Stagnate summers: Climate induced changes in physical mixing parameters in Missouri reservoirs

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Abstract:

Lakes and reservoirs are important environmental sentinels for climate change. As air temperatures rise so do the temperatures of these water bodies affecting their physical, chemical, and biological properties. Being used for drinking water supplies, fisheries, and human recreation, these long term potential changes can be an important factor for their use. Climate change has been associated with altering physical reservoir parameters, such as mixing depth, water temperatures, and water chemistry. Using a historical dataset to find both break points and monotonic trends that may indicate climate having influenced our reservoirs we found little in terms of monotonic trends. However, we did witness changes in all systems in regards to break points for almost every parameter. Our systems cannot directly correlate to having had climate change based effects, as we can neither support or refute its evidence in our reservoirs as changes relating to climate do not only impact physical parameters but also animal and plant communities, and social factors such as use (influenced by cyanobacteria blooms). It is even plausible that increased in reservoir production and turbidity could lead to shifts in physical trends that would otherwise be different in non-affected reservoirs. Over all more information is needed to create a better picture of exactly how climate change is impacting the physical mixing parameters in Missouri reservoirs as they are complex and varied systems.

Introduction:

Climate change is a pressing concern in our stochastic world and can have potential negative effects in areas ranging from limnology, marine biology, and agriculture. Lakes and reservoirs are important environmental sentinels for changes in temperatures and other external factors (Wetzel 2001). Climate attributed impacts have been seen in a variety of lakes such as Lake Simcoe but has never been looked at directly in Missouri systems. In Lake Simcoe attributes associated with climate change, such as increased number of days the lake was stratified were reported (North et al.2013, Adrian et al.2012). This case was however in a much higher latitude, and much larger lake that experiences ice cover durations through the winter so it is not a perfect reflector of our relatively small temperate reservoirs. A select grouping of lakes in Wisconsin better represents our water bodies. These lakes were analyzed and had simulations ran to determine potential effects in smaller bodies of water. Under their simulation of 2x CO_2 into the environment (used as a substitution for climate change) their smaller lakes (Crystal and Sparkling) ~66% of the time there will be a change in stratification due to climate change, and on the larger ones (Trout and Mendota) there will be ~46% (De Stasio et al. 1996). The structure and properties of our inland reservoirs having large surface areas compared to depth, compound with frequent manipulation for hydrologic energy, recreation, and in lake maintenance (dredging, algaecide applications, etc), and unique zones (riverine, transitionary, lacustrine, etc) leads to a situation which may not reflect natural lakes and makes their study even more important as reservoirs are increasing in number globally (Zarfl et al. 2014). Knowledge of exactly how reservoirs function in relation to other systems will be necessary for future management (Wetzel 2001, Zarfl et al. 2014). Our tendency to generalize lakes and reservoirs on the same scale is rather unfounded and often leads to the prediction of mixing depths far in excess of what actually occurs in manmade structures (Jones et al. 2011).

Our goal in this project is to see if climate change has impacted physical mixing parameters in Missouri Reservoirs including finding patterns based on latitude, land cover, and lake size. We will accomplish this through a variety of analysis looking at a long-term data set ranging from 1989 to present to compare trends. The reservoirs that will be examined cover a minimum 15 year span during that time. These changes have been seen on other systems (North et al 2013) and our goal is to see if they are also found in our reservoirs.

Methods

Historical collection and Site information:

Missouri is a state filled with reservoirs with 323 regularly sampled our only naturally occurring lakes being oxbow's associated with rivers (Jones et al. 2008). Encompassing multiple ecoregions (Ozark Highlands, Great Plains, Ozark Boarder) we have unique topography, land use, and climate conditions (mild winters, hot dry summers, with moderate ice cover possible in northern regions) (Jones and Knowlton 1993). We avoided all reservoirs with known manipulation (dredging, aeration, draining) in our study. Missouri is on the edge of where warm dimictic lakes and monomictic lakes collide making it of interest for climate study (Kalff 2002). Reservoirs throughout the state vary in physical attributes such as; scale, depth, protection, geological position, and many other factors that could potentially affect their individual responses to warmer air temperatures (Table 1).

