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Changing snow depth in the Great Lakes basin: Implications and trends

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Abstract

In the Great Lakes basin of North America, snow plays a critical role in the regional hydroclimate, where snow ablation events can serve both as a resource and a hazard. The frequency and magnitude of an ablation event is governed by the availability of meteorological conditions to ablate snow, and the physical presence of snow to be ablated. While the meteorological conditions leading to ablation have been well documented, examining changes in atmospheric conditions alone have been unable to completely explain observed ablation trends. As such, this study applies a gridded snow depth dataset to evaluate snow depth variability, while speaking to the implications of such variability on ablation frequency and water resources. Snow cover is present in the basin from November – April, with the more northerly regions (Lake Superior and Lake Huron basins) exhibiting a deeper and more seasonally-persistent snowpack. Seasonal basin-wide snow depth decreased by approximately 25% from 1960-2009, with some of the most significant decreases occurring north of Lake Superior. Surface air temperatures are negatively associated snow depth, and warming temperatures are likely contributing to snow depth declines. These regional decreases in snow depth spatially corroborate previously observed decreases in the frequency of ablation events in the basin, and highlight the importance of examining both snow cover and meteorological conditions when seeking to explain snow ablation variability. The results from this study can be applied to inform water resource management decisions in the region.

Keywords: snow, Great Lakes, Lake Superior, climate change, ablation, water resources

1.0 Introduction

Across the Northern Hemisphere, winter snow covers approximately 45-46% of the land surface, on average seasonally (Robinson et al. 1993; Estilow et al. 2015). This large extent of snow influences surface energy budgets via its high albedo, in addition to influencing the hydrologic cycle and human activity. World-wide, over one-sixth of the world's population lives in regions where snowmelt accounts for the majority of runoff (Barnett et al. 2005). In the Great Lakes basin of North America, snow and snow-derived water resources play an important role in the regional hydroclimatology, with over 50% of the annual runoff in the basin being derived from snowmelt (Barnett et al. 2005). This snowmelt-induced runoff recharges lake-water levels, and can be used for human consumption and sanitation, irrigation, generating hydroelectric power, and as cooling for thermoelectric power, among other uses. In 2007, hydroelectric power represented approximately 10% of the total electric power capacity for the American side of the basin (Tidwell and Moreland, 2011).

Snow can also result in negative effects, predominantly in the form of rapid ablation. Particularly in ephemeral regions, large ablation events pose societal and environmental hazards through snowmelt-induced flooding and the transport of concentrated pulses of excess nutrients and pollution. From 1972-2006, snowmelt-related flooding in the United States resulted in over $3.3 billion (2006 dollars) in damages (Changnon 2008). Over a shorter 1996-2005 period, approximately 7% of flood related fatalities in the United States occurred during snowmelt flooding (Ashley and Ashley 2008), including a single event impacting the northeast United States in 1996 where there were 22 fatalities (Leathers et al. 1998).

As the climate continues to change, it is critical for society to have a complete understanding of the physical mechanisms that govern snow variability such that appropriate, evidence-based, decisions can be made regarding the efficient management of water resources. Given the importance of snow as a resource and as a potential hazard, snow and snow cover ablation have been the subject of recent research in the Great Lakes region (Suriano and Leathers 2017a; Suriano 2018; Suriano and Leathers 2018). The frequency and magnitude of a snow ablation event is governed by the availability of meteorological conditions to ablate snow, and the physical presence of snow to be ablated. The frequency of ablation events across the entire Great Lakes basin as a whole are not found to exhibit long-terms trends from 1960-2009; however, some individual sub-regions do exhibit significant trends (Suriano and Leathers 2017a). Over the same period, the synoptic-scale atmospheric conditions that provide favorable meteorological conditions for ablation are changing; the frequency of rain-on-snow and Great Lakes surface high-pressure synoptic weather types are significantly decreasing and increasing, respectively (Suriano 2018; Suriano and Leathers 2018). These results suggest the variability in synoptic-scale circulation may be having an effect on the frequency and magnitude of ablation events within portions of the Great Lakes basin. However, to fully comprehend snow ablation across the basin, the mechanisms responsible, and what changes may occur in the future, examination of the variability in snow depth is necessary.

Prior research into snow cover extent and snow depth variability has included the Great Lakes region as a portion of typically a much larger study region (Frei and Robinson, 1999; Frei et al., 1999; Brown, 2000; Dyer and Mote, 2006). These studies collectively find snow cover and/or snow depth across the Northern Hemisphere and/or North America has generally decreased. A large-scale decrease in snow extent supports research finding the frequency of snow ablation events across much of North America is declining (Dyer and Mote 2007). While these studies give some indication of the historical behavior of snow over the Great Lakes basin, they are focused on larger-scales; findings by Suriano and Leathers (2017a) show the Great Lakes basin may not necessarily fit the pattern for the rest of the continent with respect to snow ablation. As such, a more spatially-focused and detailed study on snow cover in the Great Lakes basin is warranted.

In this study, a snow depth climatology from 1960-2009 is developed for the Great Lakes basin using a 1-degree gridded snow depth dataset (Mote et al. 2018). Average snow depth and variables related to the length of the snow season are analyzed at seasonal and intra-seasonal timescales, including an investigation of long-term variability and trends over the 50-year time period. The Great Lakes basin is analyzed at three different spatial scales: the basin as a single entity, the basin divided into its five primary sub-basins (Superior, Michigan, Huron, Erie, and Ontario), and the basin at the individual 1-degree grid cell level. Such an approach allows for the importance of scale to be highlighted for snow depth spatial and temporal variability. Section two details the methodological approach and the gridded snow depth dataset employed in the study. The third section reports the study's findings with respect to snow depth for each of the three scales and speaks to the possible forcing mechanisms of snow depth variability and trends. Section four emphasizes the importance of conducting analysis at different scales while placing this study's results into the context of recent research on Great Lakes basin snow ablation. The fifth and final section provides some concluding remarks, noting the importance of future research in the region.

2.0 Data and Methodology

2.1 Snow Depth, Temperature, and Snowfall Data

Mean daily snow depth, snowfall, and maximum temperature data are obtained from a quality-controlled dataset of gridded variables over much of North American (Mote et al. 2018). In the creation of the dataset, observations at surface stations in the United States and Canada were subjected to quality control procedures and validation before and after interpolation onto a 1-degree x 1-degree latitude-longitude grid (see: Dyer and Mote 2006; Kluver et al. 2017; Suriano and Leathers 2017a). Interpolation was conducted using Spheremap, which takes a modified version of Shepard's inverse-distance algorithm, and interpolates onto a two-dimensional Cartesian plane before projecting the interpolation onto a spherical lattice (Willmott et al. 1984). Within each 1-degree grid cell, a variable search radius was used for identifying observation stations, as station density varies with both space and time. Within the Great Lakes basin, station density is sufficient for analysis, with many grid cells containing over 15 observation stations. Further detail of the interpolation procedure and station density is discussed in Dyer and Mote (2006) and Kluver et al. (2017), respectively. These data are presently available at the National Snow and Ice Data Center (NSIDC; http://nsidc.org/data/G10021).

Daily data across the September – August season are obtained from 1960-2009, with the 1960 season beginning in September of 1959. While the addition of more recent years into the analyzed sample size would be preferred, this dataset currently ends on December 31, 2009. Despite the lack of the most recent years, this dataset is advantageous over other snow depth data products, such as the National Operational Hydrologic Remote Sensing Center (NOHRSC) Snow Data Assimilation System (SNOWDAS) due to its consistent and exclusive use of Cooperative Observer Network stations, and due to its length of record. A long length of record allows for a climatological perspective on snow within the region.

2.2 Great Lakes Basin Definitions

This study examines snow depths at different spatial scales, including 1) the Great Lakes basin as a single entity, 2) the five primary sub-basins of the basin corresponding to each of the Great Lakes (Superior, Michigan, Huron, Erie, and Ontario), and 3) the Great Lakes basin at the individual grid cell level. To determine the spatial boundaries of these domains at the 1-degree resolution of the gridded dataset, a centroid method was applied. If the centroid of a specific grid cell was contained by the geographic boundary of the basin, that grid cell was considered within the specific basin (Suriano and Leathers 2017a). The geographic boundary of the Great Lakes basin and the primary sub-basins are based on the United States Geological Survey's "Watershed Boundary Dataset" (http://nhd.usgs.gov/wbd.html), and 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 the boundary of the Great Lakes basin (including the Ontario sub-basin), based on the specific case where the centroid method was deemed inappropriate (Suriano and Leathers 2017a). Across the Great Lakes basin, there are 57 1-degree grid cells, with the primary sub-basins of Superior, Michigan, Huron, Erie, and Ontario respectively containing 19, 9, 15, 8, and 6 grid cells (Figure 1; Table 1).

2.3 Methodology

To develop a long-term climatology of snow depth and examine key features of the snow season, an areal-weighted average snow depth is calculated daily within each sub-basin and for the entire Great Lakes basin. Daily snow depths are then scaled up to monthly and seasonal (Sep-Aug) values for analysis. Beyond examining average snow depths spatially across the basin over different domains, this study also investigates the length of the snow season, the start and end dates of the snow season, and long-term variability and trends. In all cases, trend analysis is conducted using ordinary least squares linear regression, where trends are deemed significant with a p-value less than 0.05. It is hypothesized seasonal snow depth magnitude will have significantly decreased across the basin from 1960-2009.

