Spatiotemporal Variability of Great Lakes Basin Snow Cover Ablation Events

Zachary J. Suriano* and Daniel J. Leathers

Department of Geography, University of Delaware

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*Corresponding Author Present Address:
Zachary J. Suriano, 211 Pearson Hall, University of Delaware
Newark, DE 19716-2541, USA
Email: zsuriano@udel.edu
Phone: +1 302.831.2294
Fax: +1 302.831.6654
Abstract

In the Great Lakes basin of North America, annual runoff is dominated by snowmelt. This snowmelt-induced runoff plays an important role within the hydrologic cycle of the basin, influencing soil moisture availability and driving the seasonal cycle of spring and summer Lake levels. Despite this, relatively little is understood about the patterns and trends of snow ablation event frequency and magnitude within the Great Lakes basin. This study uses a gridded dataset of Canadian and United States surface snow depth observations to develop a regional climatology of snow ablation events from 1960-2009. An ablation event is defined as an inter-diurnal snow depth decrease within an individual grid cell.

A clear seasonal cycle in ablation event frequency exists within the basin and peak ablation event probability is latitudinally dependent. Most of the basin experiences peak ablation frequency in March, while the northern and southern regions of the basin experience respective peaks in April and February. An investigation into the inter-annual frequency of ablation events reveals ablation events significantly decrease within the northeastern and northwestern Lake Superior drainage basins and significantly increase within the eastern Lake Huron and Georgian Bay drainage basins. In the eastern Lake Huron and Georgian Bay drainage basins, larger ablation events are occurring more frequently, and a larger impact to the hydrology can be expected. Trends in ablation events are attributed primarily to changes in snowfall and snow depth across the region.
1. Introduction

In snow-dominated regions, snow ablation is a critical hydrologic process, influencing soil moisture, stream flow, and groundwater. While important to regional hydrology, snow ablation also represents a societal and environmental hazard through snowmelt-induced flooding and excess nutrient and pollution transport (Changnon 2008; Ashley and Ashley 2008). In the Great Lakes basin of North America, snowmelt is the primary driver behind the seasonal cycle of Great Lakes water levels in the spring and summer, and dominates the annual runoff into the basin (Quinn 2002; Barnett et al. 2005; Figure 1). This suggests that changes to the frequency and timing of snowmelt events could substantially change the timing of runoff into the basin and seasonal lake-water levels. Such water-level changes impact a variety of environmental and ecological factors in the Great Lakes basin including fish habitats, sediment-water nutrients, aquatic vegetation, and marsh bird breeding abundance (Barry et al. 2004; Timmermans et al. 2008; Steinman et al. 2012; Chow-Fraser 2013).

While the physical processes behind snow ablation have been extensively studied in a variety of North American regions (e.g. Grundstein and Leathers 1998; Leathers et al. 2004; McCabe et al. 2007; Mazurkiewicz et al. 2008), there has been relatively limited research into the spatiotemporal variability of North American snow cover ablation. Dyer and Mote (2007) did examine the seasonal timing of collective North American ablation events, detecting a shift towards an earlier onset of ablation during the 1960-2000 period. This supports decreasing trends of snow cover in the spring across the continent (Frei et al. 1999; Dyer and Mote 2006). In light of this conclusion and understanding the importance of snowmelt to the hydrology of the Great Lakes basin, it is critical to understand when and where ablation events are occurring specifically in the Great Lakes basin, and if there are significant changes to their seasonal timing.
This research examines the spatial patterns and trends of snow ablation frequency and magnitude from 1960-2009 within the Great Lakes basin to determine the seasonal distribution of ablation events and ascertain if changes to the frequency or seasonal timing of ablation events are occurring. Additionally, as there is substantial variability in the snowfall and snow cover climatologies within basin (Suriano and Leathers 2017a,b); this research investigates the spatial and temporal variability of ablation events and trends at a sub-basin scale seeking to identify particular regions within the basin with a higher susceptibility to changing climatic conditions.

