Response to Reviewer 3

The authors thank the reviewer for comments regarding this manuscript, and we appreciate the time that the reviewer has taken to carefully review the manuscript. We have addressed the Reviewer's comments and criticisms below.

This paper consists of a sensitivity study of three lakes in the Madison area to changes in meteorological forcing, and compares the responses to these changes among these three lakes utilizing some fairly standard metrics like phenology, max/mean temperatures and stability metrics. I think it could be published, but I'm not entirely convinced of its originality and I have some comments about methodology as well. If the paper is to be revised, they need to do a better job of distinguishing this from the many other papers out there that discuss this sort of sensitivity analysis.

This paper overall looks at two factors (i) the relative influence of wind speeds vs air temperature and (ii) the role of lake size and depth in response of water temperature variables to climate changes. Research investigating the relative importance of other climatic variables in comparison to air temperature are few. Furthermore, to the best of our knowledge, studies that look at changes in non-air temperature climate variables in addition to changes in air temperature do so in either single-lake studies or studies that may encompass a large geographic area. In our study, we investigate lakes that do not undergo identical changes in meteorological variables. We aim to understand how lakes of different size and depth respond to the same changes over a long term. From a management perspective, understanding how lake size and shape alter the lake temperature response is the first step into forecasting changes in chemical and biological components of the lake ecosystem. The key contribution of this manuscript is the investigation into lake morphometry differences under wind speeds and air temperature. To the best of our knowledge, this type of studied for a long historical time period (104 years) have yet reported before. We have edited the introduction, discussion, and conclusion sections of the paper to make this contribution and significance more clear to the readers.

My main methodological concern with this paper is that it attempts to look at the role that lake area has on the response to changes in meteorological conditions, but uses a 1-dimensional model to do so. They include an empirical adjustment to account for lake area, but it seems to me that at this stage, you're not looking at the response dependence on lake area, you're looking at the response dependence on an empirical lake area adjustment. Why not just use a 3D model? Computing is cheap these days.

The authors thank the reviewer for this critical comment. We agree, that there are drawbacks to using a one-dimensional approach, as stated as an empirical lake area adjustment. We respond the comment from the following two perspectives:

From the computing perspective, using a comprehensive 3D models for 3 different lakes over a period of 104 years is still not a cheap task. Based on a paper from Reimer and Wu (2016, Water Resources Management), running a 3D model on Lake Mendota has been developed under a high performance computing (HPC) server based upon Rocks Cluster 6.0, an open-source Linux cluster distribution capable of scalable and parallel computing. The server with AMD Opteron 3.2 GHz Processor and 64 Central Processing Units (CPUs). Model input data is temporarily stored on the server for model simulation. Afterwards, each model simulation runs in parallel mode with 8 CPUs. In the modeling configuration, the time ratio of run time to modeled time is 1:72." Based on this time ratio, running a 104 year simulation on Lake Mendota would take 1.4 years of run time using their 64 CPU set-up. Fish Lake and Lake Wingra are smaller lakes. So in theory it would take less time to run. Our modeling experience (Reimer and Wu, 2016) suggested that modeling run time of ~3 years would for all three lakes would take tremendous amount of time. Overall, the additional information provided from a 3D model doesn't justify such a significant computational effort.

From data availability perspective, any 3D model simulations requires observation data only collected at the deep hole, but also spatially distributed data across the surface of the lake (Kamarainen et al., 2007, Zhang et al., 2015, and Kimura et al., 2016). In reality, we do not have 3D data for three lakes over for the period 1911-2014. If we decide to conduct this 3D modeling, we should have at least wind direction information. Based upon the best of the authors' knowledge, such data for the duration of that time period is not available. As a result, the authors structured the research using a one-dimensional model to include an empirical adjustment (which has been used on other studies of lakes with varying surface areas and shown to be a valid adjustment) for a 100+ year time period than from using a three-dimensional model for only a 35-year time period. Indeed, this type of long-term study using one-dimensional model is not an easy task. Nevertheless, the outcome of the 1-D modeling provide insights to address the response of water temperatures and stratification in lakes with different morphometry (water depth and surface area) to changing air temperature and wind speed over the period 1911-2014.

Kamarainen, A., Yuan, H.L, Wu, C.H., Carpenter, S.R., 2009. Estimates of phosphorus entrainment in Lake Mendota: A comparison of one-dimensional and three-dimensional approaches, *Limnology and Oceanography: Methods*. 7, 553-567

Kimura, N., Wu, C.H., Hoopes, J.A., and Tai, A. 2016, Diurnal thermal dynamic processes in a small and shallow lake under non-uniform wind and weak stratification, *Journal of Hydraulic Engineering-ASCE*, 142(11), 04016047,

Reimer J.R. and Wu, C.H., 2016. Development and application of a Nowcast and Forecast system tool for planning and managing a river chain of lakes, *Water Resources Management*, 30(4), 1375-1393.

Zhang, Y.J., Ateljevich, E., Yu, H.C., Wu, C.H., Yu, J.C.S., 2015. A new vertical cooridnate system for a 3D unstructured-grid system, *Ocean Modelling*, 85(1), 16-31.

One result I found very strange is their description of the "nonlinear" response of some of the lakes to various perturbations. They state that the response depends on whether they are perturbing, for instance, air temperature in the positive direction or negative direction (p12. Lines 10-15, again lines 20-25). There's nothing special about the base case, so the division they point out is artificial.

Thank you to the reviewer for pointing out that this wording is strange. We reference from the base case since that case encompasses the historical observations of meteorological conditions and the air temperature and wind speed were perturbed from that historical condition. We have rewritten the sections to address, instead of saying "nonlinear", the change caused from an increase or decrease in air temperature or wind speed from this base case.

If they are going to discuss step changes in various parameters, they should probably reference the van Cleave and Lenters paper that does this for Lake Superior.

The Van Cleave et al paper uses a different method for determining step changes, and focuses significantly on ice cover. However, we have referenced the difference in step changes between Lake Superior and our lakes for surface water temperatures as suggested by the reviewer in the following: "These increases in epilimnetic temperatures are similar to those found for European lakes (Woolway et al., 2017b) in response to regional climate changes, although Woolway et al. (2017b) demonstrated a substantial increase in annually averaged lake surface water temperatures in the lake 1980s in response to an abrupt shift in the climate, which is not apparent in epilimnion water temperatures for our study lakes. Additionally, Van Cleave et al. (2014) showed a regime shift in July – September Lake Superior surface water temperatures after 1997, driven by El Niño in 1997-1998; however we do not find a similar regime shift in our study lakes, which may be due to geographical differences in meteorology or morphometric differences from the larger Lake Superior."

On a more minor note, they should specify what bulk turbulence method they are using in the model.

Thank you to the reviewer for pointing out that this wasn't clear in the manuscript. We have revised the model description as "Surface layer mixing is based on potential energy required for mixing, and introduction of turbulent kinetic energy through convective mixing, wind stirring, and shear mixing (Imerito, 2010; Yeates and Imberger, 2003). Layer mixing occurs when the turbulent kinetic energy, stored in the topmost layers, exceeds a potential energy threshold (Yeates and Imberger, 2003)."

I was confused by the statement "all parameters and coefficients are kept constant" (p. 5 line 26). What parameters are these?

Thank the reviewer for pointing out this confusion. The parameters referred to are the model parameters and coefficients – they are constant throughout the simulation rather than being time-varying. Some confusion may be from this sentences placement within the paragraph. We have moved the sentence later in the paragraph. It now follows the sentences which specify the model parameters. "…Parameters relevant to the open water period are provided in Table 2. Ice cover model parameters can be found in Hamilton et al. (in review), Magee and Wu (2016), and Magee et al., (2016). During the entire simulation period, all model parameters and coefficients are kept constant. …"

Do they use the same sediment temperature model for all three lakes? Is this justified?

Yes, we use the same model to estimate heat transfer from the sediments to the water column (eq 1 and 2), and the same equation to estimate sediment temperature (eq 3) for all three lakes. Given the distance between lakes, it is likely justified to assume that over the long-term modeling period, sediment temperature changes at all three lakes follow a very similar sinusoidal pattern during the year. Based on data from Hennings and Connelly (Hennings, R. G. and Connelly, J. P.: Average ground-water temperature map, Wisconsin, Wisconsin Geological and Natural History Survey., 2008.), groundwater temperatures at all three lakes have the same average and vary similarly throughout the year. At these depths, groundwater temperatures are an appropriate proxy for sediment temperatures. Since groundwater temperatures have the same average and vary similarly throughout the year at all three locations, we feel that although the equation for sediment temperature was developed for Lake Mendota, it is justified to use it for all three of the lakes in this study.

Response to Reviewer 4

The authors thank Reviewer for their helpful and constructive comments. We have addressed the comments to improve the quality of the manuscript. We have addressed comments in the reply provided below.

General comments

This is a well written paper describing an interesting topic in climatology and limnology: 'How has lake temperature and stratification responded to a changing climate, and how can we expect these responses to differ among lakes'. Magee and Wu use an exceptional dataset of >100 years and focus on the effects of changing air temperature and wind speed on water temperature and stratification patterns in three lakes situated near Madison, Wisconsin (US), which are characterized by different morphometric features. Similar results have been presented in the literature for lakes elsewhere (see specific details below), but the strengths of this paper is the across-lake comparison and the use of a one-dimensional lake model to disentangle the different factors which contribute to a lakes response to climate change. The authors use the one-dimensional lake model (DYRESM-WQ), which has been used frequently by the limnological community during the past 20 or so years. I must admit, I am not a fan of using models that are not openly available (this is my understanding of DYRESM), especially as many other one-dimensional lake temperature models are openly available to the community. For example, the General Lake Model (GLM), Freshwater Lake model (FLake), and MyLake all have similar capabilities to DYRESM but are open-access. If my understanding is incorrect and DYRESM is openly available, please state this in the methods. The authors use DYRESM to reconstruct the thermal and stratification regime of the lakes during the last century and for sensitivity studies exploring the lake responses to changes in mean annual air temperature and wind speed.

I found the aim of this paper clearly described, the results very convincing and presented in a reasonable manner, and I think the paper will be well received by the limnological community. Specifically, this paper investigates what, in my opinion, is currently lacking in the scientific literature. Specifically, many of the previous studies that have examined the response of lake surface water temperature to climate change have focused on the past few decades. Thus, having a study focusing on lake temperature responses from the start of the 20th century is an important contribution. I do believe this is an important topic, and one that deserves some attention - particularly given the recent emphasis on the rapid warming of lakes from around the world, and the numerous ecological and socioeconomic consequences of increasing lake surface water temperature, in addition to their interactions within the climate system.

Overall, I think this paper is well written, the data is well chosen and the analysis is reasonable. I can see this paper being a benchmark for future studies and an important contribution to the literature. I think there is great potential for this paper to be valuable to the community.

We thank the reviewer for the kind comments. We appreciate that the reviewer thinks the paper would be useful or valuable for the limnology community. Regarding the accessibility of DYRESM, the authors agree that this is valid concern. While this paper deals specifically with open water temperature comparisons across the three lakes, the authors have been working for a number of years on additional analysis in the three study lakes dealing with also ice cover (see Magee and Wu, Hydrological Processes, 2016), water clarity (see Magee et al, HESS, 2016), and dissolved oxygen and fish habitat (ongoing research). Because of the long-term goal, we select one model that was capable of simulating not only temperature and dissolved oxygen, but also the biogeochemical processes in the lakes. When the time modeling work was originally initiated, such open source models were not available. Flake doesn't incorporate biogeochemical processes, and MyLake has some issues in regard to the number of algal groups incorporated and biogeochemical processes incorporated into the model when compared to those in DYRESM-WQ. For those reasons, FLake and MyLake were not chosen. Additionally, at the onset of the study, the GLM model, while available for use, was not at the time able to simulate ice cover accurately (see Yao et al, Hydrological Processes, 2014). At the time of project initiation, DYRESM-WQ was superior to the available open source models in terms of meeting all the goals of our overall research agenda with only one model development. However, the authors do appreciate the reviewer's comments regarding open source modeling and we will, of course, keep these comments in mind when moving forward with future research questions.

Specific Comments

Introduction

In general, the introduction is well written. However, the literature review seems rather limited and many of the recent studies covering this topic have been overlooked. For example, see the O'Reilly et al. (2015) paper and references therein for an update of some recent paper in this topic. Also, in the opening paragraph, the authors refer to decreasing wind speeds but not referred to some of the important papers in this topic, such as Vautard et al. (2010) who demonstrated that wind speeds globally have been decreasing. In addition, of great relevance to the current study is the paper by Woolway et al. (2017a) who followed a very similar approach to that described in this paper when reconstructing the thermal dynamics of Vortsjarv (Estonia) - they also investigated the response of lake temperature dynamics to changes in air temperature and wind speed.

