Analysis of Long Term Photosynthetically Active Radiation Data from McMurdo Dry Valley Lakes to Identify Turbidity Stratification Patterns

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Abstract

The current study focused on four perennially ice covered, meromictic, fresh water lakes in the Taylor Valley of the McMurdo Dry Valley region: West and East Lobe Bonney, Fryxell, and Hoare. Data from these lakes have been collected annually for more than 25 years, and are cataloged in the McMurdo Dry Valley Long Term Ecological Research database. The objectives of the current study were to determine whether turbidity stratification patterns could be identified within the four McMurdo Dry Valley Lakes, to look for seasonal and annual changes in those stratification patterns, and to correlate environmental data to identify potential causes of the turbidity. To identify patterns in turbidity, extinction coefficient depth profiles were calculated using photosynthetically active radiation data collected annually during the past 29 years. Averaging the profiles revealed distinct stratification of turbidity layers that were shown to be relatively stable across all recorded years. To examine potential causes of turbidity revealed by the extinction coefficient data, chlorophyll-a profiles were compiled for the same years, and compared to those of the extinction coefficients. Within the photic zones of Lake Hoare and East and West Lobe Bonney, chlorophyll-a was significantly correlated with turbidity. A linear plot of extinction coefficients against time revealed that later season average turbidity is much higher than that of early season turbidity, and that turbidity increases with depth in the photic zones of all lakes. Future research focusing on stream flow data could help identify the causes of the increase in late season turbidity observed in this study, and analysis of environmental data other than chlorophyll could help to determine what other phenomena control turbidity gradients in Lakes Fryxell and Hoare.

Introduction

The McMurdo Dry Valley (MDV) lakes are unique when compared to other lakes on Earth. Five key features make these lakes novel and of scientific significance: (1) they have perennial ice cover; (2) their only source of new water is glacial melt; (3) they are devoid of higher order plant life; (4) most are hydraulically terminal; and (5) lack of wind-driven mixing leads to a permanently stratified water column (Howard-Williams et al, 1998). Due to their uncommon nature, these lakes have been subjects of study for many years. The MDV was formally designated as a Long Term Ecological Research (LTER) site in 1993

(www.mcmlter.org). Long-term data on the Antarctic lakes are a critical asset in identifying components of global climate change. ***The objective of this study was to determine if turbidity stratification patterns could be identified within the McMurdo Dry Valley Lakes, to look for temporal changes of any stratification patterns found within the lakes, and to determine what causes the turbidity.***

The first long-term photosynthetically active radiation (PAR) data as part of the McMurdo LTER was collected during the summer season of 1993-1994, and can be found on the McMurdo LTER website. Data for this study was taken from the 1996-1997 summer season through the 2014-2015 season. PAR is the light wavelengths that are absorbed by photosynthetic organisms: 400 to 700 nanometers (Sigree, 2005). Measuring PAR allows us to quantify the energy available to phototrophs and is key to understanding the basic ecology in an environment (Fritsen and Priscu, 1999). This study compares long-term PAR water column profiles from four McMurdo Dry Valley lakes to identify turbidity stratification patterns within each lake. *The initial hypothesis was that, by comparing patterns in PAR across almost twenty years of data, turbidity stratification patterns would be identified, and that there have been time periods within each lake in which mixing or other layer-disturbing events occurred.* These potential disturbances or differences in stratification could indicate influxes of glacial run off, and point towards a warmer period in the region's climate.

Background

The lakes chosen for this study were Lake Fryxell, the east and west lobes of Lake Bonney, and Lake Hoare. All four lakes are terminal, meromictic, freshwater lakes located in Taylor Valley. Each is completely covered year round by about four meters of ice, and they vary in depth from 19 meters to approximately 40 meters. The chemical, physical, and biological properties of the lakes have been studied annually for more than three decades (Priscu, 1998). The data utilized in this study was previously analyzed for short time periods (Foreman et al, 2004), but has never been applied across all 20 years of PAR data collected by the McMurdo Dry Valleys LTER project.

