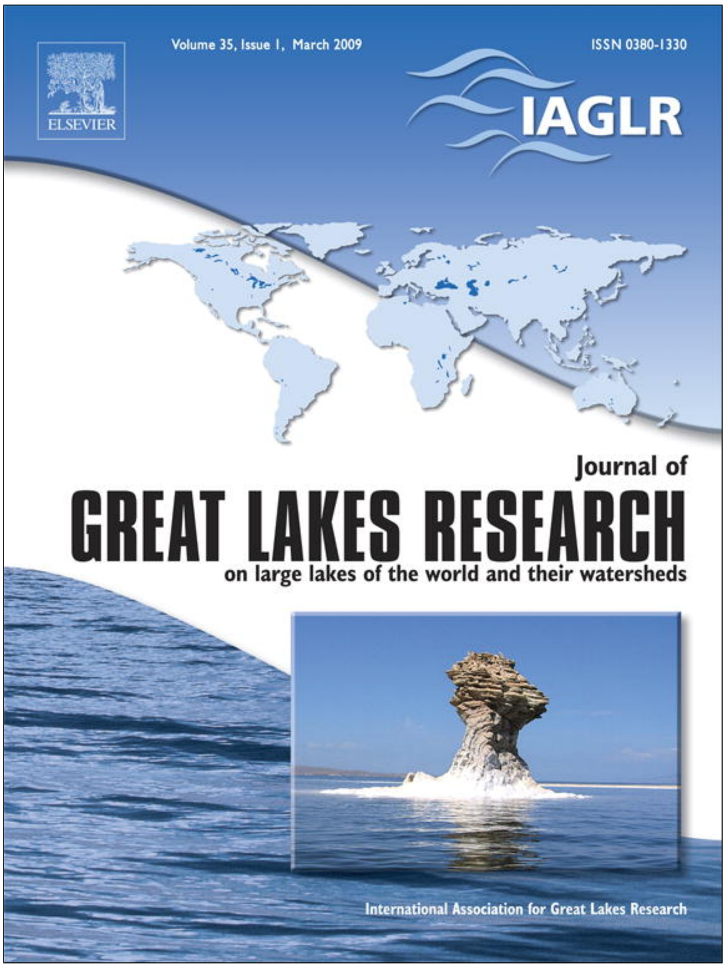
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A new look at lake-effect snowfall trends in the Laurentian Great Lakes using a temporally homogeneous data set

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ABSTRACT

Snowfall data are subject to quality issues that affect their usefulness for detection of climate trends. A new analysis of lake-effect snowfall trends utilizes a restricted set of stations identified as suitable for trends analysis based on a careful quality assessment of long-term observation stations in the lake-effect snowbelts of the Laurentian Great Lakes. An upward trend in snowfall was found in two (Superior and Michigan) of the four snowbelt areas. The trends for Lakes Erie and Ontario depended on the period of analysis. Although these results are qualitatively similar to outcomes of other recent studies, the magnitude of the upward trend is about half as large as trends in previous findings. The upward trend in snowfall was accompanied by an upward trend in liquid water equivalent for Superior and Michigan, while no trend was observed for Erie and Ontario. Air temperature has also trended upward for Superior and Michigan, suggesting that warmer surface waters and less ice cover are contributing to the upward snowfall trends by enhancing lake heat and moisture fluxes during cold air outbreaks. However, a more comprehensive study is needed to definitely determine cause and effect. Overall, this study finds that trends in lake-effect snowfall are not as large as was believed based on prior research.

Introduction

Snowfall in the North American Great Lakes region is enhanced by the rapid modification of cold air masses passing over the relatively warm waters of the Great Lakes. Heat and moisture fluxes from lake surfaces give rise to precipitation where none would have occurred without the presence of the Great Lakes or result in intensification of precipitation from larger-scale meteorological processes (e.g., Niziol, 1987; Niziol et al., 1995; Schroeder et al., 2006). For lakes Superior, Michigan, Huron, and Ontario, large ice-free areas remain throughout most winters (Assel, 2005) and the potential for lake enhancement of snowfall is present throughout the snowfall season. Lake Erie, however, will typically nearly freeze over in January or February (Assel, 2005), reducing the lake's influence on snowfall.

The impact of this regional process on snowfall may be partially or wholly independent of (or related in complex ways to) other influences on snowfall, such as the frequency, intensity, and paths of extratropical cyclones and mean changes in climate due to natural and anthropogenic causes. Thus, snowfall trends influenced by the lake effect may differ from trends at nearby locations unaffected by the lakes (Braham and Dungey, 1984; Norton and Bolsenga, 1993; Burnett et al., 2003).

