2019

Analyzing the Effects of Coccolithophore Concentration on the Relationship Between Vertical Absorption Coefficient and Secchi Disk Depth

Halley Steinmetz
hjsteinmetz317@gmail.com

Michelle Staudinger
mstaudinger@usgs.gov

William M. Balch
bbalch@bigelow.org

Analyzing the Effects of Coccolithophore Concentration on the Relationship Between Vertical Absorption Coefficient and Secchi Disk Depth

Halley Steinmetz[1], Michelle Staudinger[1,2], William M. Balch[3]

University of Massachusetts Amherst, US Geological Survey, Bigelow Laboratory for Ocean Sciences

Abstract:

The study of how light passes through water, known as ocean optics, is useful in determining the constituents suspended at the surface of a water body. Understanding the composition of the water over time can answer questions about how the oceans have changed with global climate change and ocean acidification. The vertical absorption coefficient in ocean waters is an indicator characterizing how deeply light penetrates the water column. Using this information, scientists can better understand and predict the amount of primary productivity occurring in the area. Here we examine the relationship between vertical absorption coefficient and Secchi disk depth to determine if the concentration of a type of calcifying phytoplankton, coccolithophores, causes the relationship to deviate from the findings of a pivotal historical study conducted in 1929 by Poole and Atkins. Data was collected during July 2018 aboard the *R/V Endeavor* on the EN616 "Cocco-Mix" cruise in the Northwest Atlantic Ocean. Diffuse attenuation was determined using downwelling irradiance measurements gathered from a HyperPro that measures electromagnetic energy through the water column. Diffuse attenuation values were compared with Secchi disk depth measurements taken at the same time and location as the HyperPro casts. Results will contribute to our understanding of how the relationship between light extinction and Secchi disk depth changes between water bodies. This knowledge can be used to relate light extinction and Secchi disk depth in historical studies in the Northwest Atlantic that did not have access to more modern equipment to measure light extinction.

1. **Introduction**

1.1 Ocean Optics

Measuring properties of light in the ocean (known as ocean optics) provides information about primary productivity and constituents suspended in the surface layer. Optical properties can be measured using equipment such as the Secchi disk and radiometric sensors. A Secchi disk is a circular plate, 30 cm in diameter, that may be completely white or have black sections to add contrast (Pal et al., 2015). Secchi disk measurements are recorded at the depth of disappearance/reappearance from the observer as it is lowered into the water. The concentration of constituents in the water is inversely related to the depth at which the disk disappears (Pal et al., 2015). Secchi disk data have been collected since the 1860s (Pal et al., 2015). Data collection using radiometric sensors, which measure electromagnetic energy, began in the 1970s.

The passage of light through water can be measured by comparing Secchi disk depth with diffuse attenuation (loss of light intensity through a medium) or the vertical absorption coefficient, and a classic paper by Poole and Atkins (1929) demonstrated its performance and utility. Poole and Atkins (1929) were able to use photometers to determine the absorption of light at different depths, times, and atmospheric conditions. They found that changes in light at the surface caused by atmospheric conditions resulted in changes in illumination at depth. They also found that the absorption of light at the same depth could be affected by variations in horizontal distribution of phytoplankton and zooplankton and varying phosphate concentrations, though not by salinity (Poole and Atkins, 1929).

Poole and Atkins (1929) related Secchi disk depth with the vertical absorption coefficient (using percent illuminations at different depths), which they believed to be constant. However, Graham (1966) found that correlations between Secchi depth and the absorption coefficient vary dependent upon the ocean basin studied. The differences could not be fitted to a common slope between all areas where correlations were calculated, but data between the same water bodies were similar, which led to the conclusion that the Secchi disk depth/vertical absorption coefficient relationship may not be the same across all oceans (Graham, 1966). Graham concluded that light extinction in water is complex and may be affected by the constituents in the water (i.e., suspended particles that scatter light and colored dissolved organic matter (CDOM), which primarily absorbs light) (Graham, 1966). Holmes (1970) confirmed Poole and Atkins' light extinction formula using Secchi disk depth would have been too high in the area sampled for their study. However, Idso and Gilbert (1974) found that Poole and Atkins' light extinction equation was applicable where the Secchi disk depth ranged from 0.09 to 35 m, and concluded that Poole and Atkins' formula is effective when relating light absorption with Secchi depth.

1.2 Coccolithophores

A class of algae that have the potential to alter optical properties of the water when present in high concentrations are haptophytes (aka coccolithophores). Coccolithophores are a type of calcifying marine algae that have calcium carbonate disks used for a number of possible roles such as protection against their zooplankton predators (Balch, 2018). These calcium carbonate disks scatter light as it passes through water. In non-blooming conditions, coccoliths account for 10-20% of total backscattering in water and up to 90+% of backscattering in bloom conditions (Balch et al., 2005). This scattering can be detected by Earth-observing satellites (Holligan et al., 1983; Balch et al, 2005).

The goal of this project was to explore how coccolithophore concentration may impact properties of light in the water and the algorithms used to interpret measurements to determine those properties. Specifically, this study examines light absorption in ocean waters with varying concentrations of coccolithophores to better understand how scattering properties of coccoliths lead to deviations from ocean measurements in more typical (average) coccolith concentrations.

1.3 Objectives and Implications

Based on the high scattering properties of coccolithophores and their detached coccoliths as well as the varying findings of Poole and Atkins (1929), Graham (1966), Holmes (1970), and Idso and Gilbert (1974), a study was conceived to determine how coccolithophore concentration impacts the relationship between vertical absorption coefficient and Secchi disk depth. If the Secchi disk versus transmittance relationship in high coccolithophore concentrations deviate from measurements taken in standard conditions, this would indicate that their historical presence could alter perceived ocean conditions and how they have changed over time. Historically, coccolithophore blooms have only occurred over 1% of time and space, and are considered rare events. The goal of this project was to determine if different Secchi disk algorithms are needed to calculate bulk attenuation of seawater in high versus low concentrations of coccolithophores. Tracking optical properties of the ocean through time and in correspondence with anthropogenic releases of carbon dioxide can improve our understanding of how human activities impact ocean life and processes. This was tested through three specific objectives:

1) How robust is the relationship between Secchi disk depth and light absorption as derived by Poole and Atkins (1929)?

2) Does the relationship between Secchi disk depth and vertical absorption coefficient vary with high versus low coccolithophore concentration? And does the resulting relationship vary from that derived by Poole and Atkins' (1929) relationship?

3) Does the relationship change when using Poole and Atkins (1929) vertical absorption coefficient calculations compared with calculating diffuse attenuation (loss of light intensity down the water column) as calculated from an in situ radiometer? The goal of this objective was to determine whether the relationship between attenuation coefficient and Secchi disk depth is the same as the relationship between the absorption coefficient and Secchi disk depth.

2. **Methods**

2.1 Data Collection:

Data was collected on the *R/V Endeavor* EN616 "Cocco-mix" cruise in the Northwest Atlantic Ocean during July 2018 (Figure 1). A HyperPro radiometric sensor and Secchi disk were deployed consecutively at approximately noon on the day of each station on the sunny side of the ship. HyperPro data (courtesy of Brian Collister, Old Dominion University) was automatically recorded during deployment down the water column to a maximum depth of 100 m. The Secchi disk was deployed down the water column until it disappeared from the two observers' sight, then raised until it reappeared. The point of disappearance/reappearance was recorded in meters.

