Project Number WR10R002

RESPONSE OF ICE COVER, LAKE LEVEL, AND THERMAL STRUCTURE CLIMATE CHANGE IN WISCONSIN LAKES

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

Administered by:
University of Wisconsin Water Resources Institute

Funded by:
The National Institutes for Water Resources, U.S. Geological Survey 104b program
State of Wisconsin Groundwater Research and Monitoring Program

Funding Year: 2010

This project was supported by the United States Geological Survey National Institutes for Water Resources 104b program. Under the provisions of section 104 of the Water Resources Research Act of 1984, annual base grants (104b) are awarded to the Institutes or Centers that have been established in each of the 50 states, the District of Columbia, Puerto Rico, the U.S. Virgin Islands, and Guam. The annual base grants help each Institute or Center to plan and conduct applied and peer reviewed research on water resource issues. Institutes also use their base grants to help train new scientists, disseminate research results to water managers and the public, and to cooperate with other colleges and universities in their respective states and with other institutes and other organizations in their regions to promote regional coordination.

This project was also supported, in part, by General Purpose Revenue funds of the State of Wisconsin to the University of Wisconsin System for the performance of research on groundwater quality and quantity. Selection of projects was conducted on a competitive basis through a joint solicitation from the University and the Wisconsin Departments of Natural Resources; Agriculture, Trade and Consumer Protection; Commerce; and advice of the Wisconsin Groundwater Research Advisory Council and with the concurrence of the Wisconsin Groundwater Coordinating Council.

Response of Ice Cover, Lake Level, and Thermal Structure to Climate Change in Wisconsin Lakes

Principle Investigator: Chin H. Wu, University of Wisconsin-Madison

Table of Contents

List of Tables

List of Figures

Project Summary

Title: Response of Ice Cover, Water Level, and Thermal Structure to Climate Change in Wisconsin Lakes

Project I.D.: WR10R002

Investigators:

Principal Investigator: Chin Wu, Professor, Department of Civil and Environmental Engineering, University of Wisconsin-Madison

Research Assistant: Yi-Fang Hsieh, Ph.D. Student, Department of Civil and Environmental Engineering, University of Wisconsin-Madison

Research Assistant: Anastasia Gunawan, M.S. Student. Department of Civil and Environmental Engineering, University of Wisconsin-Madison.

Research Assistant: Madeline Magee, M.S. Student. Department of Civil and Environmental Engineering, University of Wisconsin-Madison.

Period of Contract: 3/2/2010-2/28/2011

Background/Need:

Previous research has shown evidence that the climate is changing worldwide, and more specifically, in Wisconsin.

Objectives:

The goal of this project was three-fold. First, taking a specific dimictic lake in southern Wisconsin, we wanted to determine how long-term changes in air temperature and wind speed affect ice cover and thermal structure in during the past century. Second, looking at northern Wisconsin and southern Wisconsin lakes, we wanted to investigate the coherence among lake climate drivers between the two locations as well as coherence of changes in lake physical variables over the period 1989-2010. Finally, using southern Wisconsin lakes, we wanted to investigate what role lake morphometry (i.e. depth and surface area) play in lake response to changing climate.

Methods:

Using the DYRESM-Ice model developed as part of this project, we simulated long-term lake physical variables of ice cover, water temperature, and water temperature to determine how the lakes have responded to the past changing climate.

Results and Discussion:

Overall, our results indicate that there has been a warming trend in air temperature for both northern and southern Wisconsin. Additionally, there has been a trend of decreasing wind speed. During this same period, there has been a decrease in overall ice cover duration and ice thickness during the study period. Additionally, there has been an increase in stratification duration in the study lakes, a decrease in hypolimnetic water temperatures, and an increase in epilimnetic water temperatures. Air temperature and wind speed are both correlated with changes in lake physical variables. There also seems to be a strong coherence between air temperatures among northern and southern lakes and a lower coherence for wind speed. For lake physical variables, there is a strong coherence in freeze dates between the north and south and epilimnetic water temperatures between northern and southern lakes. Other lake variables did not exhibit a strong coherence over the study period.

Conclusion/Implications:

DYRESM-I has demonstrated the capability in accurately predicting ice cover and water temperature over a continuous 100-year period. To our knowledge, this study presents the first attempt to continuously model both ice cover and thermal structure of a dimictic lake over a period of as long as a century. This type of modeling provides a first step toward projecting the impacts of future climate change on lakes, which can help gain better ideas of how the changing climate will affect lakes. To better understand the full effects of climate change, future modeling incorporating physical/chemical/biological interactions would be crucial and essential.

Related Publications:

Hsieh, Y.F., Robertson, D.M., Lathrop, R.C. and Wu, C.H. Influences of air temperature, wind, and water clarity on 100-year trends in ice cover and water temperature in a dimictic lake. *Limnology and Oceanography*. accepted under minor revision

Gunawan, A.A. and Wu, C.H. Coherence pattern of ice cover and thermal regime between Northern and Southern lakes of Wisconsin in response to changing climate. *To be submitted, Limnology and Oceanography*

Magee, M.R. and Wu, C.H. Long-term trends and variability in ice cover and thermal structure in three morphometrically different lakes in response to climate change. *To be submitted, Water Research*

Key Words: Ice cover, hydrodynamics, climate change, lake morphometry, lake response, long-term, coherence

Funding:

Interior, US Geological Survey
NSF-Long Term Ecological Research- North Temperate Lakes