Norton and Bolsenga (1993) identified a substantial upward trend in lake-effect snowfall near the Great Lakes from 1951 to 1980. Although not specifically focused on the lake-effect snowbelts, Leathers et al. (1993) also indicated a snowfall increase for the slightly longer period of 1945–1985 in the Great Lakes region. Burnett et al. (2003) found that trends at several stations in the lake-effect snowbelts in the Great Lakes Basin continued upward until the end of the century. Ellis and Johnson (2004) found upward trends over the 40-yr period from 1930 to 1970 at several long-term stations followed by little trend from 1970 onward.

Although these results are rather consistent, Kunkel et al. (2007) identified a number of issues concerning the quality of snowfall data. Changes in station location, observer, and measurement practices are

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among the factors that can introduce temporal inhomogeneities into the data time series. One of the examples they highlighted was an inconsistency in the snowfall time series of nearby stations in the Lake Superior snowbelt. Subsequently, Kunkel et al. (2009) performed a thorough quality assessment of snowfall data and identified a set of stations they believed to be relatively homogeneous and suitable for long-term trends analyses based on an expert assessment approach.

In this study, data from homogeneous stations located in areas where snowfall is enhanced by the lake effect were analyzed for the presence of long-term trends dating back to around the beginning of the 20th Century.

Methods

This analysis utilized a set of long-term stations identified as suitable for trends analysis by Kunkel et al. (2009). In that study, the snowfall and temperature data were obtained from the National Weather Service's Cooperative Observer Network (COOP). Routine keying of those data from 1948 and later began in 1948. Much of the pre-1948 daily data, including snowfall, has only recently become available in digital form, having been keyed under the Climate Database Modernization Program (Kunkel et al. 2005). The present study capitalizes on the expanded availability of data in digital form. The quality assessment of Kunkel et al. (2009) was limited to stations with less than 10% missing snowfall data during October through May in 1930–2004. Scott and Huff (1996) identified the areas where winter precipitation is enhanced by the lakes. Outside of these areas, stations typically receive less than 125 cm of snowfall. For this study, a station was considered to receive substantial lake-effect snow if it was located close to the southern or eastern (downwind) shore of one of the lakes within the areas identified by Scott and Huff (1996) as experiencing lake-enhanced winter precipitation and its mean annual snowfall was greater than 125 cm (a threshold chosen by examining the snowfall at stations outside of the lake-enhanced region). Of the stations meeting these two criteria, a total of 19 were judged by Kunkel et al. (2009) to be homogeneous, as assessed in the following manner (see Kunkel et al., 2009 for more detail).

Independent expert assessments of a station's quality were made by a team of scientists (note that the authors of this paper are the same as for the Kunkel et al., 2009 study) experienced in the use of snow data. The categorization of a station as homogeneous required that a majority of experts assess it as homogeneous. The experts had access to the results of several objective change point detection tests and graphical tools. A central assumption in this assessment is that multi-year fluctuations in snowfall will be spatially coherent and detectable at multiple stations.

To support the expert quality assessment, two graphs were prepared for each targeted long term station. One showed time series of annual snowfall for the station and the 14 nearest stations with at least 30 years of data. The second showed time series of the difference between the annual snowfall anomaly for the targeted station minus the annual snowfall anomaly for each of the same 14 nearest stations as shown in the annual snowfall time series graph. The times of station moves or observer changes recorded in station histories were noted on the graphs. In addition, objective screening techniques were used to detect change points and these were also shown on the graphs.

These graphs were examined independently by each expert and a judgment on a station's homogeneity was made based on the expert's knowledge and understanding of physically-reasonable behavior. The

