Assessing the Impacts of Climate Variability and Change on Great Lakes Evaporation:

Implications for water levels and the need for a coordinated observation network

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Great Lakes Water Levels: The Critical Role of Evaporation

The question has been asked many times: "Who is draining all the water out of the Great Lakes?" As with many environmental issues—in this case low lake levels—people are interested in "the cause." And with good reason: If the source of a problem is identified, the solution becomes more attainable. As with many problems, however, the issue of Great Lakes water levels is complex. Lake Superior, for example, loses almost three feet of water *every year* through the St. Marys River (Lenters, 2004). And roughly two feet of water is also lost every year just through evaporation (Figure 1). That is a total of five feet of water lost annually from the surface of Lake Superior due solely to natural processes. Relatively little water is gained or lost through direct human intervention (e.g., less than 1 inch per year flows into Lake Superior from the Long Lac diversion). So the next time the question arises about "who is draining all the water out of the Great Lakes," the answer should be that it is mostly Mother Nature. This does not necessarily mean that nature is not changing (e.g., due to human causes), but it does at least mean that one can stop looking for that secret water pipeline to the southwestern United States. As illustrated in Figure 1, the real "elephants in the room" are precipitation, evaporation, and runoff through rivers and connecting channels (Hunter et al., 2013). These are the processes that should be looked at most closely.

Evaporation is one of the most difficult water-loss processes to understand, and for a number of reasons. First of all, it is invisible. One cannot generally "see" a lake evaporating (an exception being the condensed water vapor or lake-effect clouds that sometimes hover above a lake's surface in autumn and early winter). This is in contrast to rivers, for example, where water level and flow conditions are always visible. A second reason that evaporation can be difficult to understand is that it often varies in counterintuitive ways. For example, many people assume that the Great Lakes' highest rates of evaporation are in the heat of summer (mid-July), since high temperatures are often equated with high rates of evaporation. It turns out, however, that this is simply not the case. The highest evaporation rates on the Great Lakes typically occur in late fall and early winter, when conditions are much colder (Figure 1). This is because evaporation is not directly driven by warm air temperatures, but instead by warm *water* temperatures (Lenters, 2004). More specifically, high evaporation requires three factors: 1) a large temperature difference between water and air (i.e., warm water and cold air), 2) low relative humidity, and 3) high wind speeds. If all three ingredients are present, as often occurs in the fall and winter, evaporation rates from the Great Lakes can get as high as 0.4-0.6 inches *per day*. To put this number in perspective, a 1-day loss of 0.5 inches of water from the total surface area of the Great Lakes (94,250 mi^2) represents a volumetric flow rate of 820 billion gallons per day – nearly 20 times the flow rate of Niagara Falls.

A third problem with evaporation is that it is extremely difficult to measure—so it is rarely done. Unlike a rain gage, there is no simple "evaporation gage" that can be attached to a weather station to provide direct, accurate observations of water loss from soil, plant, or water surfaces. "Pan evaporation" gages are sometimes used, but they provide only indirect estimates of evaporation and are not suitable for measuring evaporation from large, deep lakes. Instead, meteorologists and hydrologists must use

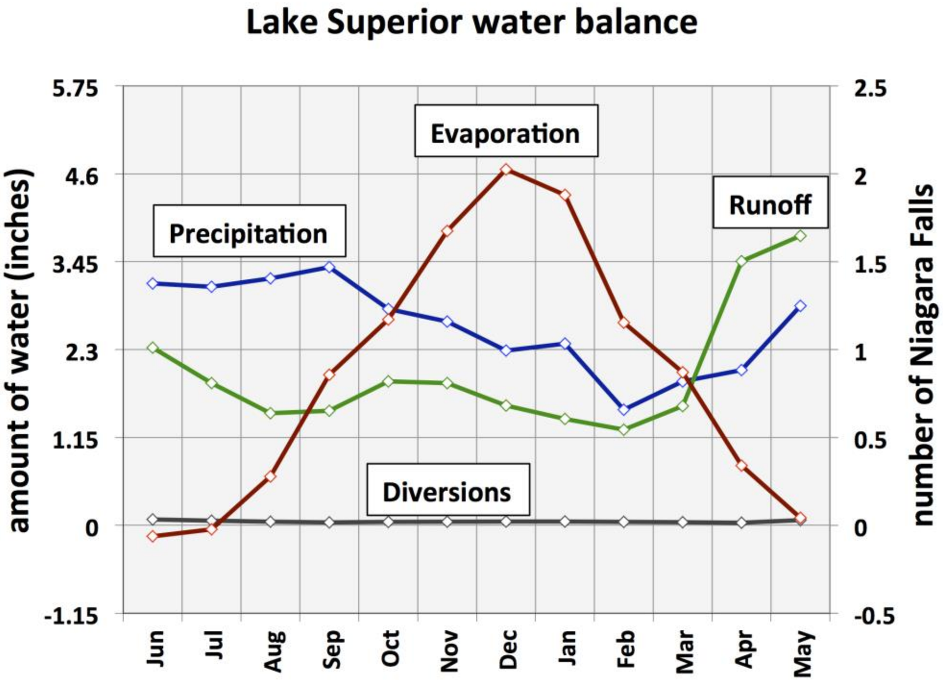

Figure 1. Four components of the monthly Lake Superior water balance, beginning with the month of June, which is the typical start of the "evaporation season." Each component is shown as a flux of water in units of inches per month (left; spread out over the surface area of Lake Superior), as well as in equivalent "number of Niagara Falls" (right). Note, in particular, the strong seasonal variation in evaporation.

