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UNCERTAINTY AND VARIABILITY OF WISCONSIN LAKES IN RESPONSE TO CLIMATE CHANGE

Chin Wu
Department of Civil and Environmental Engineering
University of Wisconsin-Madison

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Uncertainty and Variability of Wisconsin Lakes in Response to Climate Change

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Project Summary

Title: Uncertainty and Variability of Wisconsin Lakes in Response to Climate Change

Project I.D: WR11R003

Investigator(s): Principal Investigator – Chin Wu, Professor, Department of Civil and Environmental Engineering. Research Assistants – Madeline Magee, Graduate Research Assistant, Department of Civil and Environmental Engineering

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Background/Need: Many studies have shown that lake temperatures and ice cover can strongly affect water chemistry, individual organism physiology, population abundance, community structure, and food-web dynamics. Air temperature and wind speed are important factors driving these lake ecosystem properties. Understanding how lakes respond to changes in these drivers is of great interest to predict how lakes may change in the future. The response of lake ice and water temperature to long-term changes in air temperature and wind speed is integral to assess potential impacts of climate change on lake ecology.

Objectives: The purpose of this study is two-fold: first, to investigate how long-term changes in air temperature and wind speed affect the ice cover and thermal structures of a dimictic Lake Mendota, Wisconsin, USA over the past century; and second, to investigate the role of lake morphometry in long term changes, variability, and sensitivity in response to increasing air temperatures and decreasing wind speeds in the Madison, WI area. We hypothesize that changes in lake ice cover and thermal structures on Lake Mendota may be characterized by periods of abrupt changes rather than gradual trends based on observations of rapid change in the climate drivers of air temperature and wind speed. Our second hypothesis is that long term trends of changes in lake ice cover and thermal structure variables will be dependent on differences in lake morphometry (i.e. lake depth and surface area).

Methods: To address the research questions, a one-dimensional hydrodynamic model with ice cover is employed to simulate long term (1911-2014) ice cover and water temperature on Lake Mendota, Fish Lake, and Lake Wingra for both historical and future climate scenarios.

Results and Discussion:

Observations of the drivers include a change in the trend of warming air temperatures from 0.081 °C per decade before 1981 to 0.334 °C per decade thereafter, as well as a shift in mean wind speed from 4.44 m s^{-1} before 1994 to 3.74 m s^{-1} thereafter. Correlation analysis of lake variables and driving variables revealed ice cover variables, stratification onset, epilimnetic temperature, and hypolimnetic temperature were most closely correlated with air temperature, whereas freeze-over water temperature, hypolimnetic heating, and fall turnover date were more closely correlated with wind speed. Each lake variable (i.e., ice-on and ice-off dates, ice cover duration, maximum ice thickness, freeze-over water temperature, stratification onset, fall turnover date, stratification duration, epilimnion temperature, hypolimnion temperature, and hypolimnetic heating) was averaged for the three periods (1911-1980, 1981-1993 and 1994-2014) delineated by abrupt changes in air temperature and wind speed. Average summer hypolimnetic temperature and fall turnover date exhibit significant differences between the third period and the first two periods. Changes in ice cover (ice-on and ice-off dates, ice cover duration, and maximum ice thickness) exhibit an abrupt change after 1994, which was related in part to the warm El Niño winter of 1997−1998. Under-ice water temperature, freeze-over water temperature, hypolimnetic temperature, fall turnover date, and stratification duration demonstrate a significant difference in the third period (1994−2014), when air temperature was warmest and wind speeds decreased rather abruptly.

For the study of lake morphometry, we found that during the period, 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. Sensible heat flux in all 3 lakes increases over the simulation period while latent heat flux decreases. The shallow study lake had a greater change in latent heat flux and net heat flux, indicating the role of lake depth to surface heat fluxes. Furthermore, 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. It is found that the ice cover period has decreased due to earlier ice-on dates and later ice-off dates, and the maximum ice cover thickness has decreased for the three lakes during the last century. Based upon perturbations of air temperatures across the range of -10 °C to +10 °C of historical values, Fish Lake has the most occurrences of no ice cover and Lake Wingra still remains ice covered under extreme conditions (+10°C).

Conclusions/Implications/Recommendations:

The trends in ice cover and water temperature demonstrate responses to both long-term and abrupt changes in meteorological conditions that can be complemented with numerical modelling to better understand how these variables will respond in a future climate. Perturbing climate 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. Lake depth impacts the presence of stratification and magnitude of Schmidt stability, while lake surface area drives differences in hypolimnion temperature, hypolimnetic heating, variability of Schmidt stability, and stratification onset and fall overturn dates. Shallow lakes with large surface areas are most resilient to ice cover changes caused by climate and deep lakes with small surface areas are the least resilient to climate-induced ice cover changes.

Related Publications:

Magee, M. R., Wu, C. H., Robertson, D. M., Lathrop, R. C., and Hamilton, D. P.. 2016. Trends and abrupt changes in 104-years of ice cover and water temperature in a dimictic lake in response to air temperature, wind speed, and water clarity drivers, Hydrol. Earth Syst. Sci. Discuss., doi:10.5194/hess-2015-488.

Magee, M.R. and Wu, C.H. Effects of changing climate on ice cover in three morphometrically different lakes. *Accepted under revision to* Hydrological Processes

Key Words: climate change, ice cover, stratification, lakes, regime shift

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Introduction

Many studies have shown that lake temperatures and ice cover can strongly affect water chemistry, individual organism physiology, population abundance, community structure, and food-web dynamics (King et al., 1997; Schindler et al., 1990). Air temperature and wind speed are important factors driving these lake ecosystem properties. Understanding how lakes respond to changes in these drivers is of great interest to predict how lakes may change in the future (Fang and Stefan, 2009). The response of lake ice and water temperature to long-term changes in air temperature and wind speed is integral to assess potential impacts of climate change on lake ecology.