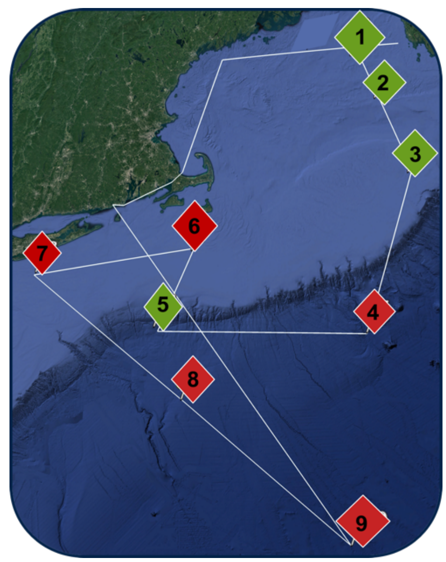


Fig. #1: Cruise track on *R/V Endeavor* cruise in July 2018. Number in diamonds indicate station number. Green diamonds indicate high coccolithophore concentration; red diamonds indicate low coccolithophore concentration.

2.3 Data processing

2.3.1 (Objective 1) The light absorption coefficient for each series in Poole and Atkins' (1929) study was calculated using the following equation: $(\ln 20/10)*(\log_{10}85-\log_{10}P20)$, where $\log_{10}85$ corrects for the assumption of 15% loss of light at the air-sea interface, (ln20/10) is a correction coefficient, and P20 is the percent illumination at 20 meters. Today, it is known that there is a ~50% loss of light at the air-sea interface (Idso and Gilbert, 1974). Note, Poole and Atkins (1929) combined natural- and base-ten logarithms in the same equation. To the best of our knowledge, no erratum was ever published by the authors regarding this so the reader was left to decipher which logarithms were intended. The relationship between vertical absorption coefficient and Secchi disk depth was determined by calculating the mean of the product of Secchi disk depth and vertical absorption coefficient for each series. A sensitivity analysis was conducted by processing the data using all combinations of natural versus base-ten equations and by correcting for 15% versus 50% loss of light at the air-sea interface. An ANOVA with a post-hoc Tukey test was used to test for differences among datasets. ANCOVAs were used to test how the different processing equations compared with the original Poole and Atkins' (1929) equation and if slopes of the corresponding regression lines differed between vertical absorption coefficient and Secchi disk depth.

2.3.2 (Objective 2) SeaBird HyperPro data were used to calculate the vertical absorption coefficient at 9 stations in July 2018. Irradiance measurements were collected and integrated between 400-700 nm wavelengths to calculate photosynthetically active radiation (PAR). Percent illumination was calculated using PAR values from the 2018 data by dividing the light at depth by the light at the surface. Poole and Atkins' methods for determining the vertical absorption coefficient were replicated using the equation: $\lambda_{0\text{-}20} = 0.115(\log_{10}85 - \log_{10}p_{20})$ (same as above, where $\lambda_{0\text{-}20}$ indicates the opacity between 0 and 20 m depth).

Once the opacity value was determined, $\lambda_{0\text{-}20}$ was multiplied by D (Secchi disk depth in meters) to get $D\lambda_{0\text{-}20}$. The mean of these values calculated at each station represents the relationship between Secchi disk depth and vertical absorption coefficient. Poole and Atkins (1929) described the average Secchi disk relationship in equation 1 below.

$$\lambda_{0\text{-}20} = 1.7/D \qquad (1)$$

The datasets containing Poole and Atkins (1929) data, 2018 high coccolithophore concentration data, and 2018 low coccolithophore concentration data were compared using an ANOVA and a post-hoc Tukey test to compare means. An ANCOVA was used to test for the ratio of variances of regressions between Secchi disk depth (independent) and absorption values (dependent) variables. Statistics were run using R software and plots of data were created using the ggplot 2 package (RStudio Team, 2016; Wickham, 2016).

2.3.3 (Objective 3) Poole and Atkins (1929) aimed to relate the vertical absorption coefficient with Secchi disk depth, but diffuse attenuation is more commonly used today to measure the loss of light intensity down the water column. Using Beer's law, the attenuation coefficient was calculated for 2018 data using PAR values for each depth down the water column, in 1 m intervals. The PAR value was $\log_e$ transformed and plotted (y-axis) against depth (x-axis) using the first measurement made closest to the surface (between 2-4 m) to the recorded Secchi disk depth for each station. The diffuse attenuation value was the absolute value of the slope of the regression line for the station. Diffuse attenuation was calculated for Poole and Atkins' (1929) raw data using measurements of voltage in units of thousand meter candles (k.m.c), measured using a photometer. Measurements were taken typically in 5 m intervals so fewer measurements were used to calculate the regression line (3-4 measurements) to the closest depth that approximately matched the recorded Secchi disk depth. The voltage measurements were $\log_e$ transformed, a regression line was calculated, and the attenuation value was equal to the absolute value of the slope of the regression line. ANCOVAs were performed to determine variances between Poole and Atkins' (1929) vertical absorption coefficient/Secchi disk depth regression line and the 2018 attenuation/Secchi disk depth regression.

3. **Results**

3.1 (Objective 1) The Secchi disk depth/vertical absorption coefficient relationship changed with variations in data processing (Table 1, Figure 2). The following equations were performed on Poole & Atkins data, listed so that every two equations alternate between accounting for 15% and 50% and all else equal, and are otherwise not listed in any particular order. The components changed in each version of each equation are bolded so that it can easily be compared with the equation listed directly before and after:

A. $(\ln 10/20)*(\log_{10}85-\log_{10}P20)$ - Poole & Atkins original equation
B. $(\ln 10/20)*(\log_{10}\mathbf{50}-\log_{10}P20)$
C. $(\ln 10/20)*(\mathbf{\ln 85-\ln}P20)$
D. $(\ln 10/20)*(\mathbf{\ln 50-\ln}P20)$
E. $(\mathbf{\log_{10}}10/20)*(\mathbf{\log_{10}85-\log_{10}}P20)$
F. $(\log_{10}10/20)*(\log_{10}\mathbf{50}-\log_{10}P20)$
G. $(\log_{10}10/20)*(\mathbf{\ln 85-\ln}P20)$
H. $(\log_{10}10/20)*(\ln\mathbf{50}-\ln P20)$

Significant differences ($p \leq 0.003$) were found when comparing Poole and Atkins' original equation and equation A with equations C, D, E, and F. Equations C and D produced datasets with significant differences ($p<0.0001$) when compared with each other and with datasets produced using equations E, F, G, and H. Equations E and F produced significantly different ($p \leq 0.0001$ to $p=0.002$) datasets when compared to equations G and H. Generally, all else being equal, datasets comparing calculations for 15% versus 50% loss of light at the air-sea interface did not have significant differences ($p \geq 1.44$), except comparisons of equations C and D ($p \leq 0.0001$). When ln and $\log_{10}$ were switched in the equation, with similar loss of light at the surface (i.e. $(\log_{10}10/20)*(\ln 85-\ln P20)$ versus $(\ln 10/20)*(\log_{10}85-\log_{10}P20)$, and when calculating for 50% loss of light at the surface), differences were not found ($p=1.0$).