Introduction

Physical lake variables, such as ice thickness and thermal structure, are sensitive to changes in climate. and they may act as indicators of climate change (Adrian, et al., 2009). Understanding how lakes respond to climate drivers is of great interest to the scientific and lake management communities. While many lake variables are sensitive to climate change, physical variables (i.e. ice cover and thermal structure) are generally more coherent with climate than chemical or biological variables (Magnuson et al., 2006). Specifically, evidence shows that lake physical variables are sensitive to air temperature and wind speed (Adrian, et al., 2009; Williams & Stefan, 2006). Increases in air temperature can (a) decrease ice cover duration and ice thickness in lakes (Magnuson et al., 2000; Williams & Stefan, 2006), (b) increase epilimnetic temperatures (Robertson & Ragotzkie, 1990), and (c) increase the length of the summer stratification period (Livingstone, 2003). Wind speed has also been established to be very important in lake mixing (Boehrer & Schultze, 2008) and ice formation (Adams, 1976). Variations of those physical variables due to changes of climate in turn affect lake ecosystems (MacKay et al., 2009). For example, changes in water temperature, lake mixing, timing and duration of stratification, and timing of ice cover affect primary production, growth rates of zooplankton, and nutrient supply (MacKay, et al., 2009). Elevated temperatures during the open water season may cause changes to plankton community compositions (Elliot et al., 2005) and changes in fish populations (Carpenter et al., 1992). To better manage lakes, it is crucial to determine how climate change will affect these physical lake variables.

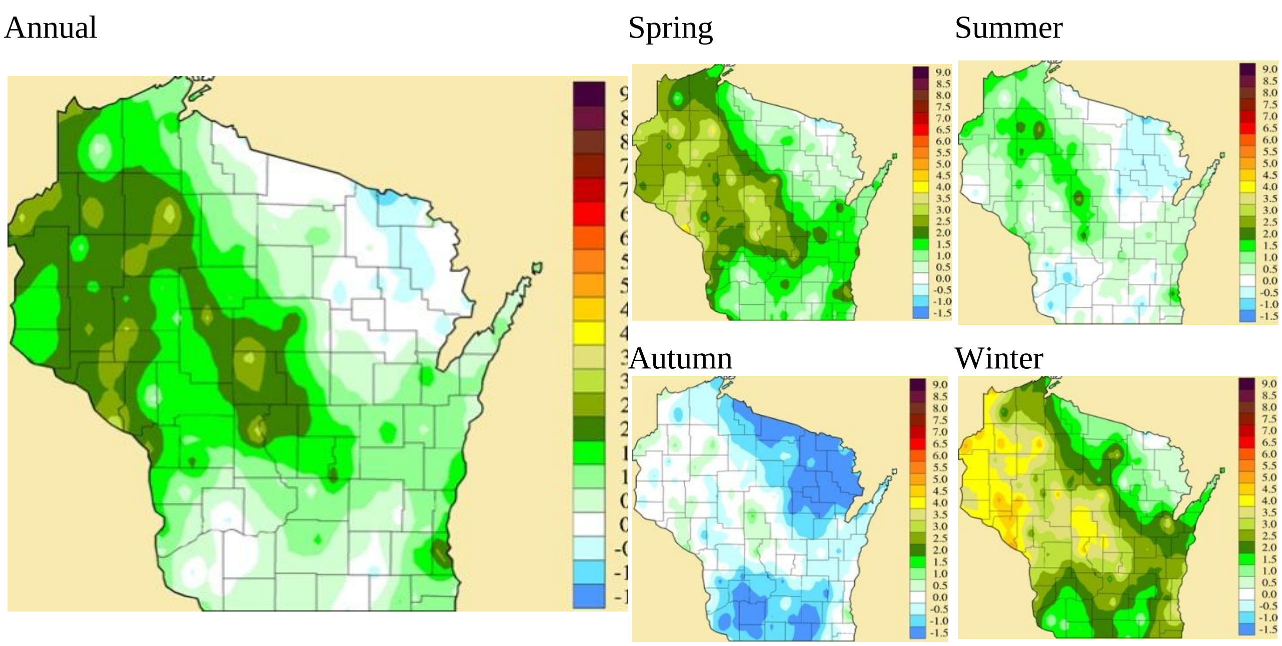

Figure 2 Change in averaged temperature (^{o}F) from 1950 to 2006 from WICCI downscaled data

Evidence shows that over the past 100 years, the global climate has been changing and may continue to change. Global average air temperature has increased by 0.74°C over the last 100 years (IPCC, 2007). Lake-rich regions like the Midwest have seen similar trends in climate change. In Wisconsin, there has been observed a climate warming of 1.1^{o}F averaged across the state. The warming trend shows the greatest warming in the spring (+1.7 ^{o}F across the state) and winter (+2.5 ^{o}F across the state), as shown in Figure 2. Except for northeast Wisconsin, the state appears to be losing the "cold" weather.

Morphometry can impact some of the same physical mechanisms as climate (Adrian et. al. 2009). Previous research has mainly investigated the response of individual lakes and the bulk response of lakes in a geographic region to changing climate (Magnuson et al., 2000). Lake morphometry is known to affect wind fetch, water circulation, and heat storage (Jeffries & Morris, 2007), which can in turn influence ice cover and thermal structure (Brown & Duguay, 2010). Energy for ice growth and decay is determined in part by heat stored in the lake which is mainly affected by the depth, area, and volume of a lake (Williams G. , 1965), and deeper lakes may take longer to freeze as they contain more water that must be cooled (Williams & Stefan, 2006). Larger lake surface area facilitates greater surface heat flux, allowing the lake to adjust to isothermal conditions more quickly (Williams & Stefan, 2006). Lakes with smaller surface areas experience smaller degrees of vertical mixing than those with larger surface area, which may be caused by the significantly large lakes increasing the effects of wind mixing. Differences in vertical mixing caused by surface area may affect the bottom water temperatures especially, as vertical mixing in spring and fall is an important mechanism for transferring heat to the lake bottom. Bathymetric variables, such as lake surface area and mean depth, might account for variability in long term lake responses to climate change. While it is known that morphometry and climate both affect the thermal properties of a lake, previous research has not determined for what variables climate is more dominant than lake morphometry and vice versa.

