

NOTES AND CORRESPONDENCE

**Increasing Great Lake–Effect Snowfall during the Twentieth Century:
A Regional Response to Global Warming?**

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11 July 2001 and 9 April 2003

ABSTRACT

The influence of the Laurentian Great Lakes on the climate of surrounding regions is significant, especially in leeward settings where lake-effect snowfall occurs. Heavy lake-effect snow represents a potential natural hazard and plays important roles in winter recreational activities, agriculture, and regional hydrology. Changes in lake-effect snowfall may represent a regional-scale manifestation of hemispheric-scale climate change, such as that associated with global warming. This study examines records of snowfall from several lake-effect and non-lake-effect sites throughout most of the twentieth century in order to 1) determine whether differences in snowfall trends exist between these settings and 2) offer possible linkages between lake-effect snow trends and records of air temperature, water temperature, and ice cover. A new, historic record of oxygen isotope [$\delta^{18}\text{O}_{(\text{CaCO}_3)}$] data from the sediments of three eastern Finger Lakes in central New York is presented as a means of independently assessing changes in Great Lakes lake-effect snowfall. Results reveal a statistically significant increasing trend in snowfall for the lake-effect sites, whereas no trend is observed in the non-lake-effect settings. The Finger Lake oxygen isotope record reflects this increase in lake-effect snow through a statistically significant trend toward lower $\delta^{18}\text{O}_{(\text{CaCO}_3)}$ values. Records of air temperature, water temperature, and lake ice suggest that the observed lake-effect snow increase during the twentieth century may be the result of warmer Great Lakes surface waters and decreased ice cover, both of which are consistent with the historic upward trend in Northern Hemispheric temperature due to global warming. Given projected increases in future global temperature, areas downwind of the Great Lakes may experience increased lake-effect snowfall for the foreseeable future.

1. Introduction

The Third Assessment Report of the Intergovernmental Panel on Climate Change (IPCC; Albritton et al. 2001) has recently concluded, as very likely, that (among other things) 1) global average surface temperature has increased over the twentieth century by $\sim 0.6^\circ\text{C}$; 2) global ocean heat content has increased since

the late 1950s; 3) the 1990s represent the warmest decade of the twentieth century; 4) there has been a reduction of ~ 2 weeks in the annual duration of lake ice cover in the Northern Hemisphere; and 5) most of the warming of the last 50 yr is attributable to human emissions of greenhouse gases. Continued anthropogenic influences on the earth's climate will likely contribute to significant regional variability in temperature and precipitation changes during the twenty-first century (Albritton et al. 2001). One area of concern is the heavily populated Great Lakes region of North America and the affect these large bodies of water will have on regional climate and hydrology. Because of their thermal capac-

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ity and climatological setting, the Great Lakes generate large quantities of lake-effect snowfall along their leeward margins during late autumn and winter when cold continental air masses travel across the ice-free lake surfaces (Eichenlaub 1979; Kunkel et al. 2000). The relative warmth of the lakes during this time of year, as compared to air temperatures, destabilizes the overlying atmosphere through vertical fluxes of heat and moisture from water to air (Niziol et al. 1995; Kristovich and Laird 1998). Heavy lake-effect snows can be natural hazards to life and property, affect air and surface traffic, create multimillion-dollar recreational industries, and influence agricultural activities, water supplies, and hydroelectric generation (Norton and Bolsenga 1993; Kunkel et al. 2000).

Using data from over 1230 weather stations around the Great Lakes, Norton and Bolsenga (1993) found significant increases in lake-effect snow between 1951 and 1980. This finding confirmed the earlier work of Eichenlaub (1970) and Braham and Dungey (1984) who also noted increases in lake-effect snowfall. Norton and Bolsenga (1993) suggested that colder air masses flowing across the lakes were responsible for the increased snowfall. A more recent study by Leathers and Ellis (1996) examined snowfall increases in the lee of Lake Erie and Lake Ontario using a synoptic climatological approach and found that winter circulation patterns most associated with lake-effect snow became more frequent between 1951 and 1982. These lake-effect circulation patterns featured westerly winds at 850 hPa, a superadiabatic lapse rate between the surface and 850 hPa, and air temperatures suitable for snowfall.

We have noticed that for Syracuse, New York (one of the snowiest cities in the United States, 25 km south-east of Lake Ontario), five of the highest seasonal snowfalls occurred during the 1990s, making the 1990s the snowiest decade ($\sim 351 \text{ cm yr}^{-1}$) of the twentieth century. In addition, the 2000/01 winter was the second snowiest season on record for Syracuse, receiving 0.5 cm less snowfall than the 1992/93 historical record of 488 cm. A review of the Syracuse snowfall record, provided by the U. S. National Climatic Data Center (NCDC), shows that snowfall at Syracuse has increased at a linear rate of 1.9 cm yr^{-1} (with significant inter-annual variation) since the early 1900s when maximum snowfalls were on the order of only 260 cm yr^{-1} (Fig. 1). Equally impressive was the late December 2001 lake snow event in the Buffalo–Niagara, New York, area, where 207 cm (81.5 in.) of snow fell during the 24–28 December period. According to the National Weather Service in Buffalo, two of the top four 24-h snowfall records were set during this event.

