Effects of Solar Radiation and Air Temp **on Thermal Stratification of Lakes**

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Background

As climate change becomes progressively more apparent, the impact to our freshwater resources will continue to increase. In temperate latitudes, increasing ocean and air temperatures will lead to an acceleration of water flowing through the hydrological cycle, causing alterations of water availability, timing, quality, and demand (Gleick 2014). Freshwater is considered to be the resource most vulnerable to climate change, and we are already seeing a major decrease in water availability paired with increasing threats to water quality (Gleick 2014).

Increasing air temperatures and more unpredictable storms will likely impact typical thermal stratification patterns in freshwater lakes. Stratification is the process of warmer water layering on top of colder, denser water, inhibiting mixing within the water column. The most notable drivers of stratification and mixing patterns are solar radiation, atmospheric heating, and wind.

Intense and prolonged stratification directly decreases the downward transport of dissolved oxygen, increasing the likelihood of hypoxia (i.e., depletion of oxygen) (Loewen 2007). Prolonged hypoxia can negatively affect aquatic life and alter biogeochemical processes that occur in bottom waters.

The fundamentals of thermal stratification and mixing of freshwater lakes are well-studied. However, as climate change intensifies, air temperatures are increasing and storms are becoming less predictable. Developing a better understanding of how different meteorological drivers affect stratification will help water managers mitigate the potential negative effects of climate change. With this in mind, we set out to characterize stratification and mixing patterns in three different lakes in both temperate and tropical regions. We hypothesized that lakes located in areas with greater solar radiation will have more intense stratification during the daytime.

From British Columbia to Peru

Our field research spanned from the Coastal Mountains of British Columbia to the high Andes of Central Peru. The three priorities we considered in choosing study sites were notable variation in altitude, similar water clarity, and similar cloud cover. Differing altitude was a priority because both solar radiation and air temperature are known to vary with altitude; for every 1000 m in altitude, solar radiation increases by 8 percent and air temperature decreases by 6.1ºC (Blumthaler et al. 1997). Water clarity influences the depth at which solar energy can penetrate into the water column and increased cloud cover reduces the amount of solar radiation capable of reaching the water. To meet these criteria, we chose Alta Lake in Whistler, British Columbia; Lake Lovely Water in Squamish, British Columbia; and Lago Junín in the small town of Junín, Peru (Table 1). Water clarity was estimated to be similar at each lake prior to this study and confirmed with a Secchi disk. Cloud cover was estimated to be similar at each lake using historical weather data.

We monitored physical lake properties and weather conditions on separate deployments at each study site between May and August 2015. Using thermistor chains (Onset Hobo Pendant Temperature/Light 8K Data) and a conductivity-temperature-depth sonde (Sontek, Inc.), we monitored the vertical temperature profiles and assessed conductivity of the water column. Vertical temperature profiles were monitored in the deepest point of each lake. Solar radiation, temperature, wind, relative

Table 1. Summary of the three lakes chosen for this study.

Lake	*Coordinates*	*Elevation (masl)*	*Max Depth (m)*	*Surface Area (km2)*
Alta Lake	50.11° N 122.98° W	641	24	0.98
Lake Lovely Water	49.78° N 123.26° W	1150	125	0.93
Lago Junin	11.02° S 76.1° W	4100	12	136

humidity, and precipitation were measured at each lake using an Onset HOBO U30-NRC portable weather station.

We assessed the intensity of thermal stratification using Relative Thermal Resistance to Mixing (RTRM) (Kortmann 1981). RTRM takes the difference in density of two adjacent water layers and divides it by the difference in density of 5ºC and 4ºC water to determine a dimensionless value describing stratification. We calculated RTRM for all thermal profiles throughout the study period in order to quantify stratification. We looked at the sum total of RTRM in the top 10 m of the water column for each lake to determine overall stratification; this allowed us to control for varying lake depth and concentrate on the area where the majority of stratification existed in each lake. Total RTRM values can range greatly between vertical profiles collected in different lakes or at different times in the same lake, ranging from 0 in lakes that are completely mixed to more than 400 in very thermally stratified lakes (Kortmann 1981).

Characterizing meteorological conditions and stratification allowed us to get a snapshot of stratification and mixing patterns at each lake and to form a better understanding of how different meteorological drivers affect stratification intensity in freshwater lakes.

Alta Lake

Alta Lake is located in Whistler, British Columbia (Table 1). The lake is popular for recreation and is host to an ecological reserve on the north end of the lake. Alta Lake was monitored from May 25 to June 7, 2015 and from July 7 to July 20, 2015.

