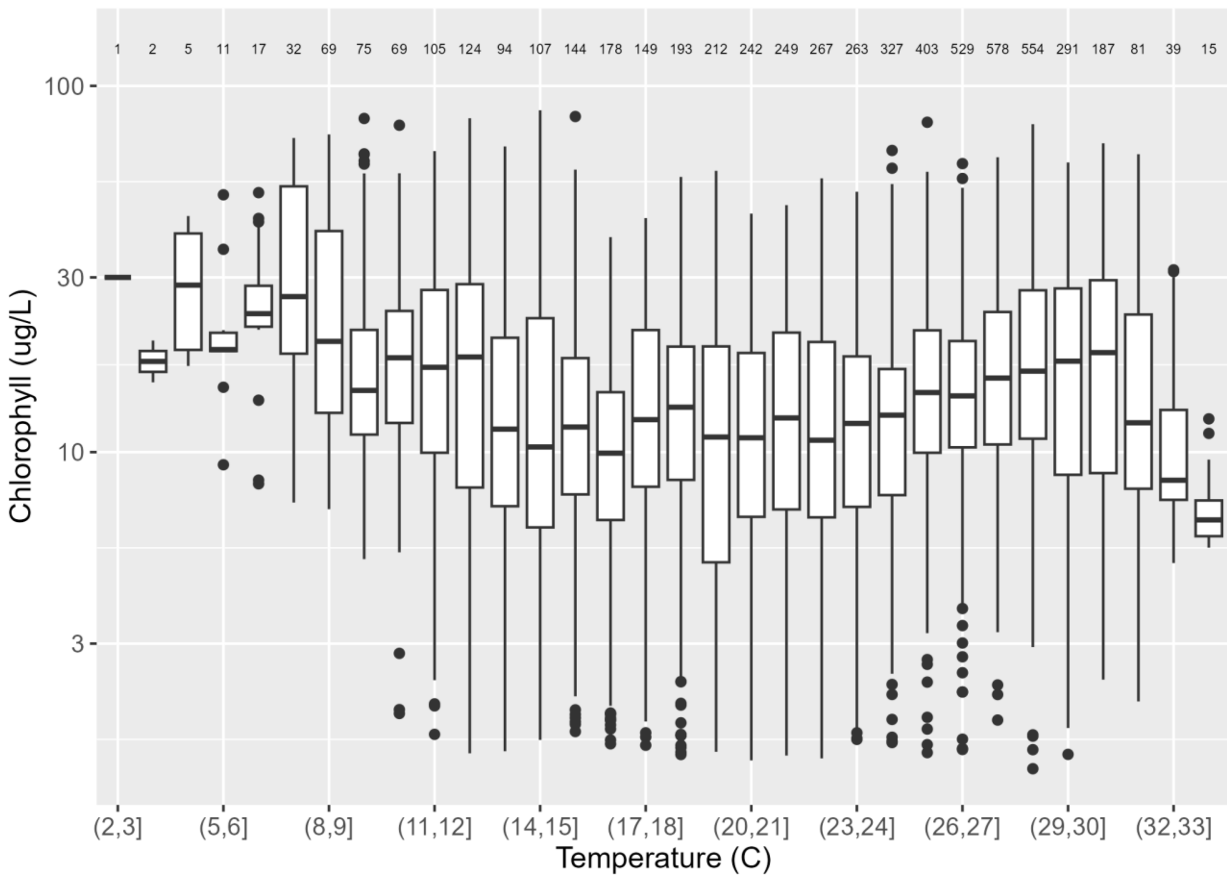

Figure 16. Chlorophyll vs. temperature for pooled data at VECOS stations.

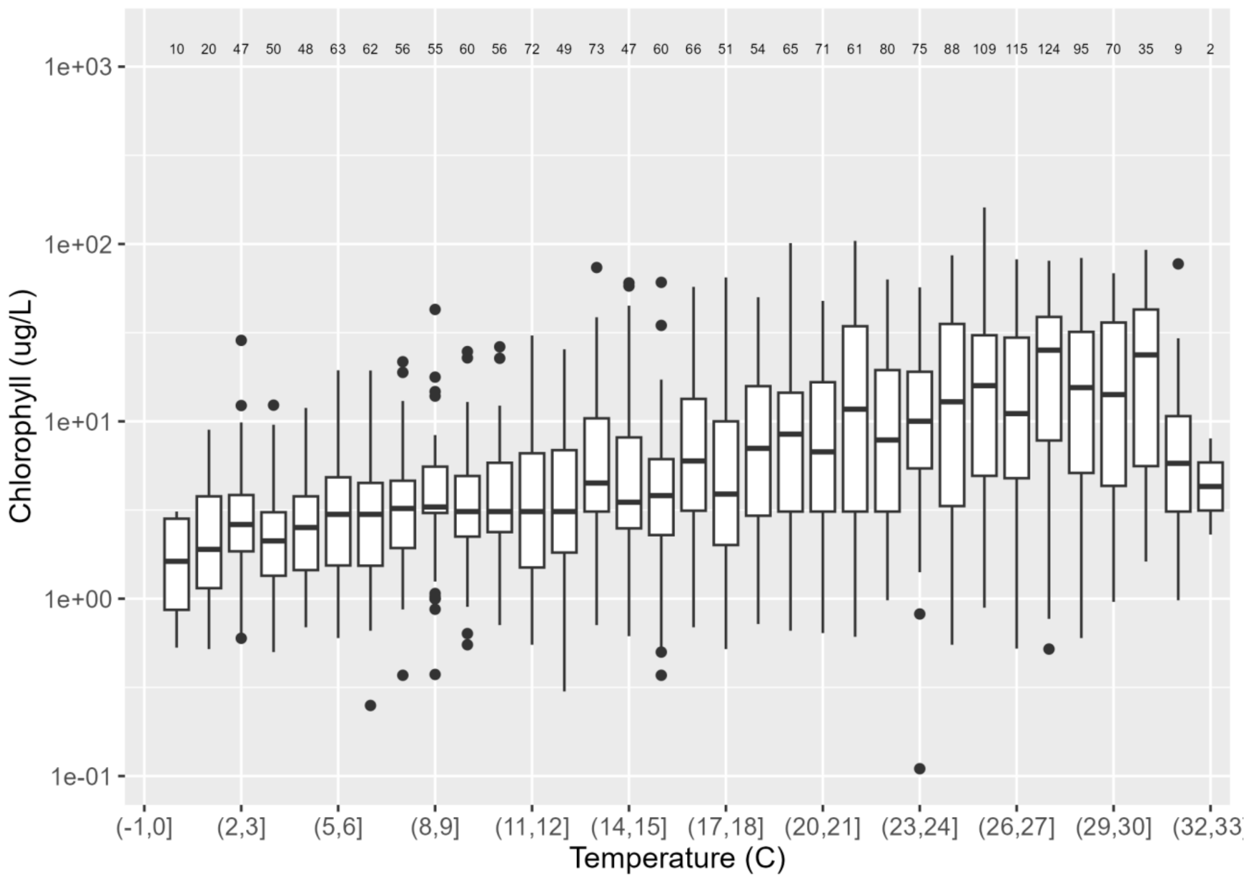

Figure 17. Chlorophyll vs. temperature for pooled data at TF stations.