more complex (and often expensive) techniques to calculate evaporation. Sometimes this involves measuring everything *except* evaporation, and then solving for evaporation as a residual (i.e., performing an "energy balance" or "water balance"). As a result of all these complexities, measurements of evaporation are much less common than observations of other water balance components, such as precipitation and runoff. The Great Lakes are an extreme example of this, given the roughly 700 streamflow gages and 800 precipitation gages that were in operation around the year 2000, when *not a single station* was devoted to the measurement of lake evaporation (Hunter et al., 2013).

One of the more accurate ways to measure evaporation—and one of the few that is actually considered a *direct* method—is the "eddy covariance" technique. This method uses sophisticated instruments to measure humidity and wind speed at high frequencies (typically 10 times per second), and this information is then used to calculate the "flux" of water vapor to or from the lake surface (i.e., condensation and evaporation, respectively). The eddy covariance technique can be very effective, and often provides estimates of other important fluxes from the water surface as well, such as heat, momentum, carbon dioxide, and other gases. Nevertheless, making measurements like this over large bodies of water such as the Great Lakes comes with its own set of challenges. For example, moving platforms (such as buoys) are problematic for the eddy covariance technique and also don't stand up to heavy freezing spray and thick, mobile ice cover. So most Great Lakes buoys are removed from the water in autumn, even though late fall to early winter is precisely the time of year when the highest evaporation rates occur (Figure 1). So in order to get direct, year-round measurements of Great Lakes evaporation, eddy covariance instrumentation must be mounted on tall, stable platforms such as lighthouses and small islands. As you can imagine, however, these are often remote and difficult to access.

Given the above considerations, it is clear that evaporation is an important but challenging process that must be taken into account when considering changes in Great Lakes water levels. But how can this be accomplished in the face of all the technical challenges that have been presented? This is the question that this GLISA-funded project set out to answer, using Lake Superior as the initial research "test bed." As part of the project, scientists initiated the first-ever direct measurements of evaporation on the Great Lakes. The scientific story that has begun to emerge from this new research describes a complex relationship among lake evaporation, ice cover, and water temperature, as well as a "new regime" for Lake Superior since 1998, characterized by reduced ice cover, warmer summer water temperatures, and enhanced evaporation rates. The results show that continued (and even expanded) monitoring of Great Lakes evaporation is needed to provide accurate observations and sound predictions of the future impacts of climate change on Great Lakes evaporation and water levels.

Scientific and Historical Background

Warming temperatures in recent decades have led to significant declines in the duration and extent of Great Lakes ice cover (Assel et al., 2003), with correspondingly longer periods of open water and an earlier start to the summer "stratification season" (Austin and Colman, 2008). At the same time, significant increases in summer water temperature have been observed in the Great Lakes, particularly since the early 1980s (Austin and Colman, 2008; Schneider and Hook, 2010). In some cases, the rate of warming is even more rapid than that of the overlying atmosphere (Lenters, 2004; Austin and Colman, 2007), which increases the lake-to-air temperature difference within the atmospheric boundary layer—a region of air that is typically stable over the Great Lakes during summer. This reduction in atmospheric stability has been associated with correspondingly stronger winds over the surface of Lake Superior (Desai et al., 2009), as well as Lakes Michigan, Huron, and Erie (Austin and Colman, 2007).

Considering the earlier discussion on what "controls" evaporation, it is reasonable to suggest that the observed increases in water temperature and wind speed, as well as reductions in ice cover and stability, would lead to higher evaporation rates. In fact, enhanced evaporation has been suggested to be the cause of much of the recent decline in Great Lakes water levels (e.g., Hunter et al., 2013; Hanrahan et al., 2010). While this may be true during summer, conditions during the winter are more complex. For example, even the basic premise of enhanced evaporation due to decreased ice cover has been questioned. A previous study of the Lake Superior water balance revealed an upward trend in modeled summer evaporation rates from 1948-1999, but a compensating downward trend in winter evaporation (Lenters, 2004). These contrasting trends were found to be associated with a more positive (i.e., upward) lake-air temperature difference in the summer, similar to findings by Austin and Colman (2007), but a more *negative* lake-air temperature difference in the winter (i.e., downward). Thus, the gap in understanding climate change effects on Great Lakes evaporation may not just be limited to the magnitude of change, but even to the *direction* of change. Such gaps in understanding highlight the need for continuous, long-term, direct measurements of evaporation from the Great Lakes.

