Response to the Reviewer

Overall, this paper does not present any breakthrough insights or new ideas; however, it does present a useful analysis of a fairly unique data set – three paired lakes in the same ecoregion for which over 100 years of data are available, and for which weather forcing is similar but differences in lake morphometry are clear. The modeling approach itself is not particularly novel, but, to my knowledge, it has not previously been applied to this rich dataset. The principal study question regarding the relative influence of morphometry vs. climate forcing is of active interest and is elucidated by application to lakes with such rich data sets. Accordingly, I recommend publication with minor revisions.

The paper is generally well written and is a logical follow-on to an earlier paper in HESS (Mage et al., 2016, HESS 20:1681, doi:10.5194/hess-20-1681-2016). There are a few items that may require further attention, as described below; however, the paper is generally acceptable. Therefore, I recommend publishing subject to minor revisions as described below.

Thank the Reviewer for taking valuable time to provide constructive and thoughtful comments on the manuscript. We have addressed the comments in a point-by-point reply below.

The submitted paper appears to have gone through an extensive and chequered review process. In the latest iteration, one reviewer was generally favorable and the other rather negative as to publication. The negative review (Reviewer #3) was largely based on critique of the selection of a 1-D model for the comparison. I do not find this to be a compelling reason to reject the paper. Indeed, 1-D (vertical) models may be preferable when looking to isolate the general impacts of external forcing on temperature trends. The potential problems with 1-D models are (1) influence of tributary inflows and (2) representation of mixing due to wind fetch. Item (1) is not a big issue for these lakes, which are natural lakes with large groundwater inputs. Item (2) is a potential concern, but it all depends on how well the 1-D model represents wind driven eddy diffusivity. In my opinion, this aspect of the paper would be fully acceptable with the addition of a few lines that address the details of how wind-driven mixing is addressed in the 1-D representation. The authors' response to Reviewer #3 that 3-D models are computationally expensive is correct, but not sufficient to answer this criticism.

We agree with the reviewer that the influence of tributary inflows is minimal for these lakes. Lake Mendota is the only lake with inflow water volume that is small compared to the overall lake volume. We have added some additional text on page 5 to further detail how the model represents mixing due to wind. Since all equations within the model are presented elsewhere (see Imerito, 2010; Yeates and Imberger, 2003), these equations are not reproduced and re-written on our manuscript.

The three lakes included in this study have somewhat similar perimeter to area ratios, so the major obstacles to the 1-D approach of comparing lakes with very different wind fetch to area ratios will not be encountered here. The lakes in question are natural, seepage-dominated lakes, so enhanced diffusion due to inflow temperatures should not be a major issue. The authors should be clear that the results may not apply to individual lakes elsewhere depending on their specific configuration.

Thank you to the reviewer for identifying these important points. We have added text to address this in the discussion section of the manuscript on page 16.

Wind-driven mixing is a bigger issue for 1-D models. Because DYRESM documentation is not readily available (see below) the authors should expand a small amount on this issue. Specifically, some notes on how wind-driven eddy diffusivity is represented should be supplied, along with any validation data to confirm the 1-D representation. I am more familiar with Hostetler-based 1-D lake models[1,2] in which wind-driven eddy diffusivity is estimated as a function of 2 m windspeed, the Brunt-Väsäilä frequency implied by the lake density-gradient, and the Ekman decay as a function of latitude[1]. These 1-D formulations generally require an expression of "enhanced" diffusivity to account for sources of turbulence not represented in the base 1-D formulation. Some additional explanation of why the 1-D Formulation is appropriate would be useful here (for instance, on p. 5 of the current draft). (See also Fang and Stefan[3] for arguments in favor of the 1-D approach.)

In response to the reviewer's suggestion, we have added additional text to further describe how the model deals with wind-driven mixing. (Yeates and Imberger (2003) previously detailed the description of the model equations used in this version of DYRESM as well as validation data from five different lakes of varying size and wind forcing. As a result, we will refer to the excellent paper and other references and not reproduce this work on our manuscript. Additionally, we have addressed why the one-dimensional model is appropriate with the discussion section of the manuscript (see pages 15 and 16).

On the other hand, 3-D lake models are indeed computationally expensive, and the extra precision does not necessarily lead to greater accuracy. A 3-D model requires data at multiple points in space and time for calibration. When these data are lacking calibration of a 3-D model is often not well constrained and subject to over-fitting. Thus, a 1-D model can be preferable for answering questions about long-term trends and forcing factors.

We agree with the Reviewer that a one-dimensional lake model for our study is preferable to answer our science questions of interest. Thanks for the Reviewer's comment and support.

Additional comments that should be addressed include the following:
• Reviewer #2 correctly noted that humidity, cloud cover, solar radiation all influence lake response, in addition to surface area and air temperature. To this list, precipitation regime could also be added, as large direct precipitation inputs can have a significant impact on stratification stability. The authors added a reasonable discussion of these issues. However, I think the main point that should be added is that the study addresses three lakes in the same ecoregion with similar climate forcing, so differences in responses relate primarily to morphometry or general climate perturbations. Another potentially important factor is water clarity, which determines how solar radiation is vertically partitioned. The authors mention some of these issues in their revision, but should present more discussion. In particular, Table 1 presents Secchi depth as a constant for each of the lakes, but is there any evidence on how this may have changed over time?

[1] Hostetler SW, Bartlein PJ. (1990) Simulation of lake evaporation with application to modeling lake level variations of Harney-Malheur Lake, Oregon. Water Resour Res 26: 2603-2612, doi:10.1029/WR026i010p02603.
[2] Subin ZM, Riley WJ, Mironov D. (2012) An improved lake model for climate simulations: Model structure, evaluation, and sensitivity analyses in CESM1. J Adv Model Earth Syst 4: M02001, doi:10.1029/2011MS000072, 2012
[3] Fang X, Stefan HG. (1996) Development and validation of the water quality model MINLAKE96 with winter data, Project Report 390, St. Anthony Falls Laboratory, Univ. of Minnesota

We have added a sentence on page 3 to clearly state that we are looking at lakes in the same region with the same climate forcing to differentiate responses that are primarily a result of morphometry differences. In the model, we use seasonal Secchi depth averages for each year. Therefore, Secchi depths in the model do change over time. Table 1 lists the lake-average value of the study period is presented in Table 1. Data from NTL-LTER (NTL LTER, 2012a) do not show a significant long-term trend in yearly averaged open-water Secchi depth values for any of the three lakes. We have added text within Section 2.3.3 to address these minor concerns about Secchi depth changes with time.

• The DYRESM model is a useful formulation. However, it is also somewhat problematic as changes in the Australian scientific establishment have resulted in the deletion of most all links to the DYRESM code and documentation. It is not immediately clear how to obtain the code today. Authors should include a note about the availability of DYREMS – and, if possible, provide a link for access to the DYRESM code as adapted for ice cover.

To address the Reviewer's question regarding the availability to access the DYRESM code, we add the statement at the acknowledgement section. Readers who are interested in accessing the DRYESM code should contact the authors: Chin Wu (Email: chinwu@engr.wisc.edu) or Madeline Magee (Email: mrmagee@wisc.edu).

Line-by-line specific comments:

10. (abstract) This posits an effect from "decreasing wind speed" – but is decreasing wind speed really a known for these lakes? If it is, it needs to be stated in the abstract.

Wind speed in Madison, WI, has been decreasing over the last 100 years. We have edited the text to note that increases in air temperature and decreases in wind speed have been observed.

13 (abstract) Make clear what is inferred from data vs. from modeling

We have edited the sentence to make clear that results of increases and decreases are from modeling results.