Over the past 100 years, climate has been changing and will continue to change (IPCC, 2013). Globally-averaged combined land and ocean surface temperature data show a linear warming trend of 0.85 °C from 1880−2012 (IPCC, 2013). This warming was most pronounced from 1979−2012, greater than 0.25 ^{o}C per decade (Hartmann et al., 2013). Increases in air temperature alter the ice cover of lakes (Butcher et al., 2015; Magnuson et al., 2000; Robertson et al., 1992) and affect their thermal structures (Robertson and Ragotzkie, 1990), evidenced by increasing epilimnetic temperatures (Arhonditsis et al., 2004), warming of the lake surface temperature (Shimoda et al., 2011), increasing temperature gradient across the thermocline (Robertson and Ragotzkie, 1990; Wilhelm and Adrian, 2008), changing thermocline depth (King et al., 1997; Schindler et al., 1990), advancing the onset of summer stratification (Austin and Colman, 2007), delaying fall turnover (King et al., 1997), increasing the strength of thermal stratification (Rempfer et al., 2010), and prolonging the stratified period (Robertson and Ragotzkie, 1990; Wilhelm and Adrian, 2008).

Trends in wind speed over the last 30–50 years have been reported in several studies that have analyzed historical wind speed records across the globe (Wan et al., 2010). Klink (2002) examined 22- to 35-year records (ranging between 1959–1995) of wind speed at seven stations in and around Minnesota and found decreasing annual wind speeds at five of the seven stations. Pryor et al.(2009) reported that the 50th and 90th percentile annual wind speeds over the period 1973–2005 across most of the U.S. have also decreased. Decreased wind speeds increase thermal stratification and can reduce whole-lake average temperature (Tanentzap et al., 2008). Interestingly, an opposing trend (increasing wind speed) has been observed in Lake Superior, North America, where the lake surface temperatures have been warming faster than air temperatures (Austin and Colman, 2007). Desai et al. (2009) suggest that the larger increase in water temperatures than air temperatures reduced the air-water temperature gradient and destabilized the atmospheric surface layer above Lake Superior, which resulted in increasing wind speed at a rate of nearly 5% per decade. Differences in wind-driven mixing may explain different temperature responses of hypolimnetic waters in large and small lakes (Winslow et al., 2015). While the importance of wind in lake heat transfer (Fu et al., 2009; Read et al., 2012), mixing, and thermal structure (Desai et al., 2009; Schindler et al., 1990) has been recognized, studies on the effects of wind speed alterations on seasonal ice cover and thermal structure of lakes are still rare.

The purpose of this study is two-fold: first, to investigate how long-term changes in air temperature and wind speed affect the ice cover and thermal structures of a dimictic Lake Mendota, Wisconsin, USA over the past century; and second, to investigate the role of lake morphometry in long term changes, variability, and sensitivity in response to increasing air temperatures and decreasing wind speeds in the Madison, WI area. We hypothesize that changes in lake ice cover and thermal structures on Lake Mendota may be characterized by periods of abrupt changes rather than gradual trends based on observations of rapid change in the climate drivers of air temperature and wind speed. Our second hypothesis is that long term trends of changes in lake ice cover and thermal structure variables will be dependent on differences in lake morphometry (i.e. lake depth and surface area). To address these two questions, a one-dimensional hydrodynamic model with ice cover is employed to simulate long term (1911-2014) ice cover and water temperature on Lake Mendota, Fish Lake, and Lake Wingra for both historical and future climate scenarios.

Procedures and Methods

Study sites

Three morphometrically different lakes, Lake Mendota, Fish Lake, and Lake Wingra, located near Madison, Wisconsin, USA, were selected for this study (Fig. 1**Error! Reference source not found.**). These lakes are chosen for (1) their morphometry differences, (2) their close proximity to one another, and (3) the availability of long-term limnological records, which were used for model calibration.

Hydrodynamic model

In this study, a one-dimensional hydrodynamic lake-ice model DYRESM-ICE is used to simulate vertical water temperature distribution and ice cover in Fish Lake, Lake Wingra, and Lake Mendota. Specifically, an ice model is added to the DYRESM-WQ (DYnamic REservoir Simulation Model-Water Quality) model (Hamilton and Schladow, 1997) that simulates vertical water temperature, salinity, and density by using discrete horizontal Lagrangian layers of uniform properties that very in thickness. The ice model is based upon a quasi-steady state assumption that the time scale for heat conduction through the ice is short relative to the time scale of meteorological forcing. Since sediment heat transfer is important to water temperature beneath ice cover (Ellis et al., 1991), the DYRESM-ICE model used in this study incorporates sediment heat flux, a main external source of lake heating after freezing occurs

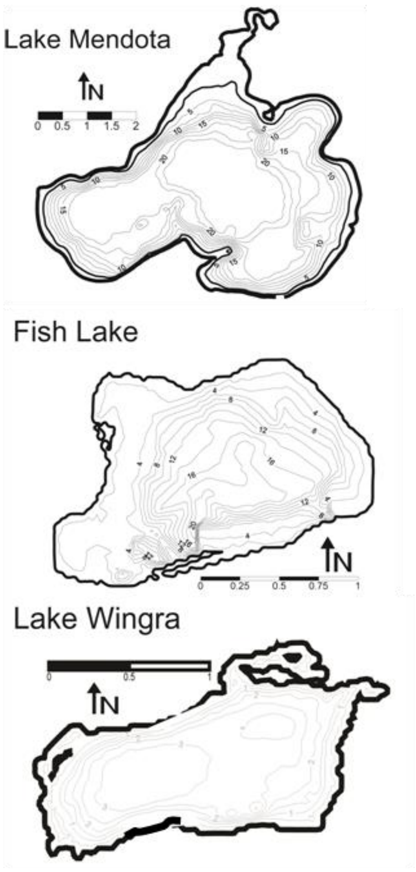


Figure 1: Bathymetric maps of Lake Mendota, Fish Lake, and Lake Wingra

Analysis

Multiple statistical methods are used to analyze the results. First, a linear regression is used to determine the trend of long-term changes. A Pearson correlation coefficient (Baron and Caine, 2000) is used to determine the coherence of lake variables (Magnuson et al., 1990) between lake pairs allowing for comparison of correlation of the lake variables to each other. Breakpoints in the air temperature trend over the study period were determined using a piecewise linear regression (PLR) method (Tomé and Miranda, 2004; Toms and Lesperance, 2003; Ying et al., 2015). Abrupt changes in mean annual wind speeds and lake ice cover and temperature variables were detected using the sequential t-test STARS (Rodionov, 2004), which can automatically detect multiple change points.

Results and Discussion

Shifts in air temperature and wind speed

Annual air temperature (Fig. 2a) had a relatively small increase from 1910 until 1980, but has increased dramatically since 1981. Based on a piecewise linear regression algorithm, there was a small warming trend of 0.081°C per decade during 1911−1980, followed by a dramatic change (a warming trend of .334°C per decade) from 1981−2014. Fig 2b shows that mean annual wind speed was 4.44 ms^{-1} until 1994, when a significant shift occurred to 3.74 m s^{-1} (15% reduction) based on the sequential t-test STARS method (Rodionov, 2004).