2. Data and Methodology

2.1 Snow Depth Data

Snow depth data spanning 1960-2009 are obtained from a quality-controlled daily North American dataset, interpolated onto a 1-degree grid (Dyer and Mote 2006; Kluver et al. 2016), presently stored at Rutgers University (http://climate.rutgers.edu/snowcover/noaamelt/). This dataset is selected over other snow depth products such as the National Weather Services’ National Operational Hydrologic Remote Sensing Center (NOHRSC) Snow Data Assimilation System (SNODAS) primarily due to its length of record and use in similar studies (Dyer and Mote 2007).

In creation of the dataset (Dyer and Mote 2006) snow depth data are interpolated from stations within the United States’ cooperative observer network (U.S. Department of Commerce 2003), and the Meteorological Service of Canada (Braaten 1996). Furthermore, data underwent a quality control procedure as described in Robinson (1989). However, likely due to the inherent and well-documented nature of snow observations (Robinson 1989; Doesken and Robinson 2009) and the interpolation scheme, snow depth values within the dataset occasionally increase or decrease between successive days, then rebound without meteorological conditions being favorable for such depth changes. This is in part attributed to a lack of consistency in station reporting. A station may
provide data one day, and then not provide it the next. While the interpolation method uses a
variable search radius, in regions with a limited number of stations or in regions where moderate-to-
large differences in snow depth values exist between stations within the same grid cell, a station not
reporting for a day then reporting the next could have a large impact on an interpolated snow depth
change. The differences in snow depth values between stations within the same grid cell could
result from variations in elevation, a high prominence of micro/meso-scale meteorological events,
or measurement errors/biases.

In light of this, further quality control on the snow depth dataset was deemed necessary prior
to performing an ablation calculation. A routine is developed to test the consistency of the daily
change in snow depth where days and grid cells are flagged when: 1) an increase in depth occurs
that is greater than 125% of new snow accumulations, and 2) snow depth decreases despite the
day’s maximum temperature remaining below -3°C and a large (10 cm) snowfall not occurring the
day before (potential for compaction of fresh snow). The additional 25% of freedom in snow
accumulations from the first criteria is the value found to maximize the efficiency of the flagging
routine, such that when depth changes are meteorologically plausible, the day is not typically
flagged. Based on this quality control procedure, data believed to be erroneous are flagged as
missing within the dataset. No effort is made to generate replacement values using physically-
or statistically-based algorithms. Within the Great Lakes basin, 2.7% of the potential gridded snow
depth measurements are flagged as missing. With this further quality control, there is greater
confidence that changes in snow depths are grounded in physical changes to the snowpack and not a
result of stations’ observational inconsistencies.

2.2 Basin Definition
To determine which of the 1-degree grid cells of the snow depth dataset constitute the Great Lakes basin, a centroid method is applied. If a grid cell’s centroid falls within the spatial boundary of the Great Lakes basin, that grid cell is considered within the basin at the 1-degree spatial resolution of the snow depth dataset. The spatial boundary of the basin is based on the Hydrological Units from the United States Geological Survey’s “Watershed Boundary Dataset” (http://nhd.usgs.gov/wbd.html), and from the “Drainage Areas Dataset” by Natural Resources Canada (http://geogratis.gc.ca/). A single grid cell (42.5°N, 77.5°W) was added to this basin definition as a vast majority of the cell fell within the basin with the exception of a relatively narrow band that included the cell’s centroid. Fifty-seven 1-degree grid cells constitute the Great Lakes region, bounded approximately by 41-51° North latitude and 75-93° West longitude (Figure 2).