Our study sites are as follows: Forest Lake, a medium sized northern lake with a watershed in both forested and agriculture located in the Great Plains (GP) ecoregion of Missouri and defined as mesotrophic when viewing total phosphorus. Viking Lake, another northern GP lake of moderate size and with similar conditions as Forest Lake. Lake Capri, a southern lake with an urban shoreline this lake is located in the South East portion of the state in a forested watershed. Table Rock Lake, our largest lake and the only lake with any manipulation (hydrologic energy) this lake is in the Ozark Highlands in South West Missouri with a forested watershed with close proximity to a major city center (Branson MO; Table 1).

The historical data encompasses 29 years was collected during the summer months from May to September. With this long-term collection, consistency was maintained in terms of sampling location (nearest the dam) and what information was collected (Secchi, water temp, dissolved oxygen (DO), and depth). YSI (models 50B [oldest], 85, and 550A [newest]) with accuracy of +/- 0.1-0.30C and resolutions of 0.10C. multi parameter sondes were used to collected different criteria (depth, temperature, do) increments ranging from <0.5 to ~5m dependent on lake depth, changes shown on the YSI, and pre-determined criteria (Secchi depth, DO).

Analysis:

Mixing depth/stratification, epilimnetic temperature, hypolimnetic temperature, and the average temperature of the whole water column were calculated for each sampling date, 4 times per year for a total of 29 years. To acquire mixing depth information we have used historical data sets containing profiles of water temperature (°C). The software used to determine the mixing depth was "dplyr", and "rLakeAnalyzer" (Read et al. 2011). We calculated the epilemnetic and hypolimnetic mean temperatures. For whole column temperatures we calculated from surface to 0.5m above bottom in all but our deepest lakes.

After finding both the mixing depths and average temperatures in our selected categories we found break point(s) if any in our long-term data (Oosterbaan 2005). These break points, or points of significant change with or without directionality, were used to run Mann-Kendall monotonic trend analysis to find any statistically relevant trends in the data (

Wilkinson, Blank, and Gruber 1996). This analysis will give us the slope of change on either side of the break point (when applicable) or the entirety of the lakes recorded history. Surface water temperatures were compiled and compare to historic trends where surface waters have increased in other lakes [as much as 0.34^0 C+/year in some cases] (O'Reilly et al. 2016) Using a two tailed t-test (significance of P=.05) we looked at the first and last year collections and compared the epilemnetic and whole column temperatures based off of ecoregion to compare potential ecoregion differences.

Historical Depth and temperature were measured with a YSI. In most cases the YSI never hit bottom as there is a .5m suspended weight to keep the YSI positioned on a proper trajectory and hold it in place, this instead hit bottom.

Results and Figures:

Mixing Depth:

All lakes had break points Occurring between late 1990's and early 2000's for all lakes except Viking which occurred in 2011.Table Rock and Capri show no trend on either side of the break point. Forest and Viking show trends only before the breakpoints (Figure 1). Even without trends the average values show an increase in depth of mixing for Viking and Capri over recent years, trends may not be apparent due to low number of consistent years at this point (Table 1).

Temperatures:

Overall temperatures appeared to increase up until the break points and decline afterwards, since there are no consistent statistically significant trends at this time we cannot make this assumption as a trend for our reservoirs per our Mann Kendal analysis. Looking at yearly averages the more recent years show more variation than years before the break point (Figure 1).

<u>Epilimnion Temperatures</u>:

All abrupt shifts occurred in the late 90's with the exception of Forest in 2004. Table Rock and Capri show no trend on either side of the breakpoint. Forest shows significant monotonic trends for epilemnetic temperature only before the break point. Viking shows significant trends on either side of the break point (Table 2).

Hypolimnion Temperatures:

Break points occurred before 2000 with the exception of Forest Lake in 2004. Table Rock and Forest showed no trend on either side of the break point. Capri showed a monotonic trend only before the break point Viking had significant monotonic trends on either side of the break point (Table 3)

Whole water Column temperatures:

Significant abrupt shifts were found in all reservoirs except for Table Rock. All abrupt shifts occurred before 2001. Forest and Capri had monotonic trends before but not after the break point. Viking had a monotonic trend after but not before the breakpoint, however temperatures do seem to be declining rapidly in Viking Lake (Table 4).

