

Lake Ice: Winter, Beauty, Value, Changes, and a Threatened Future

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What is special about lake ice? First, the limnology of the lake is transformed to a new state, unique to ice-covered lakes. Second, ice associated with lakes provides a beauty not gifted to us from lakes without ice. Third, lake ice has value to humans for ecological and cultural services and, at times, even goods. Fourth, trends and variability in ice cover signal changes in climate; ice cover can be a miner's canary, warning us of environmental changes. Fifth, the sensitivity of lake ice to a warming climate indicates the future of ice cover is threatened by human activity.

Winter

One way to define the start of winter for temperate and boreal lakes is by the date on which ice first covers an entire lake (see cover photo). Ice cover's arrival denotes a change in state, dramatically altering lake mixing, light penetration, chemistry, biology, and as importantly, our human interactions with a lake. The first date of complete ice cover would rarely be coincident with December 21, the winter solstice. Similarly, the last date of complete ice cover in late winter or early spring would rarely be coincident with the vernal equinox on March 21. Using ice cover to define limnological winter means that the winter period differs among regions, among lakes in the same area, and among years for the same lake. Two consequences of using ice on and ice off of a lake to delineate the winter mode is that the actual duration of winter is a numerical variable and that it heralds the presence of winter conditions and under-ice processes in individual lakes.

The maximum density of freshwater is 4°C, so in the fall at temperatures above 4°C, warmer water floats above the cooler waters. However, as winter approaches

and the lake cools to temperatures of 4°C or less, the water cooler than 4°C floats above the warmer water below. When water temperatures reach 0°C at the lake surface, ice can begin to form. Regardless, under-ice water temperatures, while colder than summer waters, are still above freezing and support aquatic life, even on the coldest days that we experience.

Winter conditions begin to develop as soon as ice covers a lake and initiates sequential changes in physics, chemistry, and biology. Lake area and depth greatly influence the formation of ice cover and

thus the limnological conditions under the ice. One might expect that water at the undersurface of the ice would be 0°C and at the bottom of the lake would be 4°C. However, in the real world the temperatures under the ice differ greatly from lake to lake (Figure 1)

Ice cover formation is delayed in larger, deeper lakes compared with smaller, shallower lakes for two reasons. First, lakes with larger volumes of water take longer to lose their heat in fall. Second, even after the lake's average water temperature reaches 4°C and

