Response to Reviewer 1

- This manuscript by Magee & Wu is based on an extraordinary data set of 104 years and focuses on effects of changing air temperature and wind speed on water temperature and stratification patterns of lakes with differing morphometry. The lakes are situated close to each other which is a great asset in this kind of research. The long data sets on basic variables and drivers is a good argument for publication and the results based on these data are fairly convincing. They are also logical and actually so logical that they very often leave a feeling that 'I already know this'. This may at least partly be due to simplification of morphometry to lake depth and surface area, but also due to lack of deep discussion; big part of 'Discussion' actually belong to 'Results' and to certain extent to 'Methods'. Thus restructuring and extending the real discussion (starting from 4.4.), the paper would certainly improve.

  The authors thank Reviewer 1 for taking the time to review and providing helpful comments to improve the manuscript. Following the suggestion, the authors are restructuring the paper and extending the discussion section. We have addressed additional comments in a point-by-point reply and carefully address the issues raised in the revised manuscript.

- Some parts of the paper are also technically challenging for the reader since they are based on listing the numerical results one by one; a good example is section 3.5.

  The authors thank the reviewer for this comment. We have addressed the structure of the writing in Sec. 3.5 that is challenging for readers. Specifically, we avoid listing the numerical results one-by-one without meaningful interpretation. Instead, we present the results in Figure 7 and Table 4. We summarize the overall and trends and related thermal characteristics in the manuscript (see Page 11, Line 6-12).

- The authors should also think about leaving Lake Wingra out completely; I suggest this because this paper has strong focus on lake stratification and Lake Wingra is a polymictic lake. The problem with Lake Wingra becomes obvious in Tables 2, 3 and 4 – lots of N/A markings.

  The authors thank the reviewer for this comment. Lake Wingra does stratify on daily or weekly timescales during the summer months (Kimura et al, 2016). Summer Schmidt stability was calculated at daily timescales, and then averaged for each year before comparing coherence among the lake pairs. Higher average stability for one year on Lake Wingra would indicate that the lake experienced more days of stratification during the period. This phenomenon can be coherent with changes in stability for the other two lakes.

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

- I also find it strange that in a paper where models are such an elemental part, they are not properly described; besides the equation for light extinction (eq 1), the authors only use references to published articles.

The authors thank the Reviewer 1 for this comment. Indeed, the description of the model have been described in great detail in the papers (Magee and Wu, 2016 in *Hydrological Processes* doi/10.1002/hyp.10996/full, Magee et al, 2016 in *Hydrology and Earth System Sciences*, DOI:10.5194, 20(5), 1681-1702). As a result, we did not intend to repeat the information in the manuscript and only refer to those published papers. Furthermore, we address the concerns raised by the reviewer. The equation for light extinction is included in the manuscript as it is a new updated component. We have edited and re-written portions of the manuscript to document additional details on the model subroutines that directly affect horizontal processes in the lake. In addition, we detail parameterizations and describe how they influence the results of this analysis. We summarize the change of the manuscript in the following:

- Page 4, Line 12-30: Section 2.2 Model description for hydrodynamics modeling

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

- Page 13, Line 25-Page 14 Line 26 in Discussion for model uncertainty

“Model parameters used to characterize the lake hydrodynamics were taken from literature values. These values may be expected to have small variability between lakes; however, previous studies have shown that many of the hydrodynamic parameters are insensitive to changes of ±10% (Tanentzap et al., 2007). Here, the model was validated against an independent dataset for each lake to determine if the model fits measured data and functions adequately, with errors within the range of those from other studies. Adjustments were made to limit uncertainty and errors associated with changes in location and techniques of meteorological measurements. Inflow and outflow measurements were assessed by the USGS for quality assurance and control, but uncertainty for both quantity and water temperature is unknown. The effects of these uncertainties are not be large as the inflow and outflow are small in comparison to lake volume (Madeline and Wu, 2016). The combination of uncertainties in parameters and observed data can 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 challenging and difficult (Gal et al., 2014; Tebaldi et al., 2005) Small, stratified lakes generally lack large horizontal temperature gradients (Imberger and Patterson, 198, Kamarainen et al., 2009), 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, Kamarainen et al., 2009), and spatial variations in wind stress can produce horizontal variations in temperature profiles (Imberger and Parker, 1985, Kimura et al., 2016). To address the role of internal wave activity and benthic boundary layer mixing, the pseudo two-dimensional deep mixing model by Yeates and Imberger (2003) is employed here. This mixing model has been shown to accurately characterize deep mixing that distributes heat from the epilimnion into the hypolimnion, thus weakening stratification, and the rapid distribution of heat entering the top of the hypolimnion from benthic boundary layer mixing, which strengthens stratification (Yeates and Imberger, 2003).

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, Magee et al, 2016), 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.”

- More emphasis should also be given to description of gap filling and calibration data; both are now somewhat superficial.

We have provided more description and re-written the text for additional clarity concerning gap-filling and calibration data. More detailed description of gap filling and calibration data can be found in other manuscripts (Magee et al, 2016; Magee and Wu, 2016).

Besides these more general comments, I list here some more detailed ones:

1. I found it a little bit strange that sediment heat fluxes were hardly mentioned in this paper. Although there may have been no data on this or these fluxes were not included in models, they should have been tackled somehow at least in 'Discussion'.

Sediment heat flux is included in the model. This description can be found in other published papers (Magee et al, 2016, Magee and Wu, 2016). We have added detail about sediment heat flux within the model section in the manuscript (Page 5 Line 1-12) as follows:

"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} $°C^{-1}$, and dT/dz is estimated as:

$$\frac{dT}{dz} = \frac{T_S - T_W}{z_{sed}} \tag{2}$$

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:

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

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

2. The readers would benefit from some more information about the lakes. Especially information on lake clarity (water colour etc; cf. Table 1) would have been useful in a paper with such a strong focus on lake stratification.

The authors thank the reviewer for this comment. Additional information on the lakes has been added to Table 1, including fetch, shoreline development, landscape position, Secchi depth, surface water chlorophyll concentration, and DOC in each lake. Specific values of lake water color is not collected by the NTL-LTER program as other data were.

3. As a reader I would also appreciate information on fetch for each lake; now the word 'fetch' and importance of fetch is mentioned several times, but the reader is left with the bathymetric maps to figure out the fetch

The authors apologize for neglecting to include this value explicitly in the manuscript. Information on lake fetch for each lake has been added to Table 1.

4. It is said that water level in Fish Lake has raised considerably and this has probably affected some of the results. However, nothing is said about the possible reason behind this phenomenon. Related to climate, human activity or what?

Thank you to Reviewer 2 for pointing out this statement which was not properly described. The text (Page 4 Line 2-4) has been changed to read
"the water level of the lake rose by 2.75 meters due to an increase in regional groundwater recharge causing increased groundwater flow to the lake (Krohelski et al., 2002). The increase in regional groundwater recharge may be the result of increased infiltration from snowmelt after increased snowfall and less frost-covered soil."

5. The authors state that Fish Lake does not always turn over completely in spring. This is an important piece of information, since in small, dark coloured boreal lakes this is a fairly common observation and it is believed that it is weather/climate driven change. It would be nice if the authors could dig deeper in this observation, especially since they have such a long time series.

After analyzing data, Fish lake does always mix each spring. However, low water temperatures of only 5~6°C in the hypolimnion, indicating that long mixing periods do not occur and little heat is added into the hypolimnion during spring mixing. During the historical period, the phenomenon occurred 4 times, and it may be related to lower spring wind speeds. Perturbation analysis suggests that this phenomenon could occur from low wind speeds and low air temperatures (see Page 12 Line 27-Page 13 Line 5).

6. Fish Lake and Lake Wingra have Secchi-depth results only from 1995 onwards. This appears problematic; could you give more explanation on this.

Fish Lake and Lake Wingra became part of the NTL-LTER program in 1995 and regular Secchi depth measurements were taken starting then. The authors agree with Reviewer 1 that it is not perfect to use seasonal averages for the historical period before 1995. However, given the strongly seasonal dynamic of water clarity and light extinction in the lakes, using seasonal averages of Secchi depth to estimate light extinction are preferably to a constant light extinction for the lakes, which is not representative of observed phenomenon in the lakes. To address this concern, we have added comments on the discussion (P14, L19-26): "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, , Magee et al, 2016), 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."

7. Data on below-ice Secchi-depth were used which I to certain extent understand, but since it is not that common practice to measure Secchi under the ice, it would be useful to have some more information.

Light extinction, which can be estimated from Secchi depth, greatly influences water temperatures and overall temperature profile. Including light extinction in winter more reliably reproduces under-ice water temperatures and as a result, water temperatures at the time of ice-off. Temperature profiles at ice-off impact the timing of stratification and the hypolimnetic water temperature through the summer. Properly characterising and capturing these phenomena in the model enables accurate reproduction of water temperatures during the historical period. For this study, the authors choose to utilize the available data from previous ecological and water quality studies conducted on the lakes to better inform the model for more reliably reproducing water temperature profiles.

8. Figure 3 shows that in general simulations resulted in slightly lower temperatures in comparison to observations. Did you make this clear also in text?

The authors thank the reviewer for pointing out this. We have made this clear in the text of the manuscript (see Page 13, Line 9-13): "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."

9. The possible importance of internal waves is mentioned only on general level and not properly discussed in relation to the study lakes

The reviewer is correct that we did not explicitly explain how the model deals with internal waves nor how internal waves affect hydrodynamics in each of the lakes. To address this, we have added sentences on the manuscript (See Page 14, L7-17: "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 challenging and difficult (Gal et al., 2014; Tebaldi et al., 2005). Small, stratified lakes generally lack large horizontal temperature gradients (Imberger and Patterson, 1981, Kamarainen et al., 2009), 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, Kamarainen et al., 2009), and spatial variations in wind stress can produce horizontal variations in temperature profiles (Imberger and Parker, 1985, Kimura et al., 2016). To address the role of internal wave activity and benthic boundary layer mixing, the pseudo two-dimensional deep mixing model by Yeates and Imberger (2003) is employed here. This mixing model has been shown to accurately characterize deep mixing that distributes heat from the epilimnion into the hypolimnion, thus weakening stratification, and the rapid distribution of heat entering the top of the hypolimnion from benthic boundary layer mixing, which strengthens stratification (Yeates and Imberger, 2003).

10. Using wording 'increasing (decreasing)' is clumsy for the reader

The authors thank the reviewer for this comment. We have revised the text to make the writing clearer for readers.

11. Throughout the text there is repetition, e.g. in 'Results' sentences which belong to 'Material' and are already tackled there. Check the whole manuscript for that

We thank the reviewer for pointing out this issue in the manuscript. The authors have removed and moved sections of the manuscript to address this issue.

12. Table 1: The meaning of the row ‘Groundwater’ is not clear to me

The table is revised to show groundwater inflow type of the lakes. For example, “discharge” lakes are those which have a net groundwater discharge into the lake. “Flowthrough” lakes are those which have small net inflow or outflow. Specifically, Lake Wingra have high groundwater inflows and outflows which result in small net inflow into the lake.

13. In Figure 4, the legend contains some description of results

The authors thank the reviewer for pointing out this comment. We have removed the description of the results out of the legend.

14. In Figure 6, results on Lake Wingra should be left out (= zero line). And in general, the stability index is somehow funny in this context since the lake was known to be polymictic

As suggested by Reviewer 1, we remove Lake Wingra out of this figure. To address stability, please see our previous response concerning the inclusion of Lake Wingra.

15. The real discussion starts in 4.4. and all before that should be merged with ‘Results’. An indication of that is the fact that for instance in 4.3.1 and 4.3.2 there are no references in the text.

The authors thank the Reviewer 1 for this comment. As suggested, we have restructured the discussion by moving Sections 4.2 and 4.3 to the Results section and emphasized the results in terms of physical mechanisms that influence the simulated and observed responses.

16. There are some spelling mistakes in the text, please check.

The typos have been fixed within the manuscript. Thank you to the reviewer for pointing out these mistakes to the authors. We have re-reviewed the manuscript carefully for any typographical errors.

Response to Reviewer 2

- The authors use an extensive dataset on water temperatures from three neighboring lakes to test and validate a one-dimensional lake temperature model. The model is subsequently used for reconstruction of the thermal and stratification regime of the lakes during the last century and for sensitivity studies exploring the lake response to changes in mean annuals of air temperature and wind speed. The idea behind the sensitivity experiments is to elucidate the dissimilarity in the response of lakes with different depths and surface areas subject to identical external atmospheric forcing. The problem statement is clear. The methods are generally relevant to the questions stated in the study (except the application of a 1d time-depth model to investigation of the effects of horizontal extensions on lake thermics, which requires additional justification, see below).

  The authors thank the reviewer for the positive comments and insightful comments on the manuscript. We have addressed the comments in a point-by-point reply on the revised manuscript.

- My major concern is the analysis of the results, which looks superficial, and representation of the outcomes, which is lengthy and poorly structured. The analysis is confined to descriptive presentation of model outcomes without an insight into the physical mechanisms producing the observed effects.

  We appreciate the comment concerning the analysis of results and structure of the paper. We have restructured the manuscript to address the points raised in both reviews and performed additional analysis and discussion to provide more insight into the physical mechanisms producing the observed effects.

- Verbal presentation of trends in lake thermal characteristics covering several paragraphs is exhausting and not really informative.

  The authors thank the reviewer for this comment. We have addressed the verbal presentation of trends in lake thermal characteristics in Sec. 3.5, specifically. For the revised manuscript, we avoid listing the numerical results one-by-one without meaningful interpretation. Instead, we present the results in Figure 7 and Table 4. We summarize the overall and trends and related thermal characteristics in the manuscript (see Page 11, Line 6-12).

- The manuscript presents a nice set of data and numerical results, which can serve as a basis for a well-thought study, but has little value for the reader in its present form.

  Following the previous section, we have greatly revised throughout the manuscript (see the changes in Result Sections and Discussion Sections.

- The manuscript requires a more detailed description of the model and discussion on its uncertainties and relevance to the real lake processes; the discussion should be rethought, moving the accent from the descriptive listing of the model responses to varying inputs to the discussion on the physical mechanisms producing the responses.

The authors thank the Reviewer 2 for this comment. As suggested, we restructured the discussion by moving Sections 4.2 and 4.3 to the "Results" section and emphasizing results in terms of physical mechanisms that are influencing the simulated and observed responses. The model was first developed by other researchers, and detailed descriptions of the model are presented elsewhere, which can be found in references. For the revised manuscript, we have added more detailed description of processes and described the parameterization of horizontal processes to improve the discussion, specifically on effects of non-linear surface momentum and the role that fetch differences play on lake thermal structures. Additionally, we restructured the "Methods" section to provide details on parameterization, calibration, and gap-filling of data in the manuscript.

Here are some major critical points:

- Effects of lake surface area on the response to the atmospheric forcing are continuously mentioned throughout the manuscript and are among the main subjects of the model sensitivity runs. However, the entire discussion is based on the outputs of a one-dimensional model, i.e. none of the physical processes depending on the horizontal dimensions are modeled directly, but parameterized in the model. Hence, the response of the model outcomes to varying surface area does not necessarily coincide with the response of real lakes to the same perturbations. To analyze properly the modeling results the authors need to (i) present the details on the model parameterizations related to the effects of horizontal advection, wind fetch, horizontally varying depth, and other horizontal processes, such as mixing by internal waves and upwelling of hypolimnetic waters in near-shore areas of the lake; (ii) when discussing the modeling results state clearly which of them can be extrapolated on the real lakes, which horizontal processes are missed by the model, and how it can affect the real situations; (iii) differentiate between the effects produced by increase of the wind energy input due to larger surface area from those produced by increase of the thermal inertia due to larger lake volume, like, in particular, timing of the stratification onset (Section 4.3.1).

The authors thank the reviewer for this comment. Since the model was developed by previous studies. We do not repeat the description of model equations. Instead, we have listed specific equation numbers in references to be clear about which equations the model uses and how horizontal processes are parameterized in the model. Specifically, we address the reviewer's three comments as follows:

- Page 4, Line 12-30: Section 2.2 Model description for hydrodynamics modeling and parameterizations

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

- Page 14, Line 7-17 in Discussion for model limitation and uncertainty

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 challenging and difficult (Gal et al., 2014; Tebaldi et al., 2005) Small, stratified lakes generally lack large horizontal temperature gradients (Imberger and Patterson, 198, Kamarainen et al., 2009), 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, Kamarainen et al., 2009), and spatial variations in wind stress can produce horizontal variations in temperature profiles (Imberger and Parker, 1985, Kimura et al., 2016). To address the role of internal wave activity and benthic boundary layer mixing, the pseudo two-dimensional deep mixing model by Yeates and Imberger (2003) is employed here. This mixing model has been shown to accurately characterize deep mixing that distributes heat from the epilimnion into the hypolimnion, thus weakening stratification, and the rapid distribution of heat entering the top of the hypolimnion from benthic boundary layer mixing, which strengthens stratification (Yeates and Imberger, 2003).