Here, the snow season is defined as the length of time (in days) between the first and last occurrence of a snow depth exceeding 2.54 cm (1 inch) during a September-August season. The 2.54 cm threshold is based on the measurement recording practices of surface observations in the United States for snow depth; the first non-trace snow depth in the United States Cooperative Observer Network (COOP) is 0.5 inches, and is rounded to the nearest inch, or 1.0 inches (2.54 cm). This threshold was also utilized to match the threshold applied in previous studies (Suriano 2018; Suriano and Leathers 2018).

Similar to how 1960-2009 September-August snow depths are calculated for the Great Lakes basin at three different spatial scales, seasonal values of total snowfall, average maximum temperature, average minimum temperature, and snow ablation event frequency were also calculated from the daily 1-degree gridded dataset (Mote et al. 2018). For consistency with previous studies (e.g. Suriano 2018), a snow ablation event was defined as an inter-diurnal decrease in snow depth in excess of 2.54 cm, only on days where the maximum daily surface temperature exceeded 0°C. For further discussion on the rationale behind the snow ablation definition and how frequency is calculated, see Suriano and Leathers (2017a).

3.0 Results

3.1 Entire Great Lakes Basin

Examining the frequency of days with snow cover (snow days), snow cover is common in the basin. From 1960-2009, over 54% of days are snow days, with nearly 160 days yr^{-1} (SD: 12.7 days) exhibiting a depth of at least 2.54 cm (Table 2). The snow season (as defined as the time between the first and last occurrence of depths exceeding 2.54 cm), begins on November 10th and concludes on April 18th on average, with a basin-wide average snow depth during that period of 20.3 cm (SD: 5.7 cm). Within the seasonal cycle, a unimodal distribution of average monthly snow depth is apparent with a peak corresponding to approximately 33 cm occurring in February, and average snow cover in excess of 25.0 cm in January - March (Figure 2).

Snow cover in the Great Lakes basin has not been static from 1960-2009. Average basin-wide snow depth exhibits substantial variability during the snow season, and a statistically significant linear decreasing trend (Figure 3). From 1960-2009, snow depth decreased by 0.10 cm yr^{-1} ($p < 0.05$) or 5.0 cm over the 50-year period. Based on a linear fit, this represents a reduction in snow depth of approximately 25% from 1960 to 2009. Average snow depth in February, the month with the deepest snowpack on average, exhibits a similar decreasing trend of 0.18 cm $year^{-1}$ (not shown), while the frequency of days with a snowpack of at least 5.08 cm and 15.24 cm both are significantly declining ($p < 0.05$). The evolution of the seasonal cycle in the basin during the study period is also evident by examining decadal-scale average snow depth (Figure 4). While a shift in the snow season timing is not apparent, snow depth was greatest during the decades of 1970-79 and 1960-69, and at a minimum during the decades of 2000-09 and 1990-99, reflecting the general decline noted previously.

Prior literature has illustrated how the Great Lakes basin does not always behave homogeneously with regards to snow (e.g. Suriano and Leathers 2017a), and as such, examination of snow depth variability at various scales is warranted. Section 3.2 examines average snow depth characteristics for each of the five primary sub-basins: Lake Superior, Lake Michigan, Lake Huron, Lake Erie, and Lake Ontario while section 3.3 examines similar variables at the individual grid cell level.

3.2 Sub-basins of the Great Lakes basin

Generally, the more northerly basins exhibited deeper average snowpacks and longer snow seasons that started earlier and ended later (Table 3). The snow season in the Lake Superior basin, for instance, begins and ends, on average, on October 29th and April 26th, respectively, for an average length of 180 days. In contrast, the Lake Erie basin snow season runs from approximately November 23rd to March 10th, nearly two months shorter than that of Lake Superior. The frequency of snow days also follows a similar pattern, regardless of the snow depth magnitude threshold examined. The greatest number of snow days occurred in the Lake Superior basin, followed in descending order by the basins of Lake Huron, Lake Ontario, Lake Michigan, and Lake Erie.

The variability and trends in the basins of Lake Superior and Lake Michigan, the two most western sub-basins, are examined in greater detail at this sub-basin scale. From 1960-2009, the two basins exhibited significant decreases in snow season average snow depth of 0.31 cm yr^{-1} ($p < 0.05$) and 0.04 cm yr^{-1} ($p < 0.05$), respectively (not shown). Such declines represent linearly-extrapolated 26 to 33% decreases from approximately 61.4 cm and 6.0 cm in 1960, to 45.7 cm and 4.0 cm in 2009, respectively. In the Lake Superior basin, there are significant decreases in the frequency of snow days with depths of at least 2.54 cm ($p < 0.01$), at least 5.08 cm ($p < 0.05$), at least 15.24 cm ($p < 0.05$), and at least 30.48 cm ($p < 0.1$) of 0.36 d yr^{-1}, 0.28 d yr^{-1}, 0.40 d yr^{-1}, and 0.51d yr^{-1}, respectively. The Lake Erie basin was the only sub-basin to exhibit noteworthy trends with regards to the snow season timing. Significant at the $p < 0.1$ level, the start date of the Lake Erie snow season began approximately 11.5 days later at the end of the 1960-2009 period when compared to the beginning. Similarly, the length of the snow season declined from approximately 135 days in 1960 to approximately 117 days in 2009, a 13% reduction (not shown). No significant trends are noted for the basins of Lake Ontario and Lake Huron.

3.3 Individual grid cells of the Great Lakes basin

An evaluation of the average snow depth across the Great Lakes basin at the individual grid cell level indicates a distinct seasonal cycle; greater depths advance into the basin from the north during the late fall and early winter, then recede during the spring (Figure 5). For the months examined (November – April), local-scale processes, such as lake-effect snow, are evident in the average snow depth, with greater depths located along the Lakes' leeward shores. These localized processes are superimposed upon a broader latitudinal gradient of snow depths, with greater depths occurring to the north. The greatest snow depths generally occur during February, with the average snowpack depth surrounding Lake Superior at that time exceeding 50 cm.

The greatest temporal changes are noted north of Lake Superior, where snow depth declines range from 0.19 cm yr^{-1} ($p < 0.05$) to over 0.51 cm yr^{-1} ($p < 0.01$; Figure 6a). Significant decreases are most apparent during the months of January, February, March, and April in this region, where in some cases snow depth is declining by over 0.96 cm yr^{-1} ($p < 0.01$) in a given month, an approximate decrease of 58% from 1960 levels by 2009 (Figure 7). More modest decreases in snow depth are detected broadly throughout the Great Lakes basin, including small portions of all of the other four Lakes (Huron, Michigan, Erie, and Ontario).

3.4 Explanations of Basin-Scale Snow Depth Decreases

With this study detecting significant decreases in snow depth, further investigation is warranted into the physical forcing mechanism(s) responsible. As detailed in section 2.3, seasonal timeseries of total snowfall, average maximum temperature, average minimum temperature, and total snow ablation event frequency were calculated from the daily 1-degree x 1-degree gridded dataset (Mote et al. 2018). Timeseries for the basin as a whole and for the individual grid cells are generated for analysis with their respective snow depth counterparts. Due to snow predominantly occurring during the months of November-April, analysis is restricted to only those months here.

The average, basin-wide, November – April values for maximum and minimum temperature, total snowfall, and ablation event frequency from 1960-2009 are 1.8 °C, -8.3 °C, 206.4 cm, and 7.8 events yr^{-1}, respectively. During the 1960-2009 period, the average minimum and maximum temperatures within the basin significantly increased by 0.3 ($p < 0.01$) and 0.2 °C decade^{-1} ($p < 0.05$), respectively (Figure 8). For minimum temperature, this represents an increase from approximately -9.2 °C in 1960, to approximately -7.4 °C in 2009, an increase of nearly two degrees Celsius based on a linear fit. The maximum temperature increase was less intense, with an increase of 1.1 °C over the 50-year period. The frequency of ablation events and seasonal total snowfall did not exhibit significant changes ($p > 0.05$).

To aid in determining if these meteorological features influenced basin-wide snow depth trends and/or variability, timeseries of the previously-mentioned variables are correlated with snow depth. After detrending to limit the likelihood of spurious correlations resulting from underlying monotonic tendencies for the variables, all four variables are found to be significantly correlated ($p < 0.01$) with snow depth (Table 4). Lesser (greater) seasonal snow depths occur during seasons with warmer (cooler) average minimum and maximum temperatures, and during seasons when snowfall totals are reduced (enhanced). A shallower (deeper) snowpack is also significantly associated with fewer (more) ablation events in an individual snow season. With both minimum and maximum air temperatures being correlated with seasonal snow depth across the basin, and also significantly increasing during a period of snow depth decline, it is likely the increase in air temperatures are at least partially responsible for these snow depth declines at the basin-wide scale.

3.*5 Explanations of Sub-Basin-Scale Snow Depth Decreases*

Causes of snow depth decline at the individual grid cell level are also investigated using similar techniques as in the previous section. Linear trends in seasonal 1960-2009 variables of total snowfall, average minimum and maximum temperatures, and total frequency of ablation are shown spatially in the GLB in Figure 6 (b-e). Trends in seasonal snowfall across the basin are generally increasing or non-existent from 1960-2009. The regions roughly corresponding to the lake-effect snowfall belts downwind of Lake Superior, Lake Huron, and Lake Ontario are exhibiting the greatest and most significant increasing trends (Figure 6b).

