A Tale of Two Lakes: An Analysis of Lake Optics and Their Effects on Turbulence

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by
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Contents

Abstract

This paper aims to analyze and compare the optic properties which regulate turbulence in Lake Lacawac and Lake Giles and how these conditions change as the lakes warm and darken. Lake Giles and Lake Lacawac are both strongly stratified and have very different compositions and sizes. Despite their differences, Lake Giles is evolving to resemble Lacawac's structure and behavior. After analyzing how our two subject lakes change in response to warming and darkening, we asses what such changes are likely to follow in a whole range of lakes represented by Lacawac and Giles in terms of composition and inner mechanism. The inner mechanisms of the lakes are mapped using turbulence parameters such as *vertical eddy diffusivity* K_z and the *rate of dissipation of turbulent kinnetic energy* ε.

1
Lakes are Lenses with Life in Them

As climate change progresses, the energy cycle of lakes is interrupted[1]. More energy is being absorbed by lakes than ever before and the stability of underwater ecosystems is threatened as a result. Even without climate change as a factor, the ecosystems in question already depend on many sensitive factors such as water composition. There exists a direct link between water composition and the energy absorbed by lakes, these two factors take turns affecting each other. Water composition influences lakes' optical properties, which establish not only how much energy it will absorb, but also how said energy will affect the lake and alter its initial optical properties. Different dissolved gasses and solid particle content contribute to a lake's absorption and reflexive rates of solar radiation. This is what is meant by 'water composition'. *Absorption* is the rate at which light energy is transformed into heat energy as it travels deeper into the lake[2]. As energy is inputted into a lake, it plays a role either strengthening or disrupting the lake's inner structure, depending on the source of the inputted energy and the type of energy itself, as we will see. The lake's inner structure can regulate or limit the parameters of habitable regions in the water and thus moderate the abundance of life in underwater environments. Any

[1] Pilla, Browning-Related Decreases in Water Tansparency Lead to Long Term Increases in Surface Water Temperature and Thermal Stratification in Two Small Lakes

[2] Wetzel, Limnological Analyses. Second Edition, 1991

input of energy will either effect underwater mixing or constrain it, redefining the lake's composition, in turn affecting its optical properties and how much energy is absorbed by the lake from then on. As lakes darken, their energy absorption rates increase, resulting in less movement in the water between the different layers, which results in less mixing and more darkening and so on. At the same time, the potential for growth inside the lakes drastically decreases. The specifics behind this process will be made clear gradually throughout this thesis (for now please accept this only to understand the environmental impact of energy increase and thus the necessity for this study).

A healthy aquatic ecosystem must see continuous mixing so as to redistribute nutrients and microorganisms homogeneously. Microorganisms such as phytoplankton are a critical piece in the nutrition cycle of aquatic environments. Yet they only thrive in an area with very particular conditions near the surface called the photic region. Microorganisms need light to photosynthesize as well as they need warmth, both of which are most abundantly found at the surface. However, an excess of either of these may harm microorganisms, so the ideal zone for them is not right at the surface and not too far below, but rather some depth range where their needs can be met in moderation, this is called the photic region. As lakes darken their absorption rates increase. Higher absorption rates mean more heat which lowers the upper limit of the photic region, but this also means light will not travel as deep, which raises the lower limit of the photic region. Too much change shrinks the photic region to a dangerous level, jeopardizing a lake's ecosystem.

My goal is to analyse the energy dissipation in two particular lakes, Lake Lacawac and Lake Giles. Through my analysis, my aim is to accomplish the following: relate the differences in the lakes' internal behaviors to the differences in their compositions, and assess how the changes in composition and energy cycles harm the potential to develop or sustain life in these lakes.

1.1 Background on Solar Radiation

To talk about the way light behaves when traveling through or reflecting from lakes, we must first establish how we will address the light energy they interact with. Solar radiation that reaches the surface of the earth ranges between 300nm (ultraviolet) and 3000nm (infrared). *Photosynthetically active radiation* (PAR) is that between 390nm and 710nm, and despite making up less than a third of the spectrum showering the earth's surface, it accounts for somewhere between 46% and 48% of the energy impinging on the surface of the earth[3]. The *Radiant Flux* refers to the electromagnetic flow over time and is expressed as *photons/sec* but we will use the more familiar measure of power *joules/sec*, also known as *watts*. When we study particular lakes, we generalize the radiation exposure by breaking up the lake into discrete vertical columns of water where we can isolate effects such as light penetration or temperature as they vary solely by depth. In the next chapter I will expand on these vertical profiles we compose using data. When we look at these discrete columns of water, we break up the radiant flux into power found only within each particular column, we call this *irradiance*. Irradiance is radiant flux per unit area, so it is denoted using $watts/m^2$.

1.2 Light and Lakes

The process which determines how much and what type of solar radiation reaches a lake's surface is dependent on a plethora of factors. Variables affecting how much radiation reaches the surface of a lake begin with the journey of solar radiation, originating from its emission from the sun and through the atmosphere. Solar radiation is critical because it introduces energy into the lakes as it gets absorbed and turned into heat and is also used by organisms in them to photosynthesize. Latitude, time of the day, and season play big roles in regulating radiation exposure as different regions might either see the sun for

[3]Strickland, 1958; Talling, 1957; Westlske, 1965; Kirk 1983; Wetzel, Limnological Analyses. Second Edition, 1991

months at a time or only for an hour or two a day just above the horizon. When considering how much solar radiation a lake is exposed to, direct radiation is not the only one that matters. Some portion of sunlight scatters when it passes the atmosphere, and depending on the incident angle of the sun, scattered radiation will make up a portion of the total radiation impinging on lakes. When the sun is at a 10° angle from the perpendicular, scattered sunlight might contribute about 20 to 40% of the light hitting a lake [4].

What kind of light is absorbed and reflected by lakes depends on the water composition. Water composition refers to solid particles suspended in the water and more importantly, to dissolved organic compounds (The dissolved organic matter in a lake is defined as the percentage of particulate matter which will not be filtered out by minuscule pores, typically between 0.2 and 0.7 micrometers). The reflected radiation is not entirely that which was not absorbed by water, a significant portion of it is light scattered by a plethora of suspended materials. Distilled water has been shown to be most absorbent with infrared wavelengths which quickly warm the water. While pure water does not absorb much in the lower (blue/purple) wavelengths, absorption resumes in the ultraviolet wavelengths and roughly 53% of the surface light energy is absorbed as heat energy within a meter of depth[5].

Different dissolved organic compounds affect the pigmentation of the water in different ways, meaning they determine the rates at which different wavelengths get absorbed. In other words, using distilled water absorption properties as baseline behavior, one must create a refraction coefficient using the reflexive and absorption properties of dissolved organic compounds present in a particular body of water. For example, the absorption properties of pure water mentioned before change when a small presence of humic acids is introduces into the water. In this case absorption increased in the lower wavelengths[6]. The water composition of the two subject lakes will be a critical piece in explaining the lakes'

[4]Wetzel, 1991
[5]Ibid
[6]Hutchinson, 1957; Wetzel, 1983, 1991

internal structure. By internal structure I mean the conditions of the water at different depths for each of these lakes, I will get into the specifics in the following chapter.