17. (abstract) "larger lakes have more variability": This needs to be qualified as to what is mean by "larger lakes". You are comparing three relatively small lakes. The conclusions likely do not apply to Lake Superior.

We have edited the text to clarify that the results apply to the lakes within this study.

p. 1, 24. Text states that land and ocean surface temperature anomalies increased from 1850 to 2012. An anomaly is a departure from an expectation, so you need to state what basis is used for the anomaly assessment.

The basis is 1961-1990, and we have added this to the text.

p.3, 6: "Large surface areas increase the effects of vertical wind mixing…" Isn't it a ratio of wind fetch to depth that is more important here?

Rueda and Schladow (2009) used simulations and scaling arguments to investigate the effects of a decrease in the surface area of the Salton Sea. Mixing in general is stronger in larger basins due to greater

mechanical energy fluxes across the free surface, regardless of the depth of the lake. Addition of greater mixing fluxes across the free surface will increase as surface area increases regardless of the depth of the lake(s). We make no claims as to whether the ratio of wind fetch to depth or surface area itself is more important to determining long term water temperature differences. Only that lakes with larger surface areas have greater mechanical energy fluxes than lakes with smaller surface areas.

p.5,line 28: Provide a reference for the assumed value of Ksed.
The reference has been added.

p. 7, line 16: Text implies that meteorological data are entered into the model on a daily basis. Is this true? If so, explain how daily cycles of heating and cooling of the epilimnion and their effect on vertical stability are incorporated into the model.
As described in section 2.2, water temperature, surface heat fluxes, water budget, and ice thickness are all calculated at 1 hour timesteps, so daily cycles of heating and cooling are incorporated into the model at these time steps. However, inputs of cloud cover, air pressure, wind speed, and air temperature are assumed to be constant values throughout the day. We are limited to the daily constant values by the resolution of meteorological observations, which are not available at an hourly resolution for the full duration of the 100-year study period. Similarly, precipitation is also assumed to be uniformly distributed throughout the day. However, shortwave radiation, which is a critical driver for determining diurnal changes in epilimnion temperatures are assumed to have a sinusoidal distribution throughout the day. This distribution is computed based on lake latitude and the Julian day.

p. 8, line 24: I agree with the prior reviewers in having some discomfort here about the discussion of adjusting "the minimum water level thickness" as a calibration parameter. This may be warranted in terms of finding an appropriate minimum thickness that correctly resolves the thermocline position, but needs to be better explained. If is also unclear why it is appropriate to choose "one minimum layer thickness" for all three lakes.
Model predictions are driven in part by the thickness of the horizontal layers to detect changes in vertical density stratification (Imberger et al., 1978; Tanentzap et al., 2007), which needs to be sufficiently small to properly resolve the changes in density and water temperature that occur at the thermocline, as the reviewer has correctly stated. If a layer becomes smaller than the minimum water layer thickness during any time step, then it is merged with the smaller of the layer above or below, taking on the characteristics of that layer. If the minimum layer thickness is too large, then the resolution around the thermocline is not enough to appropriately calculate changes in density and temperature that occur over a very small vertical distance. We have added text in the model calibration section to make this clearer to the readers. We choose to use one layer thickness for all three lakes so that differences in water temperature, heat fluxes, and stratification among the three lakes are limited to differences in morphometry of the lakes rather than differences in model implementation.

p. 9, line 25-29: Perturbation tests examine response to changes in air temperature and wind speed. These tests assume "the water balance is maintained." This seems unlikely if increased air temperature leads to increase ET. However, that is the nature of one-parameter perturbation tests – but, the limitation should be acknowledged.

Thank you for this comment. We have added a sentence to point out (acknowledge) this limitation of the study. Our approach would exclude changes in water level (and as a result water temperature and stratification) based on ET changes with altered air temperatures and wind speeds as well as differences in precipitation under future climates. It also neglects effects of climate changes on water clarity, which may be observed as changes in climate drivers will alter turbidity of the lakes and algal population characteristics and overall biomass.

p. 10, line 5: Air temperature "showed a significant change in slope" – based on what test at what significance level?
This was based on breakpoint analysis with an F test to show significance at a threshold of 0.05, as in (Magee et al., 2016). Detail of this and the appropriate reference has been added to the text.

p. 10, line 15: For NS efficiencies, state the time basis (daily?)
Yes, we used a daily timescale for NS efficiencies. This has been noted in the text.

p. 10, line 23: "lake 1980s" should presumably be "late 1980s."
This has been changed in the text. We thank the reviewer for pointing out this typo which went unnoticed.

Section 3.5: Presents surface heat fluxes. Are there any direct measurements to validate these estimates?
No, there are no direct measurements to validate the surface heat flux estimates. However, equations used to derive the model surface heat fluxes are empirical equations based on direct measurements. Heat fluxes are included in this manuscript at the request of a reviewer during a previous iteration to use the full capability of the model to present useful and worthwhile results. We feel that, while the model is not suitable to put a specific value on hindcast or forecast heat fluxes for any one year with a high degree of certainty, it is suitable for informing general differences among the three lakes over the long term. This is how we have presented surface heat flux results within the text of this manuscript.

Section 3.6: Presents correlations between "lake pairs" for the energy balance. These are simulated results, right? If so, how much of the apparent correlation is due to model formulation vs. reality?
Yes, the correlations for the energy balance is for simulated results. Since we have no direct measurements of heat fluxes on these three lakes to calculate non-modeled correlations, we are unable to determine how much of the correlation is due to model formulation vs. reality. Nevertheless, calculations for the heat fluxes within the model employ the same equations for each lake and meteorological drivers for all three lakes are identical. This approach likely yields correlations that are higher than would be observed because we are excluding local differences among the lakes that may impact surface heat fluxes such as differences in wind sheltering and shading; however, differences in heat flux caused by differential water temperatures among the three lakes as a result of the different lake shapes is included.

p.13, line 1: Discussion of stratification onset: Is this based on observations or modeled results? If modeled, how does the model compare to observations?
This section is based on modeled results of the two lakes under temperature perturbation scenarios. We have added the word "simulated" to the first sentence of section 3.8 to make it clearer that the results

from this section are for simulated results after perturbing air temperature and wind speed drivers of the model. Ideally, we would compare historical stratification onset dates on years that have similar air temperature and wind speed as those of the perturbed scenarios. Air temperature and wind speed perturbations outside of +/- 2°C and +/- 10% of the historical condition are not captured extensively in the historical dataset. This limits us to only a minor set with which to compare how well the model might perform under the perturbed scenarios. Unfortunately, there are no known observations of stratification onset for any of the three lakes as water temperatures observations are generally taken at the period of 2-week intervals over the period. We can say that in every year under the historical simulation, the model hindcasts stratification onset within the appropriate time window based on observed water temperatures. We feel this indicates the model performs well in terms of correctly hindcasting stratification onset during the historical condition and likely does perform well in forecasting changes to stratification onset as air temperature and wind speed drivers are perturbed within the model.

p. 15, line 24: Missing word in "correlations air temperature".

Thank you, the line has been changed to say "…correlations between air temperature and lake temperature variables…"

p. 16, line 3: Discusses results of Woolway et al. indicating that influence of air temperature increases was minimal relative to wind speed in determining the length of stratification period. Isn't this result dependent on the surface area-to-volume ratio of the specific lake in question? Also, the length of stratification may not be the key result as the onset of stratification may determine the relative temperatures in the epilimnion and hypolimnion over the summer.

