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RESEARCH ARTICLE

Effects of changing climate on ice cover in three morphometrically different lakes

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Abstract

A one-dimensional hydrodynamic lake model (DYRESM-WQ-I) is employed to simulate ice cover and water temperatures over the period 1911–2014. The effects of climate changes (air temperature and wind speed) on ice cover (ice-on, ice-off, ice cover duration, and maximum ice thickness) are modeled and compared for the three different morphometry lakes: Fish Lake, Lake Wingra, and Lake Mendota, located in Madison, Wisconsin, USA. It is found that the ice cover period has decreased due to later ice-on dates and earlier ice-off dates, and the annual maximum ice cover thickness has decreased for the three lakes during the last century. Based upon simulated perturbations of daily mean 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). Overall, shallower lakes with larger surface areas appear more resilient to ice cover changes caused by climate changes.

KEYWORDS

climate change, ice cover, lake morphometry, lakes, long-term trend

1 | INTRODUCTION

Lake ice cover responds to changes in climate (Magnuson et al., 2000, 2006; Adrian et al., 2009). Alterations of ice cover due to changing climate can incite significant changes to lake thermodynamics and ecosystems (MacKay et al., 2009; Kirillin et al., 2012). For example, disappearance of ice cover can considerably affect photic exposure (Leppäranta et al., 2003), nutrient cycling (Järvinen et al., 2002), and oxygen conditions (Livingstone, 1993), which in turn can change the production and diversity of phytoplankton (Weyhenmeyer et al., 1999; Phillips & Fawley, 2002). Decreases in ice cover duration may lessen the prevalence of low-oxygen conditions and reduce the occurrence of winter fish kills (Fang & Stefan, 2000; Stefan et al., 2001). While those effects can be positive for large fish species, it may hurt other species as winterkill is critical for the maintenance of hypoxia-tolerant but predation-sensitive fish species (Tonn & Magnuson, 1982). As a result, understanding how lakes respond to climate drivers is of great interest to the scientific and lake management communities (Magnuson et al., 1997; Fang & Stefan, 2009). Furthermore, assessing the variations and long-term trend of ice cover in response to climate change can allow for better management of lake ecosystems.

Climate over the past century has been changing significantly, unconditionally affecting the ice regime of lakes (Kirillin et al., 2012). For example, Magnuson et al. (2000) showed that there was later ice-on and earlier ice-off from over a century (1846–1995) for Northern Hemisphere lakes and rivers. Trends of later ice-on and earlier ice-off were found in small inland lakes in the Laurentian Great Lakes region during the time span 1975–2004 (Jensen et al., 2007). Similarly, Korhonen (2006) showed a statistically significant change toward earlier ice-off and later ice-on in Finland. Meanwhile, global average air temperature has increased by 0.74°C over the last 100 years (IPCC, 2007), and various studies have reported both increasing (Pryor et al., 2005; Austin & Colman, 2007) and decreasing (Klink, 2002; Pryor et al., 2009) wind speeds. Air temperature has been shown to drive lake ice cover duration and thickness (Robertson et al., 1992; Williams & Stefan, 2006; Butcher et al., 2015); and ice-on is strongly dependent on the synoptic conditions present over a lake and quickly follow the date of air temperature falling below the freezing point (Kirillin et al., 2012). Greater wind speeds increase lake heat transfer (Read et al., 2012) but delay ice-on by breaking up thin ice during the beginning of ice formation (Adams, 1976). Greater wind shear also breaks thin ice during ice melting periods, especially on large lakes (Ashton, 1986). Understanding the response of lake ice cover to changes in air temperature and wind speed will provide insight into the response to the future climate. While the climate plays a significant role in lake ice cover, detailed research has been limited until recently.

Lake morphometry (i.e., lake depth and surface area) plays a significant role in affecting physical processes like wind mixing, water circulation, and heat storage (Jeffries & Morris, 2007; Adrian et al., 2009), which can in turn influence ice cover (Brown & Duguay, 2010; Bernhardt et al., 2011). Ice growth and decay is determined in part by heat stored in the lake, which is a function of lake depth, surface area, and volume (Williams, 1965). Deeper lakes usually take longer to freeze as their greater volume per surface area must be cooled (Williams & Stefan, 2006; Leppäranta, 2010; Kirillin et al., 2012). Lakes with larger fetch length may experience differences in ice cover early in the season and break up of skim ice (Adams, 1976) since surface area plays a role in terms of wind stress. While previous research has investigated the response of individual lakes (Austin & Colman, 2007; Perroud & Goyette, 2010; Voutilainen et al., 2014) and the bulk response of lakes in a geographic region to changing climate (Magnuson et al., 1990, 2000, Weyhenmeyer et al., 2004, 2011; Kirillin, 2010), very few studies elucidated the role of lakes of varying morphometry on the sensitivity of ice cover in response to a long-term (over a century) changing climate.

The purpose of this paper is to investigate the role of lake morphometry in long-term (1911–2014) changes, variability, and sensitivity of lake ice cover in response to increasing air temperatures and decreasing wind speed. A one-dimensional hydrodynamic lake-ice model is used to run continuous long-term simulations of ice cover and water temperature of three Madison, Wisconsin, area lakes that vary in surface area and depth, and are close to each other (<30-km distance) to experience similar daily meteorological forcing over the period 1911–2014. The application of the model allows for quantifying dates of ice cover and maximum ice thickness, which are difficult to obtain through long-term limnological records.

2 | METHODS

2.1 | Study sites

Figure 1 shows the location and bathymetry of three morphometrically different lakes: Fish Lake, Lake Wingra, and Lake Mendota, located in Madison, Wisconsin, USA. Table 1 lists the morphology and hydrology of the three study lakes. These lakes are chosen for (a) their morphology differences, (b) their proximity to one another, and (c) the availability of long-term limnological records, which are used for model calibration.

Fish Lake (43°17′N, 89°39′W) is a dimictic, eutrophic, and shallow seepage lake located in northwestern Dane County. There are no outlets or inlets for Fish Lake, although during flooding conditions, the nearby Mud Lake may overflow into Fish Lake. Fish Lake has a surface area of 87.4 ha, a mean depth of 6.6 m, a maximum depth of 19.9 m, a shoreline length of 4.3 km, and a fetch of 2 km. Fish Lake has a small

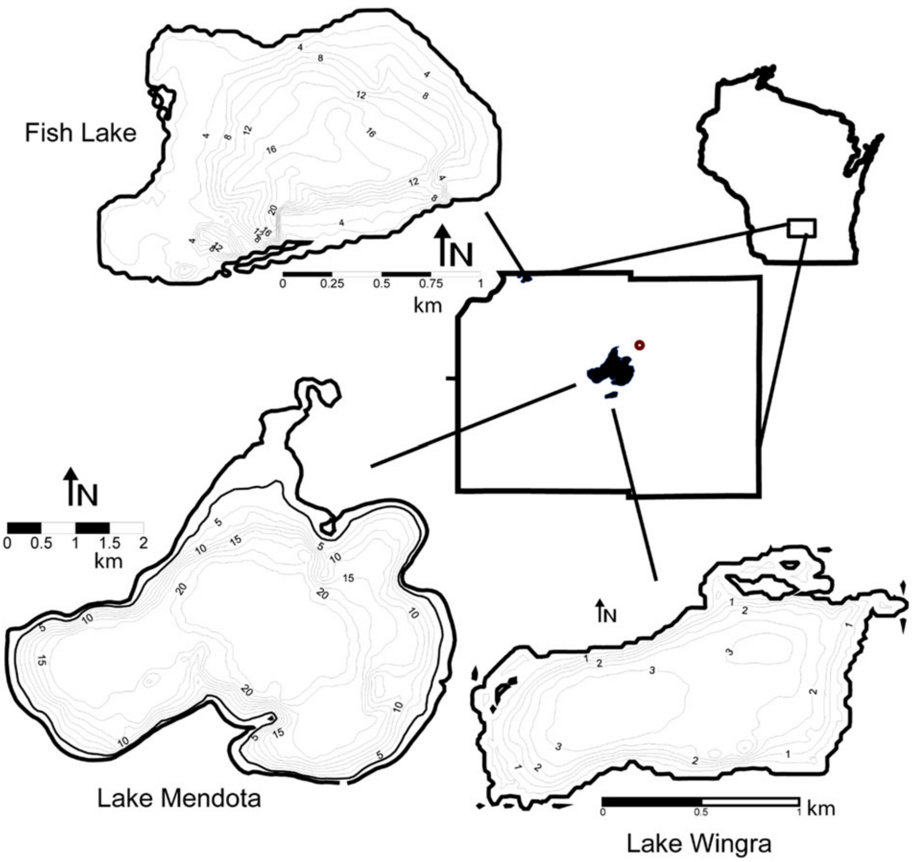

FIGURE 1 Location of three study lakes and bathymetric maps of Fish Lake, Lake Wingra, and Lake Mendota. Circle represents the location of meteorological station

TABLE 1 Morphometric and hydrologic characteristics of the three study lakes

	Fish Lake	Lake Wingra	Lake Mendota
Mean depth (m)	6.6	2.7	12.8
Max depth (m)	19.9	4.7	25.3
Surface area (ha)	87.4	139.6	3937.7
Groundwater	Groundwater flowthrough	Groundwater flowthrough	Groundwater discharge
Surface water	Seepage	Drainage	Drainage
Groundwater input (%)	6	35	30

watershed and has a shoreline development that is classified as high. During the period from 1966 to 2001, the average water level of the lake rose by approximately 2.75 m (Krohelski et al., 2002).