- Page 14, Line 27-Page 15 Line 16 by adding the importance of wind speeds in Discussion

While many have addressed the importance of changing air temperatures on water temperatures and water quality (e.g. Adrian et al., 2009; Arhonditsis et al., 2004; O'Reilly et al., 2015; Shimoda et al., 2011), fewer have investigated wind speed as a specific driver of changes to lakes (Magee et al., 2016; Snortheim et al., 2017). However, results here show that correlations between wind speeds and lake temperature variables are as high as, or higher than, correlations between air temperature and lake temperature variables (Fig. 7), highlighting the importance of 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 can offset the effects 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 statement is further supported through sensitivity analysis on stratification onset and overturn (Fig. 8 and 9), 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. However, for hypolimnetic temperatures, correlations and sensitivity indicate that decreasing wind speeds cool hypolimnetic temperatures, while increasing air temperatures warm hypolimnetic temperatures. Arvola (2009) showed that hypolimnion temperatures were primarily determined by the conditions that pertained during the previous spring turnover, which is consistent with our results showing significant ($p<0.01$) correlation between hypolimnion temperatures and wind speed (Fig. 8), but no significant correlation with air temperature or summer conditions. This could explain the conflicting results of previous research showing both warming and cooling trends in different lakes (Gerten and Adrian, 2001). Hindcasted hypolimnion temperatures (Fig. 4) show decreasing trends for Lake Mendota and Fish Lake. Combining the effects of air temperature and wind speed suggests that decreasing wind speeds, instead of increasing air temperatures, plays a more important role to change hypolimnetic water temperature for both lakes.

- Finally, we also revise the section 4.3.1 Lake Depth and 4.3.2 Surface Lake Area that address the reviewer's comment (iii).

- Do the lakes have ice cover in winter? The ice model is repeatedly mentioned in the MS, but no results on the ice regime are presented/discussed. Duration of the ice-covered period directly affects timing of the summer stratification onset and summer hypolimnetic temperatures. Any discussion on these variables is incomplete without considering the ice regime.

The authors thank the reviewer for pointing out this critical point. These lakes do have ice cover in winter. A recent paper by Magee and Wu (2016) in *Hydrological Processes* details both the ice model and the impact of air temperature changes on the three study lakes. As a result, we do not repeat the ice model and specific results of ice cover changes. Instead, we add text and make it clear that the lakes are in fact ice covered. Furthermore, we included analysis of the impact of ice cover on stratification onset and hypolimnetic temperatures in new Fig. 8 and in the results and discussion sections.

Reference:

Magee, MR and Wu, CH (2016) Effects of changing climate on ice cover in three morphometrically different lakes. *Hydrological Processes*. DOI: 10.1002/hyp.10996.

- Section 4.3 Sensitivity runs can be shortened, at least, to a half and moved from 'Discussion' to 'Results'. The actual discussion should be added, considering the reasons for the observed dependencies, their relevance to the processes in real lakes and novelty of the results compared to the state-of-the-art in this area of research.

The authors agree with this suggestion from the reviewer, and we have moved Section 4.3 to the Results section, shortened the presentation of the results, and have added discussion on the reasons for the observed relationships and add "4.2 Importance of wind-speed" as follows:

"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; Rimmer et al., 2011, Shimoda et al., 2011), fewer have investigated wind speed as a specific driver of changes to lakes (Magee et al., 2016; Snortheim et al., 2017). However, results here show that correlations between wind speeds and lake temperature variables are as high as, or higher than, correlations between air temperature and lake temperature variables (Fig. 7), highlighting the importance of 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 can offset the effects 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 statement is further supported through sensitivity analysis on stratification onset and overturn (Fig. 8 and 9), 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. However, for hypolimnetic temperatures, correlations and sensitivity indicate that decreasing wind speeds cool hypolimnetic temperatures, while increasing air temperatures warm hypolimnetic temperatures. Arvola (2009) showed that hypolimnion temperatures were primarily determined by the conditions that pertained during the previous spring turnover, which is consistent with our results showing significant (p<0.01) correlation between hypolimnion temperatures and wind speed (Fig. 8), but no significant correlation with air temperature or summer conditions. This could explain the conflicting results of previous research showing both warming and cooling trends in different lakes (Gerten and Adrian, 2001). Hindcasted hypolimnion temperatures (Fig. 4) show decreasing trends for Lake Mendota and Fish Lake. Combining the effects of air temperature and wind speed suggests that decreasing wind speeds, instead of increasing air temperatures, plays a more important role to change hypolimnetic water temperature for both lakes.

Minor comments:

- P3L16 What is 'thermocline shifts'? Please, explain.

  The authors thank Reviewer 2 for pointing out confusion due to our choice of word. 'Thermocline shifts' refers to changes in thermocline depth in response to a driver such as changes in climate. We have changed the line to read "changes in thermocline depth from warming air temperatures may be dampened…" to remove some of this confusion due to previous word choice.

- P6L29 Provide model parameters and simulation specifications here.

  We have provided addition parameters and simulation specifications as suggested within the text (see previous reply or Model description Page 4-Line 13-30, Page 5-Line 11-Page 6 Line 3)

- P9L7 Add 'summer epilimnetic' to 'temperatures'

  We did add 'summer epilimnetic' to temperature, as requested by the reviewer.

- P10L13 and other appearances: replace '0.067 days earlier decade-1 ' to '+0.067 days decade-1 '

  Following the suggestion by the reviewer, the authors have made this change to improve readability of the manuscript.

- P10L28 onwards: 'J m^{-2} ' are not correct units for heat flux. Provide flux values in understandable units.

  The authors thank the Reviewer 2 for pointing out this error in units. Indeed, the units should be W m^{-2}, and the error occurred by inadvertently carrying over units from the previous sections of text). The units are correct in the corresponding figure. We have addressed the incorrect units in the text.

- P11L17 How lake morphometry can affect the shortwave flux of solar radiation??

  The shortwave flux is the net flux at the surface of each lake. The shortwave flux is controlled in part by albedo of the surface water, by snow ice cover in the lake. Each lake may have slightly different net shortwave radiative flux for each day and average for the year.

- P14L12 and at other places: Schmidt stability is irrelevant to non-stratified lakes and cannot be used for comparison.

  P17L9 See above

  Lake Wingra does stratify on daily or weekly timescales during the summer months (Kimura et al, 2016). Summer Schmidt stability was calculated at daily timescales, and then averaged for each year before comparing coherence among the lake pairs. Higher average stability for one year on Lake Wingra would indicate that the lake experienced more days of stratification during the period. This phenomenon can be coherent with changes in stability for the other two lakes.

- P17L18 Evaporation depends on surface temperatures, not the deep water temperatures. Explain what do you mean in this sentence, or remove it and find another explanation for the phenomenon.

  We have re-written this section as follows (Page15 Line 30-Page 16 Line7): "Overall, Lake Wingra had a larger magnitude of latent and net heat fluxes than the deeper lakes. Diurnal variability in surface temperatures is larger for shallow lakes, promoting increased latent heat fluxes in these lakes (Woo, 2007). This increased response may also explain the larger change in trend for sensible heat flux since Lake Wingra responds more quickly to changes in air temperature, thus, have a larger change in sensible heat flux during each day. Interestingly, net heat flux of Lake Wingra is less coherent with the deeper lakes than the deep lakes are with each other. This may be due to the combination of more extreme temperature variability, increasing sensible and latent heat fluxes during the open water season and the lower sensitivity of ice cover duration in Lake Wingra compared to the deeper lakes (Magee and Wu, 2016)."

- P17L2529 Actually, the main driver for epilimnetic temperatures is solar radiation not air temperature. If air temperature is the 'main driver', what do you mean under 'wind. . . a more dominant mechanism'?

  The authors agree that solar radiation is the main driver for epilimnion temperatures. Nevertheless, Air-temperature increase is a natural candidate to explain the increase in the average epilimnion temperature at both short (monthly) and long (annual) timescale (Livingstone, 2003, Rimmer et al, 2011, Magee et al., 2016). What we mean is that we examine epilimnetic temperature change by running sensitivity analysis through changing air temperature and wind speed scenarios. What we find is that wind mixing is a more dominant mechanism to transfer heat from upper layers of the water column to bottom waters than is molecular diffusion of heat. While air temperature can directly influence surface water temperatures, wind speed changes can dissipate heat to the lower water levels and can act to change the response of epilimnion temperatures to air temperature changes. To clarify this confusion, we have re-written the section as follows (Page16, Line 12-17): "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)."

- P18L14-15 Explain, why stronger winds should produce higher spatial variability in wind stress. How did you estimate changes in turbulence and why do you think they are nonlinear?

We address this in the following. In the text, we do not imply that there is higher spatial variability in wind stress within the lakes themselves. Rather, increases and/or decreases in wind speed in general will result in nonlinear changes in wind stress and turbulence in all lakes. Wind stress varies with the square of wind speed, so changes in wind speed directly result in non-linear changes in wind stress on the water surface. The DYRESM model parameterizes mixing within the model by estimating the turbulent kinetic energy (TKE) and mixing layers when a potential energy threshold is exceeded. TKE in the model is introduced through convective mixing, wind stirring, and shear mixing using parameterizations that are all non-linear equations and influenced non-linearly either directly or indirectly by wind speed. So linear changes in wind speed yield non-linear changes in the turbulence estimation in the model. To clarify this, we have added the text in the manuscript (Page 16-Line 17- Page 17 Line 2) as follows:

"Surface area plays a role in lake-wide average vertical heat fluxes from boundary processes (Wüest and Lorke, 2003), and the model accounts for this by including an effective surface area algorithm to scale transfer of momentum from surface stress based on lake surface area (Yeates and Imberger, 2003). This increases transfer momentum from surface stress and vertical heat transfer for lakes with larger fetch. Accounting for this larger fetch increases mixing and vertical transfer of heat to bottom waters, reducing epilimnion water temperatures (Boehrer and Schultze, 2008) and increasing the rate of lake cooling (Nõges et al., 2011). For this reason, Lake Mendota with the large fetch experiences a smaller increase in epilimnetic water temperature compared to Fish Lake (Table 5). Additionally, momentum from surface stress scales linearly with lake area and non-linearly with wind speed (Yeates and Imberger, 2003, see Eq. 31 and 33), making momentum from surface stress, and thus, mixing, stratification, and hypolimnion temperatures more variable for lakes with larger fetch and even more variable when wind speed is increased (see Fig. 8-10). Greater variability in momentum and mixing corresponds to larger variability of Schmidt stability for Lake Mendota, with the larger surface area. Greater transfer of momentum in Lake Mendota results in the slightly deeper thermocline for the larger surface area lake (~10 m in Lake Mendota and ~6 m in Fish Lake), which may play a role in filtering the climate signals into hypolimnion temperatures. Low hypolimnetic temperature coherence between Mendota and Fish suggest that lake morphometry plays a role. This result is consistent with other studies that show lake morphometry parameter affects the way temperature is stored in the lake system (Thompson et al., 2005)."

- Table 2, Fig. 3: The model seems to produce consistently a positive bias in lake temperatures. Any explanation for this?

  The model results under predict slightly water temperatures. This under prediction is from a combination of averaging meteorological inputs over the day and comparing temperatures output on a daily timestep with observations collected typically during the afternoon when water temperatures are slightly higher than daily averages.

Typos:

- P4L12 Capitalize 'Secchi'
- P5L29 remove second appearance of 'Lake Mendota'
- P8L15 replace 'decreased' with 'decrease'
- P12L13 replace 'difficulty' with 'difficult'

All the typos have been fixed within the manuscript. We extend our many thanks to the reviewer for pointing out these mistakes to the authors. Furthermore, we have reviewed the manuscript carefully for typographical errors.

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

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Abstract. Water temperatures and stratification are important drivers for ecological and water quality processes within lake systems, and changes in these with increases in air temperature and changes to wind speeds may have significant ecological consequences. To properly manage these systems under changing climate, it is important to understand the effects of increasing air temperatures and wind speed changes in lakes of different depths and surface areas. In this study, we simulate three lakes that vary in depth and surface area to elucidate the effects of increasing air temperatures and decreasing wind speed on lake thermal variables (water temperature, stratification dates, strength of stratification, and surface heat fluxes) over a century (1911-2014). ~~Water temperatures in three morphometrically different lakes are simulated using a one-dimensional hydrodynamic lake model over the century (1911-2014) to elucidate the effects of increasing air temperature and decreasing wind speed on lake thermal variables (water temperature, stratification dates, strength of stratification, and surface heat fluxes).~~ ~~During the study period~~For all three lakes, epilimnetic temperatures increased, hypolimnetic temperatures decreased, ~~and~~ the length of the stratified season increased for the study lakes due to earlier stratification onset and later fall overturn, stability increased, and longwave and sensible heat fluxes at the surface increased. ~~Additionally, there was an abrupt change in epilimnion temperature after 1930 in both Lake Mendota and Lake Wingra, and three changes, after 1934, 1995, and 2008 for Fish Lake. There was a significant change in the slope of trend of stratification duration after 1940 in Lake Mendota and a significant change in trend after 1981 for Fish Lake. Schmidt stability showed a statistically significant increasing trend for both deep lakes, with the larger trend and greater variability in the larger surface area lake. Sensible heat flux in all three lakes increases over the simulation period while longwave heat flux decreases. The shallow study lake had a greater change in latent heat flux and net heat flux, illustrating the role of lake depth to surface heat fluxes. Sensible heat flux in all three lakes had similar timing of abrupt changes, but the magnitude of the change increased with increasing depth. Abrupt changes in latent heat flux appear to be independent of lake morphometry, indicating that the timing of change may be primarily driven by climate. Perturbing drivers showed that increasing air temperature and decreasing wind speed caused earlier stratification onset and later fall overturn. For hypolimnetic water temperature, however, increasing air temperature warmed bottom waters while decreasing wind speed cooled bottom waters, indicating that the change of hypolimnetic temperatures globally may be~~

~~influenced by local changes in wind speed.~~ Overall, lake depth influences presence of stratification, ~~lake depth impacts the presence of stratification and magnitude of~~ Schmidt stability, and differences in surface heat flux, while lake surface area ~~drives~~influences differences in hypolimnion temperature, hypolimnetic heating, variability of Schmidt stability, and stratification onset and fall overturn dates. Larger surface area lakes have greater wind mixing due to increased surface momentum. Climate perturbations indicate that larger lakes have more variability in temperature and stratification variables than smaller lakes, and this variability increases with larger wind speeds. For all study lakes, Pearson correlations and climate perturbation scenarios indicate that wind speed plays a large role on temperature and stratification variables, sometimes greater than changes in air temperature, and wind can act to either amplify or mitigate the effect of warmer air temperatures on lake thermal structure depending on the direction of local wind speed changes.