Intrigued by the results of Norton and Bolsenga (1993) and Leathers and Ellis (1996) and the strong upward trend in Syracuse snowfall, we have examined snowfall records from several lake-effect and non-lake-effect sites throughout the Great Lakes area with emphasis on the eastern lakes region. Our objectives were

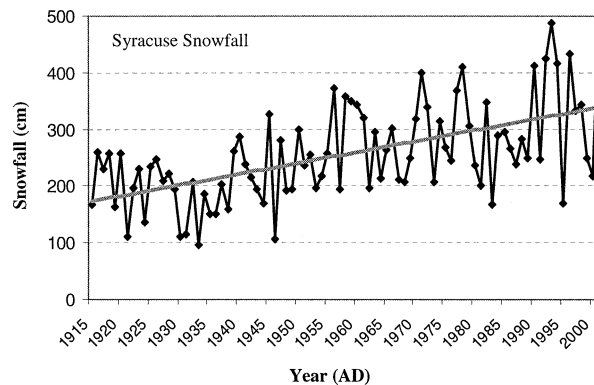


FIG. 1. Total Oct–Apr snowfall for Syracuse, NY, with statistically significant linear trend line. Note overall increase in snowfall since 1915 at an average rate of 1.9 cm yr^{-1} .

twofold: 1) to determine whether other lake-effect sites exhibit increases in snowfall similar to Syracuse; and 2) to examine snowfall at non-lake-effect sites to determine the degree to which the snowfall increases observed at the lake-effect sites are regional in character. Because lake-effect snow is strongly dependent on the temperature difference between air and water, the extent of ice cover, wind direction, and wind speed (via its influence on vertical heat and moisture flux), changes in lake-effect snow may represent regional-scale manifestations of broader-scale climate change.

The purpose of this note is to present our comparisons of the lake-effect and non-lake-effect snowfall records, and to offer possible connections between trends in lake-effect snow and previously documented records of air temperature, Great Lakes water temperature, and ice cover. We also present a newly derived historic record of calcite oxygen isotope data [$\delta^{18}\text{O}_{(\text{CaCO}_3)}$] from the sediments of three Finger Lakes in central New York. These lakes are located in a region strongly influenced by lake-effect snow and derive a considerable amount of water ($\sim 75\%$) from winter snowmelt (Michel and Kraemer 1995). Several studies have shown that water vapor derived from open surface evaporation off the Great Lakes is characterized by relatively low oxygen isotope ratios [$\delta^{18}\text{O}_{(\text{H}_2\text{O})}$] as compared to that derived from ocean sources (Gat et al. 1994; Machavaram and Krishnamurthy 1994, 1995). As a consequence, lake-effect snowfall derived from Great Lakes evaporation will have relatively low $\delta^{18}\text{O}_{(\text{H}_2\text{O})}$ values and thus influence the isotopic composition of the lake water and calcite [$\delta^{18}\text{O}_{(\text{CaCO}_3)}$] captured in the lake sediment. This record of $\delta^{18}\text{O}_{(\text{CaCO}_3)}$ should serve as an archive of lake-effect snow influence that is independent of the historical meteorological record.

2. Data

a. Cold season snowfall, total precipitation, and mean air temperature

Total cold season snowfall values were collected for 15 lake-effect sites and 10 non-lake-effect sites through-

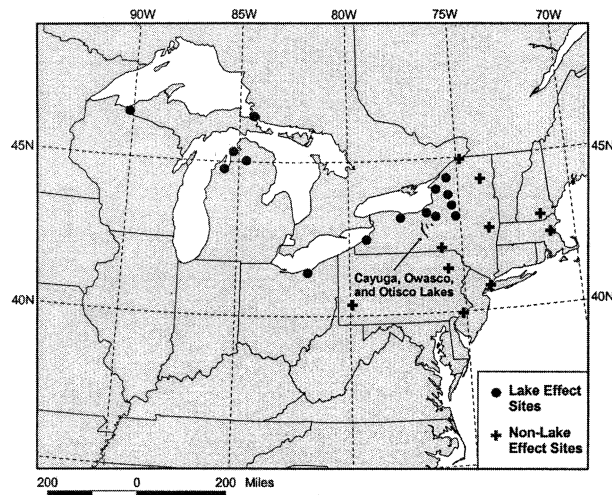


FIG. 2. Index map showing locations of Great Lakes lake-effect and non-lake-effect sites used in this study. Also shown are three eastern Finger Lakes (Cayuga, Owasco, Otisco) from which sediment box cores and stable oxygen isotope data were recovered.

out the Great Lakes region with emphasis on the eastern lakes (Fig. 2). These sites were chosen based on a review of the lake-effect snowfall maps presented by Norton and Bolsega (1993). The cold season total snowfall values were based on October–April data contained in the Monthly Summary Observations (digital database TD3220) distributed through the NCDC. The period of record for these data varies, with eight of the lake-effect sites and six of the non-lake-effect sites beginning in 1931. The remaining records begin in 1950.