There is evidence suggesting that there have been periods during which there was an increased influx of glacial melt (Foreman et al, 2004). This glacial melt can carry nutrients to an otherwise stagnant environment within the lakes. Due to this influx of water flow and nutrients, two events were hypothesized to occur. First, the nutrients may feed the otherwise starved microbes, causing an algal bloom, which would appear as a new or more turbid layer in the PAR data. Another possibility was that the increased flow would upset

the stratified layers, causing greater light displacement, and eliminating normal turbid layers. If either of these events were identified, it could be evidence to suggest a warmer period in regional climate.

Methods

Data Collection

This study primarily focuses on the use of PAR data collected along depth profiles in the McMurdo Dry Valley lakes. PAR data was collected using a Licor LI-1400 Data logger, a Licor LI-193SA spherical quantum sensor for measuring underwater PAR, and a Licor LI-190SA quantum sensor for measuring ambient PAR, from Li-Cor Biosciences (www.LICOR.com). A sample hole was drilled through the ice above the deepest part of the lake. The ambient light sensor was placed on the ice surface near the sample hole to measure light that reached the surface of the ice. The underwater sensor was slowly lowered into the hole, taking measurements at half meter increments, from the bottom of the ice layer to the bottom of the lake or until PAR decreased below the limit of detection.

Extinction Coefficient

The PAR data was recorded in units of μmol photons m^{-2} s^{-1}. To use this to identify stratified layers of turbidity, an extinction coefficient was calculated, which indicates how strongly light was diffusing in the system, rather than simply how much light existed at that depth. To calculate the extinction coefficient, Beer's Law was used (Valiela, 1995):

$$I = I_0 e^{-kz}$$

where I_0 is the measured PAR at the surface or first depth of the interval, I is the measured PAR at the second depth of the interval, z is the change in depth, and k is the extinction coefficient. This equation was then solved for k in order to plot the coefficient in a manner which allowed layers to be identified. The following equation was used for this study (Lalli and Parsons, 1997):

$$k = -\left(\frac{ln\left(\frac{I}{I_0}\right)}{\Delta z}\right)$$

The plot of extinction coefficient with respect to depth shows the amount of light scattered at each depth identifying turbidity layers. A higher k value represents a depth that is more turbid, or contains more particles which causes greater light attenuation, than depths with a lower k value. Average K values were found for all recorded data for the 4 chosen lakes.

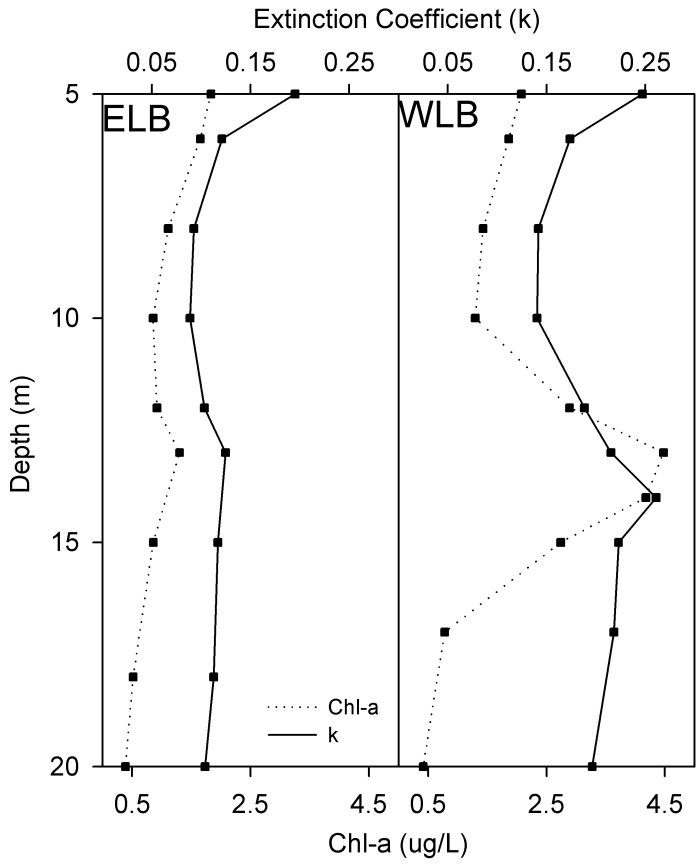


Fig. 1. Extinction coefficient and Chl-a values plotted with depth for East Lobe and West Lobe Bonney photic zones, 5m to 20m.