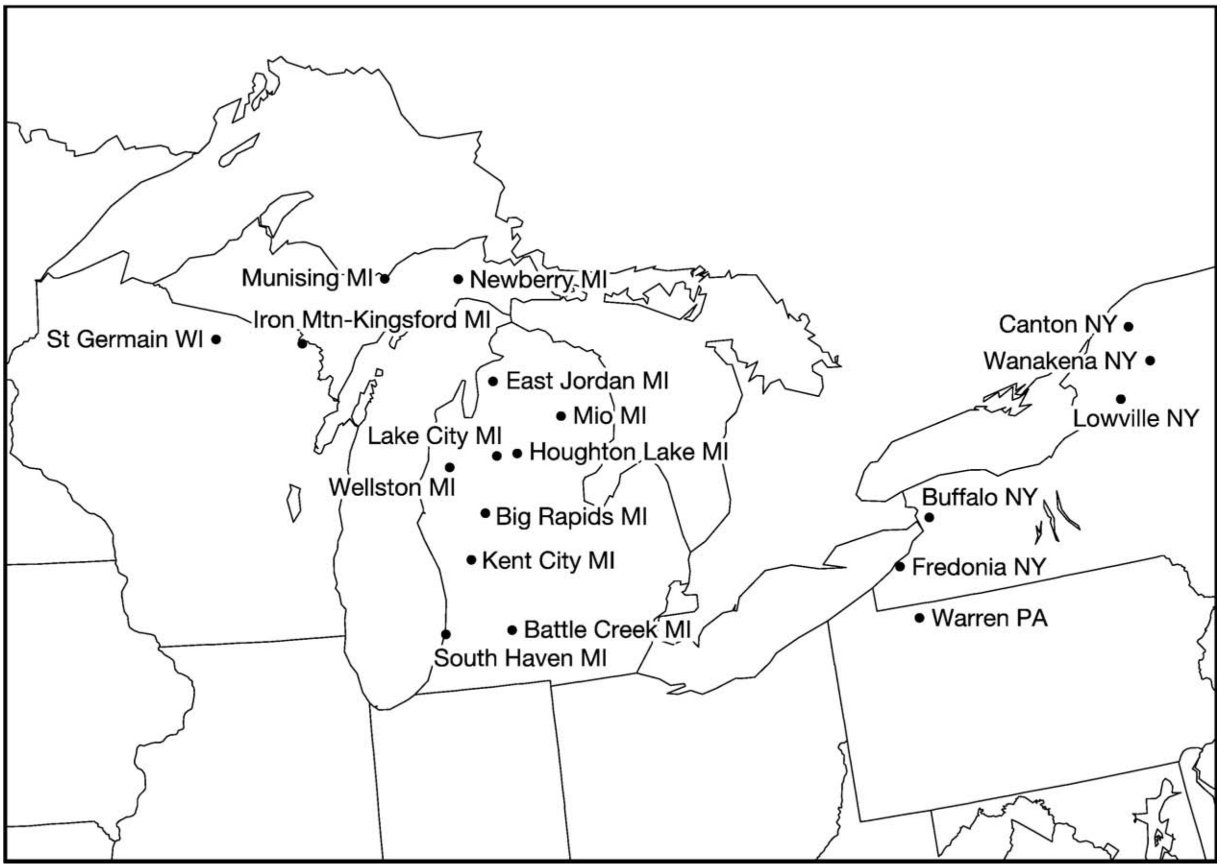

Fig. 1. Location and names of stations used in this study.

principal reasons for an expert's rejection of a station as homogenous were:

1. One or more large, relative to the natural spatial variations, step changes in the snowfall anomaly differences with adjacent stations, particularly if associated with documented station changes or objectively-determined change points.
2. A substantial portion of the missing data occurring at the ends of the time series.
3. A substantial long-term trend in the snowfall anomaly differences with all adjacent stations, that is, there is no confirming evidence of such a trend at any nearby station.
4. Step changes in the snowfall anomaly differences with adjacent stations across a data gap.

The 19 homogeneous stations (Fig. 1) are located on the south or east sides of Lakes Superior, Michigan, Erie, and Ontario. The National Climatic Data Center (NCDC) identification number, lake basin, mean annual snowfall, and period of available data are given in Table 1. Possible causes of a station's inhomogeneous behavior include station relocation, changes in instrument exposure, observer changes, and changes in observer practices. However, these are not always documented and in many cases stations exhibited clear inhomogeneous behavior without station history documentation that any of the above changes occurred.

A comparison of the stations used in previous studies with those identified as homogeneous for our study is relevant. Two of the four stations used in the Ellis and Johnson (2004) study (Ironwood, MI and Traverse City, MI) were assessed as unsuitable for trends analysis by Kunkel et al. (2009) and not used here. In the case of Ironwood, there was a large permanent increase in snowfall in the middle of the record centered in the 1960s that was not observed at nearby stations and there were documented station moves in 1955 and 1973 that could have resulted in inhomogeneities in the record. The lack of support at nearby stations combined with the near coincidence of station moves casts doubt on the physical reality of the increase, leading to the assessment of this station as inhomogeneous. In the case of Traverse City, there were no station moves, but there was a large increase in snowfall near the end of the record not seen at nearby stations. In addition, there were a number of missing years near the end of the record, leading to substantial uncertainty about recent behavior. Of the fifteen stations used by Burnett et al. (2003), the periods of record for eight were too short to qualify for use in our study. Five of the remaining seven were judged to be inhomogeneous. Two of these are Ironwood and Traverse City. The other three are Oswego, Rochester, and Watertown, all in New York. At both Oswego and Rochester, there were large snowfall increases coinciding with station moves, in the 1960s at Oswego and in the 1950s at Rochester. At Watertown, there was a shift around 1950 that coincided with a change in observer.

