Spatiotemporal Trends in Lake Effect and Continental Snowfall in the Laurentian Great Lakes, 1951–1980

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ABSTRACT

A new raster-based monthly snowfall climatology was derived from 1951–1980 snowfall station data for the Laurentian Great Lakes. An automated methodology was used to obtain higher spatial resolution than previously obtained. The increase in resolution was attained by using all available monthly snowfall data from over 1230 stations per year combined with a monthly time step to produce high-resolution grids. These monthly grids were combined to produce snow-year grids. Multiyear average grids were created and compared. This technique minimizes traditional problems associated with missing data and variable length station records.

The three 10-year average distribution maps presented here indicate a period of increasing snowfall. Windowing of the 30 seasonal grids revealed that increasing snowfall was attributable to an increase in lake effect snowfall and not to continental snowfall. The Great Lakes drainage basin was evaluated for trends within and between monthly and seasonal average snowfall through windowing of all 240 monthly grids. The graphical and statistical evaluation of these trends indicates a strong natural variation in the region's snowfall and reveals an increasing trend during the study period.

1. Introduction

The Great Lakes are located somewhat centrally within the North American continent. Their location puts them within a region normally dominated by "continental" climate. The continentality of a region relates to the degree to which it responds to the rapid heating and cooling of the surrounding landmass. However, the lakes are so large that they locally impact the region producing a "marine" climate. This impact affects many meteorological factors. In fall and winter, when little or no ice cover is established, the lakes are warmer than the air and lose heat and water through evaporation, particularly during storm events. When these storms move onshore and begin to cool, exceptionally heavy rainfalls and snowfalls occur. These areas of enhanced precipitation adjacent to each of the Great Lakes are called "lake effect zones."

In the Great Lakes region, heavy lake effect snowfalls are natural hazards that can result in loss of life or property damage. These snowfalls also pose severe problems for air and surface traffic (Bolsenga and Norton 1992). A multimillion-dollar winter recreation industry, which is dependent on snowfall, has developed within the region. Agribusiness can be strongly impacted by changes in snowfall. This is particularly true for the fruit belts located in the lake effect zones and winter wheat cropping further inland. The seasonal snowfall of the Great Lakes basin is an important feature in the hydrometeorology of the region. Snow meltwaters contribute to the water supply of the Great Lakes. Spring meltwaters impact hydroelectric power generation, commercial navigation, and riparian owners. The albedo of snow-covered ground and heat of fusion (needed to melt the snowpack) are significant heat budget elements that keep the ground surface and near-surface air cool. Once the snowpack melts, the physics of soil hydrology becomes important. In heavier snow years, high soil moisture keeps the ground surface cool due to high evaporative fluxes. These processes can delay the heating of the land surface in the spring, thereby reducing the land–lake temperature difference, which is the most important element in the region's marine climate.

Past studies on regional snowfall have relied on subjectively defined climatologies. These climatologies were normally assembled around long-term climatologic maps. The drawing of maps by hand has traditionally been a tedious undertaking. Hence, few long-term snowfall maps have been produced for the Great Lakes region (U.S. Weather Bureau 1959; Thomas 1964; Phillips and McCulloch 1972). Like all "atlas" type maps, they were cartographic end products and offered only a qualitative assessment of snowfall based on selected station data. The final drafting of these maps was subjectively enhanced from posted station average values. The maps presented here are computer generated. These maps combine many times more in-

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put data than previously utilized and employ an improved digital technique to suppress errors and increase spatial definition. Snow years 1950/51 through 1979/80 were chosen for the database due to the availability of the data. The technique yields highly detailed, regenerable snowfall maps and removes all subjectivity from the maps produced. It is the first time this technique has been used in a climatologic study.

Thomas (1964) presented maps of average annual snowfall for the Great Lakes for the 1895–1910 period and the 1931–1960 period. These maps represent a reasonable approximation of regional snowfall but are not very detailed. Phillips and McCulloch (1972) produced more detailed snowfall maps for the Great Lakes Basin for the 1931–1960 period. However, in that study, stations with as little as 10 years of actual data were used, possibly indicating that their analysis is somewhat weighted toward the latter half of the period for the U.S. side (many U.S. stations were established in the late 1940s). Their mean annual snowfall map broadly parallels the distribution pattern described in this paper for the 1951–1960 period.

A unique, time-ordered, raster-based database was established to produce the maps presented here. These data afforded new opportunities to quantitatively evaluate the trends identifiable in the maps. This potential for quantitative assessment is possibly more important than the maps produced. It is the first time that raster-based climatologic data has been hindcast and windowed to evaluate regional spatiotemporal variation. The relationship of the region's snowfall to its continental and lake effect snowfall components was quantified and graphically presented.

2. Database

All snowfall data available on magnetic tape were obtained from the Canadian Climate Centre of Environment Canada for the province of Ontario, and from the National Climatic Data Center of the National Oceanic and Atmospheric Administration for the eight Great Lakes states. Individual computer files were constructed for each station containing daily data for the station's entire period of record. A few stations have data as early as the 1840s, but most U.S. records are only available on tape after 1948.