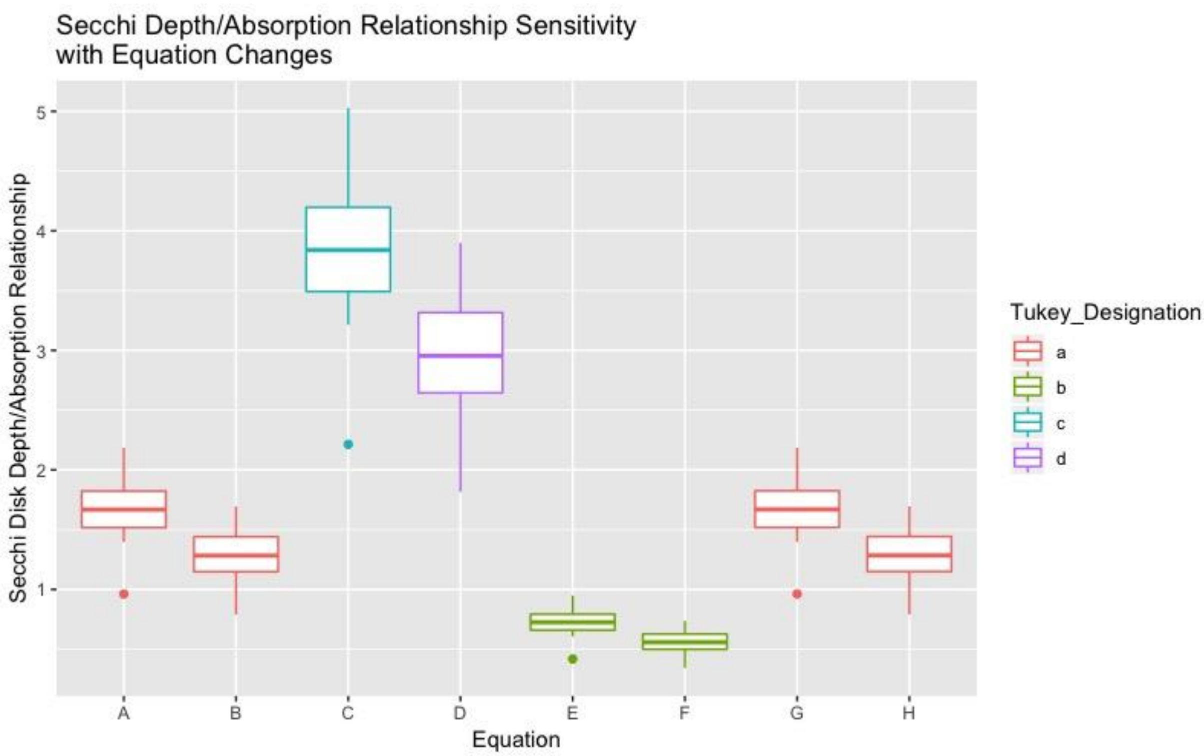
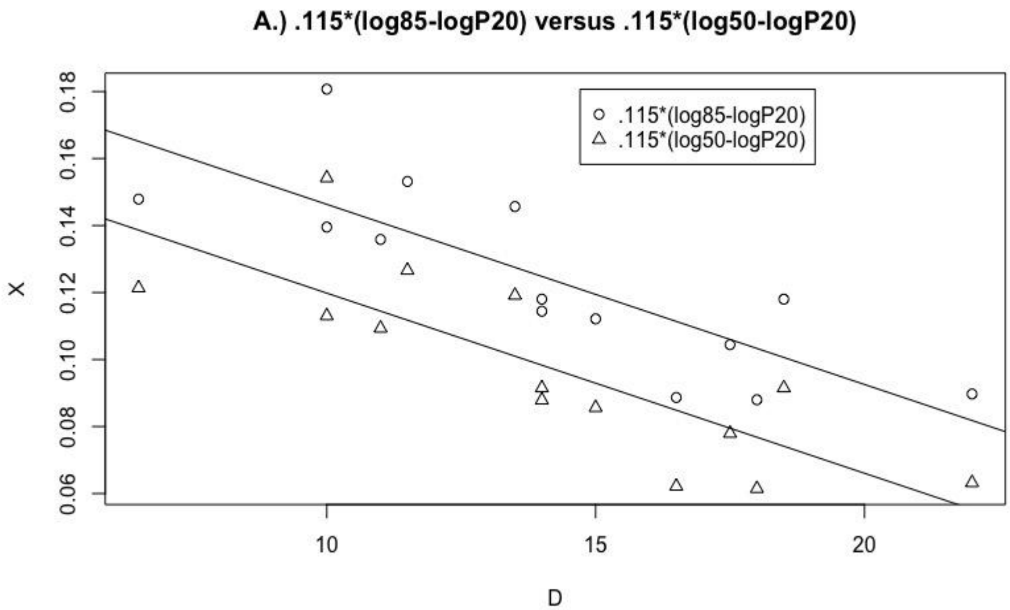


Fig. #2: Differences among datasets calculated by multiplying Secchi disk depth by vertical absorption coefficient, where the equation to calculate vertical absorption coefficient is altered to account for 15% versus 50% loss of light at air-sea interface and by changing whether ln or $\log_{10}$ transformations were used. The equations are labeled on the x-axis based on their letter designation, which are listed in Section 3.1. Box plots of the same color are not significantly different while boxplots of different colors are significantly different.