Also included with these data are the station histories for each site, which document any changes in the location or elevation of the instrumentation. Of particular interest to this study is knowledge of any fundamental changes in the procedures used for the collection of snowfall data. For example, changes in the frequency of snow depth measurements can have an impact on the daily total because of snow compaction. Lake-effect snow is especially sensitive to compaction given its high solid–liquid ratio. We also contacted representatives from the National Weather Service Office in Buffalo, New York; the Northeast Regional Climate Center in Ithaca, New York; and the Michigan State Climatologist’s Office in East Lansing, Michigan, to inquire about known changes in snow depth observational practices during the period of record.

Each snowfall series was standardized and used to develop single composite records for lake-effect and non-lake-effect locations for 1931–2001. A simple linear regression technique was used to determine whether statistically significant trends exist in the data records. Also extracted from these monthly records were October–April mean air temperatures and total liquid precipitation. As was the case with the snowfall data, the temperature and precipitation information were stan-

dardized and composited into single records for lake-effect and non-lake-effect sites.

b. Oxygen isotopes for Cayuga, Owasco, and Otisco Lakes

Box cores were collected from Cayuga, Owasco, and Otisco Lakes (Fig. 2) between 1996 and 1998 in order to evaluate the $\delta^{18}\text{O}$ values of lake waters throughout the twentieth century (Lajewski et al. 2003). Cores were extruded vertically in the field at 1-cm intervals. The age of the core sediments was determined using standard radiogenic dating techniques involving a combination of ^{137}Cs and ^{210}Pb . Because ^{137}Cs is a fallout product of above ground nuclear weapons tests, the first appearance of ^{137}Cs in a sediment profile occurs in ~ 1950 and the peak abundance of ^{137}Cs occurs in 1963 (Krishnaswamy et al. 1971). Also, ^{210}Pb , which has a half-life of 22.26 yr, is useful in dating lake sediments less than 150 yr in age (Appleby and Oldfield 1978). Using these techniques, we were able to determine the sedimentation rates and age throughout each core.

The fine-grained ($<63\ \mu\text{m}$) authigenic calcite fraction from each sample was analyzed for stable oxygen isotope ratios [$\delta^{18}\text{O}_{(\text{CaCO}_3)}$] using a Kiel III carbonate preparation device directly coupled to a Finnigan MAT 252 stable isotope ratio mass spectrometer. Results are reported in delta notation relative to Vienna-Pee Dee Belenite (VPDB), which is the international standard for reporting oxygen isotopes. Comparisons with both external and internal lab standards indicate that precision is better than $\pm 0.1\%$.

Oxygen isotope values can vary as a function of temperature and/or moisture source (lake water $\delta^{18}\text{O}$). Previous studies in the central New York area have documented that historic $\delta^{18}\text{O}_{(\text{CaCO}_3)}$ values in lake sediment vary primarily as a function of the $\delta^{18}\text{O}$ of the lake water (Hilfinger et al. 2001; Kirby et al. 2001) rather than with temperature. Therefore, the Owasco, Otisco, and Cayuga Lake $\delta^{18}\text{O}_{(\text{CaCO}_3)}$ should be most strongly associated with the $\delta^{18}\text{O}$ of the precipitation and runoff entering the lake system. As was the case with the snowfall data, a simple linear regression technique was used to determine whether the isotope data revealed statistically significant trends during the periods of data for each lake.

3. Results and discussion

The composite cold season snowfall totals for lake-effect and non-lake-effect stations are shown in Fig. 3. The lake-effect sites (Fig. 3a) reveal an overall statistically significant increasing trend since 1931 (P value = 0.0000). By contrast, non-lake-effect stations (Fig. 3b) show no significant linear trend. An examination of the linear trend in snowfall for all of the lake-effect records (Table 1) shows that 11 of the 15 lake-effect sites exhibit significant (P value < 0.05) upward trends. These results suggest that recent increases in snowfall

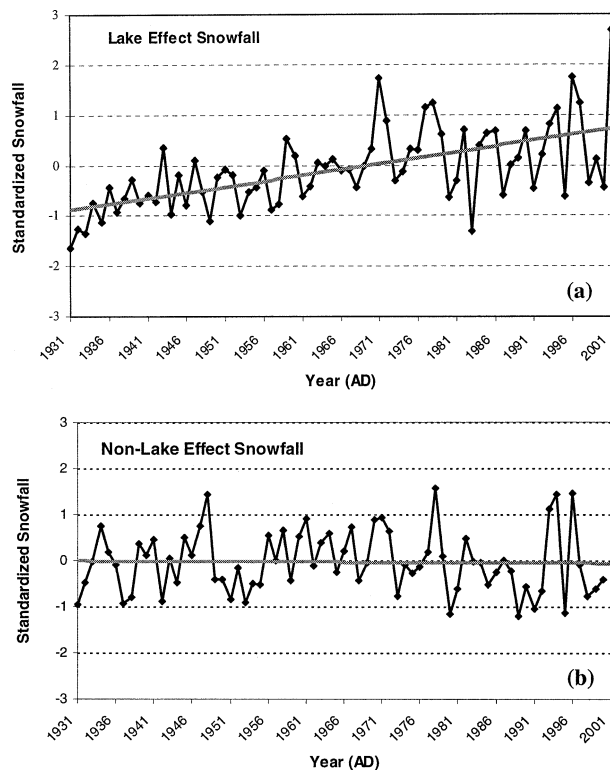


FIG. 3. (a) Composite standardized Oct–Apr total snowfall for lake-effect sites for 1931–2001. The gray line represents the linear trend in snowfall. (b) Same as (a) except for non-lake-effect sites.

observed in the lake-effect records are probably not the result of changes in processes that produce regional-scale snowfall, such as traveling cyclonic disturbances. Otherwise, similar increases in snowfall would be observed in the non-lake-effect record as well.