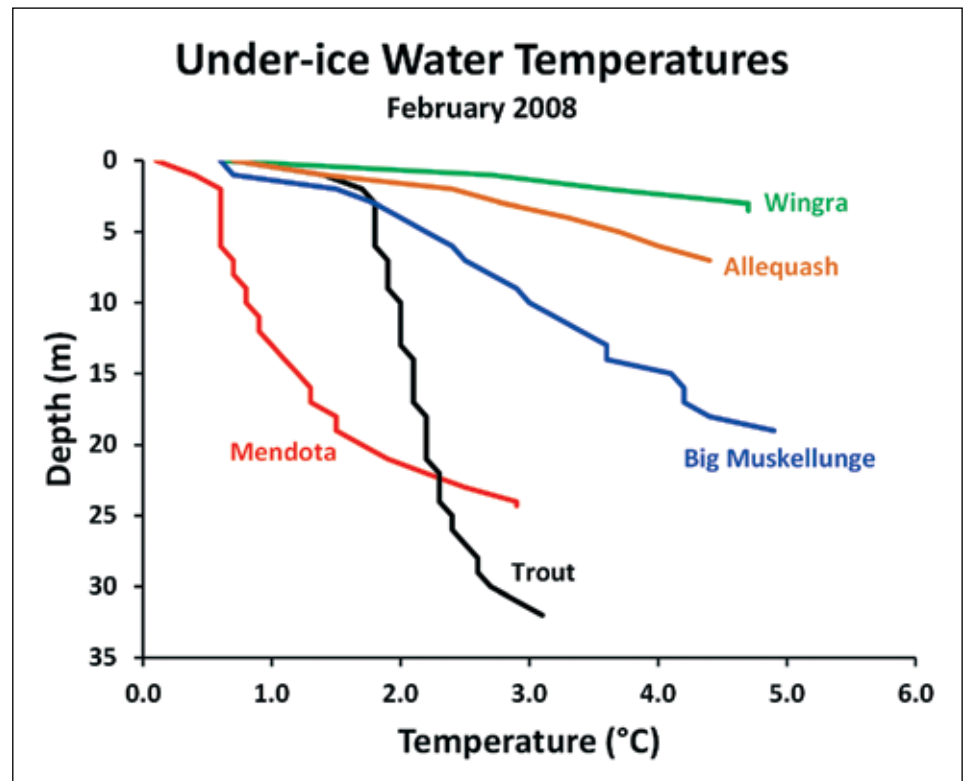


Figure 1. Under-ice water temperatures are warmer in smaller, shallower lakes; ice-on dates were sooner in the smaller, shallower lakes (Wisconsin lakes, 2008; see text for explanation). Southern Wisconsin: Lake Wingra (area 140ha, depth 4m, ice on Nov. 30), Lake Mendota (3,985ha, 25m, Dec. 25). Northern Wisconsin: Allequash Lake (north basin 112ha, 8m, Nov. 23), Big Muskellunge Lake (377ha, 19m, Dec. 3), and south Trout Lake (1,545ha, 32m, Dec. 10) (water temperature data: <https://lter.limnology.wisc.edu>).

surface waters cool to 0°C on calm cold nights, ice cover is delayed more for larger than for smaller lakes. Larger lakes have longer fetches for the wind to impart its energy to the water surface and that generates greater water column mixing and larger surface waves. The larger surface waves break up thin ice that begins to form initially around the edges of the lake. With the greater wind-driven mixing and the destruction of early ice at the shoreline, larger lakes generally have water column temperatures significantly less than 4°C before the lake surface freezes over (Figure 1). The effect of heating from the lake's bottom sediments, especially in shallow lakes, is also apparent in under-ice profiles.

With the first snow on the ice, light levels greatly decline because snow reflects the light and little is transmitted to the ice and the waters below. Clear ice actually transmits light even better than clear water. However, snowfall on thin ice can weigh the ice down and water seeps through ice cracks upward into the snow. This slushy snow then freezes to produce grey ice above the clear "black" ice that formed first (Figure 2).

A series of chemical and biological changes begin soon after a lake becomes ice-covered. Bacteria decompose organic matter near the sediment water boundary and thereby reduce dissolved oxygen concentrations, a condition that is accelerated in nutrient-rich, eutrophic lakes. Layers of water with little or no dissolved oxygen begin to form at the bottom of the lake and expand upward. In shallow lakes this de-oxygenation can reach the undersurface of the ice causing fish "winterkill" to occur. Many fish species cannot persist in shallow lakes subject to intermittent winterkill. However, some fishes like carp and bullheads can withstand low levels of dissolved oxygen for brief periods; others like mudminnows can seek out gas pockets under the ice that contain oxygen and use their gas bladder like a lung. Thus, winterkill lakes often are dominated by only a few fish species that typically are not important to recreational fisheries.

The absence of oxygen (anoxia) triggers a series of chemical changes in the bottom sediments that in some lakes include the reduction and release of iron into the overlying waters.



Figure 2. Vertical section of lake ice showing grey ice from frozen slush at top and clear ice below – Trout Lake, Vilas County WI, Feb. 2000. Small bubbles in clear ice are likely from dissolved gases in the water that were extruded as the water froze. Photo: Carl J. Bowser.

Through various processes, phosphorus, ammonium, and sulfide also build up, especially in eutrophic lakes, as does carbon dioxide. If the duration and degree of anoxia is extensive, then methane is produced in the sediments. Methane gas, because it is insoluble, forms bubbles that rise to become imbedded in the ice or coalesce as larger bubbles under the ice. When ice breaks up in spring the lake releases the trapped methane into the air as well as a puff of carbon dioxide from the supersaturated water brought to the surface as the lake mixes.

The low light levels limit plant growth and the view field of visual predators. Fishes continue to feed but their digestion is not efficient at the cold temperatures. Still, they catch prey, bite or approach the bait of ice fishers, and provide a popular winter sport on the lake ice. Free-floating algae called phytoplankton have problems staying in the water column because turbulent mixing is reduced; large and heavy species sink to the bottom. Tiny nanoplankton persist in the water column because they have larger surface areas relative to their body mass. Also, phytoplankton with flagella or cilia can remain in the water column. Some

larger diatoms even can fasten to the undersurface of the ice. However, some smaller diatoms flourish in the water under the ice especially in late winter as light levels increase. Some currents and mixing does occur but so much less than in the open water period.