A positive slope for k in Fig. 1 indicates water is becoming more turbid with depth, while a negative slope indicates less turbidity. A peak occurs at a depth that is more turbid than the depths either above or below it. This can be described as a turbid layer in the water column.

Temporal Trends

To determine if turbidity stratification changed with time, the data was analyzed in two ways. First, the water columns of each lake were divided into three sections. Each lake has a photic zone (the area in the water column which light reaches) and a non-photic zone. The photic zone was then divided into two sections: the surface layer where PAR was affected by the ice cover, and the middle layer of the lake. The non-photic zone could not be used for any part of this study due to the lack of measurable PAR. An average extinction coefficient was found for the photic and surface zones for each PAR sampling date, and plotted (Fig. 2, bottom panel). These plots show how turbidity has changed over all recorded years for the two different layers. The purpose for including the surface layer was to determine if streams carrying new sediment could be a cause for increased turbidity.

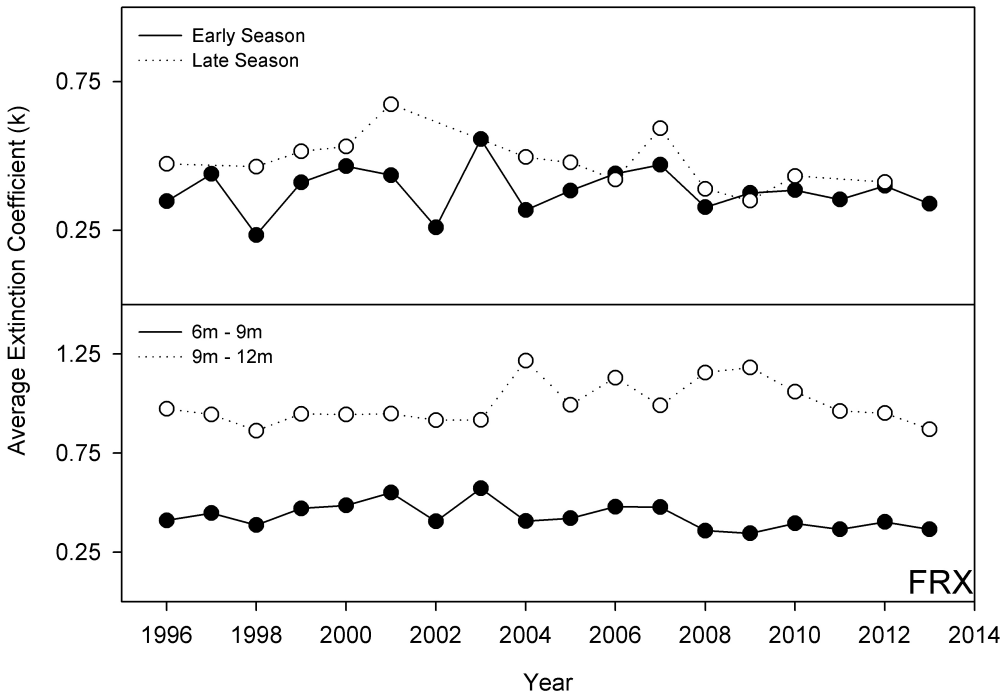


Fig. 2. Temporal trend data for Lake Fryxell, with time on the x-axis. The top panel represents early and late season surface layer data, while the bottom panel represents all-season averages for two layers in the water column.

The second temporal change study was done by separately using just the photic zone averages of the early and late season data (Fig. 2, top panel). The purpose of this was to determine if turbidity increased in late season due to the increased flowing of streams. If higher turbidity was detected in late season data, this could indicate that higher stream flow directly influenced turbidity, and thus warmer years may show similar patterns.

Chl-a

It had been hypothesized that biological cells or sediments may contribute to the turbidity of these lakes. To test this, chlorophyll-a (chl-a) data was chosen as an indicator of cells in the water column because it had been measured at various depths for all of the lakes in question, across all years of data collection and is a major pigment in photosynthetic cells. This chl-a data was analyzed in a similar manner to that of extinction coefficient, and an average for each depth was found and plotted. Chl-a and *k* were then plotted together to locate similar patterns in depth profiles. Fig. 1 demonstrates the correlation between chl-a and turbidity with depth for ELB and WLB.