Lake Wingra (43°3′ N, 89°26′ W) is a very shallow and eutrophic lake. Wingra is a drainage lake that has multiple inflowing streams and one outflow stream, Wingra Creek. Lake Wingra has a surface area of 140 ha, a mean depth of 2.7 m, a maximum depth of 4.3 m, a shoreline length of 5.9 km, and a fetch of 2 km. Like Fish Lake, Wingra is located high in the landscape, and the development along the shoreline is characterized as high. Lake Wingra is the shallowest of the three study lakes.

Lake Mendota (43°6′N, 89°24′W) is a dimictic and eutrophic lake in an urbanizing agricultural watershed (Carpenter & Lathrop, 2008). Mendota is a drainage lake, with multiple inlets and one main outlet, the Yahara River. Lake Mendota has a surface area of 3,940 ha, a mean depth of 12.8 m, a maximum depth of 25.3 m, a shoreline length of 33.8 km, and a maximum fetch of 9.8 km (Robertson & Ragotzkie, 1990). The lake is located low in the landscape, and development along the shoreline is classified as high. Lake Mendota is both the deepest and largest (by surface area) of the three study lakes.

2.2 | Model description

In this study, a previously developed one-dimensional hydrodynamic lake-ice model, DYRESM-WQ-I (Hamilton, Madeline, Magee, Wu & Kratz, 2016; Magee et al., 2016), is used to simulate vertical water temperature profiles and ice cover thickness in Fish Lake, Lake Wingra, and Lake Mendota. This model adds an ice and snow cover sub-model to the earlier DYRESM-WQ (Hamilton & Schladow, 1997). DYRESM-WQ-I simulates vertical water temperature, salinity, and density by using discrete horizontal Lagrangian layers of uniform properties that vary in thickness. More information on the hydrodynamic model simulation of water temperature and mixing can be found in Imberger and Patterson (1981), Yeates and Imberger (2003), and Hamilton and Schladow (1997). Specifically, the ice-snow model is based upon the MLI model of Rogers et al. (1995) with alterations to two-way coupling of the water-column dynamics to the ice model and the addition of a time-dependent sediment heat flux for all horizontal layers (Hamilton, Madeline, Magee, Wu & Kratz, 2016). Coupling between the hydrodynamic and ice models is in both directions, with the hydrodynamic model determining heat flux at the ice-water interface and ice cover characteristics providing boundary conditions for the hydrodynamic model. Ice-snow model equations are embedded into DYRESM-WQ in the subroutine that performs thermal transfers at the surface, with ice, snow, and water temperature determined by fluxes at the surface and at the ice-water interface. Water temperature under ice is driven by heat fluxes between the ice-water interface and radiative fluxes through the ice layer into the water column. Light extinction coefficients are calculated as a function of Secchi depth using the equation, $k = 1.1/z_s^{0.73}$ (Williams et al., 1980). Detailed description of model development may be found in Hamilton et al. (2016) and in Magee et al. (2016)

Input for the model includes lake morphometry (lake volume and surface area as a function of elevation), initial vertical profiles for water temperature and salinity, Secchi depth, meteorological variables, and inflows/outflows, discussed in detail next. The model calculates the surface heat fluxes using measured meteorological variables: total daily shortwave radiation, daily cloud cover (used to estimate long-wave radiation), air vapor pressure, daily average wind speed, air temperature, and precipitation. During the entire simulation period, all parameters/coefficients in the model are kept constant. The time step in the model for calculating water temperature, water budget, and ice thickness is 1 hr. 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. The distribution of measured shortwave radiation throughout the day is computed based on the lake latitude and the Julian day. DYRESM-WQ-I is calibrated and validated to minimize error in water level, temperature profiles, ice thickness measurements, and ice-on and ice-off dates. The overall simulation period for all three lakes is 104 years, starting on April 7, 1911 and ending on October 31, 2014 without termination. Parameters used in DYRESM-WQ-I are listed in Table 2.

2.3 | Model input data

The long-term data are compiled from various sources including the NTL-LTER (2012a), unpublished data from E. Birge, University of Wisconsin, unpublished data from D. Lathrop, Wisconsin Department of Natural Resources; Robertson (1989); Stewart (1965); and USGS (2010). The frequency of data available varies widely, from daily to annually.

Meteorological data includes daily solar radiation, air temperature, vapor pressure, wind speed, cloud cover, rainfall, and snowfall. Meteorological data for Madison, Wisconsin, have been recorded continuously since 1869, although the station locations and specific techniques have changed during this period. A continuous daily meteorological dataset from 1884 to 1988 was constructed by Robertson (1989) by adjusting for changes in site location, observation time, and

TABLE 2 Parameters values for both hydrodynamic and ice cover portions of the model in DYRESM-WQ-I

Hydrodynamic model parameters	Value	Source
Albedo	0.08	Antenucci and Imerito, 2003; Tanentzap et al., 2007
Bulk aerodynamic momentum transport coefficient	0.00139	Fischer et al., 1979
Critical wind speed ($m \cdot s^{-1}$)	4.3	Tanentzap et al., 2007
Effective surface area coefficient (m^2)	1×10^7	Yeates and Imberger, 2003
Emissivity of water surface	0.96	Imberger and Patterson, 1981
Potential energy mixing efficiency	0.2	Antenucci and Imerito, 2003; Tanentzap et al., 2007
Shear production efficiency	0.06	Antenucci and Imerito, 2003; Yeates and Imberger, 2003; Tanentzap et al., 2007
Vertical mixing coefficient	200	Yeates and Imberger, 2003
Wind stirring efficiency	0.8	Tanentzap et al., 2007
Minimum layer thickness	0.125*	Calibration parameter
Maximum layer thickness	0.6	Tanentzap et al., 2007
Vertical light attenuation coefficient	Variable*	Williams et al., 1980
Ice model parameters	Value	Source
Waveband 1, snow ice light extinction (m^{-1})	3.8	Rogers et al., 1995
Waveband 2, snow ice light extinction (m^{-1})	20	Patterson and Hamblin, 1988; Rogers et al., 1995
Waveband 1, blue ice light extinction (m^{-1})	1.5	Patterson and Hamblin, 1988; Rogers et al., 1995
Waveband 2, blue ice light extinction (m^{-1})	20	Patterson and Hamblin, 1988; Rogers et al., 1995
Waveband 1, snow light extinction (m^{-1})	6	Patterson and Hamblin, 1988; Rogers et al., 1995
Waveband 2, snow light extinction (m^{-1})	20	Patterson and Hamblin, 1988; Rogers et al., 1995
Distance of heat transfer, ice-water (m)	0.039	Vavrus et al., 1996
Density, snow ice ($kg \cdot m^{-3}$)	890	Rogers et al., 1995
Density, blue ice ($kg \cdot m^{-3}$)	917	Patterson and Hamblin, 1988; Rogers et al., 1995
Density, snow ($kg \cdot m^{-3}$)	Variable	McKay, 1968
Compaction coefficient	Variable	Rogers et al., 1995
Thermal conductivity, snow ice ($W \cdot m^{-1} \cdot C^{-1}$)	2.0	Rogers et al., 1995
Thermal conductivity, blue ice ($W \cdot m^{-1} \cdot C^{-1}$)	2.3	Patterson and Hamblin, 1988; Rogers et al., 1995
Thermal conductivity, snow ($W \cdot m^{-1} \cdot C^{-1}$)	Variable	Ashton, 1986
Thermal conductivity, sediment ($W \cdot m^{-1} \cdot C^{-1}$)	1.2	Rogers et al., 1995
Thermal conductivity, water ($W \cdot m^{-1} \cdot C^{-1}$)	0.57	Patterson and Hamblin, 1988; Rogers et al., 1995

*Indicates values calibrated in the model.

changes in surface roughness. These data are appended with recent data from the National Climate Data Center weather station located at the Dane County Regional Airport. All data appended meteorological data was obtained from http://www.ncdc.noaa.gov, except solar radiation, which was obtained from http://www.sws.uiuc.edu/warm/weather/ for St. Charles, Illinois. Further adjustments are made to wind data due to changes in observational techniques occurring in 1996 (McKee et al., 2000). To address this issue, data from the Dane County Airport are compared with those collected from the tower of the Atmospheric and Oceanic Science Building at the University of Wisconsin–Madison. Detailed comparison and adjustment can be found in Magee et al. (2016) and will not be shown here for brevity. In this study, we assume that the three lakes experience the same daily meteorological forcing for the duration of the model.