Additionally, understanding the spatial coherence of climatic drivers (e.g. air temperature and wind) among lake districts is useful in investigating the pattern of lake physical variables (e.g. ice cover and thermal regime) in response to changing climate (Kratz et al. 1998; Benson et al. 2000). Strong coherence pattern in climatic drivers, including the inter-annual and inter-seasonal variation and the long-term trend, may cause a coherent response of lake physical variables that have a profound impact on biological and chemical variables of lake. For example lake ice cover and thermal regime has significance on oxygen distribution, nutrient supply, and biological production (Hondzo and Stefan 1991; King 1997). In addition, lake ice cover can affect lake thermal regime, such as epilimnetic and hypolimnetic temperature, thermocline depth, and duration of stratification during open-water period (Mishra et al. 2011) that has an implication to vertical density variation (Dake and Harleman 1969), oxygen distribution, increase or decrease of the thermal habitat (Magnuson et al. 1990), and fertility and growth rate of fishes (McCauley and Casselman 1981; Coutant 1990). As a result, pattern of lake physical variables influenced by climatic drivers among lake districts is valuable in determining the overall coherent response among different lake districts to the changing climate.

The overall goal of this project consists of three main components. (A) The first is to investigate how long-term changes in three important drivers (air temperature, wind speed, and water clarity) affect ice cover than thermal structure in a dimictic lake during the past century including three selected study periods (1911-1981, 1982-1993, and 1994-2010) as determined by regression analysis to be distinct periods of climate drivers. (B) The second is to investigate the spatial coherence of climate drivers at different time scales: monthly, seasonal, and annual, and determine the temporal coherence of thermal regime and ice cover response between Northern and Southern lakes of Wisconsin for the selected period (1989-2009). In addition, the lake thermal regime and ice cover in response to climate variability (e.g. El Niño and La Niña year) will be investigated. (C)The final component is the investigation of the role of lake morphometry in long-term changes and variability of lake ice cover and thermal structure using the three Southern Wisconsin lakes of Lake Mendota, Fish Lake, and Lake Wingra as our study sites. For all three components of investigation, a newly developed one-dimensional hydrodynamic lake-ice model, DYRESM-I, is validated and employed to run continuously. To determine spatial coherence, the simulations are run continuously from 1989-2010, and for the long-term investigations of climate drivers and lake morphometry, simulations are run from 1910-2010.

Procedures and Methods

Study Lakes

Lakes used in the studies were: Lake Mendota (43°6'N, 89°24'W), Lake Wingra (43°3' N, 89°26' W), Fish Lake (43°17'N, 89°39'W), and Lake Monona (43° 03' N, 89° 21' W) located near Madison, Wisconsin, USA and Trout Lake (46° 01' N, 89° 39' W)located within the Trout Lake Area district in northern Wisconsin. Table 1 summarizes the characteristics of the study lakes.

Table 2 Characteristics of the study lakes.

	Depth (m)		Surface area	Hydrological type[a]		GW[b]	Surface flow		Ice cover duration[1]	Projected ΔT_{air}[d]
	Mean	Max	(ha)	GW[b]	Surface	(%)	Inlet	Outlet	(day)	(°F)
Trout Lake	14.6	35.7	1607.9	GD	DR	35[c]	4	1	135	11.5
Lake Monona	8.2	22.5	1324.0	GD	DR		3	1	105	10.5
Lake Mendota	12.8	25.3	3937.7	GD	DR	~30[d]			119	10.5
Lake Wingra	2.7	6.7	139.6	GFT	DR	35[e]	0	1	120	10.5
Fish Lake	6.6	18.9	87.4	GFT	SE	6[f]	0	0	na	10.5

[a]GD = groundwater discharge; DR = groundwater recharge; GFT = groundwater flowthrough.
[b]GW = percentage groundwater input.
[g]ΔT_{air} = projected change in annual averaged air temperature to the end of century for the A2 scenario from WICCI.
Note: Lake data are from Long Term Ecological Research (LTER) website (http://lter.limnology.wisc.edu/), Webster et al. (1996)[c], Brock et al. (1982)[d], Novitzki and Holmstrom (1979)[e], and Krohelski et al. (2002)[f].

Model Development

An ice model is added to DYRESM-WQ model (Hamilton and Schladow, 1997). The resulting model, DYRESM-I, is validated and employed to simulate vertical distribution of water temperature and ice cover in Lake Mendota. In this model, the lake is represented by a series of Lagrangian horizontal layers with uniform properties that may change in elevation and thickness in response to inflows/outflows and surface mass fluxes (evaporation and precipitation). Layer thickness is updated using an algorithm to give appropriate vertical resolutions at each time step. Mixing in the model is represented by merging the layers that are mixed when the sum of available turbulent kinetic energy (TKE) produced by wind stirring, convective overturn, and shear exceeds the potential energy required to mix the next layer below. Hypolimnetic mixing is modeled with an eddy diffusivity coefficient that is a function of the dissipation of TKE and stratification strength. More detailed descriptions of the simulation of water temperature and mixing can refer to Imberger and Patterson (1981).