Yes, the effect of air temperature vs wind speed to determine stratification and water temperature are likely to be influenced by the size and shape of the lake(s) in question. We include this reference as well as others (Kerimoglu and Rinke, 2013, Hadley et al., 2014), suggested by the previous reviewer to point out other studies in which wind speed was found to be at least as important as air temperature to changes in stratification and water temperature. The lake studied by Woolway et al. (2017) is a polymictic lake. Specifically, their study looked at the number of stratification days rather than the onset of stratification, where they found that wind speed was an important driver for number of days of stratification. On page 16, lines 10-13, we discuss how temperature in the hypolimnion over the summer are driven by conditions during spring turnover and timing of stratification onset. We have revised texts in this section to cite (Woolway et al., 2017) in the context of results of our manuscript.

p. 17, line 15-20: Discussion of heat fluxes: Is this entirely based on model results? Is there any observational evidence to confirm magnitude of heat fluxes?

Yes, the heat fluxes are based on model results. Unfortunately, there is no observational evidence regarding magnitude of the heat fluxes on these three lakes that we are aware of.

Table 4: Estimated trends need a time dimension – e.g., express in per year metrics. Also, clarify what test is used to define significance of trend.

As stated in the table heading, the time dimension for trends are in decades. i.e. each trend in in units per decade. We used a t-test to define significance of trend, and we have added an annotation to indicate this.

Table 5: Clarify that correlation is based on modeled results (?). If so, how do the modeled results compare to observations?
We have edited the table heading to indicate that the correlations are based on modeled results.

Figure 3: Results appear "cleaner" for Lake Wingra because it is shallow and more closely tied to air temperature. For Mendota and Fish Lake is there further insight to be gained by plotting simulated vs. observed temperature by depth range or by season? Are larger apparent discrepancies caused by mis-estimation of the depth of the thermocline? Also, put correlation coefficients on the X:Y plots.
We have added correlation coefficients on the XY plots in Figure 3. As you suggested, the larger errors in temperature simulations are caused in large part by the model not perfectly capturing the depth of the thermocline. In Fish Lake, especially, observations show that temperatures at the thermocline consistently changes by as much as 4°C per meter during the summer months (NTL LTER, 2012b). A difference in thermocline depth between observations and model by as little as 1 meter can yield high discrepancies between simulated and observed temperatures at those depths.

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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

10 that vary in depth and surface area to elucidate the effects of the observed 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, simulations showed that 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

15 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 the larger of our study lakes have more variability in temperature and stratification variables than the smaller lakes, and this variability increases with larger wind speeds. For all study lakes, Pearson correlations and climate perturbation scenarios

20 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

25 anomalies relative to 1961-1990 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)

5   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

10   air temperatures, showing increased epilimnetic water temperatures (Dobiesz and Lester, 2009; Ficker et al., 2017; O'Reilly et al., 2015; Shimoda et al., 2011), increased strength of stratification (Hadley et al., 2014; Rempfer et al., 2010), prolonged stratified period (Ficker et al., 2017; Livingstone, 2003; Woolway et al., 2017a), and altered thermocline depth (Schindler et al., 1990). However, hypolimnetic temperatures have undergone warming, cooling, and no temperature increase (Butcher et al., 2015; Ficker et al., 2017; Magee et al., 2016; Shimoda et al., 2011). Wind speed also strongly affects lake mixing (Boehrer

15   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. Similarly, Woolway et al. (2017a) 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,

20   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), but research into the response of lakes to isolated and combined changes in air temperature and wind speed has been limited.

25   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), increase bloom-forming cyanobacteria (Paerl and Paul, 2012), and change

30   internal nutrient loading and lake productivity (Ficker et al., 2017; Verburg and Hecky, 2009). Variations in water temperature impact the distribution, behaviour, community composition, reproduction, and evolutionary adaptations of organisms (Thomas

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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
5   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
10   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
15   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
20   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 century period (1911-2014). By examining three lakes in the same ecoregion with similar climate forcing, we aim to elucidate differences in responses that relate to
25   morphometry rather than climatic variables. Long-term changes in water temperature, stratification, heat fluxes, and stability are 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.

3

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 (2017).

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

5   energy through convective mixing, wind stirring, and shear mixing (Imerito, 2010; Yeates and Imberger, 2003). Layer mixing occurs when the turbulent kinetic energy (TKE), stored in the topmost layers, exceeds a potential energy threshold (Yeates and Imberger, 2003). To represent convective overturn, layers are checked for instabilities resulting from surface cooling, and if they exist, layers are merged and a fraction of the potential energy released becomes available as TKE. To represent wind stirring, wind stress is calculated from the wind speed and TKE is produced in the uppermost layer. Upper layers will mix with

10   lower layers if TKE is greater than the energy required for mixing. Mixing by shear flow is determined by calculating the mean horizontal velocity of the uppermost layer, which is dependent on the critical wind speed and the shear period. Yeates and Imberger (2003) improved performance of the surface mixed layer routine within the model by including an effective surface area algorithm based on observations in five lakes of different size, shape, and wind forcing characteristics (see Eq 32 in Yeates and Imberger, 2003) that reduced surface mixing in smaller, more sheltered lakes. The effective area is used to modify the

15   transfer of momentum from surface stress, as described in detail in Yeates and Imberger (2003) and not reproduced here. Their analysis developed a strong inverse relationship between the Lake number and lake-wide average vertical eddy diffusion coefficient, which configures a pseudo two-dimensional deep-mixing within the code, found to significantly improve the simulation of thermal structures observed in lakes that experienced strong wind forcing (Yeates and Imberger, 2003). Details of the surface mixed layer algorithm are not reproduced here, but can be found in Eq 27-34 of Yeates and Imberger (2003).

20   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).

25   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.

$$q_{sed} = K_{sed} \frac{dT}{dz} \tag{1}$$

where Ksed represents the sediment conductivity with a value of 1.2 Wm^{-1} °C^{-1} (Rogers et al., 1995), and dT/dz is estimated as:

30   $$\frac{dT}{dz} = \frac{T_s - T_w}{z_{sed}} \tag{2}$$

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:

5
$$T_s = 9.7 + 2.7 \sin\left[\frac{2\pi(D-151)}{TD}\right] \tag{3}$$

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
10   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
15   in Magee and Wu (2017).

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
20   precipitation. 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 (Antenucci and Imerito, 2003). Parameters relevant to the open water period are provided in Table 2. Ice cover model
25   parameters can be found in Hamilton et al. (in review), Magee and Wu (2017), 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. 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 within each year 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. There is no significant long term trend in yearly averaged open-water Secchi depth values for any of the three lakes. Light extinction coefficients were estimated from Secchi depth using the equation from Williams et al. (1980):

$$k_d = 1.1/z_s^{0.73} \tag{4}$$

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.

8

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
5   (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

10   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
15   were derived from literature values (Table 2). Within the model, the minimum layer thickness sets the limit for how small a water layer can become before it is merged with the smaller of the layer above or below. If the minimum layer thickness is too large, the model may not have the desired resolution to accurately capture changes in temperature and density that occur over small changes in depth. To calibrate this parameter, the 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
20   Vetter (2012). One minimum layer thickness was chosen for all three lakes to keep model formulation and implementation identical among the 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),
25   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.

30

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 and water clarity are maintained so that the long-term values in both lakes matches the historical record. This limits our analysis as it may exclude changes in water temperatures as a result of increased evapotranspiration, increased precipitation, or altered water clarity under future climate scenarios. 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 based on a breakpoint analysis and F test at a 0.05 significance level (Magee et al. 2016), 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 of the daily time bases 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 late 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).

