

Confronting Climate Change in the Great Lakes Region Technical Appendix

Impacts of Climate Change on Lake and River Ice Cover

*This document is a technical appendix providing further detail on the water resource information in the Report on **Confronting Climate Change in the Great Lakes Region** available at <http://www.ucsusa.org/greatlakes/> (Kling et al. 2003). The principal author contact for this background paper is John Magnuson, and co-authors include (alphabetically) Katharine Hayhoe, Lucinda Johnson, George Kling, and Brian Shuter.*

Ice cover is perhaps the most sensitive indicator of a warming climate and climate variability (Magnuson et al. 2001). Ice cover displays a threshold response to warming that is easily observed by scientists and the casual observer alike – people can relate directly to the changes in ice cover. Ice breakup or freeze over a lake are events that require no measuring technology other than a human observer, and thus long-term records have become available across the Great Lakes Region through lay observers beginning as early as the 1850s. Ice cover is closely related to air temperature and can be used to estimate past temperatures (Assel and Robertson 1995). Ice dates are also responsive to solar radiation as altered by cloud cover and snow cover (Vavrus et al. 1996, Wynne et al. 1998).

The representative response of lake ice to interannual variation in climate is demonstrated by the coherence in the year-to-year pattern of ice-off dates. Coherence can be represented by the proportion of shared variance (estimated by r^2) in two time series, in this case of ice-off dates; a value of 1.00 means that the two series are identical, while a value of 0.00 means that they vary independently of one another. At the North Temperate Lakes Long-Term Ecological Research (LTER) in Wisconsin (Magnuson et al. in press b) ice-out dates are more coherent than ice-on dates or a variety of annual water temperature measures. From 1981 to 2001 coherence for the 21 possible pairings of the seven LTER lakes was very high with a median of $r^2 = 0.92$ (range = 0.83 to 0.98), even though the seven lakes differ morphologically by factors of 3,000 in surface area and 14 in mean depth. By contrast the median coherence for water temperature between lakes was slightly lower, $r^2 = 0.86$, near the surface in summer and much lower, $r^2 = 0.31$, near the bottom. The clear implication is that a lake's surface temperature and especially its ice-off date is a representative measure of changes related to climate for the area.

While the coherent results indicate strong common behavior of lakes and common physical interaction between lakes and climate, none of the trends were statistically significant in the 21-year period even though all had slopes in the direction of earlier ice out. Short-term trends are not statistically significant owing largely to the high interannual variability in climate. Longer-term data are needed to detect trends, especially for single sites (see Kling et al. 2003, p. 14).

Long-term lake ice data make clear that the region is warming and that the warming has begun to influence the lake ecosystems. With a 150-year record on Lake Mendota in southern Wisconsin (Kling et al. 2003, Figure 9A) and a number of lakes

elsewhere in the Great Lakes region (Kling et al. 2003, Figure 8), statistically significant long-term trends can be detected even with high interannual climate variability. For Lake Mendota, ice cover has shortened from about 4 months to about 3 months per winter season over the 150-year period. The trend line explains about 17 percent of the variability in the time series. More detailed analyses of the time series indicates that the change is not linear, but occurs in steps. A step for reduced cover occurred in the 1880s and change has been rapid again since 1970. A time series model that incorporates these steps accounts for 27 percent of the variability in the series (Magnuson et al. in press b). From about 1890 until 1970 no clear trend is apparent. This clearly points to the importance of the long-term record with which slow and irregular changes can be detected despite interannual variability, and for which more complex time series analyses and process modeling can be applied. The lakes for which results are presented in the report include all those found that have long records and these are located in urban, agricultural, and forested areas. The trends are greater in the Western Great Lakes Region than in the eastern Great Lakes Region and the slopes are steeper in recent years than over the entire series.