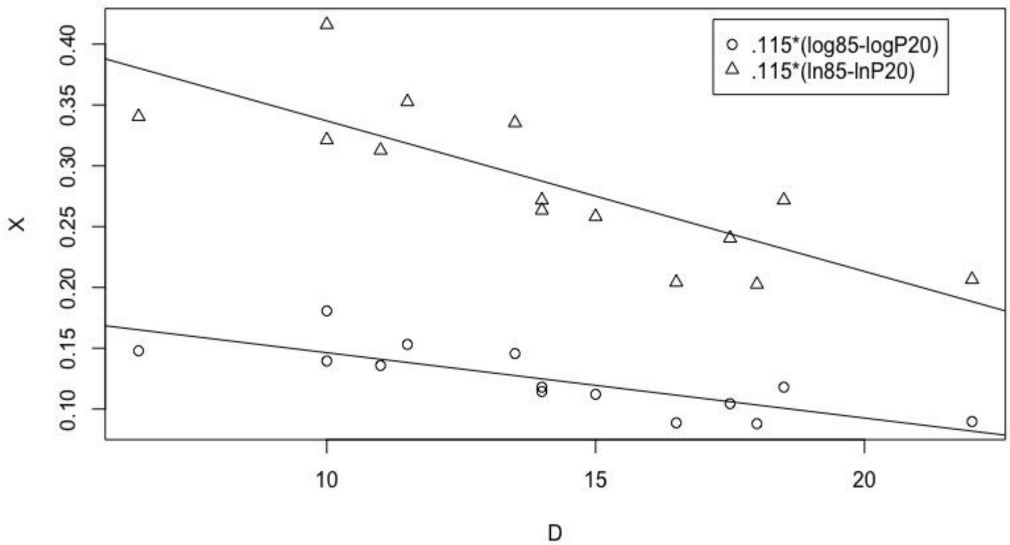
	A.) .115(log85 -logP20)	**B.) .115(log50 -logP20)**	**C.) .115(ln85 -lnP20)**	**D.) .115(ln50 -lnP20)**	**E.) .05(log85 -logP20)**	**F.) .05(log50 -logP20)**	**G.) .05(ln85-lnP20)**	**H.) .05(ln50-lnP20)**
A.) .115(log85 -logP20)		$p = 0.145$	**$p \leq 0.0001$**	**$p \leq 0.0001$**	**$p \leq 0.0001$**	**$p \leq 0.0001$**	$p = 1.000$	$p = 0.149$
B.) .115(log50 -logP20)			**$p \leq 0.0001$**	**$p \leq 0.0001$**	**$p \leq 0.01$**	**$p \leq 0.0001$**	$p = 0.141$	$p = 1.000$
C.) .115(ln85-lnP20)				**$p \leq 0.0001$**	**$p \leq 0.0001$**	**$p \leq 0.0001$**	**$p \leq 0.0001$**	**$p \leq 0.0001$**
D.) .115(ln50-lnP20)					**$p \leq 0.0001$**	**$p \leq 0.0001$**	**$p \leq 0.0001$**	**$p \leq 0.0001$**
E.) .05(log85-logP20)						$p = 0.942$	**$p \leq 0.0001$**	**$p \leq 0.01$**
F.) .05(log50-logP20)							**$p \leq 0.0001$**	**$p \leq 0.0001$**
G.) .05(ln85-lnP20)								$P = 0.144$
H.) .05(ln50-lnP20)								

Table #1: Statistical results of pairwise comparisons tests of varying components in the equations using Poole and Atkins (1929) data. The equations are labeled A, B, C, etc. as they are listed in the methods section 3.1. Significant p-values are bolded.

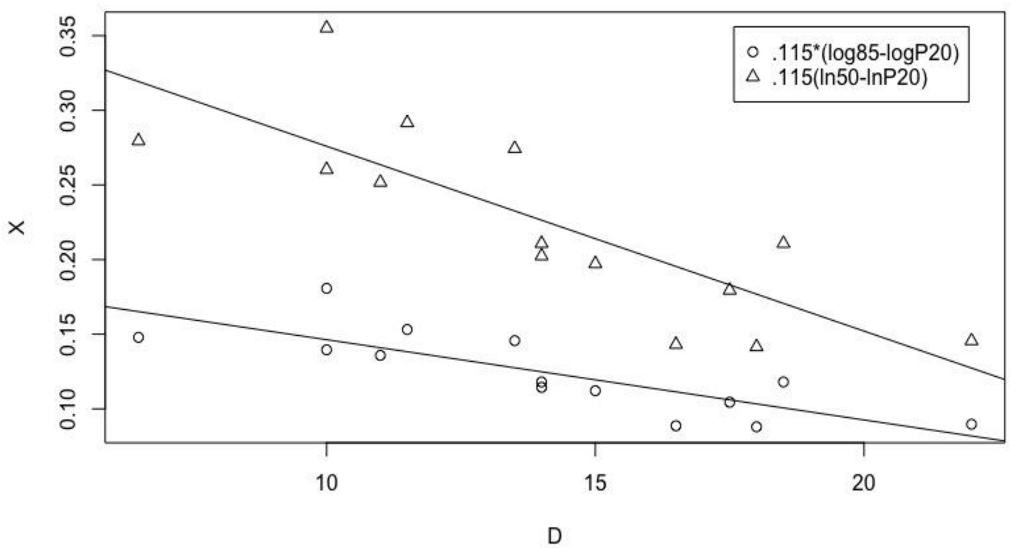
Results of the ANCOVAs (Figure 3) showed that when compared to Poole and Atkins' (1929) equation ($(\ln 10/20)*(\log_{10}85-\log_{10}P20)$), (shortened to: $.115*(\log_{10}85-\log_{10}P20)$ in the graphs), equations .115*(ln85-lnP20), .115*(ln50-lnP20), .05*(log_{10}85-log_{10}P20), and .05*(log_{10}50-log_{10}P20) have significantly different (p=0.007) ratio of variances, which shows that changes to the type of transformation used alters the results. However, this is not true when the logarithm types are reversed in Poole and Atkins' equation: (**ln**10/20)*(**log_{10}**85-**log_{10}**P20) versus (**log_{10}**10/20)*(**ln**85-**ln**P20) and (**log_{10}**10/20)*(**ln**50-**ln**P20). Accounting for 15% versus 50% does not significantly change the data because slopes are equivalent in (ln10/20)*(log_{10}85-log_{10}P20) and (ln10/20)*(log_{10}50-log_{10}P20).