The summer season is typically hot and dry, with stratification developing every spring until the water column completely mixes in the fall (fall overturn). By monitoring Alta Lake over 25 days we were able to get a snapshot of Alta's summer stratification and mixing patterns. Overall mean solar irradiance was 149 Wm^{-2} and reached a maximum of 1103 Wm^{-2} (Figure 1). Average overall air temperature was 17.1ºC and generally increased throughout the study period (Figure 1). In addition to monitoring independent variables that affect thermal inputs to the water column, we also monitored wind events as the primary source of potential mixing. Overall there were 20 wind events at Alta Lake, with an overall mean wind speed of 4.2 ms^{-1}. The depth that the wind was able to penetrate varied throughout the study period, but no wind events were capable of fully mixing the water column.

Stratification, as defined by RTRM, increased throughout the study period and was fully developed before July 8 (Figure 2). The difference in the water column temperature reached 19ºC and the total RTRM in the top 10 m of the lake ranged from 114 to 357, which was the greatest between the three lakes.

Lake Lovely Water

Lake Lovely Water is a glacial lake at 1150 m altitude in the Tantalus Mountain Range 42 km southwest of Alta Lake. Lovely Water has a surface area of 0.93 km^2 and a maximum depth of 125 m. Although remote, Lake Lovely Water is a popular destination for hikers, climbers, and skiers; the Alpine Club of Canada maintains a hut at the lake and a canoe is available for summer use. Lovely Water was monitored from June 9 to July 6, 2015.

The lake typically stays frozen longer than the surrounding lower elevation lakes and it is topographically protected on three sides by the high peaks of the Tantalus Mountain Range. Mean solar radiation was 261 Wm^{-2} and reached a peak of 1234 Wm^{-2} (Figure 1). The average overall air temperature was 15ºC