2.3 Ablation Definition and Calculation

With snow data from the cooperative network having no information on water equivalent, snow depth changes due to snowmelt have been defined as ablation (Grundstein and Leathers 1998; Leathers et al. 2004; Dyer and Mote 2007). As observed snow depth may also decrease due to sublimation, measurement errors, and compaction, these factors must be acknowledged before a snow depth decrease may be considered ablation. Sublimation can often be considerable over large scales in regions where air masses with low water vapor content are common. However, this effect is minimal over a single storm total (Dery and Yau 2002) and air masses over the Great Lakes region generally contain higher water vapor content. As such, the loss of daily snow depth due to sublimation is considered negligible, and not accounted for in this analysis. Effects of drifting snow are not accounted for in this study, as it is standard snow measurement practice to measure in areas where wind effects and drifting are minimized (U.S. Department of Commerce 2013).
In addition to sublimation and drifting, changes in snow depth not associated with melt can be attributed to non-physical processes related to the measurement process. Variation in the time of observation by Cooperative Observers Program observers can influence snow depth values (Kunkel et al. 2007). Depending on the timing of a sub-diurnal scale snowmelt or accumulation event, stations in close geographic proximity, but with different time of observations, may record different daily snow depth values. This may result in erroneous daily snow depth changes in the interpolated value not grounded in the meteorological conditions; however this impact should be minimized by the additional quality control measures taken to flag and remove unrealistic snow depth changes.

Compaction can substantially decrease snow depth without modifying the mass of the snow through destructive metamorphism of fallen snow crystals. This process results in a denser, thinner snowpack over time (Colbeck 1983a,b). With increasing deposition of snow, more overburden force is placed on the snowpack, increasing the compression or densification rate (Mellor 1977). This may increase the number of detected ablation events attributed to snowmelt. However, by incorporating temperature criteria into the ablation calculation, this influence of compaction can be minimized (Dyer and Mote 2007). As such, an event of decreasing snow depth is only considered ablation if it occurs when the maximum daily temperature on the second day of the associated event is above 0°C. Under these conditions, the snowpack can be assumed to be relatively isothermal and mature, removing the effect of snowpack compaction as effectively as possible (Dyer and Mote 2007).

In this study, an ablation event is considered an inter-diurnal decrease in snow depth greater than 2.5 cm within an individual grid cell, only during instances where the maximum daily temperature on the second day of the associated event is above 0°C. The 2.5 cm threshold is used to isolate events that could be considered hydrologically significant, and represents a measurable quantity for observers. Snow accumulations during defined ablation events are not uncommon and
additionally must be accounted for in the ablation calculation. As such, the calculated depth
decrease of a given ablation event is added to the recorded snowfall on the second day of the event.
Ablation events are examined monthly and annually in each grid cell within the Great Lakes basin from 1960-2009 during the September-August snow season. To determine the seasonal cycle of ablation event frequency and magnitude of the entire basin, events from all 57-cells are summed by month into whole basin values and monthly averages over the 50-year period are calculated. In establishing if there is a shift in the frequency and/or seasonal timing of ablation events, monthly and annual trends are calculated using simple linear regression. Trend analysis is conducted on all ablation events within the basin collectively, and for each of the 57 cells individually due to the variability of snow conditions within the basin. Autocorrelation tests are performed to examine a 1-year lag’s impact on the significance of monthly and annual trends, yielding a mean monthly value of 0.09. As no strong (> 0.3) or significant (p < 0.05) correlations existed for any month, no action is taken to address autocorrelation in the analysis.

3. Results

3.1 Basin Scale Ablation Events

Over the Great Lakes basin, snow ablation event frequency exhibits a clear seasonal pattern during 1960-2009 (Figure 3). An ablation event is defined as an inter-diurnal snow depth decrease greater than 2.5 cm day\(^{-1}\) for an individual grid cell. The frequency of events begins to increase during mid autumn and reaches maximum frequency during March, with approximately 300 events year\(^{-1}\) (σ = 79.1) across the 57 grid cells within the basin. After March, the frequency declines quickly to less than one event year\(^{-1}\) in June, yielding over 900 annual events year\(^{-1}\) (σ = 148.6) (Figure 3a). The seasonal cycle in event frequency is also examined for ablation events at four different threshold levels. Ablation threshold levels are used to investigate the magnitude of
ablation events. Thresholds are defined for the Great Lakes basin as minor, moderate, major, and extreme events, respectively, corresponding to between 2.5 and 5 cm, 5 and 10 cm, 10 and 20 cm, and greater than 20 cm change in snow depth between successive days. The threshold values were chosen based on the size distribution of events within the basin. For all threshold levels, ablation event frequency increases during the autumn and winter months, reaches a maximum in March, and then rapidly declines to a summer-time minimum (Figure 3b). The monthly means of event frequency in Figure 3b are standardized by the annual mean of each threshold level, due to the higher frequency of smaller ablation events and the successively smaller number of events with each threshold level. The pattern in Figure 3b indicates that ablation events across all threshold levels are relatively consistent in their seasonal occurrences.