The first effort to directly measure year-round evaporation rates on the Great Lakes in a sustained, continuous fashion occurred in June of 2008 in association with the International Upper Great Lakes Study (IUGLS; http://www.iugls.org), which is coordinated through the International Joint Commission (IJC). At the behest of the

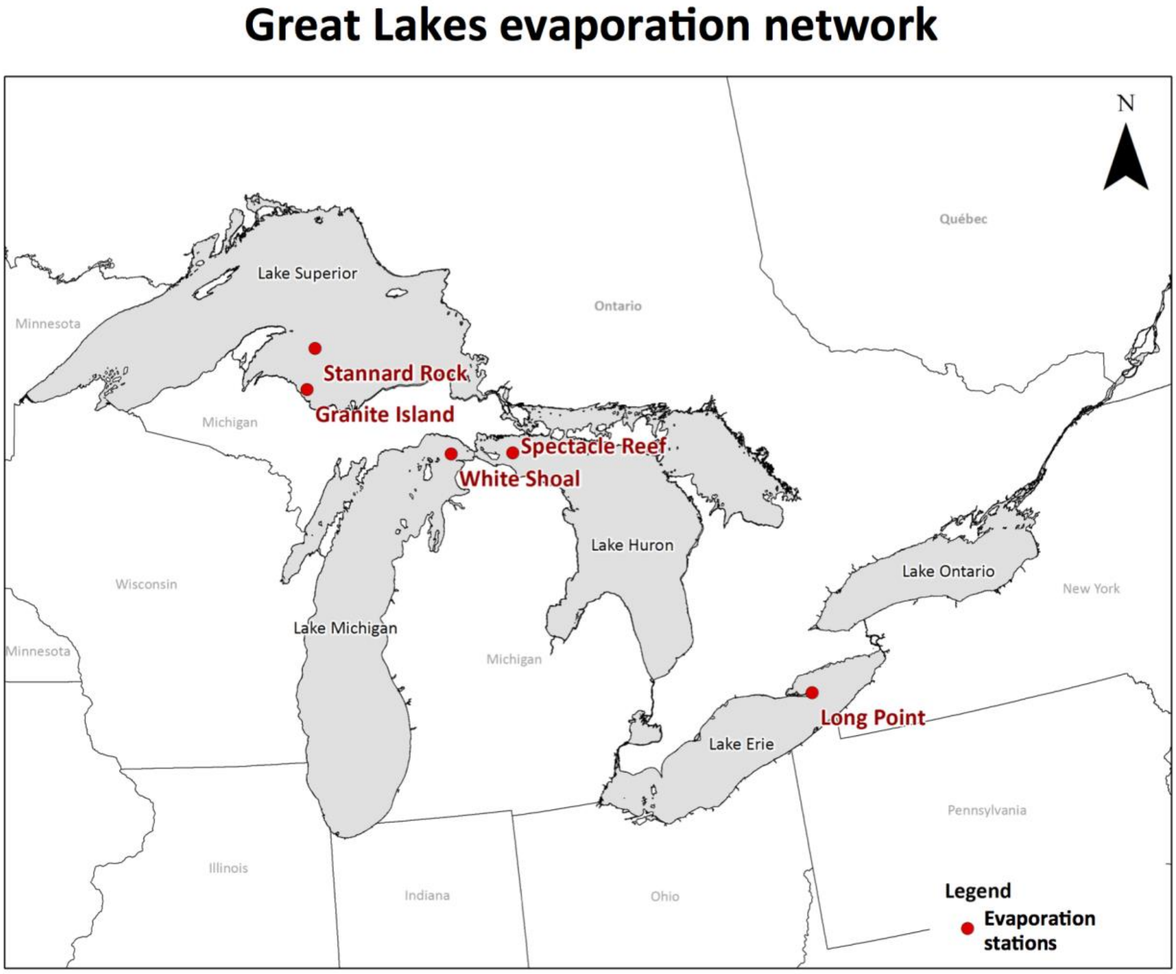

Figure 2. Map showing the new network of evaporation monitoring stations on the Great Lakes. As of November 2013, a total of five stations are in operation, with additional stations planned for the future (funding permitting). All five sites employ the full suite of meteorological instruments that are needed for applying the eddy covariance technique.

IUGLS, investigators C. Spence and P. Blanken deployed an eddy covariance station on Stannard Rock Light (Figure 2), an offshore lighthouse on Lake Superior (Blanken et al., 2011). Independent of the IUGLS effort, a second Lake Superior monitoring station was deployed on Granite Island in July of 2009 by J. Lenters, in cooperation with the private landowner (S. Holman) and investigators at Northern Michigan University (NMU). Granite Island is located in the nearshore waters of Lake Superior, just north of Marquette, Michigan (Van Cleave, 2012). Additional sites on the Great Lakes soon followed, starting with Spectacle Reef on northern Lake Huron in September 2009.

In the spring of 2011, funding was provided by GLISA to the aforementioned investigators to assist in the integration of these independent efforts to monitor and understand the impacts of climate variability and change on Great Lakes evaporation. Research results that stem, in part, from this collaborative GLISA project are described in a series of publications by Blanken et al. (2011), Spence et al. (2011), Van Cleave (2012), and Spence et al. (2013). The present GLISA white paper summarizes a number of results from this series of publications.

GLISA Project Results

Physical Controls on Lake Evaporation

Evaporation from Lake Superior is found to occur in 2- to 3-day events, and is primarily controlled by wind speed and the amount of moisture in the air (Blanken et al., 2011). Roughly 70-90% of the annual evaporation happens between the months of October and March. Most of the energy for evaporation comes from solar radiation, but the primary solar input occurs roughly five months prior to the annual peak in evaporation. Thus, there are important leads and lags in the Lake Superior system, and this leads to complexities in the atmospheric controls on Great Lakes evaporation.