1 Introduction

~~Climate over the past century has changed.~~ The past century has experienced global changes in air temperature and wind speed. ~~Globally averaged land~~Land and ocean surface temperature anomalies ~~have~~ increased ~~over the period~~ from 1850 to ~~-~~2012 (IPCC, 2013). ~~In the Northern Hemisphere, 1983-2012 was likely the warmest 30-year period of the last 1400 years (IPCC, 2013).~~ ~~In Wisconsin, the air temperature increased by 0.61°C from 1950 to 2006 (Wisconsin Initiative on Climate Change Impacts (WICCI), 2011).~~ 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). ~~Studies suggest that more intense and longer lasting heat waves will appear in the future (Meehl and Tebaldi, 2004), and there has been a trend of increasing mean temperature anomaly across the continental United States (Hansen et al., 2010).~~ ~~In Wisconsin, the air temperature increased by 0.61°C from 1950 to 2006 (Wisconsin Initiative on Climate Change Impacts (WICCI), 2011).~~ Additionally, global change in wind speed has been heterogenous. ~~Furthermore, changes in wind speeds across the globe have been observed.~~ For example, wintertime wind energy increased in Northern Europe (Pryor et al., 2005), while modest declines in mean wind speeds were observed in the United States (Breslow and Sailor, 2002). Similarly, on ~~the regional scale~~regional scales, ~~Klink (2002) reported a decreasing trend in annual wind speed at five of seven stations in and around Minnesota from 1959 to 1995 and~~ Magee et al. (2016) showed a decrease in Madison, Wisconsin wind speeds ~~occurring in Madison, Wisconsin~~ after 1994, but Austin and Colman (2007) found increased wind speeds in Lake Superior, North America. ~~. In contrast, increasing wind speeds were observed in Lake Superior, North America (Austin and Colman, 2007).~~ Significant changes to air temperature and wind speed observed in the contemporary and historical periods are likely to continue to change in the future. ~~Generally, it is recognized that air temperature and wind speed have significantly changed over the last century and will likely continue to change in the future.~~

Lake water temperature is closely related to ~~the meteorological variables of~~ air temperature and wind speed. Previous studies show that warming air temperatures have ~~caused increasing~~increased epilimnetic water temperatures (Dobiesz and Lester, 2009; Shimoda et al., 2011), increased the strength of stratification (Rempfer et al., 2010), prolonged the stratified period (Livingstone, 2003; Robertson and Ragotzkie, 1990), and altered thermocline depth (Schindler et al., 1990). ~~For instance, Lakes Superior, Michigan, and Huron exhibited increasing water temperature and increased stratification duration during between 1979 and 2006 (Austin and Colman, 2007). In contrast, h~~However, hypolimnetic temperatures have undergone either ~~both~~ warming or cooling trends depending on season (Robertson and Ragotzkie, 1990). ~~Changes in wind~~Wind speed also strongly affects lake mixing (Boehrer and Schultze, 2008), lake heat transfer (Boehrer and Schultze, 2008; Read et al., 2012), and temperature structure (Desai et al., 2009; Schindler et al., 1990). Stefan et al. (1996) found that decreasing wind speeds resulted in increased stratification and increased epilimnetic temperatures in inland lakes. ~~-~~In Lake Superior, observations show that the complex nonlinear interactions among air temperature, ice cover, and water temperature result in water temperature increases (Austin and Allen, 2011), contrary to the expected decreases in water temperature from increased wind speeds (Desai et al., 2009). ~~increased wind speeds caused by the decreasing air-water temperature differences (Desai et al., 2009) should have resulted in water temperature decreases, but observations show instead increasing water temperatures due to complex nonlinear interactions among air temperature, ice cover, and water temperature (Austin and Allen, 2011).~~ In recent years, our understanding of the effects of air temperature and wind speed on changes in water temperature and stratification has improved (Magee et al., 2016), but there still remains uncertainty in the response of lakes to isolated and combined changes in air temperature and wind speed. ~~we have improved understanding of changing air temperature and wind speed on alterations of water temperature and stratification (Magee et al., 2016). Nevertheless, there still remains uncertainty in the response to isolated and combined changes in lakes.~~

~~The lake ecosystem is significantly impacted by changes in lake water temperature~~Changes in lake water temperature influence lake ecosystem dynamics (MacKay et al., 2009). For example, increasing water temperatures ~~led to changing~~may change plankton community composition and abundance (Rice et al., 2015), alter~~ed~~ fish populations (Lynch et al., 2015), and enhance~~d~~ the dominance of cyanobacteria (Jöhnk et al., 2008). ~~Changes in these populations~~Such changes affect the biodiversity of freshwater ecosystems (Mantyka-Pringle et al., 2014). ~~-~~Furthermore, increased thermal stratification of lakes can intensify lake anoxia (Palmer et al., 2014), ~~enhance the growth of~~increase bloom-forming cyanobacteria (Paerl and Paul, 2012), and ~~induce changes to~~change internal nutrient loading and lake productivity (Verburg and Hecky, 2009). Variations in water temperature impact the distribution, ~~behavior~~behaviour, community composition, reproduction, and evolutionary adaptations of organisms (Thomas et al., 2004). Improved understanding of response of lake water temperatures and ecosystem response to air

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temperature and wind speed can better ~~Further assessment of the response of lake water temperature to changes in air temperature and wind speed will improve our understanding of ecosystem response, which can better~~ prepare management, adaptation, and mitigation efforts for a range ~~of different size~~ of lakes.

Lake morphometry ~~can complicate the response of~~complicates the response of lake water temperatures to air temperature and wind speed changes because it ~~by altering~~alters physical processes of wind mixing, water circulation, and heat storage (Adrian et al., 2009). ~~Basin morphometric characteristics such as mean~~ Mean depth, surface area, and volume ~~can~~ 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~~thermocline shifts~~ may be dampened in large lakes where ~~the depth of the thermocline~~thermocline depth is constrained by lake fetch ~~the lake's fetch~~ (Boehrer and Schultze, 2008; MacIntyre and Melack, 2010). Winslow et al.~~,~~ (2015) showed that differences in wind-driven mixing may explain the inconsistent response of hypolimnetic temperatures between small and large lakes. ~~While p~~Previous research efforts have investigated the response of individual lakes (~~Austin and Colman, 2007;~~ Voutilainen et al., 2014) and the bulk response of lakes in a geographic region to changing climate (Kirillin, 2010; Magnuson et al., 1990), but few studies have focused on elucidating the effects of morphometry, specifically lake depth and surface area, on changes in lake water temperature in response to long-term changes in air temperature and wind speed.

The purpose of this paper is to investigate the response of water temperatures and stratification in lakes with different morphometry (water depth and surface area) to changing air temperature and wind speed. To do this, we employ an existing one-dimensional hydrodynamic lake-ice model to hindcast water temperatures for three lakes with different morphometry. ~~A one-dimensional hydrodynamic lake-ice model, allowing for additional investigation into quantities that are not available in limnological records, was employed to run continuous long-term simulations of water temperature during open water and ice covered seasons of three lakes with different morphometry.~~ These lakes vary in surface area and depth and are nearby ~~were close enough to each other~~ (<30 km distance) to experience similar daily climate conditions (air temperature, wind speed, solar radiation, cloud cover, precipitation) over the ~~average temperature, wind speed, solar radiation, cloud cover, and precipitation over the~~ period 1911-2014. Long-term changes in water temperature ~~(epilimnetic and hypolimnetic temperatures)~~, stratification ~~variables (stratification onset, overturn, and duration),~~, heat fluxes, and stability ~~from both observations and model outputs~~ were used to ~~reveal~~ investigate how lake depth and surface area ~~influence and~~ alter the response of thermal structure to air temperature and wind speed changes for the three study lakes. ~~among the three study lakes~~.

Commented [M1]: What is 'thermocline shifts'? Please, explain.

Commented [MRM2R1]: The authors thank Reviewer 2 for pointing out confusion due to our word choice. 'thermocline shifts' refers to changes in thermocline depth in response to a driver such as changes in climate. We have changed the line to read "changes in thermocline depth may be dampened…" to remove some of this confusion due to previous word choice.

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 ~~close proximity~~proximity to one another, and (iii) the availability of long-term ~~limnological records~~data for model input and calibration.

Lake Mendota (43°6' N; 89°24'W; Fig.~~ure~~ 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. ~~During the summer months~~Summer (1 June - 31 August)~~, the~~ mean surface water temperature is 22.4 °C, and hypolimnetic temperatures ~~range in value~~ vary between ~~from~~ 11°C to 15 °C. Normal ~~s~~Secchi depth during the summer is 3.0 meters (Lathrop et al., 1996). Fish Lake (43°17'N; 89°39'W; Fig.~~ure~~ 1b; Table 1) is a dimictic, eutrophic, shallow seepage lake located in northwestern Dane County. From 1966 to 2001, lake level ~~the water level of the lake~~ 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 ~~The lake experiences summer stratification lasting~~ 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. ~~however, some years do not experience complete mixing in the spring and reach temperatures of only 4–5°C in the bottom waters by the end of the summer~~. ~~The a~~Average Secchi depth during the summer months is 2.4 m. Lake Wingra (43°3' N; 89°26' W; Fig.~~ure~~ 1c; Table 1) is a ~~very~~ shallow, eutrophic, drainage lake. It stratifies on short timescales of hours to weeks (Kimura et al., 2016), but does not experienced sustained thermal stratification. ~~Due to its shallow depth, Lake Wingra does not experience thermal stratification in the summer. During the summer~~Summer~~, the~~ mean water temperature is 23.9°C, and mean ~~S~~Secchi depth is 0.7 meters. All three lakes have ice cover during winter months, and a description of ice on the lakes can be found in Magee and Wu (2016)

~~**2.2 Data**~~

~~Meteorological data used in the model input 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~~

Commented [M3]: The readers would benefit from some more information about the lakes. Especially information on lake clarity (water colour etc; cf. Table 1) would have been useful in a paper with such a strong focus on lake stratification.

As a reader, I would also appreciate information on fetch for each lake; now the word 'fetch' and importance of fetch is mentioned several times, but the reader is left with the bathymetric maps to figure out the fetch.

Commented [MRM4R3]: Information on lake fetch has been added to Table 1 to provide that detail to the readers. The authors apologize for neglecting to include this value explicitly in the original submission of the manuscript.

Additional information on the lakes has been added to Table 1, including fetch, shoreline development, landscape position, Secchi depth, surface water chlorophyll concentration, and DOC in each lake. Specific values of lake water color is not collected by the NTL-LTER program as other data was, however,

Commented [M5]: It is said that water level in Fish Lake has raised considerably and this has probably affected some of the results. However, nothing is said about the possible reason behind this phenomenon. Related to climate, human activity or what?

Commented [MRM6R5]: The text has been changed to read "the water level of the lake rose by 2.75 meters due to an increase in regional groundwater recharge causing increased groundwater flow to the lake (Krohelski et al., 2002). Krohelski et al. (2002) hypothesized that the increase in regional groundwater recharge may be the result of increased infiltration from snowmelt after increased snowfall and less frost-covered soil."

Field Code Changed

Commented [M7]: The authors state that Fish Lake does not always turn over completely in spring. This is an important piece of information, since in small, dark coloured boreal lakes this is a fairly common observation and it is believed that it is weather/climate driven change. It would be nice if the authors could dig deeper in this observation, especially since they have such a long time series.

Commented [M8]: Do the lakes have ice cover in winter? The ice model is repeatedly mentioned in the ms, but no results on the ice regime are presented/discussed. Duration of the ice-covered period directly affects timing of the summer stratification onset and summer hypolimnetic temperatures. Any discussion on these variables is incomplete without considering the ice regime.

~~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).~~

~~Seasonal Secchi depths were used to determine the light extinction coefficients. Lathrop et al. (1996) compiled Secchi depth data for Lake Mendota between 1900 and 1993 (1701 daily Secchi depth readings from 70 calendar years), and summarized the data for six seasonal periods: winter (ice-on to ice-out), spring turnover (ice-out to 10 May), early stratification (11 May to 29 June), summer (30 June to 2 September), destratification (3 September to 12 October), and fall turnover (13 October to ice-on). After 1993, Secchi depths are obtained from the North Temperate Lake Long Term Ecological Research (NTL-LTER) program (). For Fish Lake and Lake Wingra, Secchi depths were compiled for 1995 to the present from the NTL-LTER program. For years with no Secchi data, the long-term mean seasonal Secchi depths were used. Light extinction coefficients were estimated from Secchi depth using the equation from Williams et al., (1980):~~

$$\cancel{k = 1.1/} \qquad (1)$$

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

~~Inflow and outflow measurements were collected from gauging stations (http://waterdata.usgs.gov/wi/nwis/sw/), and complied to calculate daily totals. In cases where inflow and outflow measurements were not available, inflow and outflow were estimated as the residual unknown term of the water budget balancing precipitation, evaporation, and lake level. The residual term was distributed evenly across the number of days between water level measurements. For Lake Mendota, water level was recorded since 1916 (http://waterdata.usgs.gov/wi/nwis/dv). Water level at Fish Lake was recorded almost daily from 1966-2003 (http://waterdata.usgs.gov/wi/nwis/dv/?site_no=05406050&agency_cd=USGS&referred_module=sw). For Lake Wingra, water level was recorded sporadically during the period of interest. When lake level information was unavailable, the long-term mean lake level was assumed for water budget calculations. Only Lake Mendota has inflowing surface water streams. Inflow temperatures were estimated following the method in (Magee et al., 2016). Groundwater temperature measurements near each lake were used to estimate the temperature of groundwater fluxes.~~

Commented [M9]: Data on below-ice Secchi-depth were used which I to a certain extent understand, but since it is not that common practice to measure Secchi under the ice, it would be useful to have some more information.

Commented [MRM10R9]: Light extinction, which can be estimated from Secchi depth, greatly influences water temperatures and overall temperature profile. Including light extinction in winter more reliably reproduces under-ice water temperatures and as a result, water temperatures at the time of ice-off. Temperature profiles at ice-off impact the timing of stratification and the hypolimnetic water temperature through the summer, so properly characterising and capturing these phenomena in the model enable a more accurate reproduction of water temperatures during the historical period. For this study, the authors choose to utilize the available data from previous ecological and water quality studies conducted on the lakes to better inform the model and more accurately reproduce water temperature profiles.

Commented [M11]: Fish Lake and Lake Wingra have Secchi-depth results only from 1995 onwards. This appears problematic; could you give more explanation on this?

Commented [MRM12R11]: Fish Lake and Lake Wingra became part of the NTL-LTER program in 1995 and regular Secchi depth measurements were taken starting then. The authors agree with Reviewer 1 that it is not ideal to use seasonal averages for the historical period before 1995; however, given the strongly seasonal dynamic of water clarity and light extinction in the lakes, using seasonal averages of Secchi depth to estimate light extinction are preferably to a constant light extinction for the lakes, which is not representative of observed phenomenon in the lakes. The authors have added comments about the uncertainty and errors caused by this assumption in the discussion.

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

2.2~~3~~ Model description

To hindcast water temperature and stratification in the three study lakes we use ~~The~~the vertical heat transfer model, DYRESM-WQ (DYnamic REservoir Simulation Model-Water Quality; Hamilton and Schladow, 1997), ~~model (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). ~~A one-dimensional layer structure is adopted based on the vertical density stratification over horizontal density variations and destabilizing forces such as wind stress and surface cooling abbreviated to ensure a one dimensional structure (Antenucci and Imerito, 2003).~~ Surface layer mixing is based on potential energy required for mixing, and introduction of turbulent kinetic energy through convective mixing, wind stirring, and shear mixing (Imerito, 2010; Yeates and Imberger, 2003). ~~Mixing and surface layer dynamics depend on a turbulent kinetic energy budget and potential energy required for mixing (Hamilton and Schladow, 1997; Sherman et al., 1978).~~ Yeates and Imberger (2003) improved performance of the surface mixed layer routine within the model by including an effective surface area algorithm (see Eq 32 in Yeates and Imberger, 2003) that reduced surface mixing in smaller, more sheltered lakes. Details of the surface mixed layer algorithm are not reproduced here, but can be found in Eq 27-34 of Yeates and Imberger (2003). Hypolimnetic mixing is parameterized through a vertical eddy diffusion coefficient, which accounts for turbulence created by the damping of basin-scale internal waves on the bottom boundary and lake interior (Yeates and Imberger, 2003). Detailed equations ~~More information~~ on the

Commented [M13]: I find it strange that in a paper where models are such an elemental part, they are not properly described; besides the equation of light extinction, the authors only use references to published articles. More emphasis should also be given to description of gap filling and calibration data; both are now somewhat superficial.

Commented [M14]: The manuscript requires a more detailed description of the model and discussion on its uncertainties and relevance to the real lake processes.

simulation of water temperature and mixing can be found in Imberger and Patterson (1981), Imerito (2010), and Yeates and Imberger (2003).

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

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

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

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

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

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

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

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

Model inputs include lake hypsography, initial vertical profiles for water temperature and salinity, Secchi depth, meteorological variables, and inflows/outflows. The model calculates the surface heat fluxes using meteorological variables: total daily shortwave radiation, daily cloud cover, air vapor pressure, daily average wind speed, air temperature, and precipitation. During the entire simulation period, all parameters and coefficients are kept constant. ~~The time step in the model for calculating w~~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 ~~was~~ is computed based on ~~the~~ lake latitude and the Julian day. Parameters relevant to the open water period are provided in Table 2. Ice cover model parameters can be found in Hamilton et al. (in review), Magee and Wu (2016), and Magee et al., (2016). ~~Model parameters and simulation specifications are identical for all three study lakes and can be found in Table 1 of Magee et al. (2016).~~ Simulations were run ~~After calibrating the model, we run the simulation period~~ for all three lakes ~~over 104 years,~~ starting on 7 April 1911 and ending on 31 October 2014 without termination.

Commented [M15]: Provide model parameters and simulation specifications here

2.3 Data

Commented [M16]: Do the lakes have ice cover in winter? The ice model is repeatedly mentioned in the ms, but no results on the ice regime are presented/discussed. Duration of the ice-covered period directly affects timing of the summer stratification onset and summer hypolimnetic temperatures. Any discussion on these variables is incomplete without considering the ice regime.