In the ice module, heat conduction equations for blue ice, snow ice (white ice) and snow are solved. The ice module is applied when surface water temperature first drops below 0°C, and the initial ice thickness is set to a minimum value of 5 cm. Snow ice is generated in response to flooding, when the mass of snow that can be supported by the ice cover is exceeded. Snow compaction is based on an exponential decay formula, with snow compaction parameters based on air temperature and snowfall/rainfall (Rogers et al. 1995). When ice thickness decreases to less than 5 cm, conduction is discontinued and open water conditions are restored. For brevity, a detailed description of the ice module is not provided here but can refer to Hsieh (2011). Figure 2 illustrates the components in DYRESM-Ice. Heat fluxes between ice or snow and the

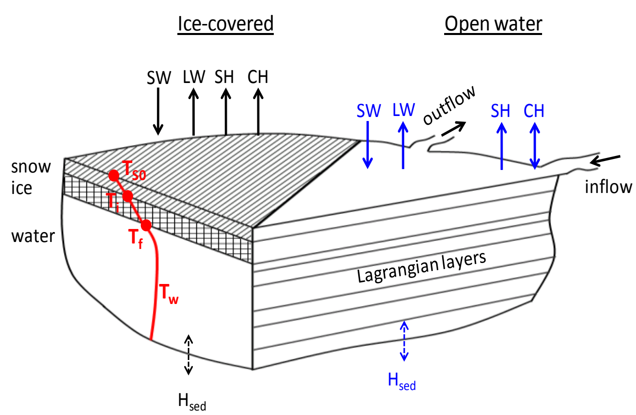

Figure 2: Schematic diagram of the hydrodynamic model. SW: shortwave radiation; LW: longwave radiation; SH: sensible heat flux; CH: conductive heat flux; H_{sed}: sediment heat flux.

atmosphere, ice and water, and bottom sediments and water are calculated to determine water column temperatures beneath the ice and the formation and ablation of ice and snow cover.

Model Calibration

Model validation was conducted by running past climate scenarios in the study lakes. Meteorological data inputs to the model were taken from records at meteorological stations close to the study lakes. Data from Minocqua Dam and Noble F. Lee Municipal Airport at Woodruff represents the climate data for northern lakes. For southern lakes, data from the Dane County Regional Airport are used. These data, taken at various sub-daily intervals, were averaged over the day to provide suitable input for DYRESM-Ice simulations. The data included air temperature, relative humidity, wind speed, total daily shortwave radiation, precipitation, snowfall, and cloud cover. Model performance was evaluated by comparing the simulated results against the measured ice thickness, ice duration, and water temperature values. Figure 3 shows an example of the performance of the model for Lake Mendota.

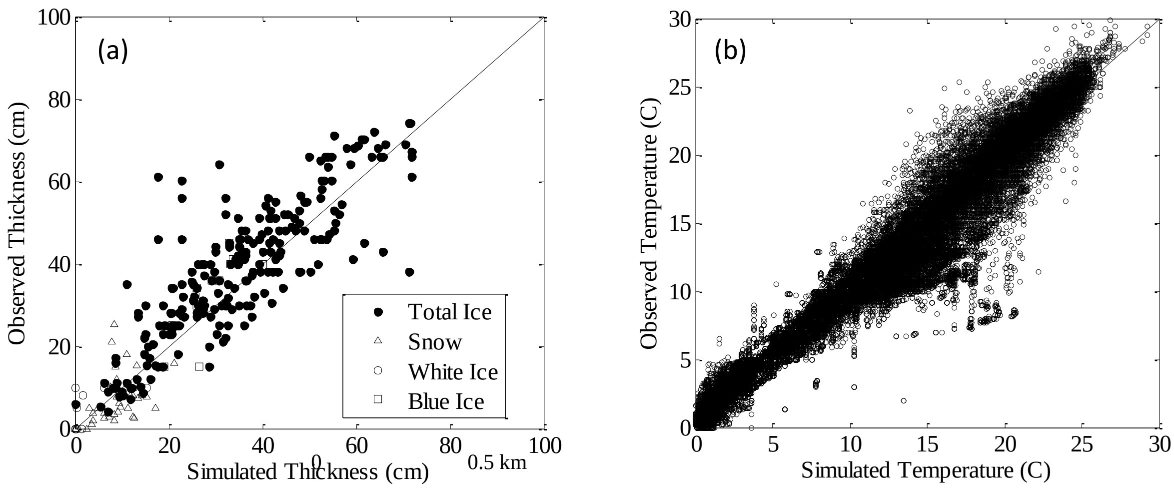

Figure 3: comparison of observed and simulated ice cover and temperature for Lake Mendota

Data Analysis.

For various portions of this project, linear regression is applied to model results and observational data to describe long-term trends and compared to the climate changes. Additionally, Pearson correlation analysis is conducted to investigate how the changes in air temperature and wind speed influence the lake variables. In this analysis, each of the lake drivers is averaged over a fixed period then paired with each of the above-mentioned lake variables from the model results to calculated correlation coefficients. The averaging period for air temperature and wind speed is chosen based on the period that gives the best correlation. Linear regression and Pearson correlation analysis was conducted to determine the coherence between the climate of the northern and southern lake districts and the coherence between the changes in lake variables. Additionally, the Fast Fourier Transform (FFT) procedure was used to determine periodicity or cycles in lake drivers (air temperature and wind speed) and lake variables (ice cover and thermal structure). In this method, the amplitude and the frequency location of the spectral peaks are detected by means of a cubic spline interpolation.