Canadian snowfall depths were recorded twice daily at climatological stations and every six hours at principal stations. U.S. observations were recorded once daily at climatological stations at 8:00 a.m. or 12:00 p.m. at principal stations. Both Canadian and U.S. observers were instructed to make their daily snowfall observations by ruler measurement from "snow boards" or as an average of several old horizon-to-surface measurements for unevenly distributed snowfalls (Canadian Climate Program 1977; National Weather Service 1989). Instructions were consistent throughout the study period. These measurements were taken independently from any concurrent snow depth- and/or snowgage-derived water equivalent observations, both of which frequently require adjustments (Goodison and Metcalfe 1990).

Monthly data files were generated from the daily files. If any daily snowfall was missing, a missing data code was entered for the monthly value. Canadian data were provided in metric units. U.S. data were converted to metric values rounding up at 0.5 mm. Using the computed monthly data as input, a final set of 30 data files was constructed, organized by snow year for the 1951 through 1980 period. The 1951 snow year began on 1 October 1950 and ended on 31 May 1951. The 30 files contain all monthly snowfall data per snow year. Any station containing one or more months of data for a given snow year was included in that snow year file.

Figure 1 illustrates the spatial coverage of 1231 snowfall stations in the 1951 snow year file. From 1951, the total number of stations reporting increased to a maximum of 1429 stations in 1966. Even though stations increased in total numbers over time, the more remote areas of Ontario and northern Minnesota remained sparsely gauged throughout the 1951–1980 period.

3. Methods

The SURFACE III software package (Interactive Concepts Incorporated 1990), developed by the Kansas Geological Survey, was used to develop a grid-based system for the later production of snowfall contour maps. Since resolution was an important consideration, a grid cell size of 2 minutes latitude by 2 minutes longitude was selected. The map grid ranged from 94° to 74°W longitude by 40° to 51°N latitude for a grid of 600 × 330, or 198 000 cells. Keying the cell boundaries to latitude and longitude was convenient for processing but produced a cell size of about 2.6 km wide by 3.7 km high. Since processing limitations were being approached, a slightly smaller cell of 2.0 km by 3.0 km was not feasible. A 1 km^2 resolution is currently used for hydrologic modeling of the Great Lakes, and snowfall modeling will match that resolution in the future.

The grid node estimates of snowfall were computed using a linear trend surface fit to weighted nearest-neighbor station data. The eight closest stations were used within a 4° range. The weighting used the inverse of the distance squared but was scaled so the most distant point received zero weight (Davis 1986). A second pass arithmetically averaged cell values over a two-column and two-row span. The smoothed monthly grids were summed to produce annual grids.

The annual grids were averaged to form multiyear averages. A second proprietary software CA-DISSPLA (Computer Associates 1990) was used to produce some of the maps and the graphs. The contouring package of CA-DISSPLA and that of SURFACE III are com-

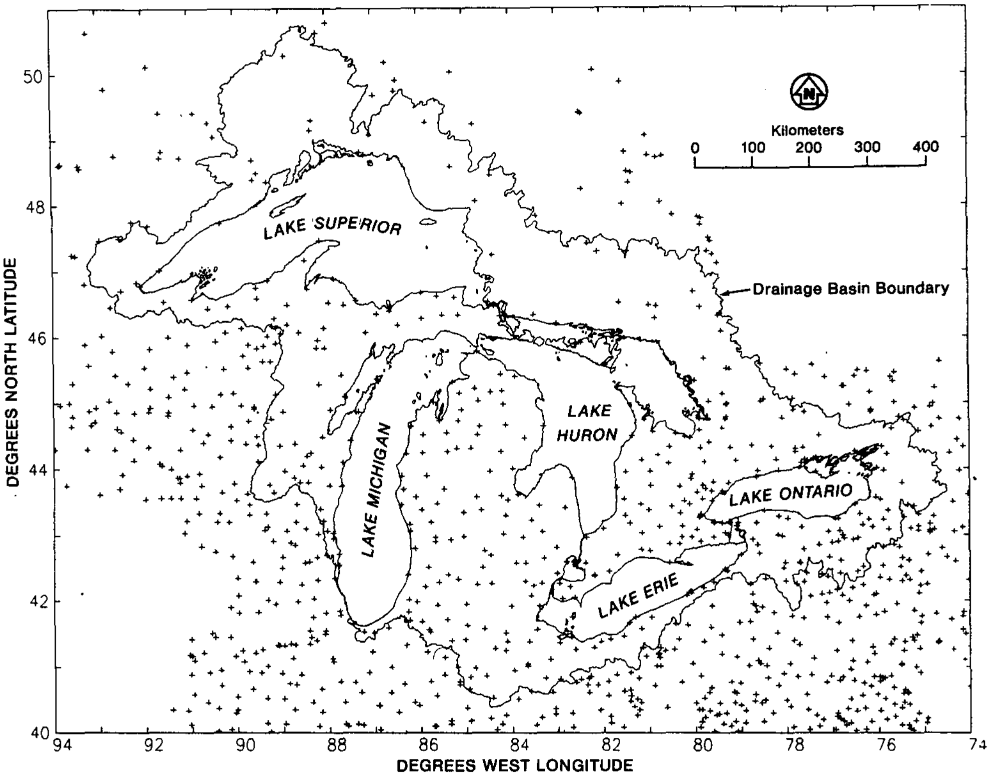

FIG. 1. Snowfall stations reporting in snow year 1951.

patible. The contours obtained from the SURFACE III package coincided with those from the CA-DISSPLA output when compared.