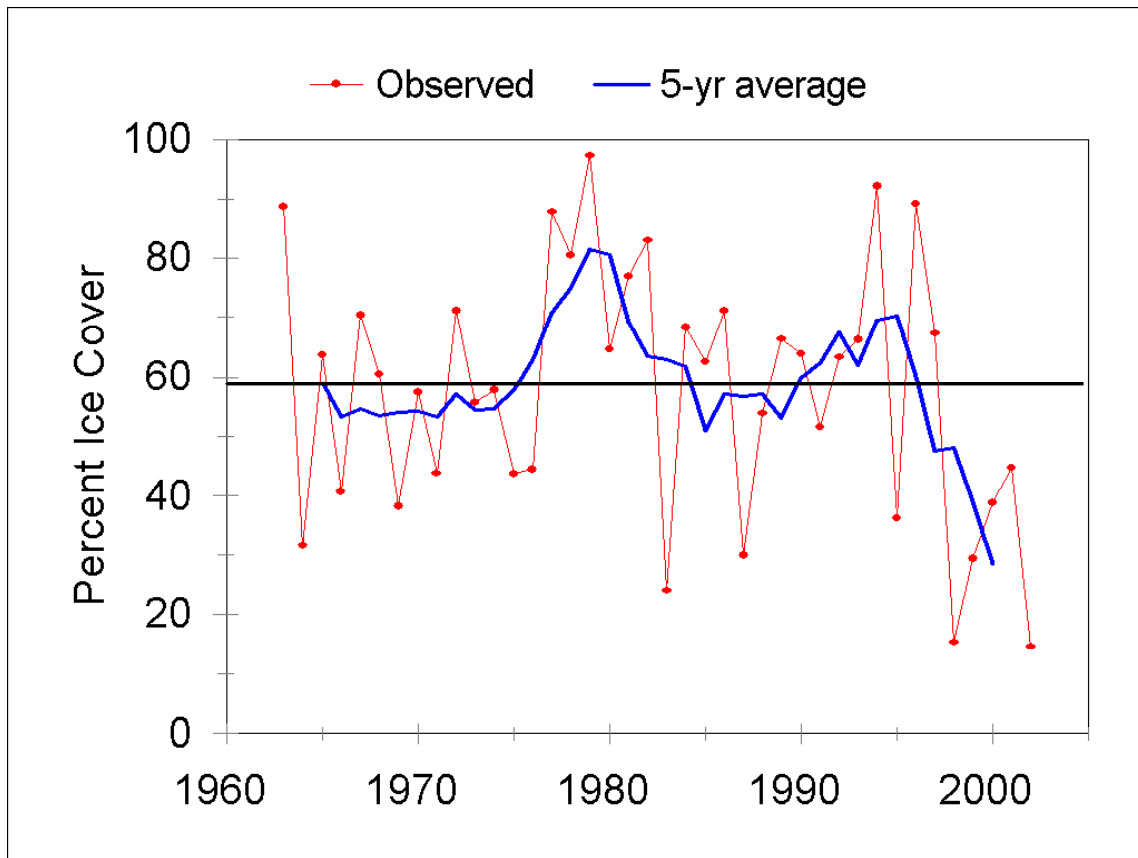
The long-term trends for reduced ice cover on lakes and rivers are apparent at local to global spatial scales. In the Madison area all observed lakes have had shortening durations of ice cover (Magnuson et al. 2000, Magnuson et al. in press a). The pattern is not unique to Madison, however, but is apparent across Wisconsin (Magnuson et al. in press a), across the Great Lakes Region (Figure 8, Clark et al. in Kling et al. 2003), and throughout the Northern Hemisphere more generally (Magnuson et al. 2000).