Trends in ablation frequency are calculated for all events greater than 2.5 cm and no significant monthly or annual trends are detected, suggesting the seasonal cycle is not significantly changing over time. Ablation events at the moderate, major, and extreme thresholds similarly exhibit non-significant trends; however, significant trends in minor ablation events (2.5 – 5 cm) are detected. The number of minor ablation events in April significantly decreased by 1.1 events year\(^{-1}\) from 1960-2009 (p < 0.05) across the basin. Additionally, the annual number of minor ablation events exhibits a significant decreasing trend (-1.9 events year\(^{-1}\), p < 0.05), indicating the decrease in annual minor ablation events could be the result of the decrease in April event frequency. This is supported by a strong statistical correlation (0.677, p < 0.01) between the number of annual and April ablation events. Minor ablation events in April represent approximately 63% of the total April events. Despite no significant trends in minor events for any other months, the decrease in minor April ablation events suggests a trend towards an earlier end to the snow melt season across the entire Great Lakes basin.
3.2 Sub-Basin Scale Spatial Patterns and Trends in Ablation Events

The Great Lakes basin covers a relatively large geographic area and snow is highly variable within the region. As such, patterns in ablation frequency are investigated at the sub-basin scale, revealing substantial spatial variability during 1960-2009. Generally, there are more ablation events at higher latitudes than at lower ones, but what is most distinctive is the enhanced frequency of events within close proximity to the leeward shores of the Lakes (Figure 4). These regions closely correspond to the lake-effect snow belts (Scott and Huff 1996), implying a relationship between ablation frequency and lake-effect snow. This is not unexpected as lake-effect snow greatly increases the depth of the snowpack in these regions (Scott and Huff 1996, Suriano and Leathers 2017a, Suriano and Leathers 2017b) and a larger and more persistent snowpack would increase the likelihood of ablation events.

There is a distinct seasonal pattern of snow ablation event frequency within the Great Lakes basin (Figure 5). For most of the region, higher ablation event probability occurs during February-April, with the region of peak probability shifting northward in later spring months. Conversely during autumn, increased event probability moves southward over the basin. This is emphasized by spatially examining the month of peak ablation event frequency within the basin (Figure 6; top panel). A majority of the basin experiences peak ablation event frequency in March, however regions in the southerly and the most northerly portions of the basin experience their peaks in February and April, respectively. While this is the case for ablation events of all sizes, the pattern is not consistent when examined for ablation events at different magnitude thresholds (Figure 6). As the threshold level for ablation events increases, the month of peak event frequency, particularly in the southern regions of the basin, tends to shift towards the earlier winter months. This is attributed to the decreasing likelihood of a progressively larger snowpack existing later into the winter season for the different threshold levels. The larger the ablation event threshold, the larger the snowpack
must be to allow for such an event to occur; often by March or April, there is not enough snow on
the ground to warrant large events in the southern regions of the basin. Thus the larger events can
only occur when there is enough snow for them to occur, typically earlier in the winter season.