As already noted, one might question whether the increase in snowfall at lake-effect sites might be attributed to changes in snow observation practices or other site-specific artifacts. In order to address this concern, we examined several pieces of information. A review of the station history records does reveal a number of changes in the location and elevation of each station. However, these changes do not occur in a pattern that would clearly explain the upward trends in snowfall that are observed at the lake-effect sites. Furthermore, the representatives we spoke with from the National Weather Service, Northeast Regional Climate Center, and Michigan State Climatologist's Office were unaware of any systematic changes in snow observational practices that would create the strong upward trend seen during the past 70 yr.

We also compared the composite snowfall and total precipitation records for the lake-effect and non-lake-effect sites (Figs. 4a and 4b). The total precipitation for the lake-effect sites exhibits a statistically significant upward trend (P value = 0.038) and indicates that the observed snow increases are accompanied by increases

TABLE 1. Regression coefficients and significance values for the linear trends in snowfall at each of the lake-effect sites. Statistically significant trends (P value < 0.05) are shown in italics.

Site	Regression coefficient	P value
Boonville, NY	-0.0074	0.4403
Charlevoix, MI	<i>0.0307</i>	<i>0.0000</i>
Cleveland, OH	0.0162	0.0998
Fredonia, NY	<i>0.0213</i>	<i>0.0003</i>
Gaylord, MI	<i>0.0194</i>	<i>0.0265</i>
Gouverneur, NY	<i>0.0163</i>	<i>0.0243</i>
Ironwood, MI	<i>0.0194</i>	<i>0.0013</i>
Lowville, NY	<i>0.0145</i>	<i>0.0211</i>
Oswego, NY	<i>0.0251</i>	<i>0.0067</i>
Rochester, NY	0.0135	0.1453
Sault Ste. Marie, MI	<i>0.0252</i>	<i>0.0171</i>
Syracuse, NY	<i>0.0225</i>	<i>0.0000</i>
Traverse City, MI	<i>0.0257</i>	<i>0.0001</i>
Utica, NY	0.0127	0.2516
Watertown, NY	<i>0.0268</i>	<i>0.0059</i>

in the liquid totals as well. No such trend in total precipitation exists in the non-lake-effect composite data. Also interesting is the larger positive upward slope seen in the lake-effect snow data when compared to the total precipitation trend. This comparison might suggest an increase in the snow–liquid ratios over the period of record. This observation is consistent with increased

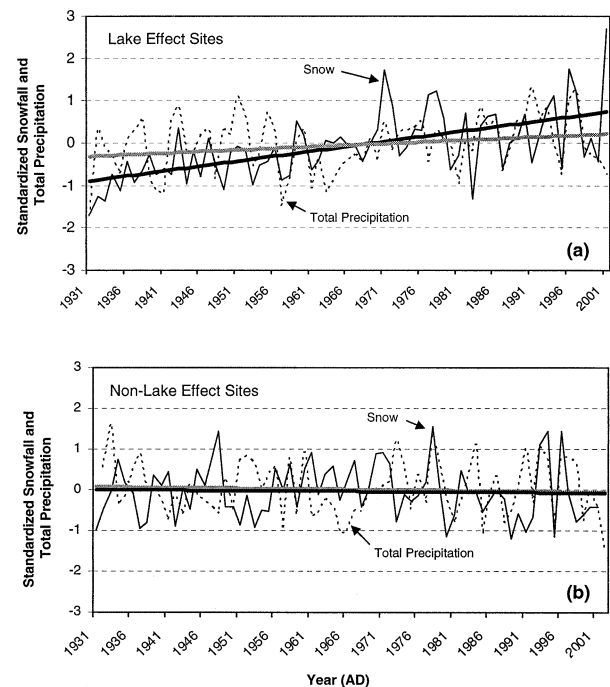


FIG. 4. (a) Composite standardized Oct–Apr snowfall and total precipitation for lake-effect sites for 1931–2001. The dark line represents the linear trend in snowfall whereas the gray line shows the linear trend for precipitation. (b) Same as (a) except for non-lake-effect sites.