In terms of mixing and thermal stratification, the period of ice cover can be thought of as one of the four seasons for a deeper lake and as a reset mechanism for the lake's biology and ecology before spring begins a new year. If this under-ice period were lost, deeper lakes that stratify both in summer and again under the ice in winter would evolve to become lakes with only two seasons – a warm, thermally stratified season in summer and a cool season of mixing throughout the rest of the year. In terms of mixing and stratification, shallow lakes that are ice-covered in winter already only have two seasons – a cool, thermally stratified season under the ice and a warm season of mixing throughout the rest of the year.

The Beauty of Ice

We believe the best way to highlight the beauty of lake ice is through photographs (Figure 3). Not surprisingly,



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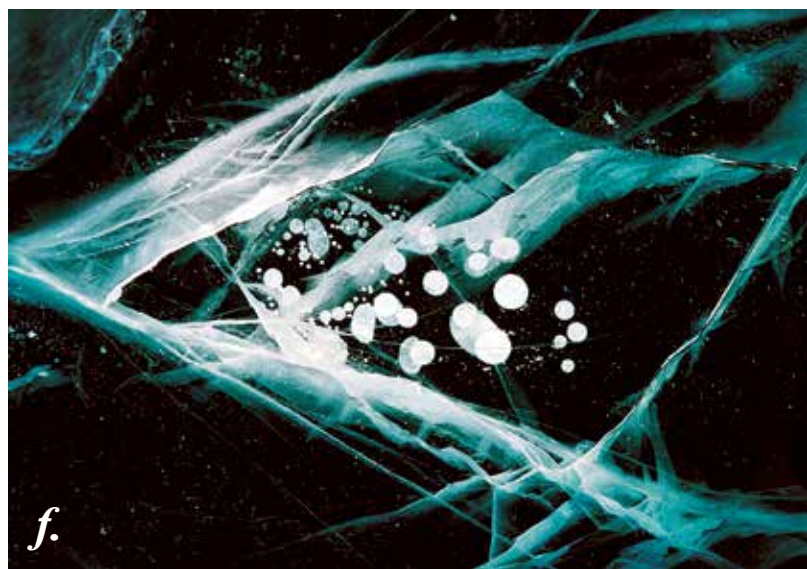
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Figure 3. Beauty of ice.

a. Dawn's first light reflected from clouds, water, and ice – Lake Mendota WI, Dec. 2003. Photo: J. Magnuson.

b. Day's early sun casts shadows across snow on the ice – Mystery Lake, Vilas County WI, early 1970s. Photo: J. Magnuson.

c. Ice formed on rocks and dripping from branches after waves splash water onto frozen surfaces soon before ice cover – Lake Mendota, Dec. 2003. Photo: J. Magnuson.

d. Pancake ice formed near shore when early ice is broken by wave action – Lake Mendota, Dec. 2003. Photo: J. Magnuson.

e. Serpentine ice ridge from Picnic Point to the University of Wisconsin Campus – Lake Mendota WI, 1970s. Photo: J. Magnuson.

f. Abstract ice art formed by methane bubbles rising from the sediment and by cracks from the expansion and contraction of ice owing to temperature changes – Crystal Lake, Dane and Columbia Counties WI, Jan. 2003. Photo: William Pielsticker.

humans have scored landscape paintings with higher marks if they contain some water. The same can be true if ice is added to a scene or view of a lake. Examples we offer include: (a) the sunrise on Lake Mendota enhanced by thin slabs of ice, broken by a storm's waves during a beginning stage of lake freeze; and (b) the glistening of early sun on the surface ice and snow of Mystery Lake in Northern Wisconsin. Other close-up examples of the beauty of lake ice include (c) ice stalagmites at the shoreline, and (d) floating pancake ice. Sometimes the beauty of lake ice is like a painter's canvas where the painter is a suite of physical and chemical processes that cause (e) serpentine ridges across the lake, or (f) cracks and bubbles of gas to form abstract art in clear ice not yet hidden by snow. In addition, unique zinging and deep thunderous sounds are generated as the ice contracts and expands with day-to-day and hourly changes in temperature.

The Value and Use of Lake Ice

The value of lake ice may be easier to understand in terms of economic activities, rather than in terms of cultural or ecological services. So let's begin there.