2.3.1 Lake morphometry

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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

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

2.3.3 Light extinction coefficient

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Seasonal Secchi depths were used to determine the light extinction coefficients. Lathrop et al. (1996) compiled Secchi depth data for Lake Mendota between 1900 and 1993 (1701 daily Secchi depth readings from 70 calendar years), and summarized the data for six seasonal periods: winter (ice-on to ice-out), spring turnover (ice-out to 10 May), early stratification (11 May to 29 June), summer (30 June to 2 September), destratification (3 September to 12 October), and fall turnover (13 October to ice-on). After 1993, Secchi depths are obtained from the North Temperate Lake Long Term Ecological Research (NTL-LTER) program (https://portal.lternet.edu/nis/home.jsp#). Open water and under-ice Secchi depths were collected for various long-term ecological research studies, including the NTL-LTER study, and used here to better characterize temperature profiles throughout the year including under ice cover. Secchi depth data for Fish Lake and Lake Wingra were available only from

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Commented [MRM18R17]: Light extinction, which can be estimated from Secchi depth, greatly influences water temperatures and overall temperature profile. Including light extinction in winter more reliably reproduces under-ice water temperatures and as a result, water temperatures at the time of ice-off. Temperature profiles at ice-off impact the timing of stratification and the hypolimnetic water temperature through the summer, so properly characterising and capturing these phenomena in the model enable a more accurate reproduction of water temperatures during the historical period. For this study, the authors choose to utilize the available data from previous ecological and water quality studies conducted on the lakes to better inform the model and more accurately reproduce water temperature profiles.

1995 to the present and collected from the NTL-LTER program. For years with no Secchi data, the long-term mean seasonal Secchi depths were used. Light extinction coefficients were estimated from Secchi depth using the equation from Williams et al. (1980):

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

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

2.3.4 Meteorological data

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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

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

2.3.6 Observation data

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

2.4 Model calibration and evaluation

Model calibration consisted of two processes: (1) closing the water balance to match simulated and observed water levels and (2) adjusting the minimum water level thickness to match simulated and observed water temperatures for each lake. Water balance for all three lakes was closed using the method described in Section 2.3.5 to match measured water levels to known values and to long term average water levels when elevation information was unknown. Model evaporation rates were not validated; we assume that evaporative water flux and heat flux were properly parameterized by the model. ~~Using known inflows, outflow, and water elevation, the water balance was closed in the method described in Section 2.2 to match measured water levels where known and long term average water levels when elevation information was unknown. We assumed that evaporative water flux and heat flux were properly parameterized by the DYRESM-WQ-I model, although we did not validate model evaporation rates.~~ Model parameters were derived from literature values (Table 2). ~~Parameters used in the model were derived from literature values (Table 1; Magee et al., 2016) with the exception of estimation of a variable light extinction coefficient calculated from observed Secchi depth (see Sect. 2.2) and adjustment of the minimum layer thickness.~~ To calibrate water temperature, minimum layer thickness was varied from 0.05 to 0.5 m in intervals of 0.025 m for the period 1995-2000 for all three lakes, similar to the method in Tanentzap et al. (2007) and Weinburger and Vetter (2012). One minimum layer thickness was chosen for all three lakes, and the final thickness was chosen to be 0.125 m as it minimized the overall deviation between simulated and observed temperature values for the three lakes.

Three statistical measures were used to evaluate model output against observational data (~~Table 2~~Table 3): absolute mean error (AME), root mean square error (RMSE), and Nash-Suttcliffe efficiencies (NS) were used to compare simulated and observed temperature values for volumetrically-averaged epilimnion temperature, volumetrically-averaged hypolimnion temperature, and all individual water temperature measurements for unique depth and sampling time combinations. Simulated and observed values are compared directly, ~~with the exception of~~except for aggregation of water temperature measurements to daily intervals where sub-daily intervals are available. Water temperatures were evaluated for the full range of available data on each lake.

2.5 Analysis

~~In this study,~~ Modelling results were analysed using linear regression, ~~a~~ 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 ~~over the study period~~ 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. ~~Finally, the c~~Coherence of lake variables (Magnuson et al., 1990) for each lake and between ~~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.

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

~~In this study, the surface mixed layer depth was determined by using LakeAnalyzer analysis (Read et al., 2011). We quantified the resistance to mechanical mixing due to the potential energy in the stratified water column as the average summer (15 July to 15 August) Schmidt number for each lake based on Idso's version of Schmidt Stability (Idso, 1973). Linear regression was used to determine the trend of long-term changes in lake variables~~. ~~Breakpoints in variables over the study period 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. Finally, the coherence of lake variables (Magnuson et al., 1990) between lake pairs was determined with a Pearson correlation coefficient (Baron and Caine, 2000).~~

3 Results

3.1 Changes in air temperature and wind speed

~~Both y~~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 ~~over the period~~from 1911−2014 (Fig.~~ure~~ 2a~~). Yearly air temperature increased at a rate of 0.145°C decade^{-1} (p<0.01); winter air temperature increased at a rate of 0.225°C decade-1 (p<0.01); spring air temperature increased at a rate of 0.165°C decade^{-1} (p<0.01); summer air temperature increased at a rate of 0.081°C decade^{-1} (p<0.05); and fall air temperature increased at a rate of 0.110°C decade-1 (p<0.05).~~ Additionally, ~~All five sets of data were further analysed for significant changes in slope and for abrupt changes in mean. Y~~yearly average air temperature, but not seasonal temperatures, showed a significant change in slope ~~from 0.081°C decade^{-1} to 0.334°C decade^{-1}~~ occurring in 1981, and summer air temperatures showed three significant abrupt changes in mean value (Fig. 2a). Yearly (-0.073 m s^{-1} decade^{-1}; p<0.01) and seasonal average (winter: -0.083 m s^{-1} decade^{-1}; spring -0.071 m s^{-1} decade^{-1}; summer: -0.048 m s^{-1} decade^{-1}; fall: -0.088 m s^{-1} decade^{-1}; p<0.01) wind speeds decreased from 1911-2014 (Fig. 2b). ~~Wind speeds for both yearly and seasonal average exhibited significant decreased in trend over the period 1911−2014 (Figure 2b). Yearly wind speed decreased at a rate of 0.073 m s^{-1} decade^{-1} (p<0.01); winter decreased at a rate of 0.083 m s^{-1} decade^{-1} (p<0.01); spring decreased at a rate of 0.071 m s^{-1} decade^{-1} (p<0.01); summer decreased at a rate of 0.048 m s^{-1} decade^{-1} (p<0.01); and fall decreased at a rate of 0.088 m s^{-1} decade^{-1} (p<0.01).~~ 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. ~~Additionally, all five sets of wind speed data showed statistically significant abrupt changes in the mean value occurring in the mid-nineties. For yearly average wind speed, a shift from 4.43 m s^{-1} to 3.74 m s^{-1} (p<0.01) occurred after 1994; for winter wind speeds, a shift~~

Commented [M19]: I find it a bit strange that sediment heat fluxes were hardly mentioned in this paper. Although there may have been no data on this or these fluxes were not included in models, they should have been tackled somehow at least in "discussion'

Commented [M20]: My major concern is with analysis of the results, which looks superficial, and representation of the outcomes, which is lengthy and poorly structured. The analysis is confined to descriptive presentation of model outcomes without any insight into the physical mechanisms producing the observed effects. Verbal presentation of trends in lake thermal characteristics covering several paragraphs is exhausting and not really informative.

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~~from 4.72 m s^{-1} to 3.92 m s^{-1} (p<0.01) occurred after 1997; for spring wind speeds, a shift from 4.59 m s^{-1} to 3.90 m s^{-1} (p<0.01) occurred after 1996; for summer, a shift from 3.70 m s^{-1} to 3.66 m s^{-1} (p<0.01) occurred after 1994; and for fall, a shift from 4.64 m s^{-1} to 3.75 m s^{-1} (p<0.01) occurred after 1994.~~

3.2 Model evaluation

~~Model output including epilimnetic~~Simulated temperatures agreed well with observations for all three lakes (Fig. 3, Table 3). ~~(Table 2), hypolimnetic (Table 2), and temperature at 1 m intervals (Figure 3; Table 2) for the three study lakes compared well with observations.~~ 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~~ for the variables~~. NS efficiencies were high (>0.85) and most above 0.90, indicating high model accuracy.

3.3 Summer ~~W~~water temperatures

~~Epilimnion for Lake Mendota (Figure 4a) and Fish Lake (Figure 4b) were defined as 0-10 m depth and 0-5 m depth, respectively, based on the surface mixed layer depth from observation and model data using LakeAnalyzer analysis (Read et al., 2011). For Lake Wingra (Figure 4c), the whole water column was "epilimnetic" because the lake did not stratify during the summer months. Lake Mendota temperatures ranged from 19.65°C to 26.1°C (mean (M) = 22.8°C, standard deviation (SD) = 1.07°C, range (R) =6.4°C); Fish Lake temperatures ranged from 25.8°C to 19.0°C (M = 22.5°C, SD = 1.3, R = 6.7); Lake Wingra temperatures ranged from 27.5°C to 20.6°C (M = 23.8, SD = 1.27, R = 6.9).~~ Lake Mendota ~~-~~and Lake Wingra had similar increasing epilimnetic water temperature trends~~ of 0.069°C decade^{-1} and 0.079°C decade^{-1}, respectively~~, while Fish Lake ~~-~~had a larger ~~trend~~ increase~~ of 0.138°C decade^{-1}~~ (~~Table 3~~Table 4). All three lakes have statistically significant (p<0.01) abrupt changes in mean ~~values~~ epilimnion temperatures over the study period. For Lake Mendota, ~~there is an abrupt change after~~a change occurs after 1930 from 22.09 °C to 22.99 °C. For Fish Lake ~~there are three shifts~~three changes were detected: first after 1934 from 21.68°C to 22.50°C, ~~then~~ after 1995 from 22.50°C to 24.26°C, ~~and finally in~~after 2008 from 24.26°C to 22.14°C. ~~For Lake Wingra, there is an abrupt change after~~Lake Wingra has an abrupt change after 1930 from 23.13°C to 24.02°C.

Lake Mendota and Fish Lake hypolimnions ~~Hypolimnetic water temperatures for Lake Mendota (Figure 4d) and Fish Lake (Figure 4e)~~ were defined as 20−25 m and 13−20 m, respectively, based ~~upon~~ on the long-term bottom depth of the metalimnion. ~~long term bottom of metalimnion depth calculated using LakeAnalyzer (Read et al., 2011). Hypolimnetic water temperatures for Lake Mendota ranged from 8.3°C to 16.7 °C (M = 12.2°C, SD = 1.7 °C, R = 8.4 °C); Fish Lake temperatures ranged from 5.8°C to 13.8°C (M = 8.6°C, SD = 1.3°C; R = 8.0°C). Opposite to those of the epilimnion,~~Lake Mendota has a larger decrease in hypolimnetic temperature than Fish Lake (Table 4), and neither has ~~Lake Mendota and Fish Lake both experienced statistically significant decreases in summer-time hypolimnetic water temperatures of 0.131°C decade^{-1} and 0.083°C decade^{-1}, respectively (Table 3). Neither lake has~~ an ~~significant~~ 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).~~The hypolimnetic heating from 15 July to 15 August was also calculated (Table 3), showing a range from 0.04 °C to 2.3°C (M = 0.84°C, SD = 0.37°C, R = 2.2°C) for Lake Mendota and a range from 0.17°C to 0.72°C (M = 0.48, SD = 0.11, R = 0.50) for Fish Lake. Neither lake has a significant abrupt change in temperature nor a significant breakpoint in linear trend during the study period.~~

3.4 Stratification and stability

~~In this paper, summer~~We characterize summer stratification by ~~stratification was characterized by 3 variables:~~ stratification onset, fall overturn, and duration of stratification (Fig. 5). ~~The dates of o~~Onset of stratification and fall turnover were defined as the day when the surface-to-bottom temperature difference was greater than (for stratification) or less than (for overturn) 2°C (Robertson and Ragotzkie, 1990). Lake Wingra experienced only short-term stratification (timescale of days-weeks) and is excluded from this analysis. ~~Since Lake Wingra did not experience seasonal stratification, only Lake Mendota and Fish Lake are considered here.~~

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

~~For stratification onset, Lake Mendota (Figure 5a) ranged from 15 April to 28 June (M = 20 May; SD = 15 days; R = 74 days) and Fish Lake (Figure 5b) ranged from 19 March to 14 May (M = 24 April, SD = 8.2 days, R = 56 days). For fall overturn, Lake Mendota (Figure 5a) ranged from 31 July to 17-October (M = 21 September; SD = 11.4 days; R = 78 days) and Fish Lake (Figure 5b) ranged from 9 September to 6 November (M = 15 October, SD = 11.0 days, R = 56 days). Stratification duration for Lake Mendota (Figure 5c) ranged from 52 days to 165 days (M = 124.7, SD = 22.8, R = 113) and for Fish Lake (Figure 5d) ranged from 142 days to 203 days (M = 173.9, SD = 13.7, R = 61). Both lakes experienced earlier stratification onset, later fall overturn, and longer stratification duration, with Lake Mendota having larger trends in all 3 variables (Table~~

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~~3). For both lakes, there was a statistically significant (p<0.01) change in the long term mean of 13.3 days earlier occurring after 1994 for Lake Mendota and of 15.1 days earlier occurring after 1993 for Fish Lake. Stratification duration in Lake Mendota exhibited a significant change in trend from +0.067 days earlier decade^{-1} to +4.5 days earlier decade^{-1} after 1940. Similarly, stratification duration in Fish Lake exhibited a significant change in trend from 0.19 days later decade^{-1} to 9.6 days earlier decade^{-1} after 1981.~~

We quantify resistance to mechanical mixing with a Schmidt number (Idso, 1973). ~~For lake stability, Lake Wingra had an average Schmidt stability value near 0 (Figure 6), indicating that the lake was easily mixed and polymictic during the period. In contrast, both Lake Mendota and Fish Lake had significantly higher stability values (Figure 6) and both lakes were stratified and more resistant to mixing. While the shallow lake Wingra showed no trend (Table 3), Lake Mendota and Fish Lake exhibited statistically significant changes in trend.~~ Lake Mendota showed greater stability in general than Fish Lake (Fig. 6) and had a larger trend of change than Fish Lake (Table 4), possibly due to a larger change in stratification and hypolimnion temperature, increasing stability.~~Furthermore, Lake Mendota had a larger number than Fish Lake (Figure 6). A larger trend was also observed in Lake Mendota (Table 3) possibly due to both a larger change in stratification variables and changing 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). ~~The modelled surface heat fluxes (Figure 7) including (a) net shortwave radiative flux; (b) net longwave radiative flux; (c) sensible heat flux; (d) latent heat flux; and (e) total heat flux on over the 104-year period on the three study lakes are examined here.~~ Magnitude of shortwave, longwave, and sensible heat fluxes are similar for all three lakes, but Lake Wingra has a larger magnitude of both latent and net heat fluxes. Net longwave is negative for all three lakes and increased in magnitude (Table 4), and sensible heat flux decreased in magnitude (became less negative; Table 4). There is no significant trend in other surface heat flux variables. Lake Wingra has a much smaller change in trend for longwave radiation than Mendota or Fish, but a larger change in trend for sensible heat flux, indicating that depth likely influences the response of those heat fluxes to air temperature and wind speed changes.