Combining the statistically significant breakpoint in air temperature trend that occurred in 1981 and the shift in wind speed in 1994, the Madison climate may be broken into three different periods. The first, from 1911−1980, was a relatively cool period and had an average wind speed of 4.44 m s^{-1}. The second period (1981−1993) occurred after the breakpoint in the air temperature trend and had a warmer air temperature and a wind speed of 4.44 m s^{-1}. The third period (1994−2014) occurred after the shift in wind speed from 4.44 m s^{-1} to 3.74 m s^{-1} and had even warmer air temperatures.

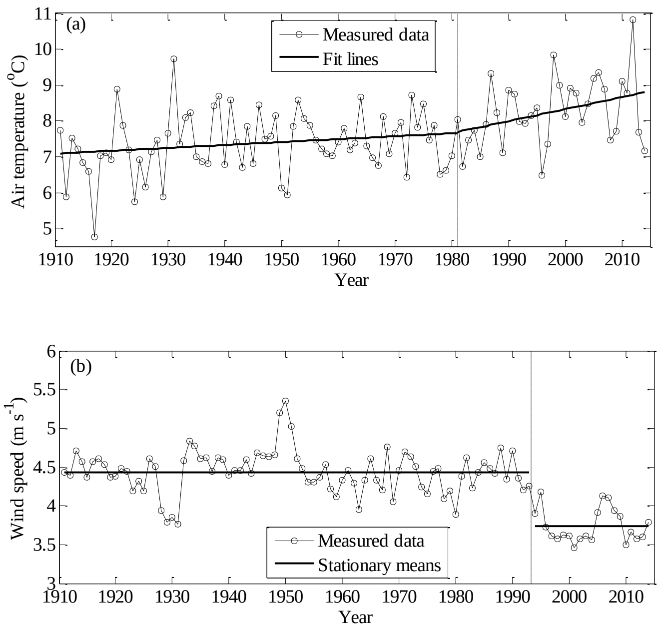


Figure 2: Historical record of annual average (a) air temperature and (b) wind speed in Madison, WI.

Abrupt changes in lake variables

To investigate the effects of abrupt changes in air temperature and wind speed on lake ice cover and water temperatures, we used the hydrodynamic model DYRESM-WQ-I to describe changes in several lake variables during 1911−2014. Simulation results were used to examine differences in mean values of these lake variables between specific periods. For each period of the selected periods, mean lake variables were calculated and the differences between periods were analysed with t-tests to determine if they were significantly different. Table 1 lists the mean values and differences for the nine lake variables during the three selected periods. Comparison of period 1 (1911-1980) to period 2 (1981-1993) of lake variables shows a shift to warmer air temperature; period 2 to period 3 (1994-2014) represents an abrupt change to lower wind speed; and period 1 to period 3 represents a shift to warmer air temperature combined with an abrupt change to lower wind speeds.

Ice cover

Three simulated ice cover variables (maximum ice thickness, ice-on date, and ice-off date) show no significant difference in means between period 1 and 2. In other words, the abrupt change in air temperature trend does not result in a different ice regime even though the ice cover variables are all highly correlated with air temperature (r >0.70). This may be because the change in air temperatures was not of sufficient magnitude to cause a particularly large change in ice cover or it may signify that other drivers are contributing to changes in ice cover variables. Additionally, no significant difference is observed between period 2 and period 3 for the ice cover variables since the wind speed and ice cover variables are only weakly correlated. The ice variables do show a statistically significant difference in mean values between periods 1 and 3, indicating that a significant shift in these variables occurs only after a sufficiently large increase in air temperature and an abrupt shift in wind speed within the time between periods 1 and 3. In other words, air temperature need to increase sufficiently to observe a statistically significant difference in ice cover. Ice cover duration, however, shows a significant difference in the mean between all periods (1−2, 2−3, and 1−3), indicating that distinct differences in ice cover duration can be affected by both trends in air temperature (i.e., there was a large enough change in air temperature between each period) and an abrupt shift in the wind speed. The combined effects of slightly later ice-on dates and earlier ice-off dates during each of the three periods resulted in statistically significant difference in mean ice cover duration values between each of the three periods.

Table 1: Mean values of climate drivers and lake variables of three hypothesized periods during 1911-2014 for Lake Mendota. Asterisk (*) mark significant differences between two periods ($p<0.05$).

Driver/Variable	Unit	Period			Difference in Mean		
		(1)1911-1980	(2)1981-1993	(3)1994-2014	(1) and (2)	(2) and (3)	(1) and (3)
Lake driver							
Air temperature (slope)	°C decade^{-1}	0.081	0.334	0.334			
Wind speed	m s^{-1}	4.44	4.44	3.74			
Lake variables							
Maximum ice thickness	cm	49.8	44.9	40.7	–4.9	–4.2	-9.1*
Ice-on date (model)	Date	21-Dec	23-Dec	29-Dec	2 days	6 days	8 days*
(observation)	Date	21-Dec	24-Dec	29-Dec	3 days	5 days	8 days*
Ice-off date (model)	Date	9-Apr	2-Apr	30-Mar	–7 days	–3 days	-10 days*
(observation)	Date	3-Apr	27-Mar	26-Mar	–7 days	–1 days	-8 days*
Ice duration (model)	Days	108.7	99.5	91.1	–9.2*	–8.4*	-17.6*
(observation)	Days	103.2	92.9	85.6	–10.3*	–7.3*	-17.6*
Under-ice water temperature	°C	1.74	1.81	2.08	0.07	0.27	0.34*
Freeze-over water temperature	°C	1.03	1.14	1.66	0.11	0.52	0.63*
Stratification onset date		24-May	17-May	18-May	–7 days	–1 days	-6 days
Mid-summer epilimnetic temperature	°C	23.0	23.2	23.4	0.2	0.2	0.4
Mid-summer hypolimnetic temperature	°C	12.0	11.8	10.9	–0.2	–0.9*	-1.1*
Epilimnion-hypolimnion temp. difference	°C	10.9	11.4	12.5	0.5	1.1	1.6*
Hypolimnetic heating (1 July–31 August)	°C	0.699	0.688	0.583	-0.011	–0.105	-0.116
Turnover date	Date	20-Sept	21-Sept	3-Oct	1 day	12 days*	13 days*
Stratification Duration	Days	119.4	127.4	138.6	8.0	11.2	19.2*