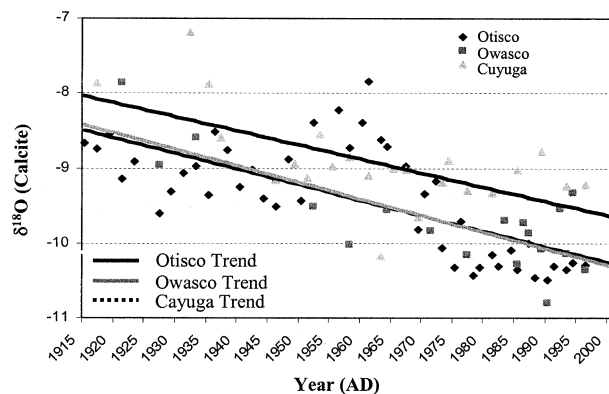


FIG. 5. Historic $\delta^{18}\text{O}$ calcite trends from Cayuga, Owasco, and Otisco Lake sediments between 1915 and 1998. Note decreasing $\delta^{18}\text{O}$ values for all three lakes as a result of increased lake-effect snowfall in the eastern Finger Lakes during the twentieth century.

lake-effect snow contributions, which typically exhibit larger snow–liquid ratios.

Finally, an enhancement in lake-effect snowfall during the twentieth century is also supported by $\delta^{18}\text{O}_{(\text{CaCO}_3)}$ data from the eastern Finger Lakes (Fig. 5). The isotopic data for each lake exhibit statistically significant trends toward lower $\delta^{18}\text{O}_{(\text{CaCO}_3)}$ values since 1915 (P value_(Otisco) = 0.0000; P value_(Owasco) = 0.0001; P value_(Cayuga) = 0.0014). This finding is consistent with increased lake-effect snow during this period. Because lake-effect snow is derived largely from Great Lakes evaporation, which yields water vapor with lower $\delta^{18}\text{O}_{(\text{H}_2\text{O})}$ values than ocean-derived water vapor (Gat et al. 1994; Machavaram and Krishnamurthy 1994, 1995), increases in lake-effect snow should result in spring runoff that also has lower $\delta^{18}\text{O}_{(\text{H}_2\text{O})}$ values. The isotopic composition of this runoff is then reflected in the $\delta^{18}\text{O}_{(\text{CaCO}_3)}$ that is precipitated from lake surface waters and deposited in bottom sediments.

Changes in precipitation at the lake-effect sites could potentially reflect some variation in the availability or type of cloud condensation nuclei (CCN). Such a change would have to be limited in some way to the lake-effect setting given the lack of snow and precipitation increases in non-lake-effect areas. Hudson (1993) highlighted the uncertainties regarding the role that CNN play in driving precipitation variability. A more recent modeling study by Feingold and Kreidenweis (2000) concluded that CNN can both enhance and suppress the number of cloud droplets and that these processes are dependent upon CNN distribution and cloud updraft velocities. Rosenfeld's (2000) study of air pollution and precipitation concluded that pollution sources of CNN suppress precipitation.

The possibility remains that changes in CNN may be reflected in the precipitation variability observed in this study. However, because of conflicting bodies of evidence as to whether changes in CNN enhance or suppress precipitation and uncertainties as to how CNN

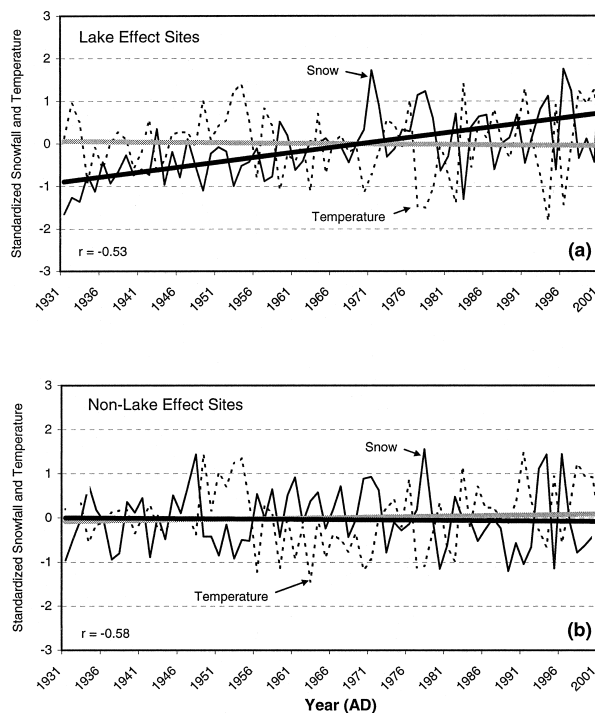


FIG. 6. (a) Composite, standardized Oct–Apr average temperature and total snowfall for lake-effect sites for 1931–2001. The dark line represents the linear trend for snowfall, whereas the gray line shows the linear trend for temperature. (b) Same as (a) except for non-lake-effect sites.

variations operate within lake-effect clouds, we favor the hypothesis that the increased lake-effect snowfall is related to a change in one or more of the meteorological or lake thermal conditions that influence lake-effect precipitation. These conditions include the temperature of the air moving across the lake, lake water surface temperature, lake ice cover, surface wind speed, wind direction, and the frequency with which lake-effect snowfall events occur (Lavoie 1972; Wilson 1977; Leather and Ellis 1996; Kunkel et al. 2002).