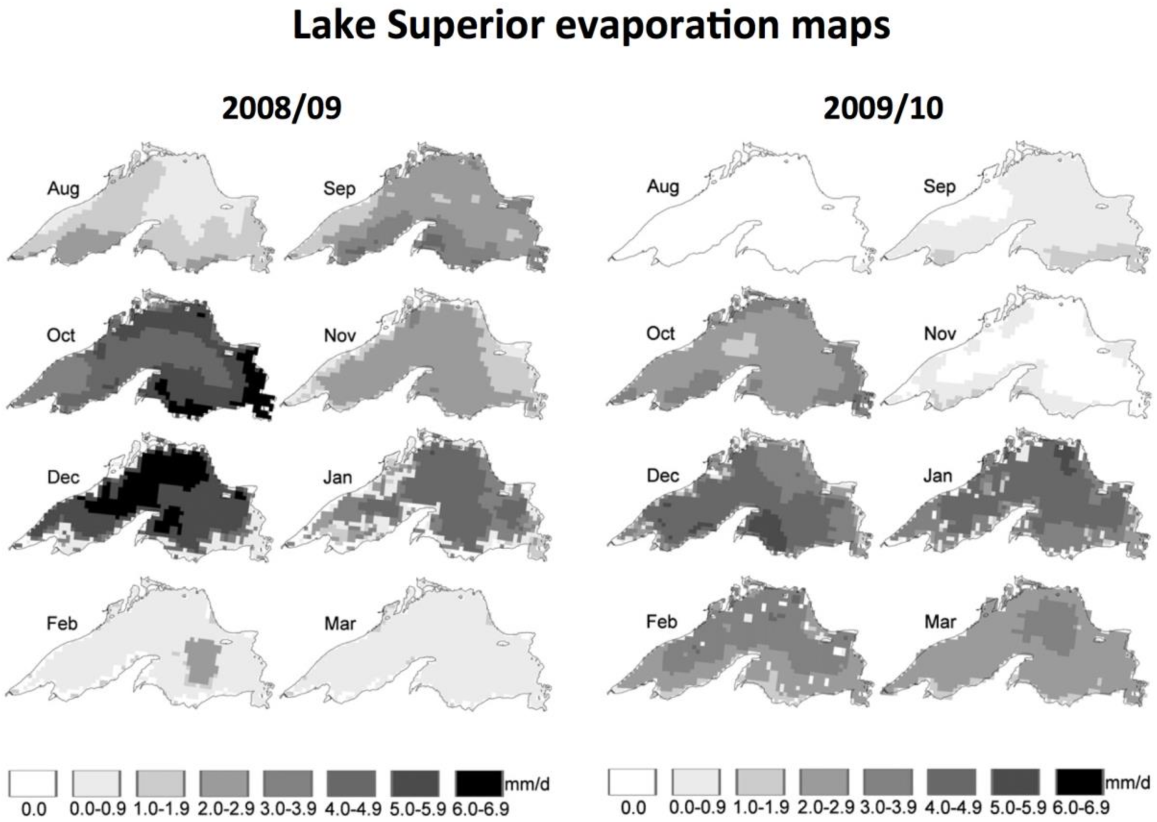

Figure 3. Maps of monthly mean evaporation rate for Lake Superior (in mm/day), based on a combination of observational data from Stannard Rock lighthouse, numerical weather model output, and satellite data (Spence et al. 2011). Results for the 2008/09 evaporation season are shown on the left, while 2009/10 is shown on the right. Note the weak February-March evaporation rates during 2008/09, which resulted from high ice coverage that winter. This high-ice winter, however, was preceded by (and caused by) *high* August-December evaporation rates.

Spatial and Temporal Variability

Measured evaporation rates at Stannard Rock Light were combined with results from a numerical weather prediction model and satellite-derived estimates of ice cover and surface water temperature to arrive at spatial maps of Lake Superior evaporation (Spence et al., 2011). Monthly maps of evaporation are shown in Figure 3 for the two study years, 2008/09 and 2009/10. The results show that the highest evaporation rates tend to occur in the nearshore regions of Lake Superior during September and October, particularly along the southern shore. This switches to offshore regions by January and February, when ice cover begins to limit evaporation in nearshore regions.

Similar to the results of Blanken et al. (2011), the annual peak in evaporation is found to occur during the months of October, December, and January. Interestingly, somewhat lower evaporation rates are observed during November, which is still considered part of the “peak” evaporation season. Although this may simply reflect warmer, humid air during these two particular Novembers, it is another reminder of the important role of leads and lags in controlling the timing of lake evaporation. High evaporation in October, for example, can lead to significantly lower water temperatures by November, which then limits evaporation rates during this part of the autumn “shoulder season.”