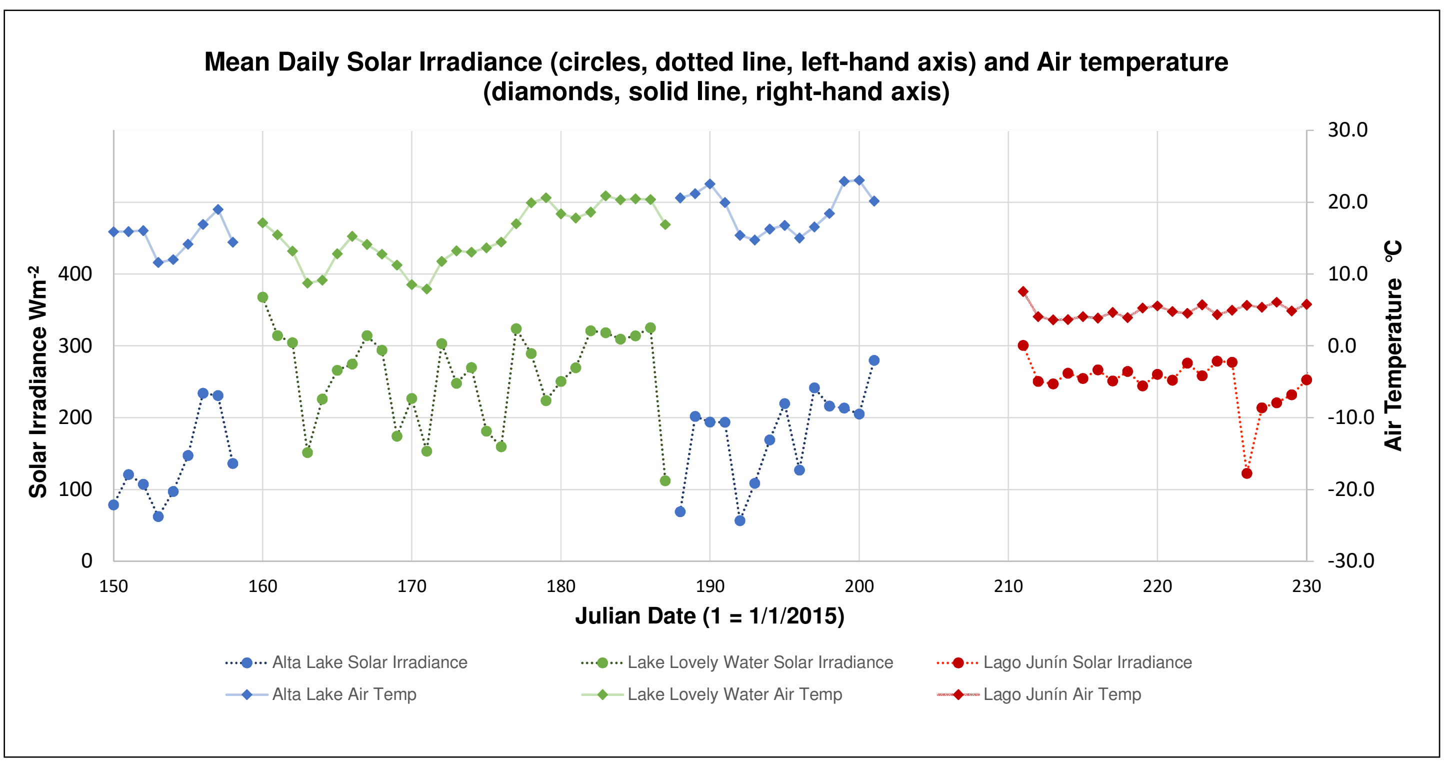

Figure 1. Mean Daily Solar Irradiance (circles, dotted line, left-hand axis) and Air temperature (diamonds, solid line, right-hand axis).

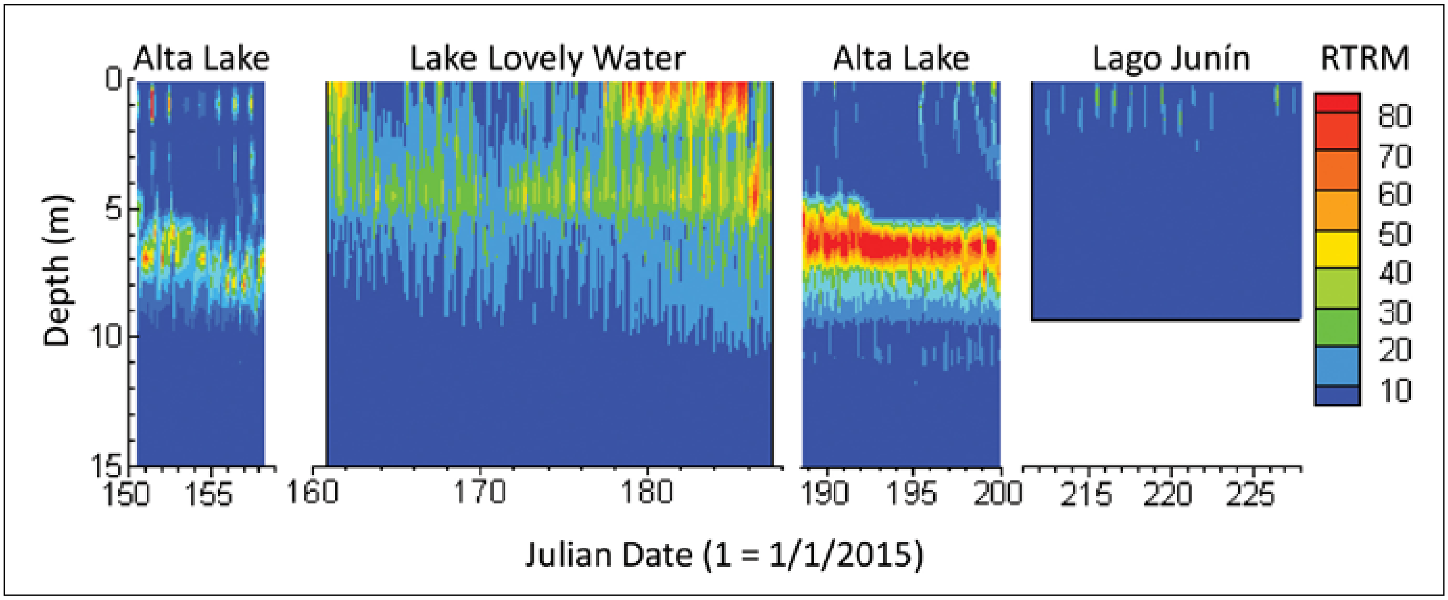

Figure 2. Vertical profiles of relative thermal resistance to mixing values for each lake created using Tecplot software.

and increased throughout the study period (Figure 1). The average wind speed was 1.9 ms^{-1} and the surface mixed layer was much shallower, indicating that wind was less at Lovely Water compared to Alta Lake, likely attributed to its protected location.

Although stratification steadily increased throughout the study period, it was notably less than Alta Lake and the maximum temperature difference in the water column reached 15ºC (Figure 2). The surface mixed layer was smaller than Alta Lake and the total RTRM in the top 10m was weaker, ranging from 73 to 246 (Figure 2). There were no observed wind events that mixed the entire water column. It is likely that stratification developed later in the summer here because it had a later ice-off date. Stratification likely continued to steadily increase until fall overturn occurred.