Seasonal Secchi depths are used to determine the light extinction coefficient in DYRESM-WQ-I. For Lake Wingra and Fish Lake, Secchi depths are obtained from the NTL – LTER (2012a) from 1995 to the present. For years with no Secchi data, the long-term mean seasonal Secchi depth was used to estimate light extinction. For Lake Mendota, Lathrop et al. (1996) compiled Secchi depth data between 1900 and 1993 (1,701 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 May 10), early stratification (May 11 to June 29), summer (June 30 to September 2), destratification (September 3 to October 12), and fall turnover (October 13 to ice-on). After 1993, Secchi depths are obtained from the NTL-LTER (2012a) .

Data for hydrology are daily inflow and outflow measurements at stream gauging stations. Collected measurements are used to estimate daily inflow and outflow for the three study lakes. In cases where inflow and outflow measurements are not available, the water budget approach of balancing inflow/outflow, precipitation, evaporation, and lake level changes is employed. Water level at Fish Lake was recorded almost daily from 1966 to 2003. Water level in Lake Wingra was recorded sporadically during the period of interest. For Lake Mendota, water level has been recorded since 1916. For instances where lake level information and inflow/outflow measurements are not available, the long-term mean lake level is assumed and used for water budget calculations. Air temperatures are used to estimate the water temperature of inflowing streams (Magee et al., 2016), and an average of groundwater temperature measurements is used for groundwater heat fluxes.

2.4 | Observation data

For model calibration and validation, observation data are from a variety of sources. Ice thickness and water temperature data were collected for Fish lake from the NTL-LTER (2012b, 2012c) program only from 1996 to 2014. For Lake Wingra, ice cover data were collected from the NTL-LTER (1996, 2012c). Ice-on is defined as the first date on which the water body is observed to be completely ice covered, and ice-off is the date of the last breakup observed before the open water phase. The dates were not fixed until the lakes remained closed at least a full day and ice persisted into a second day. In some years, observations show more than one ice-covered period; under these situations, observed ice dates are defined by the longest continuous period of ice cover duration. Water temperature information is available from the NTL-LTER (2012b) program from 1996 to 2014 with bi-weekly temperature profiles during open-water seasons and two-temperature profiles during ice cover periods. For Lake Mendota, ice thickness readings were gathered from: 1911–1916 data from E. Birge (unpublished data, University of Wisconsin); 1961–1964 (Stewart, 1965), 1975–1995 (unpublished data, D. Lathrop, Wisconsin Department of Natural Resources); and 1995–2014 data from the NTL-LTER program (2012c). Ice date information is obtained from the NTL-LTER (1996). For Lake Mendota, ice-on date is assigned if the lake has solid ice across the southwest–northeast transect of the lake (from Picnic Point to Maple Bluff) and total ice cover is greater than 50%. Ice-off is determined if the lake is ice-free across the same transect and total ice cover is less than 50%. Long-term water temperature records for Lake Mendota are from Robertson (1989) and the NTL-LTER (2012b).

2.5 | Calibration and evaluation

Using known inflow and outflows and water elevations, the water balance was achieved for the duration of the model simulation using the method described in Section 2.3. Evaporative water and heat flux from the lake are included in DYRESM. In this study, we assumed that the evaporative fluxes were properly parameterized in the model so that modeled evaporation rates were not validated. Light extinction coefficients were estimated from measured Secchi depths (see Section 2.3). Water temperature in the model was calibrated only through the adjustment of minimum layer thickness from 1995 to 2000 for all three lakes. Specifically, to calibrate minimum layer thickness, values ranging from 0.05 to 0.5 m at 0.025-m intervals were evaluated for the least amount of deviation between predicted and observed volumetrically averaged temperature values for the three lakes. A minimum layer thickness of 0.125 m is chosen as the best setting to predict water temperature at all depths. Other parameters assumed in the model were derived from literature values and are provided in Table 2.

Model performance was evaluated over the remaining years of data: 1911–1994 and 2001–2014. To evaluate the performance of the model, we use three metrics, absolute mean error (AME), root-mean square error (RMSE), and Nash–Sutcliffe (NS) efficiency, for ice cover and water temperature variables on all three lakes. Simulated and observed values are compared directly, with the exception of aggregation of water temperature measurements to daily intervals where sub-daily intervals are available.

2.6 | Air temperature perturbations

Air temperature plays a significant role in influencing changes in ice cover in the Madison Area. Studies (IPCC, 2007; Wisconsin Initiative on Climate Change Impacts (WICCI), 2011) suggest that the current trend of air temperature increase will continue to increase. To examine potential changes to ice cover (maximum ice thickness and ice cover duration) under future warmer or colder 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. For each scenario, meteorological inputs remained the same as for the original simulations but with snowfall (rainfall) conversions if the air temperature scenarios increase (decrease) above 0°C. Groundwater and surface water inflow temperatures were similarly adjusted to account for changes in air temperatures. Groundwater temperatures were perturbed in the same method as air temperatures and surface water temperatures were recalculated based on the perturbed air temperature scenarios. Additionally, the water balance is maintained so that the long-term water levels in all three lakes match the historical record.

2.7 | Analysis

Two statistical methods are used to analyze the model results. First, a linear regression is used to determine the trend of long-term changes of lake variables. Second, a Pearson correlation coefficient (Baron & Caine, 2000) is used to determine the coherence of lake variables (Magnuson et al., 1990) between winter climate variables and between lake pairs, allowing for comparison of correlation of the lake variables to each other.

3 | RESULTS

3.1 | Long-term trend of air temperature and wind speed

Figure 2 shows the yearly average air temperature and wind speed at the Madison area over the study period from 1911 to 2014. Historic measurements show that there has been a trend of increasing air temperature and decreasing wind speed over the last 104 years. Using the regression analysis, the air temperature has an increasing linear trend of approximately 1.45°C century^{-1} from 1911 to 2014. For wind speed, the decreasing linear trend has been 0.73 m·s^{-1} century^{-1} over the same period. December to March changes in air temperature and wind speed are larger than the annual change at 2.25°C·century^{-1} and −0.83 m·s^{-1}·century^{-1}, respectively. In Madison, Wisconsin, the urban heat island has a significant effect on air temperature values (Schatz & Kucharik, 2014). To determine any effect on trend from urban heat island, we compare Madison air temperatures with a nearby station at the Arlington Agricultural Research Station, 20 km north of Madison. The trend in yearly average air temperature at the station from NOAA (http://w2.weather.gov/climate/xmacis.php?wfo=mkx), available starting in 1963, shows a trend toward increasing air temperature of 0.314°C decade-1 for 1963–2014 compared to 0.397°C decade-1 for Madison using the same measurement techniques. This