2
Methods

2.1 Study Sites

Research teams led by Professor Robyn Smyth have been gathering data from two Pennsylvania lakes: Lake Lacawac and Lake Giles. Even though they both qualify as small lakes, the size difference between Lacawac and Giles is considerable. Lacawac is roughly twice as shallow and has half the surface area as Lake Giles, as seen in 2.1.1.

Their differences then extend into their fundamental compositions. Lacawac is highly humic, in other words, it is full of dissolved organic material which adds to the nutrient content of the lake and browns the water. The browning of the water (opacity) caused by the concentration of dissolved organic matter results in very limited light penetration. Lacawac is so humic in fact, Moeller's *Lake Lacawac Report on Limnological Conditions in 1992* found that two meters below the surface, the light was only 10% of that at the surface[1]. This measurement is called the *10% PAR Depth*. However, since Lacawac is browning, we expect the 10% PAR depth today to be even lower. Being so shallow and humic, Lacawac has a very small photic region near the surface where PAR is present.

[1]Moeller, Lake Lacawac Report on Limnological Conditions in 1992

(a) Lake Lacawac (b) Lake Giles

Figure 2.1.1: Figure highlighting the drastic size difference as Lacawac is roughly 1,700 feet across while Giles is roughly 2,800 feet across. Images provided by Google Maps.

Giles on the other hand has very clear waters. In fact Moeller's *Lake Giles Report on Limnological Conditions in 1991* showed a 10% PAR depth at roughly eight meters[2]. With such a low light absorption rate, there is a much larger photic region. In spite of this, Giles' photic region is subject to change as more and more heat energy is inputted into the system. The density gradient caused by heat absorption at different depths, acts as a mixing suppressor which may affect the absorption rates in Giles.

2.2 The Inner Structure of Stratified lakes

Stratified lakes are thermally structured in three distinct horizontal layers: the mixed layer, the thermocline, and the hypolimnion. Figures 2.2.1 and 2.2.2 display the water density at different depths over time for each of the two lakes. The color gradients clearly distinguish between the top mixing layer, and the hypolimnion. The thermocline however seems a little blurred and it is difficult to identify the clear boundary between it and the other layers. In order to make this identification easier, I will elaborate on the key characteristics of each layer and then use those.

[2] Moeller, Lake Giles Report on Limnological Conditions in 1991

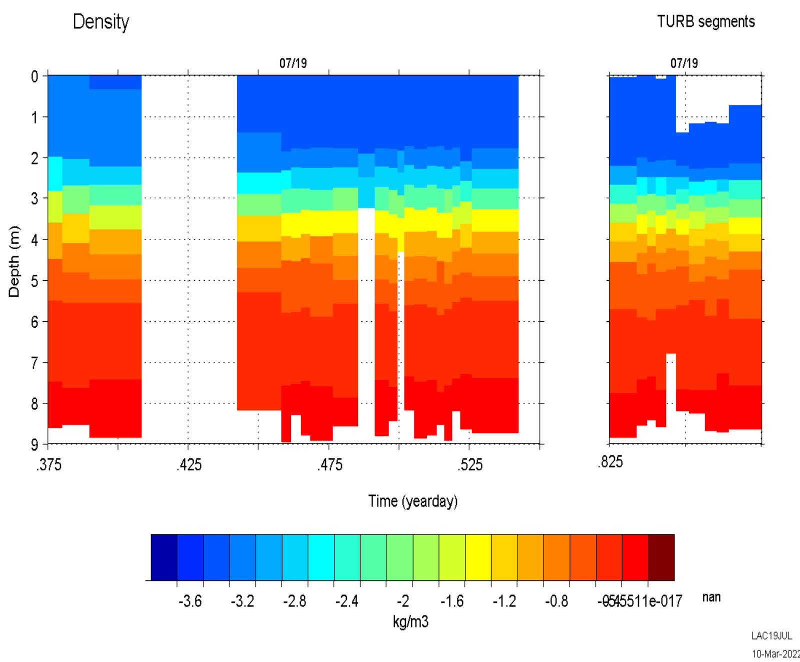


Figure 2.2.1: Water density in Lacawac according to depth plotted through time. The values plotted must be added to 1000 for the actual results. Measured in July 2022. For specific information on the data being plotted see chapter titled *Data Comprehension and Analysis*.

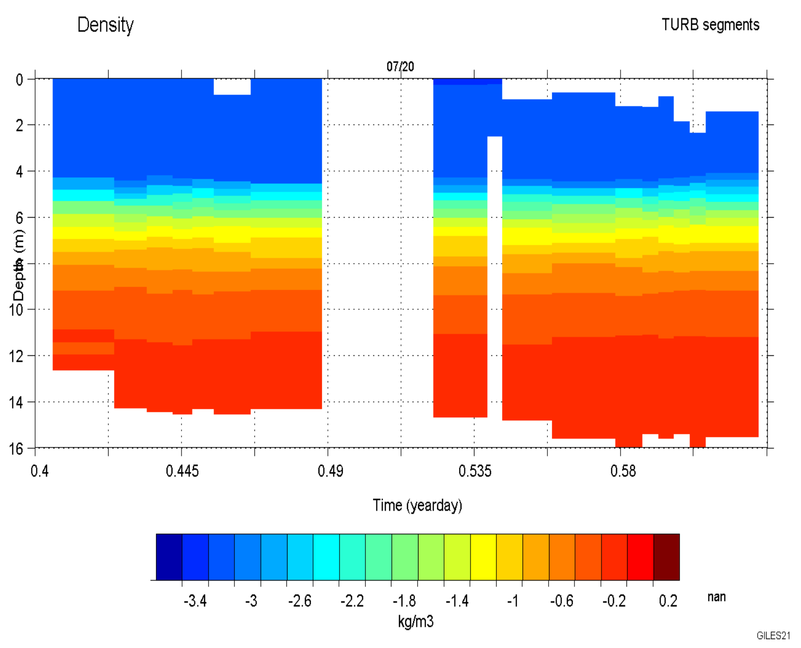


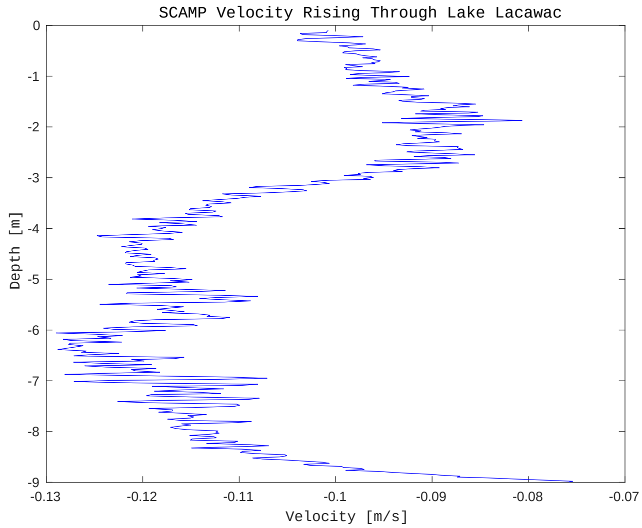
Figure 2.2.2: Same information for Lake Giles.