~~While there is no statistically significant trend in shortwave flux, latent flux, or total heat flux, figure 7c shows longwave heat flux exhibits trend toward larger magnitude flux (decreasing absolute value; -5.85 J m^{-2} for Lake Mendota, -5.80 J m^{-2} for Fish Lake, and -4.59 J m^{-2} for Lake Wingra, p<0.05 for all three lakes) and sensible heat fluxes displays an increasing trend (less negative values; 4.10 J m^{-2} for Lake Mendota, 3.65 J m^{-2} for Fish Lake, and 5.65 J m^{-2} for Lake Wingra, p<0.05 for all three~~

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Commented [M25]: Some parts of the paper are also technically challenging for the reader since they are based on listing the numerical results one by one; a good example is section 3.5

~~lakes). For shortwave radiation, an abrupt change from 1.14 J m^{-2} to -4.92 J m^{-2} occurred in Lake Mendota after 1992(p<0.01); a change from -1.97 J m^{-2} to 3.34 J m^{-2} after 1945 (p<0.01) and from 3.34 J m^{-2} to -4.84 J m^{-2} after 1992 (p<0.01) for Fish Lake; and from -4.34 J m^{-2} to 4.07 J m^{-2} after 1937 (p<0.01) and from 4.07 J m^{-2} to -5.98 J m^{-2} after 1992 (p<0.01) for Lake Wingra. Net heat flux shows no significant abrupt change for Lake Mendota, two changes for Fish Lake (-0.33 J m^{-2} to 4.00 J m^{-2} after 1964, p<0.01, and 4.00 J m^{-2} to -0.55 J m^{-2} after 1975, p<0.01), and one change for Lake Wingra (-1.15 J m^{-2} to 0.28 J m^{-2} after 1930, p<0.01). For longwave radiation, multiple abrupt changes occurred in all three lakes. For Lake Mendota: -2.09 J m^{-2} to 2.54 J m^{-2} after 1923 (p<0.01), 2.54 J m^{-2} to -0.68 J m^{-2} after 1937 (p<0.01), -0.68 J m^{-2} to 2.60 J m^{-2} after 1981 (p<0.01), and 2.60 J m^{-2} to -0.86 J m^{-2} after 1998 (p<0.01). For Fish Lake: -2.23 J m^{-2} to 2.53 J m^{-2} after 1923 (p<0.01), and 2.53 J m^{-2} to 0.10 J m^{-2} after 1937 (p<0.01). For Lake Wingra: -1.98 J m^{-2} to 3.09 J m^{-2} after 1924 (p<0.01), 3.09 J m^{-2} to -0.81 J m^{-2} after 1937 (p<0.01), and -0.81 J m^{-2} to 1.42 J m^{-2} after 1981 (p<0.01). Sensible heat flux had an abrupt change after 1926 for Lake Mendota (-1.67 J m^{-2} to 0.26 J m^{-2}, p<0.01) and after 1921 for both Fish Lake (-2.23 J m^{-2} to 0.26 J m^{-2}, p<0.01) and Lake Wingra (-3.68 J m^{-2} to 0.36 J m^{-2}, p<0.01). While the timing of the abrupt change was similar in all three lakes, the magnitude of the change appears to increase with lake depth. Latent heat flux shows statistically significant (p<0.01) changes in mean after 1926 (Lake Mendota 5.78 J m^{-2} to -2.32 J m^{-2}; Fish Lake 5.43 J m^{-2} to -2.14 J m^{-2}; Lake Wingra 6.42 J m^{-2} to -2.70 J m^{-2}) and 1996 (Lake Mendota -2.32 J m^{-2} to 5.22 J m^{-2}; Fish Lake -2.14 J m^{-2} to 4.77 J m^{-2}; Lake Wingra -2.70 J m^{-2} to 6.20 J m^{-2}) for all three lakes. Abrupt changes in latent heat flux appear to be independent of lake morphometry, suggesting that the timing of change may be primarily driven by climate. Net heat flux shows no significant abrupt change for Lake Mendota, two changes for Fish Lake (-0.33 J m^{-2} to 4.00 J m^{-2} after 1964, p<0.01, and 4.00 J m^{-2} to -0.55 J m^{-2} after 1975, p<0.01), and one change for Lake Wingra (-1.15 J m^{-2} to 0.28 J m^{-2} after 1930, p<0.01). Differences in magnitude and timing of abrupt changes in shortwave, longwave, and net heat fluxes emphasize that morphometry may play a role, it is unclear how or what the specific role may be.~~

3.6~~4.2~~ Coherence between lake pairs ~~among lakes~~

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

Commented [M26]: How lake morphometry can affect the shortwave flux of solar radiation??

Commented [MRM27R26]: The shortwave flux is the net flux at the surface of each lake, which is controlled in part by albedo of the surface water and whether the lake is ice or snow covered, so each lake may have slightly different net shortwave radiative flux for each day and average for the year.

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.

~~Epilimnetic temperature exhibited high coherence for the three lake pairs (Table 4), suggesting that inter-annual variability in epilimnion temperatures was primarily driven by climate drivers such as air temperature and wind speed. Specifically, the Mendota/Wingra pair has the highest correlation and Mendota and Wingra differ significantly in both depth and surface area. Furthermore, comparing the Mendota/Fish pair with similar depth and the Fish/Wingra pair with similar surface area suggests that both surface area and depth impact coherence between lake pairs; and surface area differences may drive asynchronous patterns to a greater extent than does depth differences for epilimnetic water temperature. The lower correlation for the Mendota/Fish and Fish/Wingra pairs of lakes may be due to the difference in abrupt changes for Fish Lake epilimnion temperature in comparison to the other two lakes. Likely, the large change in lake depth from the period 1966–2001 (Krohelski et al., 2002) may be impacting the coherence between Fish Lake and the other two lakes, which have had relatively little year-to-year variation in water levels over the study period.~~

~~Hypolimnion temperature, different from epilimnion temperature, showed only moderate coherence for the Lake Mendota and Fish Lake pair (Table 4), suggesting that inter-annual variability in hypolimnion water temperatures was driven in part by factors other than climate, such as lake morphometry. For example, differences in thermocline depth (~10 m in Lake Mendota and ~6 m in Fish Lake) can play a role in filtering the climate signals into the hypolimnion temperature. This result is consistent with other studies that show lake morphometry parameters affect the time of climatic signals, especially temperature stored in the lake system (Thompson et al., 2005). Other factors like strength of stratification and fetch differences may drive differences in the timing of stratification, further affecting hypolimnetic temperatures. Moreover, Arvola (2009) showed that hypolimnia temperatures were primarily determined by the conditions that pertained during the previous spring turnover. In our study, the relatively low hypolimnetic coherence (Table 4) suggests that lake morphometry plays a role in hypolimnion temperatures.~~

~~Coherence for stratification onset and fall overturn dates were low for the Mendota/Fish Lake pair (Table 4), suggesting that surface area, not air temperature or wind speed, was the main factor driving differences in stratification onset and overturn. Schmidt stability showed high coherence for the Mendota/Fish lake pair, but low coherence between the Wingra/Fish and Mendota/Wingra lake pairs, suggesting that lake depth drives differences in coherence, while surface area has a lesser role. High coherence between the Mendota/Fish pair suggests that climate drives stability when comparing lakes of similar depth. Low coherence between the other two pairs suggests that lakes with different depths may have asynchronous behavior. Slightly lower coherence for the Mendota/Wingra pair than the Wingra/Fish pair suggests that lake surface area may also play a minor role in asynchronous behavior.~~

Commented [M28]: Schmidt stability is irrelevant to non-stratified lakes and cannot be used for comparison

Commented [MRM29R28]: Lake Wingra does stratify on daily or weekly timescales during the summer months (Kimura et al, 2016). Summer Schmidt stability was calculated at daily timescales, and then averaged for each year before comparing coherence among the lake pairs. Higher average stability for one year on Lake Wingra would indicate that the lake experienced more days of stratification during the period

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.

~~4.3~~3.8 Sensitivity to changes in air temperature and wind speed

~~To determine the sensitivity of lake water temperature and stratification in response to air temperature and wind speed, we perturbed these drivers across the range of -10°C to +10°C in 1°C temperature increments and 70% to 130% of the historical value in 5% increments, respectively. For each scenario, meteorological inputs remained the same as for the original simulation and snowfall (rainfall) conversion if the air temperature scenarios increase (decrease) above 0°C. Similarly, the water balance is maintained so that the long-term water levels in both lakes matches the historical record.~~ Response~~ults~~ of stratification onset, fall overturn, and hypolimnetic temperature to air temperature and wind speed perturbation scenarios for Lake Mendota and Fish Lake are discussed in the following. Other variables are omitted for brevity and Lake Wingra did not experience prolonged stratification under any sensitivity scenarios, so are excluded from the analysis. ~~lake response to all perturbation scenarios will be discussed in the following.~~

~~4.3.1 Stratification onset~~

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

Commented [M30]: Sensitivity runs can be shortened, at least, to a half and moved from 'Discussion' to 'Results'. The actual discussion should be added, considering the reasons for the observed dependencies, their relevance to the processes in real lakes and novelty of the results compared to the state-of-the-art in this area of research.

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 changes in temperature, while Fish Lake changes nonlinearly at a rate of +1.81 days °C^{-1} for temperature increases and -0.77 days °C^{-1} for temperature decreases from the historical condition. Standard deviation in overturn dates decreased slightly for Lake Mendota as air temperature increase, but remains consistent for Fish Lake. Both lakes have nonlinear increases in fall overturn dates with decreasing wind speed. For Lake Mendota, the change is +13.9 days (m s^{-1})$^{-1}$ for 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 decreases and -8.5 days (m s^{-1})$^{-1}$ for wind speed increases. Like onset dates, variability in overturn dates decreases with lower wind speeds and increases with higher wind speeds.

For both lakes, increases in air temperature increase hypolimnetic temperatures, while decreases in wind speed decrease temperatures (Fig. 11). Simulations show that the response of median hypolimnetic temperatures to changes in air temperatures is linear for Lake Mendota (+0.18°C$_{hypolimnion}$ C$_{air\ temperature}$$^{-1}$), but nonlinear for Fish Lake (+0.25°C$_{hypolimnion}$ C$_{air\ temperature}$$^{-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 non-linearly with wind speed perturbations for both lakes. For Lake Mendota, the change is -1.1°C (m s^{-1})$^{-1}$ for decreases and +1.8°C (m s^{-1})$^{-1}$ for wind speed increases. For Fish Lake, the change is -1.2°C (m s^{-1})$^{-1}$ for decreases and +0.8°C (m s^{-1})$^{-1}$ for wind speed increases. Variability decreases for lower wind speeds in Lake Mendota, but remains constant for Fish Lake.

~~For both Lake Mendota and Fish Lake (Figure 8a and b), increasing (decreasing) air temperature resulted in earlier (later) stratification onset. Lake Mendota exhibited a linear trend of 2.0 days earlier (later) stratification for each degree (C) increase (decrease) in air temperature. Fish Lake, however, shows a nonlinear change in stratification onset with changes in air temperatures of 1.5 days earlier stratification for each degree (C) increase in air temperature but 2.7 days later stratification for each degree (C) decrease in air temperature from the historical condition. Standard deviations in stratification onset on Lake Mendota remained fairly consistent, ranging from 15.5 to 18 days. In contrast, the standard deviation in stratification onset for Fish Lake decreased from 17.5 days to 12 days as air temperature increased. This may be due to an early limit in stratification onset for Fish Lake, thus reducing the variability of onset dates with increasing air temperatures. The above results suggest that lake surface area can complicate the response of stratification onset to changes in air temperatures. For both Lake Mendota and Fish Lake (Figure 8c and d), decreased (increased) wind speed results in earlier (later) stratification onset, however the change is nonlinear. For Lake Mendota each 1m s^{-1} decrease in wind speed results in 3.4 days earlier stratification onset and each 1m s^{-1} increase in wind speed results in 10.5 days later stratification onset; meanwhile, Fish Lake shows 3.6 days earlier stratification onset for each 1m s^{-1} decrease in wind speed and 8.1 days later stratification onset for each~~

Commented [M31]: Using wording 'increasing (decreasing)' is clumsy for the reader

Commented [MRM32R31]: The authors thank the reviewer for this comment, and we have edited the text to make the writing clearer for readers.

~~1m s^{-1} increase in wind speed. Standard deviations in both lakes see large decreases (increases) with decreasing (increasing) wind speed. Standard deviation changes from 20 days at 130 % of historical wind speed to 12 days at 70% of historical wind speed for Lake Mendota and from 15.6 days at 130 % of historical wind speed to 8.7 days at 70 % of historical wind speed for Fish Lake. As wind speed decreases (increases), the likelihood of the wind-induced kinetic energy being sufficient to mix the lake also decreases (increases). Additionally, the number of higher wind events is decreased (increased) under this scenario, leading to less (more) kinetic energy available to mix the lake later (earlier) in the season. The change in stratification onset date for both lakes is nonlinear, but Lake Mendota experiences a greater difference between decreasing and increasing wind speeds due to the large surface area of the lake increasing the nonlinear response of thermal structure to wind speed changes. Additionally, standard deviations are much larger for Lake Mendota because the large fetch of the lake causes greater variability in wind stress than for the smaller Fish Lake.~~

~~4.3.2 Fall overturn~~

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~~Lake Mendota (Figure 9a) shows a linear change in stratification overturn such that as air temperature increases (decreases) stratification overturn is 0.68 days later (earlier) with each degree (C) increase (decrease) in air temperature. For Fish Lake (Figure 9b), the change is nonlinear, with increases in air temperature causing a 1.81 days later change in stratification overturn for each degree (C) increase in air temperature, but a changes of only 0.77 day per degree (C) for decreases in air temperature from the historical condition. Standard deviation for Lake Mendota slightly decreased from 14 days to 11 days as air temperature increased from -8°C to +8°C change from the historical condition, and Fish Lake had a consistent standard deviation of 13 days (±0.75 days). Overall, for lakes with different surface areas, it appears air temperature changes have a limited impact on the variability of the stratification overturn dates to changing climate, and a larger impact on the average date of stratification overturn. For wind speed perturbations, both lakes show a nonlinear change for later (earlier) stratification overturn with decreases (increases) in wind speed. For Lake Mendota (Figure 9c), decreases in wind speed cause a change of 13.9 days later with each 1 m s^{-1} decrease in wind speed and a change of 17.1 days earlier with each 1 m s^{-1} increase in wind speed. For Fish Lake (Figure 9d), decreases in wind speed cause a change of 16.4 days later with each 1 m s^{-1} decrease in wind speed and a change of 8.5 days earlier with each 1 m s^{-1} increase in wind speed. This result suggests that lakes with large surface area, such as Lake Mendota are more sensitive to changing stratification overturn dates as wind speed decreases (increases) than lakes with smaller surface areas. As with stratification onset, decreasing (increasing) wind speeds decrease (increase) variability in overturn dates (27.6 to 10.6 days for Lake Mendota and 15.1 to 9.2 for Fish Lake). Fish Lake may have a much smaller change in standard deviation than for Lake Mendota because wind speed is a more dominant driver in Mendota than in Fish Lake, due to the difference in surface area between the two lakes.~~

4.3.3 Hypolimnetic water temperature

For Lake Mendota (Figure 10a), each degree (C) increase (decrease) in air temperature resulted in a linear change of 0.18°C increase (decrease) in hypolimnetic temperature. For Fish Lake (Figure 10b), increases in air temperature over the historical result in a water temperature increase of 0.25°C for each degree (C) of air temperature increase, and decreases in air temperature result in a water temperature decrease of 0.18°C for each degree (C) of air temperature decrease. Standard deviations for Lake Mendota and Fish Lake remain consistent with increasing (decreasing) temperature and range from approximately 2.3°C to 2.7°C for Lake Mendota and from 1.7°C to 2.2°C for Fish Lake. Changes in air temperature alter the mean hypolimnetic temperature in both lakes, but does not affect the variability of hypolimnetic temperatures. For wind speed, Lake Mendota (Figure 10c) experiences a nonlinear change in hypolimnetic temperature such that for decreasing wind speed, the water temperature decreases at a rate of 1.1°C for each m s^{-1} decrease in wind speed and for increasing wind speed, the water temperature increases at a rate of 1.8°C for each m s^{-1} increase in wind speed. For Fish Lake (Figure 10d), the hypolimnetic temperature also shows a nonlinear change; the water temperature decreases at a rate of 1.2°C for each m s^{-1} decrease in wind speed and for increasing wind speed, the water temperature increases at a rate of 0.8°C for each m s^{-1} increase in wind speed. Standard deviation in Lake Mendota decreased (increased) with decreasing (increasing) wind speeds, changing from 2.6°C at 130 % of historical wind speed to 1.8 °C at 70 % of historical wind speeds, but standard deviation in Fish Lake remained fairly constant over the perturbation scenarios, ranging from 1.3°C to 1.6°C. This indicates that wind speed changes have a much larger impact on the variability of hypolimnetic temperatures for the larger surface area lake than for smaller surface area lake. Overall, the above results of the increasing temperature perturbation show increasing hypolimnetic water temperature, while decreasing wind speed perturbations show decreasing hypolimnetic water temperatures. Historical climate (Figure 4d and 4e) indicate that hypolimnetic temperatures are decreasing. 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. For example, in Lake Mendota, a 5% decrease in wind speed will offset the impacts to hypolimnetic temperature of a 1°C increase in air temperature, while in Fish Lake, a 12-13% decrease in wind speed is necessary to offset the effects of a 1°C increase in air temperature. In other words, lakes with larger surface areas that also experience decreasing wind speeds may be more resilient to changing hypolimnion temperatures as a result of warmer air temperatures.

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4 Discussion

4.1 Model performance and comparison

The DYRESM-WQ-I~~CE~~ model reliably simulated water temperatures over long-term (1911-2014) simulations (Figure 3, ~~Table 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. ~~Deviation between measurement and observed temperatures was attributed to the input averaging, particularly daily averaging of air temperature and wind speed.~~ 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. ~~Discrepancies between modelled and measured values came in part from differences in location and sampling frequency of observations. Errors in water temperature were attributed to differences between simulated and observed thermocline depth over some years. In general, thermocline depths were within 1 m between observed and simulated, but some years differ by as much as 2.5 m.~~

T~~Overall, t~~he performance of the DYRESM-WQ-I~~CE~~ model was ~~similar to~~within those of ~~that of~~ other studies ~~in the literature~~. Perroud et al. (2009) performed a comparison of one-dimensional lake models on Lake Geneva, and RMSE for water temperatures were as high as 2°C for the Hostetler model (Hostetler and Bartlein, 1990), 1.7°C for DYRESM (Tanentzap et al., 2007), 2°C for SIMSTRAT, and 4°C for Freshwater Lake (FLake) model (Golosov et al., 2007; Kirillin et al., 2012). Similar to this study, errors in the upper layers were lower than those in the bottom of the water column ~~For all four models, errors were lower in the upper layers and larger in the bottom of the water column~~ (Perroud et al., 2009). ~~, similar to errors found in this study.~~ 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 found here~~to those here. ~~Results of~~ 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 ~~(Hostetler and Bartlein, 1990)~~, Minlake (Fang and Stefan, 1996), and General Lake Model (GLM; Hipsey et al., 2014) ~~models~~ for Harp Lake, Ontario, Canada water temperatures.