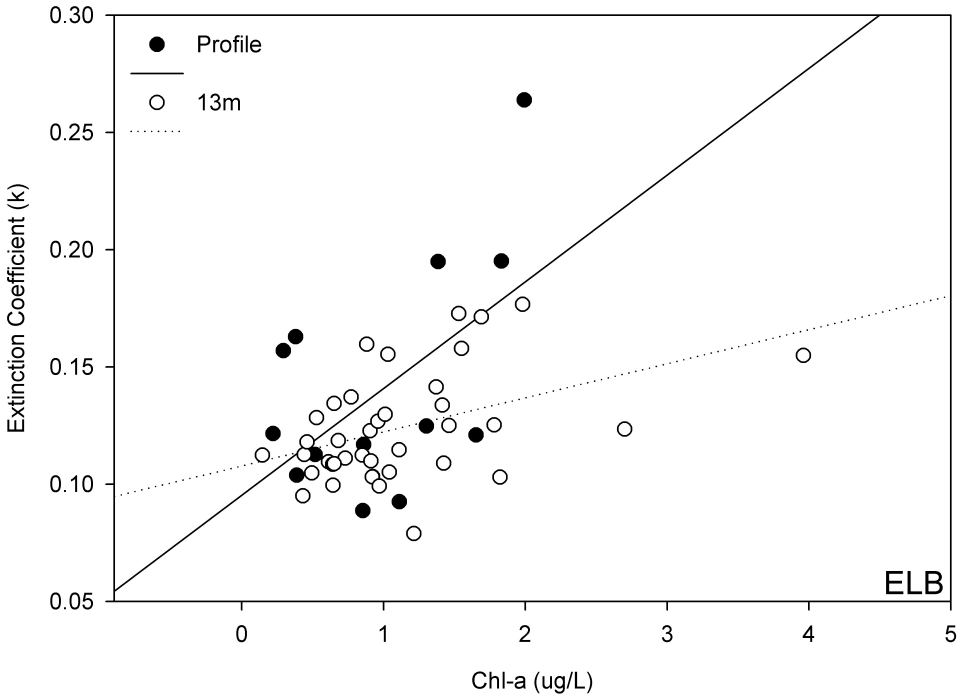


Fig. 3. Extinction coefficient values plotted on the y-axis, with chl-a values on the x-axis, demonstrating linear correlation between the two variables in ELB.

To determine if any pattern similarities were a true correlation between *k* and chl-a, another plot was made. With chl-a on the x-axis, and *k* on the y-axis, a perfect correlation between turbidity and chl-a would show linearity with an R-squared value of 1. The y-intercept of such a graph would then represent the turbidity of the water with chl-a removed, and would be near zero if the water was clear. To determine if any linearity found was significant, an R-value was found and compared to a significance chart. For this study, all linear correlations (except the FRX profile) were found to be statistically significant, though most appear very scattered when plotted. Fig. 3 demonstrates a linear correlation, with a solid line to indicate linearity of the profile data, and a dotted line showing that of data from 13m, the peak of chl-a in ELB. It should be noted that these linear correlations are not strong enough to form any predictions, but may be used to draw conclusions on relatedness.

Results and Discussion

Turbidity Patterns

By finding extinction coefficients from PAR data, and averaging the depth profiles across all recorded years, patterns were discerned. It can be seen in the graphs that each of the four lakes has varied zones of turbidity. West and East Lobe Bonney (WLB, ELB) show

turbid peaks at similar depths, 13.5m and 14m respectively (Fig. 1). These two lakes also demonstrate a downward trend in turbidity from the surface, with a high extinction coefficient close to the ice, steadily decreasing until it levels off around 9m in depth. Because these lakes are connected, sharing similar characteristics, the turbid similarities are not unexpected. Data for these lakes is considered inaccurate past 20m, the base of the photic zone, due to significant loss of light at those depths, as well as data above 5m due to influence from surface ice.