The mixed layer is the top layer. Being at the top means it receives the most heat exposure which sees the water expand to the point where it has drastically different density than the other layers. This expansion is visible in figures 2.2.1 and 2.2.2. There is a consistent density in the first two meters of Lacawac and the first four meters in Giles before the accelerated density increase in the thermocline. The reason Giles maintains lower density for more depth than Lacawac is due to its low absorption rate. Lacawac's dark water turns the light into heat energy much more quickly than in Giles. The top layer is also exposed to mechanical wind energy which contributes to additional mixing and homogeneously distributes the components in that layer. Meanwhile heat energy from radiation absorption suppresses the mixing.

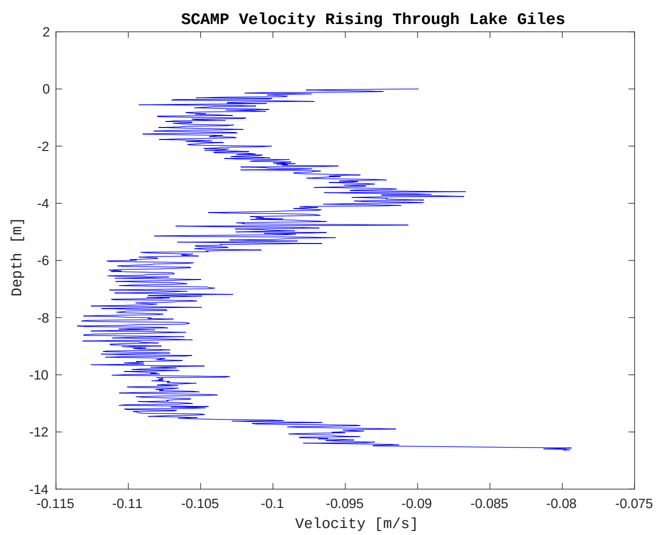
The thermocline is the middle layer, which sees the most rapid decrease in temperature by depth. While temperature decreases in an almost linear fashion through the mixed layer and the hypolimnion, the thermocline sees an exponential decrease in temperature. This drastic temperature change is what causes the inconsistent density readings between the top layer and the hypolimnion. The thermocline serves as a barrier preventing large scale mixing between the other layers. The greater the difference in density between the layers, the less likely they are to mix. The extent of this effect is visible in figure 2.2.3.

The hypolimnion is the lowest and coldest layer. Due to the low mixing levels which characterize *thermally stratified lakes*, the hypolimnion will often have low oxygen levels and is unlikely to have light levels necessary for photosynthesis. The fact that these are strongly stratified while having such different compositions makes them the perfect study subjects to predict how the layers in stratified lakes will evolve.

In summary, Lake Giles is larger, deeper, and much clearer than Lake Lacawac. Lacawac's top layer extends half as deep as Giles' and this is due Lacawac's much higher absorption rates. Yet it is possible that in spite of having much clearer water and being much deeper, Giles is evolving to resemble Lacawac's structure.

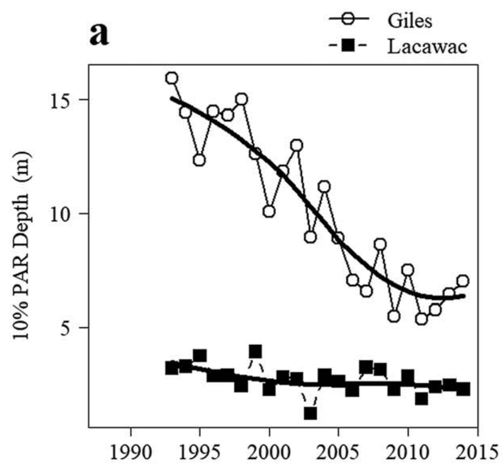


(a) LacVel

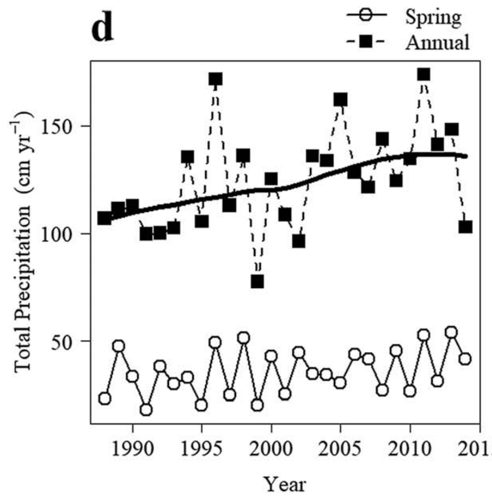


(b) GilesVel

Figure 2.2.3: Figures A and B demonstrate the velocity of SCAMP (measuring device) floating up to the surfaces of Lacawac and Giles respectively. The X-Axis is the negative velocity in m/s. In both lakes there is a clear and abrupt change in velocity. In both cases this is the moment when the device passes through the the boundaries between the layers.



(a)



(b)

Figure 2.2.4: Figure A demonstrates the 10% PAR depth at Lacawac and Giles from the late 90's up until 2015. Figure B demonstrates the precipitation in both lakes over that period.[3]

In a paper published by Pilla et al. (2018), Lacawac and Giles' properties were studied side by side over a 20 year period. The figures published in her paper exposed some very alarming observations. Figure 2.2.4 a, shows consistently low 10% PAR values for Lacawac, as I would expect. When it comes to Giles however, the 10% PAR depth clearly decreases. This decrease indicates that while the heat supply necessary to support microorganisms may be available over a wide range of depths, the real habitable region for these is further limited by the light availability. This recent decrease in PAR depth tells us that 30 years ago Giles' top layer must have extended considerably deeper than it does now. Such lower absorption rates would mean a weaker density gradient and much more mixing. Graph b in figure 2.2.4 is indicative of a trending increase in the solid particulate matter that may be introduced into the lakes by precipitation and runoff. This increase of matter and solutes is likely playing a role in darken both lakes over time, consequently affecting their absorption rates. I will not be plotting 10% PAR depth directly but the data I have measured will have given me a non quantitative understanding of the expected 10% PAR depth. I expect the data I will be analysing to match the most recent data plotted in figure 2.2.4.

2.3 Collecting Data

In the summer of 2021 I joined Professor Smyth in the most recent expedition to take data from the two lakes. We took measurements using the device known as SCAMP (Self-Contained Autonomous Micro Profiler). SCAMP is equipped with three sensors; one conductivity sensor, one fine temperature sensor, and one fast temperature sensor (See figure 2.3.1). SCAMP is weighted to the bottom of the lake where it releases the weight and begin its ascent. As it rises from the bottom of the lake at approximately 10m/s it registers 10 measurements per vertical meter of water. Each time SCAMP was sunken and resurfaced we refer to as a cast, multiple casts form a session. When the data from each session was compiled, it was mapped into graphs we referred to as profiles (such as the ones displayed in figures 2.2.1 and 2.2.2). Our aim was to record multiple sessions throughout the day over the course of several days.