Beginning v present:

Looking at different ecoregions we found no significant differences between the first year of each lakes collections for average (whole column), epilemnetic, and hypolimnetic temperatures. In most scenarios the temperatures decreased instead of increased (Table 5).

Discussion:

We found a surprising lack of monotonic trends. Most reservoirs had no trends on one or both sides of the break point in multiple criteria (mixing depth/ temperatures), however the break point alone is an indicator that there was some significant change and at this point we are unsure of exactly how it affected the water bodies. This is lack of monotonic trends is likely due to stochastic variation in the environmental conditions and reservoir characteristics (Figure 1). All significant slopes (defined by P value) fall between -1.2 and 0.26m/yr. When comparing the different ecoregions we found no significant difference between the first years recording and last for either parameter with the hypolimnion not having significant data to run a t-test in the Great Plains Region (GP) (Tables 2-5).

Physical Changes?

In this study we expect to see a decrease in stratification depth and an increased difference in epilemnetic and hypolimnetic temperatures, as the epilimnion or mixed portion of the water column continues to warm with potential increases being greater with latitude (Jones et al 2011).

Our results did not correlate with trends, likely due to variation within water bodies being that most studies have looked at natural lakes. Having both large and small lakes in our study we also leave room for inconsistencies within our systems and more reservoirs of varying size will be needed to show a better picture of how lake size affects physical changes associated with climate since smaller water bodies tend to have stronger stratification, surface temperature, and other physical trends (Folkard, Sherborne, and Coates 2007, Woolway et al. 2016). These inconsistencies with standard ideals of climate induced changes on physical mixing parameters do not rule out potential change as not all systems function the same as stated above (Winslow et al. 2017). This variance of small temperate reservoirs as (Winslow et al. 2017) supports the predictions found in models of the same lakes under our current climate scenario <2x carbon production (De Stasio et al. 1996).

We found that in both of our ecoregions, in this case being Great Plains and Ozark Highlands, there were no significant shifts in temperatures within lakes and there were too many inconsistencies to make any assumptions about latitudinal variation. These water bodies however are different in physical properties and inputs such as runoff, and Secchi depth. The Ozarks tending to have higher clarity, and lower runoff and chlorophyll (Jones and Knowlton 1993). Portions of these parameters happen to be changing, mainly in chlorophyll production as the warmer temperatures aid in increased production of both non-toxic algae and potentially toxic cyanobacteria (Paerl and Huisman 2008).

With these differences we can expect reservoirs in both regions to act differently in respect to increased environmental temperatures. In systems with high clarity there is an increased likelihood of being polymictic where those of the same depth and characteristic would be stratified with a shallower Secchi. Water bodies that would fall into these categories are often defined as Marginal lakes, where the difference in clarity can directly affect the mixing patterns of the lake (Shatwell, Adrian, and Kirlin 2016, Paerl and Hulsman 2008). Our Missouri

Reservoirs can largely be called Marginal as well as they tend to be relatively shallow (Jones and Knowlton 1993). The shallower the lake the higher likelihood of stratification due to turbidity, based off of ecoregion this would mean the southern Ozark reservoirs would have the highest likelihood of becoming polymictic due to a lack of turbidity and the Northern Plains reservoirs would remain more stable without any alteration in other parameters. Note that natural lakes and reservoirs do not act the same, shallower reservoirs will stratify more readily than natural lakes of the same depth (Jones et al 2011). This however is not necessarily the case, with the increased production in algae you can expect an increased turbidity and therefor a potential shift in normal regional patterns that are influenced by water clarity (Shatwell, Adrian, and Kirilin 2016, Paerl and Hulsman 2008).

Shifts in oxygen concentrations within the hypolimnion can occur with earlier and longer stratification which can lead to increased algal production creating a situation where the increased turbidity, stratification, and nutrients can cause an algal bloom and potentially shift mixing and other physical lake parameters (Wang et al. 2004)

Human and Animal Implications?