Lake Hoare (HOR) shows very similar trends (Fig. A.1) as WLB and ELB, though it is geographically unrelated. The data is somewhat less predictable and more varied than that of the other lakes, but a similar downward trend from 5m to 9m can be seen, followed by a steady incline in turbidity, peaking at 14.5m. Data deeper than 22m for HOR is considered inaccurate due to significant loss of light.

The extinction coefficient data differs substantially for Lake Fryxell (FRX, Fig. A.2) than for the other lakes. An extinction coefficient peak can be clearly discerned at 10.5m. The value of this peak is more than four times higher than that of the other lakes, indicating significantly higher turbidity. The data compiled for FRX also looks to be generally more predictable than that of the other lakes, with less variation between depths. Below 15m, the PAR data from FRX becomes too low or non-existent. This is a shallower base photic zone depth than that of the other lakes, set for 6m to 12m for temporal trend data.

Temporal Trends

WLB consistently demonstrates a higher average extinction coefficient at 10 to 20m than at 6 to 10m (A.8). There are also two obvious peaks that appear in both layers simultaneously. When early season and late season data are compared for WLB, late season turbidity is almost always higher than that of early season. The two layers of ELB follow each other more closely than those of WLB, despite there being almost identical depths between the two lakes (A.6). There is also less variation between early and late season data at the surface of ELB than of WLB, however, late season extinction coefficients still averaged higher than those of early season for both lakes

Temporal data from two depths of HOR seem to follow each other closely, with the only exception being a major peak in December of 2006 (A.7). This turbidity peak can also be seen in early season data, where it rises above that of late season of the same year. Other than 2006, late season data from HOR has a similar trend as WLB and ELB, and averages higher than that of early season.

The highly turbid peak of FRX can be seen in the temporal data, as well (Fig. 2). The lower depth demonstrates a much higher average turbidity than the shallow depth across

all years. As with the other three lakes previously discussed, late season data of FRX shows a higher average extinction coefficient than early season.

Chl-a Data

The chlorophyll data for WLB and ELB are very similar, with the highest peaks at the same depths, though a key difference being that ELB contains less overall chl-a than WLB. When compared to average extinction coefficient data (Fig. 1), both chl-a and *k* follow very similar trends. The deepest chl-a data used is 20m for both lakes, which is near or at the bottom of the photic zone. The lack of light at these depths can be seen in the significant drop in total chl-a. A plot of Chl-a versus *k* for WLB and ELB (Fig. A.3 and Fig. 3, respectively), shows similar results. The slope was positive in both cases. Data from the chl-a peak of each lake was then separately graphed and the resulting slopes were very similar to those of the overall data.

Chl-a in FRX had a peak resembling that of the extinction coefficient data, though it occurred 1.5m higher in the lake (Fig. A.2). When chl-a was plotted against *k*, however, the slope of the line was negative, with an R-squared value approaching zero (Fig. A.4), indicating almost no correlation between the two variables across the entire water column. The same relationship was plotted with data from the chl-a peak at 9m, resulting in a positively sloped line with a greater R-squared value indicating a closer correlation between chl-a and *k* at that depth. Similarly, the same graph with data from the turbid peak at 11m resulted in a slope that was again nearly 0, with a low R-squared value.

HOR chl-a data was different than previously discussed turbidity patterns. While the highest *k* can be found near the middle of the photic zone, the highest chl-a was found to be near the surface directly beneath the ice (Fig. A.1). The chl-a then steadily declined to a value of almost zero, a trend dissimilar to those of the other three lakes. The plot of chl-a versus *k* for HOR showed a positive slope (Fig. A.5). A plot of data from only the chl-a peak at 6m resulted in an even steeper slope, with a y-intercept near zero.

Conclusion

The objective of this study was to determine if turbidity stratification patterns could be identified within four McMurdo Dry Valley Lakes, to look for temporal changes of any stratification patterns found within the lakes, and to determine potential causes for the turbidity. It had been hypothesized that by using almost 25 years of data to find the extinction coefficient of PAR, patterns in turbidity stratification could be identified and utilized. This study shows that there are consistent turbid patterns in the photic zones of Lakes West and East Lobe Bonney, Fryxell, and Hoare in the McMurdo Dry Valleys. These

turbid layers vary from lake to lake, and are likely caused by different ecological phenomena.