The authors thank the reviewer for this comment, and we agree, that some of the most recently published literature was left out of the introduction and discussion of the manuscript. The original manuscript was submitted to Hydrology and Earth Systems Sciences in May 2016, which left a large bulk of the most recent literature (published in 2016 and 2017) outside of the paper. Taking the reviewer's comment into consideration, we have added some of the most pertinent newly published literature within the introduction and discussion where appropriate and necessary to place this research within the broader context of lake temperature investigations. To reduce length and give appropriate credit to a broad variety of research and groups, we have not included the exhaustive list of most recent literature, but rather those we feel adds the most value to our manuscript.

P2L15 - Lake water temperature is closely related to the… Equally important is humidity, cloud cover, solar radiation - in particular the surface energy fluxes. For example, the study of Schmid and Köster (2016) demonstrated that 60% of lake surface water temperature warming in Lake Zurich was caused by air temperature and 40% by increased solar radiation. Also, a paper by Wilhelm et al. (2006) demonstrated that daily extreme water temperatures (although they used the equilibrium temperature) responded to shifts in air temperature, wind speed, relative humidity, and cloud cover. Thus, one could argue that to understand fully how lake surface water temperatures will respond to climate change, one would require each of these variables to be included. This has been shown to be important for some lakes (Schmid and

Köster 2016). I realize that the authors have likely considered all of the points I've raised here, but I think they should be mentioned in the paper.

Also, important is local features. For example, the study Tanentzap et al. (2008) showed that some lakes might cool as air temperatures increase, as a response of the complicated interactions between lakes and their environment and/or internal processes.

The authors thank the reviewer for the comment. We have added a section in the discussion to address these points concerning changes in other climate variables and local lake-specific interactions, as follows: "Ultimately, lake warming or cooling may depend on the magnitudes and directions of changes of air temperature, wind speed, and other variables as climatic variables humidity, cloud cover, and solar radiation and water clarity variables are important in determining lake water temperatures. Schmid and Köster (2016) demonstrated that 40% of surface water warming in Lake Zurich was caused by increased solar radiation. Wilhelm et al. (2006) showed that daily extrema of surface equilibrium temperature responded to shifts in wind speed, relative humidity, and cloud cover in addition to changes in air temperature. However, neither study looked at lakes with seasonal ice cover, which may not account for changes in ice sheet formation and the resulting influence on lake water temperatures (Austin and Colman, 2007). Changes in underwater light conditions from increased dissolved organic carbon concentrations combined with reduction in surface wind speeds can result in cooling whole-lake average temperatures despite substantial air temperature increases, as was the case for Clearwater Lake, Canada (Tanentzap et al., 2008). Water clarity has seen both increases and decreases since the early 1990's (Rose et al., 2017), with precipitation playing a critical role in year-to-year variability (Rose et al., 2017). Further investigation into the combined effects of these climatic and lake-specific variables is warranted."

…found that decreasing wind speeds resulted in increased stratification… - This is a great example of the Woolway et al. (2017a) study.

As stated above, this paper was not published when our manuscript was originally submitted, but the authors thank the Reviewer for pointing out its relationship to our study and we have added this reference as suggested.

In terms of the influence of lake surface area altering the response of lakes to atmospheric forcing, I think more context is needed here. Specifically, numerous papers have demonstrated the importance of lake size, some of which you already cited. Some examples:

• Winslow et al. (2015), which you cite, demonstrated that small lakes demonstrate a muted response of deep water temperature to climate change.
• Read et al. (2012) demonstrated that lake size influences the relative contribution of wind and convective mixing to the gas transfer coefficient in lakes.
• Woolway et al. (2016) demonstrated that lake size can influence the magnitude of diurnal heating and cooling in lakes which has important consequences for gas transfer (Holgerson et al. 2017).
• Torbick et al. (2016) demonstrates that smaller lakes in northeast United States have been warming more rapidly than larger lakes in terms of surface water temperature.

Note I only list a few above but there are many others, which I trust the authors to find.

The authors thank the Reviewer for this list of suggested literatures, we have added additional context where suggested in the introduction and discussion. Specifically, the last two bullet points address research that was published after our manuscript was submitted to Hydrology and Earth Systems Sciences. We were aware of the new research but those paper were published after the submission of the original manuscript. We have added these new studies as suggested by the reviewer,

Methods

Is DYRESM-WQ open-access? If so, I think details of where the reader can find the source code would be useful. Similar to GLM (General Lake Model), which is openly available, I would hope DYRESM-WQ is available to the community, as all results should be reproducible by the reader.

DYRESM-WQ is not open access. As discussed above, GLM was only in the early stages of development when the modeling development and setup was first started. It was not an option for us to use in our study. Only recently has GLM successfully reproduced ice and snow cover, which was an important component of the continuous modeling and other parts of the overall study (see Magee and Wu, Hydrological Processes, 2016). Additionally, other available open-source models were not chosen because of deficiencies in simulating biogeochemical processes and dissolved oxygen, as described previously.

I would show the light attenuation coefficient as Kd (not k), as it is commonly referred in the limnological community.

The authors thank the reviewer for this comment. We have shown light attenuation coefficient at Kd, as suggested by the reviewer.

Discussion

This paper has some similarities with a paper very recently published in Climatic Change by Woolway et al. (2017b). In particular, they also analyze a > 100 year lake temperature time series from two lakes in Austria (Mondsee and Worthersee), and investigate how 20 lakes with >50 years of observations have responded to climatic warming. I would strongly encourage the authors to discuss these results and compare to their findings.

In addition, how do the abrupt shifts, which you discuss (evaluated via the Rodionov method), compare with Woolway et al. (2017b)?

The authors thank the Reviewer for these two comments. While epilimnion water temperatures are a part of this manuscript, they are not the focal point as in Woolway et al. To address the comments, we have added some sentences in the results placing our epilimnion temperature changes in the context of this work by Woolway et al in European lakes: " These increases in epilimnetic temperatures are similar to those found for European lakes (Woolway et al., 2017b) in response to regional climate changes, although Woolway et al. (2017b) demonstrated a substantial increase in annually averaged lake surface water temperatures in the lake 1980s in response to an abrupt shift in the climate, which is not apparent in epilimnion water temperatures for our study lakes."

Figures and Tables

Figure 1: Can the authors add a local map to illustrate how close these lakes are to one-another? I know this is mentioned in the text, but including a map would be useful. Also, it is rather difficult to see some of the contour values. If the contours can be re-drawn in grey, that would make the writing more understandable – or potentially redraw these as colour plot, if you are generating figures in colour.

The authors thank the Reviewer for this comment. We have added a local map with scale, as suggested to aid the reader in interpreting the distance between all three lakes. Additionally, we have re-drawn contours in grey to make the figures easier to interpret for the reader.

Figure 2. Interestingly, the step in annual air temperature seems to occur at the same time as reported by Woolway et al. (2017b) for Central Europe, a result of a global shift perhaps? Also, the wind speed change in ~1995 is consistent with the results of Woolway et al. (2017a) for Estonia, although they do not report on the exact year, but a shift can be seen from their figures.

The authors thank the Reviewer for this comment, we have added a sentence addressing the shift in annual air temperatures "A change in air temperatures also occurred in the 1980s in Central Europe (Woolway et al., 2017b), which may indicate that change in air temperature were a global phenomenon rather than local occurrence."

References:

Bichet A, Wild M, Folini S, Schär C (2012) Causes for decadal variations of wind speed over land: Sensitivity studies with a global climate model. Geophys Res Lett 39(11). doi:10.1029/2012GL051685.

Holgerson M, Farr E, Raymond P (2017) Gas transfer velocities in small forested ponds. J. Geophys Res. doi: 10.1002/2016JG003734

O'Reilly et al. (2015) Rapid and highly variable warming of lake surface waters around the world. Geophy Res Lett 42, 10773-10781.

Schmid M, Köster O (2016) Excess warming of a Central European lake by solar brightening. Water Resour Res 52:8103-8116. doi:10.1002/2016WR018651

Tanentzap AJ, et al. (2008) Cooling lakes while the world warms: Effects of forest regrowth and increased dissolved organic matter on the thermal regime of a temperate, urban lake. Limnol Oceanogr 53:404-410.

Torbick et al. (2016) demonstrates that smaller lakes in northeast United States have been warming more rapidly than larger lakes in terms of surface water temperature.

Vautard R, Cattiaux J, Yiou P, Thepaut J, Ciais P (2010) Northern Hemisphere atmospheric stilling partly attributed to an increase in surface roughness. Nature Geo Sci 3:756-761.

Wilhelm S, Hintze T, Livingstone DM, Adrian R (2006) Long-term response of daily epilimnetic temperature extrema to climate forcing. Can J Fish Aquat Sci 63:2467-2477.

Woolway, R.I., Jones, I.D., Maberly, S.C. et al. (2016). Diel surface temperature range scales with lake size. PLoS One 11(3): e0152466. doi: 10.1371/journal.pone.0152466

Woolway, R.I., Meinson, P., Nõges, P., Jones, I. D., Laas, A. (2017a). Atmospheric stilling leads to prolonged thermal stratification in a large shallow polymictic lake. Climatic Change. doi:10.1007/s10584-017-1909-0

Woolway, R.I., Dokulil, M., Marszelewski, W., Schmid, M., Bouffard, D., Merchant, C.J. (2017b). Warming of Central European lakes and their response to the 1980s climate regime shift. Climatic Change. doi:10.1007/s10584-017-1966-4

The authors thank the Reviewer for this extensive list of additional references, some of which were published after the submission of the manuscript to Hydrology and Earth Systems Sciences. We have elected to include the most pertinent new references and a few others as appropriate for enhancing introduction and discussion of the manuscript.

Response of water temperatures and stratification to changing climate in three lakes with different morphometry

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Abstract. Water temperatures and stratification are important drivers for ecological and water quality processes within lake systems, and changes in these with increases in air temperature and changes to wind speeds may have significant ecological consequences. To properly manage these systems under changing climate, it is important to understand the effects of increasing air temperatures and wind speed changes in lakes of different depths and surface areas. In this study, we simulate three lakes that vary in depth and surface area to elucidate the effects of increasing air temperatures and decreasing wind speed on lake thermal variables (water temperature, stratification dates, strength of stratification, and surface heat fluxes) over a century (1911-2014). For all three lakes, epilimnetic temperatures increased, hypolimnetic temperatures decreased, the length of the stratified season increased due to earlier stratification onset and later fall overturn, stability increased, and longwave and sensible heat fluxes at the surface increased. Overall, lake depth influences presence of stratification, Schmidt stability, and differences in surface heat flux, while lake surface area influences differences in hypolimnion temperature, hypolimnetic heating, variability of Schmidt stability, and stratification onset and fall overturn dates. Larger surface area lakes have greater wind mixing due to increased surface momentum. Climate perturbations indicate that larger lakes have more variability in temperature and stratification variables than smaller lakes, and this variability increases with larger wind speeds. For all study lakes, Pearson correlations and climate perturbation scenarios indicate that wind speed plays a large role on temperature and stratification variables, sometimes greater than changes in air temperature, and wind can act to either amplify or mitigate the effect of warmer air temperatures on lake thermal structure depending on the direction of local wind speed changes.

1 Introduction

The past century has experienced global changes in air temperature and wind speed. Land and ocean surface temperature anomalies increased from 1850 to 2012 (IPCC, 2013). Mean temperature anomaly across the continental United States has increased (Hansen et al., 2010), and studies suggest that more intense and longer lasting heat waves will continue in the future (Meehl and Tebaldi, 2004). Additionally, global change in wind speed has been heterogenous. For example, wintertime wind energy increased in Northern Europe (Pryor et al., 2005), but other parts of Europe have experienced decreases in wind speed in part due to increased surface roughness (Vautard et al., 2010), while modest declines in mean wind speeds were observed in the United States (Breslow and Sailor, 2002). Similarly, on regional scales, Magee et al. (2016) showed a decrease in Madison, Wisconsin wind speeds after 1994, but Austin and Colman (2007) found increased wind speeds in Lake Superior, North America. Significant changes to air temperature and wind speed observed in the contemporary and historical periods are likely to continue to change in the future.