Trends in minimum and maximum temperatures are broadly similar to each other, with the majority of grid cells exhibiting statistically significant ($p < 0.05$) increasing trends. The regions north of Lake Superior exhibit the greatest increases in both minimum and maximum temperature, with increases of approximately 0.6 °C decade^{-1} and 0.3 °C decade^{-1}, respectively (Figure 6d, 6e). In contrast, grid cells south of Lake Superior, predominantly in northern Wisconsin and the Upper Peninsula of Michigan, experience the smallest increases or are decreasing in temperature over this period (Figure 6d, 6e). Trends in snow ablation frequency are predominantly negative north of Lake Superior, on the order of -0.16 d yr^{-1} from 1960-2009, with the lake-effect snow belts of Lake Huron and Lake Ontario exhibiting increasing trends in excess of 0.22 and 0.18 d yr^{-1} (Figure 6c).

Visually, the regions with the greatest decreases (increases) in snow depth appear to align with the regions with the greatest increases (decreases) in air temperature and the greatest decreases (increases) in ablation frequency. Statistically, this is supported by an analysis of Pearson correlation coefficients, where the average snow depth trend in grid cells across the basin from 1960-2009 is positively correlated with ablation frequency and snowfall trends, and negatively correlated with minimum and maximum air temperatures trends (Table 5).

4.0 Discussion

One of the key findings of this study is the importance of considering multiple scales of analysis with regards to snow within the Great Lakes basin. Given the perceived consistency of the region's climate based on the proximity to the lakes, it is tempting to treat the basin as a single entity, however it may not be appropriate for all applications. This is perhaps best highlighted by comparing the difference between the snow seasons of the Lake Superior and Lake Erie sub-basins. The sub-basin of Lake Erie has an average snow depth of 7.3 cm with a snow season that is 2-months shorter than that of the Lake Superior sub-basin. As such, the climatological, environmental, and/or societal impacts of snow depth variability may not necessarily be the same between the two basins.

A decrease in snow cover of just one standard deviation of basin-wide snow depth for the Lake Erie sub-basin in a given season could represent the difference between some and no snow cover, while such a decrease for the Lake Superior sub-basin would be far less noticeable. The presence of snow cover is shown to play critical roles in albedo, soil insolation, the hydrologic cycle, and ecological habitats. Enhanced snow cover increases albedo, reducing the absorption of shortwave radiation, while enhancing longwave emission and promoting an insulating effect on underlying soil temperatures (Zhang et al. 2008). The difference in albedo and moisture fluxes between snow covered and bare surfaces also support enhanced baroclinicity, which may shift mid-latitude storm tracks (Namias, 1962; Elguindi et al. 2005; Rydzik and Desai, 2014). The trajectories of mid-latitude storms have a direct impact on social weather hazards such as additional snowfall, ablation, flooding, or wind damage (Riebsame et al., 1986) where the presence of snow cover in one part of the Great Lakes basin, and the lack of it in another, may lead to substantial differences to societal experience. As such, the Great Lakes basin should likely not be considered as a single entity for most applications with regards to snow.

In this study, we find that snow depth changes are heterogeneously distributed within the basin. The individual grid cell analysis reveals the northwest and northeast sub-basins of the Lake Superior basin are exhibiting the largest declines in average seasonal snow depth. It is likely that the signal in this region is greatly contributing to the trends noted for the entire Lake Superior basin, and for the entire Great Lakes basin.

Increasing surface air temperatures are often attributed as the cause of declining snow cover and/or snow depth (e.g. Kapnick and Delworth, 2013). Warmer air temperatures, and an associated warmer atmospheric column, decrease the likelihood of frozen hydrometeors reaching the surface, and enhanced rainfall totals may come at the expense of diminished snowfall totals (see Krasting et al. 2013; Notaro et al. 2014, among others). A decline of snow accumulations would result in a shallower snowpack. The correlations between detrended timeseries of air temperature, snow depth, ablation frequency, and snowfall support the general understanding of snow dynamics, where warmer (cooler) than normal temperatures allow for less (more) snowfall accumulations, a shallower (deeper) snowpack, and a lesser (greater) potential for snow ablation to occur. The shallower the snowpack, the lower the frequency of ablation events, likely due to the lesser potential a shallower snowpack provides for more ablation events to occur.

While this pathway is theoretically valid, snowfall does not appear to be declining significantly across the basin, and is increasing in some regions. This lack of decline in snowfall may be due to the production of both synoptically-forced and lake-effect snow. A warmer column would result in less synoptically-forced snowfall, but may or may not result in less lake-effect. Atmospheric warming is expected to also warm lake-water temperatures, potentially enhancing boundary layer instability over the lakes, leading to higher snowfall totals (Notaro et al. 2014; Suriano and Leathers 2016). Concurrently, warmer lake-water temperatures would limit lake ice growth and enhance evaporation. Such changes would, in theory, yield a greater potential of lake-effect snowfall, as lake-ice concentration above 70% begins to inhibit the heat and moisture fluxes necessary for development (Gerbush et al., 2008). A lack of ice may lead to more lake-effect snowfall due to a longer lake-effect unstable season (Niziol et al. 1995) and/or via greater instability and convection. Increases in lake-effect snow specifically may partially explain the lack of snowfall decreases across the basin that should otherwise be apparent if only synoptically-forced snowfall was considered.

While snow cover in the Great Lakes basin is significantly declining from 1960-2009, significant trends obtained via linear regression are subjective to the study period used. For basin-wide snow cover, it should be noted that by adjusting the study period to only include the most recent three decades (1980-2009), the decreasing trend is no longer statistically significant. In this case, the relatively higher snow depths in the 1970s, and to a lesser amount the 1960s, are important for detecting the climatological trend and are acknowledged here. Such a result is still valid for the entire basin however, and is similar to findings of recent studies detailing decreases in snow depth and snow cover across North America over the last half-century or more (Frei and Robinson, 1999; Frei et al., 1999; Brown, 2000; Dyer and Mote, 2006).

Snow depth results presented in this study corroborate findings on the variability of snow ablation events and the atmospheric conditions responsible. In the northwest and northeast sub-basins of the Lake Superior basin, Suriano and Leathers (2017a) identified large decreases in the frequency of snow ablation events from 1960-2009, on the order of a 50% reduction. This region spatially matches the region noted in this study exhibiting a significant decrease in snow depth. A progressively shallower snowpack over time would lessen the potential for an ablation event to occur, as there must be sufficient snow on the ground to be ablated to be considered an event. As such, a shallower snowpack is able to 'withstand' fewer ablation events before it is depleted, preventing any further events until new accumulations occur.

Suriano and Leathers (2017a) also identified a region along the eastern shores of Lake Huron, south of the Georgian Bay, where the frequency of ablation events is increasing by approximately 74%. This region matches the only grid cell found in this study to exhibit a large increase in seasonal snow depth (cell: 44.5°N, 80.5°W; Figure 6a). Previous research finds this region has experienced significantly more lake-effect snowfall over the 1960-2009 period (Suriano and Leathers 2017b). This could then indicate an increase in snow depth of the same period, however increasing trends of snow depth east of Lake Huron, noted in this study, were not statistically significant. It is possible that increases in lake-effect snowfall occurred concurrently with decreases or non-existent trends in synoptically-forced snowfall from mid-latitude cyclones. Thus, the combination of more snowfall from one source, and less snowfall from another source, would yield a snowpack with a similar depth over time. In essence, the statistical significance of the increasing trend of lake-effect snow would then be dampened by steadier, or decreasing trends in mid-latitude cyclone-induced snowfall, leading to a lack of significance in 1960-2009 trends in snow depth. This then would suggest the detected increase in ablation events (Suriano and Leathers 2017a) was associated with changes in the meteorological conditions that lead to ablation. Examining Suriano (2018), this appears to be a plausible explanation. For the basin of Lake Huron, the frequencies of surface high-pressure and weakly-classified synoptic-scale weather systems that lead to ablation are significantly changing in favor of more ablation-causing conditions (for definitions of these weather systems, see Suriano (2018)). High-pressure overhead and weak synoptic weather types are increasing in frequency in the broader Lake Huron region by 35 and 77%, respectively, from 1960-2009. This analysis indicates that the change in ablation frequency east of Lake Huron, noted in Suriano and Leathers (2017a), is likely not a result of changing snow depths, but more likely the result of changing atmospheric patterns that provide more favorable meteorological conditions for ablation.

Increases in clear-skies associated with these synoptic types would increase the amount of incoming shortwave radiation reaching the surface, increasing the amount of shortwave absorbed by the snowpack and aiding in melt, and thus declining snow depths.

In the Great Lakes basin, snow cover is a major component of the hydrologic cycle as the predominate contributor to annual runoff. As such, variability and/or changes in snow seasonality, magnitude, and persistence may carry wide-spread anthropogenic and environmental impacts. Detected decreases in snow depth in the Great Lakes basin lessens the risk of snowmelt-inducing flooding associated with ablation events; A shallower snowpack contains less water, and thus decreases the runoff associated with a rapid melt event, when compared to a similar event with a deeper pack. Snowmelt flooding events of a smaller magnitude may lessen the influx of excessive nutrient and pollutant pulses into the basin's waterways while also potentially limiting the damage to infrastructure and loss of life caused by the runoff and flooding itself.

Snowmelt is also the dominant control on the water levels of the Great Lakes in spring and summer (Quinn 2002). Research has shown variability in the timing and magnitude of rising spring lake levels has detrimental effects on wildlife in the basin, including fish habitats, aquatic vegetation, and march bird breeding abundance (Barry et al, 2004; Fracz & Chow-Fraser, 2013; Steinman et al. 2012, among others). A decline in snow pack lessens the magnitude of spring runoff and perhaps would result in a more gradual increase in lake levels in the spring, or potentially result in an early onset of peak ablation and thus an earlier rise to lake-levels would occur. This may potentially place excessive strain on ecological habitats, but also to the closely managed water resources and/or power generation that partially depends on spring snowmelt during the end of the cold season in generating hydroelectric power (see Vicuna et al. 2008).