Results and Discussion

Relative importance of lake drivers

Pearson correlation analysis is conducted to investigate how changes in air temperature and wind speed influenced the lake variables (i.e., ice dates, maximum ice thickness, freeze-over water temperature, mid-summer epilimnetic and hypolimnetic temperatures, summer hypolimnetic heating, and dates of stratification onset and fall turnover) and their relative importance for Lake Mendota

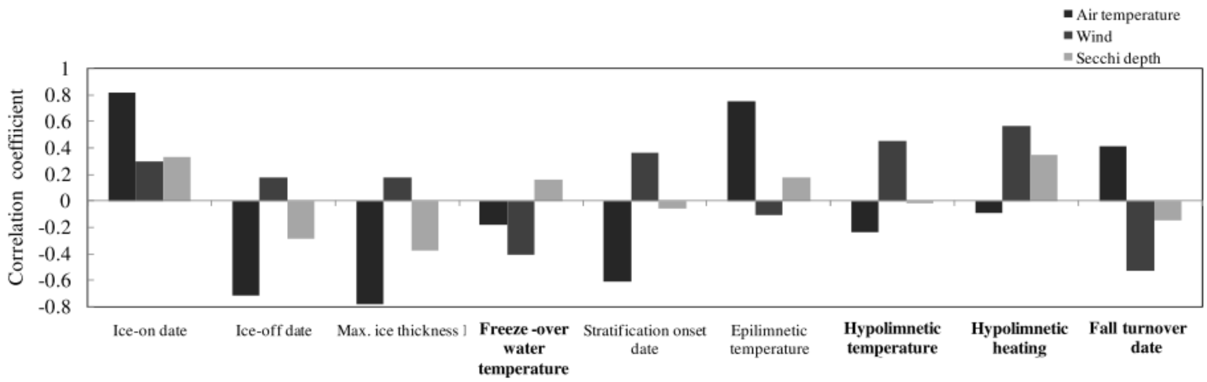

Figure 4: correlation coefficients between lake variables and drivers. Bold font emphasizes variables that are more correlated with wind speed than air temperature. The critical value for significan correlation ($p<0.05$) is 0.194 ($n=99$)

Air temperature, wind speed, and water clarity have been shown to be three important drivers to affect lake ice cover and thermal structure (see Figure 4). Based on the results, air temperature is the most important driver for the ice cover variables (i.e., ice-on and ice-off dates, and maximum ice thickness) and two of the stratification variables (onset of stratification and epilimnetic temperature). Wind speed is the most important driver of freeze-over water temperature, hypolimnetic temperature, hypolimnetic heating, and date of fall turnover. For several of the variables (onset of stratification, hypolimnetic temperature, and fall turnover date), both air temperature and wind speed are dominant drivers. Nevertheless water clarity in this study is found to be a less dominant driver, but can play some role in ice-off date, maximum ice thickness, and hypolimnetic heating.

The date of the onset of stratification is negatively correlated with air temperature and positively correlated with wind speed, indicating that warmer air temperatures and lower wind speeds result in earlier stratification. Austin and Colman (2007) suggested that the declining ice cover combined with higher air temperatures cause the earlier onset of stratification in Lake Superior at a rate of 0.5 day/yr. However, no correlation between ice-off date and the onset of stratification is found for Lake Mendota in this study.

Coherence between northern and southern lakes

(i) Air temperature and wind speed as climatic drivers

Figure 5 shows the coherence of air temperature and wind speed for monthly, seasonal, and inter-annual from 1989 to 2009. A strong spatial coherence ($p<0.05$) of air temperature and different time scales between northern and southern Wisconsin suggests that air temperature is a function of large-scale air masses. In addition, there was also an observed similar pattern of warm and cold years associated with El Niño and La Niña events in northern and southern Wisconsin. The analysis of wind speed coherence indicates that it has a significant coherence at inter-annual level, but has variability of low and strong coherence at monthly and seasonal scale. Depending on the

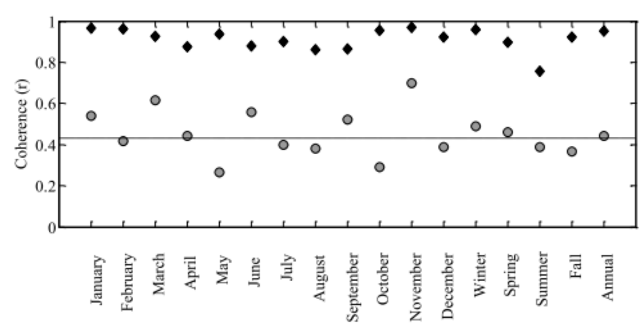

Figure 5: Coherence of annual and seasonal mean air temperature (black filled) and wind speed (gray filled) between lake districts. Dashed line represents the value where strong coherence is defined (0.433 when $p<0.05$).

period of the year where it has low coherence, wind speed acts as a local-scale climate driver that depends on the local topography and varying pressure gradient. In addition, there is a tendency for the coherence of the climatic drivers between northern and southern Wisconsin to be less significant at smaller time-scale (e.g. monthly compared to seasonal) as the variability of the climatic drivers gets larger.