Snowfall anomalies were calculated for each station as the difference between the snowfall and the 1971–2000 mean, the current standard period used by NCDC and other national centers for calculating climatic normals. Water equivalent of the snowfall was also estimated as the sum of the liquid water equivalent on days with snowfall. This estimate is not quite accurate since the 24-hour liquid water equivalent may contain both rain and solid precipitation, but there is no general way to separate them. Another potential source of uncertainty in the water equivalent estimates is the use of the 10:1 ratio (e.g. 10 cm snowfall = 1 cm liquid water equivalent) for estimating water equivalent from snowfall observations. Kunkel et al. (2007) showed evidence that this estimation procedure was widely used early in the 20th Century but its usage decreased over time. Since the actual ratio is generally higher than 10:1 for most stations, decreasing usage over time can introduce an artificial downward trend in the water equivalent. To estimate the potential impact of its usage on water equivalent trends, Kunkel et al. (2007) developed an empirical relationship between this ratio and temperature that was specific to each station, using daily observations when the ratio was not 10:1 (implying that the two variables were measured independently). This empirical relationship (a function of temperature and snowfall) was then applied on each day when the ratio was 10:1 to estimate the water equivalent. Factors other than temperature (e.g. Baxter et al. 2005) also affect the ratio, but the lack of a full set of meteorological observations back to the late 1800s preclude more sophisticated schemes to estimate the water equivalent. In this article, the recorded water equivalent data and values adjusted for the use of the 10:1 ratio are compared and used as likely bounds on the actual trends.

Lake basin air temperature was calculated by averaging the temperature data for the chosen lake-effect snow stations. The study of Kunkel et al. (2005) had examined these temperature data, identifying and removing outliers. Although no additional assessment of the homogeneity of the temperature data was done for this study, the factors affecting temperature homogeneity are the same as for snowfall. Thus, the high quality of the snowfall data is highly likely to apply to the temperature data.

Results

Time series of total annual snowfall anomalies for individual stations were organized by lake (Fig. 2). The four stations in the Lake

Table 1
Station information, including name, cooperative observer station number, lake drainage basin, mean snowfall, and period of record (snow seasons)

Station name	ID number	Lake	1971–2000 mean (cm)	Period of record
Munising, MI	205690	Superior	372	1911(12)–2006(07)
Newberry State Hospital, MI	205816	Superior	290	1896(97)–2001(02)
Iron Mtn-Kingsford, MI	204090	Superior	162	1899(00)–2006(07)
St. Germain 2 SE, WI	477480	Superior	158	1912(13)–2006(07)
East Jordan, MI	202381	Michigan	271	1926(27)–2006(07)
Mio Hydro Plant, MI	205531	Michigan	151	1896(97)–1988(89)
Lake City Exp Farm, MI	204502	Michigan	195	1898(99)–2006(07)
Wellston Tippy Dam, MI	208772	Michigan	234	1918(19)–2006(07)
Houghton Lake 6 WSW, MI	203932	Michigan	140	1917(18)–2006(07)
Big Rapids Waterworks, MI	200779	Michigan	175	1896(97)–2006(07)
Kent City 2 SW, MI	204320	Michigan	140	1929(30)–2006(07)
Battle Creek 5 NW, MI	200552	Michigan	135	1895(96)–2000(01)
South Haven, MI	207690	Michigan	152	1895(96)–2006(07)
Buffalo WSCMO AP, NY	301012	Erie	246	1922(23)–2006(07)
Fredonia, NY	303033	Erie	215	1914(15)–2006(07)
Warren 1 SSW, PA	369298	Erie	158	1926(27)–2006(07)
Canton 3 SE, NY	301185	Ontario	224	1922(23)–2006(07)
Wanakena Ranger School, NY	308944	Ontario	325	1910(11)–2006(07)
Lowville, NY	304912	Ontario	304	1893(94)–2006(07)