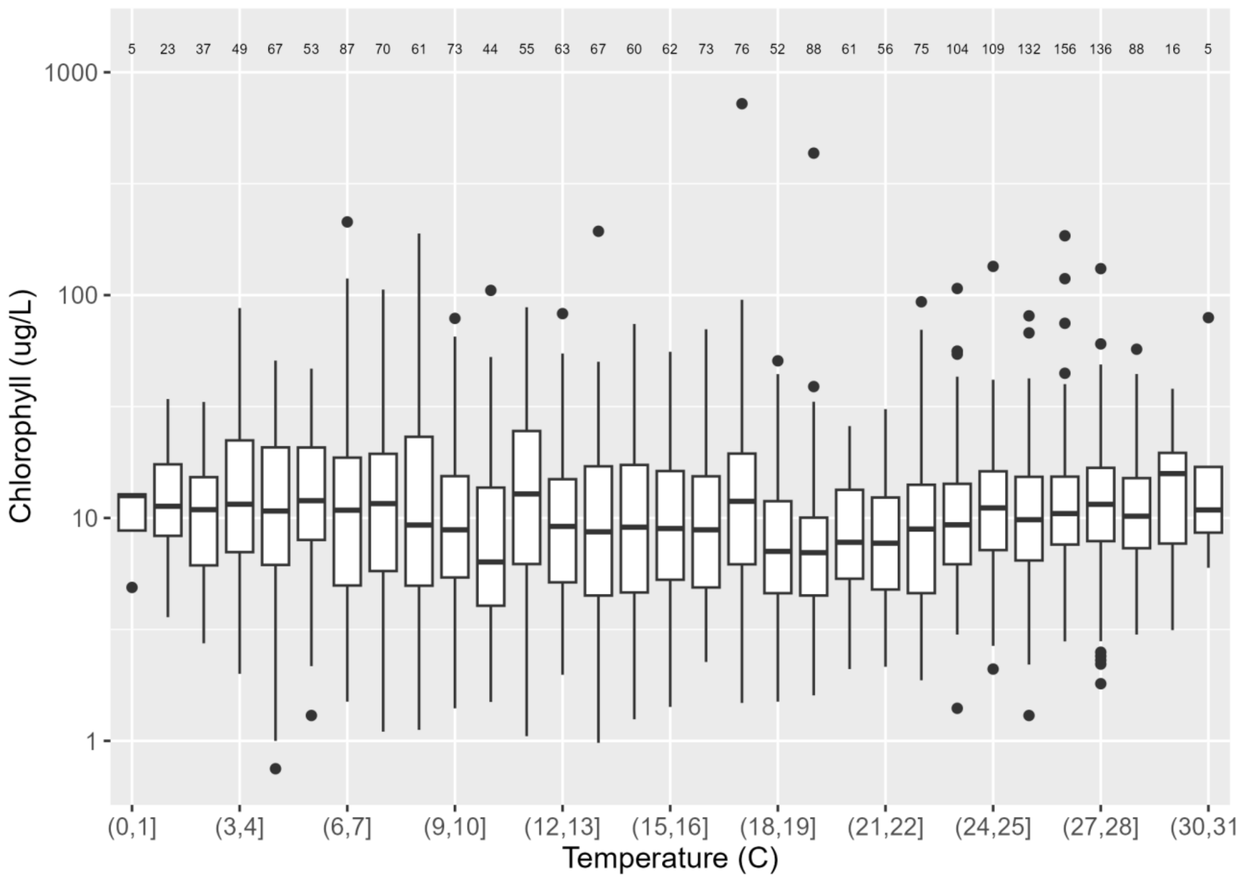

Figure 18. Chlorophyll vs. temperature for pooled data at LE stations.

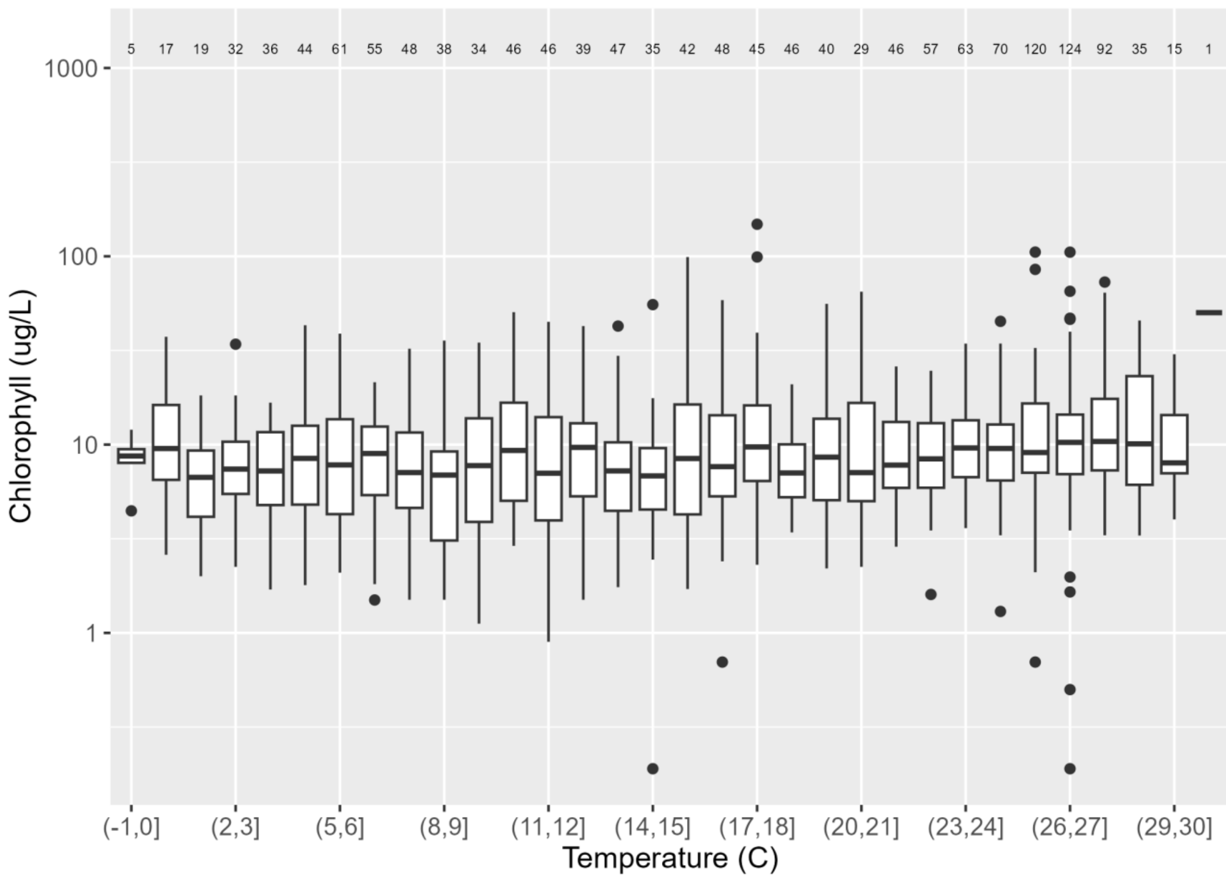

Figure 19. Chlorophyll vs. temperature for pooled data at CB stations.