Finally, while not necessarily as prominent as in regions of the western United States, declining and variable snow depths in the Great Lakes basin also carry implications for early-warm season drought. Shallower snowpacks that experience greater ablation during the winter, may note a shift or magnitude change in seasonal runoff. This would reduce soil moisture during the spring and summer (see Mastin et al. 2011) and thus increase the potential for the development of drought while increasing fire risk (Mahanama et al., 2012; Westerling et al. 2006). Collectively, snow cover within the Great Lakes basin warrants investigation and the specific results of this study can help inform water management practices within the region. While the study does not offer specific advice when it comes to ‘best practices’, it provides further evidence that the Great Lakes basin is, and may continue to, be in a zone of transition with regards to snow-derived water resources.

5.0 Conclusions

Utilizing a 1-degree gridded dataset of snow cover across North America (Mote et al. 2018), this study developed a climatology of snow depth in the Great Lakes basin, quantifying the spatial and temporal variability from 1960-2009. Snow is evaluated at multiple scales: for the entire basin, for primary sub-basins, and for individual grid cells, to provide insight into the importance of scale when evaluating snow trends and variability in the region. Snow cover in the basin is common from November through April, however substantial spatial variability exists. A broad latitude-dependent gradient is evident with greater snow depths to the north. To the lee of the individual Great Lakes, snow depths are greater (i.e. deeper), likely due to lake-effect processes.

Temporal variability is also evident as all three analyzed scales exhibit statistically significant decreasing trends of seasonal snow depth. Average basin-wide September-August snow depth declines by approximately 25% from 1960-2009, likely due to increasing minimum and maximum daily temperatures. At the sub-basin scale, average snow depth of the Lake Superior and Lake Michigan basins significantly decreased by 25-30%. Examination at the individual grid cell level revealed multiple spatially coherent regions of significant trends in snow depth. The northwest and northeast Lake Superior drainage basins exhibit the largest decrease in seasonal snow depth, ranging between 0.2 and 0.5 cm yr^{-1} from 1960-2009. In this region, February has both the greatest snow depth and greatest decreasing trend. Other regions, such as in western New York and northern Michigan also exhibit significant decreases in seasonal snow depth.

The regionally specific trends in snow depth and correlations between snow depth, snowfall, temperature, and ablation frequency, corroborate previous findings in the literature of changing snow ablation event frequency and synoptic-scale meteorological conditions (Suriano and Leathers 2017a; Suriano and Leathers 2018). Snow cover ablation is dependent on both the meteorological conditions to ablate snow, but also the physical presence of snow to be ablated. In order to document changes in ablation frequency (and/or magnitude) and quantify the reasons behind the changes, snow depth variability must be accounted for.

Future work in this region on snow and snow cover ablation should consider the relationships presented here between snow depth, air temperature, and ablation frequency. While a broad increase in air temperature is evident, the magnitude of an ablation event is dependent not on temperature, but the net surface energy flux. Such fluxes vary depending on the specific weather pattern ablating the snow, and an investigation into the long-term variability of specific synoptic-scale ablation-inducing weather pattern's energy fluxes is currently underway. Furthermore, relatively little is known about the magnitude and timing of snowmelt-inducing flooding events in the region. Future work will identify and track the frequency of these flooding events to determine if detected changes in snow depth and snow ablation frequency are indeed altering the frequency and/or intensity of flooding events.

7.0 References

Ashley ST, Ashley WS (2008) The storm morphology of deadly flooding events in the United States. *International Journal of Climatology,* 28: 493-503. doi:10.1002/joc.1554.

Barnett TP, Adam JC, Lettenmaier DP. (2005) Potential impacts of a warming climate on water availability in snow-dominated regions. *Nature*, 438: 303-309, doi:10.1038/nature04141.

Barry MJ, Bowers R, De Szalay FA (2004) Effects of hydrology, herbivory and sediment disturbance on plant recruitment in a Lake Erie coastal wetland. *American Midland Naturalist* 151: 217-231.

Brown RD (2000) Northern Hemisphere snow cover variability of Canadian monthly snow depths, 1946-1995. *Atmos. Ocean*, 36: 37-45.

Changnon SA (2008) Assessment of Flood Losses in the United States. *J. Contemp. Water Res. Educ.*, 138: 38–44, doi:10.1111/j.1936-704X.2008.00007.x.

Dyer JL, Mote TL (2006) Spatial variability and trends in observed snow depth over North America. *Geophys. Res. Lett.,* 33, doi:10.1029/2006GL027258.

Dyer JL, Mote TL (2007) Trends in snow ablation over North America. *Int. J. Climatol.*, 27: 739–748, doi:10.1002/joc.1426.

Elgundi N, Hanson B, Leathers DJ (2005) The effects of snow cover on mid-Latitude cyclones in the Great Plains. *Journal of Hydrometeorology*, 6, 263-279.

Estilow TW, Young AH, Robinson DA (2015) A long-term Northern Hemisphere snow cover extent data record for climate studies and monitoring. *Earth System Science Data* 7: 137-142, DOI: 10.5194/essd-7-137-2015.

Fracz A, Chow-Fraser P (2013) Impacts of declining water levels on the quantity of fish habitat in coastal wetlands of eastern Georgian Bay, Lake Huron. *Hydrobiologia* 702: 151-169. DOI: 10.1007/s10750-012-1318-3.

Frei A, Robinson DA (1999) Northern Hemisphere snow extent: Regional variability 1972-1994. *International Journal of Climatology* 19: 1535-1560.

Frei A, Robinson DA, Hughes MG (1999) North American snow extent: 1900-1994. *International Journal of Climatology* 19: 1517-1534.

Gerbush MR, Kristovich DAR, Laird NF (2008) Mesoscale boundary layer and heat flux variations over pack ice-covered Lake Erie. *Journal of Applied Meteorology and Climatology* 47: 668-682.

IPCC (2013) Climate Change 2013: The Physical Science Basis. Contribution of Working Group 1 to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker TF, Qin D, Plattner GK, Tignor M, Allen SK, Boschung J, Nauels A, Xia Y, Bex V, Midgley PM (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp, doi: 10.1017/CB0981107415324.

Kapnick S, Delworth T (2013) Controls of Global Snow Under a Changed Climate. *Journal of Climate* 26: 5537-5562 DOI: 10.1175/JCLI0D-12-00528.1.

Kluver D, Mote TL, Leathers DJ, Henderson GR, Chan W, Robinson DA (2017) Creation and Validation of a Comprehensive 1° by 1° Daily Gridded North American Dataset for 1900–2009: Snowfall. *J Atmospheric Ocean Technol*, 33: 857–871,doi:10.1175/JTECH-D-15-0027.1

Krastling J, Broccoli A, Dixon K, Lanzante J (2013) Future changes in Northern Hemisphere snowfall. *Journal of Climate* 26: 7813-7828, DOI: 10.1175/JCLI-D-12_00832.1.

Leathers DJ, Kluck T, Kroczynski S (1998) The severe flooding event of 1996 across north-central Pennsylvania. *Bull. Am. Meteorol. Soc.*, 79: 785-797.

Mahanama S, Livneh B, Koster R, Lettenmaier D, Reichle R (2012) Soil moisture, snow and seasonal streamflow forecasts in the United States. *Journal of Hydrometeorology* 13: 189-203, DOI: 10.1175/JHM-D-11-046.1.

Mastin MC, Chase KJ, Dudley RW (2011) Changes in spring snowpack for selected basins in the United States for different climate-change scenarios. *Earth Interactions* 15, DOI: 10.1175/2010EI368.1.

Mote TL, Estilow TW, Henderson GR, Leathers DJ, Robinson DA, Suriano ZJ (2018). *Daily Gridded North American Snow, Temperature, and Precipitation, 1959-2009, Version 1.* Boulder, Colorado USA. NSIDC: National Snow and Ice Data Center. DOI: 10.7265/N5028PQ3.

Namias J (1962) Influences of abnormal heat sources and sinks on atmospheric behavior. *Proceedings of the International Symposium on Numerical Weather Prediction*, Tokyo, Japan, Meteorological Society of Japan, 615-627.

Niziol T, Snyder W, Waldsteicher J (1995) Winter weather forecasting throughout the Eastern United States. Part IV: lake effect snow. *Weather Forecast* 10: 61-77.

Notaro M, Lorenz D, Hoving C, Schummer M (2014) Twenty-first century projections of snowfall and winter severity across Central-Eastern North America. *Journal of Cliamte* 27: 6526-6550, DOI: 10.1175/JCLI-D-13-00520.1.

Quinn FH (2002) Secular changes in Great Lakes water level seasonal cycles. *Journal of Great Lakes Research*, 28: 451-465.

Riebsame WE, Diaz HF, Moses T, Price M (1986) The Social Burden of Weather and Climate Hazards. *Bulletin of the American Meteorological Society* 67: 1378-1388.

Robinson DA, Dewey KF, Heim RR (1993) Global snow cover monitoring: An update. *Bulletin of the American Meteorological Society* 74: 1689-1696.

Rydzik M, Desai AR (2014) Relationship between snow extent and midlatitude disturbance centers. *Journal of Climate*, 27: 2971-2982. DOI: 10.1175/JCLI-D-12-00841.1.

Steinman AD, Ogdahl ME, Weinert M, Thompson K, Cooper MJ, Uzarski DG (2012) Water level fluctuation and sediment-water nutrient exchange in Great Lakes coastal wetlands. *Journal of Great Lakes Research* 38: 766-775. DOI: 10.1016/j.jglr.2012.09.020.