The SURFACE III package was used to make difference grids from the decadal average grids. These grids could then be contoured and evaluated. SURFACE III blanking of the Great Lakes and the land area outside the drainage basin was extracted and saved. This blanking defined the Great Lakes drainage basin as a window within the grid. This window was used with the authors' coded Fortran to process all 240 grids to determine average monthly snowfall over the basin by averaging the 52 000 plus cells within the window. Continental and lake effect windows were defined, and average monthly and annual values were similarly computed for them. These high-resolution grid values are gradiented representations of snowfall based on all available data. As such, each cellular value in the 30-year average grid might be considered a "geographically defined normal." Moreover, when windowed and spatially averaged, the values obtained are superior to station averages, thiessen-weighted station averages, or isohyetal averages. This superiority is due to the cellular values being equivalent to a detailed representation of isohyets, and isohyetal averages being better than the other two methods when nonlinear interpolation is used (Linsley et al. 1958).

The identification of trends within a climatologic time series is desirable. Unfortunately, statistical theory derives its results under the assumption that there is no relation between successive pairs of observations, an assumption that is usually not justified with meteorological data (Panofsky and Brier 1958). Spatial averaging increases the effective number of independent samples and thereby decreases the standard error of estimate as study areas increase in size (Leith 1973). The Great Lakes drainage basin is 508 830 km^2. Since the current technique utilizes data outside the basin, the effective area of the spatial average becomes somewhat larger. The use of cumulative meteorological means is reasonable when studying interannual fluctuations, since they may reveal time-varying structures that do not appear in the raw data or in more traditional statistical analysis (Lozowski et al. 1989). The windowed annual values were plotted along with simple regression lines computed by STAT/LIBRARY (IMSL Inc. 1991). The monthly basin averages were grouped by decade and plotted along with their regression lines. These monthly data were also displayed in three-dimensional plots as monthly values, cumulative monthly values, and as a cumulative percent of the seasonal sum for temporal evaluation. The figures presented here are a compromise between detail and available space. Nuisance problems persist such as software label placement and the inability to locate additional information on products. The CA-DISSPLA software generated some shading errors, which required cut-and-paste fixes. Greater utility is possible in computer-generated products when larger format and/or color output is possible.

The objectively derived data presented here contain no adjustments for such parameters as surface elevation, slope, aspect, vegetation, wind direction, air temperature, lake surface temperature, or lake ice cover. Snowfall within the Great Lakes region can be strongly impacted by these parameters. However, the use of these data requires a daily or storm-event time step and a finer resolution that is not feasible at this time.

4. Results and discussion

Three 10-year average snowfall grids and one 30-year average snowfall grid were produced and machine contoured (Figs. 2–5). The 1951–1980 average distribution map is more detailed than any of its predecessors. The grid processing technique carries the detail of the monthly component grids forward into the long-term-average maps. Climatologists working from postings of long-term station data never encounter this type of detail. Maps generated from posted data are frequently subjectively enhanced. The appropriateness of the enhancement is dependent on the skill and experience of the climatologist. Experience is gained at discrete intervals in time for specific areas. A climatologist touring the region in the 1950s (Fig. 3) would have a different perception than another touring in the 1970s (Fig. 5). The subjective enhancement of snowfall maps made by both climatologists for any period would be influenced by this experience. Human memory recall is better for recent observations than for older observations and for unusual weather than for normal weather. Thus, subjective enhancements may be correct or incorrect and are extremely difficult to differentiate between.