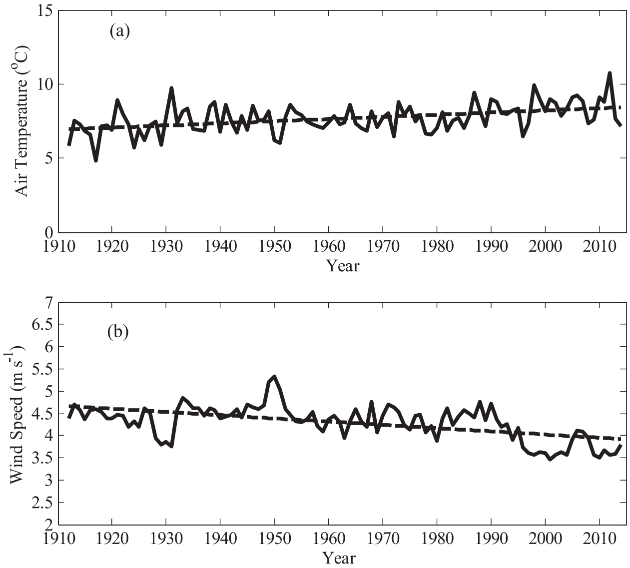

FIGURE 2 Yearly average (a) air temperature and (b) wind speed for Madison, Wisconsin area. Dashed lines denote the trend line for climate variables over the period 1911–2014

is approximately a 20% difference, implying that the change in trend in Madison, Wisconsin, may be partially due to increases in urbanization in the region, but the driving force of change is likely global increases in air temperature. Similarly, urbanization can lead to reductions in wind speed (Li et al., 2011; Grawe et al., 2013). To determine the effects of urbanization on wind speed declines, we compare measured Madison wind speed to trends to wind speed trends from Freeport, Il (~100 km south of Madison) and St. Charles, Il (~150 km southeast of Madison), which are significantly less urbanized than Madison (populations 25,000–33,000). Wind speed data for both cities is collected from http://www.sws.uiuc.edu/warm/weather/ and is available starting in 1990 for Freeport and 1988 for St. Charles. From 1990 to 2014, Freeport yearly average wind speed trend is −0.30 m·s^{-1}·decade^{-1}, while Madison is −0.23 m·s^{-1}·decade^{-1}. Similarly, St. Charles trend in yearly average wind speed is −0.33 m·s^{-1}·decade^{-1} from 1988 to 2014, while Madison is −0.29 m·s^{-1}·decade^{-1}. Higher decreasing trend for the less urbanized cities indicate that the trend in decreasing wind speeds in Madison, Wisconsin, is not significantly impacted by urbanization in the area.

3.2 | Model errors and statistics

Figure 3 compares simulations by the DYRESM-WQ-I model and observations of ice covers and water temperatures over long-term (104 years) simulations. Discrepancies between modeled and

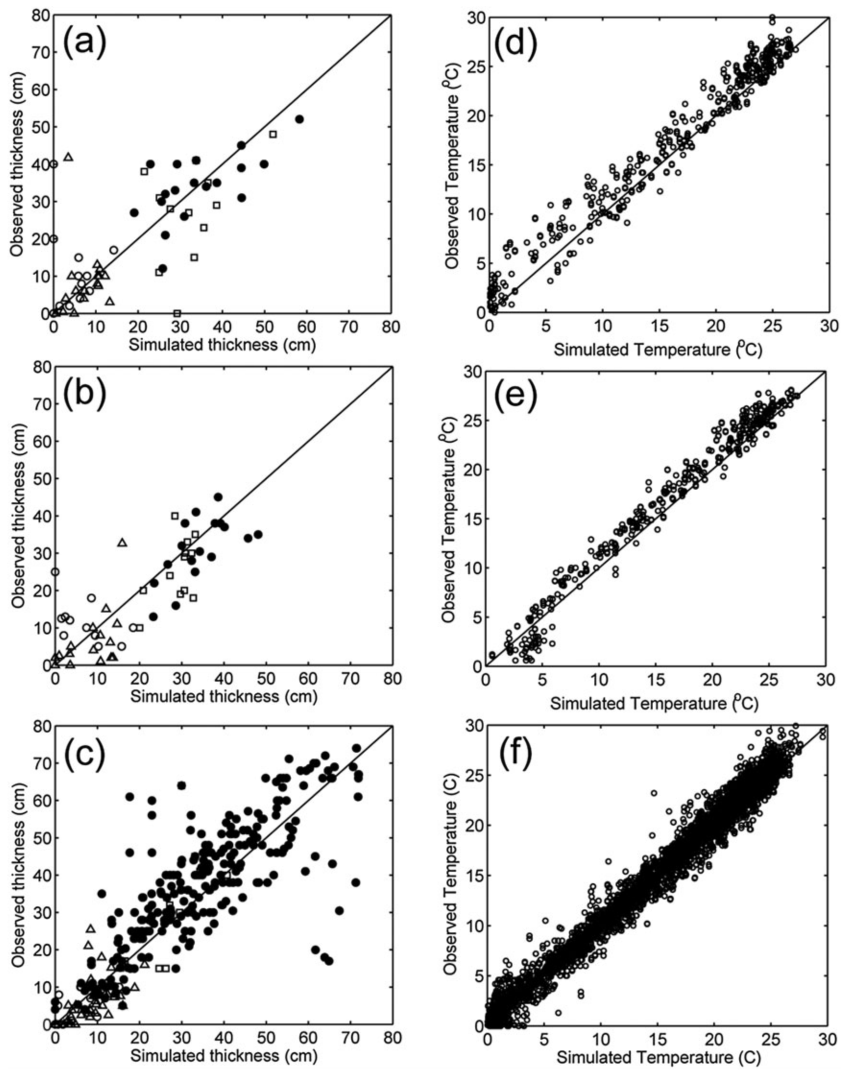

FIGURE 3 Comparison of observed and simulated total ice (●), snow cover (⍰), white ice (○), and blue ice (□) for (a) Fish Lake, (b) Lake Wingra, and (c) Lake Mendota. Comparison of observed and simulated lake surface water temperatures (°C) for (d) Fish Lake, (e) Lake Wingra, and (f) Lake Mendota

measured values come from several sources. Average daily air temperatures and wind speeds are used in the model, and average daily values are output from the model. Figure 4 compares simulated and observed total ice cover for all three lakes during the winter of 2009–2010. In general, thermocline depths are within 1 m between observed and simulated, but some years differ by as much as 2.5 m, significantly impacting the fit of the model near the thermocline for Lakes Mendota and Fish. Table 3 lists AME, RMSE, and NS efficiencies for all validation parameters. AME and RMSE for all variables are low and less than standard deviations (SDs) for variables. NS efficiencies are high (>0.85) and most above 0.90, indicating high model accuracy.

3.3 | Ice-on and ice-off dates

Figure 5a–c shows the simulated (filled circles) and observed (open circles) ice-on and ice-off dates for Fish Lake, Lake Wingra, and Lake Mendota, respectively, over the 104-year period. Modeled ice dates are defined by the dates between which the longest continuous frozen period for that winter occurred. In general, the model accurately simulated the ice-on and ice-off dates for both Lake Wingra (AME = 6.1 days ice-on, 4.6 days ice-off; RMSE =8.2 days ice-on, 6.0 days ice-off) and Lake Mendota (AME = 2.6 days ice-on, 5.7 days ice-off; RMSE =4.0 days ice-on, 7.4 days ice-off). Table 4 shows the trend (days/century), mean, SD, and range of ice-on and ice-off dates over the period 1911–2014. All three lakes experience trends to later ice-on, earlier ice-off, and shorter ice cover duration. Trends in ice dates are significant for all three lakes ($p < 0.05$). Fish Lake and Lake Mendota have similar means and SDs of ice cover

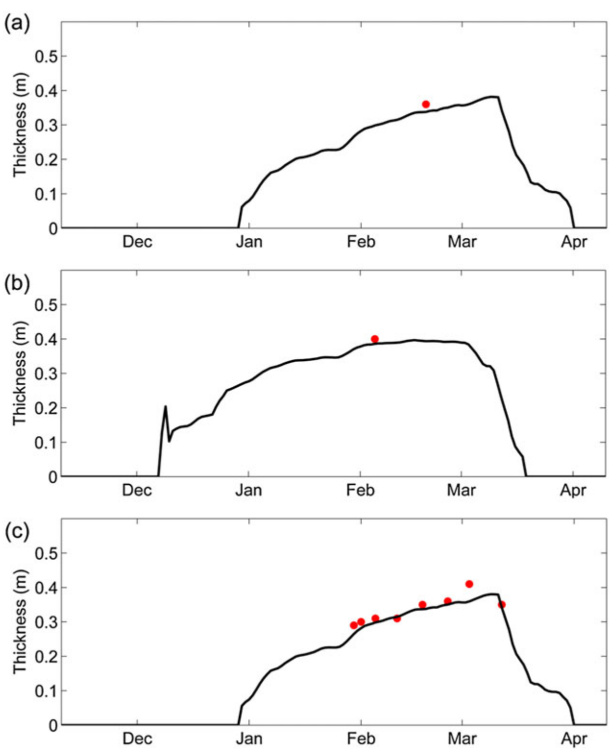

FIGURE 4 Simulated (solid black lines) and observed (red dots) total ice thickness for (a) Fish Lake, (b) Lake Wingra, and (c) Lake Mendota for the winter of 2009–2010