Lake water temperature is closely related to air temperature and wind speed. Previous studies have mainly focused on warming air temperatures, showing ~~show that warming air temperatures have~~ increased epilimnetic water temperatures (Dobiesz and Lester, 2009; Ficker et al., 2017; O'Reilly et al., 2015; Shimoda et al., 2011)~~(Dobiesz and Lester, 2009; Shimoda et al., 2011)~~, increased ~~the~~ strength of stratification (Hadley et al., 2014; Rempfer et al., 2010)~~(Rempfer et al., 2010)~~, prolonged ~~the~~ stratified period (Ficker et al., 2017; Livingstone, 2003; Woolway et al., 2017a)~~(Livingstone, 2003; Robertson and Ragotzkie, 1990)~~, and altered thermocline depth (Schindler et al., 1990). However, hypolimnetic temperatures have undergone ~~either warming or cooling trends depending on season~~warming, cooling, and no temperature increase (Butcher et al., 2015; Ficker et al., 2017; Magee et al., 2016; Shimoda et al., 2011)~~(Robertson and Ragotzkie, 1990)~~. Wind speed also strongly affects lake mixing (Boehrer and Schultze, 2008), lake heat transfer (Boehrer and Schultze, 2008; Read et al., 2012), and temperature structure (Desai et al., 2009; Schindler et al., 1990). Stefan et al. (1996) found that decreasing wind speeds resulted in increased stratification and increased epilimnetic temperatures in inland lakes, and Woolway et al. (2017a) similarly found that decreasing wind speeds increased days of stratification for a polymictic lake in Europe. In Lake Superior, observations show that the complex nonlinear interactions among air temperature, ice cover, and water temperature result in water temperature increases (Austin and Allen, 2011), contrary to the expected decreases in water temperature from increased wind speeds (Desai et al., 2009). In recent years, our understanding of the effects of air temperature and wind speed on changes in water temperature and stratification has improved (Kerimoglu and Rinke, 2013; Magee et al., 2016; Woolway et al., 2017a)~~(Magee et al., 2016)~~, but research into ~~there remains uncertainty in~~ the response of lakes to isolated and combined changes in air temperature and wind speed has been limited.

Changes in lake water temperature influence lake ecosystem dynamics (MacKay et al., 2009). For example, increasing water temperatures may change plankton community composition and abundance (Rice et al., 2015), alter fish populations (Lynch et al., 2015), and enhance the dominance of cyanobacteria (Jöhnk et al., 2008). Such changes affect the biodiversity of freshwater ecosystems (Mantyka-Pringle et al., 2014). Furthermore, increased thermal stratification of lakes can intensify lake anoxia (Ficker et al., 2017; Palmer et al., 2014)~~(Palmer et al., 2014)~~, increase bloom-forming cyanobacteria (Paerl and Paul,

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2012), and change internal nutrient loading and lake productivity (Ficker et al., 2017; Verburg and Hecky, 2009)(Verburg and Hecky, 2009). Variations in water temperature impact the distribution, behaviour, community composition, reproduction, and evolutionary adaptations of organisms (Thomas et al., 2004). Improved understanding of response of lake water temperatures and ecosystem response to air temperature and wind speed can better prepare management, adaptation, and mitigation efforts for a range of lakes.

Lake morphometry complicates the response of lake water temperatures to air temperature and wind speed changes because it alters physical processes of wind mixing, water circulation, and heat storage (Adrian et al., 2009). Mean depth, surface area, and volume strongly affect lake stratification (Butcher et al., 2015; Kraemer et al., 2015). Large surface areas increase the effects of vertical wind mixing, an important mechanism for transferring heat to the lake bottom (Rueda and Schladow, 2009), and changes in thermocline depth from warming air temperatures may be dampened in large lakes where thermocline depth is constrained by lake fetch (Boehrer and Schultze, 2008; MacIntyre and Melack, 2010). Lake size has been demonstrated to influence the relative contribution of wind and convective mixing to gas transfer (Read et al., 2012), and lake size can influence the magnitude of diurnal heating and cooling in lakes (Woolway et al., 2016), which both have implications for calculating metabolism and carbon emissions in inland waters (Holgerson et al., 2017). Winslow et al. (2015) showed that differences in wind-driven mixing may explain the inconsistent response of hypolimnetic temperatures between small and large lakes. Previous research efforts have investigated the response of individual lakes (Voutilainen et al., 2014) and the bulk response of lakes in a geographic region to changing climate (Kirillin, 2010; Magnuson et al., 1990), but few studies have focused on elucidating the effects of morphometry, specifically lake depth and surface area, on changes in lake water temperature in response to long-term changes in air temperature and wind speed.

The purpose of this paper is to investigate the response of water temperatures and stratification in lakes with different morphometry (water depth and surface area) to changing air temperature and wind speed. To do this, we employ an existing one-dimensional hydrodynamic lake-ice model to hindcast water temperatures for three lakes with different morphometry. These lakes vary in surface area and depth and are nearby (<30 km distance) to experience similar daily climate conditions (air temperature, wind speed, solar radiation, cloud cover, precipitation) over the period 1911-2014. Long-term changes in water temperature, stratification, heat fluxes, and stability were used to investigate how lake depth and surface area alter the response of thermal structure to air temperature and wind speed changes for the three study lakes.

2 Methods

2.1 Study sites

Three morphometrically different lakes, Lake Mendota, Fish Lake, and Lake Wingra, located near Madison, Wisconsin, United States of America (USA), were selected for this study. These lakes are chosen for (i) their morphometry differences, (ii) their proximity to one another, and (iii) the availability of long-term data for model input and calibration.

Lake Mendota (43°6' N; 89°24'W; Fig. 1a; Table 1), is a dimictic, eutrophic, drainage lake in an urbanizing agricultural watershed (Carpenter and Lathrop, 2008). The lake stratifies during the summer, and typical stratification periods lasts from May to September. Summer (1 June - 31 August) mean surface water temperature is 22.4 °C, and hypolimnetic temperatures vary between 11°C to 15 °C. Normal Secchi depth during the summer is 3.0 meters (Lathrop et al., 1996). Fish Lake (43°17'N; 89°39'W; Fig. 1b; Table 1) is a dimictic, eutrophic, shallow seepage lake located in northwestern Dane County. From 1966 to 2001, lake level rose by 2.75 meters due to increased groundwater flow from higher than normal regional groundwater recharge (Krohelski et al., 2002). Krohelski et al. (2002) hypothesized that the increase in recharge may be the result of increased infiltration from snowmelt after increased snowfall and less frost-covered soil. Summer stratification lasts from the beginning of May to mid-September. Mean surface water temperature 23.9°C and hypolimnetic temperatures are normally near 8°C during summer months; however, some years reach temperatures of only 5-6 °C in the hypolimnion due to shortened spring mixing durations. Average Secchi depth during the summer months is 2.4 m. Lake Wingra (43°3' N; 89°26' W; Fig. 1c; Table 1) is a shallow, eutrophic, drainage lake. It stratifies on short timescales of hours to weeks (Kimura et al., 2016), but does not experienced sustained thermal stratification. Summer mean water temperature is 23.9°C, and mean Secchi depth is 0.7 meters. All three lakes have ice cover during winter months, and a description of ice on the lakes can be found in Magee and Wu (2016)

2.2 Model description

To hindcast water temperature and stratification in the three study lakes we use the vertical heat transfer model, DYRESM-WQ (DYnamic REservoir Simulation Model-Water Quality; Hamilton and Schladow, 1997), which employs discrete horizontal Lagrangian layers to simulate vertical water temperature, salinity, and density with input including inflows, outflows, and mixing (Imberger et al., 1978). The model has been previously used on a variety of lake types and is accepted as a standard for hydrodynamic lake modelling (Gal et al., 2003; Hetherington et al., 2015; Imberger and Patterson, 1981; Kara et al., 2012; Tanentzap et al., 2007). DYRESM-WQ adopts a one-dimensional layer structure based on the importance of vertical density stratification over horizontal density variations. A one-dimensional assumption is based on observations that the density stratification found in lakes inhibits vertical motions while horizontal variations in density relax due to horizontal advection and convection (Antenucci and Imerito, 2003; Imerito, 2010). Surface exchanges include heating due to shortwave radiation penetration into the lake and surface fluxes of evaporation, sensible heat, long wave radiation, and wind stress (Imerito, 2010). Surface layer mixing is based on potential energy required for mixing, and introduction of turbulent kinetic energy through convective mixing, wind stirring, and shear mixing (Imerito, 2010; Yeates and Imberger, 2003). Layer mixing occurs when the turbulent kinetic energy, stored in the topmost layers, exceeds a potential energy threshold (Yeates and Imberger, 2003). Yeates and Imberger (2003) improved performance of the surface mixed layer routine within the model by including an effective surface area algorithm (see Eq 32 in Yeates and Imberger, 2003) that reduced surface mixing in smaller, more sheltered lakes. Details of the surface mixed layer algorithm are not reproduced here, but can be found in Eq 27-34 of Yeates and Imberger (2003). Hypolimnetic mixing is parameterized through a vertical eddy diffusion coefficient, which accounts for turbulence created by the damping of basin-scale internal waves on the bottom boundary and lake interior (Yeates and Imberger, 2003). Detailed equations on the simulation of water temperature and mixing can be found in Imberger and Patterson (1981), Imerito (2010), and Yeates and Imberger (2003).

Sediment heat flux is included as a source/sink term for each model layer. A diffusion relation from Rogers et al. (1995) is used to estimate q_{sed}, heat transfer from the sediments to the water column.

$$q_{sed} = K_{sed}\frac{dT}{dz} \qquad (1)$$

where Ksed represents the sediment conductivity with a value of 1.2 Wm^{-1} $°C^{-1}$, and dT/dz is estimated as:

$$\frac{dT}{dz} = \frac{T_s - T_w}{z_{sed}} \qquad (2)$$

where dT/dz is the temperature gradient across the sediment-water interface, T_w is the water temperature adjacent to the sediment boundary, z_{sed} is the distance beneath the water-sediment interface at which the sediment temperature becomes relatively invariant, and is taken to be 5 m (Birge et al., 1927). T_s derived from Birge et al. (1927) and seasonally variant as follows:

$$T_s = 9.7 + 2.7\sin\left[\frac{2\pi(D-151)}{TD}\right] \qquad (3)$$

where D is the number of days from the start of the year and TD is the total number of days within a year.

The ice component of the model, DYRESM-WQ-I, is based on the three-component MLI model of Rogers et al., (1995), with the additions of two-way coupling of the hydrodynamic and ice models and time-dependent sediment heat flux for all horizontal layers. The model assumes that the time scale for heat conduction through the ice is short relative to the time scale of meteorological forcing (Patterson and Hamblin, 1988; Rogers et al., 1995), an assumption which is valid with a Stefan number less than 0.1 (Hill and Kucera, 1983). The three-component ice model simulates blue ice, white ice, and snow thickness (see Eq. 1 and Fig. 5 of Rogers et al., 1995). Further description of the ice model can be found in Magee et al. (2016) and Hamilton et al. (in review). Details on ice cover simulations in response to changing climate for the three lakes can be found in Magee and Wu (2016)

Model inputs include lake hypsography, initial vertical profiles for water temperature and salinity, Secchi depth, meteorological variables, and inflows/outflows. The model calculates the surface heat fluxes using meteorological variables: total daily shortwave radiation, daily cloud cover, air vapor pressure, daily average wind speed, air temperature, and precipitation. ~~During the entire simulation period, all parameters and coefficients are kept constant.~~ Water temperature, water budget, and ice thickness is calculated at 1 hr timesteps. Snow ice compaction, snowfall and rainfall components are updated at a daily time step, corresponding to the frequency of meteorological data input. Cloud cover, air pressure, wind speed, and temperature are assumed constant throughout the day, and precipitation is assumed uniformly distributed. Shortwave radiation distribution throughout the day is computed based on lake latitude and the Julian day. Parameters relevant to the open water period are provided in Table 2. Ice cover model parameters can be found in Hamilton et al. (in review), Magee and Wu (2016), and Magee et al., (2016). During the entire simulation period, all model parameters and coefficients are kept constant. Simulations were run for all three lakes starting on 7 April 1911 and ending on 31 October 2014 without termination.

2.3 Data

2.3.1 Lake morphometry

Height (m), area (m2), and volume (m3) which describe the hyposgraphic curves for each lake were calculated using bathymetric maps of each lake from the Wisconsin DNR.

2.3.2 Initial conditions

Initial conditions for each lake include a temperature and salinity profiles for the first days of the simulations. For Lake Mendota, initial conditions were obtained from the NTL-LTER database on the first day of simulation [NEED CITATION HERE]. For Fish Lake and Lake Wingra, initial conditions after ice off were unavailable for 1911, and were assumed to be the average of all available initial conditions for the lake from ±7 days of the Julian start date for all years with available data.