Analysis of simulated maximum ice thickness, ice-on, ice-off, and ice cover duration using the method of Rodionov (2004) shows that the most statistically significant timing of the shift in these ice cover variables occurs in the winter of 1997-1998, but a major shift in the air temperature or wind speed data was not observed at that time. The unusual winter of 1997-1998 strongly drove the statistically significant difference in mean values between periods 1 and 3 rather than the abrupt shift in wind speed in 1994. Interestingly, similar results have been reported in Lake Superior, where statistically significant step changes were found in winter ice duration and maximum wintertime ice extent; these step changes account for most of the long-term trends in ice cover for the lake (Van Cleave et al., 2014). The timing of this step change may be attributed to a combination of the longer term changes in meteorological conditions and the short-term annual change occurring in the warm El Niño winter of 1997-1998 (Van Cleave et al., 2014). Mueller et al. (2009) found that a similar climate shift between 1997 and 1998 initiated a change in lake ice phenology from infrequent to frequent summer loss in several high-Arctic lakes. Similarly, lakes in Poland show a considerable statistical relationship between ice cover and the North Atlantic Oscillation winter indexes (Skowron, 2009), indicating that ice cover may be driven by other large oscillations as well.

Water temperature and stratification

Means of five simulated lake variables (under-ice water temperature, freeze-over water temperature, epilimnion-hypolimnion temperature difference [indicative of strength of stratification], and duration of stratification) over the three periods have significant ($p<0.05$) differences only between period 1 and period 3. This change likely occurs because of the combined effects of large changes in air temperature and a change in wind speed. Both air temperature and wind speed are significantly correlated with these five lake variables. Each driver alone may not be strong enough to cause a major shift in the lake variables, but their combined effects may reinforce the drivers of abrupt change in ice and thermal phenology. Further work is required to examine how the major drivers may either reinforce or dampen lake ice and temperature responses, particularly in relation to directional shifts predicted under climate change.

Fall turnover date, highly correlated with wind speed, exhibits a significant ($p <0.05$) shift in the mean value in 1994, corresponding with the abrupt shift in the wind speed. Interestingly, hypolimnetic water temperatures, which are not significantly correlated with wind speed, but are correlated with air temperatures, also show a significant ($p<0.05$) shift in the mean value in 1994. Hypolimnetic heating, significantly correlated with wind speed ($r = 0.49$), does not exhibit a significant breakpoint, nor are any of the mean differences among the three periods significant. Given the high correlation between wind speed and hypolimnetic heating, it is hypothesized that there should be a shift in hypolimnetic heating caused by the abrupt shift in wind speed in 1994. The lack of statistically significant step change may be explained by the simultaneous high correlation between Secchi depth and hypolimnetic heating ($r = 0.35$), indicating that water clarity may act to inhibit heating regardless of changes in wind speed, or it may be acting to filter or mitigate the effects of the wind speed shift. Finally, mean onset date of stratification and mid-summer epilimnetic temperature exhibit no difference among the three periods. This may be due to two processes: (i) the climate signal is being filtered out by the lake; or (ii) the external perturbation of the system is not yet strong enough to trigger a major shift in the system's internal dynamics.

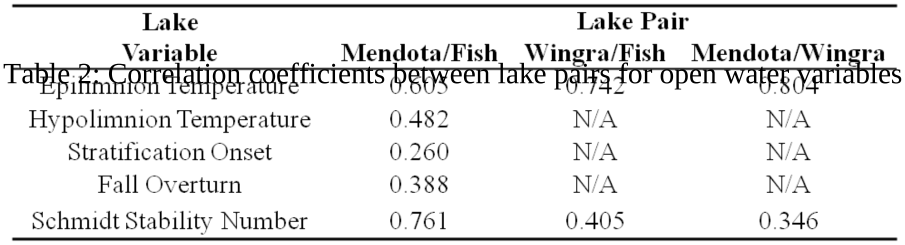
Role of lake morphometry on response to historical climate changes

Temperature and stratification variables

Pearson correlation coefficients in open water lake variables were calculated for pairs of study lakes (Table 2). Pair 1, Lake Mendota and Fish Lake, had similar depths but different surface areas, illustrating the effects of surface area differences. Pair 2, Lake Wingra and Fish Lake, had similar surface areas, but shallow and deep water depths, addressing the effects of lake depth. Pair 3, Lake Mendota and Lake Wingra, had both differing surface areas and water depths.

Epilimnetic temperature exhibited high coherence for all three pairs, suggesting that inter-annual variability in epilimnion water temperatures was primarily driven by climate drivers. Comparing the Mendota/Fish pair and the Fish/Wingra pair, the pair with similar surface area has higher correlation than the pair with similar depth. This suggests that both lake surface area and lake depth impact coherence between lake pairs; and surface area differences drive asynchronous patterns to a greater extent than does depth differences for epilimnetic temperature. Hypolimnion temperature, different from epilimnion temperature, showed only moderate coherence for the

Table 2: Correlation coefficients between lake pairs for open water variables



Lake Variable	Lake Pair Mendota/Fish	Wingra/Fish	Mendota/Wingra
Epilimnion Temperature	0.605	0.742	0.804
Hypolimnion Temperature	0.482	N/A	N/A
Stratification Onset	0.260	N/A	N/A
Fall Overturn	0.388	N/A	N/A
Schmidt Stability Number	0.761	0.405	0.346

Mendota/Fish pair, suggesting that inter-annual variability in hypolimnion water temperatures was driven by both climate drivers and other factors, 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. Other factors like strength of stratification and fetch differences may drive differences in the timing of stratification, further affecting hypolimnetic temperatures. Arvola et al. (2009) showed that hypolimnion temperatures were primarily determined by the conditions that pertained during the previous spring turnover. In our study, the relatively low hypolimnetic coherence for Lake Mendota and Fish Lake (Table 2) suggest that both climate drivers and lake morphometry play equally important roles in hypolimnion water temperatures. Coherence for stratification onset and fall overturn dates were low for the Mendota/Fish pair, suggesting that lake surface area may be a factor in driving differences between stratification onset and fall overturn in the lakes.