Lack of oxygen and potential effects on internal nutrient loading leads to potential implications for both humans and the environment. With the potential for cyanobacteria blooms you risk taste and odor issues with drinking water, potential toxic release, and impaired body contact (Jones et al. 2011, Wilhelm and Adrian 2008). Drinking water that is impaired by microsystin toxin can lead to hepatic damage and death in severe enough cases and is not limited to only human implications as any animal that consumes said water could be at risk (Groham 1962). These aspects can create a dilemma for civil engineers and citizens of locations that rely on small reservoirs for drinking water (Krol et al. 2010).

Wildlife can be impacted in many ways from kills to reductions productivity since many temperate fishes use temperature to cue reproduction (Winslow et al. 2017, Drobney and Frederickson 1979). Increased temperatures affect animals directly and indirectly as harmful algae blooms and other negative environmental conditions can lead to secondary infections in due to weakened immune systems (Soos and Wobeser 2011). Spread of invasive is likely if warming continues due to prolonged time period when spread is viable (limited ice cover) increased flooding, and increases in survivability/reproduce of temperate and tropical species (Rahel and Olden).

Conclusion:

We found no solid evidence to state that climate change is impacting the physical properties of our reservoirs. This does not fully represent all aspects of climate impacts on small temperate reservoirs, yet shows some innate stability in our systems. Increased air temperatures are influencing other factors in systems such as cyanobacteria that may mask other impacts by influencing other physical factors. A potential for climate to shift and begin to directly affect our systems in the more typical forms found in northern lakes is still possible. O'Riley and Sharma et al. 2016 predict a 20% increase in algal blooms over the next 100 years and 5% for toxic algae indicating a need for further study.

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Table 1: Lake Characteristics

Significant statistical information for mixing depth, epilimnetic, hypolimnetic, and whole column temperatures including breakpoint years, significance of any monotonic trends before or after break points, and if significant the slopes.

Lake	*Characteristic*	*Break Point (Year)*	*Slope Before BP (m/yr)*	*Slope After BP (m/yr)*	*Trend Before BP (significant)*	*Trend After BP (significant)*
Forest Lake	*Z-Mix*	*2003*	--	--	*No*	*No*
Table Rock	*Z-Mix*	*2004*	--	--	*No*	*No*
Capri	*Z-Mix*	*1999*	*-0.076*	--	*Yes*	*No*
Viking	*Z-Mix*	*2011*	*0.06*	--	*Yes*	*No*
Forest Lake	*Epi-Temp*	*2004*	*0.26*	--	*Yes*	*No*
Table Rock	*Epi-Temp*	*1997*	--	--	*No*	*No*
Capri	*Epi-Temp*	*1994*	--	--	*No*	*No*
Viking	*Epi-Temp*	*1997*	*-0.80*	*-0.36*	*Yes*	*Yes*
Forest Lake	*Hypo-Temp*	*2004*	--	--	*No*	*No*
Table Rock	*Hypo-Temp*	*1996*	--	--	*No*	*No*
Capri	*Hypo-Temp*	*1995*	*-1.12*	--	*Yes*	*No*
Viking	*Hypo-Temp*	*1997*	*-1.20*	*-0.69*	*Yes*	*Yes*
Forest Lake	*Whole-Temp*	*2001*	--	--	*Yes*	*No*
Table Rock	*Whole-Temp*	*None*	--	--	--	--
Capri	*Whole-Temp*	*1994*	*-0.99*	--	*Yes*	*No*
Viking	*Whole-Temp*	*1997*	--	*-0.313*	*No*	*Yes*

Table 6: Beginning and End year change

Significance found via a two tailed T test on first and last year average and epi temperatures for each ecoregion. OH= Ozark Highland, GP=Great Plains.

Lake	Ecoregion	Average Temp (C) First Year	Last Year	Epi Temp (C) First Year	Last Year	Hypo Temp (C) First Year	Last year	*ΔTemp (Surface) Significance	*Δ Temp (Epi) Significance	*Δ Temp (Hypo) Significance
Table Rock	OH	23.08	22.42	26.43	27.50	20.15	17.35	Not Significant	Not Significant	Not Significant
Capri		20.81	18.60	26.20	24.08	15.41	13.44	p=0.584/ t=0.645	p=0.788/ t=0.306	p=0.552/t=0.708
Forest Lake	GP	15.62	19.38	15.62	23.69	None	12.48	Not Significant	Not Significant	**Insignificant Data
Viking		23.52	19.04	26.17	21.93	20.67	10.48	p=0.935/ t=0.9106	p=0.755/t=-0.358	

*Change in temperatures (C)

** Too few points to make any significant correlation per T-test (2)

Table 1: Physical Lake Parameters

Physical information from each lake. Trophic state is based on total phosphorus measures.