(ii) Spatial coherence of lake physical variables

The computed temporal coherence mean of physical variables of interest from Trout Lake-Lake Monona pair ($\bar{r}$) was 0.43. For ice cover period (freeze date, break-up date, and annual maximum ice thickness) and thermal regime response (epilimnetic temperature, hypolimnetic temperature, onset of stratification date, and fall turnover date), the computed mean of coherence was 0.52 and 0.36, respectively. Figure 6 describes the spatial coherence of seven lake ice cover and thermal regime variables from model simulation result for 21 years. During ice cover period, ice freeze date had a strong coherence (r = 0.75), and ice break-up date had a lower coherence (r = 0.38). Maximum ice thickness annual variation (r = 0.42) had a weaker coherence compared to ice freeze date, but stronger than ice break-up date. For lake thermal regime, coherence was the strongest for epilimnetic temperature (r = 0.80). In the contrary, hypolimnetic temperature was not coherent (r = –0.15). This result was similar to that found by Benson et al. (2000), which the coherence was strong for epilimnetic temperature and it was weak for hypolimnetic temperature between Madison Lake Area and Trout Lake Area. In addition, coherence of water surface temperature was investigated at different temporal scales: monthly, seasonal, and annual. Except for month of January, February, and March and winter season, water surface temperature had a strong coherence (p < 0.05) between Trout Lake and Lake Monona. The grand average of monthly coherence (January – December) was 0.58 and the overall average of seasonal coherence (winter – fall) was 0.62, while the average of annual coherence was 0.69. In addition, the coherence found for onset of stratification date and fall turnover date was low (r = 0.17 and r = 0.29, respectively).

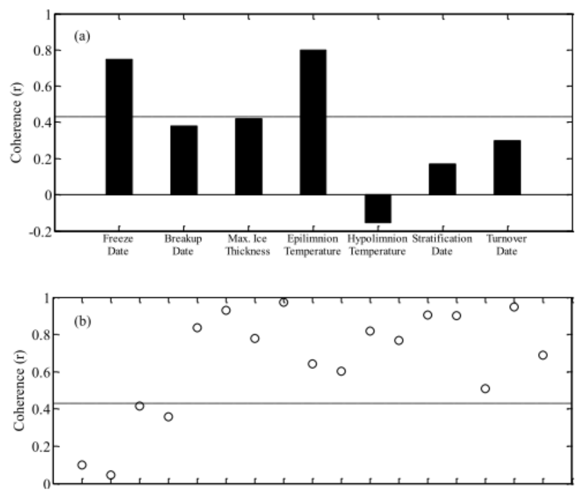

Figure 6: Coherence for seven lake ice cover and thermal regime variables between Trout Lake in northern Wisconsin and Lake Monona in southern Wisconsin (a). Coherence of near surface water temperature for monthly, seasonal, and annual scale (b). Dashed line represents the critical value for significant correlation (p < 0.05)

Effect of lake morphometry on climate change response

(i) Long term trends of variables

Trends for the nine lake variables for each lake during the 100-year study period are given in Table 2. The direction of the trend for each of the three lakes is the same, although the magnitude of the trend can differ greatly among the three lakes. For example, ice on dates in all three lakes have a linear trend of occurring later during the study period; however Lake Mendota and Lake

Wingra have relatively small changes of 7.1 days and 4.4 days, respectively, while Fish Lake has a large change of 20.9 days earlier ice-on per 100 years. Since the early 1900s, the air temperatures near Madison, Wisconsin have increased at a rate of 1.36°C per 100 years, and the wind speeds have decreased at a rate of 0.61 m/s per 100 years. The statistically significant long term trends found in the nine studied lake variables indicate that the changing air temperature and wind speed are influencing these lake variables.

Table 2: trends in lake physical variables for each of the three lakes from 1911-2010

	Lake Mendota	Lake Wingra	Fish Lake
Ice On	7.1 days later	4.4 days later	21.1 days later
Ice Off	9.6 days earlier	15.7 days earlier	14.8 days earlier
Ice Duration	16.7 fewer days	20.1 fewer days	35.9 fewer days
Maximum Ice Thickness	13 cm less	11 cm less	14 cm less
Stratification Onset	11.5 days earlier	N/A	8.1 days earlier
Fall Overturn	11.8 days later	N/A	16.4 days later
Stratification Duration	23.2 more days	N/A	24.5 more days
Summertime Epilimnetic Temperature	0.72°C increase	1.80°C	1.88°C increase
Summertime Hypolimnetic Temperature	0.83°C decrease	N/A	1.20°C decrease

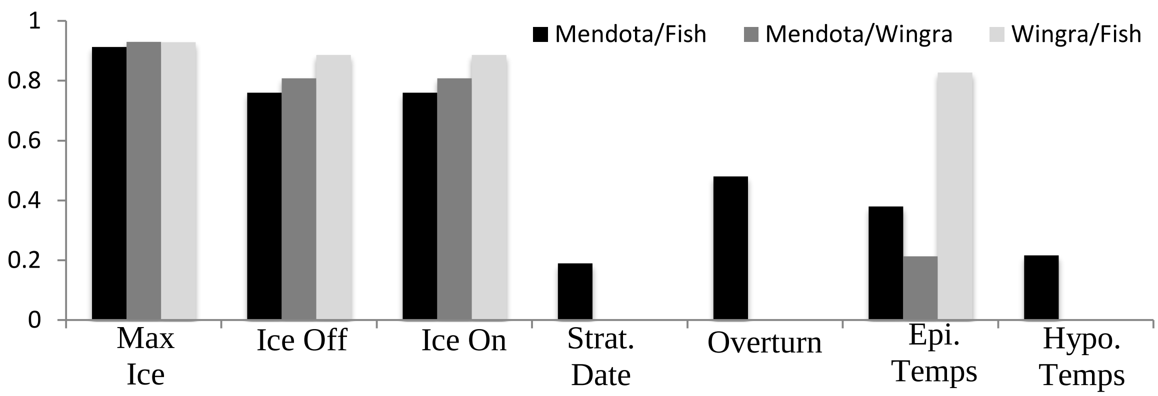

Figure 7: Correlation coefficients for lake groupings. Black is for Lake Mendota and Fish Lake, dark grey is for Lake Mendota and Lake Wingra, and light grey is for Lake Wingra and Fish Lake.