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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
5   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
10   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
15   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).
20   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
25   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 simulated 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 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 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. For Lake Mendota stratification onset dates have a larger change for wind speed increases than decreases (-3.4 days $(m\ s^{-1})^{-1}$ for decreases and +10.5 days (m

13

s^{-1})$^{-1}$ for wind speed increases), as does Fish Lake (-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 in temperature, while Fish Lake has a larger change for air temperature increases (+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. 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 consistent for Lake Mendota (+0.18°C$_{hypolimnion}$ C$_{air\ temperature}$$^{-1}$) for both increases and decreases from the base case, but not so for Fish Lake (+0.25°C$_{hypolimnion}$ C$_{air\ temperature}$$^{-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 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

5   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

10 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

15 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

20 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

25 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

30 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). Tributary inflows may also contribute to enhanced diffusion due to inflow momentum; however, lakes used in this study are seepage-dominated lakes with little to no tributary contribution, so this phenomenon does not prevent the one-dimensional model from being applicable in this study. This one-dimensional assumption here and corresponding model results may not apply elsewhere for lakes with large inflow volumes.

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; Kimura 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 between air temperature and lake temperature variables (Fig. 8), 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. 9 and 10), 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. Other studies have also found that wind speed can be as important or even more important than air temperature for influencing lake stratification and water temperatures. For example, Woolway et al. (2017a) found that for polymictic Lake Võrtsjärv, wind speed is the key factor on the number of stratified days and 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

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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

5   temperatures. Arvola (2009) showed that hypolimnion temperatures were primarily determined by the conditions that pertained during the previous spring turnover and timing of stratification onset, 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