Effects of ice cover are also evident in Figure 3, as 2008/09 was a high-ice year, while 2009/10 was a low-ice year. For example, evaporation from Lake Superior was significantly lower in February and March of 2009 (compared to 2010), as a result of the more expansive ice coverage that spring. Interestingly, however, evaporation rates were *higher* during the autumn of 2008 leading up to the high-ice winter. This reflects the strong cooling effect of evaporation on water temperatures and ice formation, and suggests the potential for compensating effects during spring and autumn. Although Spence et al. (2011) examined only two years of evaporation data, the results of their work are corroborated by Van Cleave (2012), who examined evaporation / ice cover relationships over a much longer 38-year period (discussed below), using data from NOAA’s Great Lakes Environmental Research Laboratory (GLERL).

Interactions with Ice Cover and Water Temperature

In a recent, long-term study of the interactions among Lake Superior evaporation, ice cover, and water temperature, Van Cleave (2012) uncovered a number of interesting relationships. For example, although it is well known that Lake Superior has much less ice cover than it did just a few decades ago (as well as warmer summer water temperatures), this new study discovered that the long-term trends are not linear through time. Instead, there was a significant "step change" that took place during the warm winter of 1997/98, which happened to also be an El Niño year. Figure 4 shows an example of this step change for ice cover, although similar shifts were also found for summer evaporation and water temperature (Van Cleave, 2012). The result of these step changes is a 39-day decline in ice duration, a 3°C increase in summer water temperatures, and a notably earlier start to the evaporation season (i.e., higher evaporation rates in July and August). Although the exact reasons for these step changes are not yet known (i.e., the "external" causes), the similar timing suggests that the changes in ice cover, evaporation, and water temperature are all strongly linked.

In addition to examining long-term trends, Van Cleave (2012) investigated year-to-year differences in Lake Superior ice cover, water temperature, and evaporation over a 38-year period to see if there was any correspondence among the three variables. Similar to previous results (e.g., Austin and Colman 2007), the study

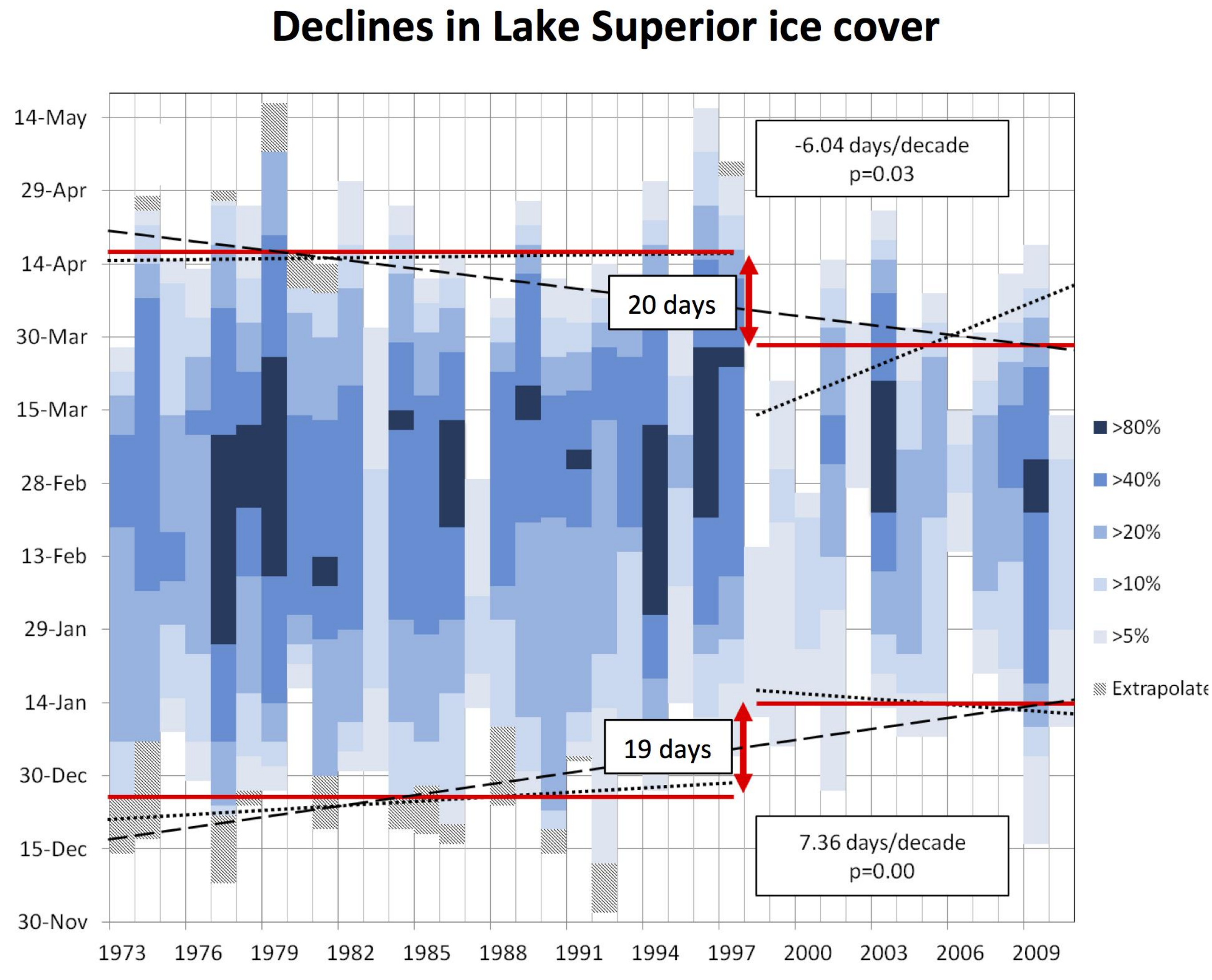

Figure 4. Lake Superior fractional ice coverage (in %), showing a significant decline from 1973-2010 (Van Cleave 2012). Also shown are the linear trends in ice formation and breakup dates (dashed lines), as determined from the 5% ice cover threshold. Red lines show the non-linear "step change" that took place during the winter of 1997/98.