It was important to collect data at different times throughout the day in order to get a full picture of the inner workings of each lake. The 24 hour energy cycle of a lake can be broken into two main parts. The first, during the morning and mid day when the lakes absorb heat energy from the sun. The second is during the evening and night when the air is cooler than the water and so the lake releases the heat energy harnessed throughout the day back into its environment. During these different processes, then the inner workings of the lakes will behave differently at different times and by extension will give different values for the same turbulence parameters (covered in the Chapter titled, *Data Interpretation and Analysis*), even at the same depth.[4]

[4] Since we only worked with data from the summer I only had to worry about capturing the different behaviors exhibited over a 24 hour cycle. Moeller's "Report on Limnological Conditions" analyzed the behavior of these same lakes over a year long cycle.

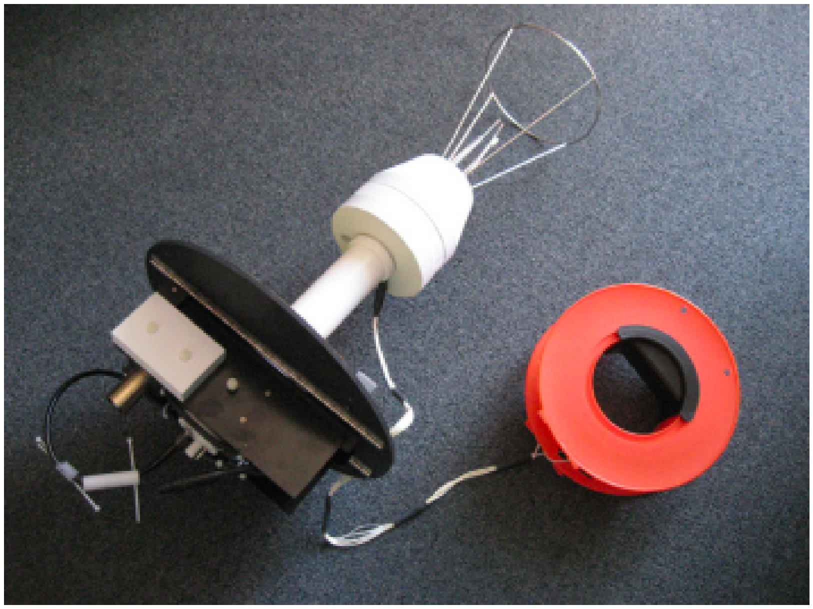


Figure 2.3.1: SCAMP pictured. The scanners are the three prongs guarded by the cone-shaped cage. Below are the wooden floats used to regulate the instrument's buoyancy. The circular bottom section allows SCAMP to glide downwards at an angle to avoid measuring its own wake as it rises to the top. Lastly the string attached to the orange wheel serves to reel SCAMP back in after it has surfaced.

With multiple casts, the measured data is Fourier transformed into a gradient using the Batchelor fit method (Batchelor, 1959) using the code published by Smyth in 2010(Smyth, 2010). Temperature and conductivity gradients created from SCAMP data are taken and used to calculate vertical eddy diffusivity and rate of dissipation of turbulent kinetic energy. These are then compiled and log averaged to map the prevalence of each parameter at different depths.

We want to analyze how the optic properties of the lakes cause them to react to their environment, so we must ensure that the data we analyze is responding to identical meteorological conditions. Lacawac and Giles are in close enough proximity to each other that we can assume they both experience the same conditions in the air around them at the same time. There is a device called ARTHUR (Aquatic Resource for High-Frequency Underwater Research) afloat in the middle of Lacawac which measures weather conditions

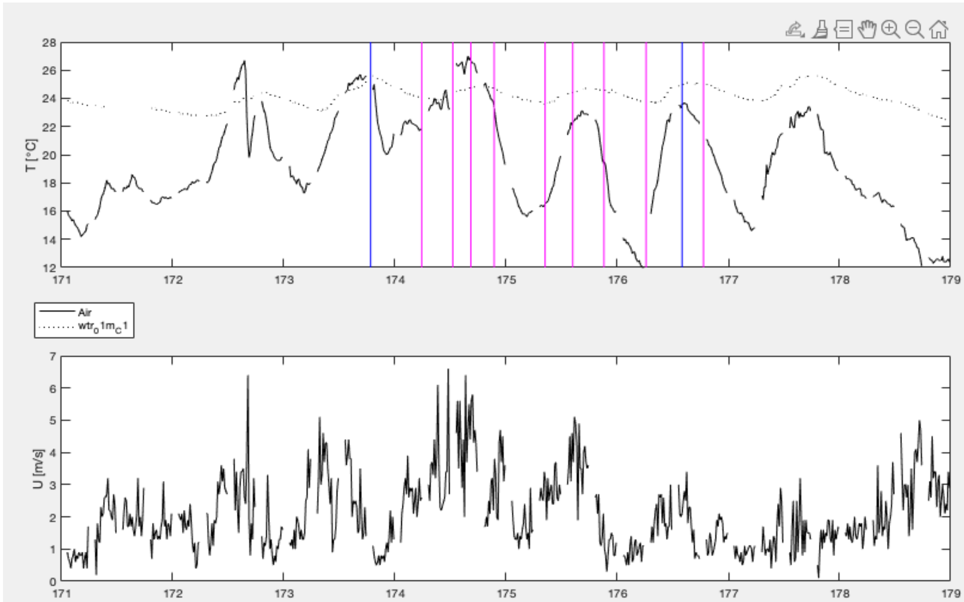


Figure 2.3.2: ARTHUR data for air and water surface temperatures (top) and wind speed (bottom) graphed for the time data was being recorded. The vertical lines on the top plot are the times when data was taken from Giles (purple) and Lacawac (pink).

such as air temperature and wind speed[5]. ARTHUR data is used to display the weather conditions around the lakes as a function of time, giving us a more thorough interpretation of SCAMP data.

2.4 Obstacles

Due to a number of setbacks we were only able to collect two data sets from Giles in the 2021 trip. This was a significant restriction on our data because we can only interpret Giles data we can compare to Lacawac. The data being compared must have been taken under identical weather conditions otherwise, we cannot know which properties to attribute certain behaviors to. Lake Giles is located in a gated community, so in order to access it we needed permission from the homeowners association. Unfortunately, they were not very cooperative and so we ended up with a very underwhelming amount of samples from Lake Giles. Another big setback was SCAMP's field experience. SCAMP was developed

[5]ARTHUR data is freely available to the public on their website

in the 90's by a very small department and was quickly overshadowed by the rise of more compact technology. Not only did this mean SCAMP was very old and more easily prone to be damaged, but also that the mechanical support department for SCAMP had been dissolved over time and in the case that maintenance or reparations were needed, they would be very difficult, if not impossible to get. When we were finally able to go to both Lacawac and Giles in similar dates, SCAMP began to fail.