Ice cover variables

For the ice cover variables, correlation coefficients of pairs of lakes are high, e.g. ice on dates (Fish-Mendota: $r = 0.99$, Wingra-Fish: $r = 0.99$, Mendota-Wingra: $r = 0.99$), ice-off dates (Fish-Mendota: $r = 0.99$, Wingra-Fish: $r = 0.99$, Mendota-Wingra: $r = 0.99$), and maximum ice thickness Fish-Mendota: $r = 0.98$, Wingra-Fish: $r = 0.93$, Mendota-Wingra: $r = 0.90$). The results suggest that morphometry does not play a significant role in the coherence of ice cover among the three study lakes. Similar results were reported in Alaska, where the average degree of coherence of ice-out within lake districts was 0.74 (Arp et al., 2013). The range of within-district coherence appeared similar among lakes within a district with varying elevations, lake size, and other morphometric and physiographic attributes (Arp et al., 2013), indicating that ice cover loss in lakes is driven primarily by air temperature. Nevertheless, previous studies showed the actual rate of decay and development of ice-free conditions do vary greatly from lake to lake within a region, depending on a number of factors, particularly lake morphometry and landscape setting (Brown and Duguay, 2010; Gao and Stefan, 1999; Williams et al., 2004).

Effects of climate sensitivity on lake response

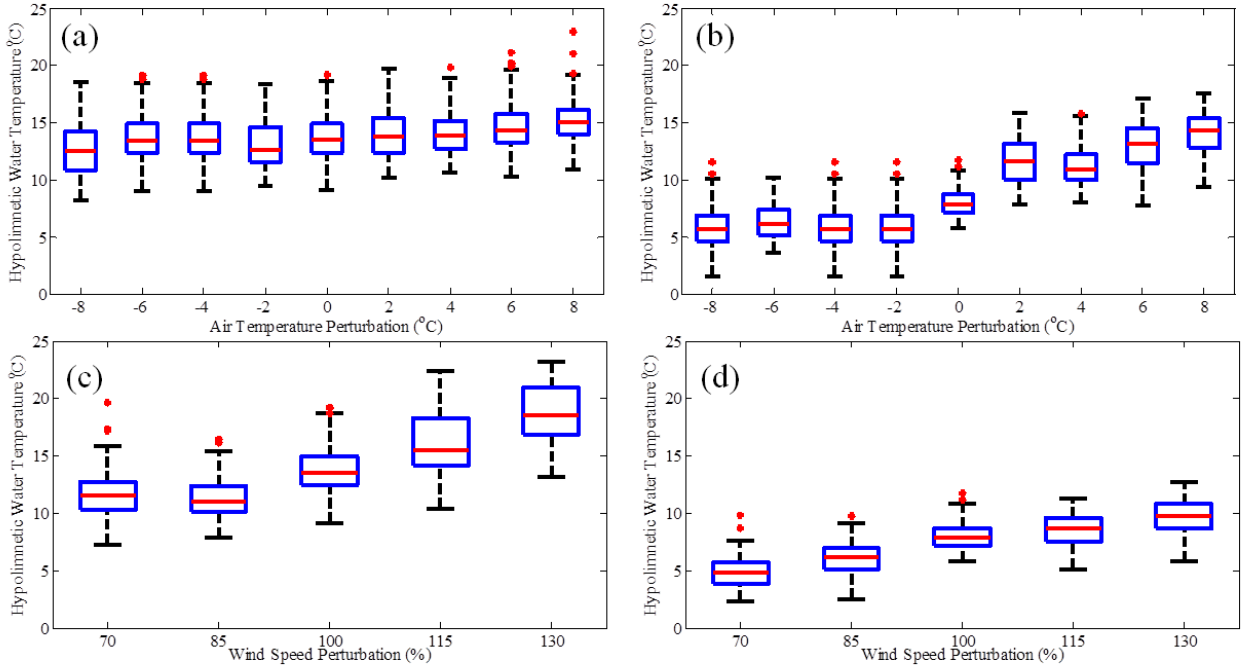
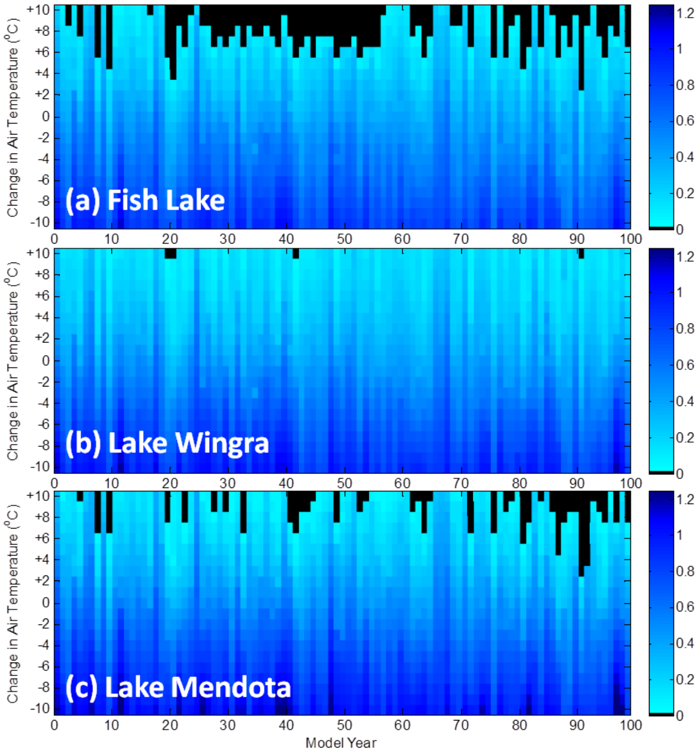


Figure 3: hypolimnetic water temperatures under select air temperature perturbations for (a) Lake Mendota and (b) Fish Lake and hypolimnetic water temperatures under select wind speed perturbations for (c) Lake Mendota and (d) Fish Lake.

For hypolimnetic water temperatures, changes with air temperature for both Lake Mendota and Fish Lake were linear, but changes under altered wind speeds were nonlinear. Temperature perturbations show increasing hypolimnetic water temperature for increasing air temperature, while decreasing wind speed perturbations show decreasing hypolimnetic water temperatures. Historically, hypolimnetic temperatures have been decreasing. Combining the effects of air temperature and wind speed, it appears that wind speed decreases are a larger driver of 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. This indicates that lakes with larger surface areas that also experience decreasing wind speeds may be more resilient



to increasing air temperatures increasing hypolimnetic water temperatures.