found that years with high ice cover were usually followed by cooler summer water temperatures and lower evaporation rates. On the other hand, Van Cleave (2012) also found that these same high-ice winters were *preceded by high evaporation rates* during the autumn and early winter. Similar to the results of Spence et al. (2011), this reflects the strong cooling influence of evaporation, indicating that periods of high/low evaporation can significantly affect the timing and duration of Lake Superior ice cover. Thus, not only is the research showing that ice cover affects lake evaporation, but also the reverse—namely, that evaporation affects ice cover.

The Importance of Spring and Autumn

Lake Superior is a very large and deep lake, and this strong "thermal inertia" is one of the reasons for the important leads and lags that have been identified in evaporation, ice cover, and water temperature. Spence et al. (2013) show that this results in an important role for weather systems during the spring and fall "shoulder seasons." November air temperatures, for example, are found to be critical in determining the onset and duration of ice cover on Lake Superior. This, in turn, can impact annual evaporation rates. Similarly, low ice cover and high spring air temperatures cause an early ice breakup date and premature start to the evaporation season.

A dramatic example of this occurred following the consecutive low-ice winters of 2009/10 and 2010/11 (Figure 5). Spurred in part by warm spring air temperatures during March of 2010, Lake Superior was ice-free by April 9 of that year—roughly one month earlier than each of the other three years in the study (Spence et al., 2013). This early ice breakup and warm spring led to significantly above-normal summer water temperatures in