3
Data Interpretation and Analysis

3.1 Conceptual Background

The next step is to understand the variables I will be using to visualize the movements within the lakes. Recalling from the previous chapters, turbulent movements inside the lakes are dictated by the lake's optical properties; dark waters with high absorption rates suppress turbulent movement more than clear waters with low absorption rates. Through Smyth's code we obtained parameters of turbulence mentioned before: *vertical eddy diffusivity* K_z and *rate of dissipation of turbulent kinetic energy* ε. By understanding both of these we will get a clearer picture of what optical properties make sense given the turbulent activity seen in the lakes.

There are two main types of turbulent exchanges, one of which is caused mainly by wind shearing at the top layer. When a lake's top layer is subjected to prolonged wind shearing, the friction at the boundary between the layers provokes disturbances which facilitate the mixing that stratified layers typically prevent. The disturbances at the layer boundaries come to thermal equilibrium as they exchange heat. Once the wind calms down, the water's optical properties make it so that heat absorption from sunlight reaches the same depth and re-establishes strong boundaries between the layers by heating up water until it reaches a particular density distinct from that of the layers underneath. The second type of turbulence happens at night when the water temperature is higher than the air temperature, this is called *penetrative convection turbulence*. In convection turbulence the top parcels of water in a lake give heat to the air and become more dense, consequently falling to the bottom of the lake as a warmer parcel of water rises to take its place. The problem with the two types of turbulent movements is that neither SCAMP nor the code from Smyth (2010) can tell what caused the measured disturbances in the water. The only reason this matters is because convection turbulence caused by parcels rising or falling can happen well into the day even though it is a process independent of optical properties.

We see examples of turbulent mixing every day when we pour milk in our coffee or when the smoke from burning incense twirls as it mixes with the air around it. In both examples we see the mixing of two substances; milk and coffee in one, and smoke and air in the other. We see the same type of mixing between the layers in stratified lakes when there is enough shearing energy input.

Although stratification is a consequence of minimal mixing, most lakes are subject to some level of mixing in spite of low flow. This mixing is what we define as our first turbulence parameter, *vertical eddy diffusivity* denoted as K_z with units of $\frac{m^2}{s}$. We only concentrate on the vertical element of this variable because of the properties of stratified lakes. Since stratified lakes are layered vertically, the different regions are referred to by depth, and coordinates in the horizontal plane become irrelevant. Vertical eddy diffusivity tells us the rate at which two unit surface areas from different thermal layers mix at different depths. In the context of the coffee and milk example, K_z would be the rate at which the milk and the coffee become one fluid. Yet mixing will not happen continuously without some supply of energy.

Thinking back to the coffee and milk analogy, when one pours milk into coffee, it is necessary to stir in order to properly mix it. We do this to introduce energy into the environment to facilitate the mixing. This is because in order for milk to push through the coffee, the milk must have some momentum of its own. As the mixing occurs, the milk is forced to collide against the coffee, therefore losing its momentum. It is through this momentum loss that turbulent motion dissipates kinetic energy. In lakes, the energy dissipated by turbulence may be from the movement of rising or falling parcels of water (as previously mentioned in convection turbulence) or mechanically by wind hitting the lake surface. We call this turbulence parameter the *rate of dissipation of turbulent kinetic energy* denoted by ε with units of $\frac{m^2}{s^3}$.

There are many ways of calculating *vertical diffusivity* and while I will include an equation for readers to relate the variables, I encourage to think critically on what K_z is fundamentally; a determinant of vertical flux of heat, momentum, and solutes. SCAMP instruments directly measure two of these three values for us and the only remaining one would be momentum, which the code from Smyth (2010) found. One of the equation for *vertical diffusivity* is as follows:[1]

$$K_z = \gamma \frac{\varepsilon}{N^2} \tag{3.1.1}$$

Where *buoyancy frequency* N, is the natural frequency with which the vertical stratified layers of a lake oscillate (similarly to water in a bathtub rushing back and forth when the bathtub is on a rocking container such as a boat only significantly milder). Buoyancy frequency is found with the relation $N^2 = -\frac{g}{\rho}\frac{d\rho}{dz}$ and γ is the mixing constant for which I used the value 0.2. This relationship shows that not only are ρ and N^2 inversely proportional, but the same is true between N^2 and K_z for each layer (constant density). This means that for each particular layer K_z is proportional to ρ.

The formula for the rate of dissipation of turbulent kinetic energy ϵ is a little bit more complex and requires a bit more context. As SCAMP measures temperatures it keeps track of variations in T, which the code from Smyth (2010) compares with those from idealized Batchelor spectra. This comparison finds the best fit and with that the *Batchelor wavenumber* k_B, the first value needed to calculate ε. The second value needed is the *rate*

[1]Bieito Fernández Castro, Small-Scale Turbulence and Mixing: Energy Fluxes in Stratified Lakes, 2021

of dissipation of temperature variance, denoted by ${\chi_T}^2$. The Batchelor wavenumber is the a value determined by fitting an estimate for the rate of dissipation of temperature into the Batchelor spectrum[3]. The final formula of ϵ takes the form:

$$\varepsilon = vD_T^2 k_B^4 \tag{3.1.2}$$

where D_T is the molecular diffusivity of heat, a value proportional to χ_T, and v is simply kinematic viscosity. To summarize, we have profiles for vertical eddy diffusivity K_z and rate of dissipation of turbulent kinetic energy ε. The goal is to analyze these profiles in the context of the lakes' respective water composition and asses if our findings match our expectations. I expect Lacawac to have higher temperatures in the top layer as light is completely absorbed by its dark composition. This should result in a larger difference in the densities of the different layers in Lacawac (refer to figure 2.2.1). This difference in densities, caused by heat absorption, should act as a turbulence suppressor. This set of conditions means we expect active K_z values only in the top mixing layer, similarly with ε. While Giles is not as dark as Lacawac, I expect to see it replicate these behaviors except with a slightly cooler mixing level.

3.2 Data Analysis

Now that the behaviors described by ε and K_z are clear, let us look at the two subject lakes and interpret what the variables are telling us about the conditions of the water.

Notice in figure 3.2.1, both days had nearly identical air and surface water temperatures, yet the wind speed differed moderately between the two. The wind speed peak was almost double on the day data was gathered from Lacawac, which is something that will need to be taken into account when comparing the plots from the SCAMP data.