Lago Junín

The third lake of this study was Lago Junín, located at 4100 m in the Peruvian Andes. The lake is made up of three basins and the outflow is regulated by a hydroelectric dam. This study focused primarily on the main basin, which has a surface area of 136 km^2 and a maximum depth of 12 m. The lake is surrounded by a belt of totora reeds (*Schoenoplectus totora)* up to 3 km wide, as well as a number of towns and small villages. Contamination from surrounding agriculture, untreated wastewater effluent, and poor waste management is known to be present in the lake. Additionally, Lago Junín is fed by the San Juan River, which is contaminated by metals from upstream mining activity. Lago Junín was monitored from July 30 to August 16, 2015.

Three light to moderate rainfall days were observed at Lago Junín; weather conditions were generally clear during the morning and stormier in the afternoons. Despite having 2800 m more elevation than Lovely Water, the observed mean solar radiation was not greater, with a maximum of 1277 Wm^{-2} (t-test, $p>0.1$) (Figure 1). Junín had notably colder air temperatures, ranging from -5.5º C to 16.5ºC with a mean of 4.9ºC (Figure 1). Due to the large surface area of the lake and the expansive surrounding environment, Junín had the greatest amount of wind power with an overall mean of 3.1 ms^{-1}.

Similar to many other high altitude tropical lakes, Lago Junín did not present with typical summer stratification. The water column became isothermal and mixable every day with short periods of stratification in the first 2 m around noon every day. Total RTRM values in the top 10 m of the lake were also minimal and less than the other lakes, ranging from 0 to 63 (Figure 2).

Conclusions

Despite Alta Lake having the lowest overall solar radiation, it had the highest consistent RTRM values and the largest water temperature gradation (19ºC) of all three lakes (Figure 2). Similarly, although Lake Lovely Water and Lago Junín had similar solar radiation they did not have similar intensity of surface stratification; this could be explained by notable differences in average wind power (1.9 $m{\cdot}s^{-1}$ at LW and 3.1 $m{\cdot}s^{-1}$ at LJ) and atmospheric heating (10.2ºC avg. difference) at the two lakes. Alta Lake also had the least amount of difference between day and nighttime temperatures, whereas Lovely Water and Lago Junín experienced greater convective heat loss overnight.

Greatest overall stratification at Alta Lake does not support our original hypothesis that lakes with greater solar radiation will present with more intense stratification. Both Alta Lake and Lake Lovely Water had continually developing stratification throughout the summertime, whereas Lago Junín did not stratify for more than a few hours at a time. Instead it was continually mixed throughout most of the day except for around noon. The lack of stratification in Lago Junín was likely due to lower energy inputs (solar radiation and atmospheric heating) relative to greater mixing power present (e.g., convective and wind). Additionally, reduced conductive and radiated heat absorbed by Lago Junín could be due to wind-induced reflection, the flat surrounding landscape, and greater evaporation due to aridity. Our findings from Lago Junín are congruent with preconceived theories that high elevation tropical lakes are perennially mixed (Wetzel 2001).

Management implications

Comparisons between the three lakes show that overall air temperature and diurnal air temperature variation may be a stronger meteorological force on stratification than solar radiation and re-affirms the fact that surrounding geography drives meteorological forces such as wind. As global air temperatures increase, stratification in freshwater lakes has been shown to increase, exacerbating water quality issues where prolonged stratification and hypoxic conditions already exist. Although typical stratification patterns are well-understood regionally, increased characterization of stratification and meteorological conditions at individual lakes is needed in order to better understand location-specific lake conditions and how they are responding to changes in our climate.

Acknowledgements

Special thanks to the Quest University Summer Fellowship Program for making this project possible and to Greyson Herdman (Quest University Canada '15) for his time and dedication as our field research assistant in Peru.

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Kestrel Kunz graduated from Quest University Canada in 2016 with an interdisciplinary undergraduate degree focused around the question: How can we best manage freshwater resources? She is an avid whitewater kayaker and outdoor enthusiast, which drives her passion for understanding freshwater issues on both a local and global level. Kestrel currently lives in Crested Butte, Colorado, and works for American Whitewater, a national river conservation non-profit, and as a ski patroller. The work described here was completed as part of the Quest University summer research fellowship program in 2015 and was the foundation of Kestrel's undergraduate thesis.

Rich Wildman is a water resources scientist with Geosyntec Consultants in Portland, Ore. He is part of his firm's surface water modeling group, which solves a wide range of problems by using computer models of lakes, reservoirs, rivers, and stormwater. While a professor at Quest University Canada, he served as Kestrel's undergraduate adviser for the work described here.