10   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.

15   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.

20   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

25   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.

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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, 2017). 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

5   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

10   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

15   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

20   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;

25   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

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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

5   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

10   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 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 ($\mu g\ L^{-1}$)[‡]	4.8	5.1	10.5
dissolved organic carbon ($\mu g\ L^{-1}$)[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

[‡] 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

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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.

Variable	Lake Mendota				Fish Lake				Lake Wingra			
	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

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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 $p < 0.1$ using a t-test

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

Lake Variable	Mendota/Fish	Lake Pair 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

(a) Lake Mendota

(b) Fish Lake
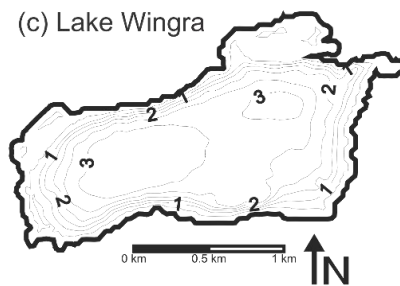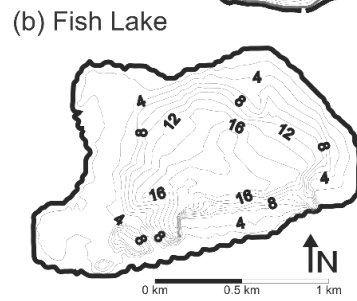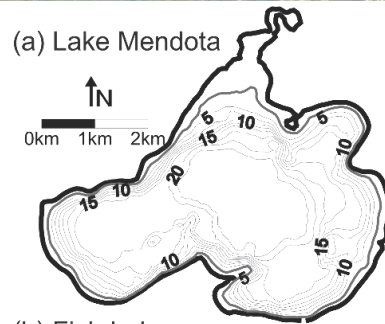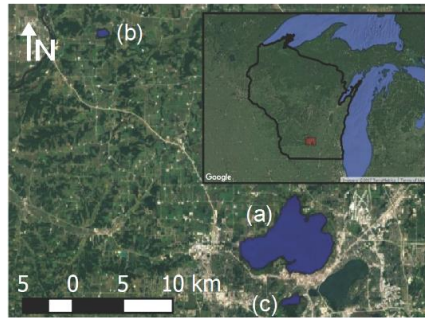
(c) Lake Wingra

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
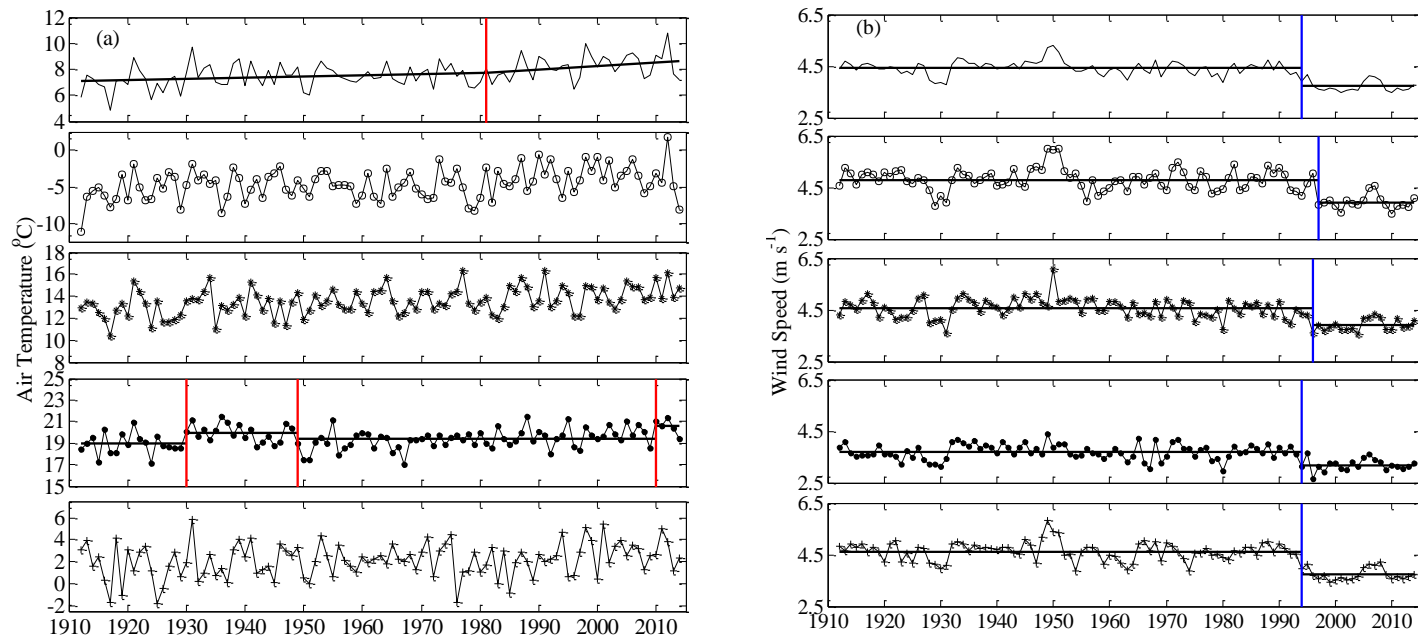
Figure 2: Yearly (solid line), winter (open circle), spring (asterisk), summer (solid circles), and fall (cross) (a) air temperature and (b) wind speeds for Madison, WI, USA. Red line in yearly air temperature figure represents a breakpoint in the trend of average air temperature increase from 0.081° 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.
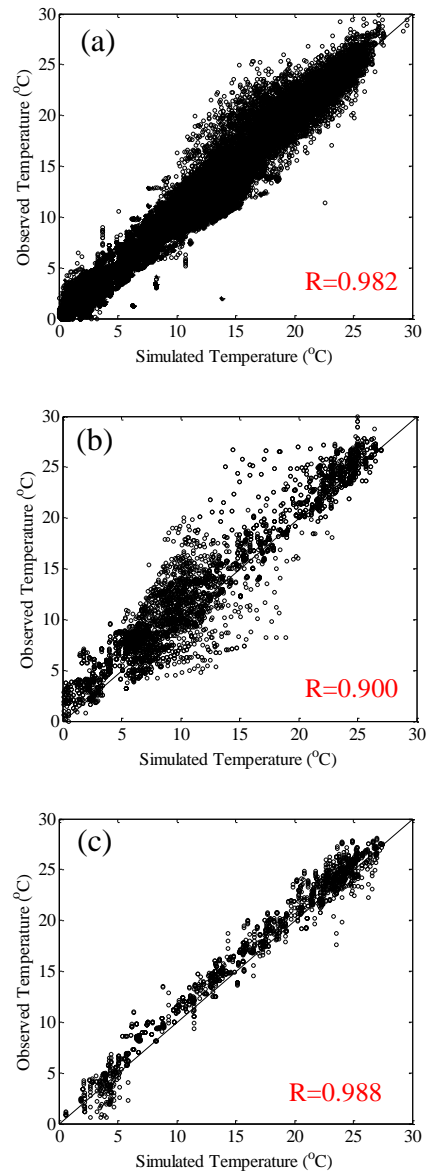
Figure 3: Comparison of observed and simulated water temperatures for (a) Lake Mendota, (b) Fish Lake, and (c) Lake Wingra. Each point represents one observation vs. simulation pair with unique date and lake depth.
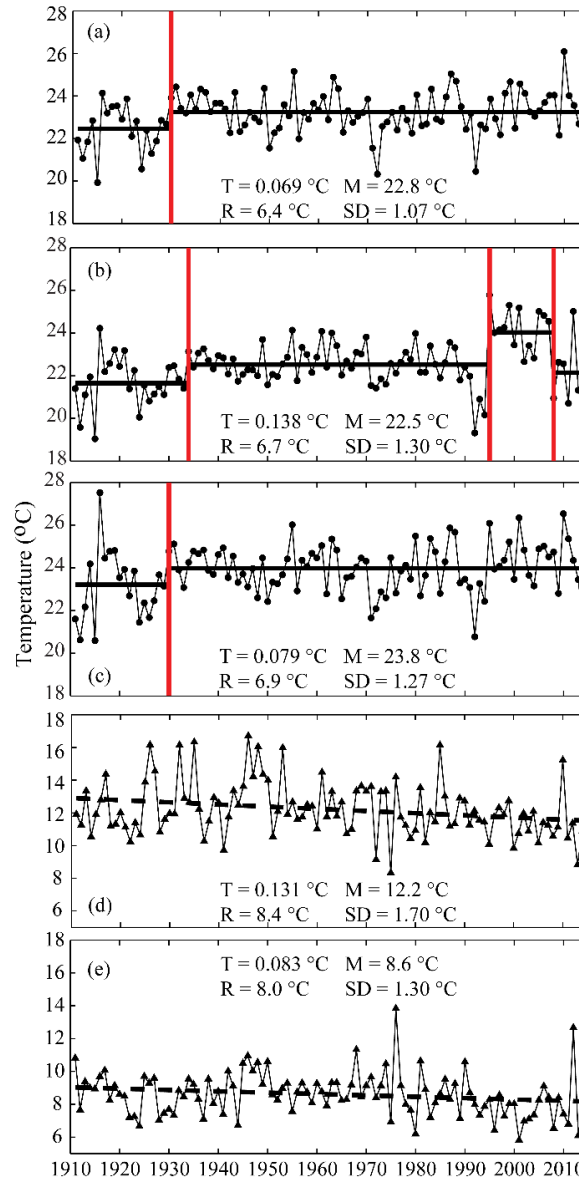
Figure 4: Mean summertime (July15-August15) epilimnetic temperatures for (a) Lake Mendota, (b) Fish Lake, and (c) Lake Wingra, and mean summertime (July 15-August 15) hypolimnetic temperatures for (d) Lake Mendota and (e) Fish Lake. In (a), (b), and (c), solid red lines represent statistically significant ($p < 0.5$) 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).