A clear-cut example was the use of lake ice for food preservation. In Madison, Wisconsin, and many other locations, lake ice was cut into blocks and stored with sawdust and then sold locally during the warm season or shipped by rail to many locations. Lake Monona in Madison had a train track conveniently located along its northern shore from where ice was loaded for shipping as far away as New Orleans. While ice cutting shifted to Lake Mendota by the early 1900s when Monona became polluted from Madison's sewage, lake ice production gradually was overtaken by ice machine ice within the next several decades. However, as the overall demand for ice increased during the early 1900s, hot summers created concerns of large-scale "ice famines" when short winters limited the amount of lake ice that could be cut and stored. All ice-cutting activities ended in the first half of the 1900s when the refrigerator replaced the icebox as a common kitchen appliance. Some "old timers" still call a refrigerator an icebox.

Lake ice also can provide a surface for transportation by foot, skis,

sled, or motor vehicle. Ice roads are still used today. At Bayfield, Wisconsin on Lake Superior, an ice road replaces the open-water ferry to Madeline Island in winter. This ice road is how children get to school and home again, and how their parents get to work and to shop at the grocery stores in Bayfield. Sometimes ice cover allows people to move more freely on a solid surface in an area without roads or with congested streets. One example comes from the University of Wisconsin's Trout Lake Station in northern Wisconsin when the original cabin-like laboratories were moved to the new Station site across the lake to serve as student housing. The problem was how to get the old lakeshore labs out of the woods and around the lake: answer – slide them onto the lake ice, pull them across, and slide them into the new location.

An example of an ecological service is that ice cover reduces evaporative water loss from a lake's surface. The longer the duration and greater the extent of ice cover on the lake, the lower the evaporative losses. The implications for the water budget and the water levels are apparent. Less ice cover on Lake Michigan and on all lakes, for that matter, contributes to lower lake levels.

Lake ice also has a cultural value in religion. Two well-known examples are a Shinto tradition on Lake Suwa in the Japanese Alps, and Lake Constance, a subalpine lake between Germany and Switzerland.

For Suwa, the Shinto custom has been to note the formation of ice pressure ridges on the lake as evidence that the male God had crossed the lake from his shrine to visit the female God in her shrine on the other side of the lake. A religious ceremony would then take place near the ice ridge. The priests also recorded the dates when ice first covered the lake. The records of the ice on Lake Suwa were first recorded by the Shinto Shrine in 1443 and have continued to the present.

For Lake Constance, the religious ice record began even earlier in the 9th century. The custom was to carry a statue of the Madonna from a church on one side of the lake to a church on the other side every winter when the ice was present and strong enough to cross. Ice sufficient for crossing is rare, especially in the last

century or two. The last occasion was in 1963 and before that in 1830.

Most values of lake ice apparent to many people are for the services they provide as a platform for a host of activities (Figure 4): ice boating, ice skating, ice hockey, ice fishing, skiing, kite boarding, snowmobiling, making artistic designs in the snow or on the ice, or simply walking on the lake. The early popularity of ice boating on the Madison lakes is perhaps best said in this newspaper quote: "There is poetry and fascination in the reckless sweep of the ice boat – no wonder that it has superseded all other winter sports" (*Wisconsin State Journal*, Jan. 19, 1878).

A wonderful aspect of these services of lake ice is that access is available to all. These services also have economic effects. In addition, winter ice provides a solid platform for lake research, management, and importantly for outreach and education.

In some cases lake ice not only provides access, but also the attraction for ecotourists. In years with safe ice, many visit the Lake Superior ice caves along the Apostle Islands National Lakeshore (Figure 5). The lake ice provides the walking trail to and along the ice caves; groundwater seeping from shoreline cliffs freezes to form frozen stalactites, stalagmites, and icefalls. These interesting and beautiful structures appear like the stone features that form in limestone caves found elsewhere.

Ice breakup (Figure 6) can be a spectacular event to observe as the ice near shore melts first (a) and the ice sheet begins to be blown down wind across the lake. When the moving ice sheet meets the opposite shore its momentum can cause a pileup of ice on the shore (b). Both visual and auditory senses perceive the power when ice chunks clunk and scrape against each other and the shore as well as the tintinnabulation from crystals pushed upwards against each other and the shore. The power of the ice can modify the shore and damage shoreline infrastructure (c).

Sometimes what attracts people onto the ice is a human-created structure or event (Figure 7). The Statue of Liberty emerging from the ice on Lake Mendota is one example (a). A University of Wisconsin–Madison student-organization



Figure 4. Lake ice provides many services.

a. Perfect day to learn ice hockey from an expert – Vilas Park, Madison, Feb. 2006.