To examine sensitivity changes on ice cover (maximum ice thickness and ice cover duration) under cold or warm temperatures, we perform temperature perturbations by increasing and decreasing daily air temperature values for the first 100 years of the simulation period in 1°C intervals, bounded at -10°C and +10°C.

Figure 4 shows plots of maximum ice thickness with air temperature perturbations for 100 model years. Under the increasing air temperature, Fish Lake has the most occurrences of no ice cover (indicated by black color in Fig. 4). Lake Mendota has fewer ice-free occurrences because the larger lake surface area facilitates greater surface heat flux, which allows the lake to adjust to isothermal conditions and form ice more quickly. In contrast, almost all the ice cover remains in Lake Wingra as it has lower heat storages and responds more quickly to changes in air temperature. Overall, the results indicate that the deeper lakes are more at risk for thin or no ice conditions than shallow lakes. For cooler air temperatures (i.e. the bottom half of the colorplots), Fish Lake, Lake Wingra, and Lake Mendota all show similar increases in maximum ice thickness.

Conclusions and Recommendations

Figure 4: Maximum ice thickness (in m) for (a) Fish Lake, (b) Lake Wingra, and (c) Lake Mendota for air temperatures ranging from -10 to +10 °C perturbations of historical temperatures

Changes in meteorological factors over the past 104 years were examined on Lake Mendota to determine if there have been abrupt shifts, rather than linear changes. Based on a change in the trend of air temperature increase occurring in 1981 and a major shift in wind speed in 1994, the Madison climate is divided into three distinct periods: 1911−1980, with relatively low air temperatures and mean wind speeds of 4.44 m s^{-1}; 1981−1993, with higher air temperatures and mean wind speeds of 4.44 m s^{-1}; and 1994-2014 with still higher air temperatures and mean wind speed of 3.74 m s^{-1}. Ice cover duration exhibited a significant difference in the mean among all three periods, while ice-on, ice-off, and maximum ice thickness only show a significant difference between period one and three, indicating that only with a large change in air temperature and an abrupt shift in wind speeds are change in the ice cover variables statistically different. Mid-summer hypolimnetic temperature and fall turnover date both reveal significant (p <0.05) differences in the mean value in 1994, corresponding with the abrupt shift toward lower wind speeds. Some lake variables (under-ice water temperature, freeze-over water temperature, epilimnion-hypolimnion temperature difference, and stratification duration) may not be driven by either the change in air temperature trend or the abrupt shift in wind speed alone, but a shift in the mean of the lake variables does occur in 1994 when both the air temperatures are warmest and the wind speed experienced an abrupt shift. The exact timing of shifts may be difficult to define because of extreme changes in weather in specific years and it may mask the longer term changes in meteorological conditions (i.e. abrupt shifts).

Analysis of ice cover on three different study lakes indicates that shallow lakes, such as Lake Wingra, are more resilient to changes in air temperature than their deeper counterparts. Even under extreme increases in air temperature, model results indicate that Lake Wingra will still have ice cover, whereas the deeper Fish Lake and Lake Mendota will not. Since the shallow depth in Lake Wingra facilitates heat loss more quickly during the winter, causing ideal conditions for ice cover even under extreme warm air temperatures. Additionally, lakes with large surface areas can cool more quickly through wind mixing, which allows for easier ice formation on those lakes compared to lakes of similar depth with smaller surface areas. Overall, shallow lakes with large surface areas are most resilient to ice cover changes caused by climate and deep lakes with small surface areas are the least resilient to climate-induced ice cover changes

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 will be determined by whether the lake experiences an increase or decrease in wind speeds. Overall, lake depth and lake surface area impact the changing thermal structure in response to climate change. Fish Lake has a much earlier average stratification onset and later fall overturn because of its smaller surface area and less wind-mixing, and the effects of the changing trend is more immediate due to the already long stratified period. A larger magnitude of trend for these changes is shown in Lake Mendota, indicating that larger and deeper lakes are more susceptible to changing climate. Lake Mendota experienced greater variability in stability between high and low air temperature and high and low wind speed years than Fish Lake, suggesting that stability in the larger surface area is more susceptible to changes in the climate variables that in the lake with smaller surface area.

References

Arhonditsis, G.B., Brett, M.T., DeGasperi, C.L., Schindler, D.E., 2004. Effects of Climatic Variability on the Thermal Properties of Lake Washington. Limnol. Oceanogr. 49, 256–270.

Arp, C.D., Jones, B.M., Grosse, G., 2013. Recent lake ice-out phenology within and among lake districts of Alaska, U.S.A. Limnol. Oceanogr. 58, 2013–2028. doi:10.4319/lo.2013.58.6.2013

Arvola, L., George, G., Livingstone, D.M., Järvinen, M., Blenckner, T., Dokulil, M.T., Jennings, E., Aonghusa, C.N., Nõges, P., Nõges, T., Weyhenmeyer, G.A., 2009. The Impact of the Changing Climate on the Thermal Characteristics of Lakes, in: George, G. (Ed.), The Impact of Climate Change on European Lakes, Aquatic Ecology Series. Springer Netherlands, pp. 85–101.

Austin, J.A., Colman, S.M., 2007. Lake Superior summer water temperatures are increasing more rapidly than regional air temperatures: A positive ice-albedo feedback. Geophys. Res. Lett. 34, L06604. doi:10.1029/2006GL029021

Baron, J.I.L.L.S., Caine, N.E.L., 2000. Temporal coherence of two alpine lake basins of the Colorado Front Range, U.S.A. Freshw. Biol. 43, 463–476. doi:10.1046/j.1365-2427.2000.00517.x

Brown, L.C., Duguay, C.R., 2010. The response and role of ice cover in lake-climate interactions. Prog. Phys. Geogr. 34, 671–704. doi:10.1177/0309133310375653

Butcher, J.B., Nover, D., Johnson, T.E., Clark, C.M., 2015. Sensitivity of lake thermal and mixing dynamics to climate change. Clim. Change 129, 295–305. doi:10.1007/s10584-015-1326-1

Desai, A.R., Austin, J.A., Bennington, V., McKinley, G.A., 2009. Stronger winds over a large lake in response to weakening air-to-lake temperature gradient. Nat. Geosci. 2, 855–858. doi:10.1038/ngeo693

Ellis, C.R., Stefan, H.G., Gu, R., 1991. Water Temperature Dynamics and Heat Transfer Beneath the Ice Cover of a Lake. Limnol. Oceanogr. 36, 324–335.