Trophic index based on that for Phosphorus from Wetzel, 2011.

Category	**Max Depth**	**Years Sampled**	**Surface area**	**Secchi Depth (Avg)**	**Lng**	**Lat**	**Trophic State (TP)**	**Ecoregion**
Unit	**Meter (m)**	**1989-2016**	**m2**	**Meter (m)**	**Deg**	**Deg**	μg/L	——
Forest Lake	30.7	25	2315600	1.3	40.1688	-92.65916	Mesotrophic	GP
Table Rock	66	28	121053600	3.3	36.595	-93.31083	Oligotrophic	OH
Capri	21	28	418400	4.3	37.13388	-90.6275	Oligotrophic	OH
Viking	14.5	25	2072800	1.2	39.9377	-94.05694	Mesotrophic	GP

*Ozark Highlands (OH): Glacial Plains (GP) (Jones and Knowlton 1993)

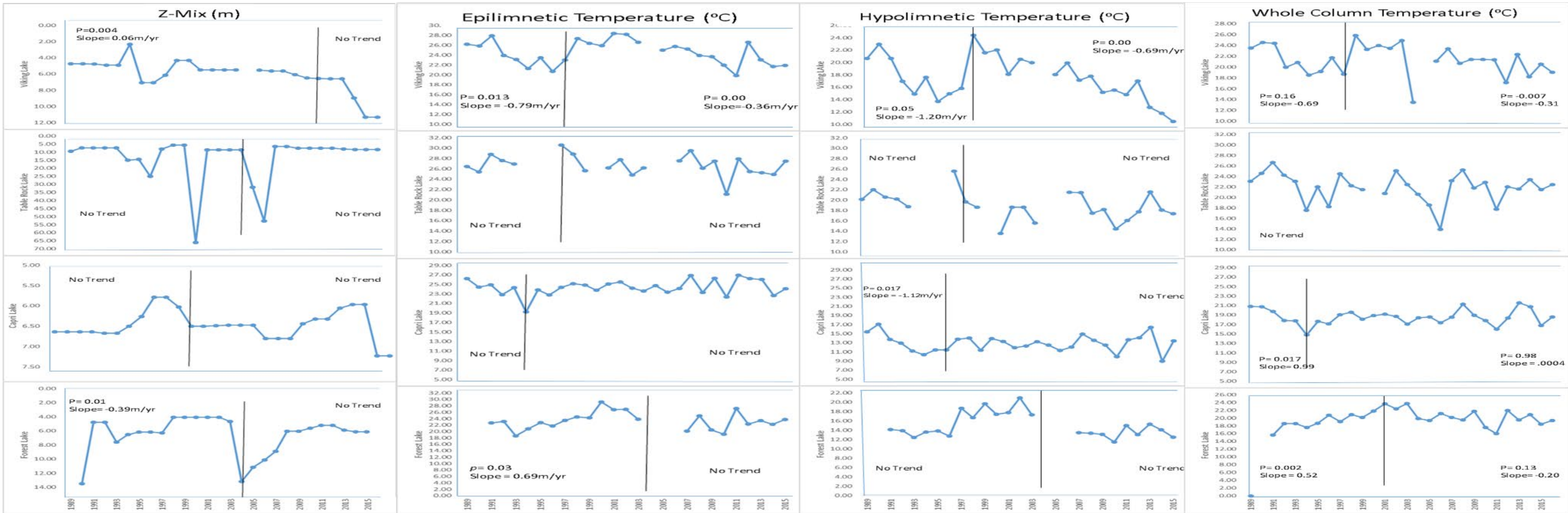

Figure 1.

Graphical depictions of changes in Z-mix, Epilemnetic, Hypolimnetic, and Whole Column temperatures over the course of the data collection. Vertical lines indicate break points, or significant changes in the mixing or temperatures of the water. These break points show that there is significant change even if it is not significantly linear in any direction.