Suriano ZJ, Leathers DJ (2016) Twenty-first century snowfall projections within the eastern Great Lakes region: detecting the presence of a lake-induced snowfall signal in GCMs. *International Journal of Climatology* 36: 2200-2209. DOI: 10.1002/joc.4488.

Suriano ZJ, Leathers DJ (2017a) Spatiotemporal Variability of Great Lakes Basin Snow Cover Ablation Events. *Hydro. Proc.*, 31: 4229-4237. doi:10.1002/hyp.11364.

Suriano ZJ, Leathers DJ (2017b) Synoptically classified lake-effect snowfall trends to the lee of Lakes Erie and Ontario. *Clim. Res.*, 74: 1-13, doi:10.3354/cr01480.

Suriano ZJ (2018). On the role of snow cover ablation variability and synoptic-scale atmospheric forcings at the sub-basin scale within the Great Lakes watershed. *Theoretical and Applied Climatology*. In Press. DOI: 10.1007/s00704-018-2414-8

Suriano ZJ, Leathers DJ (2018) Great Lakes basin snow cover ablation and synoptic-scale atmospheric circulation. *Journal of Applied Meteorology and Climatology* 57: 1497-1510. DOI: 10.1175/JAMC-D-17-0297.1.

Tidwell V, Moreland B (2011) Energy and Water in the Great Lakes. Great Lakes Commission Report. 71 pp.

Vicuna S, Leonardson R, Hanemann M, Dale L, Dracup J (2008) Climate change impacts on high elevation hydropower generation in California's Sierra Nevada: A case study on the Upper American River. *Climatic Change* 87: 123-137, DOI: 10.1007s10584-007-9365-x.

Westerling A, Hidalgo H, Cayan D, Swetnam D (2006) Warming and earlier spring increases western U.S. forest wildfire activity. *Science* 313: 940-943. DOI: 10.1126/science.1128834.

Willmott C, Rowe C, Philpot W (1984) Spheremap. Center for Climatic Research, Department of Geography, University of Delaware, Newark DE.

Zhang Y, Wang S, Barr AG, Black TA (2008) Impact of snow cover on soil temperature and its simulation in a boreal aspen forest. *Cold Regions Scientific Technology* 52: 355-370, DOI:10.1016/j.coldregions.2007.07.001.

8.0 Table and Figure Captions

Table 1. Information regarding the drainage basin area (in km^2), number of grid cells representing the drainage basins at the 1° resolution, and the approximate central location of the Lake Superior, Michigan, Huron, Erie, and Ontario drainage basins.

Table 2. Summary statistics for the Great Lakes basin during the snow seasons of 1960-2009. The snow season is defined as the days between the first and last occurrence of a snow depth exceeding 2.54 cm. The average snow season depth is the snow depth during each snow season averaged over the 50-year time period.

Table 3. Summary statistics for the five primary sub-basins of the Great Lake Basin during the snow seasons of 1960-2009. The snow season is defined as the days between the first and last occurrence of a snow depth exceeding 2.54 cm. The average snow season depth is the snow depth during each snow season averaged over the 50-year time period.

Table 4. Correlation coefficient from an ordinary least-squares linear regression of 1960-2009 November-April average Great-Lakes basin snow depth and (1) total snowfall, (2) snow ablation frequency, (3) maximum temperature., and (4) minimum temperature. Two asterisks (**) denote a statistically significant correlation and a p-value of less than 0.01, while one asterisk (*) denotes a p-value of less than 0.05.

Table 5. Pearson correlation coefficient of 1960-2009 November-April linear trends in Great-Lakes basin snow depth at the individual grid-cell scale and (1) total snowfall trends, (2) snow ablation frequency trends, (3) maximum temperature trends, and (4) minimum temperature trends. Two asterisks (**) denote a statistically significant correlation and a p-value of less than 0.01, while one asterisk (*) denotes a p-value of less than 0.05.

Figure 1. The Great Lakes basin at the 1-degree resolution, adapted from Suriano (2018). Colors correspond to the five primary drainage basins (red-Superior, yellow-Huron, blue-Michigan, green-Erie, teal-Ontario). [1.5 column fitting]

Figure 2. Seasonal cycle of Great Lakes basin snow depth (cm) from 1960-2009. [1.5 column fitting]

Figure 3. Inter-annual variability of Great Lakes basin average snow-season snow depth (cm) 1959-2009 (in blue). The snow season is defined as the days between the first and last occurrence of a depth of at least 2.54 cm from a Sep-Aug year. The linear trend line shown (in black) depicts a statistically significant decrease. [1.0 column fitting]

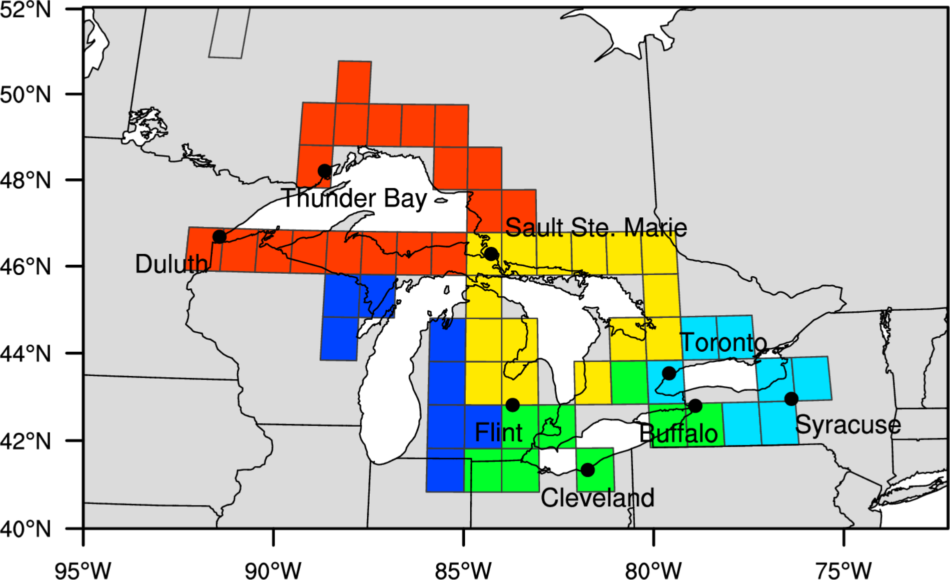
Figure 4. Seasonal cycle of mean Great Lakes basin snow depth (cm) by decade: 1960s (red), 1970s (purple), 1980s (teal), 1990s (orange), and 2000s (green). [1.0 column fitting]

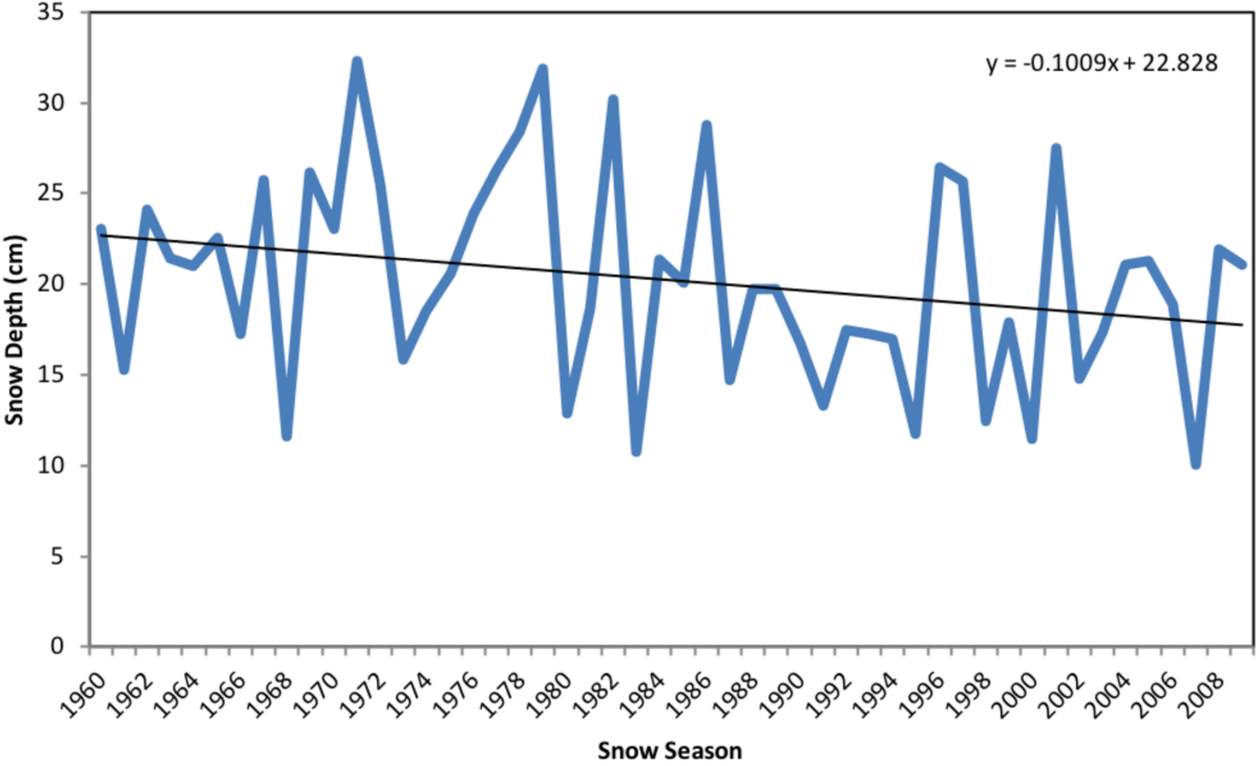
Figure 5. Average snow depth across the Great Lakes basin by 1-degree grid cell for a) November, b) December, c) January, d) February, e) March, and f) April. Darker blues denote a deeper snowpack in cm. [2.0 column fitting]