Crowe (1985) produced a mean winter snowfall map

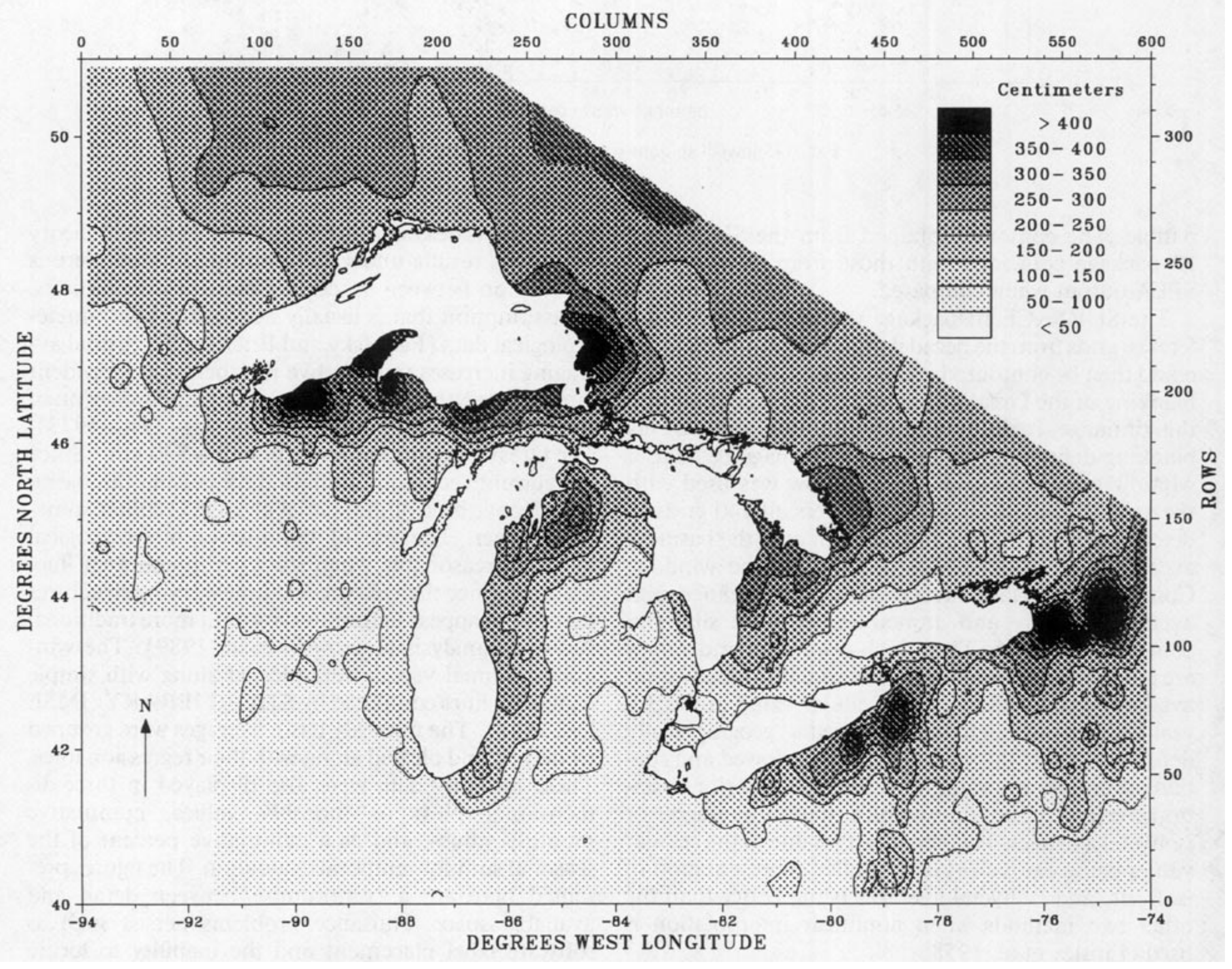

FIG. 2. Average 1951–1980 Great Lakes seasonal snowfall.

for the 1951–1980 period for southern Ontario using all stations with 10 or more years data. He used "normal" snowfall values from the Canadian Climate Program (1982) normals publication. These values were estimated by using adjustments with nearby "standard" stations if the stations had 10–20 years of record, but stations with 20–29 years of record were unadjusted. He drew a subjectively adjusted map from these posted values. The snowfall map he presented was similar in pattern to Fig. 2. However, the values were slightly higher, apparently weighted toward the latter portion of the period with more reporting stations. Eichenlaub et al. (1990) produced a mean winter snowfall map for the 1951–1980 period for the state of Michigan. They used data from 136 snowfall stations with 20 years or more of data allowing up to three months of estimated data per station per snow year. In the present study, no data were estimated; 145–159 stations per year were used for Michigan, and regions along the state borders were influenced by station data in adjacent states. Although the Eichenlaub et al. snowfall map was generated via computer, it was subsequently subjectively enhanced. This enhancement is most evident in the near-shore areas south of Lake Superior and east of Lake Michigan where contours have been closed and/or moved slightly inland from the lake. The snowfall pattern presented in Fig. 2 for the lower peninsula of Michigan is very close to theirs. The upper Peninsula was more subjectively defined by Eichenlaub et al., particularly along the western end. Their interpretation is inconsistent with that presented in Fig. 2 where the Michigan border area was impacted by the adjacent Wisconsin snowfall data, which they did not consider.

At 79°W north of 40°N, there is a north–south orientation of the isopleths with steep gradients both to the east and to the west evident in Figs. 2–5. This trend coincides geographically with the drainage divide between the Allegheny and the Susquehanna rivers. During the period 1951–1980, this highland area received