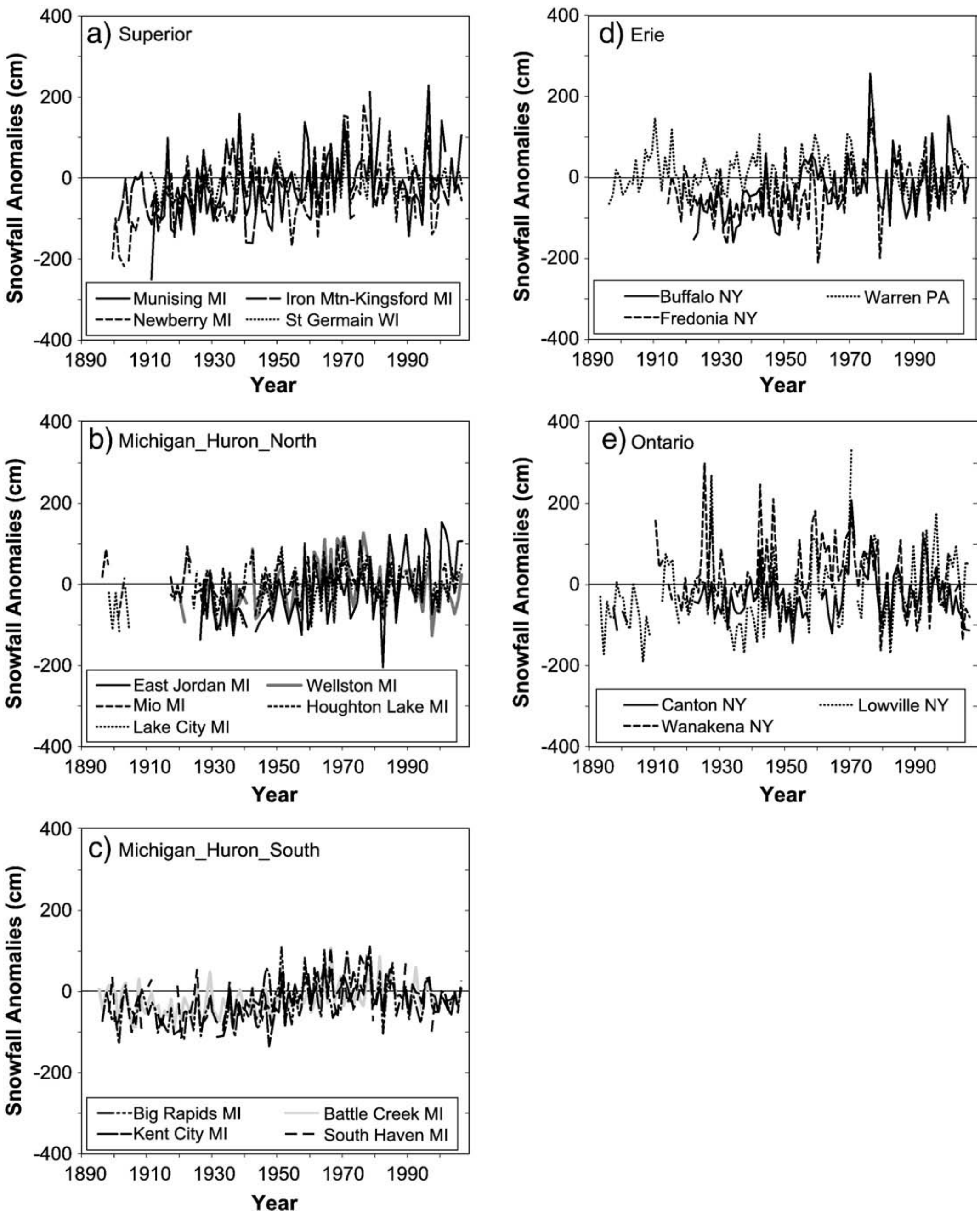

Fig. 2. Station time series of annual snowfall anomalies (cm) for stations in the a) Superior, b) Michigan–Huron North, c) Michigan–Huron South, d) Erie, and e) Ontario basins.

Superior snowbelt (Fig. 2a) showed qualitatively similar behavior in snowfall anomaly values. Although interannual variability dominated, there was an upward tendency in snowfall from the beginning of the record around 1900 to the 1930s and then little change thereafter. The nine stations in the Lake Michigan snowbelt (Figs. 2b and c) were also qualitatively similar in showing generally below average values before about 1950, and rising to near average after 1950. For Lake Erie (Fig. 2d), Warren (PA) and Buffalo (NY) showed similar values to that of the Lake Michigan stations. However, Fredonia (NY) exhibited little change in snowfall throughout the study period. For Lake Ontario (Fig. 2e), the absolute snowfall variability was higher than for the other lakes; a notable feature was an occasional year with very high snowfall totals. The three stations exhibited similar anomalies, except that values in Lowville were lower than that of the other two stations during the 1930s and 1940s. There was little evidence of a trend, although the snowfall totals for Lowville were quite low in the 1890s and 1900s; Lowville was the only station that measured snowfall during those two decades.

A composite snowfall time series for each lake was developed by averaging the anomalies for all stations in the lake-effect snowbelt of that lake. Then, a linear least-squares fit was done. The starting year for stations varied from the 1890s to the 1920s; thus, prior to the 1920s the composite time series represented fewer stations than for the 1920s onward. Therefore, the early portion of the composites was perhaps more uncertain, and, for this reason, two linear fits were made to each composite, one for the entire period of record and the other for the period 1925–2007. The resulting time series and linear fits are displayed in Fig. 3. In the case of Lakes Superior and Michigan–Huron, there were visible upward trends for both fitted periods. These trends were statistically significant at the 99% level except for the 1925–2007 trend for Lake Superior, which is smaller than the period of record trend and not quite statistically significant.