Model parameters used to characterize the lake hydrodynamics were taken from literature values. These values may be expected to have small variability between lakes; however, previous studies have shown that many of the hydrodynamic parameters are insensitive to changes of ±10% (Tanentzap et al., 2007). Here the model was validated against an independent dataset for each lake to determine if the model fits measured data and functions adequately, with errors within the range of

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Commented [M35]: Effects of lake surface area on the response to the atmospheric forcing are continuously mentioned throughout the manuscript and are among the main subjects of the model sensitivity runs. However, the entire discussion is based on the outputs of a one-dimensional model, i.e. none of the physical processes depending on the horizontal dimensions are modelled directly, but parameterized in the model. Hence, the response of the model outcomes to varying surface area does not necessarily coincide with the response of real lakes to the same perturbations. To analyse properly the modelling results the authors need to (i) present the details on the model parameterizations related to the effects of horizontal advection, wind fetch, horizontally varying depth, and other horizontal processes, such as mixing by internal waves and upwelling of hypolimnetic waters in near-shore areas of the lake; (ii) when discussing the modelling results state clearly which of them can be extrapolated on the real lakes, which horizontal processes are missed by the model, and how it can affect the real situations; (iii) differentiate be-tween the effects produced by increase of the wind energy input due to larger surface area from those produced by increase of the thermal inertia due to larger lake volume, like, in particular, timing of the stratification onset (Section 4.3.1)

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those from other studies. Adjustments were made to limit uncertainty and errors associated with changes in location and techniques of meteorological measurements. Inflow and outflow measurements were assessed by the USGS for quality assurance and control, but uncertainty for both quantity and water temperature is unknown. The effects of these uncertainties may not be large as the inflow and outflow are small in comparison to lake volume. The combination of uncertainties in parameters and observed data may be high; however, as all parameters and observational methods were kept consistent among the three lakes, the validity of the model in predicting differences among the three lake types is adequate.

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

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

~~Limitations in the model and simulations presented here arise from uncertainties in observations and model parameters and the assumption of one-dimensionality in both the model and field data. Quantifying this type of uncertainty is extremely difficulty (Gal et al., 2014; Tebaldi et al., 2005). Generally, small, stratified lakes 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); spatial variations in wind stress can produce horizontal variations in temperature profiles (Imberger and Parker, 1985). Neither of which are captured in the one-dimensional model approach nor by the collection of observation data at a single in-lake location. Futhermore, light extinction estimated from Secchi depths can have a large degree of measurement uncertainty (Smith and Hoover, 2000), leading to uncertainty in water temperature simulations (Hocking and Straškraba, 1999). Locations and techniques of meteorological measurements changed at various times throughout the 104 years study period. We have made significant efforts in adjustments to limit uncertainty and errors associated with these changes. While inflow and outflow measurements were assessed by the USGS for quality assurance and control, uncertainty for both quantity and water temperature is unknown, especially in consideration of having to fill in missing data to fully simulate the time period.~~

~~Overall, the effects of many uncertainties on simulated temperatures may not be large as the inflow and outflow are small in comparison to lake volume. Model parameters used to characterize the lake hydrodynamics were taken from literature values. These values may be expected to have some small variability between lakes since previous studies have shown that many of the hydrodynamic parameters are insensitive to changes of ±10% (Tanentzap et al., 2007). the model was validated against an independent dataset for each lake to determine if the model fits measured data and functions adequately, with errors within the range of those from other studies. The combination of uncertainties in parameters and observed data may be high; however, as all parameters and observational methods were kept consistent among the three lakes, the validity of the model in predicting differences among the three lake types is adequate. We reason that the model accuracy is sufficient to meet the objectives of identifying morphometry-caused differences in lake response for both past and future climate changes.~~

~~4.2 Coherence among lakes~~

~~Temporal coherence, the similarity of lake responses over time, shows that adjacent lakes respond coherently to climate (Magnuson et al., 1990; Thompson et al., 2005). Furthermore, lakes with comparable physical features exhibit higher coherence than lakes with different physical properties (Novikmec et al., 2013). Large correlation coefficients, indicative of high temporal coherence between lakes, are largely due to synchronous patterns in lake variables driven by climate (Magnuson et al., 1990; Palmer et al., 2014). In this study, the 3 lakes were formed into 3 distinct pairs for comparing the coherence of physical lake variables. Pair 1, Lake Mendota and Fish Lake, have similar depths but different surface areas, illustrating the effects of surface area differences. Pair 2, Lake Wingra and Fish Lake, have similar surface areas, but shallow and deep water depths, addressing the effects of lake depth. Pair 3, Lake Mendota and Lake Wingra, have both differing surface areas and~~

~~water depths. Pearson correlation coefficients (Table 4) in lake variables were calculated for pairs of the study lakes. This method allows us to easily identify coherence differences that may be driven by lake surface area or lake depth while simultaneously accounting for differences in climate that may impact the results of similar analysis covering lakes over a broad region.~~

~~Epilimnetic temperature exhibited high coherence for the three lake pairs (Table 4), suggesting that inter-annual variability in epilimnion temperatures was primarily driven by climate drivers such as air temperature and wind speed. Specifically, the Mendota/Wingra pair has the highest correlation and Mendota and Wingra differ significantly in both depth and surface area. Furthermore, comparing the Mendota/Fish pair with similar depth and the Fish/Wingra pair with similar surface area suggests that both surface area and depth impact coherence between lake pairs; and surface area differences may drive asynchronous patterns to a greater extent than does depth differences for epilimnetic water temperature. The lower correlation for the Mendota/Fish and Fish/Wingra pairs of lakes may be due to the difference in abrupt changes for Fish Lake epilimnion temperature in comparison to the other two lakes. Likely, the large change in lake depth from the period 1966–2001 (Krohelski et al., 2002) may be impacting the coherence between Fish Lake and the other two lakes, which have had relatively little year-to-year variation in water levels over the study period.~~

~~Hypolimnion temperature, different from epilimnion temperature, showed only moderate coherence for the Lake Mendota and Fish Lake pair (Table 4), suggesting that inter-annual variability in hypolimnion water temperatures was driven in part by factors other than climate, such as lake morphometry. For example, differences in thermocline depth (~10 m in Lake Mendota and ~6 m in Fish Lake) can play a role in filtering the climate signals into the hypolimnion temperature. This result is consistent with other studies that show lake morphometry parameters affect the time of climatic signals, especially temperature stored in the lake system (Thompson et al., 2005). Other factors like strength of stratification and fetch differences may drive differences in the timing of stratification, further affecting hypolimnetic temperatures. Moreover, Arvola (2009) showed that hypolimnia temperatures were primarily determined by the conditions that pertained during the previous spring turnover. In our study, the relatively low hypolimnetic coherence (Table 4) suggests that lake morphometry plays a role in hypolimnion temperatures.~~
~~Coherence for stratification onset and fall overturn dates were low for the Mendota/Fish Lake pair (Table 4), suggesting that surface area, not air temperature or wind speed, was the main factor driving differences in stratification onset and overturn. Schmidt stability showed high coherence for the Mendota/Fish lake pair, but low coherence between the Wingra/Fish and Mendota/Wingra lake pairs, suggesting that lake depth drives differences in coherence, while surface area has a lesser role. High coherence between the Mendota/Fish pair suggests that climate drives stability when comparing lakes of similar depth. Low coherence between the other two pairs suggests that lakes with different depths may have asynchronous behavior. Slightly~~

lower coherence for the Mendota/Wingra pair than the Wingra/Fish pair suggests that lake surface area may also play a minor role in asynchronous behavior.

4.2 3 Sensitivity to changes in air temperature and wind speed

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

4.23.1 Stratification onset

For both Lake Mendota and Fish Lake (Figure 8a and b), increasing (decreasing) air temperature resulted in earlier (later) stratification onset. Lake Mendota exhibited a linear trend of 2.0 days earlier (later) stratification for each degree (C) increase (decrease) in air temperature. Fish Lake, however, shows a nonlinear change in stratification onset with changes in air temperatures of 1.5 days earlier stratification for each degree (C) increase in air temperature but 2.7 days later stratification for each degree (C) decrease in air temperature from the historical condition. Standard deviations in stratification onset on Lake Mendota remained fairly consistent, ranging from 15.5 to 18 days. In contrast, the standard deviation in stratification onset for Fish Lake decreased from 17.5 days to 12 days as air temperature increased. This may be due to an early limit in stratification onset for Fish Lake, thus reducing the variability of onset dates with increasing air temperatures. The above results suggest that lake surface area can complicate the response of stratification onset to changes in air temperatures. For both Lake Mendota and Fish Lake (Figure 8c and d), decreased (increased) wind speed results in earlier (later) stratification onset, however the change is nonlinear. For Lake Mendota each 1m s^{-1} decrease in wind speed results in 3.4 days earlier stratification onset and each 1m s^{-1} increase in wind speed results in 10.5 days later stratification onset; meanwhile, Fish Lake shows 3.6 days earlier stratification onset for each 1m s^{-1} decrease in wind speed and 8.1 days later stratification onset for each 1m s^{-1} increase in wind speed. Standard deviations in both lakes see large decreases (increases) with decreasing (increasing) wind speed. Standard deviation changes from 20 days at 130 % of historical wind speed to 12 days at 70% of historical wind speed for Lake Mendota and from 15.6 days at 130 % of historical wind speed to 8.7 days at 70 % of historical wind speed for Fish Lake. As wind speed decreases (increases), the likelihood of the wind-induced kinetic energy being sufficient to mix the lake also decreases (increases). Additionally, the number of higher wind events is decreased (increased) under this scenario, leading to less (more) kinetic energy available to mix the lake later (earlier) in the season. The change in stratification onset

~~date for both lakes is nonlinear, but Lake Mendota experiences a greater difference between decreasing and increasing wind speeds due to the large surface area of the lake increasing the nonlinear response of thermal structure to wind speed changes. Additionally, standard deviations are much larger for Lake Mendota because the large fetch of the lake causes greater variability in wind stress than for the smaller Fish Lake.~~

~~4.2~~3~~.2 Fall overturn~~

~~Lake Mendota (Figure 9a) shows a linear change in stratification overturn such that as air temperature increases (decreases) stratification overturn is 0.68 days later (earlier) with each degree (C) increase (decrease) in air temperature. For Fish Lake (Figure 9b), the change is nonlinear, with increases in air temperature causing a 1.81 days later change in stratification overturn for each degree (C) increase in air temperature, but a changes of only 0.77 day per degree (C) for decreases in air temperature from the historical condition. Standard deviation for Lake Mendota slightly decreased from 14 days to 11 days as air temperature increased from -8°C to +8°C change from the historical condition, and Fish Lake had a consistent standard deviation of 13 days (±0.75 days). Overall, for lakes with different surface areas, it appears air temperature changes have a limited impact on the variability of the stratification overturn dates to changing climate, and a larger impact on the average date of stratification overturn. For wind speed perturbations, both lakes show a nonlinear change for later (earlier) stratification overturn with decreases (increases) in wind speed. For Lake Mendota (Figure 9c), decreases in wind speed cause a change of 13.9 days later with each 1 m s^{-1} decrease in wind speed and a change of 17.1 days earlier with each 1 m s^{-1} increase in wind speed. For Fish Lake (Figure 9d), decreases in wind speed cause a change of 16.4 days later with each 1 m s^{-1} decrease in wind speed and a change of 8.5 days earlier with each 1 m s^{-1} increase in wind speed. This result suggests that lakes with large surface area, such as Lake Mendota are more sensitive to changing stratification overturn dates as wind speed decreases (increases) than lakes with smaller surface areas. As with stratification onset, decreasing (increasing) wind speeds decrease (increase) variability in overturn dates (27.6 to 10.6 days for Lake Mendota and 15.1 to 9.2 for Fish Lake). Fish Lake may have a much smaller change in standard deviation than for Lake Mendota because wind speed is a more dominant driver in Mendota than in Fish Lake, due to the difference in surface area between the two lakes.~~

~~4.2~~3~~.3 Hypolimnetic water temperature~~

~~For Lake Mendota (Figure 10a), each degree (C) increase (decrease) in air temperature resulted in a linear change of 0.18°C increase (decrease) in hypolimnetic temperature. For Fish Lake (Figure 10b), increases in air temperature over the historical result in a water temperature increase of 0.25°C for each degree (C) of air temperature increase, and decreases in air temperature result in a water temperature decrease of 0.18°C for each degree (C) of air temperature decrease. Standard deviations for Lake Mendota and Fish Lake remain consistent with increasing (decreasing) temperature and range from~~

~~approximately 2.3°C to 2.7°C for Lake Mendota and from 1.7°C to 2.2°C for Fish Lake. Changes in air temperature alter the mean hypolimnetic temperature in both lakes, but does not affect the variability of hypolimnetic temperatures. For wind speed, Lake Mendota (Figure 10c) experiences a nonlinear change in hypolimnetic temperature such that for decreasing wind speed, the water temperature decreases at a rate of 1.1°C for each m s^{-1} decrease in wind speed and for increasing wind speed, the water temperature increases at a rate of 1.8°C for each m s^{-1} increase in wind speed. For Fish Lake (Figure 10d), the hypolimnetic temperature also shows a nonlinear change; the water temperature decreases at a rate of 1.2°C for each m s^{-1} decrease in wind speed and for increasing wind speed, the water temperature increases at a rate of 0.8°C for each m s^{-1} increase in wind speed. Standard deviation in Lake Mendota decreased (increased) with decreasing (increasing) wind speeds, changing from 2.6°C at 130 % of historical wind speed to 1.8 °C at 70 % of historical wind speeds, but standard deviation in Fish Lake remained fairly constant over the perturbation scenarios, ranging from 1.3°C to 1.6°C. This indicates that wind speed changes have a much larger impact on the variability of hypolimnetic temperatures for the larger surface area lake than for smaller surface area lake. Overall, the above results of the increasing temperature perturbation show increasing hypolimnetic water temperature, while decreasing wind speed perturbations show decreasing hypolimnetic water temperatures. Historical climate (Figure 4d and 4e) indicate that hypolimnetic temperatures are decreasing. 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. For example, in Lake Mendota, a 5% decrease in wind speed will offset the impacts to hypolimnetic temperature of a 1°C increase in air temperature, while in Fish Lake, a 12-13% decrease in wind speed is necessary to offset the effects of a 1°C increase in air temperature. In other words, lakes with larger surface areas that also experience decreasing wind speeds may be more resilient to changing hypolimnion temperatures as a result of warmer air temperatures.~~

4.2 Importance of wind speed

While many have addressed the importance of changing air temperatures on water temperatures and water quality (e.g. Adrian et al., 2009; Arhonditsis et al., 2004; O'Reilly et al., 2015; Shimoda et al., 2011), fewer have investigated wind speed as a specific driver of changes to lakes (Magee et al., 2016; Snortheim et al., 2017). However, results here show that correlations between wind speeds and lake temperature variables are as high as, or higher than, correlations air temperature and lake temperature variables (Fig. 7), highlighting the importance of considering wind speeds as drivers of lake temperature and stratification changes. For many variables (e.g. stratification dates, epilimnetic temperatures, stability), correlation is opposite for air temperature and wind speed variables, indicating that wind speed increases may offset the effect of air temperature increases, while locations with decreasing wind speeds may experience a greater impact on water temperature and stratification than with air temperature increases alone. This is further supported through sensitivity analysis on stratification onset and overturn (Fig. 8 and 9), 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. However, for hypolimnetic temperatures, correlations and sensitivity indicate that decreasing wind speeds may cool hypolimnetic temperatures, while increasing air temperatures warm hypolimnetic temperatures. Arvola (2009) showed that hypolimnion temperatures were primarily determined by the conditions that pertained during the previous spring turnover, which is consistent with our results showing significant (p<0.01) correlation between hypolimnion temperatures and wind speed (Fig. 8), but no significant correlation with air temperature or summer conditions. This could explain the conflicting results of previous research showing both warming and cooling trends in different lakes (Gerten and Adrian, 2001). Hindcasted hypolimnion temperatures (Fig. 4) show decreasing trends for Lake Mendota and Fish Lake. Combining the effects of air temperature and wind speed, it suggests that wind speed decreases are a larger driver to hypolimnetic water temperature changes than increasing air temperatures for both lakes.