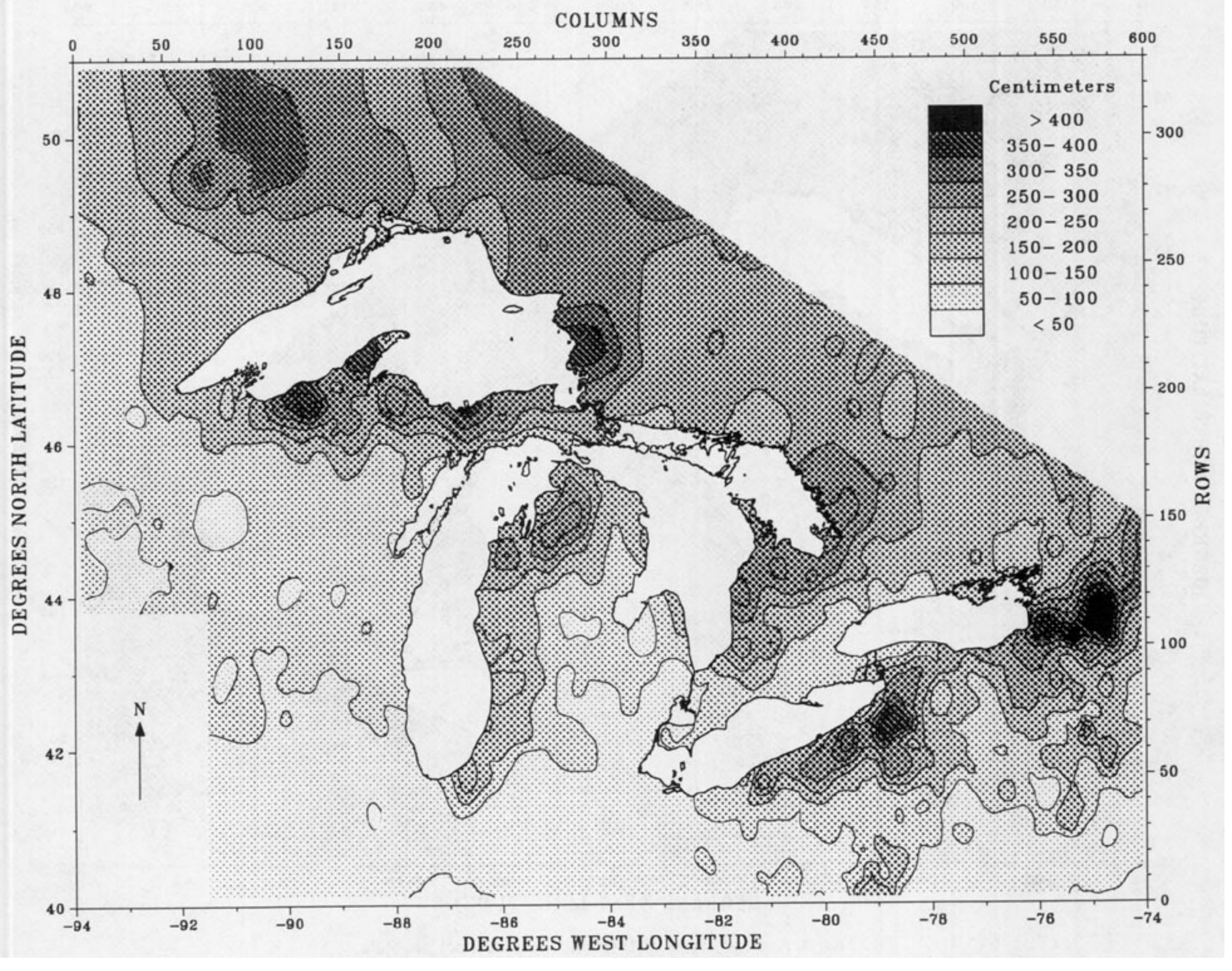

FIG. 3. Average 1951–1960 Great Lakes seasonal snowfall.

the greatest seasonal snowfall during the 1961–1970 period. Although not shown, there is a continuing increase in snowfall from this area southwest into the mountains of West Virginia. Part of this increase has been ascribed to lake effect storms (Johnson 1987) brought inland by mesoscale circulation associated with active Alberta systems (Richman et al. 1991).

Overall, snowfall increased in southern Ontario from the 1951–1960 to the 1971–1980 period (Figs. 3–5). Thomas (1975) noted a similar trend when evaluating recent (1940–1970) climatic fluctuations in Ontario and Quebec. Using data from the airports at Toronto, Ottawa, Montreal, and Quebec City he found annual snowfalls decreasing to 1953, then rising. Using decadal-mean values, he indicates these four stations have increased about 25 cm during the 1960s compared to a decadal average centered at 1953. While evaluating snowfall variability in the United States during the 1940–1990 period, Zapotocny (1991) found that nearly every station examined in the midwest and Great Lakes region showed a significant increase.

The 1951–1960 (Fig. 3) Great Lakes regional snowfall patterns are similar to the 1961–1970 patterns (Fig. 4). Moderate increases in amounts of snowfall to the south and east of Lake Superior are evident, and similar increases are seen along some portions of the eastern shores of the other Great Lakes in lake effect regions. The southeastern portion of the state of Michigan shows nearly the same contour pattern and amounts during the 1951–60 and the 1961–70 period.

Non-lake effect regions within the basin exhibited few discernable changes between the 1950s and 1960s. There was a modest increase in continental snowfall in Ontario during the 1970s. The 1971–1980 (Fig. 5) patterns are less similar to the preceeding decade (Fig. 4) than the preceeding two decades (Fig. 3–4) are similar to each other. Lake effect regions received increased snowfall during the 1960s, and these regions extended