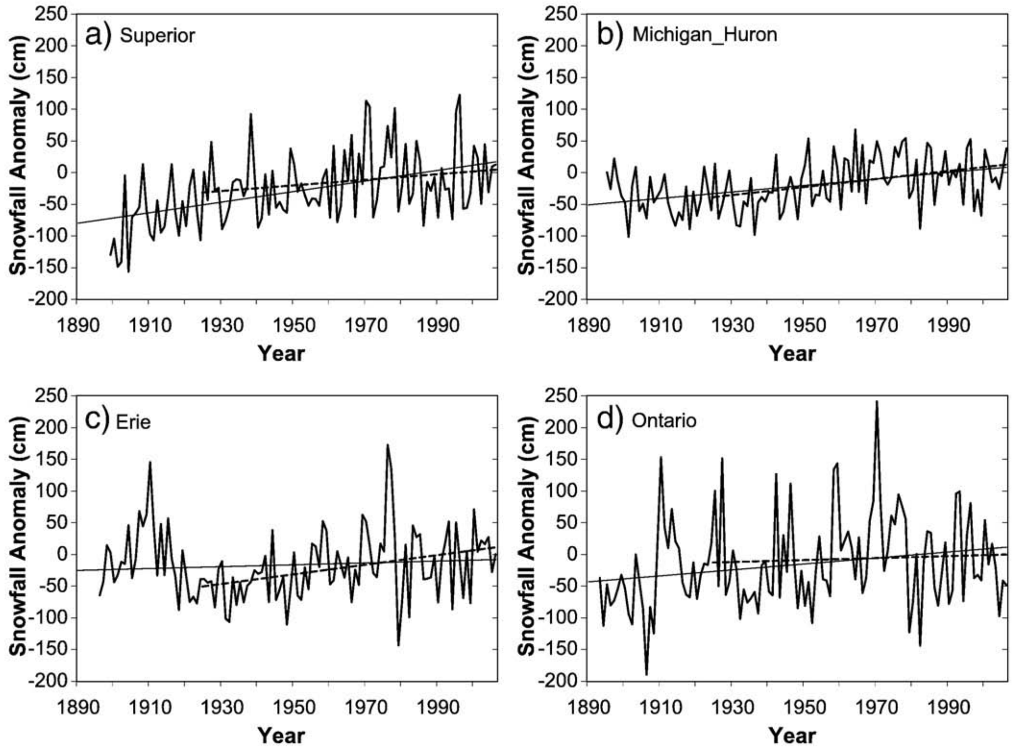

Fig. 3. Composite time series of annual snowfall anomalies (cm) for the a) Superior, b) Michigan–Huron, c) Erie, and d) Ontario basins. These were produced by averaging the anomalies of the stations displayed in Fig. 2. Lines represent a linear least-squares fit to the time series for the entire period of record (solid) and for 1925–2007 (dashed).

In the case of Lakes Erie and Ontario, only a single station was available prior to 1920 and trends for the two periods were quite different. The period of record trend for Lake Erie was not statistically significant but the 1925–2007 trend was upward and statistically significant at the 99% level. The results for Lake Ontario are just the opposite; the period of record trend was upward and statistically significant at the 95% level while the 1925–2007 trend was not statistically significant.

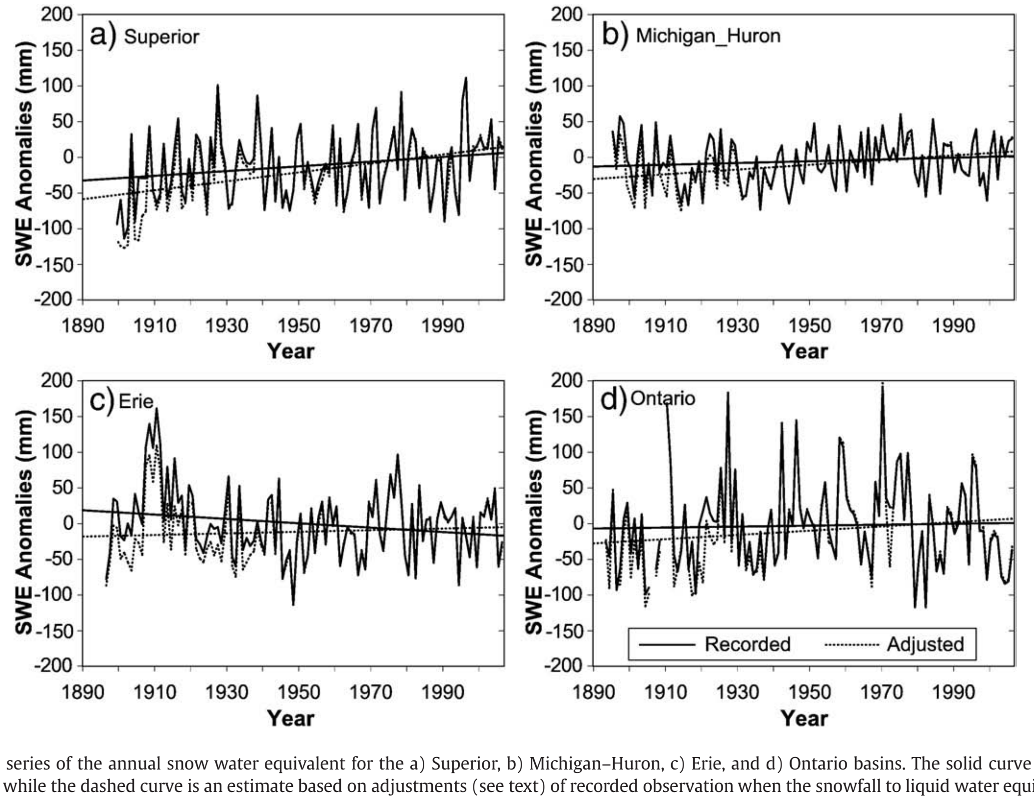

Fig. 4. Composite time series of the annual snow water equivalent for the a) Superior, b) Michigan–Huron, c) Erie, and d) Ontario basins. The solid curve is calculated from the recorded observations, while the dashed curve is an estimate based on adjustments (see text) of recorded observation when the snowfall to liquid water equivalent ratio is equal to 10. Lines represent a linear least-squares fit to the time series.