TABLE 3 Absolute mean error (AME), root-mean square error (RMSE), and Nash–Sutcliff (NS) efficiency for ice cover and water temperature variables on Fish Lake, Lake Wingra, and Lake Mendota

	Fish Lake				Lake Wingra				Lake Mendota			
Variable	*n*	AME	RMSE	NS	*n*	AME	RMSE	NS	*n*	AME	RMSE	NS
Total ice thickness (cm)	19	4.83	5.83	0.98	18	5.73	5.98	0.92	251	7.8	7.9	0.97
Blue ice thickness (cm)	19	7.11	10.1	0.95	18	5.31	5.84	0.93	21	5.5	3.3	0.96
White ice thickness (cm)	19	6.92	7.20	0.97	18	2.54	6.72	0.92	21	1.99	2.3	0.99
Snow thickness (cm)	19	4.23	4.75	0.98	18	4.42	4.75	0.93	49	4.0	3.7	0.94
Ice-on date (day)	N/A	N/A	N/A	N/A	59	2.00	3.08	0.97	103	1.80	2.43	0.99
Ice-off date (day)	N/A	N/A	N/A	N/A	61	2.29	3.48	0.97	103	2.52	3.30	0.98
Ice duration (day)	N/A	N/A	N/A	N/A	54	3.56	4.88	0.95	103	2.82	3.75	0.98
Epilimnetic temperature (°C)	263	1.23	1.45	0.95	N/A	N/A	N/A	N/A	3,239	0.69	0.3	0.99
Hypolimnetic temperature (°C)	263	1.63	1.94	0.92	N/A	N/A	N/A	N/A	3,239	1.04	0.53	0.96
Temperature at 1 m interval (°C) overall range of values for depths	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	85,566	0.5–1.56	0.25–0.75	0.95–0.99

Note. n = number of measurements and N/A represents errors that cannot be determined due to availability of measurement data.

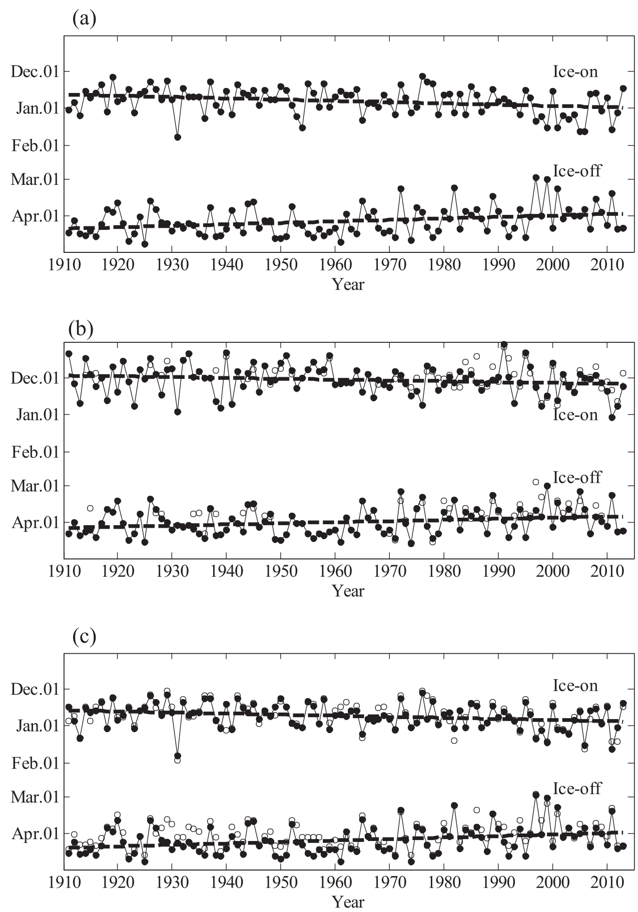

FIGURE 5 Ice-on and ice-off dates for (a) Fish Lake, (b) Lake Wingra, and (c) Lake Mendota. Filled circles are modeled ice-on and ice-off dates, while open circles are observed ice dates. Dashed lines denote the trend line for ice cover dates over the period 1911–2014

dates. Trends in ice-on dates are slightly smaller than SDs (5% for Fish Lake; 13% for Lake Mendota), trends in ice-off dates are approximately equal to SDs, and trends in total ice cover duration are larger than SDs (25% Fish Lake; 19.5% Lake Mendota). For Lake Wingra, the mean for ice-on dates and ice-off dates are earlier than those of Fish Lake and Lake Mendota. Nevertheless, the ice duration is longer than that of Fish Lake and Lake Mendota. The trends in ice-on, ice-off, and ice duration are smaller than SDs (43% ice-on; 15% ice-off; 8.4% duration), suggesting that the shallower lake is more resilient to climate changes.

3.4 | Evolution of ice cover and lake surface temperature

Figure 6a and 6b shows the ice growth and decay evolution and lake surface temperature for the three lakes under the air temperatures with an extremely warm (1997–1998) and cold (1935–1936) January–March wintertime period, respectively. During the wintertime from December 1997 to March 1998, the air temperatures varied from −18.3°C to 17.8°C, with an average temperature of −1.6°C. Due to the shallow depth of Lake Wingra, the lake cooled down rapidly, allowing ice formation as early as November 16, 1997 and disappeared shortly after. The complete ice cover started on

TABLE 4 Trends, means, standard deviations (SD), and range in lake physical variables for the three studied lakes from 1911–2014

	Fish Lake				Lake Wingra				Lake Mendota			
	Trend (century^{-1})	Mean	SD	Range	Trend (century^{-1})	Mean	SD	Range	Trend (century^{-1})	Mean	SD	Range
Ice-on (days)	10.6 days later*	December 23	11.2	51	7.0 days later*	November 30	12.3	61	9.0 days later*	December 21	10.4	53
Ice-off (days)	12.2 days earlier*	April 3	12.0	51	9.4 days earlier*	March 29	11.1	48	12.3 days earlier*	April 4	12.0	55
Ice duration (days)	22.9 fewer days*	100.0	18.3	85	16.4 fewer days*	119.1	17.9	89	21.4 fewer days*	104.0	17.9	87
Maximum ice thickness (cm)	11.8 cm less*	48.3	10.8	50.0	7.6 cm less*	44.0	9.65	45.0	12.8 cm less*	47.2	11.0	51.9

*Indicates significant to $p < 0.05$.