Appendix – Observed Chlorophyll vs. Temperature at Additional Stations

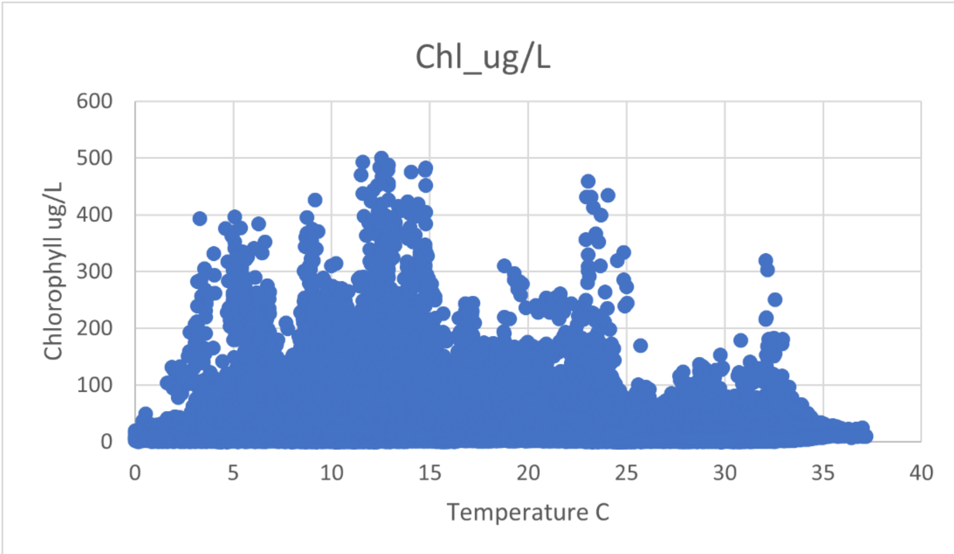

Figure A-1. Discrete observations at Otter Point, Bush River.

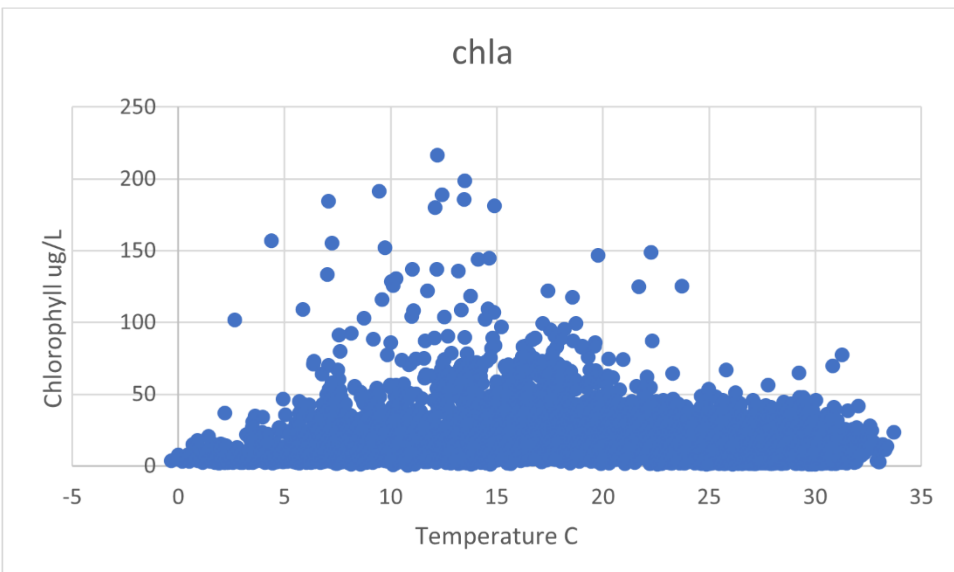

Figure A-2. Daily-average observations at Otter Point, Bush River.

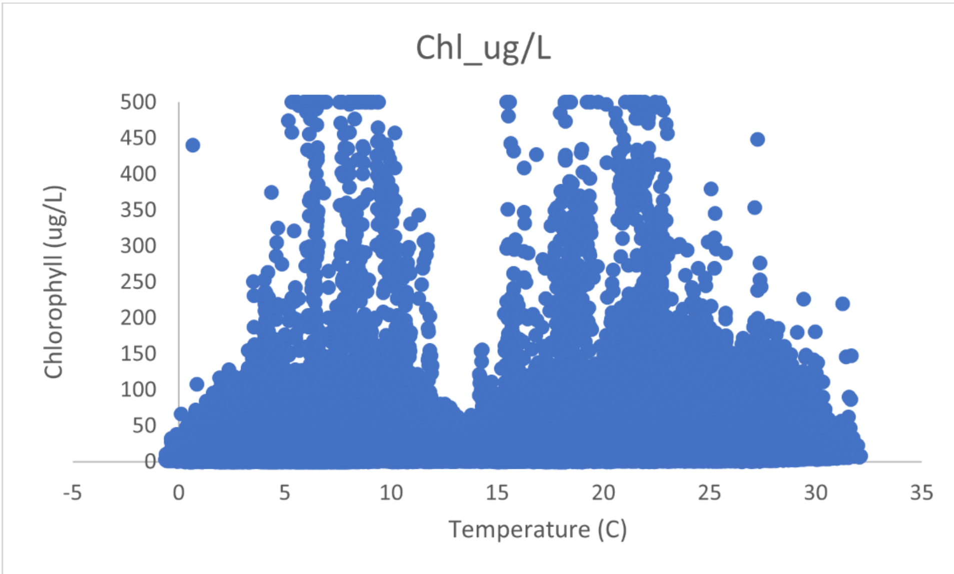

Figure A-3. Discrete observations at Masonville Cove.

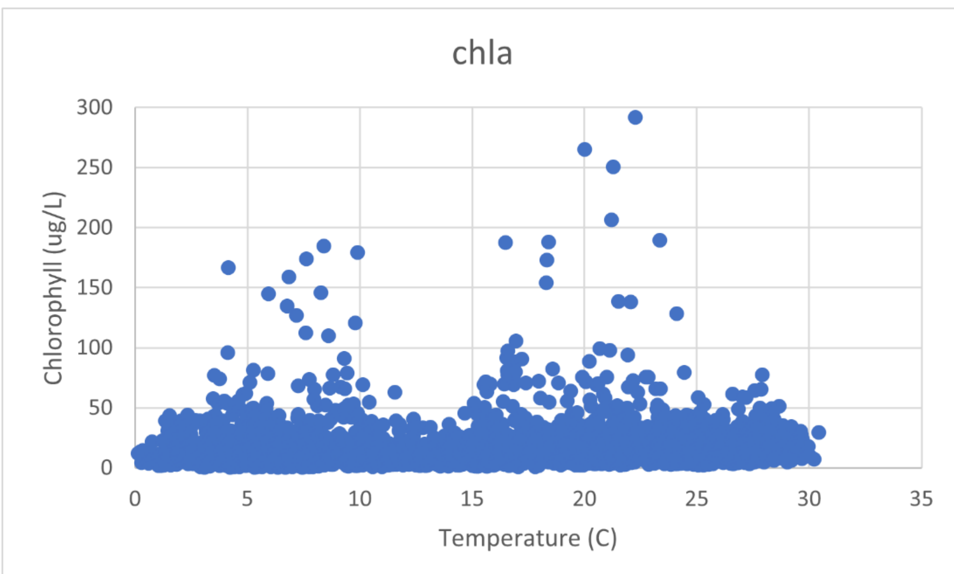

Figure A-4. Daily-average observations at Masonville Cove.