Similar to snowfall, composite time series of the water equivalent were developed by averaging the anomalies for all stations for each lake. The calculation was done both directly from the recorded values and from the adjusted values as described in the Methods section. For Lake Superior (Fig. 4a), there was an upward trend for both methods of estimating the water equivalent. The upward trend was larger for the adjusted estimate. Both trends were statistically significant, the recorded values at the 95% level and the adjusted estimates at the 99% level. For Lake Michigan (Fig. 4b), the trend of the adjusted estimates was upward and statistically significant at the 99% level, but there was no trend in the recorded values. For Lake Erie, there was a statistically significant (95% level) downward trend in the recorded values, but no trend in the adjusted estimates. For Lake Ontario, neither time series had a statistically significant trend, although the adjusted estimate had a visible upward trend.

Lake-effect snowfall is strongly affected by both air temperature and lake water temperature (Kunkel et al. 2002). Lake surface water temperature observations (available from the National Buoy Data Center) are at best available only back to the late 1970s, but air and lake surface water temperatures are strongly correlated and air temperature observations are available back to 1895. Thus the analysis here is restricted to correlations with air temperature. Fig. 5 displays time series of temperature for each of the lakes for the cold season (November–March) and the entire year. The cold season and annual anomalies were very close to each other for all lakes. There was an upward trend for Lakes Superior and Michigan from the beginning of the record to about mid-century, then a slightly downward trend into the 1970s, followed by a trend upward. For Lake Superior, a linear fit to the entire time series was statistically significant at the 99% level for annual temperature and at the 95% level for the cold season. For Lake Michigan, a linear fit was statistically significant at the 99% level for both annual and cold season temperatures. The behavior of Lake Erie air temperature was somewhat similar but the cold season trend was not statistically significant while the annual time series was significant at the 95% level. For Lake Ontario, the time series did not exhibit any visible trends and linear fits were not statistically significant.

Discussion

The snowfall data issues that Kunkel et al. (2007) discussed (e.g. lack of spatial consistency in temporal trends, temporal changes in observer practices such as use of the 10:1 ratio for estimation) present a challenge to trends analysis. However, careful quality-control procedures have identified a subset of long-term stations (some with records more than a century in duration) for which non-climatic temporal heterogeneities appear to be minimal.

In this study, an upward trend in snowfall was found in two of the four snowbelt areas (Lakes Superior and Michigan), both for a period of record analysis extending back to the turn of the 20th Century and for 1925–2007. The results for Lakes Erie and Ontario were mixed, depending on the period used for the trend analysis; in these two cases only a single station was available prior to 1920, heavily influencing the period of record trends. These results are qualitatively similar to other recent studies, but there are some differences. Ellis and Johnson (2004) showed results for Ironwood in the Superior snowbelt, indicating about a 50% (relative to the 1971–2000 normal) increase in snowfall during the 20th Century. However, Kunkel et al. (2009) judged this station to be temporally inhomogeneous and unsuitable for trends analysis and for this reason it was not included in our analysis. The four Superior stations that we considered suitable for trends analysis indicate a somewhat smaller increase in snowfall of about 25% for the same time period. Burnett et al. (2003) found an increase of more than one standardized anomaly during 1931–2001 for a set of stations representing all four snowbelts. An average of the four lake time series in Fig. 3, converted to standardized anomalies (not shown), indicates a smaller upward trend of 0.6 standardized anomalies. Most of the fifteen stations that Burnett et al. (2003) used were not employed in this study because Kunkel et al. (2009) judged them to be inhomogeneous or they failed our period of record or