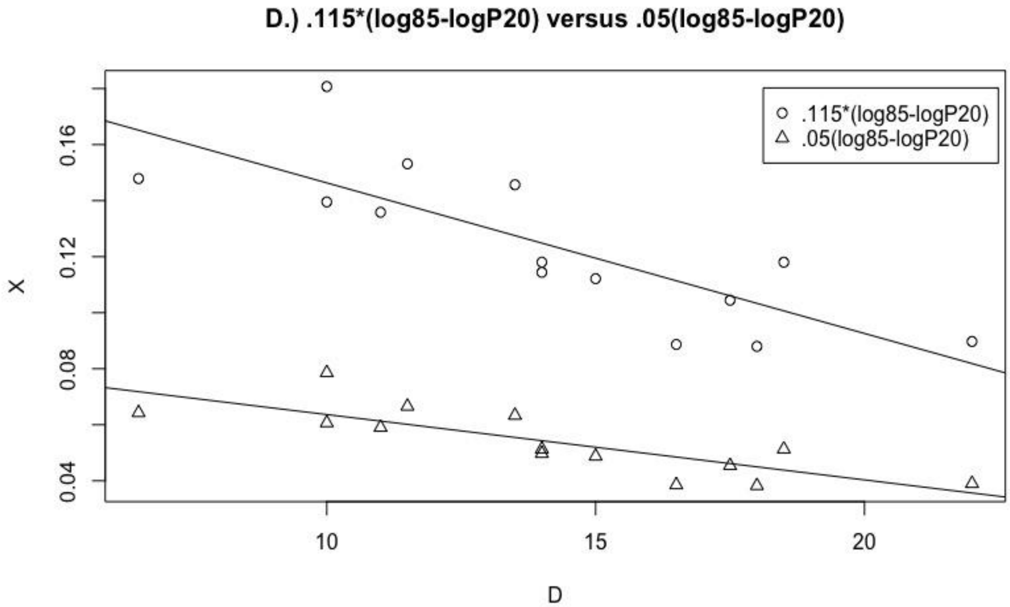


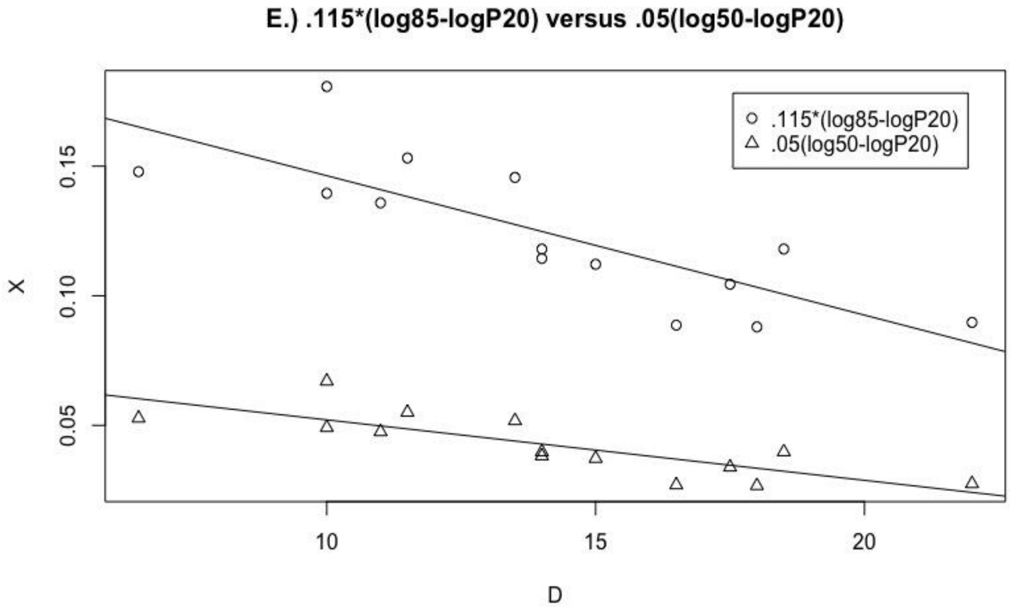
B.) .115*(log85-logP20) versus .115*(ln85-lnP20)

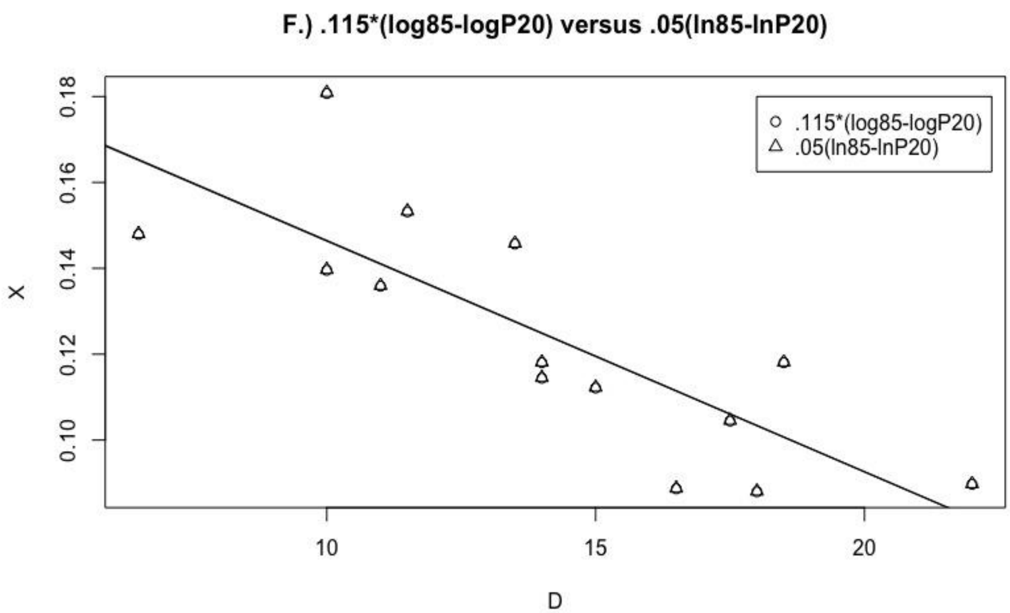


C.) .115*(log85-logP20) versus .115(ln50-lnP20)




D.) .115*(log85-logP20) versus .05(log85-logP20)
.115*(log85-logP20)
.05(log85-logP20)
X
0.04
0.08
0.12
0.16
10
15
20
D


E.) .115*(log85-logP20) versus .05(log50-logP20)
.115*(log85-logP20)
.05(log50-logP20)
X
0.05
0.10
0.15
10
15
20
D


F.) .115*(log85-logP20) versus .05(ln85-lnP20)
.115*(log85-logP20)
.05(ln85-lnP20)
X
0.10
0.12
0.14
0.16
0.18
10
15
20
D

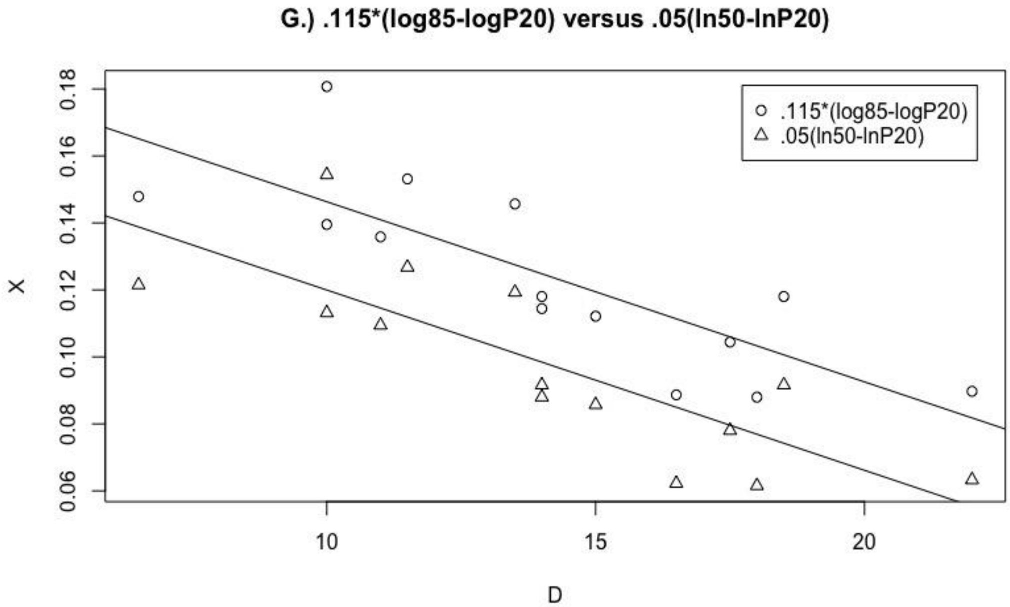


Fig. #3A-G: Plots are labeled A-G in title section of the plot. In each plot, the x-axis (labeled "D") is the Secchi disk depth for the series/station and the y-axis (labeled "x") is the calculated vertical absorption coefficient for each series/station.