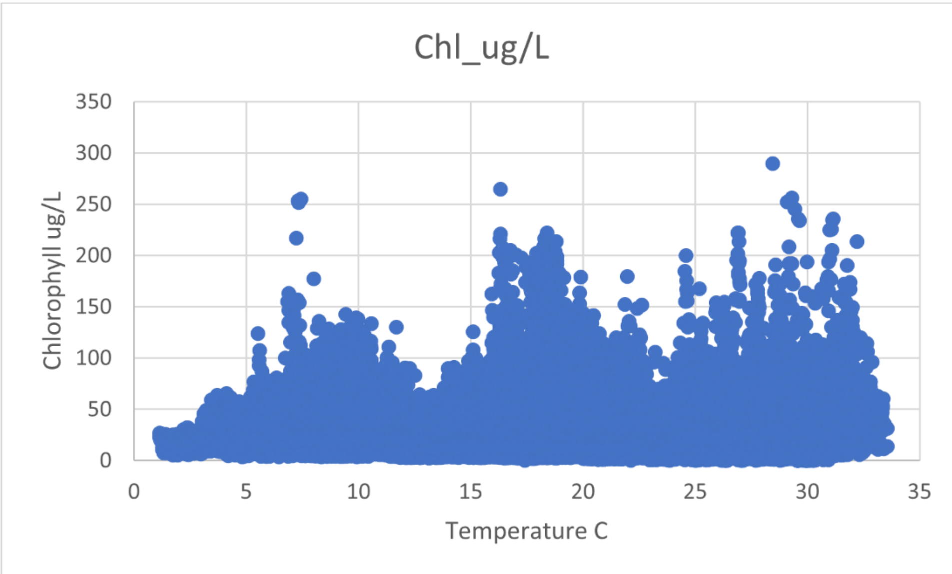

Figure A-5. Discrete observations at Possum Point.

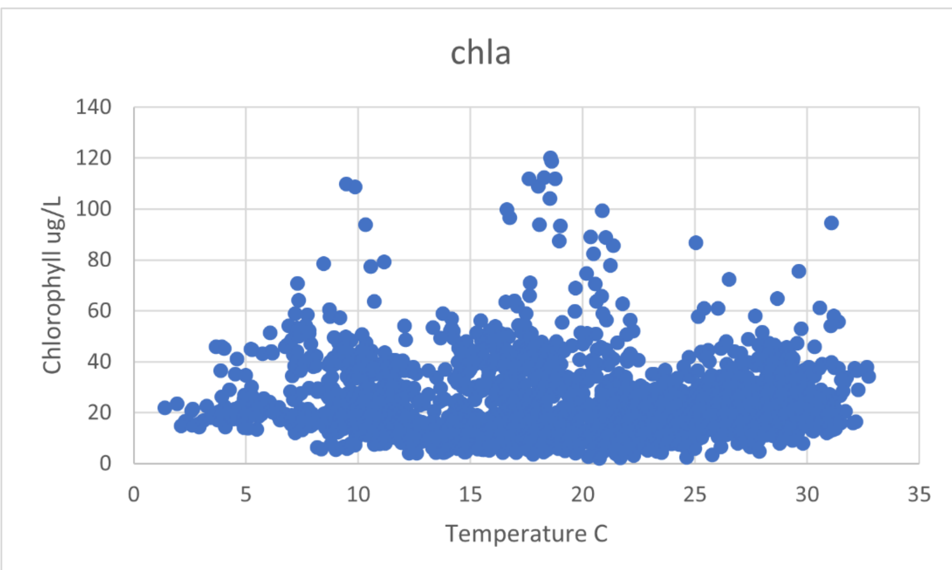

Figure A-6. Daily-average observations at Possum Point.

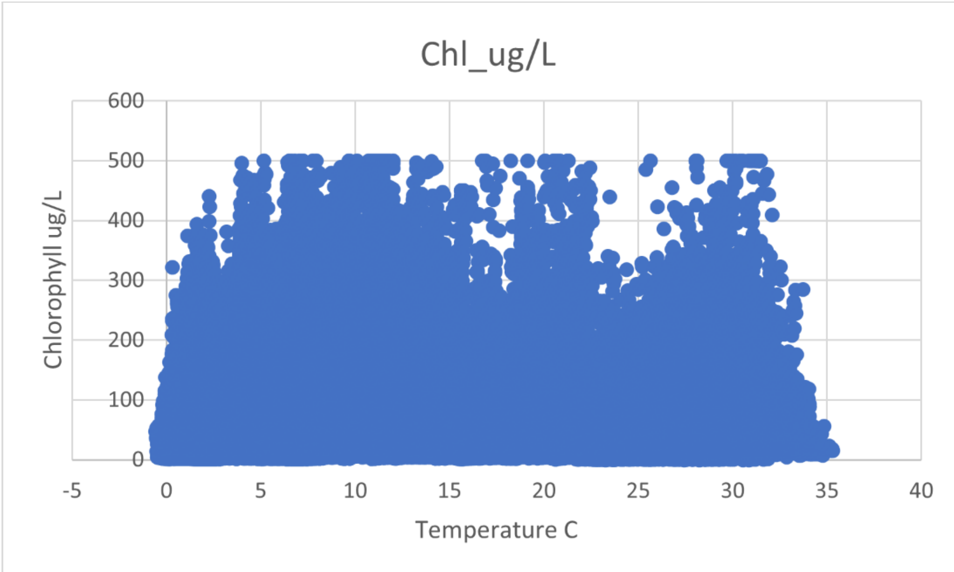

Figure A-7. Discrete observations at Sycamore Point.

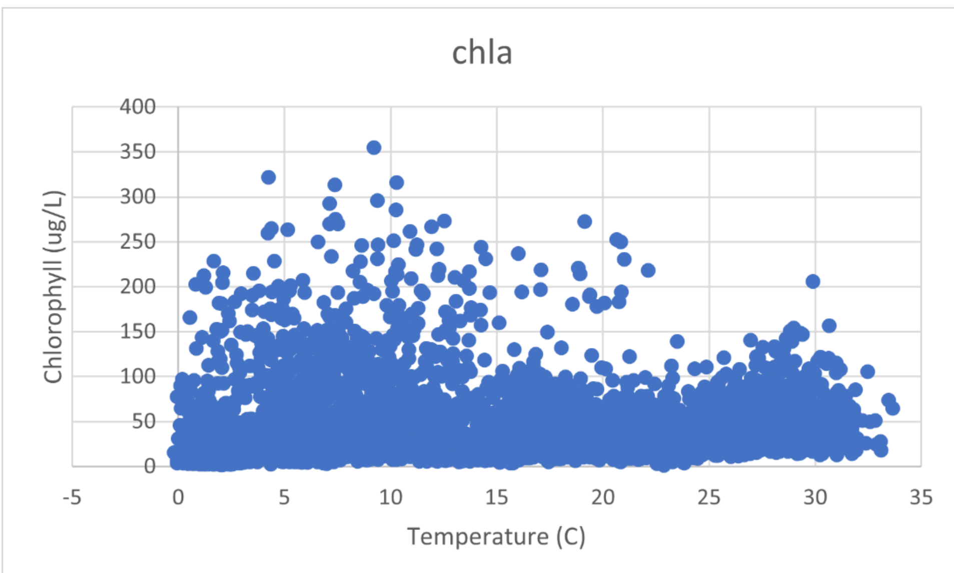

Figure A-8. Daily-average observations at Sycamore Point.