2.3.3 Light extinction coefficient

Seasonal Secchi depths were used to determine the light extinction coefficients. Lathrop et al. (1996) compiled Secchi depth data for Lake Mendota between 1900 and 1993 (1701 daily Secchi depth readings from 70 calendar years), and summarized the data for six seasonal periods: winter (ice-on to ice-out), spring turnover (ice-out to 10 May), early stratification (11 May to 29 June), summer (30 June to 2 September), destratification (3 September to 12 October), and fall turnover (13 October to ice-on). After 1993, Secchi depths are obtained from the North Temperate Lake Long Term Ecological Research (NTL-LTER) program (https://portal.lternet.edu/nis/home.jsp#). Open water and under-ice Secchi depths were collected for various long-term ecological research studies, including the NTL-LTER study, and used here to better characterize temperature profiles throughout the year including under ice cover. Secchi depth data for Fish Lake and Lake Wingra were available only from 1995 to the present and collected from the NTL-LTER program. For years with no Secchi data, the long-term mean seasonal Secchi depths were used. Light extinction coefficients were estimated from Secchi depth using the equation from Williams et al. (1980):

$$k_d = 1.1/z_s^{0.73} \quad (4)$$

where k_d is the light extinction coefficient and z_s is the Secchi depth (m).

2.3.4 Meteorological data

Meteorological data used to hindcast the historical period consisted of daily solar radiation, air temperature, vapor pressure, wind speed, cloud cover, rainfall, and snowfall over a period of 104 years from 1911 to 2014. Air temperature, wind speed, vapor pressure, and cloud cover were computed as an average of the whole day, while solar radiation, rainfall, and snowfall were the daily totals. Meteorological data was gathered from Robertson (1989), who compiled a continuous daily meteorological dataset for Madison Wisconsin from 1884 to 1988 by adjusting for changes in site location. Appended to this dataset is data from the National Climate Data Center weather station at the Dane County Regional Airport. All data other than solar radiation can be obtained from http://www.ncdc.noaa.gov/, for Madison (MSN), and solar radiation can be obtained from http://www.sws.uiuc.edu/warm/weather/. Adjustments to wind speed were made based on changes in observational techniques occurring in 1996 (McKee et al., 2000) by comparing data from Dane County Airport with that collected from the Atmospheric and Oceanic Science Building instrumentation tower at the University of Wisconsin-Madison (http://ginsea.aos.wisc.edu/labs/mendota/index.htm). Detail of this adjustment can be found in Magee et al. (2016) and Hsieh (2012).

2.3.5 Inflow and outflow data

Daily inflow and outflow data for Lake Mendota was obtained and described in detail by Magee et al. (2016). Details of data collection and gap-filling can be found there and are not reproduced for brevity. Inflow and outflow data for Fish Lake and Lake Wingra follow a similar process. Inflow and outflow were estimated as the residual unknown term of the water budget balancing precipitation, evaporation, and lake level. USGS water level data from 1966-2003 (http://waterdata.usgs.gov/wi/nwis/dv/?site_no=05406050&agency_cd=USGS&referred_module=sw) was used to estimate inflow and outflow from surface runoff and groundwater inflow. For early years of simulation, where lake level information was not available, the long-term mean lake level was assumed for calculations. Krohelski et al. (2002) determined that surface runoff accounted for two-thirds of inflowing water while groundwater inflow accounted for one-third of total inflow over the period 1990-1991. Using these values, we attributed two-thirds of the inflowing water as surface runoff using air temperatures to estimate the runoff temperature similar to the method for Lake Mendota in Magee et al. (2016) and one-third of inflowing water as groundwater inflow using an average of groundwater temperature measurements (Hennings and Connelly, 2008). For Lake Wingra, water level was recorded sporadically during the period of interest, and was assumed to be the long-term mean lake level for water budget calculations. As in Fish Lake, Lake Wingra has no surface inflow streams, with inflow values attributed equally to direct precipitation, surface runoff, and groundwater inflow (Kniffin, 2011). Groundwater inflow temperatures were estimated using an average of measurements (Hennings and Connelly, 2008), and surface and direct precipitation were estimated as air temperature.

2.3.6 Observation data

Observation data used for model calibration came from a variety of sources. For Lake Mendota, long term water temperature records were collected from Robertson (1989) and the NTL-LTER (2012b). Ice thickness data were gathered from E. Birge, University of Wisconsin (unpublished); D. Lathrop, Wisconsin Department of Natural Resources (unpublished); Stewart (1965); and the NTL-LTER program (2012a). Frequency of temperature data varied from one or two profiles per year to several profiles for a given week. Additionally, the vertical resolution of the water profiles varied greatly. For Fish Lake and Lake Wingra, water temperature data were collected from NTL-LTER only from 1996-2014 (2012b).

2.4 Model calibration and evaluation

Model calibration consisted of two processes: (1) closing the water balance to match simulated and observed water levels and (2) adjusting the minimum water level thickness to match simulated and observed water temperatures for each lake. Water balance for all three lakes was closed using the method described in Section 2.3.5 to match measured water levels to known values and to long term average water levels when elevation information was unknown. Model evaporation rates were not validated; we assume that evaporative water flux and heat flux were properly parameterized by the model. Model parameters were derived from literature values (Table 2). To calibrate water temperature, minimum layer thickness was varied from 0.05 to 0.5 m in intervals of 0.025 m for the period 1995-2000 for all three lakes, similar to the method in Tanentzap et al. (2007)

and Weinburger and Vetter (2012). One minimum layer thickness was chosen for all three lakes, and the final thickness was chosen to be 0.125 m as it minimized the overall deviation between simulated and observed temperature values for the three lakes.

Three statistical measures were used to evaluate model output against observational data (Table 3): absolute mean error (AME), root mean square error (RMSE), and Nash-Suttcliffe efficiencies (NS) were used to compare simulated and observed temperature values for volumetrically-averaged epilimnion temperature, volumetrically-averaged hypolimnion temperature, and all individual water temperature measurements for unique depth and sampling time combinations. Simulated and observed values are compared directly, except for aggregation of water temperature measurements to daily intervals where sub-daily intervals are available. Water temperatures were evaluated for the full range of available data on each lake.

2.5 Analysis

Modelling results were analysed using linear regression, sequential t-test, and Pearson correlation coefficient. Linear regression was used to determine the trend of long-term changes in lake variables. Breakpoints in variables were determined using a piecewise linear regression (Magee et al., 2016; Ying et al., 2015). A sequential t-test (Rodionov, 2004; Rodionov and Overland, 2005) was used to detect abrupt changes in the mean value of lake variables. The variables were tested on data with trends removed using a threshold significance level of $p = 0.05$, a Huber weight parameter of $h = 2$, and a cut-off length $L = 10$ years. Coherence of lake variables (Magnuson et al., 1990) for each lake and between lake pairs was determined with a Pearson correlation coefficient (Baron and Caine, 2000). The three lakes were paired to compare coherence of lake variables with surface area difference (Mendota/Fish pair), depth differences (Fish/Wingra pair), and both surface area and depth differences (Mendota/Wingra). Additionally, temperature, stratification, and heat flux variables for all three lakes are correlated to air temperature and wind speed drivers, ice date and durations, and to temperature, stratification, and heat flux variables within each lake.

To determine the sensitivity of lake water temperature and stratification in response to air temperature and wind speed, we perturbed these drivers across the range of -10°C to +10°C in 1°C temperature increments and 70% to 130% of the historical value in 5% increments, respectively. For each scenario, meteorological inputs remained the same as for the original simulation and snowfall (rainfall) conversion if the air temperature scenarios increase (decrease) above 0°C. Similarly, the water balance is maintained so that the long-term water levels in both lakes matches the historical record. Inflow temperatures are recalculated for each lake to account for increases or decreases in temperature because of air temperature changes.

3 Results

3.1 Changes in air temperature and wind speed

Yearly average air temperatures (+0.145°C decade^{-1}; p<0.01); and seasonal air temperatures (winter: +0.225°C decade^{-1}; spring +0.165°C decade^{-1}; summer +0.081°C decade^{-1}; fall +0.110°C decade^{-1}; p<0.05) increased from 1911−2014 (Fig. 2a Additionally, yearly average air temperature, but not seasonal temperatures, showed a significant change in slope occurring in 1981, and summer air temperatures showed three significant abrupt changes in mean value (Fig. 2a). Yearly (-0.073 m s^{-1} decade^{-1}; p<0.01) and seasonal average (winter: -0.083 m s^{-1} decade^{-1}; spring -0.071 m s^{-1} decade^{-1}; summer: -0.048 m s^{-1} decade^{-1}; fall: -0.088 m s^{-1} decade^{-1}; p<0.01) wind speeds decreased from 1911-2014 (Fig. 2b). A change in air temperatures also occurred in the 1980s in Central Europe (Woolway et al., 2017b), which may indicate that change in air temperature were a global phenomenon rather than local occurrence. Significant shifts (p<0.01) in the mean occurred in the mid-nineties for all seasons, but there were no changes in rate of wind speed decreases.

3.2 Model evaluation

Simulated temperatures agreed well with observations for all three lakes (Fig. 3, Table 3). The model was validated with all available data for all three lakes during the period 1911−2014. AME and RMSE for all variables were low and less than standard deviations. NS efficiencies were high (>0.85) and most above 0.90, indicating high model accuracy.

3.3 Summer water temperatures

Lake Mendota and Lake Wingra had similar increasing epilimnetic water temperature trends, while Fish Lake had a larger increase (Table 4). All three lakes have statistically significant (p<0.01) abrupt changes in mean epilimnion temperatures over the study period. For Lake Mendota, a change occurs after 1930 from 22.09 °C to 22.99 °C. For Fish Lake three changes were detected: first after 1934 from 21.68°C to 22.50°C, after 1995 from 22.50°C to 24.26°C, after 2008 from 24.26°C to 22.14°C. Lake Wingra has an abrupt change after 1930 from 23.13°C to 24.02°C. These increases in epilimnetic temperatures are similar to those found for European lakes (Woolway et al., 2017b) in response to regional climate changes, although Woolway et al. (2017b) demonstrated a substantial increase in annually averaged lake surface water temperatures in the lake 1980s in response to an abrupt shift in the climate, which is not apparent in epilimnion water temperatures for our study lakes. Additionally, Van Cleave et al. (2014) showed a regime shift in July – September Lake Superior surface water temperatures after 1997, driven by El Niño in 1997-1998; however we do not find a similar regime shift in our study lakes, which may be due to geographical differences in meteorology or morphometric differences from the larger Lake Superior.

Lake Mendota and Fish Lake hypolimnions were defined as 20−25 m and 13−20 m, respectively, based on the long-term bottom depth of the metalimnion. Lake Mendota has a larger decrease in hypolimnetic temperature than Fish Lake (Table 4), and neither has an abrupt change in temperature nor a significant breakpoint in linear trend during the study period (Fig. 4). Change in summer (15 July – 15 August) hypolimnetic heating was an order of magnitude larger for Mendota than for Fish Lake (Table 4).

3.4 Stratification and stability

We characterize summer stratification by stratification onset, fall overturn, and duration of stratification (Fig. 5). Onset of stratification and fall turnover were defined as the day when the surface-to-bottom temperature difference was greater than (for stratification) or less than (for overturn) 2°C (Robertson and Ragotzkie, 1990). Lake Wingra experienced only short-term stratification (timescale of days-weeks) and is excluded from this analysis.

Lake Mendota has larger trend in earlier stratification onset, fall overturn, and stratification duration than Fish Lake (Table 4), with most of the difference in stratification duration caused by larger change in stratification onset date for Lake Mendota. For both lakes, a significant (p<0.01) shift in onset date occurred at similar times, with shift of 13.3 days earlier for Lake Mendota after 1994 and 15.1 days earlier for Fish Lake after 1993. No change in trend occurred for stratification onset or overturn, but stratification duration shifted from +0.067 days decade^{-1} to +4.5 days decade^{-1} after 1940 for Lake Mendota and from -0.19 days decade^{-1} to +9.6 days decade^{-1} after 1981 for Fish Lake (Fig. 5).

We quantify resistance to mechanical mixing with a Schmidt number (Idso, 1973). Lake Mendota showed greater stability in general than Fish Lake (Fig. 6) and had a larger trend of change than Fish Lake (Table 4), possibly due to a larger change in stratification and hypolimnion temperature, increasing stability. There was no significant abrupt shift or change in trend for any of the three lakes during the study period.

3.5 Surface heat fluxes

Modelled surface heat fluxes included net shortwave, net longwave, sensible heat, latent heat, and total heat fluxes (Fig. 7). Magnitude of shortwave, longwave, and sensible heat fluxes are similar for all three lakes, but Lake Wingra has a larger magnitude of both latent and net heat fluxes. Net longwave is negative for all three lakes and increased in magnitude (Table 4), and sensible heat flux decreased in magnitude (became less negative; Table 4). There is no significant trend in other surface heat flux variables. Lake Wingra has a much smaller change in trend for longwave radiation than Mendota or Fish, but a larger change in trend for sensible heat flux, indicating that depth likely influences the response of those heat fluxes to air temperature and wind speed changes.