4.34 Role of morphometry on water temperature and stratification

4.~~34~~2.1 Lake depth

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

~~results show increased Schmidt Stability over the long term for Fish Lake and Lake Mendota (Table 3), but no trend in Lake Wingra. Indeed, (Kraemer et al., 2015) showed that mean lake depths can explain the most variation in stratification trends and lakes with greater mean depths have larger changes in their stability, consistent with our results for Lake Mendota and Fish Lake (Table 3). 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). 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. For radiative fluxes at the surface of the lake, shallow Lake Wingra had a similar magnitude of shortwave (Figure 7a), longwave (Figure 7b) and sensible heat (Figure 7c) fluxes as Lake Mendota and Fish Lake, but relatively larger magnitude of latent (Figure 7d) and net heat fluxes (Figure 7e). The result indicates that lake depth can play a large role in the magnitude of latent heat fluxes as shallow lakes have larger latent heat flux and thus more evaporation, possibly due to the overall warmer temperatures throughout the water column compared to lakes with cool bottom waters. Additionally, the magnitude of abrupt changes in sensible heat flux appear to be influences by water depth, with increasing depth decreasing the magnitude of shift in mean sensible heat flux after the abrupt change.~~

~~4.3~~4~~.2~~4.3.2 Surface area

Lake surface area impacts the effects of climate changes on water temperatures and stratification. ~~Lake size can alter the effects of climate changes with the increasing air temperature and decreasing wind speeds on increasing epilimnetic water temperatures in Fish Lake and Lake Mendota.~~ Air temperature is significantly correlated ($p<0.01$) with epilimnion temperature for all three lakes, as is wind speed ($p<0.05$). ~~Air t~~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 ~~emperature, responsible for heat transfer between the atmosphere and lake, is the main driver to epilimnetic water temperatures~~ (Boehrer and Schultze, 2008; Palmer et al., 2014). ~~While increasing air temperatures are well documented to increase epilimnetic water temperatures (Livingstone, 2003; Robertson and Ragotzkie, 1990), the exact~~

Commented [M37]: Evaporation depends on surface temperatures, not the deep water temperatures. Explain what do you mean in this sentence, or remove it and find another explanation for the phenomenon

Commented [M38]: Actually, the main driver for epilimnion temperatures is solar radiation not air temperature. If air temperatures is the 'main driver', what do you mean under 'wind…a more dominant mechanism?'

~~relationship is nontrivial (Robertson and Ragotzkie, 1990).~~ However, wind mixing can act as a mechanism of heat transfer ~~Wind mixing, a more dominant mechanism of heat transfer~~ (Nõges et al., 2011), and ~~, can act to dampen the effects of air temperature increase 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). ~~As a result, decreasing wind speeds increase epilimnion water temperatures (Figure 4 and Table 3).~~ Surface area plays a role in lake-wide average vertical heat fluxes from boundary processes (Wüest and Lorke, 2003), and the model accounts for this by including an effective surface area algorithm to scale transfer of momentum from surface stress based on lake surface area (Yeates and Imberger, 2003). This increases transfer momentum from surface stress and vertical heat transfer for lakes with larger fetch. Accounting for this ~~Nevertheless,~~ larger fetch increases mixing and vertical transfer of heat to bottom waters, reducing epilimnion water temperatures (Boehrer and Schultze, 2008) and increasing the rate of lake cooling (Nõges et al., 2011). For this reason, Lake Mendota with the large fetch experiences a smaller increase in epilimnetic water temperature compared to Fish Lake (Table 5). Additionally, momentum from surface stress scales linearly with lake area and non-linearly with wind speed (Yeates and Imberger, 2003, see Eq. 31 and 33), making momentum from surface stress, and thus, mixing, stratification, and hypolimnion temperatures more variable for lakes with larger fetch and even more variable when wind speed is increased (see Fig. 8-10). Greater variability in momentum and mixing corresponds to larger variability of Schmidt stability for Lake Mendota, with the larger surface area. ~~Trend and variability of Schmidt stability may also be affected by lake size. Compared with Fish Lake, Lake Mendota with a significantly larger fetch experiences greater variability in Schmidt stability that exhibits greater magnitude changes when compared to Fish Lake (Figure 6).~~ Greater transfer of momentum in Lake Mendota results in the slightly deeper thermocline for the larger surface area lake (~10 m in Lake Mendota and ~6 m in Fish Lake), which may play a role in filtering the climate signals into hypolimnion temperatures. Low hypolimnetic temperature coherence between Mendota and Fish suggest that lake morphometry plays a role. This result is consistent with other studies that show lake morphometry parameter affects the way temperature is stored in the lake system (Thompson et al., 2005). Increased momentum on Lake Mendota from the larger surface area may also limit the impact of ice off dates on stratification onset and hypolimnetic temperatures because the lake has ample momentum to sustain mixing events regardless of ice off dates, while Fish Lake's small surface area limits mixing making ice-off dates and stratification more highly correlated.

~~Sensitivity results by perturbation climate drivers indicate that lake surface area plays a role in the nonlinear response and variability of stratification onset, stratification overturn, and hypolimnetic water temperatures to changes in wind speed. The magnitude of the nonlinear change and change in variability is larger for Lake Mendota than Fish Lake. The larger surface area, and resulting larger fetch, for Lake Mendota causes the increased nonlinearity of response and increased variability. Larger fetch for Lake Mendota causes stronger wind stress on the water surface when compared to Fish Lake, and the change~~

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~~in stress with increases or decreases in wind speed is nonlinear. Larger wind speeds furthermore result in more variability of wind stress in lakes with larger surface areas and the resulting change in turbulence is also nonlinear. Results in this study indicate that lakes with larger surface areas will have a more nonlinear response to changes in wind speed than lakes with smaller surface areas for stratification onset (Figure 8), fall overturn (Figure 9), and hypolimnetic water temperature (Figure 10).~~

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. ~~Study results show for three lakes with differing morphometry, the combination of increasing air temperatures and decreasing wind speeds yields warmer epilimnion temperatures, lower hypolimnion water temperatures, earlier stratification, later fall overturn, increased stratification duration, decreased hypolimnetic heating, and increased stability.~~ Increased stratification durations and stability may have lasting impacts on fish populations (Gunn, 2002; Jiang et al., 2012; Sharma et al., 2011) and warmer epilimnion temperatures affects the phytoplankton community (Francis et al., 2014; Rice et al., 2015). Shallow lakes respond more directly to changes in climate, which drives differences in surface heat flux compared to deeper lakes, and wind speed may be a larger driver to temperature structure than air temperatures, with importance of air temperatures increasing as lake depth increases. Larger surface area lakes have greater wind mixing, which influences differences in temperatures, stratification, and stability. Climate perturbations indicate that larger lakes have more variability in temperature and stratification variables than smaller lakes, and this variability increases with greater wind speeds. ~~Results indicate that over the historical climate, smaller surface area influences wind mixing, while larger and deeper lakes appear to respond more readily to changes in climate. Additionally, differences in stability between the larger Lake Mendota and smaller Fish Lake suggest that stability in lakes with larger surface areas are more variable than those with small surface areas. Climate perturbations support these historical results and provide additional insight on the individual and combine effects of air temperature increases and changes in wind speed. Increasing air temperature and decreasing wind speeds have a doubling effect toward longer stratification duration.~~ 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. ~~Wind speed specifically plays a more dominant role in stratification onset and overturn and hypolimnetic water temperatures, indicating~~This reveals that air temperature increases are not the only climate variable that managers should plan for when planning mitigation and adaptation techniques. Previous research has shown uncertainty in the changes in hypolimnion water temperatures for dimictic lakes, however the perturbation scenarios indicate that while increasing air temperature always increases hypolimnion temperature, wind speed is a larger driving force, and the ultimate hypolimnion temperature response may be primarily determined by whether the lake experiences an increase or decrease in wind speeds.

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Table 1: ~~**Morphometric and hydrologic characteristics of the three study lakes**~~**Lake characteristics for the three study lakes**

	Lake Mendota	**Fish Lake**	**Lake Wingra**
m~~M~~ean d~~D~~epth (m)	12.8	6.6	2.7
~~M~~maximum d~~D~~epth (m)	25.3	18.9	4.7
s~~S~~urface a~~A~~rea (ha)	3937.7	87.4	139.6
s~~S~~horeline l~~L~~ength (km)	33.8	4.3	5.9
lake fetch (km)	9.2	1.2	2.0
shoreline development	high	high	high
landscape position	low	high	high
Secchi depth (m)*	3.0	2.4	0.7
chlorophyll (μg L^{-1})‡	4.8	5.1	10.5
dissolved organic carbon (μg L^{-1})Δ	5.71	6.95	7.01
~~Groundwater~~	~~Groundwater Discharge~~	~~Groundwater Flowthrough~~	~~Groundwater Flowthrough~~
lake type~~Surface Water~~	Drainage	Seepage	Drainage
groundwater inflow type	discharge	flowthrough	flowthrough
g~~G~~roundwater i~~I~~nput (%)	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

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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 ~~2~~3: Absolute mean error (AME), root-mean square error (RMSE), and Nash-Sutcliff efficiency (NS) for water temperature variables on Lake Mendota, Lake Wingra, and Fish Lake. n = number of measurements, N/A represents errors that cannot be determined because Lake Wingra is a polymictic lake and does not have an epilimnion or hypolimnion.

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

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

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

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

Table 45: Correlation coefficients for lake pairs 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

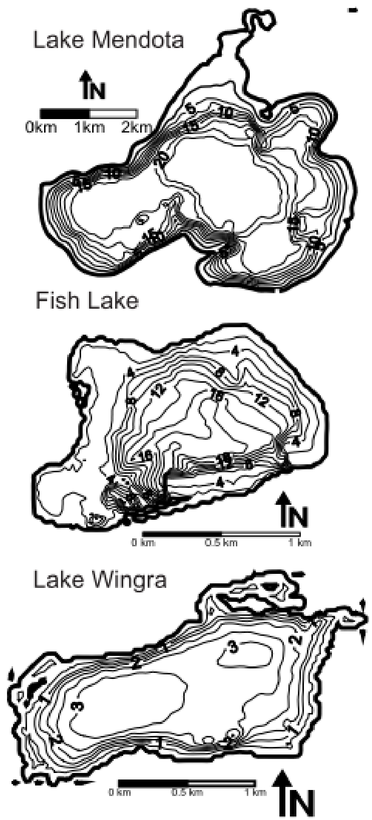

Figure 1: Bathymetric maps of Lake Mendota, Fish Lake, and Lake Wingra

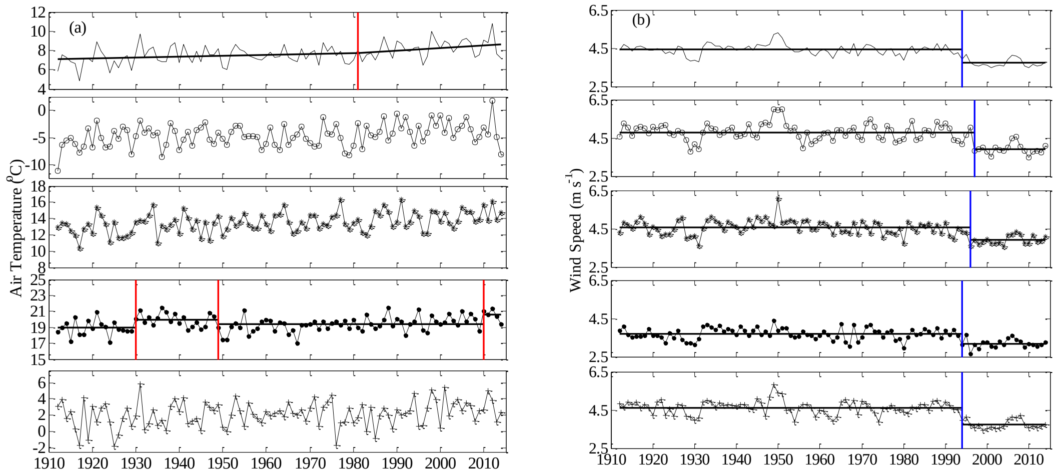

Figure 2: Yearly (solid line), winter (open circle), spring (asterisk), summer (solid circles), and fall (cross) (a) air temperature and (b) wind speeds for Madison, WI, USA. Red line in yearly air temperature figure represents a breakpoint in the trend of average air temperature increase from 0.081° 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.

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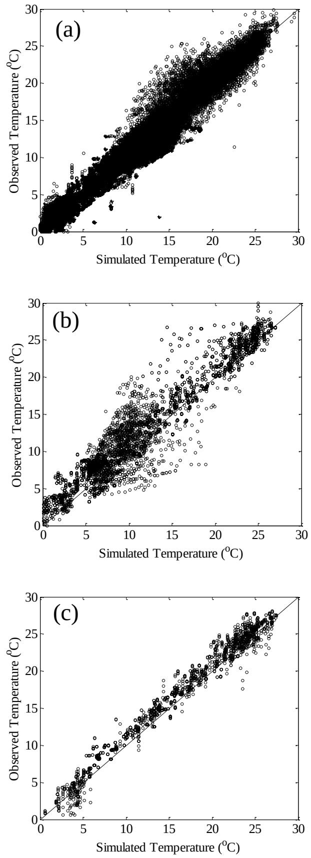

Figure 3: Comparison of observed and simulated water temperatures for (a) Lake Mendota, (b) Fish Lake, and (c) Lake Wingra. Each point represents one observation vs. simulation pair with unique date and lake depth.

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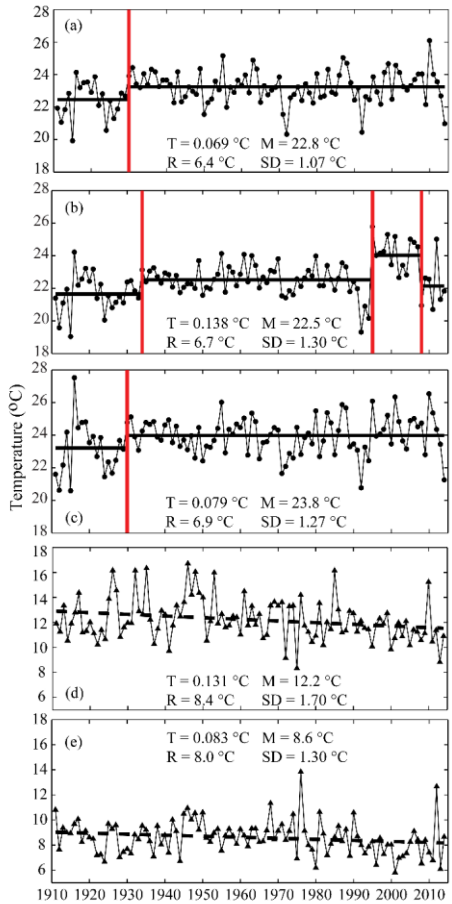

Figure 4: Mean summertime (July15-August15) epilimnetic temperatures for (a) Lake Mendota, (b) Fish Lake, and (c) Lake Wingra, and mean summertime (July 15-August 15) hypolimnetic temperatures for (d) Lake Mendota and (e) Fish Lake. In (a), (b), and (c), solid red lines represent statistically significant (*p* < 0.5) locations of abrupt changes in epilimnion temperatures and solid lines represent mean temperatures for each period. In (d) and (e) ~~solid~~ 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,

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and the whole water column for Wingra based on surface mixed layer depth calculated using LakeAnalyzer (Read et al., 2011). ~~Hypolimnetic temperatures show no significant abrupt changes. Neither epilimnetic nor hypolimnetic temperatures for any lakes have significant changes in long-term trends~~.

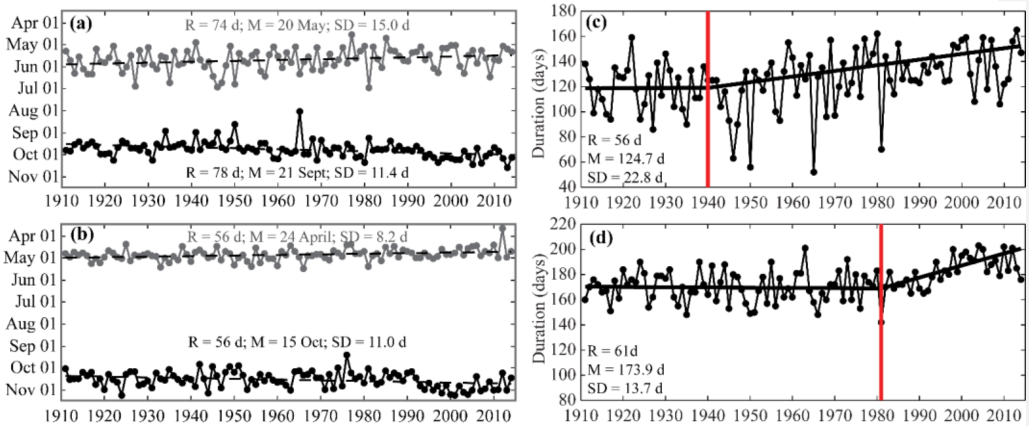

Figure 5: Stratification onset (gray) and overturn (black) dates for (a) Lake Mendota and (b) Fish Lake. Stratification duration for (c) Lake Mendota and (d) Fish Lake. Dark circles are modelled results and dashed lines denote the trendline for the 104-year period. In (a) and (b) dashed~~solid~~ lines 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.