Norton and Bolsegna (1993) hypothesized that the lake-effect snow increases were related to decreasing air temperature. In order to explore this possibility, we examined the composite cold season air temperature records for our lake-effect and non-lake-effect sites. These temperature data, along with their associated snowfall records, are shown in Figs. 6a and 6b. Neither temperature record exhibits a significant linear trend. When compared with the snow records, statistically significant negative relationships do emerge in the lake-effect ($r = -0.53$, P value = 0.0000) and non-lake-effect ($r = -0.58$, P value = 0.0000) settings. Although cooler temperatures are clearly associated with increased snowfall, changes in mean winter temperature cannot be used to explain the upward trend in snowfall at the lake-effect sites. The overall negative relationship between temperature and snowfall at all sites may be linked to cold air advective processes associated with synoptic-scale

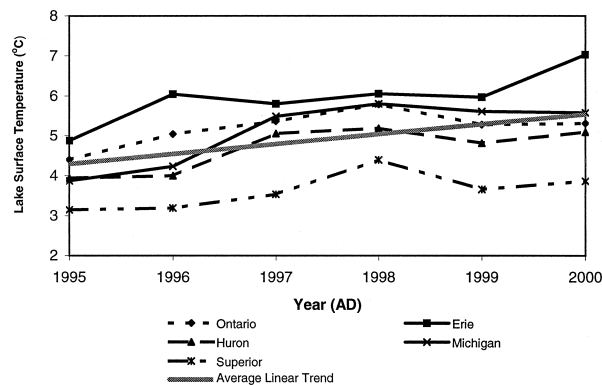


FIG. 7. Oct–April average surface water temperatures for the Great Lakes for 1995–2000. The gray line represents the linear trend for the composite standardized record for all the Great Lakes.

events during which all stations receive snow. Alternatively, the snow itself may serve to reduce temperatures via localized changes in surface radiative processes such as those described by Groisman et al. (1994). Although beyond the scope of this study, one might hypothesize that individual lake-effect snow events may be associated with increasingly cooler air temperatures for those days during which lake effect is occurring. If this condition is true, its impact is not being expressed in the mean winter temperature record.

As an alternative hypothesis, we suggest that increased lake-effect snowfall is the result of changes in Great Lakes whole-lake thermal characteristics that involve warmer lake surface waters and a decrease in lake ice cover. Evidence that the Great Lakes are warming comes from a variety of direct and proxy data. A recent record of satellite derived Great Lakes surface temperatures from the National Oceanic and Atmospheric Administration (NOAA) CoastWatch Program provides temperatures for the ice-free portions of the Great Lakes since 1995. Using these data, the snow season average water temperatures were determined for each of the Great Lakes (Fig. 7). Also included in Fig. 7 is the linear trend in the composite temperature record for all the Great Lakes. Although this dataset is limited, it does show a statistically significant upward trend (P value = 0.0264) in snow season lake surface temperature since the mid-1990s. Using a much longer record of water temperatures collected at seven nearshore water intake sites, McCormick and Fahnenstiel (1999) found warming at five of the sites during the twentieth century. Based on these warming trends, McCormick and Fahnenstiel (1999) concluded that the summer stratified season for the lakes has increased by ~ 14 – 18 days since the beginning of the twentieth century. In addition, ice record data from the Great Lakes region indicate that the beginning of the ice season has started increasingly later and ended earlier since the 1850s (Assel and Robertson 1995). This finding is consistent with data for the entire Northern Hemisphere, which shows that first

freeze dates averaged 5.8 days $(100 \text{ yr})^{-1}$ later and ice breakup dates 6.5 days $(100 \text{ yr})^{-1}$ earlier since 1850 (Magnuson et al. 2000).

Collectively, these data indicate a general warming and increased whole-lake heat content for the Great Lakes, similar to that reported by Albritton et al. (2001) for the oceans since 1950. These changes in the thermal characteristics of the Great Lakes may be contributing to the significant increases in the amount of lake-effect snowfall along the leeward margins of the lakes. This change in thermal character does not appear to be related to winter air temperatures, which does not show an upward trend (Fig. 6). Given the thermal capacity and lagged temperature response of the lakes, it is likely that air temperature conditions in the other seasons play a role in driving the thermal characteristics of the lakes during winter. Earlier work by Bolsegna and Norton (1993) document upward trends in air temperature during the spring, summer, and autumn seasons between 1901 and 1987. Increases in air temperature during these seasons may be having a more significant impact on the Great Lakes water temperatures and lake-effect snowfall than are the cold season air temperatures observed during the snow.

The recognition that significant local changes in lake-effect precipitation can accompany more modest regional-scale climate change was made by Davis et al. (2000) in a pollen-based study of Holocene climate in the western Great Lakes. Their study revealed a clear distinction between Holocene precipitation patterns at sites with strong Great Lakes influence and those not influenced by the lakes. Sharp increases in precipitation throughout the lake-effect sites during the late Holocene relative to non-lake-effect sites with similar regional climate profiles, support the conclusion that lake-effect snowfall is influenced by larger-scale climate variability and may be especially sensitive to global warming. In fact, Davis et al. (2000, p. 968) concluded that “. . . lake-effect snowfall is sensitive to continental-scale changes in climate and could be affected by future climate change.”