While no long-term trend in annual ablation event frequency is detected for the Great Lakes
basin as a whole, there are significant long-term trends in annual frequency at the sub-basin scale
indicating certain regions may be more susceptible to changing climatic conditions (Figure 7). The
most spatially coherent region exhibiting significant trends in annual ablation event frequency is in
the north of the basin, consisting of portions of the northwestern and northeastern Lake Superior
drainage basins (for region, see Figure 2). In this region, trends range from -0.11 events year\(^{-1}\) (p <
0.05) to -0.22 events year\(^{-1}\) (p < 0.01) indicating significant decreases in the annual number of
ablation events over time. This is particularly apparent in the trends of minor ablation events (not
shown). Significant decreases in annual event frequency for the minor threshold level range from
approximately -0.05 (p < 0.05) to -0.17 events year\(^{-1}\) (p < 0.01), indicating relatively small ablation
events are becoming less common.

As regions north of Lake Superior experience decreases in the frequency of annual ablation
events, parts of the eastern Georgian Bay and eastern Lake Huron drainage basins (Figure 2)
experience significant increases in ablation event frequency (Figure 7). These sub-basins have
respective increasing trends of 0.21 events year\(^{-1}\) (p < 0.01) and 0.15 events year\(^{-1}\) (p < 0.01) that
indicate significant increases in the frequency of ablation events during 1960-2009. In the eastern
Lake Huron region, annual ablation event frequency is significantly increasing (p < 0.05) for the
three largest ablation threshold levels: moderate, major, and extreme (not shown). This indicates
that ablation events, particularly larger events, are becoming more common within these sub-basins.

4. Discussion and Conclusions
A regional climatology of snow cover ablation event frequency is developed for the Great Lakes basin where an ablation event is defined as an inter-diurnal snow depth decrease exceeding a critical value within an individual grid cell. Ablation event frequency is examined collectively, and at different threshold levels (minor: 2.5-5 cm, moderate: 5-10 cm, major: 10-20 cm, extreme: 20+ cm) to allow for an investigation into the magnitude of ablation events. Analysis identifies a clear seasonal cycle in ablation event frequency, with March representing the peak month of event frequency for the basin at all threshold levels. Examining the spatial variability of the seasonal cycle within the basin, most of the basin experiences peak ablation frequency in March. However, regions generally in the northern and southern portions of the basin experience respective peak ablation event frequencies in April and February. Dyer and Mote (2007) found peak ablation event frequency for North America occurs in April. This earlier peak in the Great Lakes basin is expected as the basin represents the southerly edge of typical North American snow cover. The latitude-dependent seasonal pattern in ablation event probability follows the seasonal cycles of incoming solar radiation, temperature, and vapor pressure that provide the energy necessary for snow cover ablation. This increased energy impacts the Great Lakes basin prior to locations further north, aiding in explaining the differing peak detected in this study compared to Dyer and Mote (2007).

Multiple studies have noted a change in the seasonal cycle of snow cover and ablation in diverse regions over North America, with snow cover exhibiting decreasing trends during the spring months, tending towards earlier snowmelt (Frei and Robinson 1999; Frei et al. 1999; Brown 2000; Dyer and Mote 2006; Dyer and Mote 2007). In this study, no significant shift in the seasonal cycle of all monthly snow ablation events is detected for the Great Lakes basin. However, the annual frequency of specifically minor ablation events (2.5 - 5 cm) within the basin significantly decreases in conjunction with declining events in April. This decline in minor ablation event frequency
suggests a trend towards an earlier end to the snow melt season across the entire Great Lakes basin. This is likely associated with changes in basin snow cover during the spring, and will be further examined in future work.

At the sub-basin scale, significant trends in the annual frequency of ablation events are detected in two spatially coherent regions. In the northwestern and northeastern Lake Superior drainage basins, annual ablation event frequency significantly decreases by as much as 0.22 events year$^{-1}$ ($p < 0.01$). Linearly extrapolated, this reduces the number of events per year from approximately 23.4 in 1960, to less than 12.3 events per year in 2009; a reduction of nearly 50% (Figure 8a). Minor ablation events additionally exhibit significant decreasing trends in these sub-basins. These trends indicate ablation events, particularly smaller ablation events, are becoming less frequent. The decreasing trend in this region is attributed to significantly decreasing trends in snow depth in this region stretching northwest into central Canada (Dyer and Mote 2006). Dyer and Mote (2006) attribute this change in snow depth, in part, to extra-tropical cyclones that track over the region changing in frequency and/or intensity (Isard et al. 2000), resulting in changing temperature and precipitation patterns in the region. With a shallower snowpack, fewer ablation events can occur.