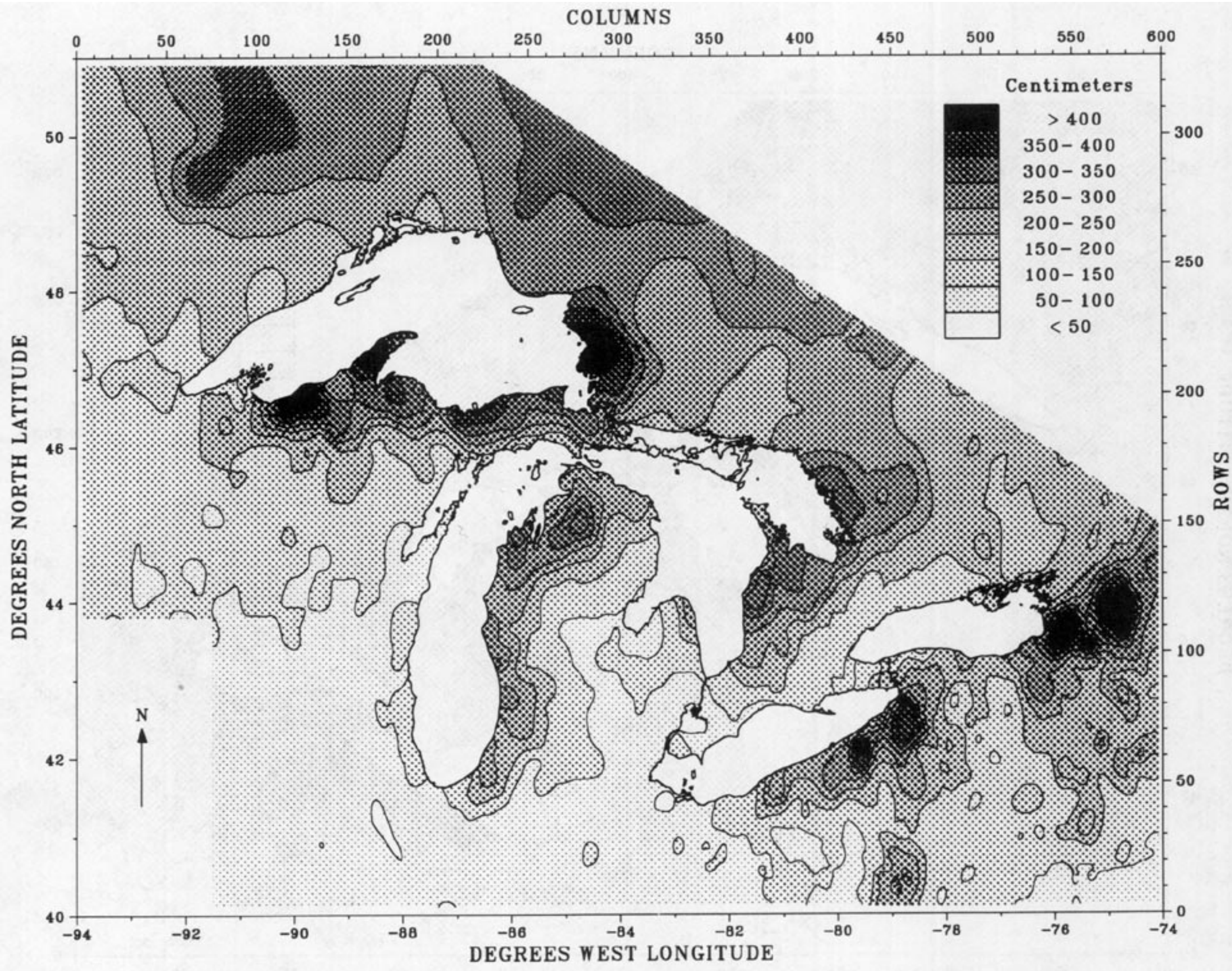

FIG. 4. Average 1961–1970 Great Lakes seasonal snowfall.

further inland during the 1970s. Eichenlaub (1986) also identified decadal increases in snowfall amounts in the lake effect regions in Michigan. Isopleth gradients increased south of Lake Superior and east of Lake Ontario. Groups of stations were examined in this study within the three time periods for the south shore of Lake Superior. The overall increase in snowfall was evident at all stations in the area and was not an artifact of a few exceptionally high values. The isopleth pattern was somewhat influenced by one new station located near the tip of the Keweenaw Peninsula in Michigan (47.467°N, 87.867°W).

The 1971–1980 decade in the southern Lake Superior area was further examined by contouring a section of the 1971–1975 and 1976–1980 average grids (Fig. 6) at higher resolution. The stations reporting at the end of each period were also posted. These stations change minimally and the regional isopleth pattern is essentially the same from the one five-year period to the other. The latter five-year period's snowfall was higher than the earlier five-year period. While investigating long-term snowfall records, Eichenlaub et al. (1990) found that seasonal snowfall at Calumet-Houghton in the Keweenaw Peninsula (47.167°N, 88.500°W) fluctuated moderately during the first third of this century, but steadily increased during the latter two-thirds to about 250-cm additional snowfall by the early 1980s when it leveled out. This increasing trend was also evident along Lake Michigan. Using 10-year moving averages, they found that seasonal snowfalls east of Lake Michigan at Muskegon, Michigan (43.167°N, 86.233°W), peaked in 1970 and at Lansing, Michigan (42.767°N, 84.600°W) in 1978. The seasonal snowfall increases at Muskegon, located in a lake effect zone, were much higher than those at Lansing, located in a continental zone. From 1930 to 1980, upstream air temperatures flowing across Lake Michigan declined (Dungey and Braham 1982), producing