Considering that the IPCC is projecting a 1.4° – 5.8°C increase in global surface temperatures by the end of the twenty-first century (Albritton et al. 2001), areas downwind of the Great Lakes may experience increased lake-effect snowfalls for the foreseeable future. Such an increase would continue as long as winter air temperatures remain favorable for snow development. Using a general circulation modeling approach, Kunkel et al. (2002) addressed the question of how increasing atmospheric CO_2 and its associated global warming might influence Great Lakes lake-effect snowfall. These authors concluded that, by the end of the twenty-first century, the number of lake-effect snow events would decrease significantly near the southern Great Lakes because of fewer below freezing days. However, it seems likely that lake-effect snow conditions may become more favorable in the near future as lake temperatures

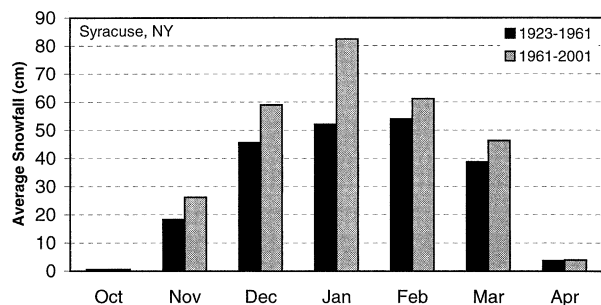


FIG. 8. Oct–Apr average monthly snowfall for Syracuse, NY, for the periods 1923–61 and 1962–2001.

rise while winter air temperatures remain cold enough to produce snow.

4. Future research

The data and interpretations presented in this paper represent some of the first steps in the broader understanding of the connections between Great Lakes lake-effect snowfall, temperature, and regional-scale climate change. Moreover, we are especially interested in the impact of observed and predicted global warming on lake-effect processes. A more thorough examination of the historical snowfall record and its relationships with key processes involved in lake-effect snow development represent the next steps in this study. Questions and issues yet to be addressed include the following:

- 1) What is the intraseasonal structure of the historical lake-effect snow increases throughout the entire Great Lakes region? Are these increases related to changes in early snowfall or has snow increased throughout all cold season months? For example, average monthly snowfall at Syracuse for the periods 1923–61 and 1962–2001 is shown in Fig. 8. These data show that snowfall increases have occurred in all months. However, the month of greatest snowfall has shifted from February in the earlier part of the record to January in the later years. Might such a shift be related to warmer lake temperatures during January when air masses moving across the Great Lakes are potentially very cold?
- 2) Future work should focus on a more thorough examination of available instrumental and remotely sensed records of Great Lakes thermal characteristics, with special focus on the relationships between snowfall and lake surface temperatures, water stratification features, and whole-lake heat content. Also important is the examination of available records of lake ice to address the role that ice cover variability plays in driving observed lake-effect snowfall trends.
- 3) What is the climatology of individual lake-effect snow events and how have the severity and frequency of such events changed over time? Such a climatology, which is beyond the monthly and sea-

sonal resolution presented in this work, will provide insight into the degree to which snowfall increases are the result of an enhancement of lake-effect processes or a more frequent occurrence of lake-effect events, similar to that proposed by Leathers and Ellis (1996).

Increasing snowfall totals within Great Lakes lake-effect snowfall regions throughout the twentieth century, and its likely connection with global warming processes, offers insight into the ways in which global/regional-scale climate variability can influence local-scale climates. Furthermore, the potential for continued warming in the future poses significant implications for communities and hydrologic systems that are influenced by lake-effect precipitation. Among such implications include increased expenditures for snow removal, increases in severe spring flooding, changes in soil moisture, higher lake and river levels, and recreational impacts. The continued study of lake-effect snow and the ways in which it is influenced by broader-scale climate change is justified by the role that lake-effect precipitation plays throughout the entire Great Lakes region.

Acknowledgments. We would like to thank the National Weather Service in Buffalo, New York, The Northeast Regional Climate Center in Ithaca, New York, and the Michigan State Climatologist's Office in East Lansing, Michigan, for their assistance in addressing changes in snow depth observation practices. We would also like to thank the Colgate University Research Council for supporting this work.

REFERENCES

- Albritton, D. L., and Coauthors, 2001: Summary for policy makers. *Climate Change 2001: The Scientific Basis*, J. T. Houghton et al., Eds., Cambridge University Press. [Available online at <http://www.ipcc.ch>.]
- Appleby, P. G., and F. Oldfield, 1978: The calculation of lead-210 dates assuming a constant rate of supply of unsupported lead-210 to the sediment. *Catena*, **5**, 1–8.
- Assel, R. A., and D. M. Robertson, 1995: Changes in winter air temperatures near Lake Michigan, 1851–1993, as determined from regional lake-ice records. *Limnol. Oceanogr.*, **40**, 165–176.
- Bolsenga, S. J., and D. C. Norton, 1993: Great Lakes air temperature trends for land stations, 1901–1987. *J. Great Lakes Res.*, **19**, 379–388.
- Braham, R. R., and M. J. Dungey, 1984: Quantitative estimates of the effect of Lake Michigan on snowfall. *J. Climate Appl. Meteor.*, **23**, 940–949.
- Davis, M., C. Douglas, R. Calcote, K. L. Cole, M. G. Winkler, and R. Flakne, 2000: Holocene climate in the western Great Lakes National Parks and lakeshores: Implications for future climate change. *Conserv. Biol.*, **14**, 968–983.
- Eichenlaub, V. L., 1970: Lake effect snowfall to the lee of the Great Lakes: Its role in Michigan. *Bull. Amer. Meteor. Soc.*, **51**, 403–412.
- , 1979: *Weather and Climate of the Great Lakes Region*. University of Notre Dame Press, 335 pp.
- Feingold, G., and S. Kreidenweis, 2000: Does cloud processing of aerosol enhance droplet concentration? *J. Geophys. Res.*, **105D**, 351–361.