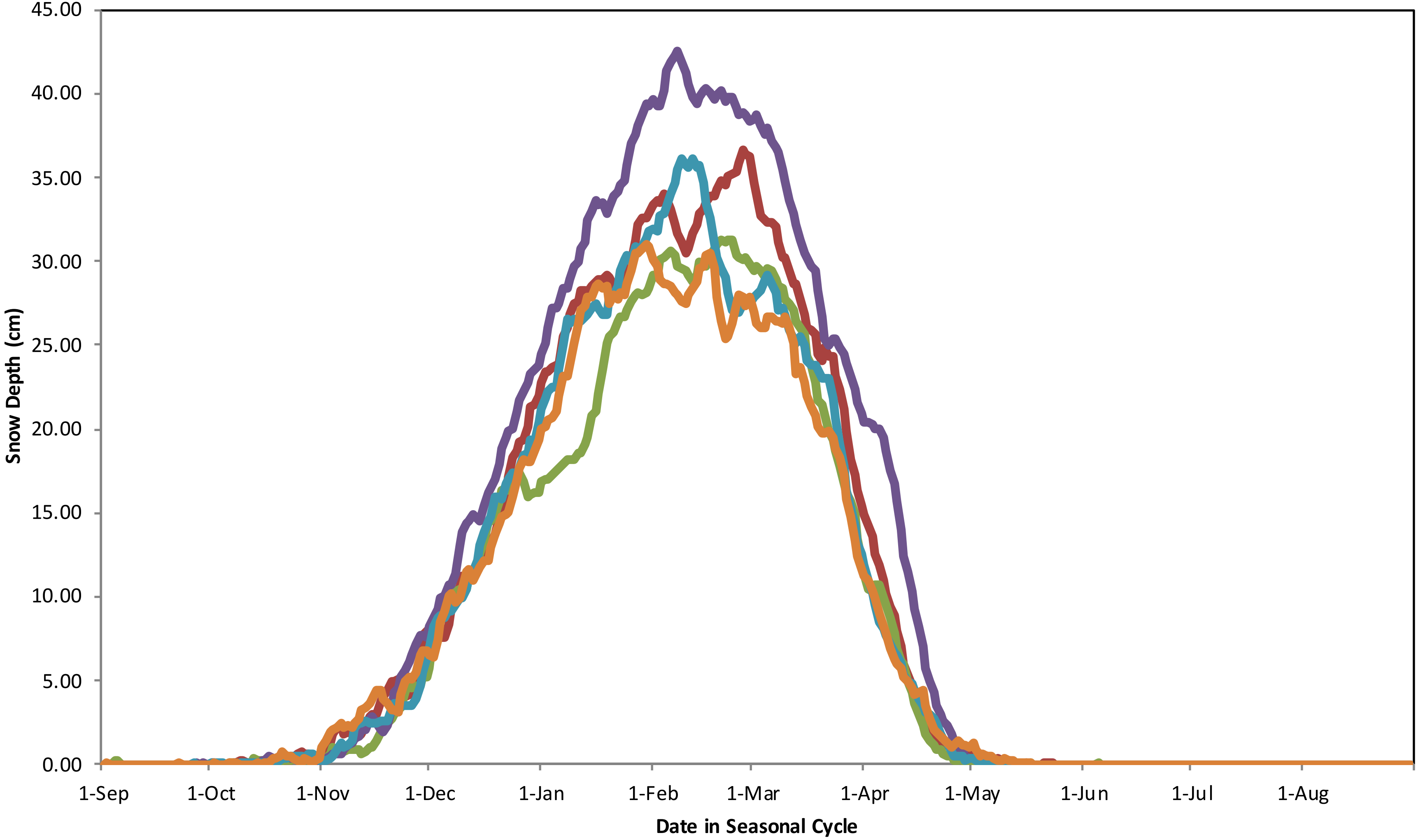
Figure 6. Linear trends by grid cell of 1960-2009, Nov-Apr (a) average snow depth (cm yr^{-1}), (b) total snowfall (cm yr^{-1}), (c) average ablation event frequency (days yr^{-1}), (d) average minimum temperature (°C yr^{-1}), and (e) average maximum temperature (°C yr^{-1}). Blues denote negative trends in and reds denote positive trends. Cells marked with an "x" denote statistical significance with a p-value of < 0.05.

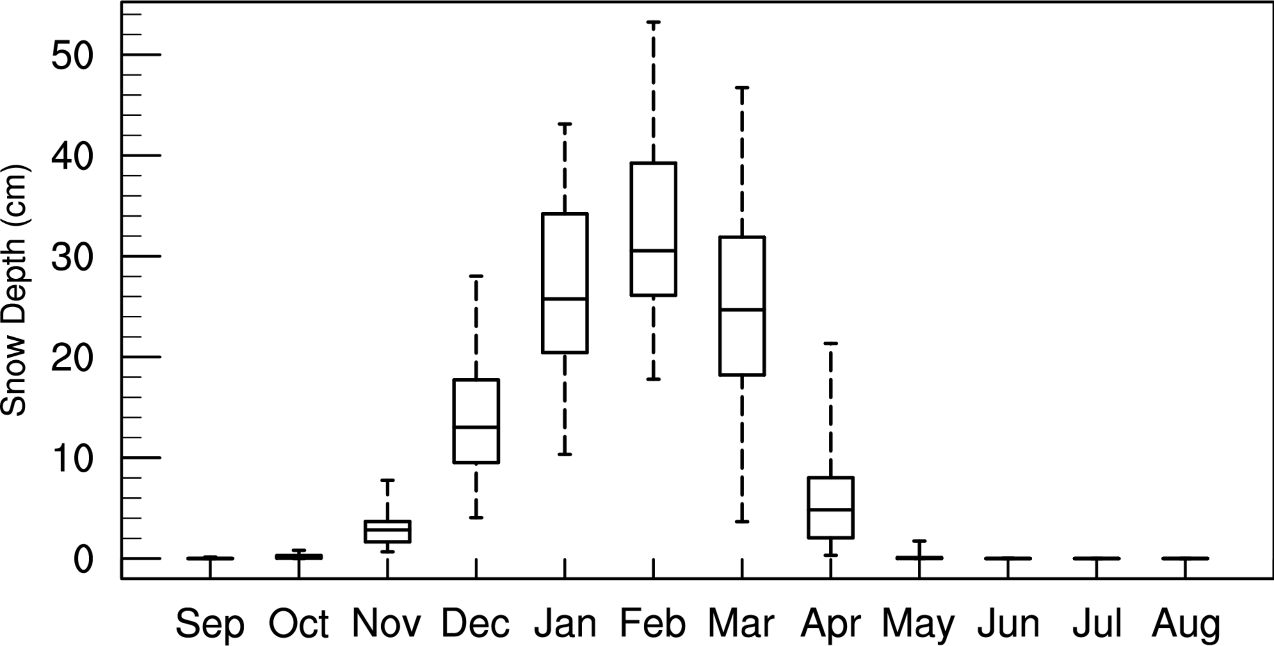
Figure 7. Linear trends of 1960-2009 average snow depth by grid cell (cm yr^{-1}) for (a) November, (b) December, (c) January, (d) February, (e) March, and (f) April. Blues denote negative trends in and reds denote positive trends. Cells marked with an "x" denote statistical significance with a p-value of < 0.05.

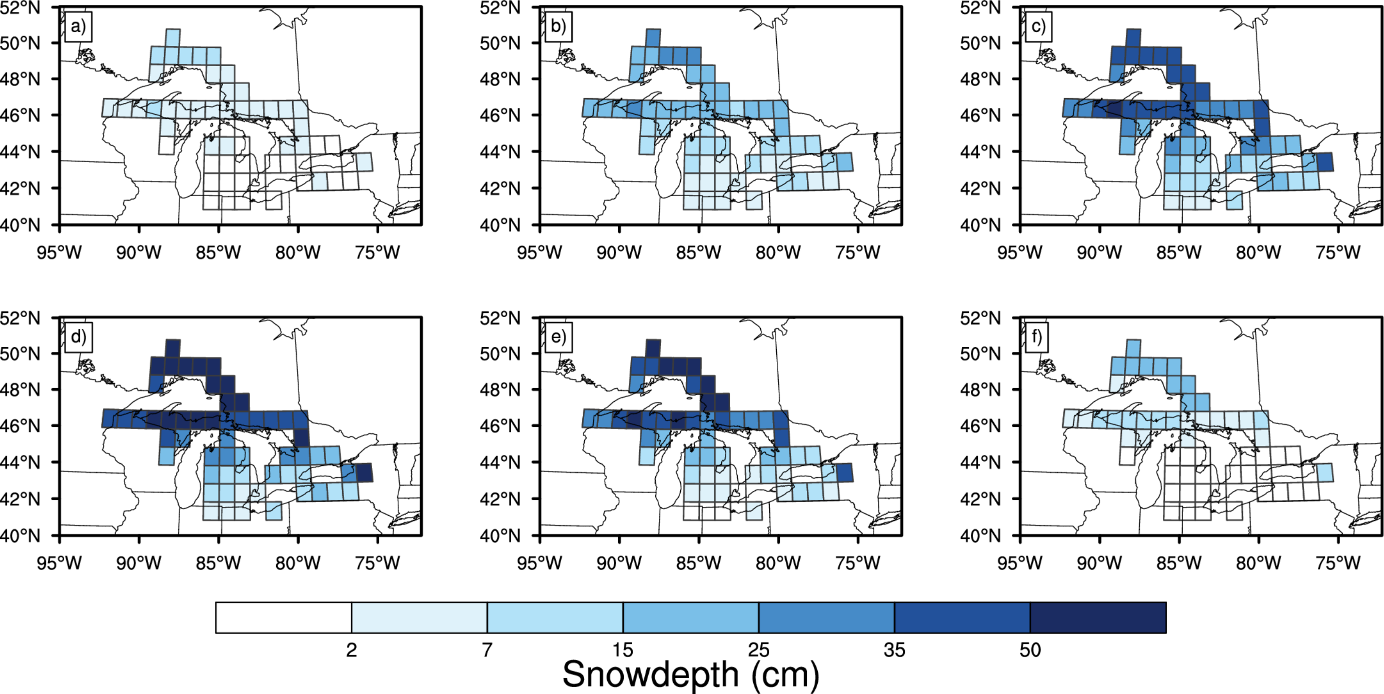
Figure 8. November-April basin-wide average minimum (blue; bottom) and maximum (red; top) temperature from 1960-2009 in °C. Linear trends lines (dashed) and their corresponding equations are also depicted. Both variables exhibit statistically significant trends ($p < 0.05$).