The second region exhibiting significant trends in annual ablation event frequency is in the eastern Georgian Bay and eastern Lake Huron drainage basins. Regions in these sub-basins exhibit significant increases in ablation events by as much as 0.21 events year$^{-1}$ ($p < 0.01$). Over the 50-year period, this represents a linearly extrapolated increase in the annual number of events by 74% from approximately 14.5 in 1960, to over 25 annual events in 2009 (Figure 8b). The frequencies of the largest ablation threshold levels (moderate, major, and extreme) are also significantly increasing. This is an indication that larger ablation events are becoming more common in these sub-basins, and a larger impact to the hydrology can be expected. Larger daily ablation events may increase
snowmelt-related runoff and increase flooding event risk. These increasing trends in ablation frequency are attributed to significant increases in lake-effect snowfall in the region (Suriano and Leathers 2017b), where more snowfall creates a larger snowpack and increases the associated potential for more or larger ablation events to occur.

The results of this study have highlighted the nature of snow cover ablation events for the Great Lakes basin, and emphasized the spatial variability at the sub-basin scale. Changes to the frequency of ablation events will influence the occurrence and magnitude of snowmelt-induced runoff into the Lakes that may impact water resources, ecological habitats, and/or terrestrial flooding events. Understanding the regional complexities to snow ablation is critical for communities preparing for the impacts of a changing climate. Further research is currently ongoing, investigating the atmospheric conditions associated with ablation events in the Great Lakes basin. This future work will explore the relationships between synoptic-scale weather patterns and ablation frequencies, seeking to explain some of the changes in ablation frequency detected in this study.

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6. References


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7. Figures

Fig. 1. Monthly 1960-2009 averaged runoff into the basin (black-solid), over lake evaporation (grey-solid), and over lake precipitation (black-short dash) on the left y-axis in mm over the lake surface, and lake-water levels (grey-long dash) on the right y-axis in meters. Runoff, evaporation, and precipitation data come from the Great Lakes Environmental Research Laboratory (https://www.glerl.noaa.gov/) while lake-water levels are provided by the U.S. Army Corps of Engineers (http://www.lre.usace.army.mil/).
Fig. 2. Map depicting the 57 1-degree grid cells (dark edges) representing the Great Lakes Basin. Portions of two sub-regions are highlighted based on significant trends in the annual number of ablation events: the northeastern and northwestern Lake Superior drainage basins (black), and the eastern Lake Huron and eastern Georgian Bay drainage basins (dark grey).
Fig. 3. Average monthly ablation event frequency across the Great Lakes basin from 1960-2009 (a), and (b) standardized average monthly ablation event frequency for the four defined threshold levels from 1960-2009.
Fig. 4. Total number of ablation events greater than 2.5 cm across the Great Lakes basin from 1960-2009. Darker shades represent progressively more events (in days).
Fig. 5. Probability of an ablation event greater than 2.5 cm from 1960-2009 across the Great Lakes basin for October through April (fraction). Lighter shades represent a lower probability while darker shades represent higher probability.
Fig. 6. Month of peak ablation event frequency for all ablation events, and for events at the defined threshold levels across the Great Lakes basin from 1960-2009. Colors indicate different months.
Fig. 7. Trend (a) and statistical significant (b) in the annual frequency of ablation events across the Great Lakes basin from 1960-2009. For panel (a), in days year$^{-1}$, brown shades represent negative trends while blue represent positive trends. In panel (b), reported in 1 – p-value, darker red shades correspond to lower p-values and thus higher statistical significance.
Fig. 8. Annual frequency of snow ablation events (solid) and associated trend line (dashed) in the (a) northwest and northeast Lake Superior drainage basins, and (b) eastern Georgian Bay and eastern Lake Huron drainage basins.