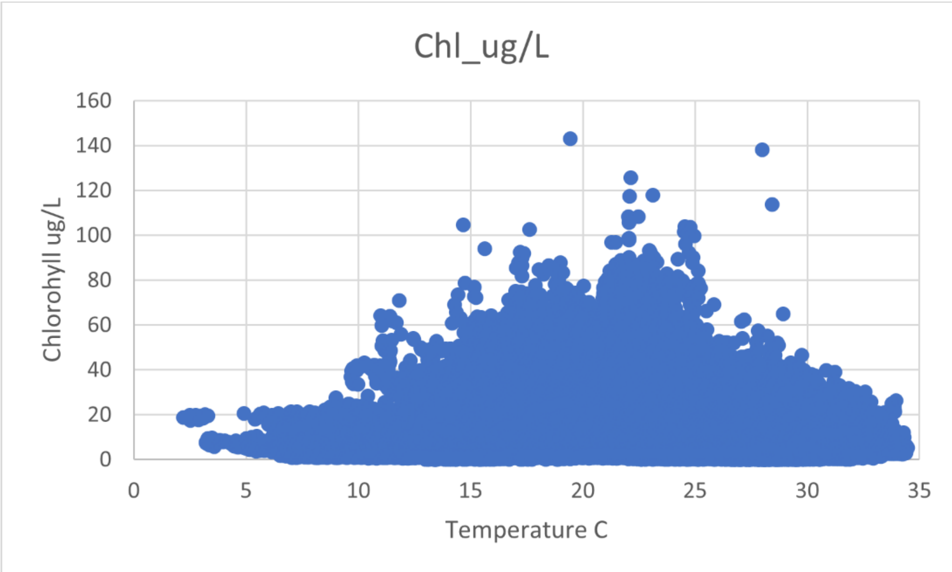

Figure A-9. Discrete observations at Piscataway.

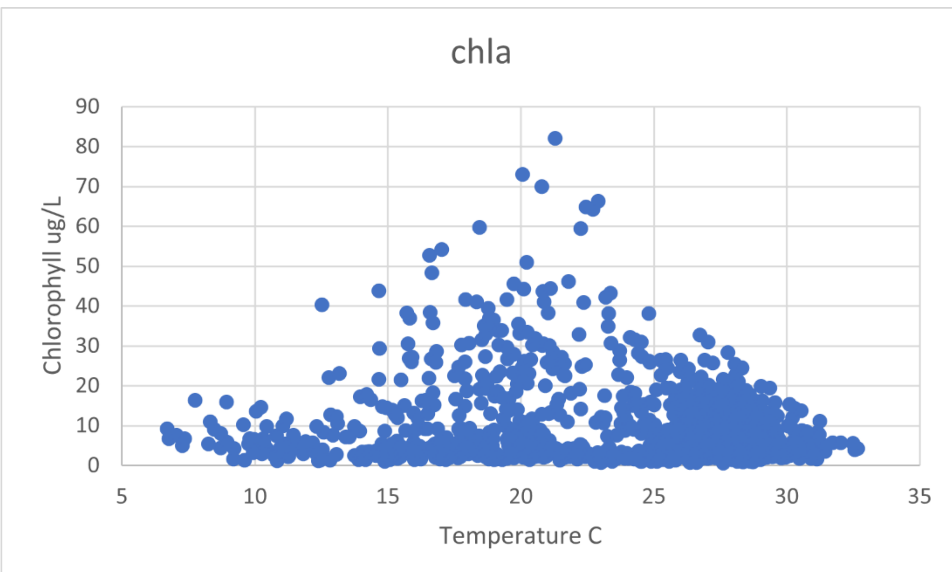

Figure A-10. Daily-average observations at Piscataway.

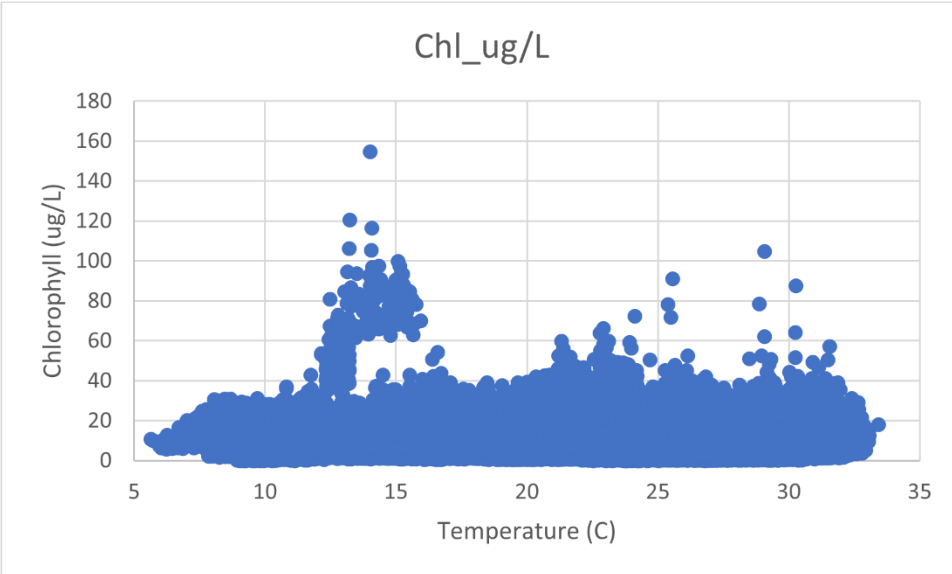

Figure A-11. Discrete observations at Mattawoman.

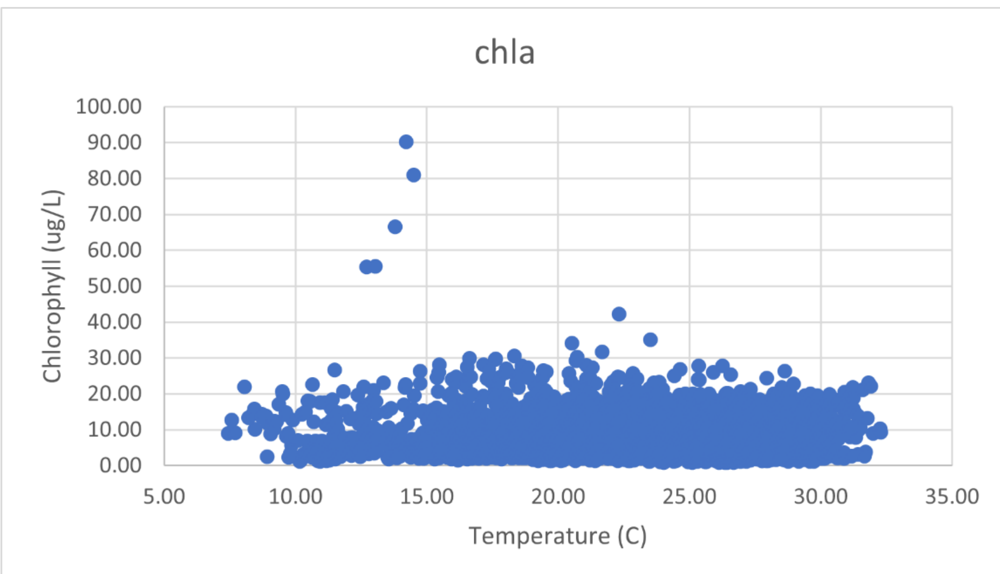

Figure A-12. Daily-average observations at Mattawoman.