It was found that the greatest turbid peaks in West and East Lobe Bonney are similar in that they are at the same depth and both show a strong correlation between extinction coefficient and chl-a, suggesting that the photosynthetic cells suspended in the water column play a significant role in causing turbidity in the lakes. The y-intercepts found in the chl-a versus *k* plots indicate that there is still some background turbidity in the water, which is not explained by the cells. This study is unable to explain this background turbidity.

This study also determined that Lake Hoare displays similar turbidity patterns to those of ELB and WLB, with a turbid peak at 14m. However, the depth of greatest correlation between chl-a and *k* was found to be at the 6m, which is near the surface and is the chl-a maximum point. At this depth, the y-intercept was found to be almost zero, indicating that there is very little background turbidity. It can be concluded that chl-a still plays a significant role in causing turbidity in the water column, but that the background turbidity varies. To verify this, further analysis on the background turbidity of HOR must be conducted.

Lake Fryxell showed the greatest extinction coefficient values. At 10.5m, FRX waters are more turbid than any other depth in the photic zones of the four lakes in this study. When chl-a and *k* were compared, it was determined that the greatest turbidity in FRX is not caused by suspended photosynthetic cells. At the ch-a peak, there was a correlation similar to the other lakes studied, which indicates that something is causing turbidity at lower depths that is not present at higher ones. Further study is needed to determine the cause of this higher turbidity, but it is hypothesized that high levels of iron sulfide at the chemocline is the likely contributor.

While there were no major findings on temporal trends in turbidity patterns, a few observations were made. The first was that all four lakes show an increased average turbidity in the lower portion of the photic zones. This is due to the chl-a peaks being similarly positioned in the water column. The exceptions to this are FRX, with the largest turbidity layer that is not caused by chl-a, and HOR, which has higher background turbidity in its deeper section of the photic zone. Secondly, all four lakes show an increased average turbidity near the surface in later season data than that of early season data. This is almost certainly caused by higher stream flows as the valley temperatures increase later in the summer. To further test this observation, stream flow data may be examined.

Future studies are required in order to determine exact causes of turbidity in the water columns of the four lakes which were not explained by chlorophyll levels. Stream flow and temperature data will also assist in studying the cause of high turbidity in later season data.

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Appendix

Graphs

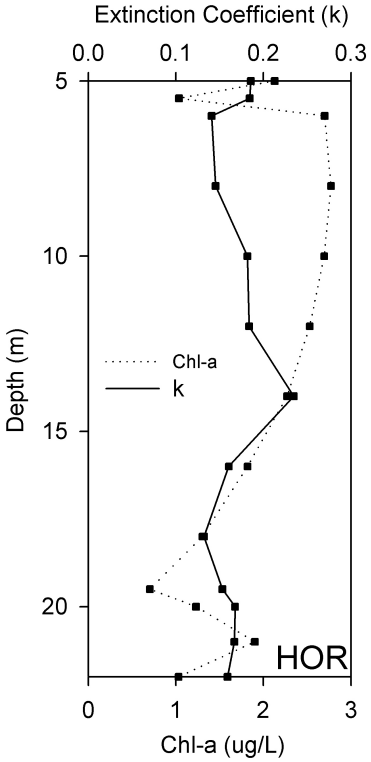


Fig. A.1. Extinction coefficient and Chl-a values plotted with depth for the Lake Hoare photic zone, 5m to 22m.

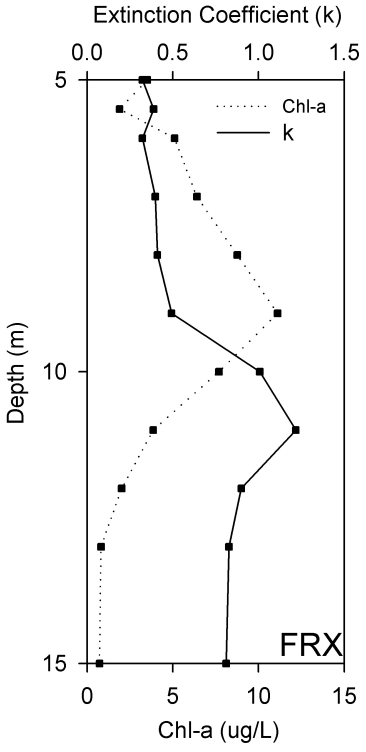


Fig. A.2. Extinction coefficient and Chl-a values plotted with depth for the Lake Fryxell photic zone, 5m to 15m.