3.6 Coherence between lake pairs

Pearson correlations for all variables and lake pairs are significant (Table 5). Shortwave, longwave, sensible, and latent heat fluxes show high correlation for lake pairs, suggesting that morphometry has little impact on variability among lakes. Similarly, epilimnion temperatures have high temporal coherence. However, Fish Lake pairs have lower correlations, which may be a result of changes to lake depth (Krohelski et al. 2002) compared to stable water levels in Mendota and Wingra. Low coherence between the Mendota/Fish pair for hypolimnion temperature and stratification dates suggest that fetch differences impact variability. Stability, however, is lower for pairs with Lake Wingra, indicating that lake depth plays a role in temporal coherence of stability. Similarly, Lake Wingra pairs have lower coherence of net heat flux although the coherence of heat flux components is relatively high. Depth may be influencing a non-linear response of net heat flux that is not present in the components of the flux.

3.7 Correlations between lake variables

Generally, direction and magnitude of Pearson correlation between lake variables are similar for each of the three lakes, however, there are some notable exceptions (Fig. 8). Ice off dates are significantly correlated with stratification onset dates and hypolimnetic temperature on Fish Lake, but those correlations do not exist for Lake Mendota. Stratification onset is significantly correlated with hypolimnetic temperature and stability in Lake Mendota, but not significantly correlated on Fish Lake. Summer air temperatures are more highly correlated with stability than summer wind speed for Lake Mendota and Fish Lake, but the opposite is true for Lake Wingra, where summer air temperature is not significantly correlated. Additionally, hypolimnion temperature is more highly correlated with stability in Lake Mendota, whereas epilimnion temperature is more highly correlated with stability in Fish Lake.

3.8 Sensitivity to changes in air temperature and wind speed

Response of stratification onset, fall overturn, and hypolimnetic temperature to air temperature and wind speed perturbation scenarios for Lake Mendota and Fish Lake are discussed in the following. Other variables are omitted for brevity and Lake Wingra did not experience prolonged stratification under any sensitivity scenarios, so are excluded from the analysis. In our analysis, we refer to the “base case” as the meteorological values that represent the historical period from 1911-2014, and refer to perturbations in air temperature and wind speed from that base case.

Stratification onset generally occurs earlier on Fish Lake than Lake Mendota for all scenarios (Fig. 9). Simulations show that the response of median onset dates to changes in air temperature is ~~linear~~ the same for both increases and decreases from the base case (-2.0 days °C^{-1}) for Lake Mendota, but for Fish Lake, the change is ~~nonlinear~~ magnitude of change is larger for air temperature decreases (-1.5 days °C^{-1} for temperature increases and +2.7 days °C^{-1} for temperature decreases). Variability in Lake Mendota onset remains consistent across scenarios, but decreases for Fish Lake as air temperatures increase. This may be from interaction between ice cover and stratification onset on Fish Lake but not on Lake Mendota. ~~Both lakes have a nonlinear decrease in stratification onset date with decreasing wind speed.~~ For Lake Mendota stratification onset dates have a larger change for wind speed increases than decreases ~~, the change is~~ (-3.4 days (m s^{-1})$^{-1}$ for decreases and +10.5 days (m s^{-1})$^{-1}$ for wind speed increases), as does Fish Lake~~. For Fish Lake, the change is~~ (-3.6 days (m s^{-1})$^{-1}$ for decreases and +8.1 days (m s^{-1})$^{-1}$ for wind speed increases). Variability in onset dates decreases with lower wind speeds and increases with higher wind speeds.

Fall overturn typically occurs slightly early on Lake Mendota than Fish Lake for all scenarios (Fig. 10). For Lake Mendota, stratification overturn dates change at a rate of +0.68 days °C^{-1} with positive and negative perturbations ~~changes~~ in temperature, while Fish Lake has a larger change for air temperature increases ~~changes nonlinearly at a rate of~~ (+1.81 days °C^{-1} for temperature increases and -0.77 days °C^{-1} for temperature decreases) from the historical condition. Standard deviation in overturn dates decreased slightly for Lake Mendota as air temperature increase, but remains consistent for Fish Lake. ~~Both lakes have nonlinear increases in fall overturn dates with decreasing wind speed.~~ For stratification overturn dates on Lake Mendota, the change is +13.9 days (m s^{-1})$^{-1}$ for wind speed decreases and -17.1 days (m s^{-1})$^{-1}$ for wind speed increases. For Fish Lake, the change is +16.4 days (m s^{-1})$^{-1}$ for wind speed decreases and -8.5 days (m s^{-1})$^{-1}$ for wind speed increases. Like onset dates, variability in overturn dates decreases with lower wind speeds and increases with higher wind speeds.

For both lakes, increases in air temperature increase hypolimnetic temperatures, while decreases in wind speed decrease temperatures (Fig. 11). Simulations show that the response of median hypolimnetic temperatures to changes in air temperatures ~~is linear~~is consisten for Lake Mendota (+0.18°$C_{hypolimnion}$ $C_{air\ temperature}^{-1}$) for both increases and decreases from the base case, but ~~nonlinear for~~not so for Fish Lake (+0.25°$C_{hypolimnion}$ $C_{air\ temperature}^{-1}$ for air temperature increases and -0.18 °$C_{hypolimnion}$ $C_{air\ temperature}^{-1}$ for air temperature decreases). Standard deviations under varying air temperature scenarios remain consistent for both lakes. Hypolimnion temperatures change inconsistently with increases and decreases in wind speed for ~~change non-linearly with wind speed perturbations for~~ both lakes. For Lake Mendota, the change is -1.1°C (m s^{-1})$^{-1}$ for decreases and +1.8°C (m s^{-1})$^{-1}$ for wind speed increases. For Fish Lake, the change is -1.2°C (m s^{-1})$^{-1}$ for decreases and +0.8°C (m s^{-1})$^{-1}$ for wind speed increases. Variability decreases for lower wind speeds in Lake Mendota, but remains constant for Fish Lake.

4 Discussion

4.1 Model performance and comparison

The DYRESM-WQ-I model reliably simulated water temperatures over long-term (1911-2014) simulations (Figure 3, Table 4). Generally, simulated temperatures were lower than observed values. Some may be attributed to timing of observations, which in most instances occur during midday, when water temperatures may be slightly higher than daily averages, as output from the model. Slight deviation is also expected due to averaging of air temperature and wind speeds. In general, thermocline depths were within 1 m of observed values, but some years differ by as much as 2.5 m, contributing additional error in water temperature comparison for depths near the thermocline.

The performance of the DYRESM-WQ-I model was within those of other studies. Perroud et al. (2009) performed a comparison of one-dimensional lake models on Lake Geneva, and RMSE for water temperatures were as high as 2°C for the Hostetler model (Hostetler and Bartlein, 1990), 1.7°C for DYRESM (Tanentzap et al., 2007), 2°C for SIMSTRAT, and 4°C for Freshwater Lake (FLake) model (Golosov et al., 2007; Kirillin et al., 2012). Similar to this study, errors in the upper layers were lower than those in the bottom of the water column (Perroud et al., 2009). Fang and Stefan (1996) gave standard errors of water temperature of 1.37°C for the open water season and 1.07°C for the total simulation period for Thrush Lake, MN, similar to those here. Nash-Sutcliff efficiency coefficients for all 3 study lakes were within the ranges found in Yao et al. (2014) for the Simple Lake Model (SIM; Jöhnk et al., 2008), Hostetler, Minlake (Fang and Stefan, 1996), and General Lake Model (GLM; Hipsey et al., 2014) for Harp Lake, Ontario, Canada water temperatures.

Model parameters used to characterize the lake hydrodynamics were taken from literature values. These values may be expected to have small variability between lakes; however, previous studies have shown that many of the hydrodynamic parameters are insensitive to changes of ±10% (Tanentzap et al., 2007). Here the model was validated against an independent dataset for each lake to determine if the model fits measured data and functions adequately, with errors within the range of those from other studies. Adjustments were made to limit uncertainty and errors associated with changes in location and techniques of meteorological measurements. Inflow and outflow measurements were assessed by the USGS for quality assurance and control, but uncertainty for both quantity and water temperature is unknown. The effects of these uncertainties may not be large as the inflow and outflow are small in comparison to lake volume. The combination of uncertainties in parameters and observed data may be high; however, as all parameters and observational methods were kept consistent among the three lakes, the validity of the model in predicting differences among the three lake types is adequate.

The main limitation in the model and resulting simulations is the assumption of one-dimensionality in both the model and field data. Quantifying the uncertainty from this limitation can be difficult (Gal et al., 2014; Tebaldi et al., 2005) Small, stratified lakes generally lack large horizontal temperature gradients (Imberger and Patterson, 1981), allowing the assumption of one-dimensionality to be appropriate. However, short-term deviations in water temperature and thermocline depth may exist due to internal wave activity, especially in larger lakes (Tanentzap et al., 2007), and spatial variations in wind stress can produce horizontal variations in temperature profiles (Imberger and Parker, 1985). To address the role of internal wave activity and benthic boundary layer mixing, the pseudo two-dimensional deep mixing model by Yeates and Imberger (2003) is employed here. This mixing model has been shown to accurately characterize deep mixing that distributes heat from the epilimnion into the hypolimnion, thus weakening stratification, and the rapid distribution of heat entering the top of the hypolimnion from benthic boundary layer mixing, which strengthens stratification (Yeates and Imberger, 2003).

Additionally, light extinction significantly impacts thermal stratification (Hocking and Straškraba, 1999) and light extinction estimated from Secchi depths can have a large degree of measurement uncertainty (Smith and Hoover, 2000), which may result in uncertainty in water temperatures. To address this uncertainty, where available, we use measured Secchi depth values, which has been shown to improve estimates of the euphotic zone over fixed coefficients (Luhtala and Tolvanen, 2013). Secchi depths were unavailable for portions of the simulation period, and average values for the season were used. Analysis comparing using the method of known Secchi depths to both seasonally-varying average Secchi depths and constant Secchi depths for the lakes indicates that seasonally-varying averages do not significantly decrease model reliability when compared to year-specific values, but do show improvement over constant Secchi depths.

4.2 Importance of wind speed and other variables

While many have addressed the importance of changing air temperatures on water temperatures and water quality (e.g. Adrian et al., 2009; Arhonditsis et al., 2004; O'Reilly et al., 2015; Shimoda et al., 2011), fewer have investigated wind speed as a specific driver of changes to lakes (Magee et al., 2016; Snortheim et al., 2017). However, results here show that correlations between wind speeds and lake temperature variables are as high as, or higher than, correlations air temperature and lake temperature variables (Fig. 87), highlighting the importance of considering wind speeds as drivers of lake temperature and stratification changes. For many variables (e.g. stratification dates, epilimnetic temperatures, stability), correlation is opposite for air temperature and wind speed variables, indicating that wind speed increases may offset the effect of air temperature increases, while locations with decreasing wind speeds may experience a greater impact on water temperature and stratification than with air temperature increases alone. This is further supported through sensitivity analysis on stratification onset and overturn (Fig. 8 9 and 109), which show that for Madison-area lakes, increasing air temperatures and decreasing wind speeds have a cumulative effect toward earlier stratification onset and later overturn. This is similar to results of Woolway et al. (2017a), which found that for polymictic Lake Võrtsjärv, wind speed is the key influence on the number of stratified days and that the influence of air temperature increases was minimal; results of Kerimoglu and Rinke (2013), which found that a 30% increase in wind speed can compensate up to a 5.5 K increase in air temperature; and Hadley et al. (2014), which suggest that the combination of increased air temperature and decreased wind are the primary drivers of enhanced stability in Harp Lake since 1979, although no significant change in the timing of onset, breakdown, or duration of stratification was observed. However, for hypolimnetic temperatures, correlations and sensitivity indicate that decreasing wind speeds may cool hypolimnetic temperatures, while increasing air temperatures warm hypolimnetic temperatures. Arvola (2009) showed that hypolimnion temperatures were primarily determined by the conditions that pertained during the previous spring turnover, which is consistent with our results showing significant (p<0.01) correlation between hypolimnion temperatures and wind speed (Fig. 8), but no significant correlation with air temperature or summer conditions. This could explain the conflicting results of previous research showing both warming and cooling trends in different lakes (Gerten and Adrian, 2001). Hindcasted hypolimnion temperatures (Fig. 4) show decreasing trends for Lake Mendota and Fish Lake. Combining the effects of air temperature and wind speed, it suggests that wind speed decreases are a larger driver to hypolimnetic water temperature changes than increasing air temperatures for both lakes. This is particularly notable as current research into changes in lake water temperature and stratification have been dominated by studying air temperature effects to the neglect of the role of wind speed changes.