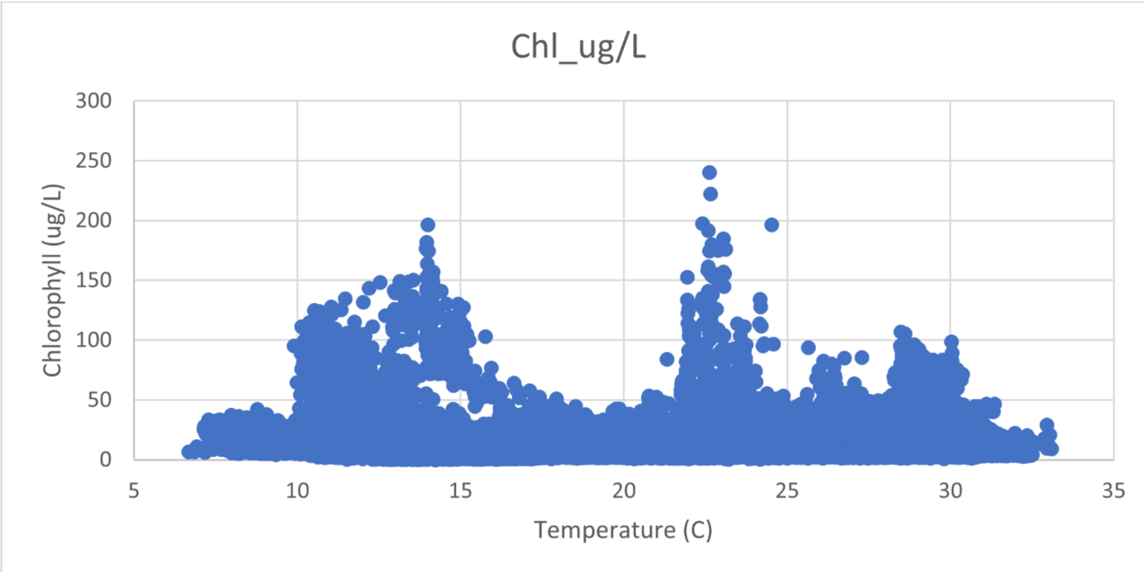

Figure A-13. Discrete observations at St. Georges Creek.

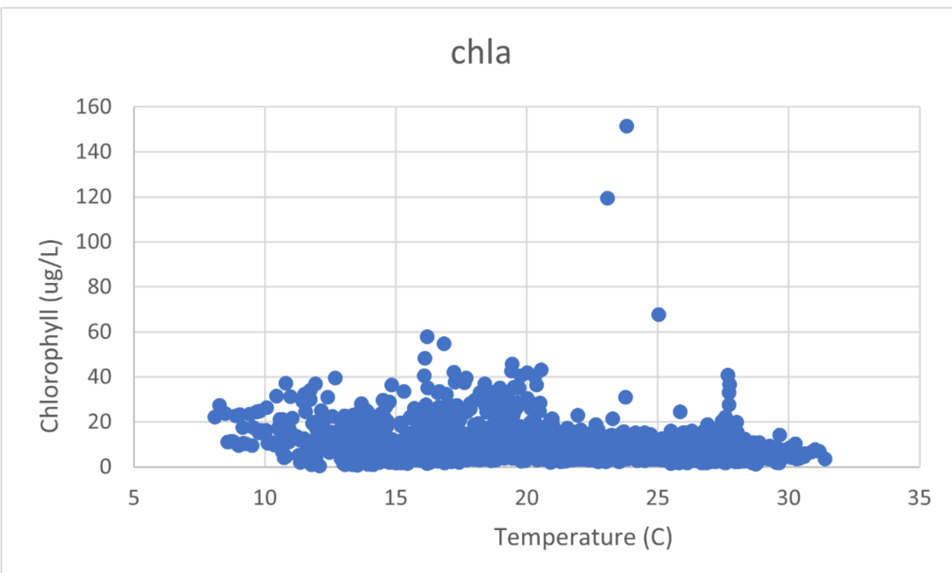

Figure A-14. Daily-average observations at St. Georges Creek.

Part II – Piecewise Quantile Regression Analysis on Continuously Monitored Chlorophyll and Temperature to Inform the Chesapeake Bay Algal Growth Rate-Temperature Model

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Piecewise Quantile Regression Analysis on Continuously Monitored Chlorophyll and Temperature to Inform the Chesapeake Bay Algal Growth Rate-Temperature Model

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VA Department of Environmental Quality

Introduction

The Modeling Workgroup has been asked to re-evaluate the algal growth rate model used in the Phase 6 Bay Model, which included climate change parameterization. This model predicts increasing photosynthetic rate with increasing temperature up to 37°C, above which there is an indefinite flattening of the rate. Since water temperatures approaching 37°C do not presently occur in Bay waters, this model cannot be empirically verified. This has led to a discussion of whether the model should be modified in accordance with what has been observed. In Part I of this report, a relationship is recommended that predicts an increasing photosynthetic rate with increasing temperature up to 32°C, above which the rate gradually decreases (see Figure 1 in Part I). The recommended model is informed primarily by visual inspection of continuously monitored datasets of chlorophyll (via fluorescence) and water temperature collected at 14 sites in Maryland and Virginia Bay mainstem and tributaries.

While visual inspection of the selected datasets does lend support to the proposed growth rate model, a statistical method applied to a larger set of datasets is preferable for decision-making purposes. Statistical models can not only provide a systematic way of visualizing relationships that are readily apparent, but they can also reveal relationships that are not obvious.

Regression analysis is a category of statistical methods for estimating relationships between a dependent variable (e.g., chlorophyll) and one or more independent variables (e.g., temperature). Ordinary least squares (OLS) linear regression is the most common form of regression analysis, whereby one finds the line that minimizes the sum of squared differences between the observed data and the predictions of the line (i.e., the linear function of the independent variable). OLS regression produces the mean response of a dependent variable in relation to an independent variable. This method is frequently used because most investigations are only concerned with characterizing how a population responds to a variable "on average". However, a weak or absent mean response does not actually indicate that the independent variable does not have an effect on the population. It may be that the effect occurs only when there are interactions with factors not accounted for in the regression model. If these interactions occur only some of the time or they only impact some of the target population, an approach that centers on the mean response will likely not detect an effect. When characterizing complex ecological relationships, it is almost always the case that there are factors not accounted for in any given statistical model.