(ii) Variability and coherence among the lakes

While lake variables in all three study lakes have experienced the same direction of change over the past 100 years, the specific value of that change, and variability of the lake changes have differed among the study lakes. Figure 7 shows the correlation coefficient of the lake variables for pairs of study lakes. The pairs are (i) Mendota and Fish Lake, (ii) Lake Mendota and Lake Wingra, and (iii) Lake Wingra and Fish Lake. Ice cover variables (i.e. maximum ice thickness, ice-on date, ice-off date) have high correlation coefficients among the lake variables. Open water season variables (stratification onset, fall overturn, epilimnetic temperatures, and hypolimnetic temperatures) have low correlation coefficients, with the exception of the epilimnetic temperatures of Lake Wingra and Fish Lake. Differences in trends and variability, along with comparisons of correlation coefficients, indicate that differences in lake morphometry may be an important component when determining the response of lake variables to changes in the climate.

(iii) Importance of lake bathymetry under changing climate

The smaller surface area of Fish Lake compared to Lake Mendota likely causes the lake to respond more to changes in climate. Smaller surface lakes tend to gain heat faster in the spring and summer (Boehrer & Schultze, 2008), which likely contributes to the difference in epilimnetic water temperature between the two lakes. Although the main driver to epilimnetic water temperature is air temperature (Boehrer & Schultze, 2008), the larger surface area of Lake Mendota causes a dampening of the heat flux between the epilimnion and the air. Additionally, Fish Lake's smaller surface area allows for the surface of the lake to gain heat faster than for Lake Mendota, causing earlier average stratification onset and less mixing time (Figure 6) for Fish Lake when compared to Lake Mendota, resulting in warmer average hypolimnetic water temperatures in Lake Mendota and cooler average hypolimnetic water temperatures in Fish Lake. Trend in stratification onset dates are larger for Lake Mendota than for Fish Lake. This likely has to do with the effects of decreasing wind speed, which is very important in stratification onset (Hsieh, et al., in press). The larger fetch of Lake Mendota allows the wind to more greatly affect wind mixing in the lake, so a reduction in wind speed likely has a greater effect of stratification onset in the larger Lake Mendota than the smaller Fish Lake. Ice-on dates for Lake Mendota and Fish Lake are very similar, indicating that the differences in surface area do not have as large of an effect on freezing dates.

Comparing Fish Lake and Lake Wingra allows us to investigate the different role that depth plays in a lake's response to the changing climate. A more shallow lake has a smaller amount of heat storage than a deeper lake (Williams, 1965), which allows for shallow lakes to respond more quickly to changes in climate. Lake Wingra does not stratify in the summer months, because it's shallow depth allows wind-induced and heat-transfer-induced mixing throughout the whole depth of the lake. The trend in summer-time epilimnetic water temperatures for both lakes is not statistically different, which may indicate that the depth of the lake is not a major factor in the response of the epilimnion to changes in air temperature. Additionally, Lake Wingra experiences significantly earlier ice-on dates than Fish Lake because the increased depth of Fish Lake results in more heat stored, which takes longer to cool to a freezing temperature.

Conclusion and Recommendations

The one-dimensional hydrodynamic ice model, DYRESM-I, is used to simulate the ice cover and thermal structure of five lakes, Lake Mendota, Lake Wingra, Fish Lake, Lake Monona, and Trout Lake. The model successfully reproduces the variations and trends of ice-cover and thermal structure during this period. Simulated stratification onset dates have occurred earlier, fall overturn has occurred later, and stratification duration has increased for all three study lakes. As a result of earlier stratification dates, summer-time hypolimnion water temperatures have decreased. Additionally, epilimnetic water temperatures have increased due to the trend of increasing air temperatures. Ice-on dates have occurred later, ice-off has been happening earlier, and ice-cover period has decreased for all study lakes during the various study periods. These results agree well with the observed data and previous studies.

Overall, results indicate that of the three lakes, Fish Lake has been more affected by the changing climate over the past 100 years than the other two lakes have. All three study lakes show the same statistically significant trends in lake variables over the past 100 years, corresponding to statistically significant changes in lake drivers over the same period. Analysis of periodicity indicates that the lake drivers and the lake variables generally do not share the same cyclic nature, likely due to how the morphometry and hydrology of the lakes affects the response. Fish Lake, with the smaller surface area, responded more drastically to changes in climate drivers than did Lake Mendota. Additionally, Fish Lake also responded more drastically than did Lake Wingra, which is significantly more shallow. Results indicate that the small, deeper lake is more responsive to changes in the Madison area climate.

Correlation results indicate that air temperatures are the most important drivers of the ice cover variables (ice-on and ice-off dates, and maximum ice thickness) and two stratification variables (date of the onset of stratification and epilimnetic temperatures). Wind speeds are the most important drivers of water temperature when the lake freezes, mid-summer hypolimnetic temperature, summer hypolimnetic heating, and date of fall turnover. Both air temperature and wind speed are dominant drivers of the onset of stratification, hypolimnetic temperature, and fall turnover date. Secchi depth is never the single dominant driver, but in combination with wind speed is important in driving hypolimnetic heating. The wind-dominated variables reveals a regime shift around 1994, which results from the amplified effects of a reduction in wind speed and warming air temperatures.