Ultimately, lake warming or cooling may depend on the magnitudes and directions of changes of air temperature, wind speed, and other variables as climatic variables humidity, cloud cover, and solar radiation and water clarity variables are important in determining lake water temperatures. Schmid and Köster (2016) demonstrated that 40% of surface water warming in Lake Zurich was caused by increased solar radiation, and Wilhelm et al. (2006) showed that daily extrema of surface equilibrium temperature responded to shifts in wind speed, relative humidity, and cloud cover in addition to changes in air temperature. However, neither study looked at lakes with seasonal ice cover, which may not account for changes in ice sheet formation and the resulting influence on lake water temperatures (Austin and Colman, 2007). Other studies have demonstrated that ice cover changes do not directly influence summer surface water temperatures (Zhong et al., 2016), in agreement with our modelling results (Fig. 8). Changes in underwater light conditions from increased dissolved organic carbon concentrations combined with reduction in surface wind speeds can result in cooling whole-lake average temperatures despite substantial air temperature increases, as was the case for Clearwater Lake, Canada (Tanentzap et al., 2008). Water clarity has seen both increases and decreases since the early 1990's (Rose et al., 2017), with precipitation playing a critical role in year-to-year variability (Rose et al., 2017). Further investigation into the combined effects of these climatic and lake-specific variables is warranted.

4.3 Role of morphometry on water temperature and stratification

4.2.1 Lake depth

Lake depth plays a key role in determining thermal structure and stratification of the three lakes in this study. Even under the extreme increases in air temperature, Lake Wingra remained polymictic and did not become dimictic like Lake Mendota or Fish Lake. Additionally, Schmidt stability exhibited no trend on the shallow lake, unlike for the deeper two (Table 4). Due to lower heat capacity, shallow lakes respond more directly to short-term variations in the weather (Arvola et al., 2009), and heat can be transferred throughout the water column by wind mixing (Nõges et al., 2011). This was particularly evident in correlations among drivers and lake variables, where air temperature did not have a significant correlation with stability for Lake Wingra, but wind speed was highly correlated. For shallow lakes, wind speed may be a larger driver to temperature structure and stability, with the importance of air temperature increasing with lake depth. Deep lakes have a higher heat capacity so that greater wind speeds are required to completely mix the lake during the summer months, resulting in more temperature stability and higher Schmidt stability values for deeper Lake Mendota and Fish Lake. Our study is consistent with previous research showing mean lake depths can explain the most variation in stratification trends and lakes with greater mean depths have larger changes in their stability (Kraemer et al., 2015). Overall, Lake Wingra had a larger magnitude of latent and net heat fluxes than the deeper lakes. Diurnal variability in surface temperatures is larger for shallow lakes, promoting increased latent heat fluxes in these lakes (Woo, 2007). This increased response may also explain the larger change in trend for sensible heat flux since Lake Wingra responds more quickly to changes in air temperature, thus, have a larger change in sensible heat flux during each day. Interestingly, net heat flux of Lake Wingra is less coherent with the deeper lakes than the deep lakes are with each other. This may be due to the combination of more extreme temperature variability, increasing sensible and latent heat fluxes during the open water season and the lower sensitivity of ice cover duration in Lake Wingra compared to the deeper lakes (Magee and Wu, 2016). Ice cover significantly reduces heat fluxes at the surface (Jakkila et al., 2009; Leppäranta et al., 2016; Woo, 2007), and larger changes in ice cover duration for Lake Mendota and Fish Lake compared to Lake Wingra would reduce synchrony of heat fluxes among the three lakes.

4.3.2 Surface area

Lake surface area impacts the effects of climate changes on water temperatures and stratification. Air temperature is significantly correlated ($p<0.01$) with epilimnion temperature for all three lakes, as is wind speed ($p<0.05$). Increasing air temperatures are well documented to increase epilimnetic water temperatures (Livingstone, 2003; Robertson and Ragotzkie, 1990), since air temperature drives heat transfer between the atmosphere and lake (Boehrer and Schultze, 2008; Palmer et al., 2014). However, wind mixing can act as a mechanism of heat transfer (Nõges et al., 2011), and cool the epilimnion through increased surface mixed-layer deepening. Decreasing wind speeds may increase epilimnion temperatures above that from air temperature increases alone (Fig. 8). Surface area plays a role in lake-wide average vertical heat fluxes from boundary processes (Wüest and Lorke, 2003), and the model accounts for this by including an effective surface area algorithm to scale transfer of momentum from surface stress based on lake surface area (Yeates and Imberger, 2003). This increases transfer momentum from surface stress and vertical heat transfer for lakes with larger fetch. Accounting for this larger fetch increases mixing and vertical transfer of heat to bottom waters, reducing epilimnion water temperatures (Boehrer and Schultze, 2008) and increasing the rate of lake cooling (Nõges et al., 2011). For this reason, Lake Mendota with the large fetch experiences a smaller increase in epilimnetic water temperature compared to Fish Lake (Table 5). Additionally, momentum from surface stress scales linearly with lake area and non-linearly with wind speed (Yeates and Imberger, 2003, see Eq. 31 and 33), making momentum from surface stress, and thus, mixing, stratification, and hypolimnion temperatures more variable for lakes with larger fetch and even more variable when wind speed is increased (see Fig. 9-11). Greater variability in momentum and mixing corresponds to larger variability of Schmidt stability for Lake Mendota, with the larger surface area. Greater transfer of momentum in Lake Mendota results in the slightly deeper thermocline for the larger surface area lake (~10 m in Lake Mendota and ~6 m in Fish Lake), which may play a role in filtering the climate signals into hypolimnion temperatures. Low hypolimnetic temperature coherence between Mendota and Fish suggest that lake morphometry plays a role. This result is consistent with other studies that show lake morphometry parameter affects the way temperature is stored in the lake system (Thompson et al., 2005). Increased momentum on Lake Mendota from the larger surface area may also limit the impact of ice off dates on stratification onset and hypolimnetic temperatures because the lake has ample momentum to sustain mixing events regardless of ice off dates, while Fish Lake's small surface area limits mixing making ice-off dates and stratification more highly correlated.

5 Conclusion

The combination of increasing air temperatures and decreasing wind speeds in Madison-area lakes resulted in warmer epilimnion temperatures, cooler hypolimnion temperatures, longer stratification, increased stability, and greater longwave and sensible heat fluxes. Increased stratification durations and stability may have lasting impacts on fish populations (Gunn, 2002; Jiang et al., 2012; Sharma et al., 2011) and warmer epilimnion temperatures affects the phytoplankton community (Francis et al., 2014; Rice et al., 2015). Shallow lakes respond more directly to changes in climate, which drives differences in surface heat flux compared to deeper lakes, and wind speed may be a larger driver to temperature structure than air temperatures, with importance of air temperatures increasing as lake depth increases. Larger surface area lakes have greater wind mixing, which influences differences in temperatures, stratification, and stability. Climate perturbations indicate that larger lakes have more variability in temperature and stratification variables than smaller lakes, and this variability increases with greater wind speeds. Most significantly, for all three lakes, wind speed plays as large as, or a larger role in temperature and stratification variables than does air temperatures. This reveals that air temperature increases are not the only climate variable that managers should plan for when planning mitigation and adaptation techniques. Previous research has shown uncertainty in the changes in hypolimnion water temperatures for dimictic lakes, however the perturbation scenarios indicate that while increasing air temperature always increases hypolimnion temperature, wind speed is a larger driving force, and the ultimate hypolimnion temperature response may be primarily determined by whether the lake experiences an increase or decrease in wind speeds. Understanding this role in the context of three lakes of differing morphometry is important when developing a broader understanding of how lakes will respond to changes in climate. Lake water temperatures play a driving role in chemical and biological changes that may occur under future climate scenarios, and identifying differences in this response across lakes will aid in the understanding of lake ecosystems as a whole and provide critical information to guide lake management and adaptation efforts.

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Table 1: Lake characteristics for the three study lakes

	Lake Mendota	Fish Lake	Lake Wingra
mean depth (m)	12.8	6.6	2.7
maximum depth (m)	25.3	18.9	4.7
surface area (ha)	3937.7	87.4	139.6
shoreline length (km)	33.8	4.3	5.9
lake fetch (km)	9.2	1.2	2.0
shoreline development	high	high	high
landscape position	low	high	high
Secchi depth (m)*	3.0	2.4	0.7
chlorophyll (μg L^{-1})ǂ	4.8	5.1	10.5
dissolved organic carbon (μg L^{-1})Δ	5.71	6.95	7.01
lake type	Drainage	Seepage	Drainage
groundwater inflow type	discharge	flowthrough	flowthrough
groundwater input (%)	30	6	35

* Secchi depth measured from 1 June – 31 August

ǂ surface chlorophyll from open water season

Δ dissolved organic carbon is the average of all measurements for each lake

Table 2: DYRESM-WQ-I model parameters. Ice cover parameter can reference Magee et al. (2016) and Magee and Wu (2016).

Parameter	Value
albedo	0.08 [i,ii]
bulk aerodynamic momentum transport coefficient	0.00139 [ii]
critical wind speed ($m\ s^{-1}$)	4.3 [ii]
effective surface area coefficient (m^2)	$1x10^7$ [iii]
emissivity of water surface	0.96 [iv]
potential energy mixing efficiency	0.2 [i,ii]
shear production efficiency	0.06 [i, ii, iii]
vertical mixing coefficient	200 [iii]
wind stirring efficiency	0.8 [ii]
minimum layer thickness	0.125*
maximum layer thickness	0.6 [ii]
vertical light attenuation coefficient	variable [v]

* indicates value calibrated in the model

sources: [i] Antenucci and Imerito, 2003; [ii]Tanentzap et al., 2007; [iii]Yeates and Imberger, 2003; [iv]Imberger and Patterson, 1981; [v]Williams et al., 1980

Table 3: Absolute mean error (AME), root-mean square error (RMSE), and Nash-Sutcliff efficiency (NS) for water temperature variables on Lake Mendota, Lake Wingra, and Fish Lake. n = number of measurements, N/A represents errors that cannot be determined because Lake Wingra is a polymictic lake and does not have an epilimnion or hypolimnion.

	Lake Mendota				**Fish Lake**				**Lake Wingra**			
Variable	n	AME	RMSE	NS	n	AME	RMSE	NS	n	AME	RMSE	NS
Epilimnetic temperature (°C)	3,239	0.69	0.3	0.99	263	1.23	1.45	0.95	N/A	N/A	N/A	N/A
Hypolimnetic temperature (°C)	3,239	1.04	0.53	0.96	263	1.63	1.94	0.92	N/A	N/A	N/A	N/A
temperature at 1m interval (°C) overall range of values for depths	85,566	0.5-1.56	0.25-0.75	0.95-0.99	5,522	0.85-1.93	1.98-2.42	0.85-0.91	1,897	0.63-0.85	0.41-0.96	0.99

Table 4: Trends and in lake physical variables for the 3 studied lakes from 1911-2014. Trends are represented as units decade^{-1}.