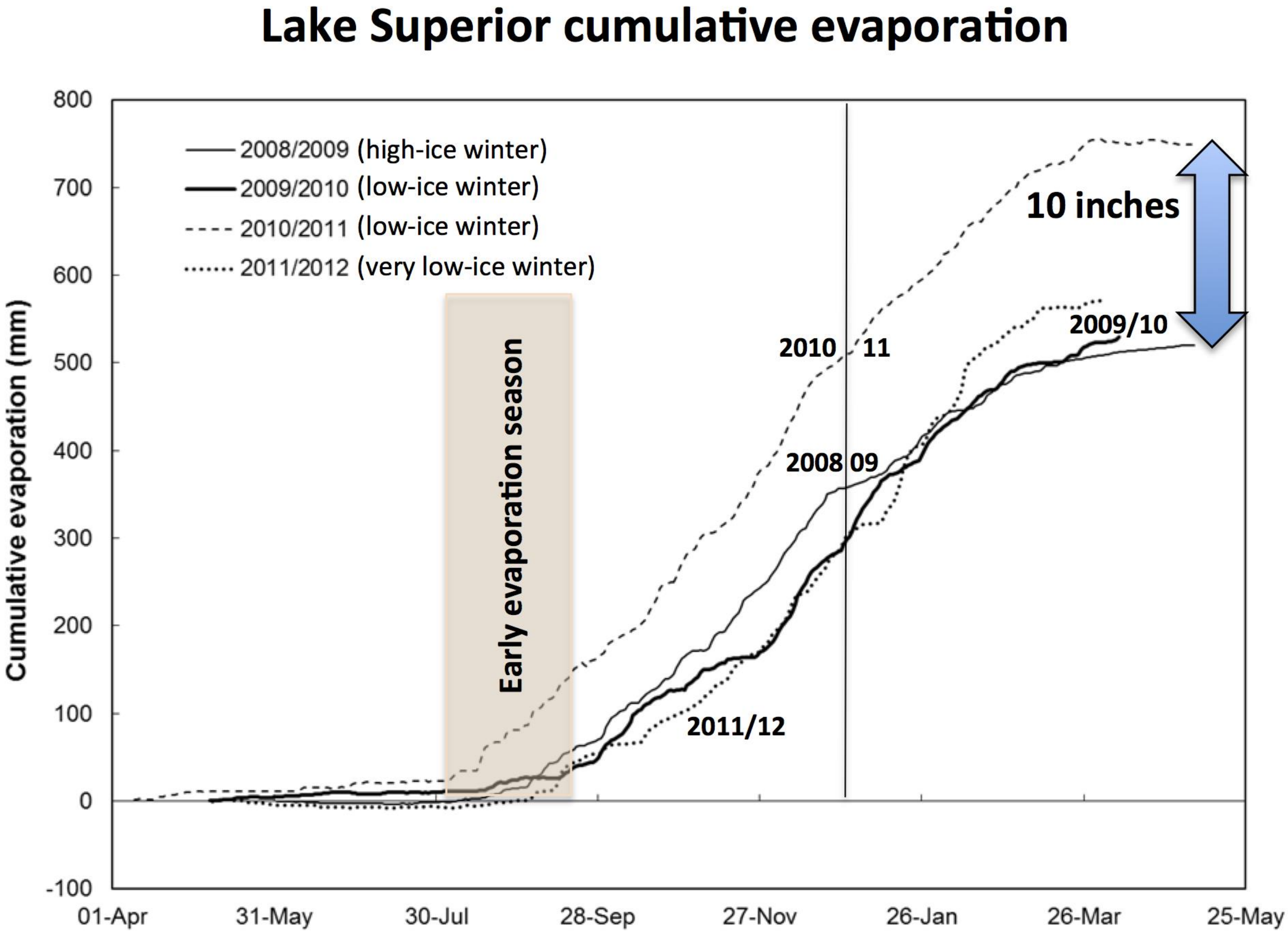

Figure 5. Four years of cumulative evaporation from Lake Superior, using direct meteorological measurements at Stannard Rock lighthouse (Spence et al. 2011). Each annual curve begins at the date of ice breakup and continues through the remainder of the evaporation season. Note, in particular, the much higher total evaporation during the 2010/11 season – roughly 10 inches greater than the other three years. This high-evaporation year resulted primarily from an early onset of the evaporation season during the particularly warm summer of 2010 (highlighted in orange).

2010 and an early start to the 2010/11 evaporation season (Figure 5). As a result, Lake Superior's annual evaporation for 2010/11 was roughly 10 inches greater than the high-ice year of 2008/09. While 10 inches of water may not sound like a lot, this is only an example of what **one or two** unusually warm years can do. Consider, for example, what Lake Superior might look like in the future if **most years** were similar to these two anomalous years. Unless climate change also leads to significant increases in precipitation to compensate for the increased evaporation rates, the net result will be persistently lower water levels for the Great Lakes.

Stakeholder Engagement: Toward a Coordinated Great Lakes Evaporation Network

To facilitate outreach with decision-makers and the broader community, a public forum was hosted at NMU on August 24, 2012 to discuss results from the GLISA project and gather feedback from the public. The stakeholder workshop was broadly advertised to the local Marquette and surrounding communities, and invited speakers included researchers from NOAA-GLERL, the local National Weather Service office in Negaunee, and various universities in the Great Lakes region. The workshop gave researchers the opportunity to engage the community in a discussion of how the data that are being collected at offshore sites on the Great Lakes are being used for scientific research, operational forecasting, and general public use, as well as how such data services can be improved in the future. Roughly 20 people were in attendance at the forum, which was followed by a short lunch and field trip to the Granite Island monitoring station. The public forum also coincided with the launch of the GLISA project website (http://myweb.nmu.edu/~gip/), which includes links to the workshop presentations, puplications from the GLISA project, and real-time data from the Granite Island research site (see also: http://www.graniteisland.com/index.shtml)

Two of the GLISA project investigators (Blanken and Spence) are members of the Hydroclimate Technical Working Group (TWG) of the IJC's International Upper Great Lakes Study. Participation in the IUGLS has allowed the group to remain engaged with members of the TWG, as well as with water resource managers on both sides of the international border. Results from the GLISA-funded research have also helped to identify the atmospheric processes that control Great Lakes evaporation, as well as the potential implications of climate change. These results are expected to be of significant value to decision-makers for defining the level of risk associated with climate conditions that may enhance or reduce evaporation and water levels. The results will also help define future needs for lake evaporation monitoring and research to further reduce uncertainty in water budget estimation and to provide sound information for drafting regulation strategies for the Great Lakes.

Finally, in recognition of the need identified during the IUGLS for continued (and expanded) long-term monitoring of Great Lakes evaporation, the GLISA investigators have formed a grassroots network of individuals and organizations to help define a vision for a sustained, coordinated Great Lakes evaporation network. The GLISA-funded research has shown that no two years are alike when it comes to Great Lakes evaporation, ice cover, and water temperatures; and that long-term changes in the Lakes' water balance are occurring as a result of climate change. Continued observations over each of the Great Lakes is needed to better understand these seasonal, interannual, and long-term variations. The membership of the newly formed grassroots network is multi-national and crosses a variety of sectors, including universities, government research labs, and the private sector. Initial discussions amongst investigators have focused primarily on issues related to the existing network of stations (Figure 2), such as data protocols and access, equipment maintenance, and funding sources. Future discussions will include an assessment of needs related to network expansion, as well as sustained, long-term funding. It is anticipated that data collected through the evolving Great Lakes evaporation network will eventually be made widely available through partnerships with the Great Lakes Observing System (GLOS), the National Weather Service, and the National Data Buoy Center (NDBC).

Summary

As illustrated in Figure 6, a new understanding of the impacts of climate variability on Great Lakes evaporation is emerging as a result of the GLISA-funded research. This "new paradigm" has revealed complex interactions among evaporation, ice cover, and water temperature—clearly demonstrating that ice cover does not simply act as a "cap" on evaporation, as has often been assumed in the past. Rather, the cooling effects of evaporation exert important feedbacks on lake temperature and ice cover that can actually result in above-normal evaporation rates immediately prior to winters with high ice cover. Conversely, winters with low ice cover are typically followed by warm summer water temperatures and an early start to the evaporation season. This latter effect has been especially noticeable during recent warm winters, which has dire implications for Great Lakes water levels as the climate continues to warm.