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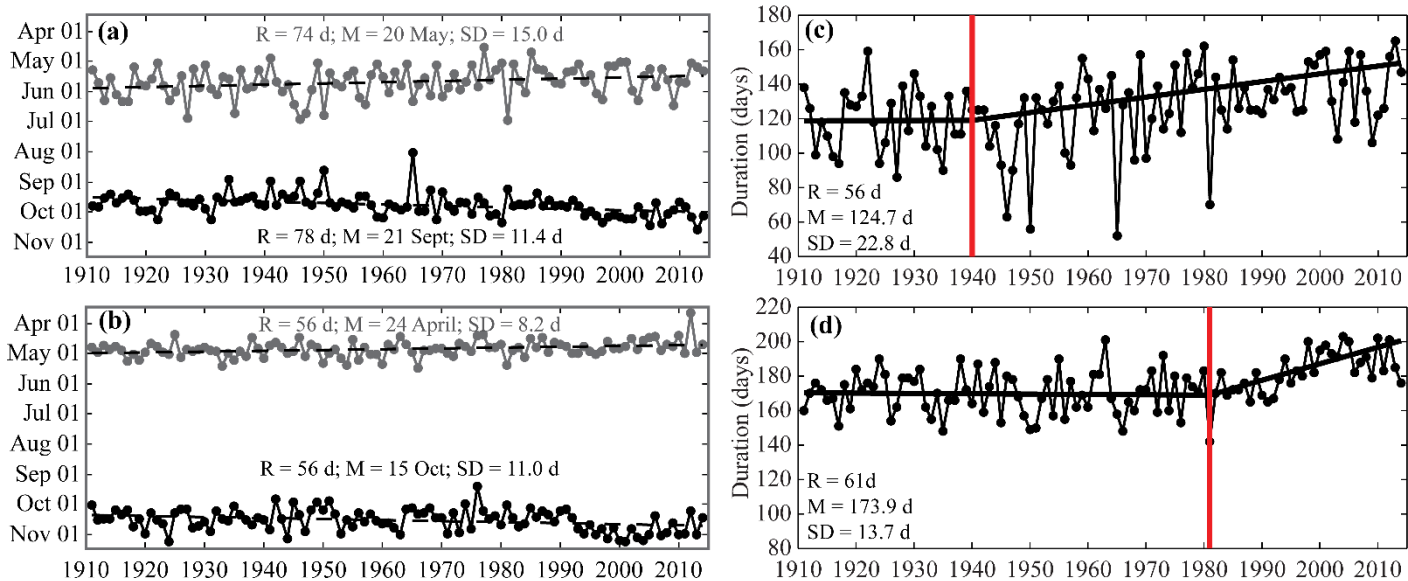
Figure 5: Stratification onset (gray) and overturn (black) dates for (a) Lake Mendota and (b) Fish Lake. Stratification duration for (c) Lake Mendota and (d) Fish Lake. Dark circles are modelled results and dashed lines denote the trendline for the 104-year period. In (a) and (b) dashed lines represent 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.
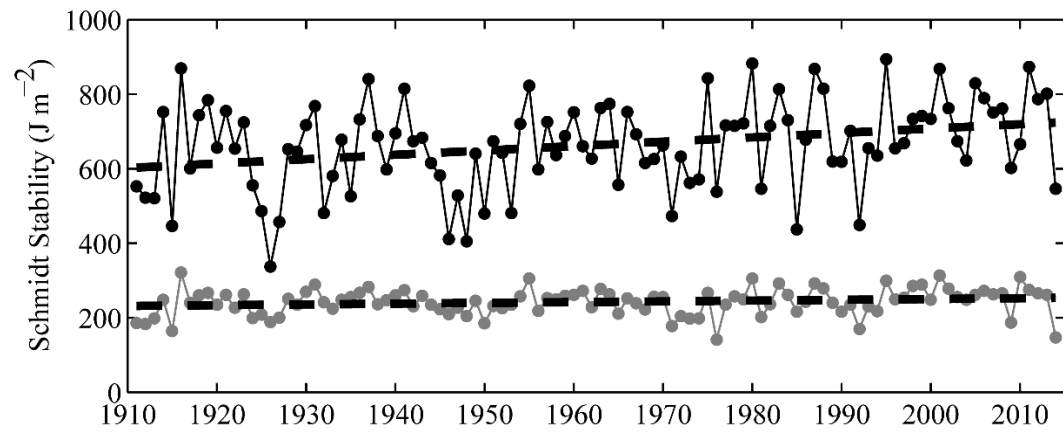
Figure 6: Yearly average summer-time (15 July - 15 August) Schmidt stability values for Lake Mendota (black) and Fish Lake (gray). Dashed lines represent the long-term trend for each lake.
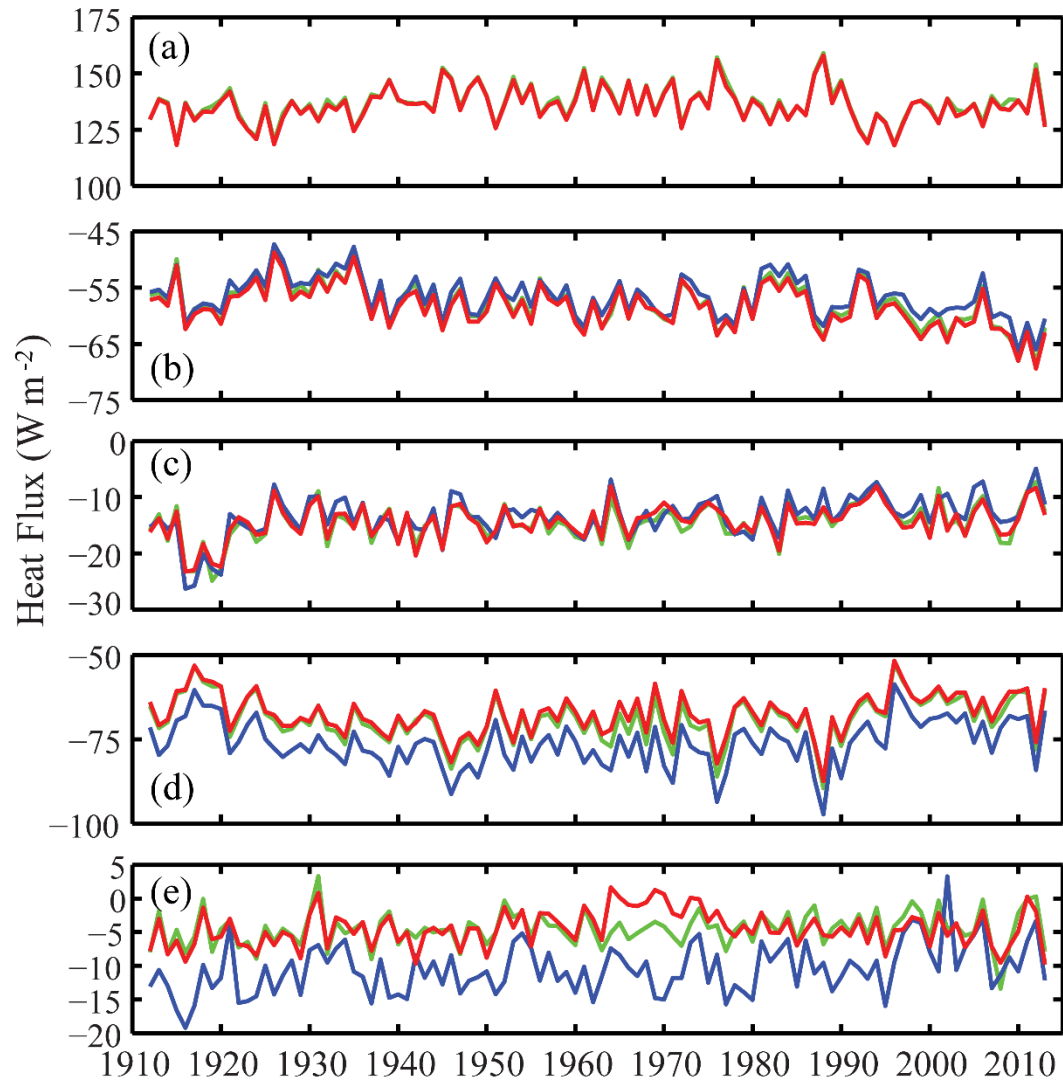
Figure 7: Yearly average (a) radiation flux, (b) long wave radiative flux, (c) sensible heat flux, (d) latent heat flux, and (e) total heat flux at the lake surface for Lake Mendota (solid