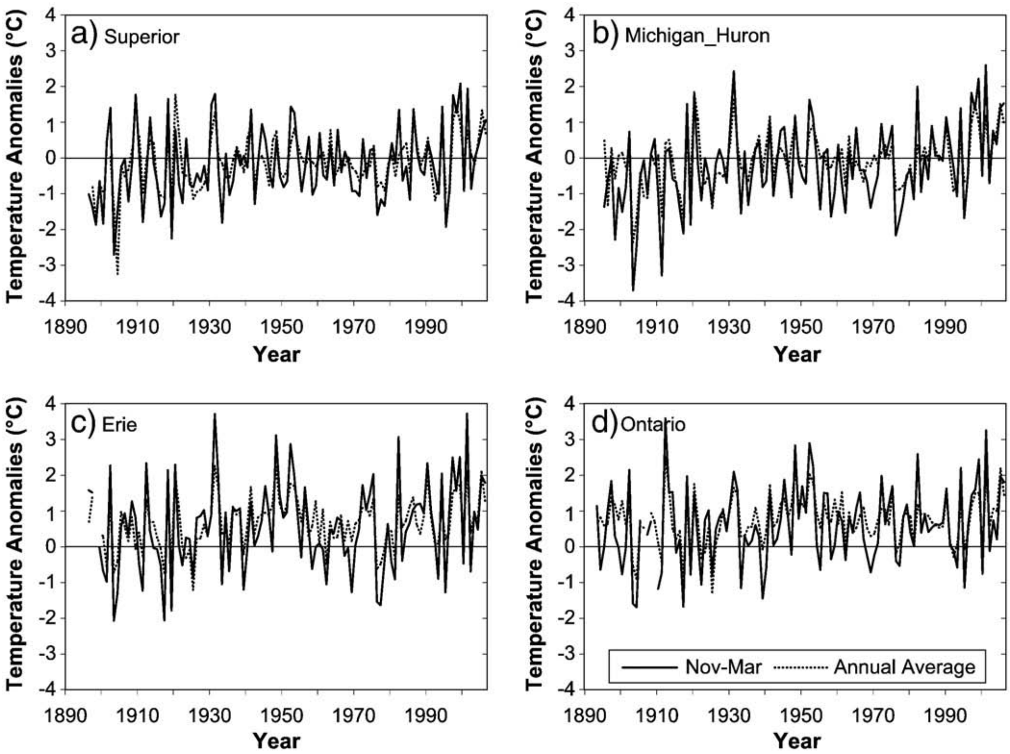

Fig. 5. Time series of average air temperature for November–March and for the entire year for the a) Superior, b) Michigan–Huron, c) Erie, and d) Ontario basins. These were calculated as the average of temperatures for the same set of stations used in the snowfall analysis.

missing data criterion. Thus, the use of a high-quality subset of long-term stations indicates that the magnitude of the upward trend was about half as large as found in recent studies.

The results for the liquid water equivalent of snowfall vary depending on whether the recorded values are used directly or an adjustment is made to compensate for the widespread use of the 10:1 ratio early in the period of record. Assuming that the adjusted values more closely reflect the actual physical changes in climate, the upward trend in snowfall is accompanied by an upward trend in liquid water equivalent for Superior and Michigan, while no trend is observed for Erie and Ontario.

A thorough investigation of the causes of these trends is beyond the scope of this study. However, a preliminary examination of the behavior of temperature, a key element affecting lake-effect events, provides insights into the consistency of the trends and points to future directions of research. Specifically, air temperature has also trended upward for Superior and Michigan; therefore, it is plausible that warmer surface waters and less ice cover (Assel et al. 2003) are contributing to the upward snowfall trends by enhancing lake heat and moisture fluxes during cold air outbreaks. However, lake-effect snowfall is affected both by regional conditions, such as the state of the lake surface, and by large-scale circulation patterns that modulate the frequency and intensity of cold air outbreaks and the thermodynamic characteristics of the atmosphere. Ellis and Leathers (1996) identified trends in surface synoptic types associated with lake-effect snowfall events although that study was limited to a 32-year period ending in the 1981–82 winter. A more comprehensive study is needed to definitely determine cause and effect for the results found here. Such a study, which ideally would probe the 3-dimensional structure of the atmosphere during potential lake-effect events, is now limited by sparse data availability for the early half of the 20th Century. However, an ongoing project to extend meteorological reanalysis products back to the late 19th Century (Compo et al. 2006) may largely overcome this limitation and provide an opportunity to expand our understanding of these observed trends.

Conclusions

Snowfall data are subject to quality issues that affect their usefulness for detection of climate trends. A new analysis of lake-effect snowfall trends utilizes a restricted set of stations identified as suitable for trends analysis based on a careful quality assessment of long-term observation stations in the lake-effect snowbelts of the Laurentian Great Lakes. Thus there is an enhanced level of confidence that the results presented here are due to physical changes in the climate system.

An upward trend in snowfall was found in two of the four snowbelt areas (Lakes Superior and Michigan), both for a period of record analysis extending back to the turn of the 20th Century and for 1925–2007. The results for Lakes Erie and Ontario are mixed, depending on the period of analysis. Although these results are qualitatively similar to outcomes of other recent studies, the magnitude of the upward trends is about half as large as trends in previous findings. The upward trend in snowfall was accompanied by an upward trend in liquid water equivalent for Superior and Michigan, while no trend was observed for Erie and Ontario. Air temperature has also trended upward for Superior and Michigan, suggesting that warmer surface waters and less ice cover are contributing to the upward snowfall trends by enhancing lake heat and moisture fluxes during cold air outbreaks. However, a more comprehensive study is needed to definitely determine cause and effect. Overall, this study finds that trends in lake-effect snowfall are not as large as was believed based on prior research.

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