This consistency in the direction of the trends does not necessarily translate to consistent interannual behavior of lakes around the Northern Hemisphere. Wynne et al. (1996) observed that lakes in the western Great Lakes area were more coherent if they were oriented WNW/ESE relative to each other as opposed to other compass directions. Moreover, as the distance between the lake pairs increases their behavior is less coherent. In other words, the short-term interannual variation is not necessarily spatially coherent. For example, the coherence between LTER lakes in northern Wisconsin had a median of $r^2 = 0.92$ while that between lakes in northern and southern Wisconsin was somewhat lower, $r^2 = 0.80$, but still high enough to indicate broad statewide patterns of behavior. However, large-scale climate drivers such as the El Niño Southern Oscillation tend to impart common interannual behaviors across a region (Anderson et al. 1996, Robertson et al. 2000, Magnuson 2002). Longer oscillatory behaviors in climate such as the North Atlantic Oscillation and changes in the strength of the Aleutian Low also cause coherent behavior among widely scattered lakes (Benson et al. 2000, Magnuson et al. 2002).

Some lakes provide ice thickness data, but rarely are these records available over the long term (Gronskaya 2000). The Laurentian Great Lakes often do not freeze over completely and estimates have been made since 1963 of the maximum extent of ice cover on each lake and all of the lakes combined (Assel et al. 2003), which is termed the Annual Maximum Ice Concentration (AMIC). For the Laurentian Great Lakes in total the extent of ice has been highly variable ranging from more than 90% ice-covered to ice only around the shorelines (Figure 1). Trends since 1963 are not statistically significant even though significant trends do occur with the longer-term ice-on and ice-off data on number of Great Lakes bays (Assel et al. 1995, Assel and Robertson 1995). The data suggest that ice extent has been declining since the 1970s. The extent of ice does

respond to large-scale regional climate drivers such as the El Niño Southern Oscillation (Assel et al. 2003) as did the ice-off dates for the inland lakes of the region.

Figure 1. Ice cover in all the Great Lakes combined has been lower in recent years, but there is no long-term linear trend from the early 1960s to present (Assel and Norton 2002).



Lake and river ice is also a useful indicator of climate variability and change because the dynamics of ice cover duration, ice-on dates, and ice-off dates provide insights and have implications for those interested in managing human interactions with climatic changes. Several examples given below were adapted from those developed in respect to fisheries from Magnuson (2001).

- Fisheries resources, water resources, agriculture and urban systems are responsive to climate variability and change; *IMPLICATION*: complex human and ecological systems do respond to climate change and variability.
- Time series data on human and ecological systems are often too short in duration to see first hand the longer-term dynamics and the trends associated with global warming; *IMPLICATION*: we must maintain measurement and monitoring systems and rely on other observers.

- Climate drivers have large-scale regional footprints and operate over long distances; *IMPLICATION*: dynamics of human and ecological systems tend to have strong regional and global patterns.
- Human and ecological responses to climate change and variability should occur over the same array of time scales evident in cryosphere (ice) records; *IMPLICATION*: we must plan for both short-term and long-term climate variability and change.
- Long-term change will likely occur in steps over relatively short periods that are difficult, if not impossible, to predict in detail at present; *IMPLICATION*: we must expect surprises and plan or manage for the unexpected.
- Inter-decadal and shorter-term variations are greater in magnitude than are the long-term trends; *IMPLICATION*: managers will have to respond in the near term for large interannual variations in climate.
- Unusual years (i.e., those differing significantly from the long-term historical average) are becoming more frequent and more extreme; *IMPLICATION*: we must expect that an unusually warm (or dry or wet) year will occur and prepare and design structures and systems that will function adequately under current and future extreme conditions.
- Responses of human and ecological systems to climate change and variability may be amplified, dampened, or lagged; *IMPLICATION*: lags between climate drivers and responses of the human and ecological systems will likely occur, so we must take a longer-term view.
- Ice conditions can have direct and indirect effects on human and ecological systems; *IMPLICATION*: the loss of ice or even the thinning of ice can affect our well-being and economic activities. For example, thinning or loss of ice can cause increased winter mortality of people on lakes and prevent or limit winter activities such as fishing on lakes.

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