Fang, X., Stefan, H.G., 2009. Simulations of climate effects on water temperature, dissolved oxygen, and ice and snow covers in lakes of the contiguous U.S. under past and future climate scenarios. Limnol. Oceanogr. 54, 2359–2370. doi:10.4319/lo.2009.54.6_part_2.2359

Fu, G., Charles, S.P., Yu, J., 2009. A critical overview of pan evaporation trends over the last 50 years. Clim. Change 97, 193–214. doi:10.1007/s10584-009-9579-1

Gao, S., Stefan, H.G., 1999. Multiple Linear Regression for Lake Ice and Lake Temperature Characteristics. J. Cold Reg. Eng. 13, 59–77. doi:10.1061/(ASCE)0887-381X(1999)13:2(59)

Hamilton, D.P., Schladow, S.G., 1997. Prediction of water quality in lakes and reservoirs. Part I — Model description. Ecol. Model. 96, 91–110. doi:10.1016/S0304-3800(96)00062-2

Hartmann, D.L., Klein Tank, A.M.G., Rusticucci, M., Alexander, L.V., Brönnimann, S., Charabi, Y., Dentener, F.J., Dlugokencky, E.J., Easterling, D.R., Kaplan, A., Soden, B.J., Thorne, P.W., Wild, M., Zhai, P.M., 2013. Climate change 2013: the physical science basis: Working Group I contribution to the Fifth assessment report of the Intergovernmental Panel on Climate Change. Cambridge University Press, New York.

IPCC, 2013. Summary for Policymakers, in: Stocker, T., Qin, D., Plattner, G.-K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V., Midgley, P.M. (Eds.), Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, New York, NY, USA.

King, J.R., Shuter, B.J., Zimmerman, A.P., 1997. The response of the thermal stratification of South Bay (Lake Huron) to climatic variability. Can. J. Fish. Aquat. Sci. 54, 1873–1882. doi:10.1139/f97-093

Klink, K., 2002. Trends and Interannual Variability of Wind Speed Distributions in Minnesota. J. Clim. 15, 3311–3317. doi:10.1175/1520-0442(2002)015<3311:TAIVOW>2.0.CO;2

Magnuson, J.J., Benson, B.J., Kratz, T.K., 1990. Temporal coherence in the limnology of a suite of lakes in Wisconsin, U.S.A. Freshw. Biol. 23, 145–159. doi:10.1111/j.1365-2427.1990.tb00259.x

Magnuson, J.J., Robertson, D.M., Benson, B.J., Wynne, R.H., Livingstone, D.M., Arai, T., Assel, R.A., Barry, R.G., Card, V., Kuusisto, E., Granin, N.G., Prowse, T.D., Stewart, K.M., Vuglinski, V.S., 2000. Historical Trends in Lake and River Ice Cover in the Northern Hemisphere. Science 289, 1743–1746. doi:10.1126/science.289.5485.1743

Pryor, S.C., Barthelmie, R.J., Young, D.T., Takle, E.S., Arritt, R.W., Flory, D., Gutowski, W.J., Nunes, A., Roads, J., 2009. Wind speed trends over the contiguous United States. J. Geophys. Res. Atmospheres 114, D14105. doi:10.1029/2008JD011416

Read, J.S., Hamilton, D.P., Desai, A.R., Rose, K.C., MacIntyre, S., Lenters, J.D., Smyth, R.L., Hanson, P.C., Cole, J.J., Staehr, P.A., Rusak, J.A., Pierson, D.C., Brookes, J.D., Laas, A., Wu, C.H., 2012. Lake-size dependency of wind shear and convection as controls on gas exchange. Geophys. Res. Lett. 39, L09405. doi:10.1029/2012GL051886

Rempfer, J., Livingstone, D.M., Blodau, C., Forster, R., Niederhauser, P., Kipfer, R., 2010. The effect of the exceptionally mild European winter of 2006-2007 on temperature and oxygen profiles in lakes in Switzerland: A foretaste of the future? Limnol. Oceanogr. 55, 2170–2180. doi:10.4319/lo.2010.55.5.2170

Robertson, D.M., Ragotzkie, R.A., 1990. Changes in the thermal structure of moderate to large sized lakes in response to changes in air temperature. Aquat. Sci. 52, 360–380. doi:10.1007/BF00879763

Robertson, D.M., Ragotzkie, R.A., Magnuson, J.J., 1992. Lake ice records used to detect historical and future climatic changes. Clim. Change 21, 407–427. doi:10.1007/BF00141379

Rodionov, S.N., 2004. A sequential algorithm for testing climate regime shifts. Geophys. Res. Lett. 31. doi:10.1029/2004GL019448

Schindler, D.W., Beaty, K.G., Fee, E.J., Cruikshank, D.R., Debruyn, E.R., Findlay, D.L., Linsey, G.A., Shearer, J.A., Stainton, M.P., Turner, M.A., 1990. Effects of climatic warming on lakes of the central boreal forest. Science 250, 967–970. doi:10.1126/science.250.4983.967

Shimoda, Y., Azim, M.E., Perhar, G., Ramin, M., Kenney, M.A., Sadraddini, S., Gudimov, A., Arhonditsis, G.B., 2011. Our current understanding of lake ecosystem response to climate change: What have we really learned from the north temperate deep lakes? J. Gt. Lakes Res. 37, 173–193. doi:10.1016/j.jglr.2010.10.004

Skowron, R., 2009. Changeability of the ice cover on the lakes of northern Poland in the light of climatic changes. Bull. Geogr. Phys. Geogr. Ser. 103–124.