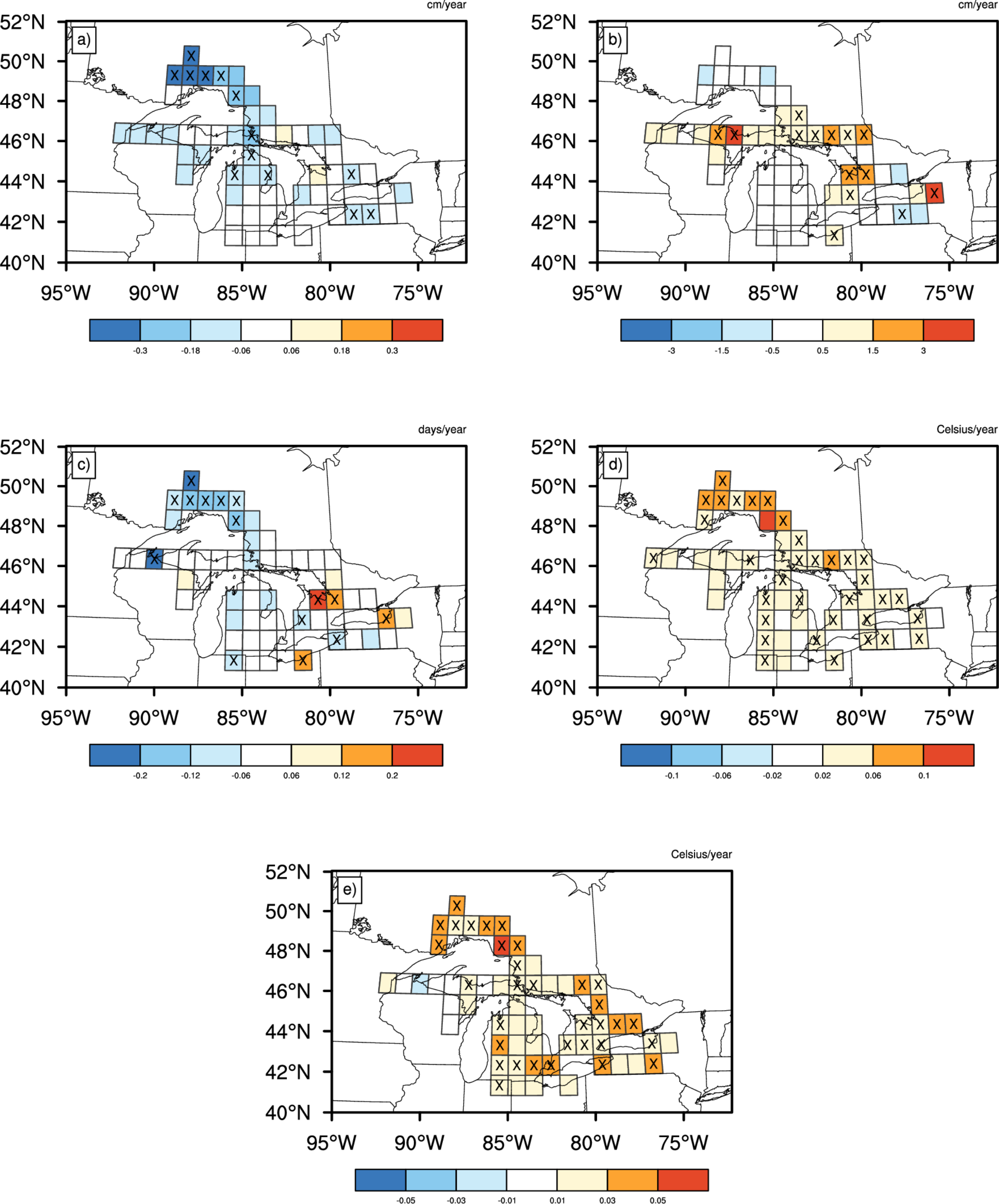

52°N
50°N
48°N
46°N
44°N
42°N
40°N
95°W
90°W
85°W
80°W
75°W
Thunder Bay
Duluth
Sault Ste. Marie
Toronto
Flint
Buffalo
Syracuse
Cleveland

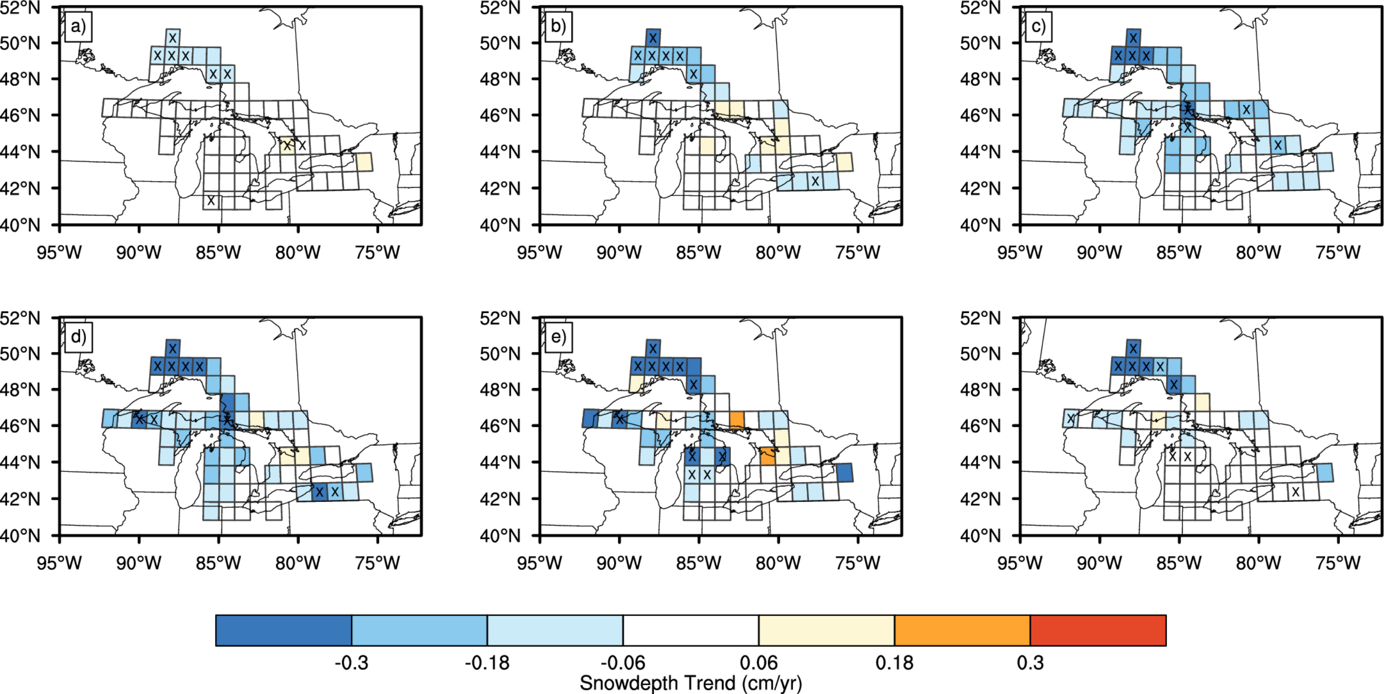

35
30
25
20
15
10
5
0
Snow Depth (cm)
y = -0.1009x + 22.828
1960
1962
1964
1966
1968
1970
1972
1974
1976
1978
1980
1982
1984
1986
1988
1990
1992
1994
1996
1998
2000
2002
2004
2006
2008
Snow Season