Photo: Madison Parks Staff.

b. Ice hockey – Lake Mendota’s Cherokee Marsh, Mar. 2006. Photo: Eric Eikenberry.

c. Ice fishing – Lake Mendota, Jan. 2008. Photo: Susan Jones, Dane County WI, Office of Lakes and Watersheds.

d. Ice wind boarding – Lake Mendota, Feb. 1998. Photo: Carl J. Bowser.



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party campaigned that they would buy the Statue of Liberty and bring it to Lake Mendota if they were elected; they were, and they did in winter 1978-79. It reappears intermittently in certain winters. Another example (b) is the use of the Madison lakes for “Kites on Ice,” where kite flyers from around the country and the world came to fly their wonderfully designed kites. In recent years the festival has not been held in Madison, partly because good ice conditions are too uncertain to plan ahead for the events.

A Sign of Change

Sometimes we refer to the ice cover on lakes as a climatometer. You will not

find that word in any standard dictionary. Even so, lake ice is an excellent measure of long-term trends and variability in winter climate and weather; it is better than a standard weather station in a few ways. First, it is relatively easy to record and does not even require a thermometer or a computer. Second, it is an integrated measure that depends on the weather for several months before ice on, through the period of ice cover, and several months before ice off. Third, lake-ice dates have been recorded on Lake Mendota and a number of other lakes around the Northern Hemisphere for about 150 years, significantly longer than we have maintained weather stations in most

locations. One does not get distracted by day-to-day differences in weather; thus longer trends and variability are easier to visualize. What you do need is a succession of dedicated observers who record the date of ice on and ice off using the same methods over multiple human generations. Lake Suwa has records extending over six centuries, about ten lakes have 150-year records, and many lakes have 30 to 100 years of data. Most of these are available in the data archives of National Oceans and Atmospheric Agency’s National Snow and Ice Data Center (NOAA/NSIDC).

Ice-cover duration for Lake Mendota has become shorter over the last 159 years



c.

e. Polar plunge tests the strong or the silly – Lake Mendota, 2004. Photo: UW-Madison, University Communications.

f. Seventh grade students measuring water clarity during “Schoolyard LTER” at the Center for Limnology’s Trout Lake Station – Mar. 2014. Photo: Carol Warden.

g. Researchers take a break to pose – Mystery Lake, Vilas County WI, winter 1968-69. Photo: J. Magnuson.

h. Removing unwanted carp when they aggregate under the ice – Lake Wingra WI, Mar. 2008. Photo: David Liebl.



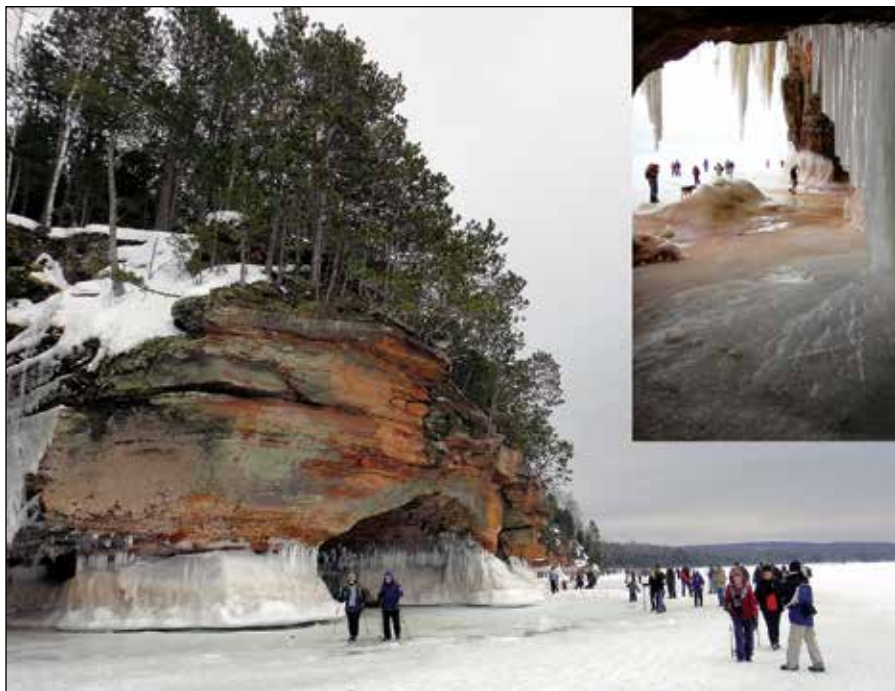
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<< Figure 5. Ecotourism at ice caves on the mainland of the Apostle Islands National Lakeshore – Lake Superior WI, Mar. 2014. Photo: Catherine L. Hein.



a.



b.



c.