Quantile regression has been recommended for ecologists because it maximizes one's ability to find relationships between two variables whenever the variables are subject to complex interactions that can potentially lead to unequal variation of the dependent variable for different ranges of the independent variable (Cade and Noon, 2003). With this method, lines can be fitted through the data through all portions of the probability distribution, allowing one to make inferences about correlation and causality beyond what one would expect to see "on average".

Algal photosynthetic rate is a variable that is dependent on a suite of factors–temperature, light availability, nutrient availability and composition–operating in concert on varying time scales. It is also a variable that reflects the collective growth of a diverse assemblage of different phytoplankton taxa, which can have varying sensitivities to the aforementioned variables. For this reason, algal composition can also be quite variable over time and in space. Moreover, the ecological concept of limiting factors is quite relevant to our understanding of algal growth in response to temperature. According to Cade and Noon (2003), this necessitates a statistical approach that examines rates of change in the quantiles near the "maximum" response. Limiting factors, such as light or nutrient availability, can exert pressure at the upper end a population's distribution before a relationship is strong enough to be detected in the population's "middle". For this reason, a number of researchers (Determan et al. 2021, Lusiana et al. 2019, Xu et al., 2015) have advocated using quantile regression instead of OLS regression to characterize the relationship between nutrients and algal growth.

Temperature is a limiting factor that exerts an upper limit on phytoplankton algal growth (Eppley, 1972). In the recommended algal growth rate model, the upper limit of growth occurs at 32°C, above which growth gradually decreases. The Modeling Workgroup has been asked to consider whether these are reasonable assumptions to use for the Mainstem Bay Model and the Multiple Tributary Models. Piecewise quantile regression is well-suited for this problem. With a piecewise regression approach, we can use monitoring data to characterize the chlorophyll-temperature relationships on either side of the temperature breakpoint of the proposed algal growth model—32°C. While we can use quantile regression to estimate the relationship of chlorophyll to temperature over all quantiles, for the analysis presented here, we will focus on the conditional 50th percentile and the conditional 90th percentile. The former has been selected to characterize the average response of chlorophyll to temperature in a manner that is robust against outliers. The latter has been selected because it represents the quantile that is close to the maximum response but still within the range of a normal condition.

Methods

Datasets collected at 20 sites were selected for this analysis. These datasets were generated from sondes programmed to take measurements of a suite of physicochemical parameters, including temperature and fluorescence, every 15 minutes over multiple warm-weather seasons. The sites are split evenly across Maryland and Virginia. To be included in the examination, a dataset had to span at least two summer seasons and contain at least 50 chlorophyll observations at temperatures greater than 32°C, with a maximum observed temperature of at least 33.5°C. For the Maryland datasets, the first ten datasets meeting the aforementioned criteria in the data download table on the Eyes of the Bay data website[1] were selected. For the Virginia datasets[2], all six of the datasets collected by the Virginia Institute of Marine Science (VIMS) in the James River estuary (including the Chickahominy River but excluding the Elizabeth River) were selected. The other four datasets were also generated by VIMS and represent sites located in the York River, the Lynnhaven River, and the Bay side of the Eastern Shore. The examined datasets collectively represent Bay conditions between 2001 and 2022.

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[1] Maryland datasets were generated by Maryland Department of Natural Resources and are available for download on the Eyes on the Bay website: https://eyesonthebay.dnr.maryland.gov/contmon/ContMon.cfm

[2] Virginia datasets are available for download on the Virginia Estuarine and Coastal Observing System website: http://vecos.vims.edu/.

Piecewise quantile regression was performed on all 20 datasets. Individual linear models were developed for the following temperature ranges: 1) temperatures less than or equal to 32°C and 2) temperatures greater than 32°C. The conditional 50th and 90th percentile responses were modeled for these two ranges. The signs and statistical significance of the resulting 80 slopes were enumerated to make an inference about the weight of evidence for or against the proposed algal growth rate model.

Results

Chlorophyll responded to increasing summertime temperature in a positive fashion at temperatures less than or equal to 32°C at 16 of the 20 sites (Table 1). For this temperature range, a positive slope for the conditional 50th percentile was accompanied by a positive slope in the conditional 90th percentile in 14 of the sites. There were two sites where the conditional 50th percentile relationship was positive but the 90th percentile relationship was negative. There were only two sites where both quantiles showed a negative response. There were no sites where the conditional 50th percentile response was negative but the 90th percentile response was positive.

In contrast, there were more negative responses to increasing temperature at temperatures greater than 32°C. Both quantiles showed a negative response at nine sites and either quantile showed a negative response at four sites. There were only two sites where both quantiles showed a positive response. Non-statistically significant slopes (p-value greater than 0.1) were computed more frequently at temperatures greater than 32°C than at temperatures less than 32°C. Such slopes cannot be statistically distinguished from zero (i.e., no response can be detected).

In general, the conditional 50th and 90th percentile responses were in agreement in 52% of the cases and were unambiguously discordant (e.g., statistically significant positive slope in one,

Table 1. Summary of Quantile Regression Analysis.

Plus signs (highlighted in green) indicate positive relationships between chlorophyll-a and temperature, while negative signs indicate negative relationships. ns = Slope is not statistically significant (p > 0.1). All statistically significant results had a p-value less than 0.05.

Station	Segment	Year Range	Relationship at temps <= 32°C		Relationship at temps > 32°C		Sample size >32°C	Maximum temperature observed (°C)
			50th	90th	50th	90th		
JMS099.00	JMSTFU	2006-2008	+	+	-	-	5181	36.2
JMS073.37	JMSTFL	2006-2008	+	+	-	-	675	35.5
JMS048.78	JMSOH	2006-2008	+	-	ns	ns	426	34.8
CHK015.12	CHKOH	2006-2008	+	+	-	-	121	34.0
JMS018.23	JMSMH	2006-2008	+	+	ns	+	426	34.8
JMS002.55	JMSPH	2006-2008	+	+	+	-	55	33.6
HUN001.29	POCMH	2013-2015	ns	+	-	-	196	34.6
BBY002.74	LYNPH	2019-2020	+	+	ns	-	79	33.5
OCH001.60	CB7PH	2016-2018	-	-	ns	+	398	33.9
TSK000.23	YRKMH	2020-2022	+	+	-	-	1201	35.1
Bush River-Otter Cr	BSHOH	2010-2022	ns	-	+	ns	5570	37.2
Wicomico-Little Monie Cr	WICMH	2010-2022	+	+	+	+	3124	35.2
Patuxent R.	PAXTF	2010-2022	+	+	ns	-	125	33.5
Back R. - Riverside	BACOH	2014-2022	+	+	-	-	317	34.2
Bush R. -Church Pt	BSHOH	2008-2010	+	-	ns	-	250	34.2
Susquehanna Flats	CB1TF	2007-2017	+	+	-	-	773	34.2
Gratitude Marine	CB3MH	2009-2011	+	+	-	-	201	34.0
Tilgman Island	CB4MH	2017-2019	-	-	+	+	115	33.7
Chester R. - Deep Landing	CHSTF	2003-2006	+	+	+	-	620	34.4
Choptank R. - Mulberry Pt	CHOMH1	2001-2003	+	+	-	-	399	35.3

statistically significant negative slope in the other) in 10%. Non-statistically significant slopes occurred four times more frequently in the 50th percentile than in the 90th percentile. Negative responses were associated with the 90th percentile 1.7 times more frequently than the 50th percentile.