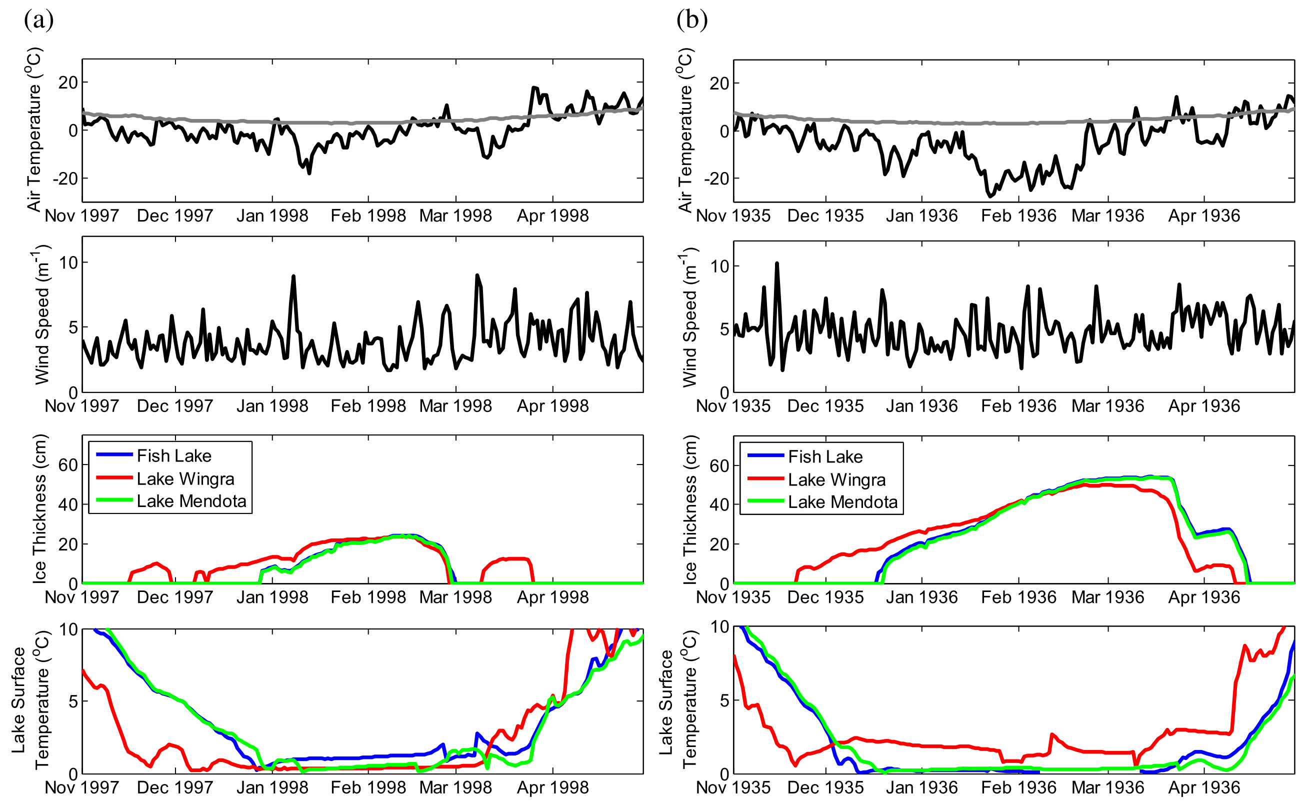

FIGURE 6 Evolution of ice thickness and lake surface temperature for (a) extreme maximum wintertime air temperature year 1997–1998 and (b) for extreme minimum wintertime air temperature year 1935–1936. Top plots show the daily average air temperature (black line) and the long-term daily average air temperature (grey line). Second plots are the daily average wind speed. Third plots and forth plots show the ice thickness evolution and lake surface temperature for Fish Lake (blue), Lake Wingra (red), and Lake Mendota (green)

December 8, 1997, and the lake continuously froze over for the wintertime period until February 27, 1998. After 12 days, ice was formed again due to a sudden drop of the air temperature and the ice was off on March 26, 1997. This feature of intermittent ice-on and ice-off in Lake Wingra was strongly correlated with the air temperature. In contrast, both Fish Lake and Lake Mendota, which are significantly deeper than Lake Wingra, did not have ice cover until December 28, 1997 (Fish Lake) and December 27, 1997 (Lake Mendota), and the ice was off approximately the same day as Lake Wingra. Afterwards, the sudden drop in air temperature did not prompt ice growth, indicating lake morphometry, specifically water depth, plays an important factor in ice formation. For the extremely cold wintertime from November 1935 to April 1936, the air temperatures varied from −27°C to 14.4°C, with an average temperature of −7.8°C. All three lakes experienced early ice-on dates and late ice-off dates. Specifically, the earliest ice cover for Lake Wingra was on November 21, 1935. The ice cover for Fish Lake occurred on December 18, 1935, and for Lake Mendota on December 19, 1935. The ice-off dates were as late as April 13 for Lake Wingra and April 16 for Lake Mendota and Fish Lake. The results show that ice-on dates are earlier for shallower lakes and ice-off dates are later for deeper lakes.

Overall, the ice cover formation process consists of an initial rapid growth, increasing ice thickness responding to below-freezing air temperatures, and reaching a maximum thickness in lake wintertime (Ashton, 1986). Ice formation is preceded by intense radiative and convective heat loss from the warmer lake surface to the colder atmosphere (Kirillin et al., 2012) and follows the date that air temperature falls below freezing with a slight delay. For Figure 6a and 6b, all three study lakes under both extreme temperature years, the ice cover, once formed, follows a fairly similar progression of growth. In the later stage, ice growth is independent of lake characteristics and instead depends primarily on air temperatures (Brown & Duguay, 2010). Eventually, the ice growth plateaus at the maximum ice thickness, with maximum ice thickness occurring around the same time in all three lakes. In the majority of years, ice decay occurs quickly (<2 weeks) and each lake follows a similar pattern of ice decay with ice-off dates in all three lakes occurring within a few days. However, differences are observed in cold years, as shown in the winter 1935–1936. Ice-off occurs slightly later in the deeper Lake Mendota and Fish Lake than the shallower Lake Wingra, possibly due to the decreased ice thickness in Wingra. Furthermore, later periods of below freezing air temperatures may result in an anomalous period of late ice growth in all three lakes.

3.5 | Maximum ice thickness

Figure 7 shows the maximum ice thickness for the three lakes over the period 1911–2014., and Table 4 lists the trend (cm·century^{-1}), mean (cm), SD (cm), and range (cm) of thein maximum ice thickness. The magnitude of trend is larger than the SD for Fish Lake (9%) and Lake Mendota (16%) but smaller for Lake Wingra (21%). Fish Lake and Lake Mendota have a greater magnitude change in the trend of maximum ice thickness than does the shallower Lake Wingra.

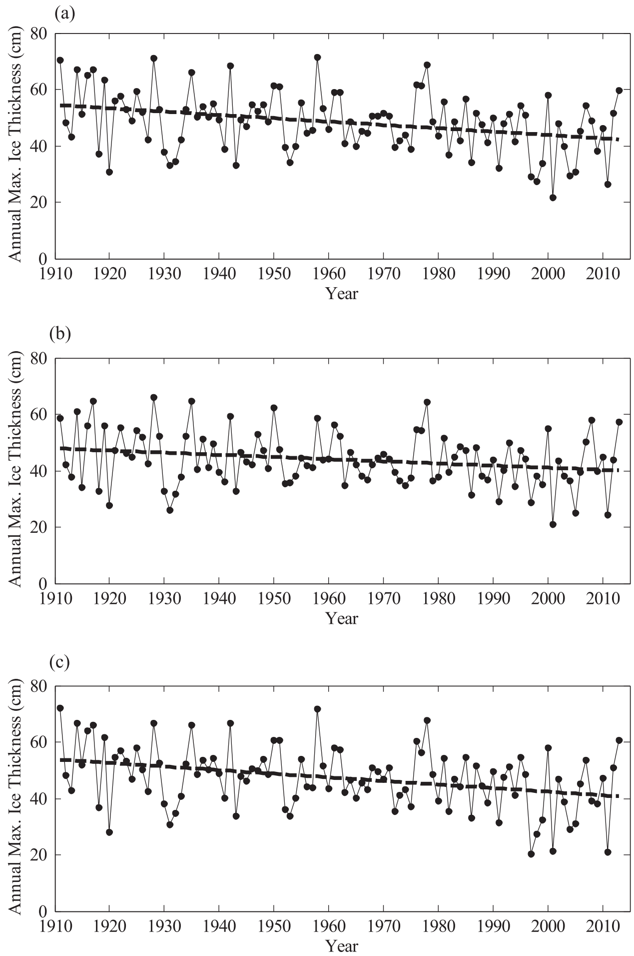

FIGURE 7 Yearly maximum ice thickness (in centimeters) for (a) Fish Lake, (b) Lake Wingra, and (c) Lake Mendota. Dashed lines denote the trend line for maximum ice thickness

3.6 | Ice cover under air temperature perturbations

Figure 8 shows colorplots of maximum ice thickness for each of 100 years under a range of −10°C to +10°C air temperature perturbations. Black color indicates no ice cover during that model year. Results show multiple years of no ice cover for both Fish Lake and Lake Mendota as air temperature increases as small at +4°C. In contrast, only four instances of no ice cover for Lake Wingra as air temperature increases up to +10°C. Figure 9 shows the results of air temperature perturbations (increases only) on ice growth for 1916–1917, an example of a cold year. As air temperature perturbations increase, ice-on date becomes later, ice-off date occurs earlier, and ice thickness decreases. Interestingly, for the case of +10°C air temperature, the delay of ice-on date in Lake Wingra is not as dramatic as those in Fish Lake and Lake Mendota, yielding the longer ice cover duration in Lake Wingra.