black line), Fish Lake (black dashed line), and Lake Wingra (solid grey line). Trends and abrupt changes for heat fluxes are not shown on the plots for clarity.
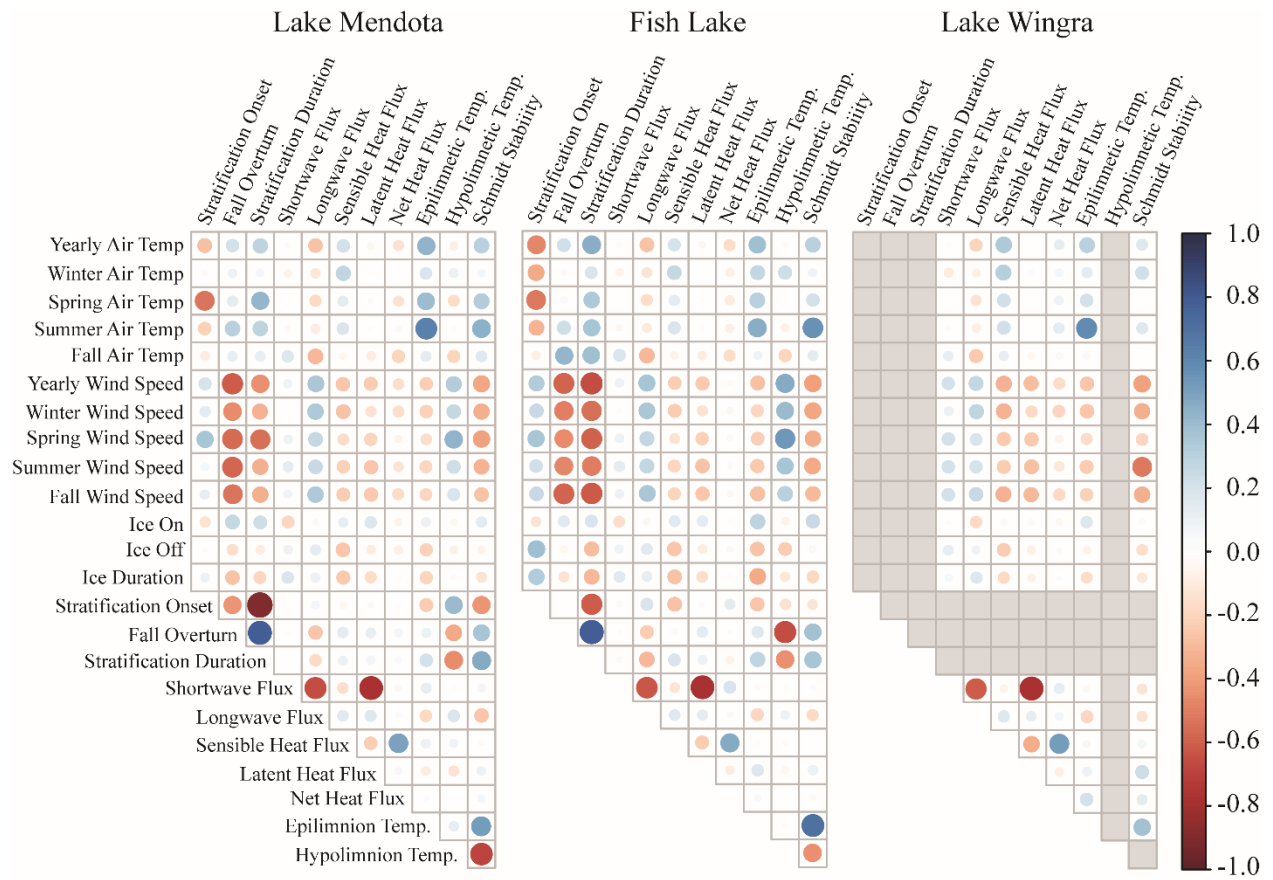
Figure 8: Plots of Pearson correlation coefficients among climate (air temperature and wind speed) variables and lake variables for the three study lakes.
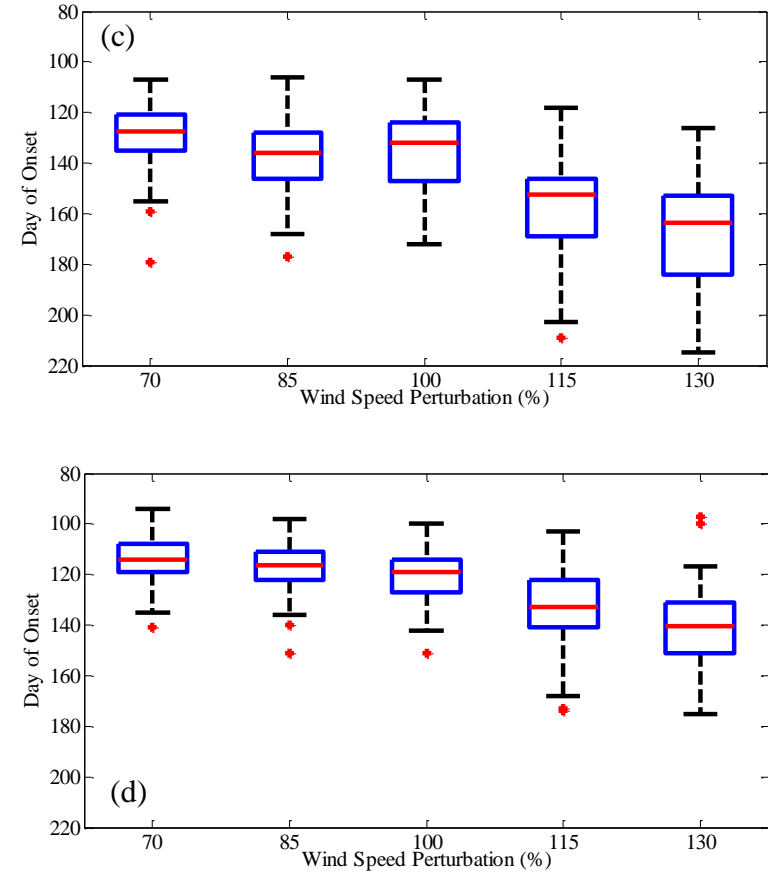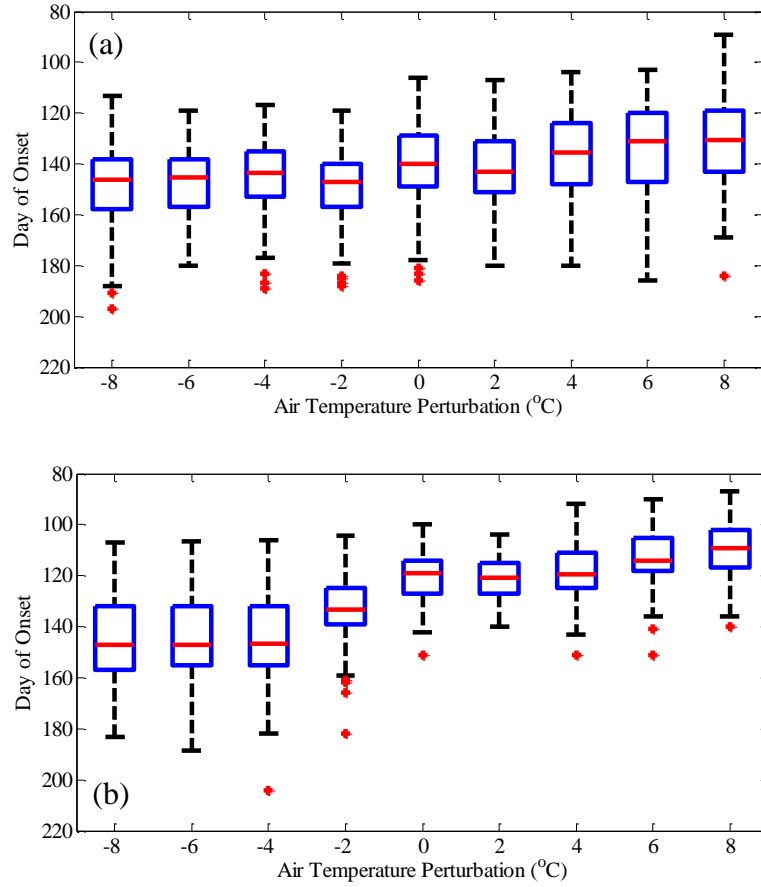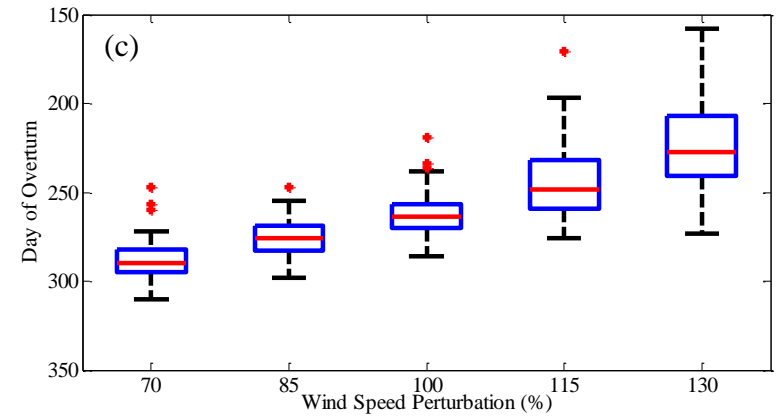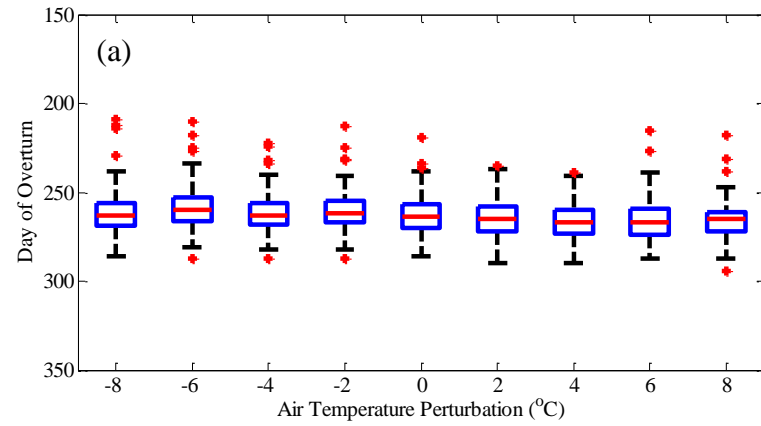
Figure 9: Day of stratification onset under select air temperature perturbation scenarios for (a) Lake Mendota and (b) Fish Lake and day of stratification onset under select wind speed perturbation scenarios for (c) Lake Mendota and (d) Fish Lake. The box represents the 25th and 75th quartiles and the 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.