	.115*(log_{10}50-log_{10}P20)	.115*(ln85-lnP20)	.115*(ln50-lnP20)	.05*(log_{10}85-log_{10}P20)	.05*(log_{10}50-log_{10}P20)	.05*(ln85-lnP20)	.05*(ln50-lnP20)
.115*(log_{10}85-log_{10}P20)	p=1	**p≤0.01**	**p≤0.01**	**p≤0.01**	**p≤0.01**	p=0.997	p=0.997

Table #2: Statistical results of pairwise comparisons of equation A with equations B-H (full equations and varying components listed in section 3.1). Significant differences are bolded.

3.2 (Objective 2) Significant differences were found in comparisons of the Poole and Atkins dataset, with high and low coccolithophore concentration datasets (ANOVA F = 24.407, p<0.001). The Secchi disk depth/vertical absorption coefficient relationship determined by Poole and Atkins (1929) was significantly different from both the high (p≤0.001) and low (p≤0.001) 2018 coccolithophore concentration datasets (Figure 4); however, the high and low 2018 coccolithophore concentration datasets were not statistically different from each other (Tukey p-value = 0.8).

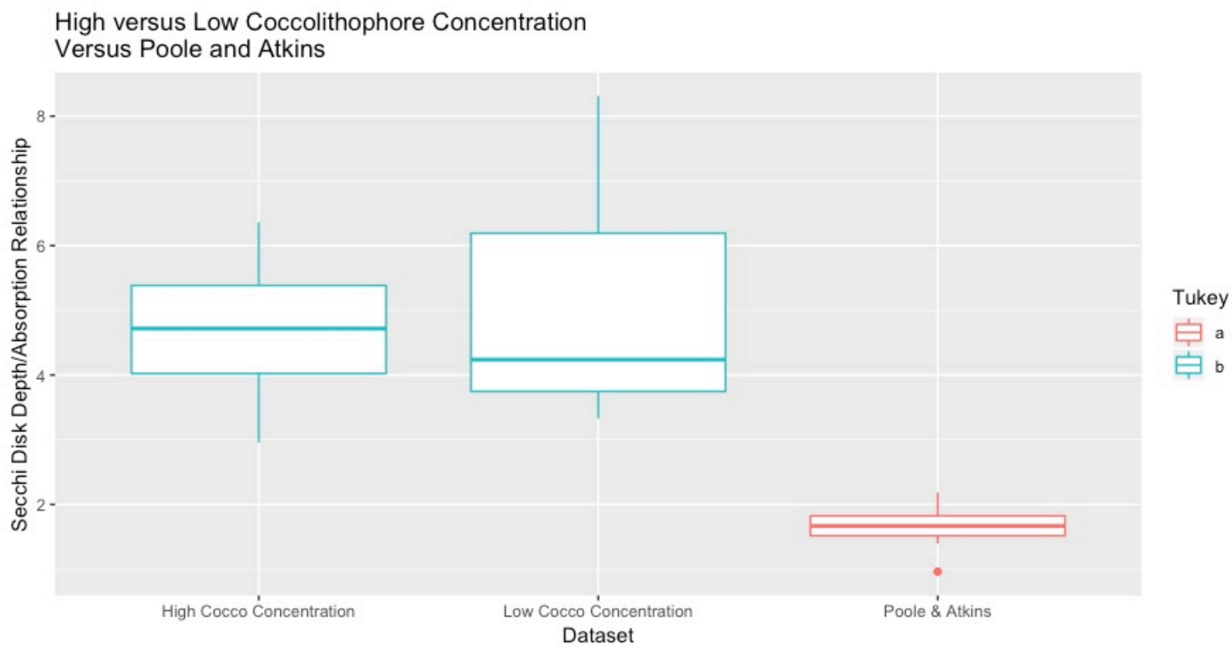


Fig #4: Results comparing the relationship between Secchi disk depth and vertical absorption coefficient for datasets of high and low coccolithophore concentrations, and Poole and Atkins (1929) (x-axis). The y-axis shows the result of Secchi disk depth * vertical absorption coefficient. Colors of the bar and whisker plots show that datasets of the same color are not significantly different, but datasets of different colors are significantly different from each other.

3.3 (Objective 3) No differences in slopes were found in comparisons of calculated attenuation coefficient*Secchi disk depth values using Poole and Atkins' (1929) data, absorption coefficient*Secchi disk depth values from Poole and Atkins (1929), and attenuation coefficient*Secchi disk depth values from 2018 data (p-values ranged from 0.058 to 0.12; F = 2.25).