4 | DISCUSSION

4.1 | Model performance and comparison

Discrepancies between modeled and observed ice thicknesses can be partially attributed to differences in location and timing of ice observations. Ice measurements made at multiple locations in Lake Mendota (Hsieh, 2012, 2013) showed inhomogeneity in ice thickness, with ice in the middle of the lake approximately 12 cm thicker than at littoral locations. This finding is consistent to the finding by Bengtsson (1986), who showed spatial variations in ice and snow depths for a medium-to-large lake (as those in this study). As a result, the discrepancy between model and measured ice values may be expected in years when ice thickness varied spatially. Errors in water temperature (Figure 3d–f) are predominantly a result of differences between simulated and observed thermocline depth over some years, and some slight mismatches in timing of stratification onset and overturn.

The performance of the DYRESM-WQ-I model is similar to that of other studies in the literature. Using Minnesota lake model (Minlake), 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, and errors of 6 cm for snow thickness and 11 cm for ice thickness. Perroud et al. (2009) simulated water temperature on Lake Geneva and compared RMSE using several one-dimensional lake models: 1.7°C for DYRESM (Tanentzap et al., 2007), 2°C for the Hostetler model (Hostetler & Bartlein, 1990), 2°C for a k-epsilon type turbulence SIMSTRAT model (Perroud et al., 2009), and 4°C for a Freshwater Lake (Flake) model (Golosov et al., 2007; Kirillin et al., 2012). For all four models, errors were lower in the upper layers and larger in the bottom of the water column, similar to errors found in this study. On Baker Lake, Nunavut, Canada, the model, MyLake, produced mean absolute differences between model and observations of 11 cm in ice thickness (Dibike et al., 2011). Other models including LIMNOS (Vavrus et al., 1996) on Lake Mendota, Wisconsin; MLI (Rogers et al., 1995) on Harmon Lake, British Columbia, and CLIMo (Duguay et al., 2003) on lakes in Alaska and Manitoba produced similar errors between modeled and observed ice thickness and snow covers. Recent study by Yao et al. (2014) shows that ice cover over a 16-year period can be reasonably modeled using the four models, that is, Minlake, Simple Lake Model (Jöhnk et al., 2008) SIM, Hostetler, and General Lake Model (GLM, Hipsey et al., 2014). In our study, results of NS efficiency coefficients for all three study lakes are significantly improved over the Minlake, SIM, Hostetler, and GLM lake models for all ice cover variables (i.e., ice-on dates, ice-off dates, and ice thickness) using the DYRESM-WQ-I model. Nevertheless, future efforts should be devoted to increase model accuracy and predictability of lake ice dynamics.

4.2 | Coherence among lakes

Temporal coherence can be described as the correlation between two signals over time, that is, the similarity of lake responses over time. Previous research showed that spatially close lakes respond coherently to climate (Magnuson et al., 1990; Thompson et al., 2005), but those with comparable physical features exhibit substantially higher coherence than lakes with different physical properties (Novikmec et al., 2013). Large correlation coefficients indicate high temporal coherence between lakes, thus exhibiting synchronous patterns in the lake variables (Magnuson et al., 1990) that are largely driven by climate (Palmer et al., 2014). In this study, the three lakes are formed into three distinct pairs for comparison. Pair 1, Fish Lake and Lake Mendota, has deep

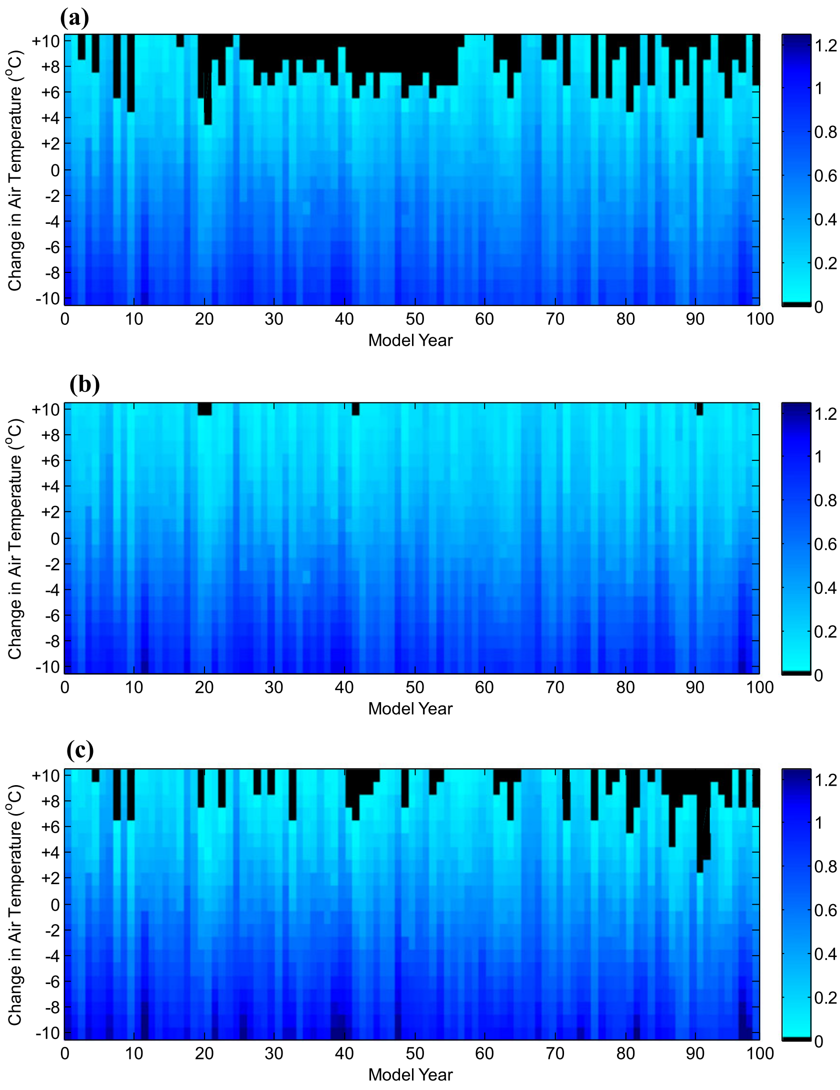

FIGURE 8 Maximum ice thickness (in meters) for (a) Fish Lake, (b) Lake Wingra, and (c) Lake Mendota as the air temperature is changed by intervals of 1°C

depths but different surface areas, illustrating the effects of surface area differences. Pair 2, Lake Wingra and Fish Lake, has similar surface areas, but shallow and deep water depths, addressing the effects of lake depth. Pair 3, Lake Mendota and Lake Wingra, has both differing surface areas and water depths. The coherence of ice cover variables for the three pairs is discussed in the following.

For the ice cover variables, correlation coefficients of pairs of lakes are high, for example, 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 among lakes within a region, depending on a number of factors, particularly lake morphometry and landscape setting (Gao & Stefan, 1999; Williams et al., 2004; Brown & Duguay, 2010).

4.3 | Sensitivity to air temperature change

Under the warmer air temperatures, Fish Lake has the most occurrences of no ice cover (indicated by black color in Figure 8). Lake Mendota has fewer ice-free occurrences because the larger lake surface area facilitates greater total heat input, 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 this shallower lake with lower heat storage responds to air temperature more sensitively. Overall, the results indicate that deeper lakes are more at risk for thinner or no ice conditions than shallow lakes. Under 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.