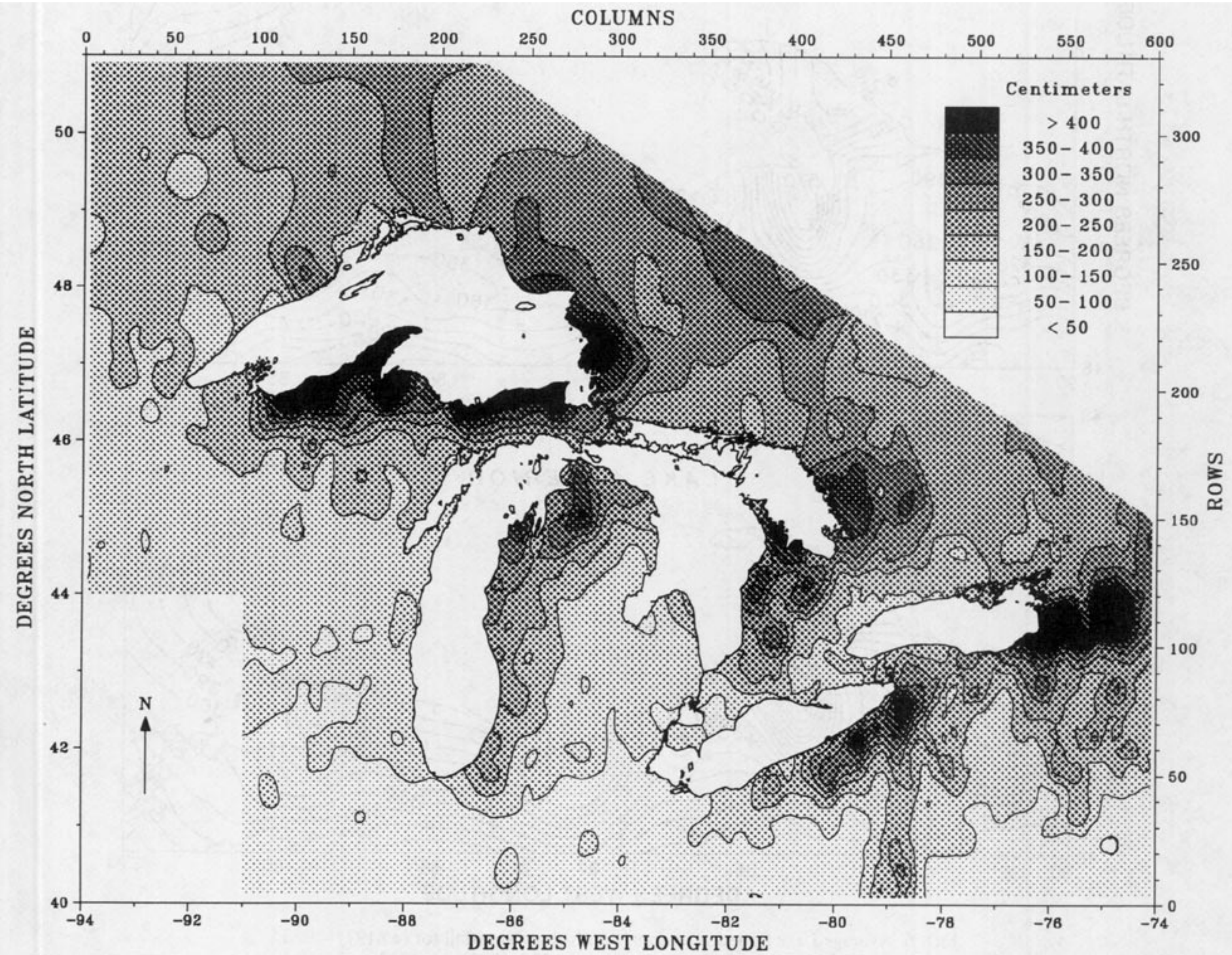

FIG. 5. Average 1971–1980 Great Lakes seasonal snowfall.