DYRESM-I has demonstrated the capability in accurately predicting ice cover and water temperature over a continuous 100-year period. To our knowledge, this study presents the first attempt to continuously model both ice cover and thermal structure of a dimictic lake over a period of as long as a century. This type of modeling provides a first step toward projecting the impacts of future climate change on lakes, which can help gain better ideas of how the changing climate will affect lakes. To better understand the full effects of climate change, future modeling incorporating physical/chemical/biological interactions would be crucial and essential (MacKay et al., 2009).

References

Adams, W. (1976). Diversity of lake-cover and its implications. *Musk-Ox , 18*, 86-98.

Adrian, R., O'Reilly, C. M., Zagarese, H., Baines, S. B., Hessen, D. O., Keller, W., et al. (2009). Lakes as sentinels of climate change. *Limnology and Oceanography , 54* (6, part 2), 2283-2297.

Boehrer, B., & Schultze, M. (2008). Stratification of Lakes. *Reviews of Geophysics , 46*.

Brown, L. C., & Duguay, C. R. (2010). The response and role of ice cover in lake-climate interactions. *Progress in Physical Geography , 34* (5), 671-704.

Carpenter, S., Fisher, S., Grimm, N., & Kitchel, J. (1992). Global change and fresh-water ecosystems. *Annu. Rev. Ecol. Syst. , 23*, 119-139.

Elliot, J., Thackeray, S., Huntigford, C., & Jones, R. (2005). Combining a regional climate model with a phytoplankton community model to predict future changes in phytoplankton in lakes. *Freshwater Biology , 50* (8), 1404-1411.

Hamilton, D., & Schladow, S. (1997). Prediction of water quality in lakes and reservoirs. Part 1-Model description. *Ecological Modelling , 96*, 91-110.

Hsieh, Y-F (2011). *Modeling Ice Cover and Water Temperature of Lake Mendota. PhD Thesis.* Madison, Wisconsin. University of Wisconsin-Madison.

Intergovernmental Panel on Climate Change (IPCC). (2007). *Working Group 1 Report: The Physical Science Basis. Intergovernmental Panel on Climate Change Fourth Assessment Report*. Cambridge: Cambridge University Press.

Jeffries, M., & Morris, K. (2007). Some aspects of ice phenology on ponds in central Alaska, USA. *Annals of Glaciology , 46*, 398-403.

Livingstone, D. M. (2003). Impact of secular climate chnage on the thermal structure of a large temperate central European lake. *Climate Change , 57*, 205-225.

MacKay, M. D., Neale, P. J., Arp, C. D., De Senerpont Domis, L. N., Fang, X., Gal, G., et al. (2009). Modeling lakes and reservoirs in the climate system. *Limnology & Oceanography , 54* (6, part 2), 2315-2329.

Magnuson, J. J., Robertson, D. M., Benson, B. J., Wynne, R. H., Livingstone, D. M., Arai, T., et al. (2000). Historical Trends in Lake and River Ice Cover in the Northern Hemisphere. *Science , 289*, 1743-1746.

Magnuson, J. J., Kratz, T. K., Benson, B. J., & Webster, K. E. (2006). Coherent Dynamics among Lakes. In J. J. Magnuson, T. K. Kratz, & B. J. Benson (Eds.), *Long-Term Dynamics of Lakes in the Landscape* (pp. 89-106). New York, New York, USA: Oxford University Press.

Robertson, D. M., & Ragotzkie, R. A. (1990). Changes in the thermal structure of moderate to larged sized lakes in response to changes in air temperature. *Aquatic Sciences , 54* (4), 360-380.

Rogers, C., Lawrence, G., & Hamblin, P. (1995). Observations and numerical simulation of a shallow ice-covered midlatitude lake. *Limnology and Oceanography , 40*, 374-385.

Williams, S. G., & Stefan, H. G. (2006). Modeling of lake ice characteristics in North America using climate, geography, and lake bathymetry. *Journal of Cold Regions Engineering , 20*, 140-167.

Wisconsin Initiative on Climate Change Impacts. (2011). *Wisconsin's Changing Climate: Impacts and Adaptations.*

Appendix A: Awards, Publications, Reports, Patents, and Presentations

Publications:

Hsieh, Y.F., Robertson, D.M., Lathrop, R.C. and Wu, C.H. Influences of air temperature, wind, and water clarity on 100-year trends in ice cover and water temperature in a dimictic lake. *Limnology and Oceanography*. accepted under minor revision

Gunawan, A.A. and Wu, C.H. Coherence pattern of ice cover and thermal regime between Northern and Southern lakes of Wisconsin in response to changing climate. *To be submitted, Limnology and Oceanography*

Magee, M.R. and Wu, C.H. Long-term trends and variability in ice cover and thermal structure in three morphometrically different lakes in response to climate change. *To be submitted, Water Research*

Presentations:

Hsieh, Y.F. and Wu, C.H. Future Scenarios of Water Level and Ice Cover in Two Northern Wisconsin Lakes. Sciences in the Northwoods. Camp Manitowish, Boulder Junction, Wisconsin. 30 September, 2010 *oral presentation*

Magee, M.R. and Wu, C.H. Trends of Ice Cover and Thermal STructure of Three Southern Wisconsin Lakes. National Science Foundation, LTER-NTL Site Review. Trout Lake Station, WI. 8 September, 2011. *poster presentation*

Wu, C.H. and Hsieh, Y.F. Response of Wisconsin Lakes (Ice Cover, Water Level, and Thermal Structure) to Climate Change. WICCI Science Meeting. UW-Sea Grant Institute. 1 September, 2010. *oral presentation.*