	Lake Mendota	Fish Lake	Lake Wingra
Summer Epilimnetic Temperature (°C)	+ 0. 069$^{\Delta}$	+ 0.138*	+ 0.079*
Summer Hypolimnetic Temperature (°C)	- 0.131*	- 0.083*	N/A
Stratification Onset (days)	1.15 days earlier*	0.81 days earlier*	N/A
Fall Overturn (days)	1.18 days later*	1.05 days later*	N/A
Stratification Duration (days)	+ 2.68*	+ 1.86*	N/A
Hypolimnetic heating (°C)	- 0.011*	-0.0011*	N/A
Summer Schmidt stability number (J m^{-2})	+11.7*	+1.44*	no trend
Net Shortwave Flux (W m^{-2})	no trend	no trend	no trend
Net Longwave Flux (W m^{-2})	-0.585*	-0.580*	-0.459*
Sensible Heat Flux (W m^{-2})	+0.410*	+0.365*	+0.565*
Latent Heat Flux (W m^{-2})	no trend	no trend	no trend
Net Heat Flux (W m^{-2})	no trend	no trend	no trend

*indicates significant to $p<0.05$, $^{\Delta}$ indicates significant to $p<0.1$

Table 5: Correlation coefficients for lake pairs open water lake variables

Lake Variable	Lake Pair Mendota/Fish	Wingra/Fish	Mendota/Wingra
Epilimnion Temperature	0.601	0.747	0.804
Hypolimnion Temperature	0.474	N/A	N/A
Stratification Onset	0.262	N/A	N/A
Fall Overturn	0.388	N/A	N/A
Schmidt Stability Number	0.827	0.405	0.346
Net Shortwave Flux	0.995	0.925	0.922
Net Longwave Flux	0.993	0.969	0.967
Sensible Heat Flux	0.965	0.887	0.893
Latent Heat Flux	0.989	0.977	0.984
Net Heat Flux	0.722	0.630	0.532

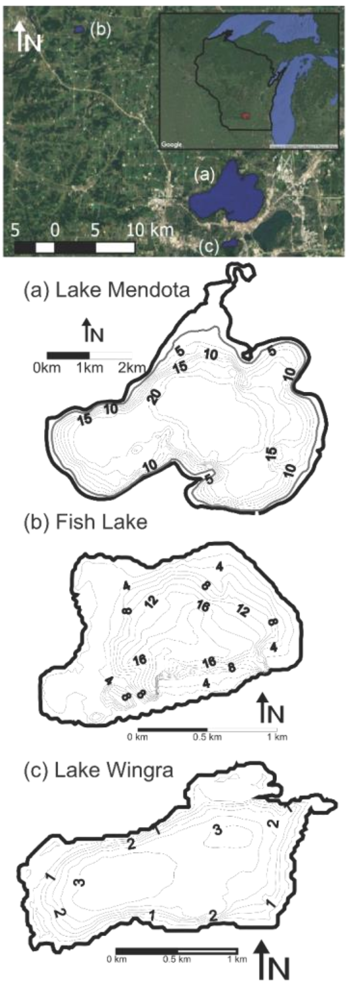

Figure 1: (top) map of study lakes in Wisconsin, USA and bathymetric maps of each lake, (a) Lake Mendota; (b) Fish Lake; and (c) Lake Wingra

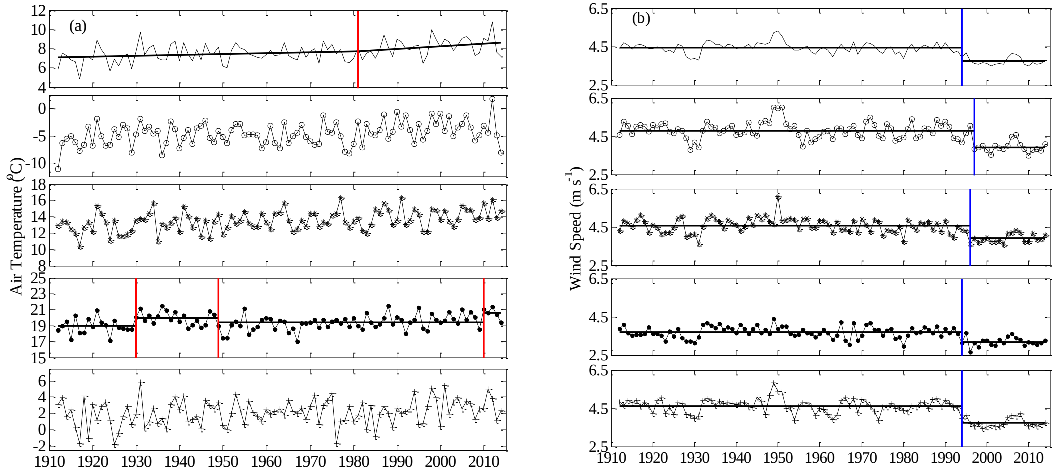

Figure 2: Yearly (solid line), winter (open circle), spring (asterisk), summer (solid circles), and fall (cross) (a) air temperature and (b) wind speeds for Madison, WI, USA. Red line in yearly air temperature figure represents a breakpoint in the trend of average air temperature increase from 0.081° C decade-1 to 0.334 °C decade^{-1} occurring in 1981. Red lines in summer air temperature figure represents abrupt changes in average summer air temperature occurring in 1930, 1949, and 2010. Blue lines in wind speed figures represent abrupt changes in average wind speed occurring in each season and in the overall yearly wind speeds. Yearly wind speed change in 1994; winter in 1997; spring in 1996; summer in 1994; and fall in 1994.

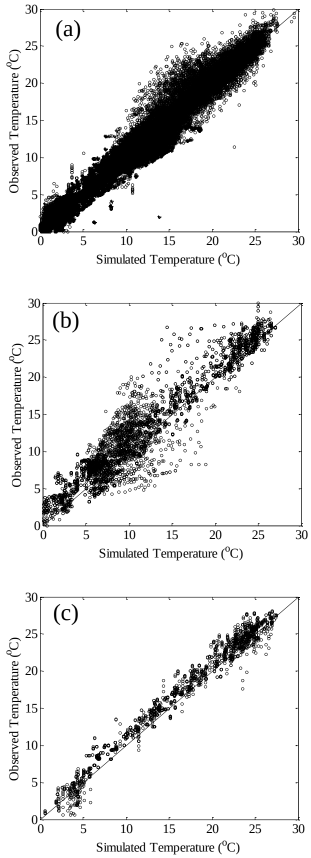

Figure 3: Comparison of observed and simulated water temperatures for (a) Lake Mendota, (b) Fish Lake, and (c) Lake Wingra. Each point represents one observation vs. simulation pair with unique date and lake depth.

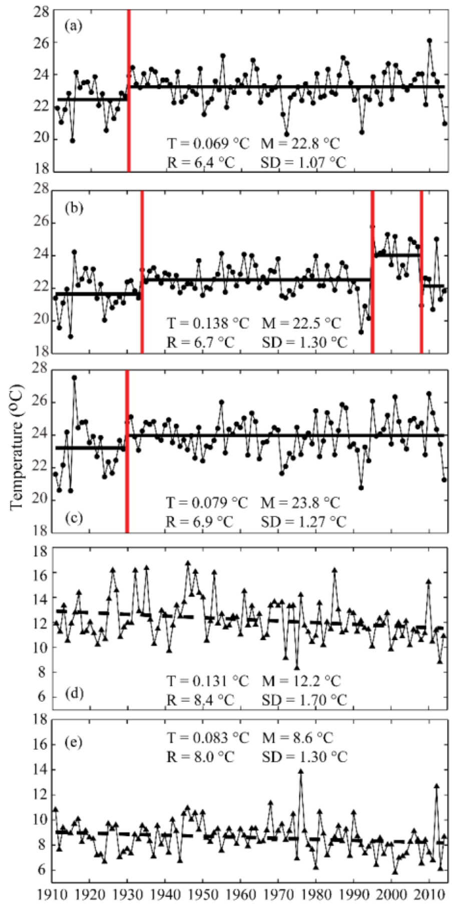

Figure 4: Mean summertime (July15-August15) epilimnetic temperatures for (a) Lake Mendota, (b) Fish Lake, and (c) Lake Wingra, and mean summertime (July 15-August 15) hypolimnetic temperatures for (d) Lake Mendota and (e) Fish Lake. In (a), (b), and (c), solid red lines represent statistically significant (p < 0.5) locations of abrupt changes in epilimnion temperatures and solid lines represent mean temperatures for each period. In (d) and (e) dashed lines represent the long-term trend over the period 1911-2014. T is the trend of water temperature change per decade, R is the range of temperatures, M is the mean temperature, and SD is the

standard deviation in temperatures for the study period. Epilimnion was defined as 0-10 m depth for Mendota, 0-5 m for Fish, and the whole water column for Wingra based on surface mixed layer depth calculated using LakeAnalyzer (Read et al., 2011). .

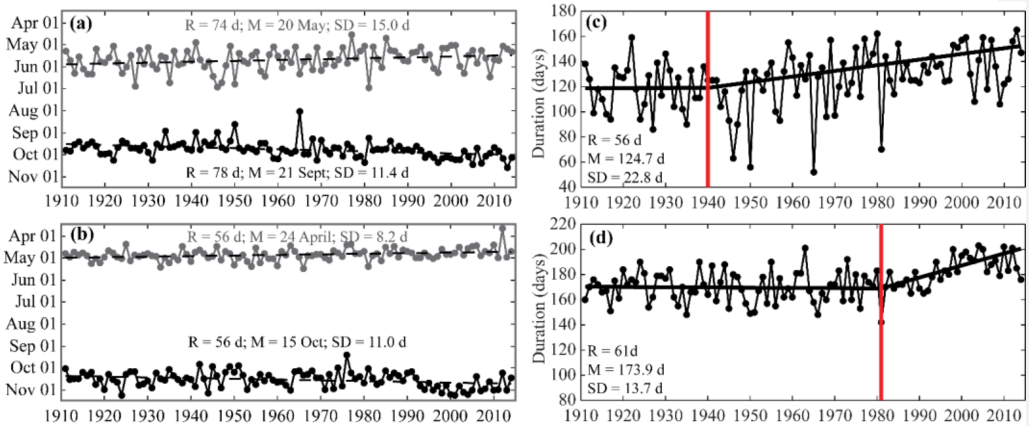

Figure 5: Stratification onset (gray) and overturn (black) dates for (a) Lake Mendota and (b) Fish Lake. Stratification duration for (c) Lake Mendota and (d) Fish Lake. Dark circles are modelled results and dashed lines denote the trendline for the 104-year period. In (a) and (b) dashed lines represent the long-term trend in stratification onset and overturn dates. In (c) and (d), solid red lines represent the timing of a statistically significant (*p*<0.01) change in trend and solid black lines represent the trend during the periods. R is the range of onset, overturn, or duration, M is the mean date for onset, overturn, or duration length, and SD is the standard deviation in dates for the study period.

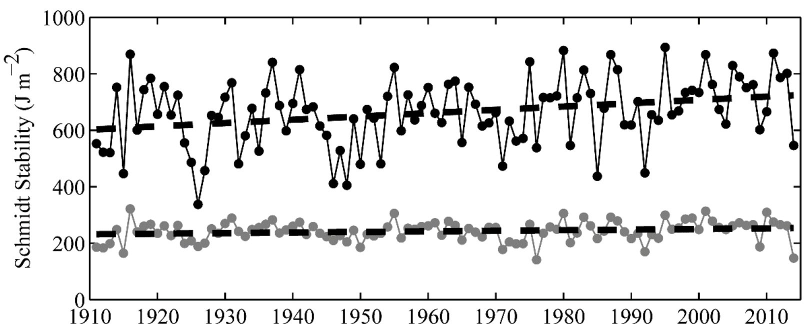

Figure 6: Yearly average summer-time (15 July - 15 August) Schmidt stability values for Lake Mendota (black) and Fish Lake (gray). Dashed lines represent the long-term trend for each lake.

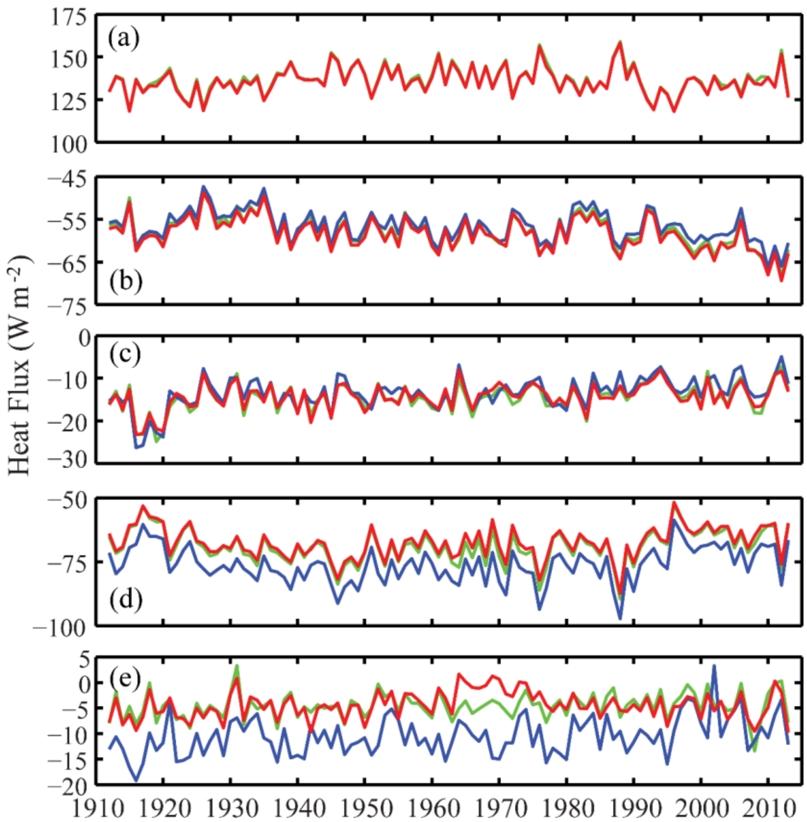

Figure 7: Yearly average (a) radiation flux, (b) long wave radiative flux, (c) sensible heat flux, (d) latent heat flux, and (e) total heat flux at the lake surface for Lake Mendota (solid black line), Fish Lake (black dashed line), and Lake Wingra (solid grey line). Trends and abrupt changes for heat fluxes are not shown on the plots for clarity.