Tanentzap, A.J., Yan, N.D., Keller, B., Girard, R., Heneberry, J., Gunn, J.M., Hamilton, D.P., Taylor, P.A., 2008. Cooling lakes while the world warms: Effects of forest regrowth and increased dissolved organic matter on the thermal regime of a temperate, urban lake. Limnol. Oceanogr. 53, 404–410. doi:10.4319/lo.2008.53.1.0404

Tomé, A.R., Miranda, P.M.A., 2004. Piecewise linear fitting and trend changing points of climate parameters. Geophys. Res. Lett. 31, L02207. doi:10.1029/2003GL019100

Toms, J.D., Lesperance, M.L., 2003. Piecewise regression: a tool for identifying ecological thresholds. Ecology 84, 2034–2041. doi:10.1890/02-0472

Van Cleave, K., Lenters, J.D., Wang, J., Verhamme, E.M., 2014. A regime shift in Lake Superior ice cover, evaporation, and water temperature following the warm El Niñ winter of 1997–1998. Limnol. Oceanogr. 59, 1889–1898. doi:10.4319/lo.2014.59.6.1889

Wan, H., Wang, X.L., Swail, V.R., 2010. Homogenization and trend analysis of Canadian near-surface wind speeds. J. Clim. 23, 1209–1225. doi:10.1175/2009JCLI3200.1

Wilhelm, S., Adrian, R., 2008. Impact of summer warming on the thermal characteristics of a polymictic lake and consequences for oxygen, nutrients and phytoplankton. Freshw. Biol. 53, 226–237. doi:10.1111/j.1365-2427.2007.01887.x

Williams, G., Layman, K.L., Stefan, H.G., 2004. Dependence of lake ice covers on climatic, geographic and bathymetric variables. Cold Reg. Sci. Technol. 40, 145–164. doi:10.1016/j.coldregions.2004.06.010

Winslow, L.A., Read, J.S., Hansen, G.J.A., Hanson, P.C., 2015. Small lakes show muted climate change signal in deepwater temperatures. Geophys. Res. Lett. 42, 2014GL062325. doi:10.1002/2014GL062325

Ying, L., Shen, Z., Piao, S., 2015. The recent hiatus in global warming of the land surface: Scale-dependent breakpoint occurrences in space and time: SCALE-DEPENDENT HIATUS IN SPACE AND TIME. Geophys. Res. Lett. 42, 6471–6478. doi:10.1002/2015GL064884

Appendix A

Publications:

Magee, M. R., Wu, C. H., Robertson, D. M., Lathrop, R. C., and Hamilton, D. P.. 2016. Trends and abrupt changes in 104-years of ice cover and water temperature in a dimictic lake in response to air temperature, wind speed, and water clarity drivers, Hydrol. Earth Syst. Sci. Discuss., doi:10.5194/hess-2015-488.

Magee, M.R. and Wu, C.H. Effects of changing climate on ice cover in three morphometrically different lakes. *Accepted under revision to* Hydrological Processes

Magee, M.R. and Wu, C.H. Response of water temperature and stratification to changing climate in three lakes with different morphometry. *Submitted to* International Journal of Limnology

Presentations:

Magee, M.R. and Wu, C.H. (March 2016). *Fish kills and oxythermal stress under climate and land use changes*. Wisconsin Ecology Symposium, Madison, WI, Poster Presentation. 60 attendees.

Magee, M.R. and Wu, C.H. (March 2016). *Fish kills and oxythermal stress under climate and land use changes*. American Water Resources Association-Wisconsin Section, Wisconsin Dells, WI, Poster Presentation. 50 attendees.

Magee, M.R. (February 2016). *Impact of climate change on ice cover and thermal structure in response to changing climate*. Environmental Engineering seminar. Madison, WI, Oral presentation. 25 attendees.

Magee, M.R. and Wu, C.H. (March 2015). *Temperature Dosage: A Novel Method for Quantifying Oxythermal Stress in Coldwater Fish Species*. American Water Resources Association-Wisconsin Section, Oconomowoc, WI, Poster Presentation. 50 attendees.

Magee, M.R. (April 2013). *Oxythermal Stress of Cisco in Fish Lake in Response to Changing Climate*. North Temperate Lakes LTER Young Scientist Meeting, 30 attendees

Magee, M.R. and Wu, C.H. (March 2013). *Oxythermal Stress of a Dimictic Lake in Response to Changing Climate*. American Water Resources Association-Wisconsin Section. Brookfield, WI. Oral Presentation. 25 attendees

Gerdts, N. and Wu, C.H. (March 2013) *Seasonal evaporation of two different morphometry lakes under changing climate.* American Water Resources Association-Wisconsin Section. Brookfield, WI. Oral Presentation. 30 attendees

Magee, M.R. and Wu, C.H. (November 2012). *Impacts of Climate Change on Ice Cover and Thermal Structure in Southern Wisconsin Lakes of Differing Morphometry.* 32nd International Symposium of the North American Lake Management Society. Madison, WI. Oral Presentation 40 attendees

Magee, M.R. and Wu, C.H. (March 2012). *Impacts of Climate Change on Ice Cover and Thermal Structure in Three Southern Wisconsin Lakes of Differing Morphometry*. American Water Resources Association-Wisconsin Section. Wisconsin Dells, WI. Oral Presentation. 30 attendees

Magee, M.R. (November 2011). *Impact of Climate Change on Ice Cover in Three Southern Wisconsin Lakes with Differing Morphometry*. North Temperature Lakes LTER Young Scientist Meeting, 25 attendees

Magee, M.R. and Wu, C.H. (September 2011). *Trends of Ice Cover and Thermal Structure of Three Southern Wisconsin Lakes*. National Science Foundation, LTER-NTL Site Review. Trout Lake Station, WI. Poster Presentation. 30 attendees

Students:

First Name: Madeline
Last Name: Magee
Campus: University of Wisconsin-Madison
Advisor First Name: Chin
Advisor Last Name: Wu
Advisor Campus: University of Wisconsin-Madison
Degree/Training *(Masters, PhD, Post-Doc, Expected Masters, Expected PhD, Expected Other, Undergraduate, Other)*: Expected PhD
Graduation Month: December
Graduation Year: 2016
Department: Department of Civil and Environmental Engineering
Contact: mrmagee@wisc.edu

First Name: Nathan
Last Name: Gerdts
Campus: University of Wisconsin-Madison
Advisor First Name: Chin
Advisor Last Name: Wu
Advisor Campus: University of Wisconsin-Madison
Degree/Training *(Masters, PhD, Post-Doc, Expected Masters, Expected PhD, Expected Other, Undergraduate, Other)*: Masters
Graduation Month: May
Graduation Year: 2015
Department: Department of Civil and Environmental Engineering
Contact: ngerdts@wisc.edu

Impact:

Results of the investigation of the impact of changing climate to Wisconsin lakes provides quality information to lake managers and other researchers. Understanding the change of water temperature may allow regulatory agencies to determine which lakes may become at risk for invasive species. This allows agencies to direct their manpower to a few specific lakes to prevent species spread rather than having to monitor a variety of lakes, some of which may not be at risk to invasive species. Additionally, as water temperature greatly affects fish species within the lakes, understanding which lakes may be at risk for fish kills due to increasing stratified period or increasing water temperatures may allow for mitigation efforts to protect important fish populations.