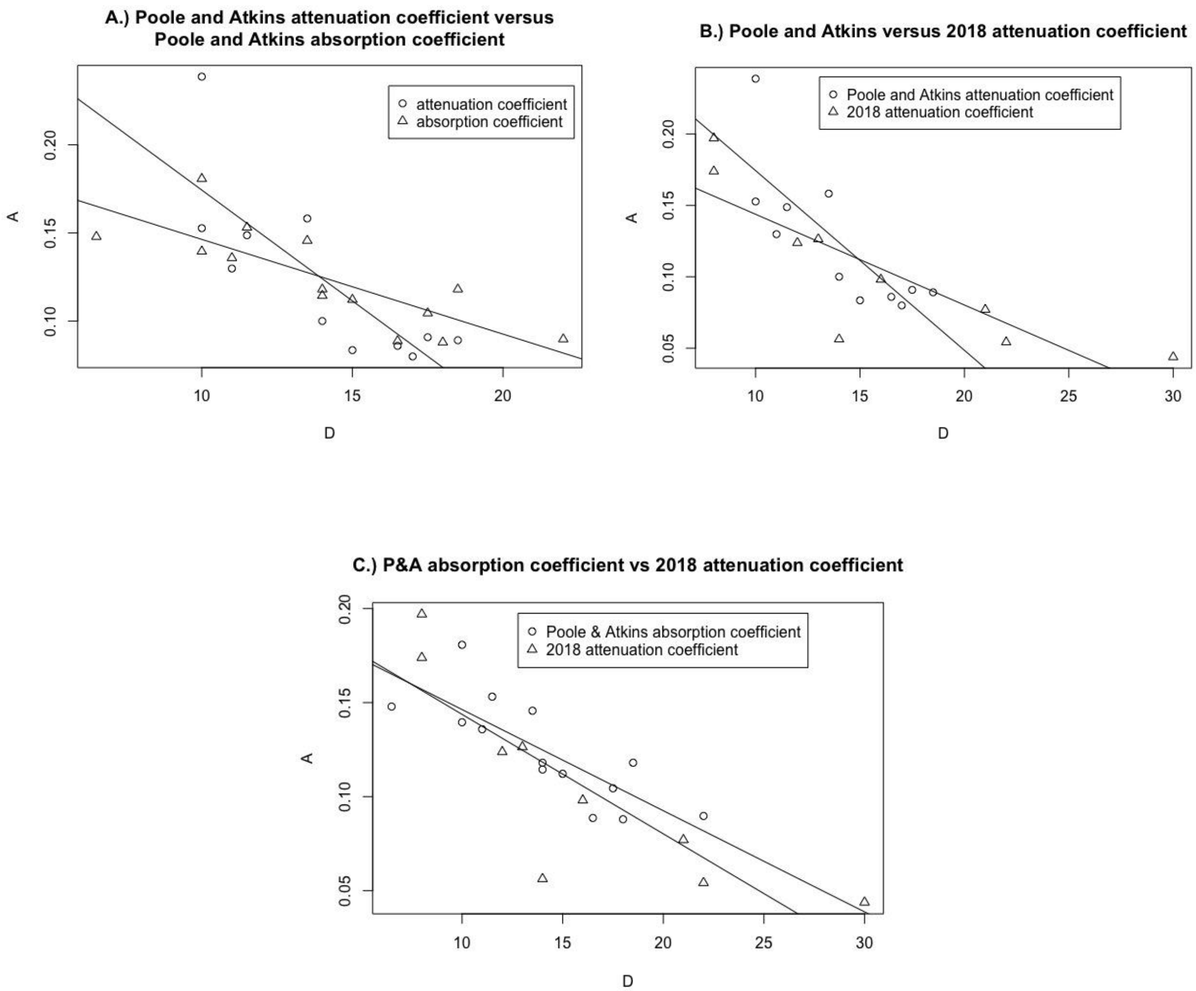


Fig. #5A-C: Comparisons of coefficient values of attenuation with vertical absorption (x). Plots are labeled A-C in plot title. X-axis ("D") is Secchi disk depth.

ANCOVA test inputs	p-value
P&A attenuation vs. P&A absorption coefficient	0.058
P&A attenuation vs. 2018 attenuation coefficient	0.94
P&A absorption vs. 2018 attenuation coefficient	0.06

Table #3: Results of ANCOVAs comparing attenuation with absorption.

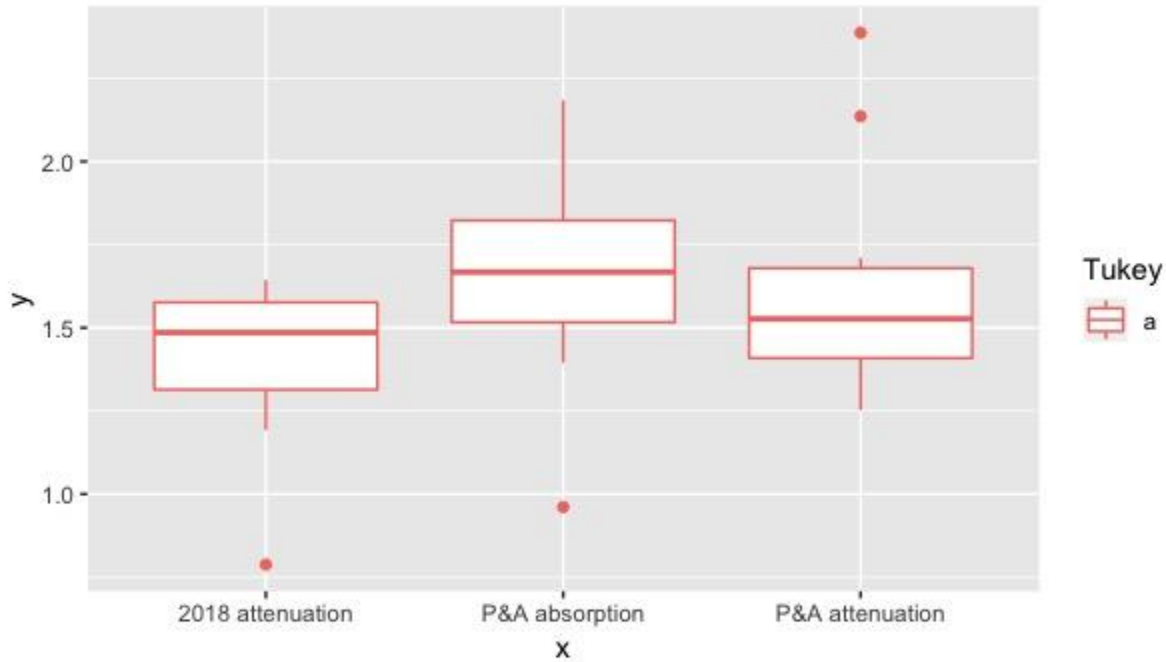


Fig #6: Box and whiskey plots comparing 2018 attenuation dataset, Poole and Atkins (1929) absorption dataset, and Poole and Atkins (1929) attenuation dataset (x-axis); absorption/attenuation * Secchi disk depth values correspond to the y-axis. Significant differences were not found.

4. **Discussion**

The results of Objective 1 indicate that the Poole and Atkins' (1929) equation should be examined to determine if there was a typographical error in their published study where the natural log and log base-10 were combined. It would be interesting to determine the equation used to calculate their results in comparison to the equation declared in the text. The results of Objective 2 show that coccolithophore concentration does not significantly impact the vertical absorption coefficient/Secchi disk depth relationship, but the 2018 data differs significantly from Poole and Atkins (1929) relationship. Results of Objective 3 suggest that variations in calculations for different inherent optical properties (absorption and attenuation) do not significantly impact results.

This study initially began with the intent to examine how coccolithophore concentration impacts the relationship between Secchi disk depth and attenuation. However, upon close examination of the classic study by Poole and Atkins (1929), questions arose as to how the authors combined different types of logarithms in their processing equations and whether their assumption of a 15% loss of light at the air-sea interface held true given different ocean conditions, and whether calculations using vertical absorption coefficient was equivalent to those using attenuation coefficient.

It is curious that Poole and Atkins (1929) chose to combine natural log with $\log_{10}$ when processing their data to calculate for vertical absorption coefficient. When examining results with variations to the usage of ln and $\log_{10}$ in the processing equation, there were significant differences when changing the sequence of ln and $\log_{10}$, though not when they were reversed in the equation. Changes to accounting for 15% versus 50% did not create a significant difference when all other parts of the equation were the same for most tests. This indicates that Poole and Atkins' (1929) equation is robust with regard to this correction. However, perhaps the test that produced significant differences when comparing 15% versus 50% loss of light was more prone to variation due to the usage of only ln in equations C & D. It is noteworthy that Poole & Atkins' (1929) conclusion (λ0-20=1.7D, where λ0-20 is opacity of water from 0-20 m) was not replicated in each shift of the equation, so would be worthwhile to investigate further how this equation was originally formulated, as well as testing their equation with their own data (provided in their original paper) to decipher whether the mixing of logarithms in their one equation was simply a typographical error and no erratum was subsequently published.

We did not find evidence that high concentrations of coccolithophores altered the relationship between Secchi disk depth and vertical absorption coefficient. It is possible (though unlikely because the p-value was large: p=0.8) that the sample sizes for high (n=5) and low (n=4) coccolithophore concentrations were too small to detect a significant difference, but more sampling could lead to the detection of a difference. This could be done through additional sampling of coccolithophore blooms in the Northwest and Northeast Atlantic Ocean. This would also help to determine if changes in primary productivity in the English Channel alter Poole and Atkins' (1929) relationship by testing the same waters as the study was originally conducted 90 years ago. However, using the same methods as Poole & Atkins (1929) for calculating vertical absorption coefficient, the 2018 data (high and low coccolithophore concentrations) were significantly different from the relationship derived by Poole and Atkins (1929) comparing vertical absorption coefficient with Secchi disk depth. Perhaps this result is due to changes between the water bodies where sampling occurred, as was found by Graham (1966) and Holmes (1970).