- Gat, J. R., C. J. Bowser, and C. Kendall, 1994: The contribution of evaporation from the Great Lakes to the continental atmosphere: Estimate based on stable isotope data. *Geophys. Res. Lett.*, **21**, 557–560.
- Groisman, P. Y., T. R. Karl, and R. W. Knight, 1994: Observed impact of snow cover on the heat balance and the rise of continental spring temperatures. *Science*, **263**, 198–200.
- Hilfinger, M. F., IV, H. T. Mullins, A. Burnett, and M. E. Kirby, 2001: A 2500 year sediment record from Fayetteville Green Lake, New York: Evidence for anthropogenic impacts and historic isotope shift. *J. Paleolimnol.*, **26**, 293–305.
- Hudson, J. G., 1993: Cloud condensation nuclei. *J. Appl. Meteor.*, **32**, 596–607.
- Kirby, M. E., H. T. Mullins, W. P. Patterson, and A. Burnett, 2001: Lacustrine isotopic evidence for multi-decadal natural climate variability related to the circumpolar vortex over the NE USA during the past millennium. *Geology*, **29**, 807–810.
- Krishnaswamy, S., D. Lal, J. M. Martin, and M. Meybeck, 1971: Geochronology of lakes. *Earth Planet. Sci. Lett.*, **11**, 407–414.
- Kristovich, D. A. R., and N. F. Laird, 1998: Observations of widespread lake-effect cloudiness: Influences of lake surface temperature and upwind conditions. *Wea. Forecasting*, **13**, 811–821.
- Kunkel, K. E., N. E. Wescott, and D. A. R. Kristovich, 2000: Climate change and lake-effect snow. *Preparing for a Changing Climate: The Potential Consequences of Climate Variability and Change*, P. J. Sousounis, and J. M. Bisanz, Eds., U.S. EPA, Office of Research and Development Global Change Research Program, 25–28.
- , —, and —, 2002: Assessment of potential effects of climate change on heavy lake-effect snowstorms near Lake Erie. *J. Great Lake Res.*, **28**, 521–536.
- Lajewski, C. K., H. T. Mullins, W. P. Patterson, and C. W. Callinan, 2003: Historical calcite record from the Finger Lakes, New York: Impact of acid rain on buffered terrane. *Geol. Soc. Amer. Bull.*, **115**, 373–384.
- Lavoie, R. L., 1972: A mesoscale model of lake effect snowstorms. *J. Atmos. Sci.*, **29**, 1025–1040.
- Leathers, D. J., and A. W. Ellis, 1996: Synoptic mechanisms associated with snowfall increases to the lee of Lakes Erie and Ontario. *Int. J. Climate*, **16**, 1117–1135.
- Machavaram, M. V., and R. V. Krishnamurthy, 1994: Survey of factors controlling the stable isotope ratios in precipitation in the Great Lakes region, USA. *Isr. J. Earth Sci.*, **43**, 195–202.
- , and —, 1995: Earth surface evaporative process: A case study from the Great Lakes region of the United States based on deuterium excess in precipitation. *Geochim. Cosmochim. Acta*, **59**, 4279–4283.
- Magnuson, J. J., and Coauthors, 2000: Historical trends in lake and river ice cover in the Northern Hemisphere. *Science*, **289**, 1743–1746.
- McCormick, M. J., and G. L. Fahnenstiel, 1999: Recent climatic trends in nearshore water temperatures in the St. Lawrence Great Lakes. *Limnol. Oceanogr.*, **44**, 530–540.
- Michel, R. L., and T. F. Kraemer, 1995: Use of isotopic data to estimate water residence times of the Finger Lakes, New York. *J. Hydrol.*, **164**, 1–18.
- Niziol, T. A., W. R. Snyder, and J. S. Waldstreicher, 1995: Winter weather forecasting throughout the eastern United States. Part IV: Lake effect snow. *Wea. Forecasting*, **10**, 61–77.
- Norton, D. C., and S. J. Bolsenga, 1993: Spatiotemporal trends in lake effect and continental snowfall in the Laurentian Great Lakes, 1951–1980. *J. Climate*, **6**, 1943–1956.
- Rosenfeld, D., 2000: Suppression of rain and snow by urban and industrial air pollution. *Science*, **287**, 1793–1796.
- Wilson, J. D., 1977: Effect of Lake Ontario on precipitation. *Mon. Wea. Rev.*, **105**, 207–214.