Since Lacawac was experiencing mildly stronger winds the day we took data there, we should expect there to be some indicator of that in the data. The presence of wind

[2] Original derivations found in Batchelor (1959) and Schwartz (1963)

[3] I will not dwell in the specifics of the Batchelor spectrum. See works by Smyth (2010), Batchelor (1959), for a better understanding of the dependence of temperature variance on wavelength

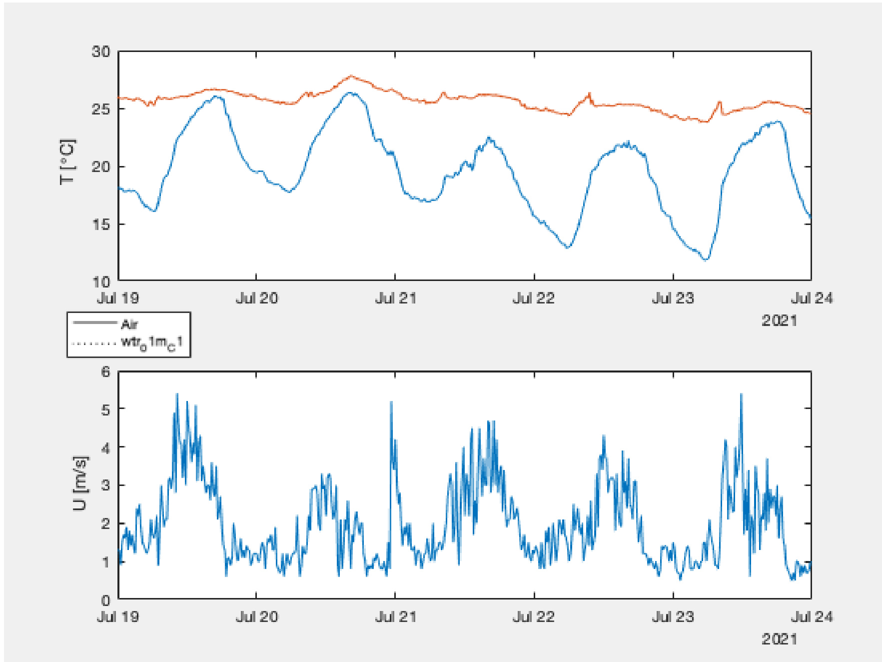


Figure 3.2.1: Just as in 2.3.2, here we see ARTHUR data for air and water surface temperatures (top) as well as wind speed (bottom) plotted over time. Water surface temperature is in orange while light blue is air temperature. The red vertical lines denote the times data was taken at Lacawac while the pink lines show the same for Giles.

energy typically implies greater mixing levels than usual and consequently greater thermal diffusion (weaker temperature gradient by depth). I wanted to attempt comparing the most recent Lacawac data (July 2022) with older data taken with slower wind speeds and similar temperatures. However, the 2015 weather data showed slower wind speeds as well as lower air temperature throughout the day. This proved not to be as meaningful an obstacle as I expected, since the 6m/s winds from July 19th were only marginally greater than the 3m/s winds from July 20th. When looking at the following profiles, the analysis must be made according to the distinct layers in a lake. Remember the distinctions made between the two lakes in the *study sites* section. Lake Giles is approximately twice as deep as Lake Lacawac and this affects the relative sizes of their stratified layers. So when we see that Giles is much warmer than Lacawac at 3 meters of depth, we must remember Giles' mixed layer is 4 meters thick while Lacawac's is only 2.

3.2.1 Temperature Gradients

It is no coincidence that the structures shown in figures 3.2.2 and 3.2.3 resemble exactly what we saw in figures 2.2.1 and 2.2.2, as both sets of figures display the same bodies of water at the same exact times. Additionally, density is a function of temperature, so the SCAMP data graphed in 3.2.2 and 3.2.3 was directly used in calculating the numbers graphed in 2.2.1 and 2.2.2. A lake's optical properties impose a cutoff on what depths absorb more heat, the cutoff parameters regulate the size and location of the different density layers. How this energy is reflected or absorbed depends on the water's composition. As previously stated, Lake Giles has a much greater surface area than Lacawac, is much deeper than Lacawac, and has much clearer water than Lacawac.

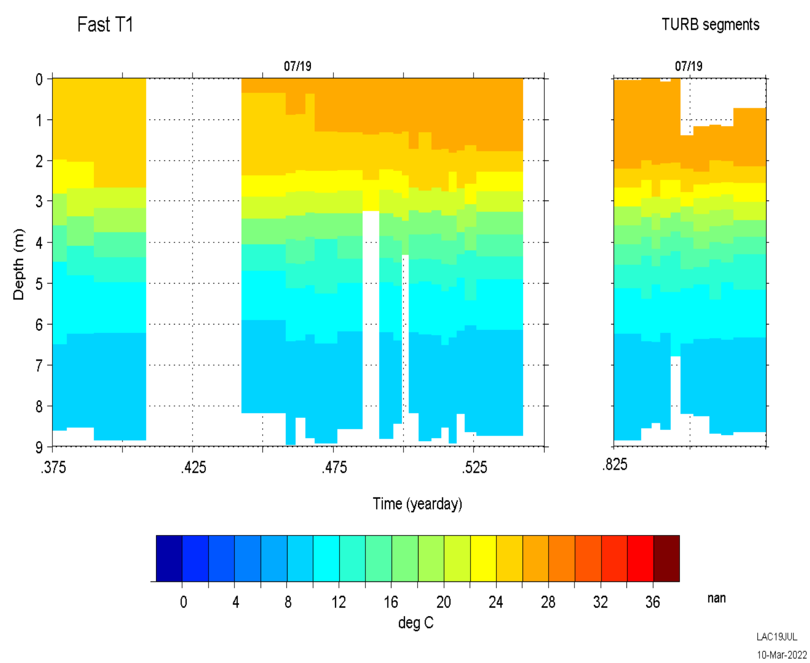


Figure 3.2.2: Temperature gradient profile for Lacawac across three casting sessions from July 19th 2022.

Lacawac's high absorption rates (caused by its very dark water composition) suggest we should expect most of the light absorption into heat to happen at the surface layer,

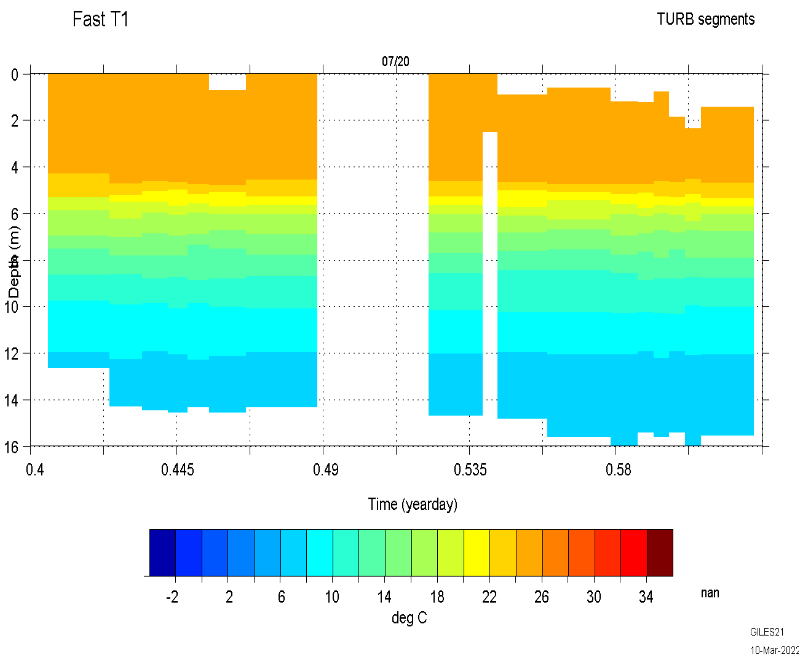


Figure 3.2.3: Temperature gradient profile for Giles across two casting sessions from July 20th 2022.

giving it a higher surface temperature than Giles. This holds because although Giles absorbs more solar radiation into heat due to its larger surface area, it does so gradually throughout as much depth as the light can reach. As expected, the Lacawac's surface layer reached a temperature around $2°C$ higher than Giles' top layer around the same time of the day with nearly identical air temperatures. Higher wind speeds should have a mild effect on Lacawac's data. We should expect it to have induced more mixing, distributing the heat further and lowering the top layer's temperature.