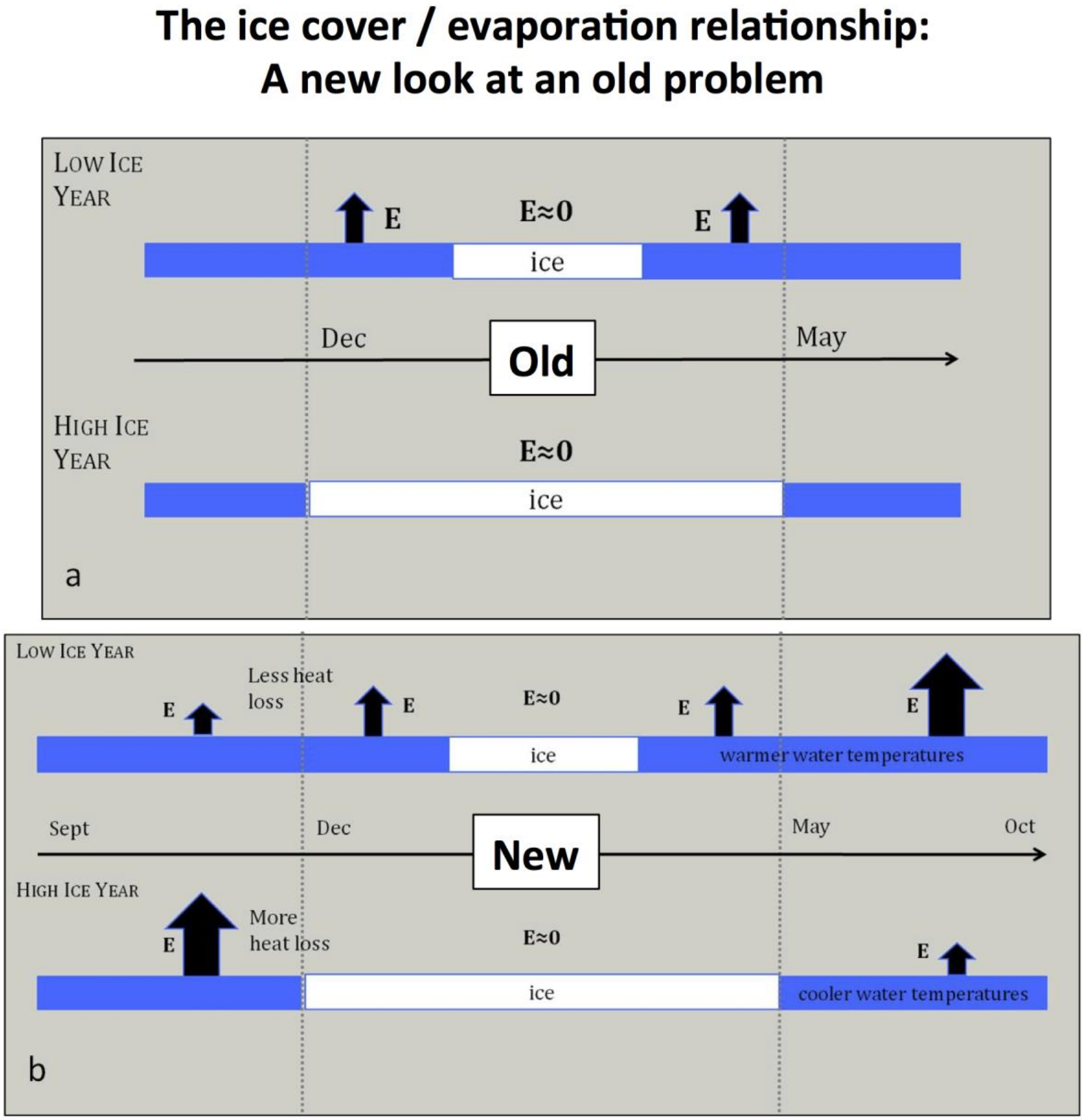

Figure 6. Illustration of the old (a) and new (b) way of thinking about Great Lakes evaporation and ice cover (adapted from Van Cleave, 2012). Previously, it has often been assumed that ice cover simply acts as a “cap” on wintertime evaporation, and so more ice means less evaporation. We’ve now learned that there are important seasonal leads and lags in the system, as illustrated in panel (b). Namely, high ice cover is often **the result of** high evaporation during the preceding fall, followed by cooler summer water temperatures and a late start to the evaporation season. To some extent, therefore, these counteracting effects can limit (or at least delay) the overall influence of ice cover.

In light of these new findings, continued long-term monitoring of Great Lakes evaporation and related hydrologic processes is paramount for understanding and predicting the future impacts of climate variability and change on Great Lakes water levels. With this in mind, the GLISA-funded investigators have begun the process of formalizing a sustainable, coordinated observation network dedicated to direct, year-round measurements of Great Lakes evaporation and over-lake meteorology. This new network is anticipated to provide a valuable real-time data stream—not only for operational Great Lakes hydrologic forecasting, but also for commercial shipping, recreational boaters, and other groups that have a vested interest in Great Lakes meteorology and maritime weather hazards.

Acknowledgements

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