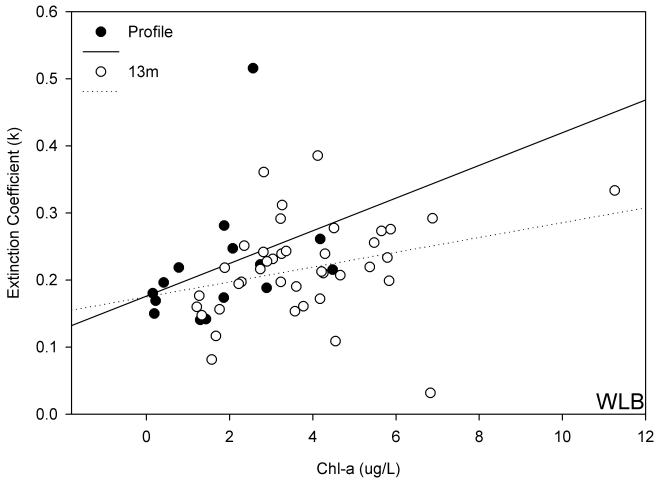


Fig. A.3. Extinction coefficient values plotted on the y-axis, with chl-a values on the x-axis, demonstrating linear correlation between the two variables in WLB.

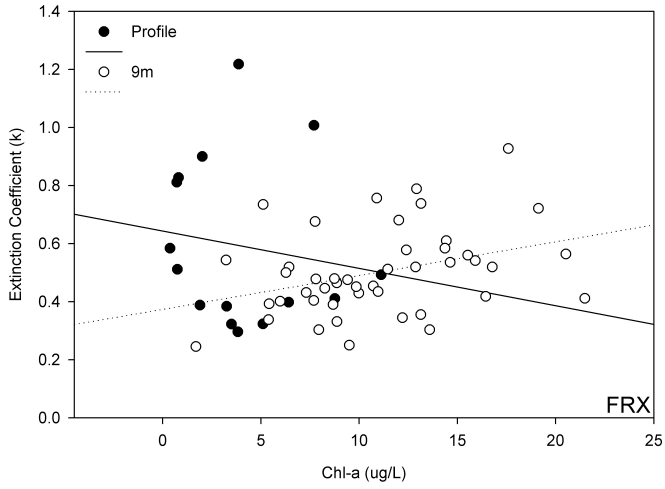


Fig. A.4. Extinction coefficient values plotted on the y-axis, with chl-a values on the x-axis (demonstrating linear correlation at 9m but not of the profile data) of FRX.

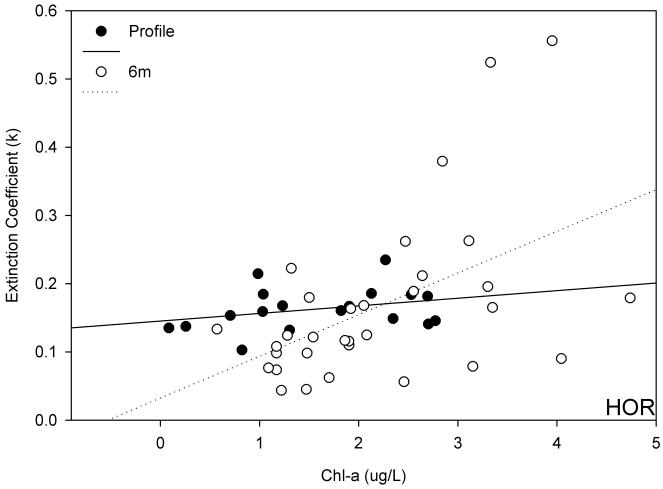


Fig. A.5. Extinction coefficient values plotted on the y-axis, with chl-a values on the x-axis, demonstrating linear correlation between the two variables in HOR.