However, a closer look at figure 3.2.1 reveals that the first of the three casts from Lacawac happened before wind speeds picked up, at roughly the same time of the day as the first cast from Giles the next day. For these measurements we have approximately identical conditions. Looking back at figures 3.2.2 and 3.2.3 with this in mind shows that my previous prediction regarding wind's effect was wrong, or at least incomplete. The fact that Giles and Lacawac had the same temperatures in their respective top layers in the late morning does not indicate that this remains the case throughout the day. Thinking back to why multiple samples are needed throughout the day, we should expect the morning time to be when the lake begins to absorb energy from the surrounding environment. It is the case that while both lakes begin the day with the same surface level temperatures, Lacawac will have a higher heat energy absorption rate and reach higher temperatures after exposure to solar radiation. That is not to say that finding they have similar conditions as they begin the day is a fruitless finding. It serves to emphasize that after each lake releases energy into its environment throughout the night, they settle on the same equilibrium temperatures because the process of giving heat to the air is independent of surface area and water composition.

3.2.2 Rate of Dissipation of Turbulent Kinetic Energy

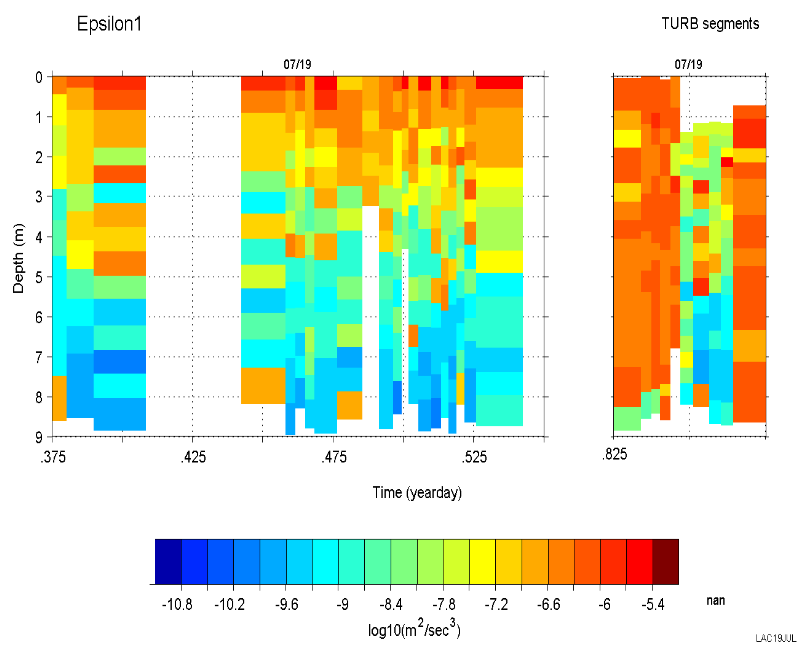


Figure 3.2.4: Rate of dissipation of turbulent kinetic energy profiles for Lacawac across three casting sessions from July 19th 2022.

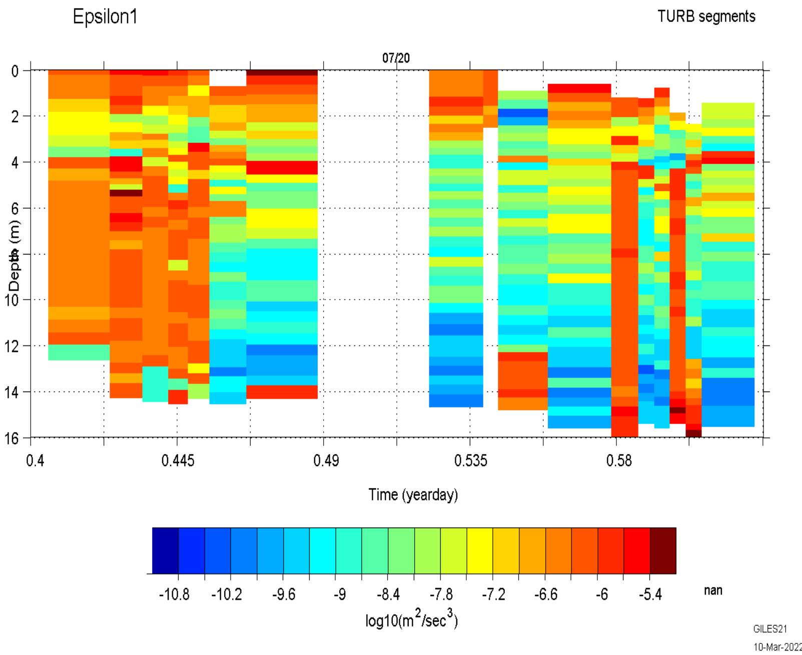


Figure 3.2.5: Rate of dissipation of turbulent kinetic energy profiles for Giles across two casting sessions from July 20th 2022.

In figures 3.2.4 and 3.2.5, ε is not as clear as the density and temperature figures. The profile for the last casting session in figure 3.2.4 sees some high values across the full depth of the lake. Since the top layer is where most of the mixing occurs, it should also be where kinetic energy dissipates through turbulence (where ε should be higher). The disparity in the data is not very significant however. The colors in the profiles may be somewhat misleading. Contrary to what a such dark shades of red may convey, these are still relatively small values. Fortunately, there is a relatively calm hypolimnion and the thermocline does have more moderate values in the first two profiles as we would have expected. Figure 3.2.5 also shows questionable high ε values for all depths for the first half of the first casting session at Giles. It is not uncommon to have higher levels of activity at the bottom of the lakes but given our chosen method for sampling data (see figure 2.3.1) SCAMP did not measure the bottom meter of the lake where it could have measured the surging ε values shown at the bottom layers of figure 3.2.5.

There are many possible explanations for the unexpected abundance of high rates of dissipation of turbulent kinetic energy. Firstly, when measuring with SCAMP, the instrument may have been mishandled. This is not uncommon and leads to partial or unusable data. However this does not seem likely to be the cause because the code to process SCAMP data is supposed to filter out data from casts where the velocity and depth do not match as SCAMP expected them to. Secondly, it may be real data showing the aftermath of strong deep mixing on both lakes as a consequence of the high winds from July 19th. This explanation is even more unlikely for many reasons. The Lakes' strongly stratified structure would have prevented deep mixing throughout all layers at such a scale. Additionally, the sudden change halfway through the first session from figure 3.2.5 would be too abrupt a stop in activity for it to be real.

The rest of the data in both figures seems reasonable enough. Lacawac shows severe activity in the mixing layer up to 2 meters of depth, then moderates slightly until 4 meters, and essentially stops in any significant amounts at the hypolimnion. Giles however, shows a pretty timid mixing layer for what little data there is at the surface in figure 3.2.5. Most of the second session for Giles behaves as expected, with some exceptions including the notable absence of surface layer data. The absence of the surface data, field notes taken at the time and the other incongruities strongly suggest that these stem from mishandling or accidental deployments of SCAMP.