To examine how each lake responds to the increasing air temperature, Figure 9 shows the results of air temperature perturbations (increases only) on ice growth for 1916–1917, an example of a cold year. As the air temperature increases, ice growth starts to more

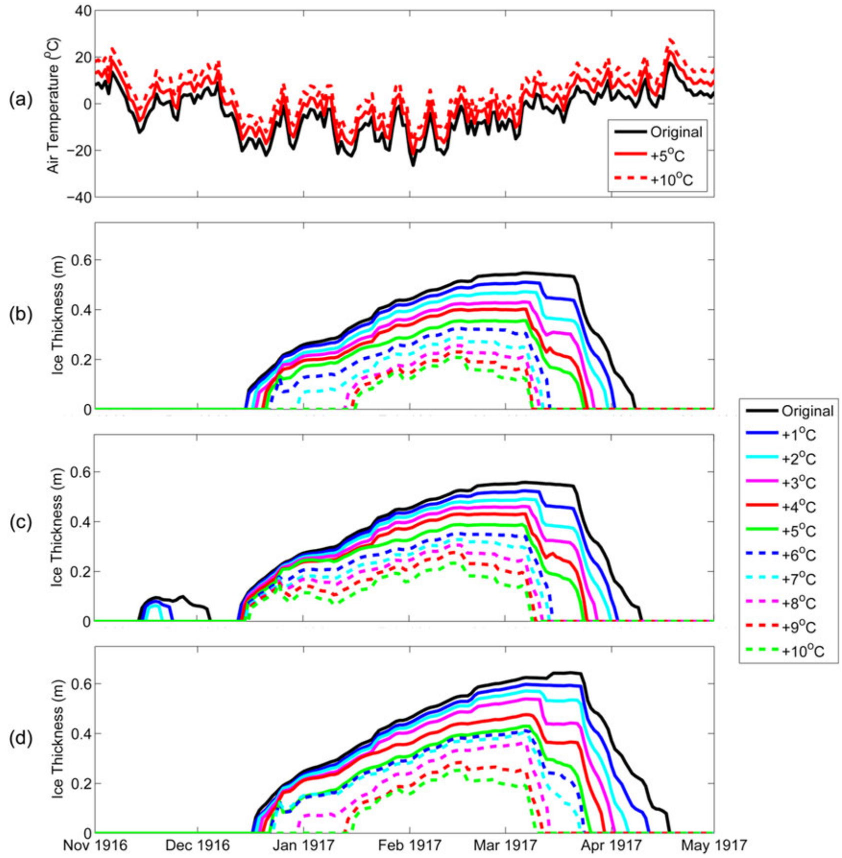

FIGURE 9 (a) Air temperatures under the original simulation and +5°C and +10°C air temperature perturbations and ice growth for (a) Fish Lake, (b) Lake Wingra, and (c) Lake Mendota perturbations for the cold winter of 1916–1917. Each line in (b)–(d) represents a one degree (C) increase in air temperature

closely resemble that of a warm air temperature year. Ice-on dates for Fish Lake and Lake Mendota occur later with some extreme differences of 30 days under changes of +7°C and +8°C in Fish Lake and +8°C and +9°C in Lake Mendota. In contrast, ice-on dates for Lake Wingra remain fairly consistent through all temperature scenarios, suggesting that cooling in a shallower lake is not sensitive to increasing air temperature. However, very early, short ice cover periods (November 15 to December 6, 1916) on Lake Wingra no longer occur after an air temperature increase of +3°C. The ice-off dates, different from ice-on dates, show consistently earlier break-off pattern for all three of the study lakes. The maximum ice thickness dramatically decreases for all three lakes, and the timing of the date of maximum ice occurs earlier in the season. Interestingly, an extreme air temperature increase of 9–10°C, the timing of ice-off among the three lakes seems to occur at the same time as lake ice melting in the springtime may be mainly governed by solar radiation (Kirillin et al., 2012).

4.4 | Role of lake morphometry

The influence of lake morphometry in terms of three attributes (i.e., lake geometry ratio, lake surface area, and lake depth) on lake ice cover are discussed in the following.

4.4.1 | Role of lake geometry ratio

For characterizing lake stratification, Stefan et al. (1996) proposed a lake geometry ratio $A_s^{0.25} : H_{\max}$, where A_s is lake surface area and $H_{\max}$ is the maximum depth. The ratio was originally obtained from a criterion as $H_{\max} = 0.34A_s^{0.25}$ (Gorham & Boyce, 1989). Geometry ratios above 6 generally represent lakes that are polymictic, and geometry ratios below 4 denote lakes that are strongly stratified (Fang & Stefan, 1997). In this study, the geometry ratios for Fish Lake, Lake Mendota, and Lake Wingra, are 1.62, 3.13, and 7.31, respectively. The large geometric ratio for Lake Wingra indicates the lake is polymictic, which can cool down quickly in the autumn (Figure 6) and enable earlier ice formation. The large geometry ratio for Lake Wingra indicates that the lake is polymictic (Kimura et al., 2016). Furthermore, smaller changes in ice cover are seen during the historical and perturbation scenarios. In other words, lakes with larger geometry ratios are more resilient to changes in air temperature than lakes with smaller geometry ratios.

4.4.2 | Role of lake surface area

While air temperature is the most significant driver for ice cover, lake surface area can also play a role in the timing and trend of ice cover formation and thickness (Williams & Stefan, 2006). Stronger winds break up initial skim ice and slightly delay the formation of continuous ice cover, leading to later ice-on dates as lake surface area (fetch) increases due to increased wind shear (Williams et al., 2004; Brown and Duguay, 2010). Due to Lake Mendota's larger fetch, decreasing wind speed in Madison, Wisconsin, would cause a smaller relative change in wind shear across Lake Mendota than in Fish Lake, explaining the slightly larger change in ice-on dates in Fish Lake than in Lake Mendota, as shown in Table 4.

The trend of ice-off dates for Fish Lake and Lake Mendota are similar, which is in agreement with previous findings of low correlation between lake surface area and ice-off dates (Williams et al., 2004;

Brown & Duguay, 2010). However, differences are evident in the extreme air temperature perturbations (Figure 9). Ice decay takes place at the top and bottom of the ice column and along the lateral edges due to both decaying and mechanical disintegration (Woo & Heron, 1989; Brown & Duguay, 2010). Field data (Jakkila et al., 2009; Leppäranta, 2010) show that bottom, internal, and surface melting are of the same magnitude, but an increasing air temperature elevates the effects of lateral ice decay (Arp et al., 2013), making the smaller lakes decrease in ice cover more rapidly than the larger Lake Mendota. The effect may explain the smaller ice duration in Fish Lake under extreme warm temperatures.

4.4.3 | Role of lake depth

Water depth is an important morphological aspect of a lake in regards to ice cover (Korhonen, 2006; Kirillin et al., 2012). A lake larger in volume (or depth) will need more time to cool down (or heat up) than a lake of similar area but with smaller volume (or shallow depth). Specifically, the ice-on dates for Fish Lake and Lake Mendota are significantly later than Lake Wingra (see Figure 5). Under extreme warm air temperatures (10°C warmer), model results show that Lake Wingra rarely experiences ice-free winters while Lake Mendota and Fish Lake have many ice-free winters (Figure 8). Brown and Duguay (2010) indicated that lake depth determines the amount of heat storage in the water, and hence, the time needed for the lake to cool and freeze. Deeper lakes require a longer period with air temperature below 0°C before they freeze over since larger heat storage requires longer times to cool to a freezing temperature (Jensen et al., 2007; Kirillin et al., 2012). Under increased air temperatures, increased heat storage and slower temperature response in deeper lakes will delay ice-on dates more than in shallower lakes. In other words, deeper lakes are more sensitive than shallow lakes to the increasing air temperature trend. Furthermore, during the historical climate, maximum ice thickness decreased at a much slower rate in the shallow Lake Wingra than the deeper Lake Mendota and Fish Lake (Table 4). This trend still holds under the extreme warm air temperature perturbations (Figure 8). Interestingly, while more resilient to changes in air temperature, Lake Wingra has experienced thinner average ice cover, compared with Fish Lake and Lake Mendota (see Table 4). This may be explained by the higher sediment heat storages and heat flux in winter in shallow lakes (Ellis et al., 1991; Fang & Stefan, 1996; Golosov et al., 2007), which can increase under-ice water temperatures and thus decrease ice thickness.

5 | CONCLUSIONS

In this study, the previously developed DYRESM-WQ-I model is employed to simulate the ice cover of three lakes with differing morphometry, Fish Lake, Lake Wingra, and Lake Mendota, from 1911 to 2014. The model reliably reproduces the interannual variations and long-term trends in ice cover for the three lakes. To our knowledge, this study presents the first attempt to model ice cover of three lakes with differing morphometries over a period of as long as a century. Simulated ice cover over the century has changed dramatically, with all three lakes experiencing later freezing, earlier breakup, shorter ice cover duration, and thinner maximum ice thickness. These results agree with the observational data and previous studies. Perturbation simulations show that a small increase in air temperature (3–4°C) may inhibit ice cover of the deeper lakes during some years, while the shallow Lake Wingra may experience ice cover even under the +10°C air temperature perturbation. Analysis of ice cover on three different study lakes indicates that shallower lakes, such as Lake Wingra, are more resilient to changes in air temperature than their deeper counterparts. Additionally, lakes with larger 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. Shallower lakes with larger surface areas appear more resilient to changes in ice cover caused by warmer air temperatures.

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