Visualizations of the regressions for selected datasets are presented in Appendix A.

Discussion

The weight of the evidence generated by this analysis leans in support of the assumptions of the recommended algal growth rate model. There is strong support for the assumption that chlorophyll increases at temperatures up to 32°C. At temperatures greater than 32°C, the results are more mixed and show more negative than positive responses. This supports the assumption of stable growth and decline at very high temperatures.

The results demonstrate the utility of quantile regression. The finding that effects are more likely to be revealed in the 90th percentile than the 50th percentile is consistent with the concept of limiting factors. Perhaps in those cases where a positive response was observed in the 90th percentile and the relationship in the 50th percentile was not statistically significant, intense bloom events coincident with an abundant supply of limiting factors sufficient to promote prolonged accelerated growth occurred at least 10% of the time but less than 50% of the time. Negative 90th percentile responses in conjunction with positive 50th percentile responses may be the result of the reverse situation—where intense blooms coincident with a limited supply of limiting factors occurred at least 10% of the time but less than 50% of the time. When limiting factors are sparse, high temperatures may exert an additional stress, leading to even more pronounced reduced photosynthetic activity. Algal blooms can also lead to elevated pH, a condition which depresses phytoplankton growth (Hansen, 2002). At the tidal fresh station JMS073.37, located in the chlorophyll maximum of the James River estuary, pH greater than 9.0 was observed 10% of the time during its summertime deployment period. Lastly, subsets of the phytoplankton community could be more sensitive to higher temperature than other algal groups. For instance, Moran et al. (2010) found that the contribution of small-celled phytoplankton (picoplankton) to total phytoplankton biomass has increased with warming temperatures in the North Atlantic Ocean.

There are a few limitations of the analysis to consider. First, 15-minute observations were used to characterize chlorophyll-temperature relationships. These data are highly autocorrelated. It is possible that performing this analysis on hourly or daily-aggregated data would produce different and more definitive results. But the downside of temporal aggregation is the considerable reduction in the number of chlorophyll observations matched to high temperatures. Another limitation is the sparseness of chlorophyll observations taken at temperatures at and above 35°C. Such high temperatures were only observed at six of the 20 sites. Finally, all of the sites are shallow (approximately 2-m deep), nearshore environments. The absence of offshore continuous monitoring datasets prevents us from understanding how much of a limitation this is.

Literature Cited

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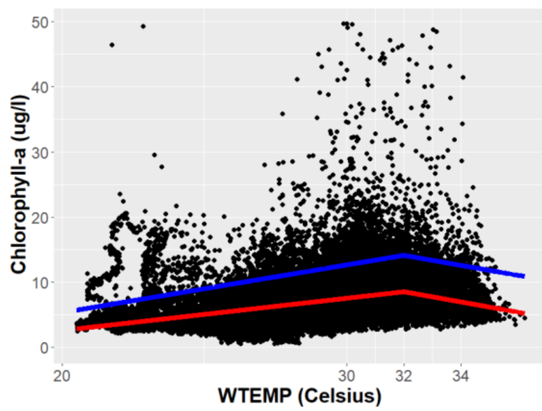
Morán X.A.G., López-Urrutia A., Calvo-Díaz A., Li W.K.W. 2010. Increasing importance of small phytoplankton in a warmer ocean. Global Change Biology 16, 1137–1144. (doi:10.1111/j.1365-2486.2009.01960.x).

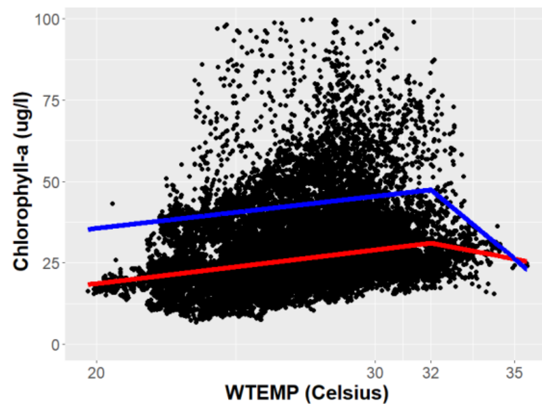
Xu, Y., Isles P.D, Rizzo D., Schroth A.W. 2015. Quantile regression improves models of lake eutrophication with implications for ecosystem-specific management. Freshwater Biology 60: doi.org/10.1111/fwb.12615.

Appendix A Quantile regression lines for selected James River datasets

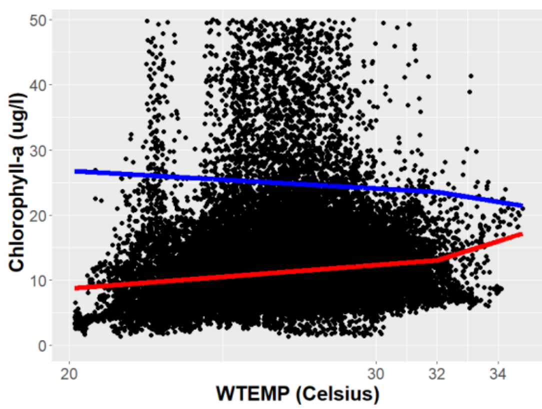
Station: JMS099.00 Segment JMSTFU



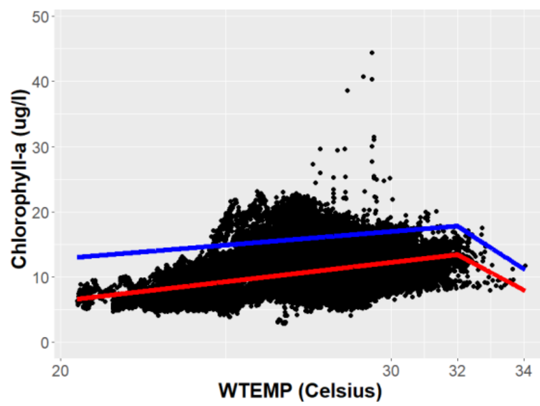
Station: JMS073.37 Segment JMSTFL

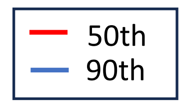


Station: JMS048.78 Segment JMSOH

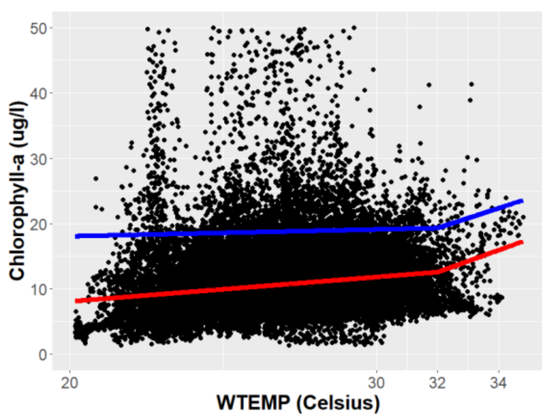


Station: CHK015.12 Segment CHKOH





Station: JMS018.23 Segment JMSMH



Station: JMS002.55 Segment JMSPH