When comparing Poole and Atkins' (1929) method of calculating vertical absorption coefficient with methods using Beer's Law for calculating the attenuation coefficient, statistically significant differences in the data were not observed. The ANOVA and ANCOVA tests comparing Poole and Atkins' (1929) attenuation data, Poole and Atkins (1929) absorption coefficient data, and 2018 attenuation indicated no significant differences. These results are interesting because the data processing methods were different, but yielded similar results, which could potentially provide insight into why Poole and Atkins (1929) chose to use their original equation.

Additional considerations arise when analyzing data collection methods between Poole and Atkins (1929) study and the data collected during 2018. Poole and Atkins (1929) collected series of data in approximately the same location in the English Channel over an extended period of time while the 2018 data was collected on, typically, consecutive days, across a 12-day time period, in different locations in the Northwest Atlantic. The change in nature of data collection could have possibly impacted the results when comparing datasets. The English Channel is an inshore area and is likely prone to greater influxes of land-based pollutants and upwelling which may increase the concentration of nutrients in the water, in comparison to the stations sampled in the 2018 study. Stations 1, 2, 3, 6, & 7 were located on the continental shelf and are known to be productive, but were further offshore so were probably not as influenced by pollution and runoff as the English Channel waters. Stations located further offshore (stations 4, 5, 8, & 9) are likely to be even less influenced by upwelling and pollution. Therefore, the sampling regions in Poole and Atkins' (1929) study might have been very different from the sampling regions in the 2018 study.

This study shows that coccolithophores likely do not influence the relationship between vertical absorption coefficient and Secchi disk depth. Therefore, if water bodies are similar apart from coccolithophore concentration, it is likely that the same relationship may be used to make inferences about light absorption using only Secchi disk depth. This result counters the result of another study (an REU student internship project completed during Summer 2018 and the inspiration for this study), which aimed to compare ocean optics, specifically comparing two methods of measuring ocean color in varying concentrations of coccolithophores. However, to increase confidence when using this relationship to interpret historical studies, it is critical to better understand which equation Poole and Atkins (1929) originally used and why.

Acknowledgements

Support for the research cruise was provided by NSF Grant OCE-1635748. Many thanks to the captain, crew, and scientists of the *R/V Endeavor*. Thank you to Michelle Staudinger and Barney Balch for their mentorship and support on this project. Thank you to Brian Collister, Old Dominion University, for sharing his HyperPro data with me, without which this project would not be possible.

References

Balch, W.M. 2018. The ecology, biogeochemistry, and optical properties of coccolithophores. *Annual Review of Marine Science 10*: 71-98.

Balch, W. M., Gordon, H.R., Bowler, B.C., Drapeau, D.T., and E. S. Booth (2005), Calcium carbonate budgets in the surface global ocean based on MODIS data, *J. Geophys. Res. Oceans*, *110*(C7), C07001, doi:07010.01029/02004JC002560.

Balch, W. M., Gordon, H. R., Bowler, B. C., et al. (2005). Calcium carbonate measurements in the surface global ocean based on Moderate-Resolution Imaging Spectroradiometer data. *Journal of Geophysical Research 110*, C07001. doi: 10.1029/2004jc002560.

Doney, S. C., Ruckelshaus, M., Emmett Duffy, J., Barry, J. P., Chan, F., English, C. A., . . . Talley, L. D. (2012). Climate change impacts on marine ecosystems. *Annual Review of Marine Science, 4*(1), 11-37. doi:10.1146/annurev-marine-041911-111611

Garaba, S. P., Friedrichs, A., Voß, D., & Zielinski, O. (2015). Classifying natural waters with the Forel-Ule colour index system: Results, applications, correlations and crowdsourcing. *International Journal of Environmental Research and Public Health, 12*(12), 16096-16109. doi:10.3390/ijerph121215044

Gordon, H. R., Boynton, G. C., Balch, W. M., et al. (2001). Retrieval of coccolithophore calcite concentration from SeaWiFS imagery. *Geophysical Research Letters 28*(8), 1587-1590. doi: 10.1029/2000gl012025.

Graham, J.J. 1966. Secchi disc observations and extinction coefficients in the central and eastern North Pacific Ocean. *Limnol. Oceanog. 11*, 184-190.

Holligan, P. M., M. Viollier, D. S. Harbout, P. Camus, and M. Champagne-Philippe (1983), Satellite and ship studies of coccolithophore production along a continental shelf edge, *Nature*, *304*(5924), 339-342.

Holmes, R.W. 1970. The secchi disk in turbid coastal waters. *Limnology and Oceanography 15*: 688-694

Idso, S.B. and Gilbert, G. 1974. On the universality of the Poole and Atkins secchi disk-light extinction equation. *Journal of Applied Ecology 11*: 399-401.

Liu, X., Li, Y., Wu, Y., Huang, B., Dai, M., Fu, F., . . . Gao, K. (2017). Effects of elevated CO2 on phytoplankton during a mesocosm experiment in the southern eutrophicated coastal water of China. *Scientific Reports, 7*(1), 1-14. doi:10.1038/s41598-017-07195-8

Mobley, C. D. (1994), *Light and water: Radiative transfer in natural waters*, 592 pp., Academic Press, New York.

Pal, S., Das, D., and Chakraborty, K. 2015. Colour optimization of the secchi disk and assessment of the water quality in consideration of light extinction co-efficient of some selected water bodies at Cooch Behar, West Bengal. *International Journal of Multidisciplinary Research and Development 2*(3): 513-518.

Pitarch, J. (2017). Biases in ocean color over a secchi disk. *Optics Express, 25*(24), n/a. doi:10.1364/OE.25.0A1124

Poole, H.H. and Atkins, W.R.G. 1929. Photo-electric measurements of submarine illumination throughout the year. *Journal of the Marine Biological Association of the United Kingdom 16*: 297-324.

Poole, H.H. and Atkins, W.R.G. 1926. On the penetration of light into sea water. *Journal of the Marine Biological Association 14*: 177-198.

RStudio Team. (2016). RStudio: Integrated Development for R. RStudio, Inc., Boston, MA URL http://www.rstudio.com/.

Uitz, J., Stramski, D., Gentili, B., D'Ortenzio, F., & Claustre, H. (2012). Estimates of phytoplankton class-specific and total primary production in the Mediterranean Sea from satellite ocean color observations. *Global Biogeochemical Cycles, 26*(2), n/a. doi:10.1029/2011GB004055

Wernand, M. R. & van der Woerd, H. J. (2010). Spectral analysis of the Forel-Ule ocean colour comparator scale. *Journal of the European Optical Society – Rapid Publications, 5* 10014s-1-10014s-7. doi:10.2971/jeos.2010.10014s

Wernand, M. R., van der Woerd, H.J., & Gieskes, W. W. C. (2013). Trends in ocean colour and chlorophyll concentration from 1889 to 2000, worldwide. *PLOS ONE, 8*(6), e63766. doi:10.1371/journal.pone.0063766

Wickham, H. (2016). ggplot2: Elegant Graphics for Data Analysis. Springer-Verlag New York.