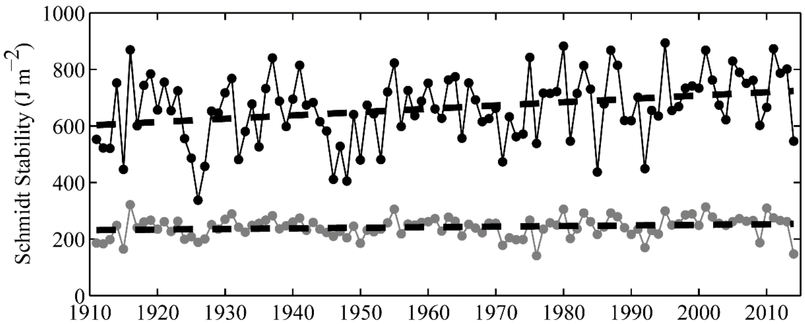

Figure 6: Yearly average summer-time (15 July - 15 August) Schmidt stability values for Lake Mendota ~~(circle~~(black) and~~,~~ Fish Lake (~~triangle~~gray). Dashed lines represent the long-term trend for each lake.

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Commented [MRM45R44]: The authors have taken the advice of Reviewer 1 and left Lake Wingra off this figure.

~~, and Lake Wingra (square).~~

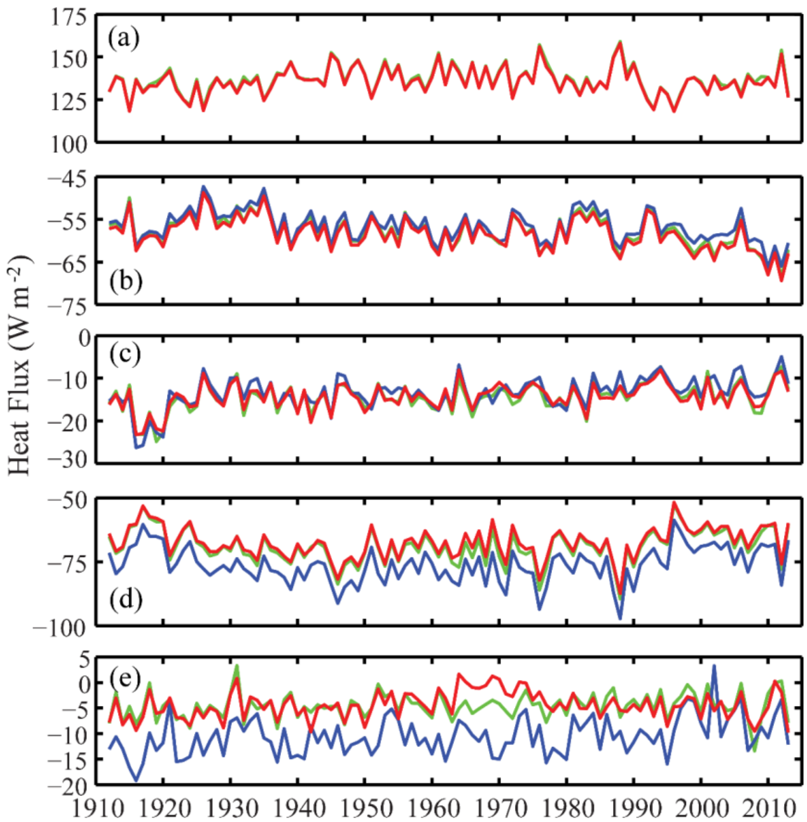

Figure 7: Yearly average (a) radiation flux, (b) long wave radiative flux, (c) sensible heat flux, (d) latent heat flux, and (e) total heat flux at the lake surface for Lake Mendota (solid black line), Fish Lake (black dashed line), and Lake Wingra (solid grey line). Trends and abrupt changes for heat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

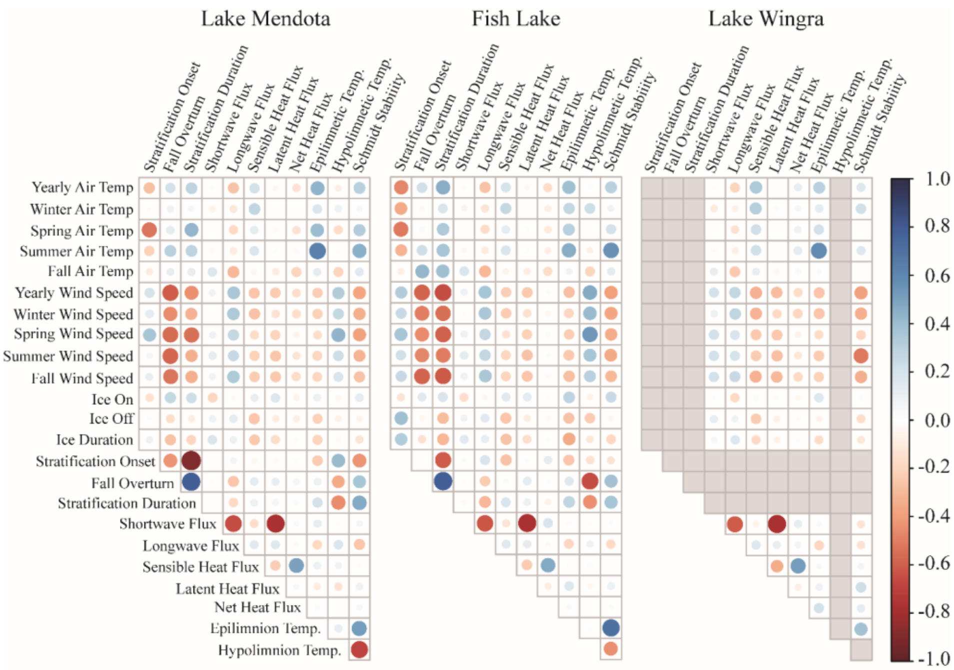

Figure 8: Plots of Pearson correlation coefficients among climate (air temperature and wind speed) variables and lake variables for the three study lakes.

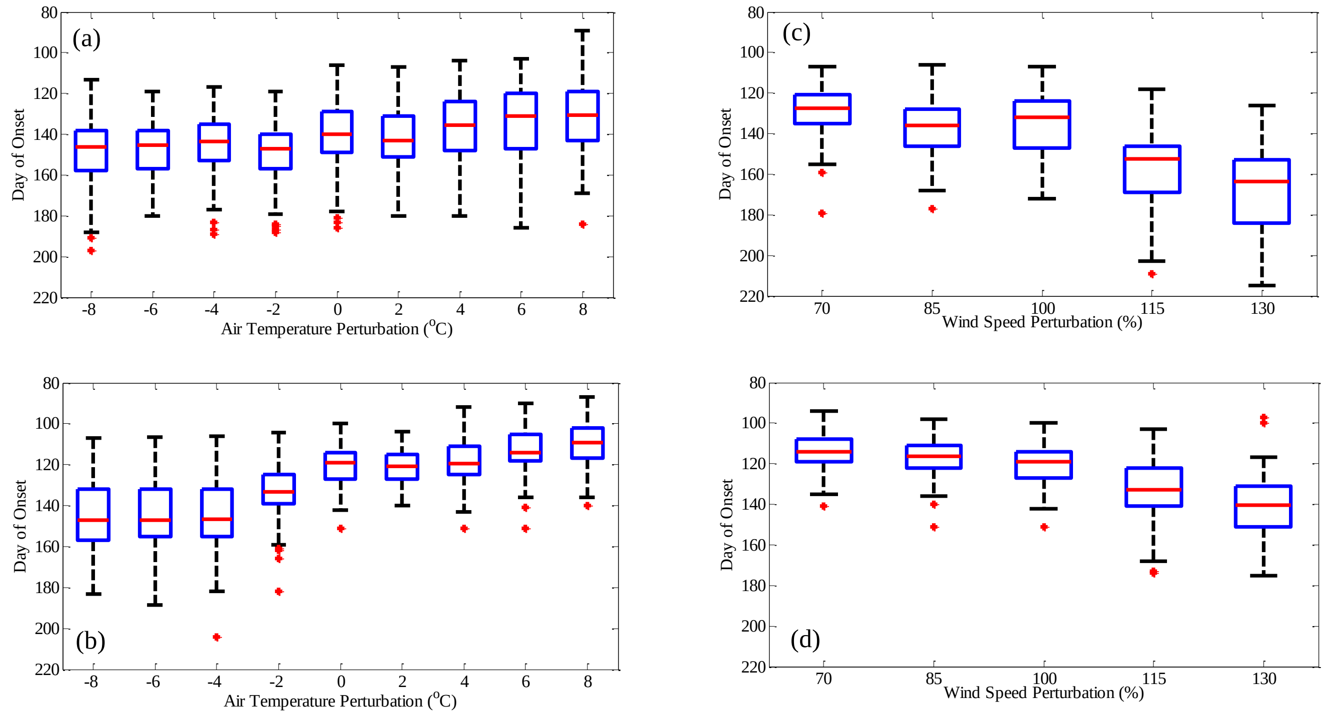

Figure 98: Day of stratification onset under select air temperature perturbation scenarios for (a) Lake Mendota and (b) Fish Lake and day of stratification onset under select wind speed perturbation scenarios for (c) Lake Mendota and (d) Fish Lake. The box represents the 25th and 75th quartiles and the 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.

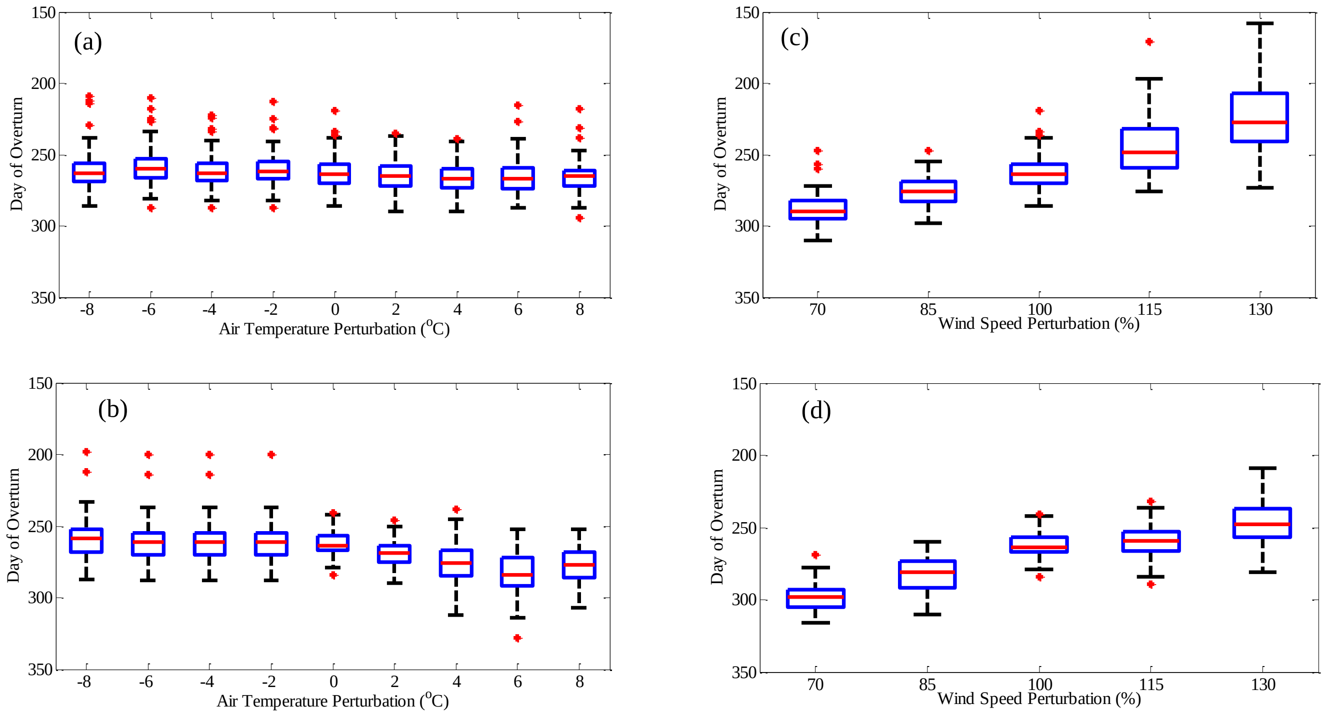

Figure 109: Day of stratification overturn under select air temperature perturbation scenarios for (a) Lake Mendota and (b) Fish Lake and day of stratification overturn under select wind speed perturbation scenarios for (c) Lake Mendota and (d) Fish Lake. The box represents the 25th and 75th quartiles 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.

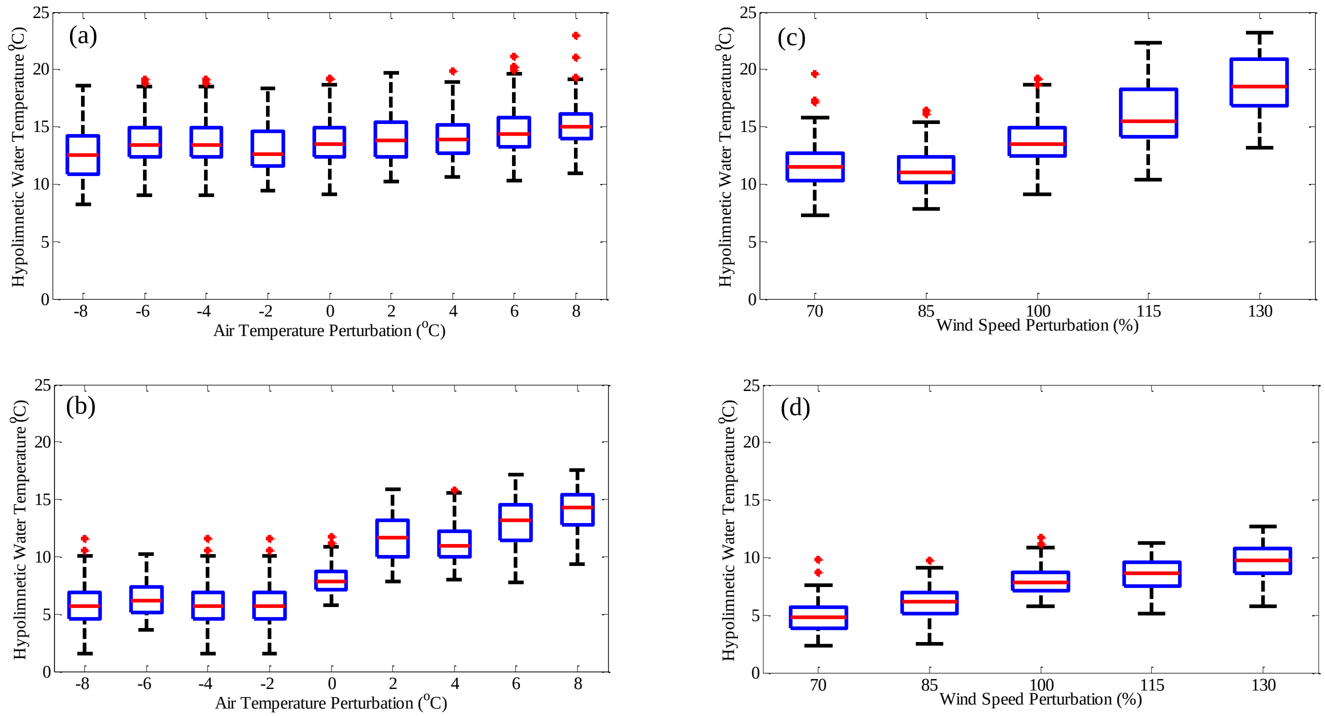

Figure 11~~10~~: Hypolimnetic water temperatures under select air temperature perturbation scenarios for (a) Lake Mendota and (b) Fish Lake and hypolimnetic water temperatures under select wind speed perturbation scenarios for (c) Lake Mendota and (d) Fish Lake. The box represents the 25th and 75th quartiles 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.