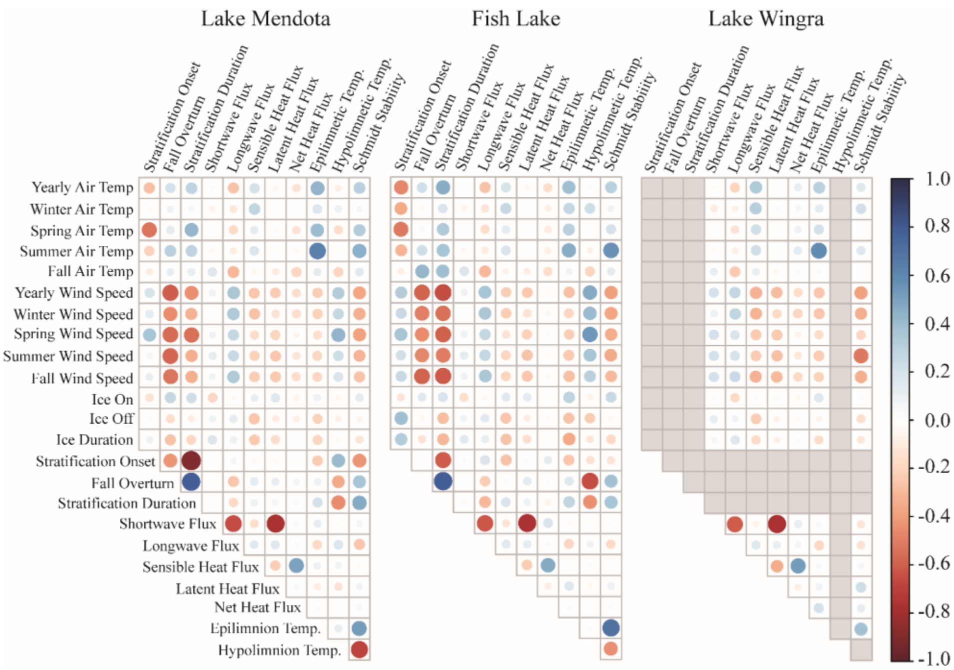

Figure 8: Plots of Pearson correlation coefficients among climate (air temperature and wind speed) variables and lake variables for the three study lakes.

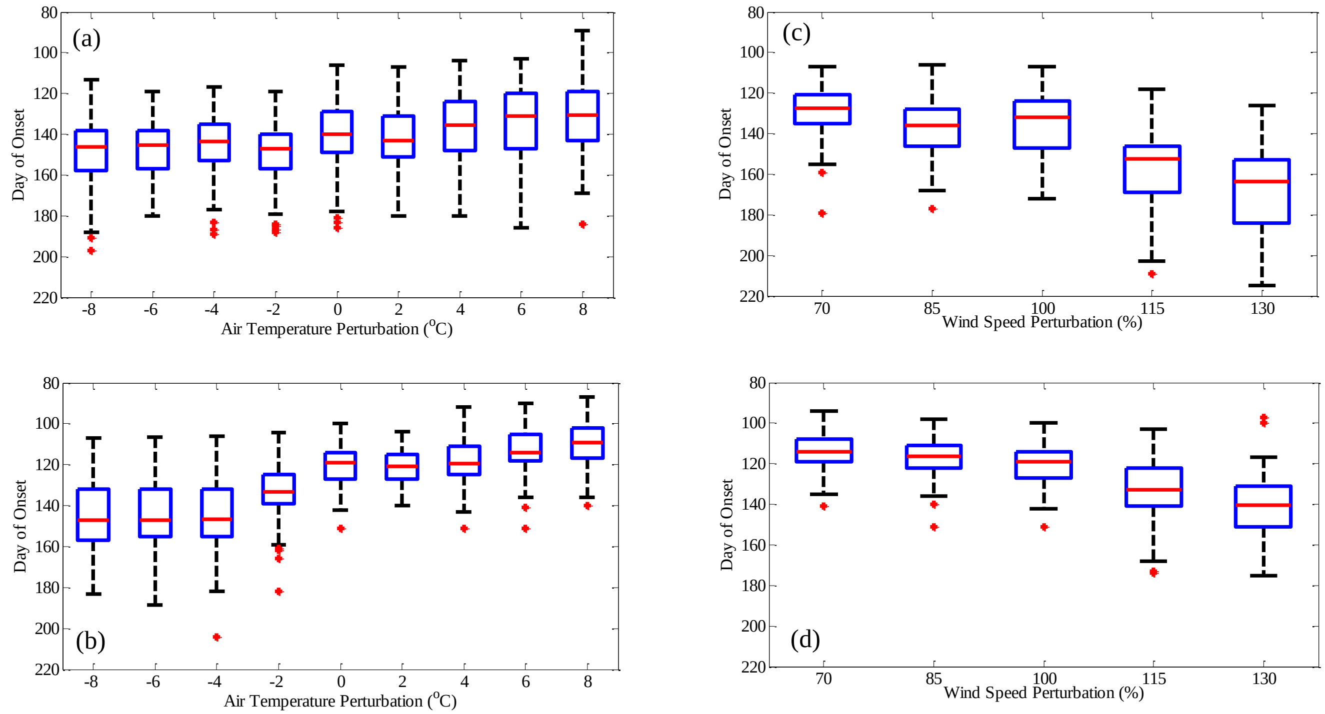

Figure 9: Day of stratification onset under select air temperature perturbation scenarios for (a) Lake Mendota and (b) Fish Lake and day of stratification onset under select wind speed perturbation scenarios for (c) Lake Mendota and (d) Fish Lake. The box represents the 25th and 75th quartiles and the central line is the median value. The whiskers extend to the minimum and maximum data point in cases where there are no outliers, which are plotted individually.

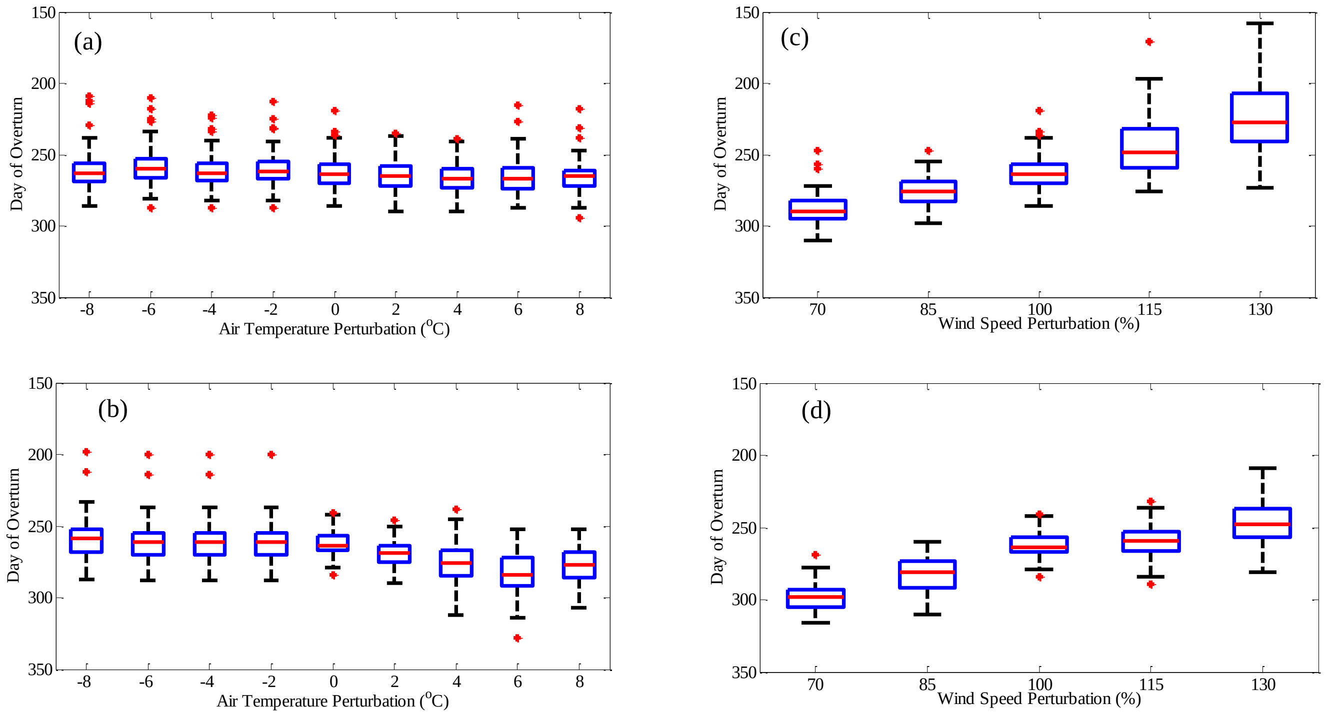

Figure 10: Day of stratification overturn under select air temperature perturbation scenarios for (a) Lake Mendota and (b) Fish Lake and day of stratification overturn under select wind speed perturbation scenarios for (c) Lake Mendota and (d) Fish Lake. The box represents the 25th and 75th quartiles and the central line is the median value. The whiskers extend to the minimum and maximum data point in cases where there are no outliers, which are plotted individually.

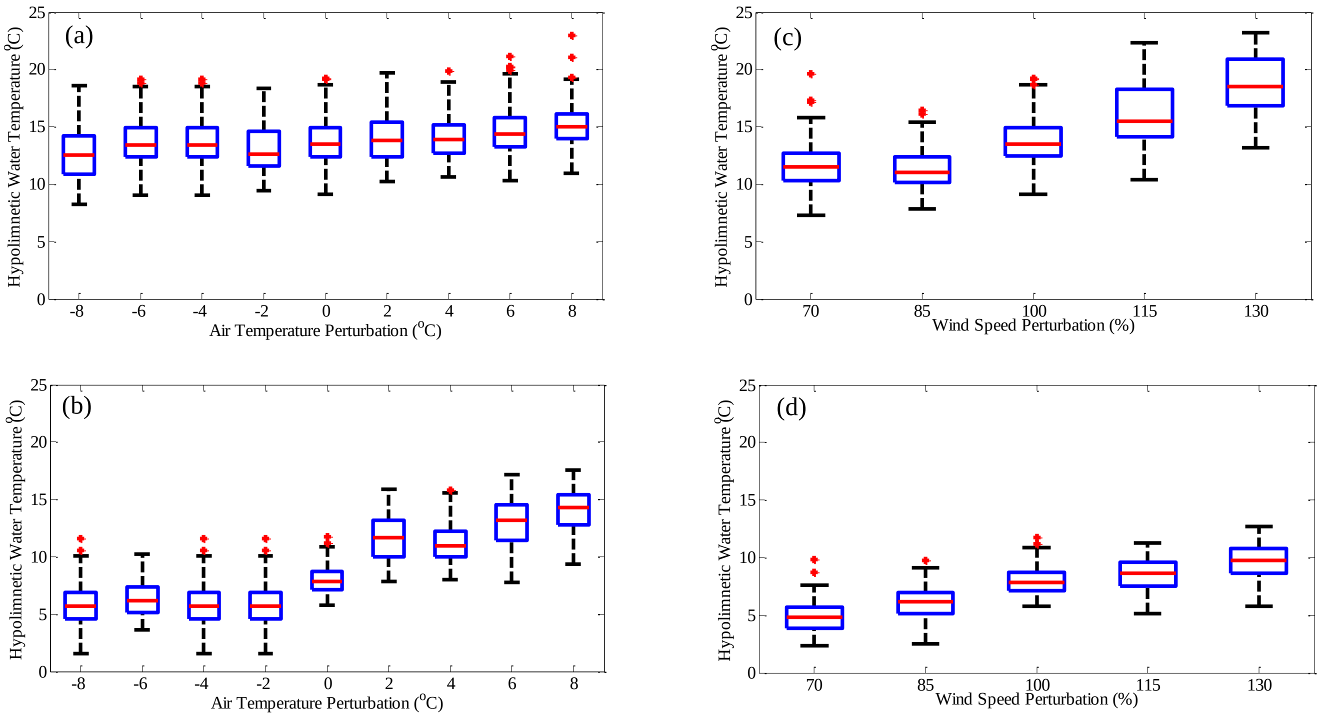

Figure 11: Hypolimnetic water temperatures under select air temperature perturbation scenarios for (a) Lake Mendota and (b) Fish Lake and hypolimnetic water temperatures under select wind speed perturbation scenarios for (c) Lake Mendota and (d) Fish Lake. The box represents the 25th and 75th quartiles and the central line is the median value. The whiskers extend to the minimum and maximum data point in cases where there are no outliers, which are plotted individually.