3.2.3 Vertical Eddy Diffusivity

As previously mentioned, ε and K_z are directly related. One is the vertical rate of mixing and the other is the resulting dissipation of kinetic energy through said mixing. With this in mind we should expect the vertical eddy diffusivity profiles in figures 3.2.6 and 3.2.7 to be more active in the same regions as figures 3.2.4 and 3.2.5. As expected the Lacawac profiles show some activity throughout the top mixing layer (first two meters of depth) with some negligible exceptions. The highest K_z value in the Lacawac profiles is at the surface layer at the very beginning of the third session. By then it would be reasonable to assume this effect was caused by the high wind levels that started earlier that day. The K_z values for Giles also behave as expected. Figure 3.2.7 shows high K_z values throughout the top mixing layers. Up to four meters in depth. The normality of these results allow for a reassuring end to the doubts formed by the irregularities from the ε profiles.

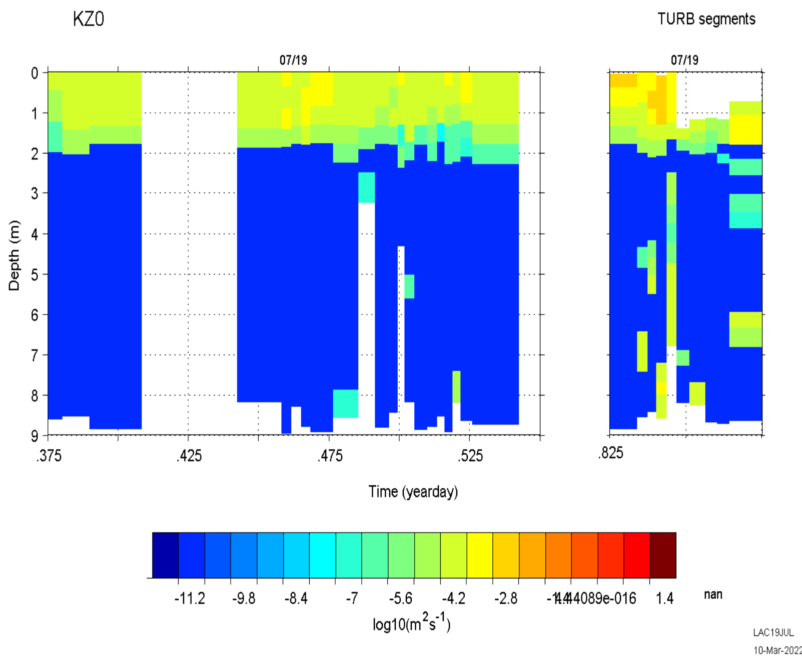


Figure 3.2.6: Vertical eddy diffusivity for Lacawac across three casting sessions from July 19th 2022.

The fact that we see K_z confined to the top layer strongly suggests that the turbulence we see there is almost exclusively due to wind shear as opposed to convection turbulence from parcels of water rising and falling through the lakes. It also makes for an interesting comparison to look back at figure 2.2.4 and check the most recently plotted 10% PAR depths (taking into account that the paper was published in 2018) and compare them to the depths at which K_z diminishes in figures 3.2.6 and 3.2.7 (taking into account that these were measured three years after Pilla's publication). This comparison clearly visualizes how different rates of light absorption manage the mixing rates within a lake.

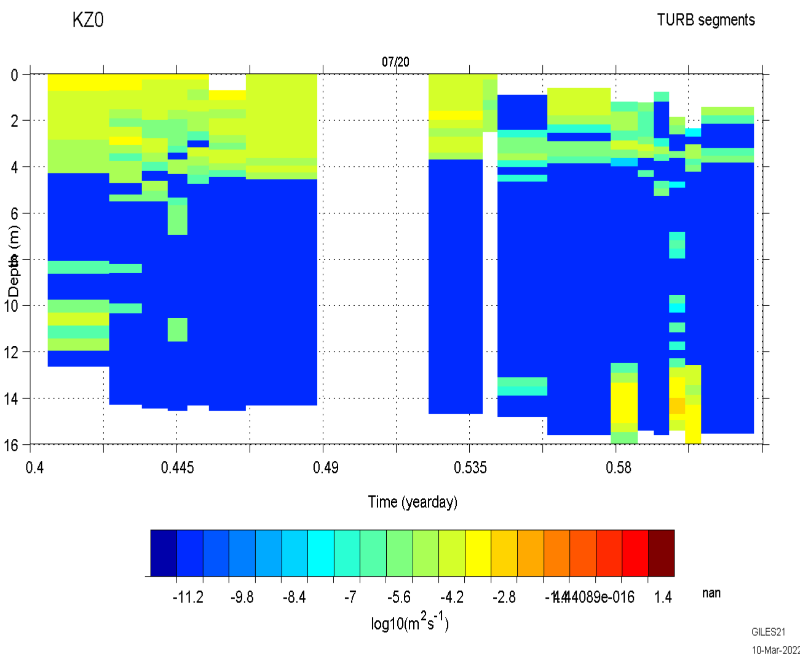


Figure 3.2.7: Vertical eddy diffusivity for Giles across two casting sessions from July 20th 2022.

4 Conclusion

SCAMP profiles have confirmed what we knew about stratified lakes in the following ways; they are vertically layered by density, the different densities at the different layers depend on their temperatures, and their temperatures depend on the light available for absorption at different depths and the redistribution of heat through physical processes. This study looked at two lakes from the Pokonos region in Northern Pennsylvania. The two have significantly different sizes and compositions. The key takeaway from this is the feedback that ensues from increased heat absorption in lakes.

Added heat acts as a turbulence suppressor by increasing the difference in density between the layers. Layer densities differ to the point where water from different layers will not mix. The precipitation increased shown in figure 2.2.4 has brought with it a simultaneous darkening in both lakes, browning in Lacawac and greening in Giles. These changes in composition act as the drivers behind the changes in light absorption. As the lakes darken they grow hotter in smaller regions near the surface. With increased temperatures near the surface, the density differences between the layers grow even more. With growing difference in densities, turbulence is suppressed more and more, furthermore the microorganisms upon which aquatic ecosystems depend on are constrained to a smaller region. The necessity for light draws them near the surface while the need for moderate warmth pushes them away.

Using the velocity per depth diagrams in figure 2.2.3 I make clear the degree to which a difference in density limits interactions between layers. By comparing findings from Pilla (2018) displayed in figure 2.2.4 with the profiles throughout the previous chapter, I achieved the goal of this paper. The layering depths match temperature gradients, density gradients, and turbulent activity (both K_z as well as ε) with 10% PAR depth, indicating an unequivocal correlation between all of these variables (there exists a degree of uncertainty due to the period of time between my measurements and pilla's).

There are multiple approaches a future study could pursue. A model may be made to track the particular ranges of the photic zones in Lake Giles and Lake Lacawac. Another future study could continue to study the same measurements made by Pilla et al. for even longer in order to continue observing the increase in light absorption Giles is undergoing.

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