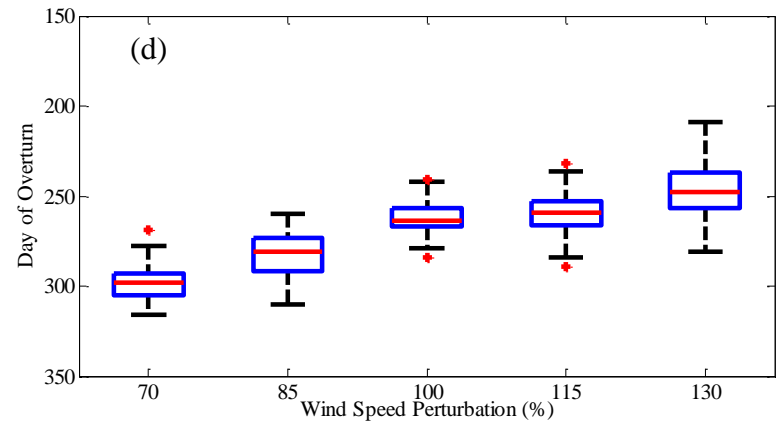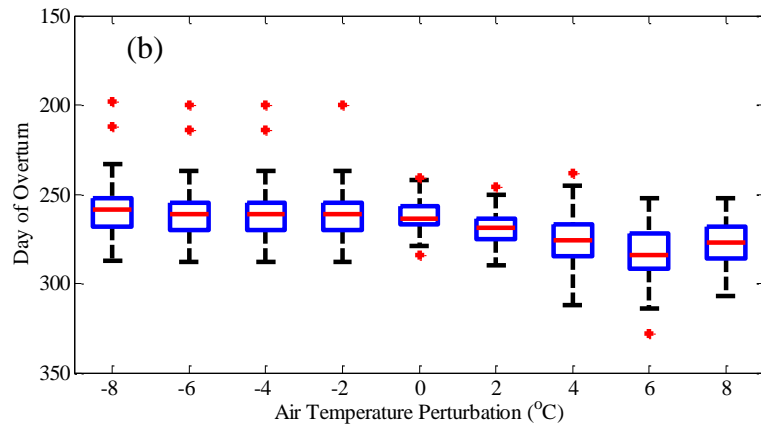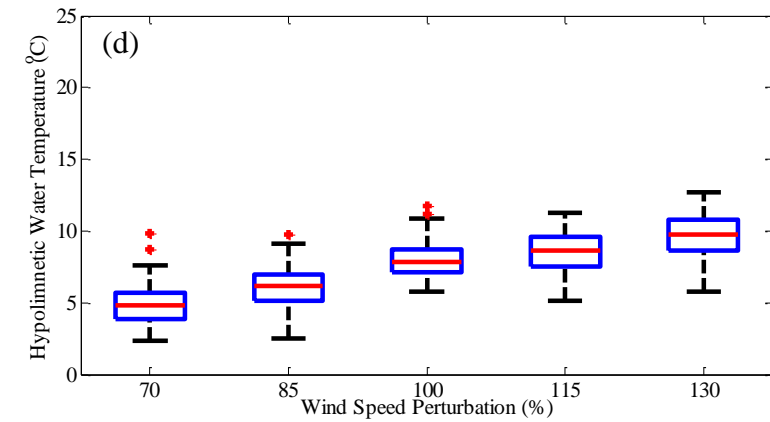
Figure 10: Day of stratification overturn under select air temperature perturbation scenarios for (a) Lake Mendota and (b) Fish Lake and day of stratification overturn under select wind speed perturbation scenarios for (c) Lake Mendota and (d) Fish Lake. The box represents the 25th and 75th quartiles 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.
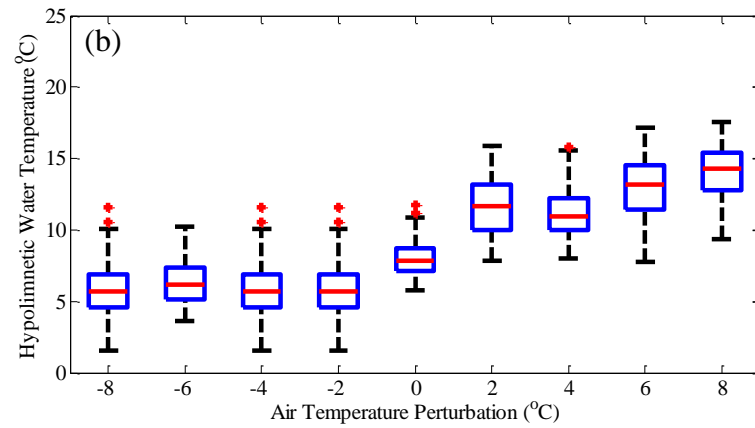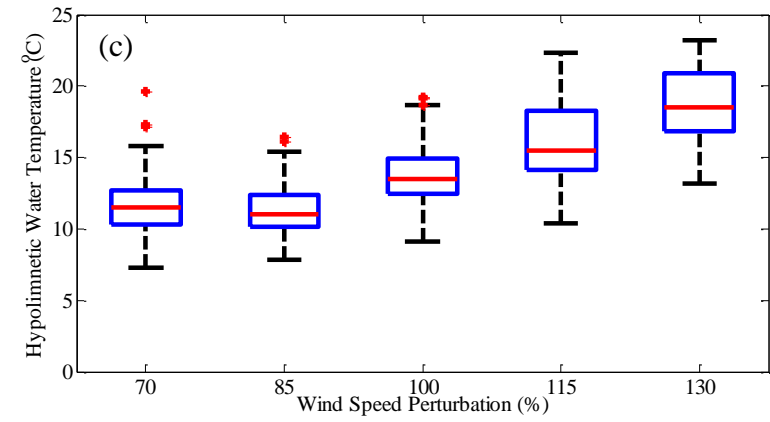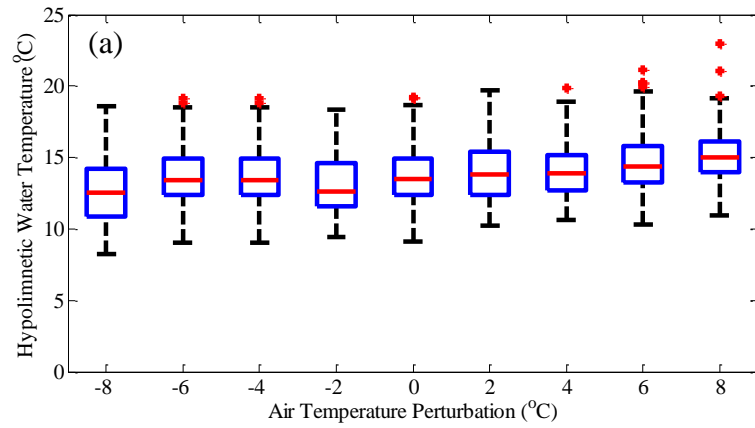
Figure 11: Hypolimnetic water temperatures under select air temperature perturbation scenarios for (a) Lake Mendota and (b) Fish Lake and hypolimnetic water temperatures under select wind speed perturbation scenarios for (c) Lake Mendota and (d) Fish Lake. The box represents the 25th and 75th quartiles 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.