Figure 6. Ice-off day.

a. Ice is beginning to melt around the lake edge and islands prior to ice-off day – Vilas County WI, Mar. 2000. Photo: Carl J. Bowser.

b. Ice beginning to push onto the shore – Lake Mendota, Apr. 2013. Photo: Clean Lakes Alliance, Madison.

c. Ice shove of fine ice crystals damaging lakeside bench – Lake Mendota, Apr. 2013. Photo: University of Wisconsin-Madison News Service.

as ice-on dates have become later and ice-off dates earlier (Figure 8). Similar long-term trends occur on lakes from around the Northern Hemisphere (Magnuson et al. 2000; Benson et al. 2012). Given the number of years in the record, the trends for the lakes are highly significant statistically; these records provide simple evidence of a warming climate.

Several other features are visible in the ice time series using ice-cover duration as an example. First, ice-cover duration differs greatly from year to year; only about 20 percent of the inter-year variability can be ascribed to the linear trend (Figure 8). Extreme years with shorter ice cover duration have become more common. Similarly, extreme years with later ice on and earlier ice off have become more common. What is causing the changes in extremes expected from a warmer climate? It is not that the durations are becoming more variable, but rather that the variability is around an average duration that has decreased progressively (Benson et al. 2012).

One cannot help but wonder why the variability is so large from year to year? Some of the explanatory mechanisms are revealed in studies by Sharma et al. (2013) and Sharma and Magnuson (2014). Ice dates were characterized by quasi-cyclic dynamics at time scales of 2-3 years (Quasi-biennial Oscillation), 3 to 7 years (El Niño Southern Oscillation), the 11-year Solar Cycle, and 20 to 50 years (multi-decadal oscillations). Each of these large-scale climate drivers contributed to the variability in ice dates; year-to-year differences in local weather were also important contributors. Still, much of the variability remains unexplained. Thus, predicting precise dates for ice-on and ice-off several months or years ahead of time is not yet possible. This unpredictability has enabled organized lotteries to develop where the entry with the closest or exact ice date or even time wins and receives a prize. Several lotteries are held in Madison for Lake Mendota. Many others are held in other parts of the world for ice-covered lakes and rivers.

A Threatened Future

The lake-ice observations discussed above do not reveal the cause of the warming trend, but our results are consistent with effects of human-caused increases in greenhouse gases such as



Figure 7. Attractions on the ice.

a. Hoofers Statue of Liberty – Lake Mendota, Feb. 2009. UW-Madison, University Communications.

b. “Kites on Ice,” view – Lake Mendota, Feb. 2004. Photo: J. Magnuson. Insert – Lake Monona, Feb. 2001. Photo: Carl J. Bowser.

carbon dioxide. As one would expect, ice is especially sensitive to a warming climate. One implication is that as greenhouse gases continue to increase, winter air temperatures will continue to increase, and ice cover will continue

to decrease. We expect that the beauty and values of lake ice will decline in proportion to the length of winter as determined by the duration of ice cover.

Losses in winter, as we knew it, have already begun and opportunities for

Ice Cover on Lake Mendota (Winters of 1855-56 to 2013-14)