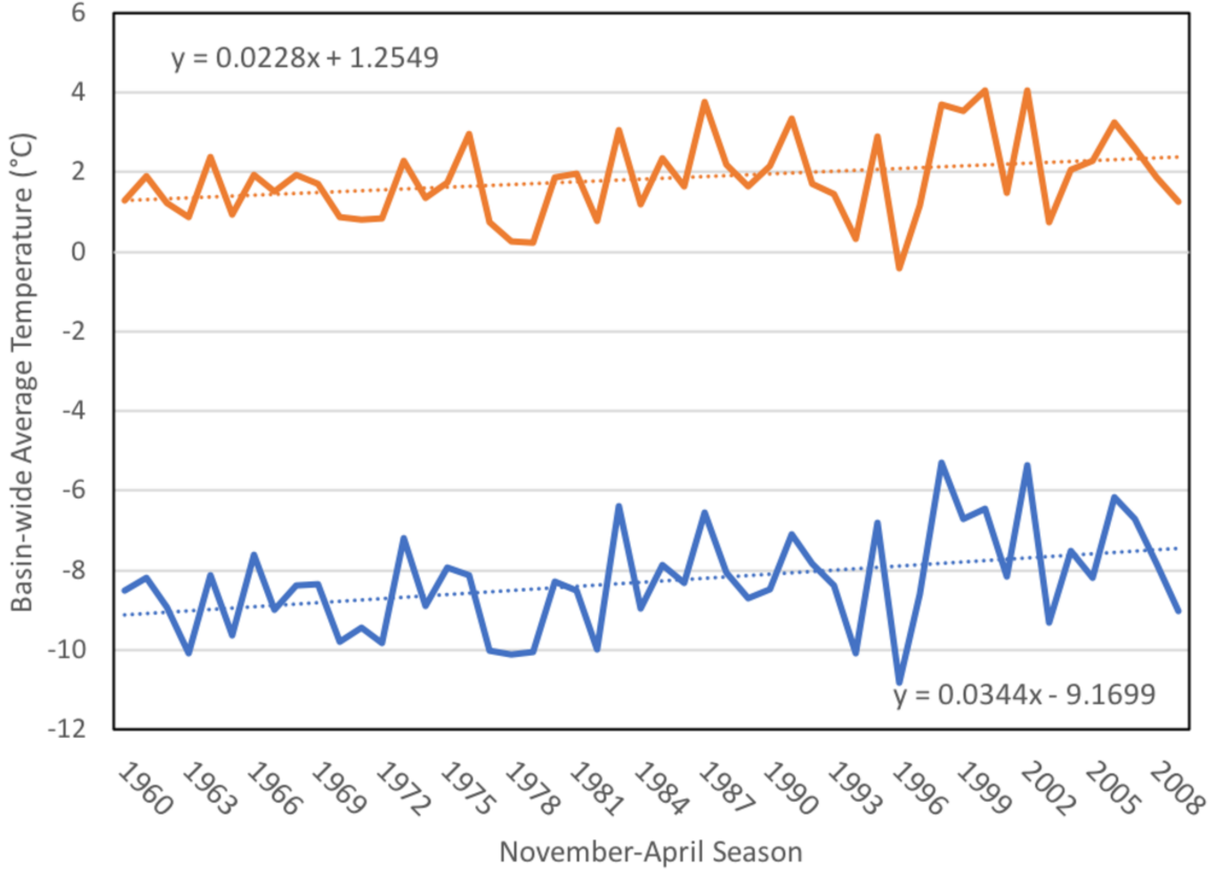

45.00
40.00
35.00
30.00
25.00
20.00
15.00
10.00
5.00
0.00
Snow Depth (cm)
1-Sep
1-Oct
1-Nov
1-Dec
1-Jan
1-Feb
1-Mar
1-Apr
1-May
1-Jun
1-Jul
1-Aug
Date in Seasonal Cycle


Snow Depth (cm)
0
10
20
30
40
50
Sep
Oct
Nov
Dec
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug


a)
b)
c)
d)
e)
f)
52°N
50°N
48°N
46°N
44°N
42°N
40°N
95°W
90°W
85°W
80°W
75°W
2
7
15
25
35
50
Snowdepth (cm)


a)
cm/year
-0.3 -0.18 -0.06 0.06 0.18 0.3
b)
cm/year
-3 -1.5 -0.5 0.5 1.5 3
c)
days/year
-0.2 -0.12 -0.06 0.06 0.12 0.2
d)
Celsius/year
-0.1 -0.06 -0.02 0.02 0.06 0.1
e)
Celsius/year
-0.05 -0.03 -0.01 0.01 0.03 0.05
52°N 50°N 48°N 46°N 44°N 42°N 40°N
95°W 90°W 85°W 80°W 75°W
X


a)
b)
c)
d)
e)
52°N
50°N
48°N
46°N
44°N
42°N
40°N
95°W
90°W
85°W
80°W
75°W
X
-0.3
-0.18
-0.06
0.06
0.18
0.3
Snowdepth Trend (cm/yr)



y = 0.0228x + 1.2549
y = 0.0344x - 9.1699
Basin-wide Average Temperature (°C)
6
4
2
0
-2
-4
-6
-8
-10
-12
1960
1963
1966
1969
1972
1975
1978
1981
1984
1987
1990
1993
1996
1999
2002
2005
2008
November-April Season

	Lake Superior Basin	**Lake Michigan Basin**	**Lake Huron Basin**	**Lake Erie Basin**	**Lake Ontario Basin**
Size of Drainage Basin (km^2)	127,700	118,000	134,100	78,000	64,030
Number of 1x1° Grid Cells	19	9	15	8	6
Approximate Central Location	47.7°N, 87.5°W	44.0°N, 87.0°W	44.8°N, 82.4°W	42.2°N, 81.2°W	43.7°N, 77.9°W

Table 1. Information regarding the drainage basin area (in km^2), number of grid cells representing the drainage basins at the 1° resolution, and the approximate central location of the Lake Superior, Michigan, Huron, Erie, and Ontario drainage basins.

	Snow Season Depth (cm)	Length of Season (days)	Season Start Date	Season End Date	Frequency of > X cm of depth (days)			
					0 cm	5.08 cm	15.24 cm	30.48 cm
Average	20.3	159.2	Nov 10	Apr 18	200	133	94	39
Standard deviation	5.7	12.7	9.7 d	8.0 d	12.3	16.8	22.3	30.7

Table 2. Summary statistics for the Great Lakes basin during the snow seasons of 1960-2009. The snow season is defined as the days between the first and last occurrence of a snow depth exceeding 2.54 cm. The average snow season depth is the snow depth during each snow season averaged over the 50-year time period.

	Lake Superior Basin	**Lake Michigan Basin**	**Lake Huron Basin**	**Lake Erie Basin**	**Lake Ontario Basin**
Average Snow Season Depth (cm)	31.6 (9.2)	13.2 (5.9)	19.8 (6.5)	7.3 (3.6)	16.0 (5.9)
Length of Snow Season (days)	179.5 (21.3)	134.2 (18.4)	148.8 (12.1)	125.8 (18.3)	143.2 (17.5)
Start of Snow Season	Oct 29 (15.4)	Nov 21 (14.6)	Nov 14 (10.5)	Nov 23 (13.2)	Nov 18 (14.8)
End of Snow Season	Apr 26 (11.1)	Apr 4 (11.6)	Apr 10 (7.9)	Mar 28 (11.9)	Apr 9 (10.8)
Days with > 0 cm of snow depth	195.7 (12.0)	153.5 (12.4)	171.8 (12.5)	138.0 (12.5)	158.1 (12.1)
Days with > 5.08 cm of snow depth	149.8 (14.6)	96.1 (23.7)	118.6 (18.0)	58.3 (21.4)	107.9 (22.0)
Days with > 15.24 cm of snow depth	122.6 (19.0)	47.3 (30.2)	81.6 (24.5)	20.1 (19.0)	60.9 (27.1)
Days with > 30.48 cm of snow depth	89.6 (27.6)	11.1 (17.0)	36.7 (28.8)	2.8 (8.3)	23.3 (23.3)

Table 3. Summary statistics for the five primary sub-basins of the Great Lake Basin (Lakes Superior, Michigan, Huron, Erie, and Ontario drainage basins) during the snow seasons of 1960-2009. The snow season is defined as the days between the first and last occurrence of a snow depth exceeding 2.54 cm. The average snow season depth is the snow depth during each snow season averaged over the 50-year time period. Standard deviation is reported in parentheses.

	Snow Depth	**Snowfall**	**Ablation Frequency**	**Minimum Temperature**	**Maximum Temperature**
Snow Depth	---	0.911**	0.422**	-0.733**	-0.743**
Snowfall	0.911**	---	0.559**	-0.622**	-0.677**
Ablation Frequency	0.422**	0.559**	---	-0.290*	-0.199
Minimum Temperature	-0.733**	-0.622**	-0.290*	---	0.935**
Maximum Temperature	-0.743**	-0.677**	-0.199	0.935**	---

Table 4. Correlation coefficient during an ordinary least-squares linear regression of 1960-2009 November-April average Great-Lakes basin snow depth and (1) total snowfall, (2) snow ablation frequency, (3) maximum temperature., and (4) minimum temperature. Two asterisks (**) denote a statistically significant correlation and a p-value of less than 0.01, while one asterisk (*) denotes a p-value of less than 0.05.

	Average Snow Depth Trend	**Total Snowfall Trend**	**Average Ablation Frequency Trend**	**Average Minimum Temperature Trend**	**Average Maximum Temperature Trend**
Average Snow Depth Trend	---	0.326*	0.711**	-0.553**	-0.300*
Total Snowfall Trend	0.326*	---	0.502**	-0.150	-0.252
Total Ablation Frequency Trend	0.711**	0.502**	---	-0.367**	-0.138
Average Minimum Temperature Trend	-0.553**	-0.150	-0.367**	---	0.603**
Average Maximum Temperature Trend	-0.300*	-0.252	-0.138	0.603**	---

Table 5. Pearson correlation coefficient of 1960-2009 November-April linear trends in Great-Lakes basin snow depth at the individual grid-cell scale and (1) total snowfall trends, (2) snow ablation frequency trends, (3) maximum temperature trends, and (4) minimum temperature trends. Two asterisks (**) denote a statistically significant correlation and a p-value of less than 0.01, while one asterisk (*) denotes a p-value of less than 0.05.