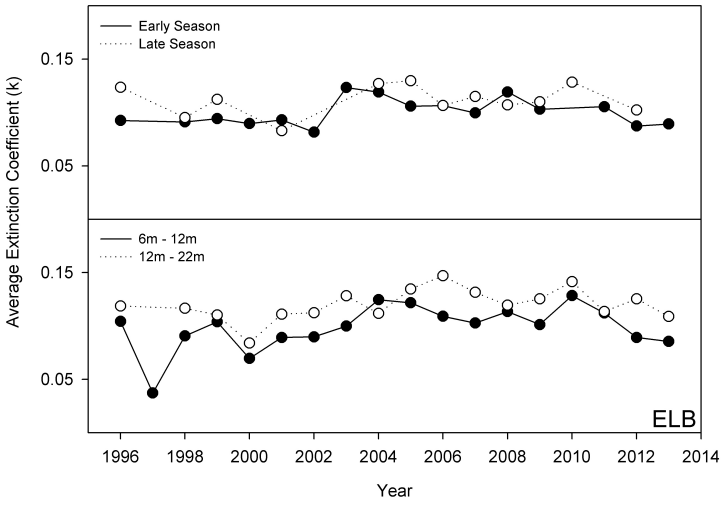


Fig. A.6. Temporal trend data for ELB, with time on the x-axis. The top panel represents early and late season surface layer data, while the bottom panel represents all-season averages for two layers in the water column.

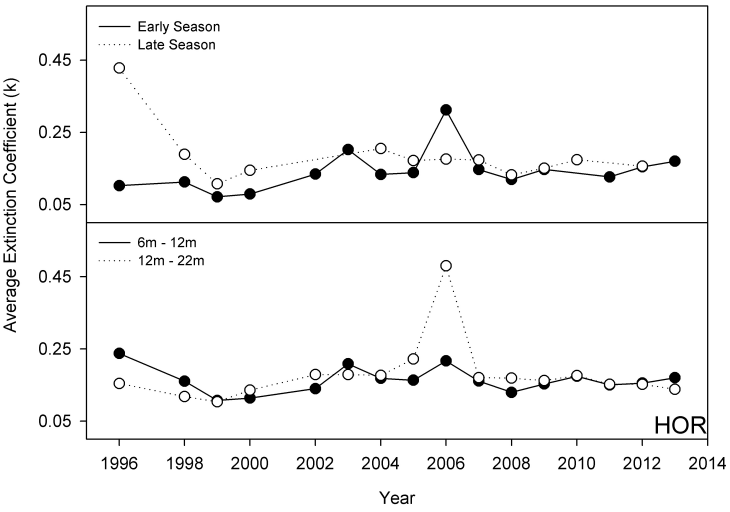


Fig. A.7. Temporal trend data for HOR, with time on the x-axis. The top panel represents early and late season surface layer data, while the bottom panel represents all-season averages for two layers in the water column.

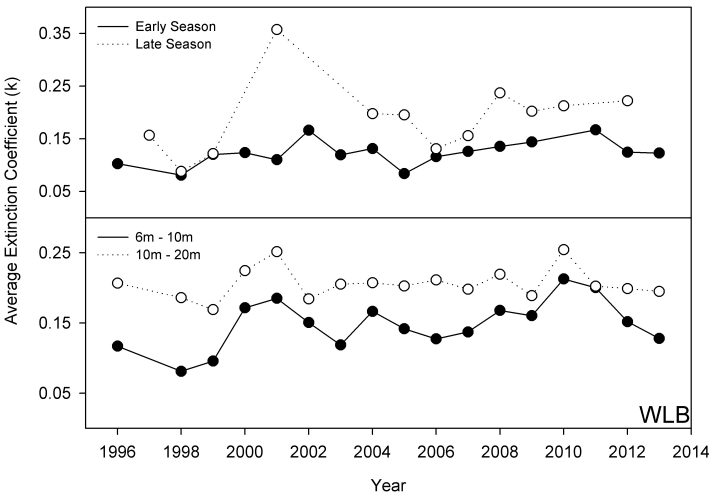


Fig. A.8. Temporal trend data for WLB, with time on the x-axis. The top panel represents early and late season surface layer data, while the bottom panel represents all-season averages for two layers in the water column.