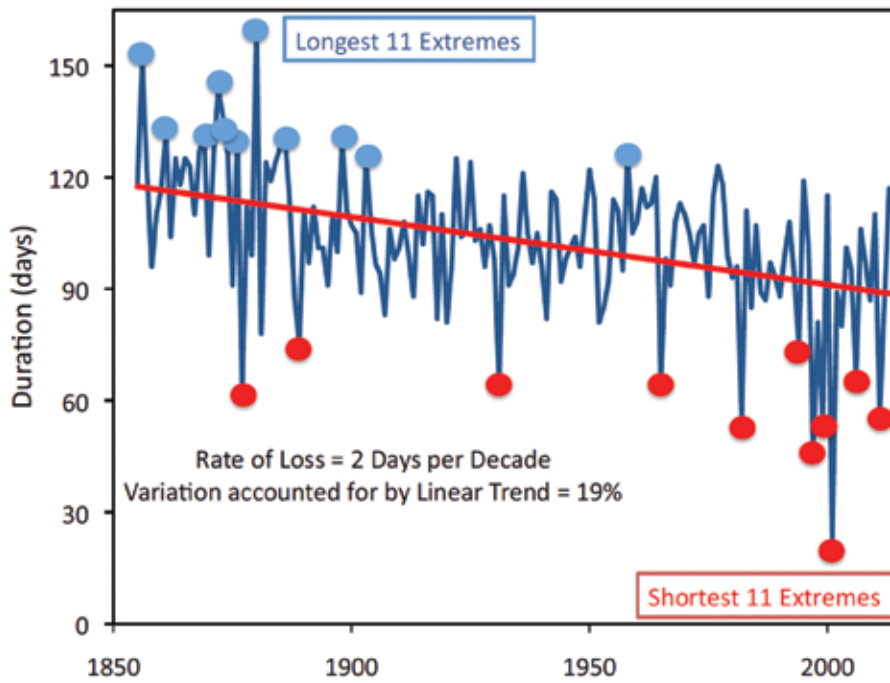


Figure 8. Ice cover duration, trends, and extremes over 159 winters from 1855-56 to 2013-14 – Lake Mendota.

winter activities on the ice have declined. For example, when the ice boating and skating print for Lake Monona was published in 1878 (Figure 9), ice durations from the early decades were 24 to 34 days longer than recent decades when averaged over 20, 30, and 40 year periods – a loss of about 25 percent. Lake Geneva, a large deep lake in southeastern Wisconsin experienced its first winters without complete ice cover in 1997 and 2001 over the 150-year record; also, in 2001 Lake Mendota had only 21 days of a thin ice cover and supported only a bit of ice fishing near shore in bays protected from the wind. Given that the ice is also thinner with our warmer winters, one would expect that falling through the ice would be more likely, not only for those on snowmobiles, but also for ice boating, skating, or only walking especially by ice fishers trying to stretch the season. Unusually late ice-on dates create dangerous situations as well. Who would expect that in mid-to-late-January, Lake Mendota ice would not be safe? However, we had a January 20, 2007, ice-on day followed by a light snow on January 21, so that on January 22, two days after freezing over, the layer of skim ice under the thin blanket of snow did not reveal the unexpected danger (Figure 10).

Given the high variability in ice cover among years, we can expect that intermittent colder winters will continue to provide opportunities for winter activities for some years well into the future. Still, more winters will be too warm to provide for winter lake-ice activities. Unfortunately, abilities to forecast the conditions for next winter or the winter after that are not precise enough to allow long-term planning and investment for ice-based events such as winter festivals, ice-boat regattas, or large ice-fishing contests.

Losses of ice cover on north temperate and boreal lakes are first occurring along the southern range of ice-covered lakes and are creeping northward. Large, deep lakes like Lake Geneva, Wisconsin, or Lake Superior are affected sooner than are small, shallow lakes or ponds. Our relationship to lake ice and the beauty and values that it provides are changing. Winter and ice-covered lakes in north temperate latitudes are a part of our culture and activities. Who are the advocates for winter and ice-covered lakes? We hope that our children, their children, and their grandchildren, will be able to experience and enjoy one of the unique feature of lakes in winter – lake ice.



Figure 9. Iceboat regatta and ice skaters – Lake Monona WI, 1878. Photo of page 189 in Harpers Weekly, Mar. 1878. Inserts: left, Ice skating, – Madison WI, Jan. 1995.; right, Iceboat – Lake Monona, Jan. 2009. Photos: Craig Wilson, Kite Aerial Photography.



Figure 10. Late ice-on day (Jan. 20) followed by a light snow hides the danger of unexpected thin ice – Lake Mendota, Jan. 22, 2007. Photo: J. Magnuson.

breakup for Northern Hemisphere lakes from 1855 to 2004. *Climatic Change*, 124: 835-847.

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Next Issue – Spring 2015 *LakeLine*

As in any field, new products and services are continually developed for managing lakes. The spring 2015 issue of *LakeLine* will have the theme, “What Works.” In this issue, we will review several methods with proven positive results and new updates, including lake oxygenation, nutrient precipitation and inactivation, Eurasian watermilfoil control, hand-pulling invasive aquatics, and early intervention to prevent zebra mussels.

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