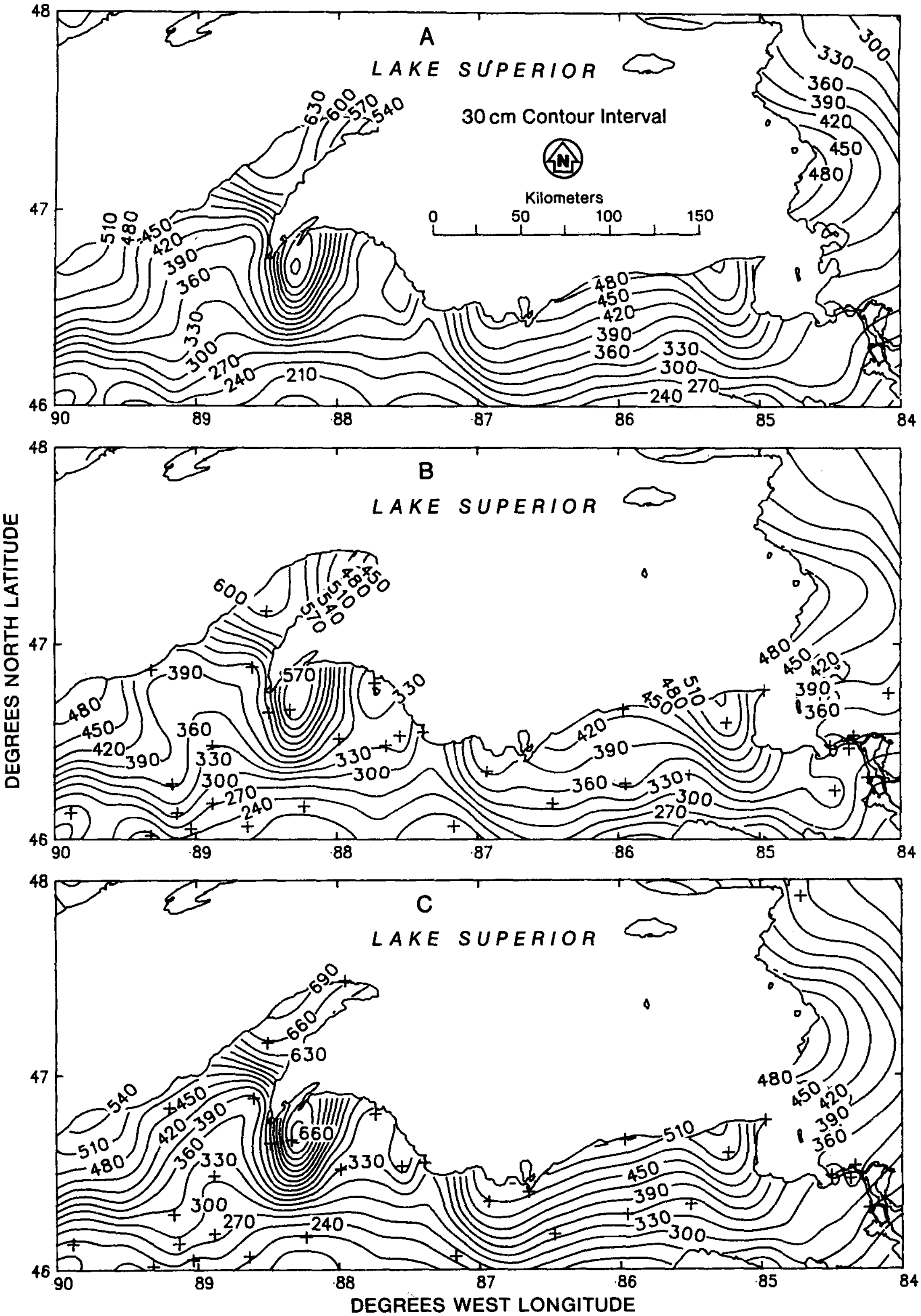

FIG. 6. Average Lake Superior seasonal south shore snowfall for (a) 1971–1980, (b) 1971–1975 with 1975 stations (+), and (c) 1976–1980 with 1980 stations (+).

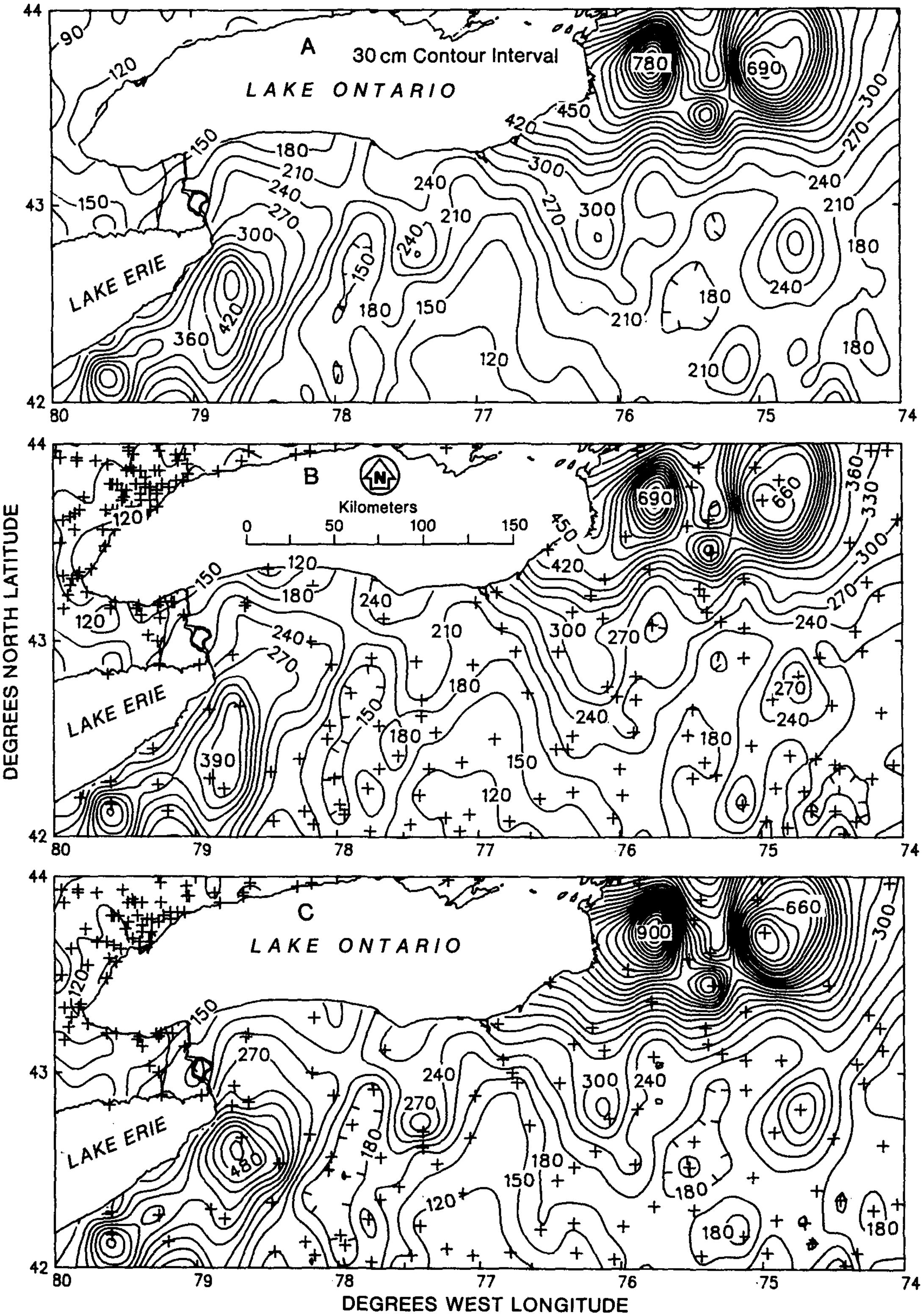

FIG. 7. Average Lake Ontario seasonal south shore snowfall for: (a) 1971–1980, (b) 1971–1975 with 1975 stations (+), and (c) 1976–1980 with 1980 stations (+).

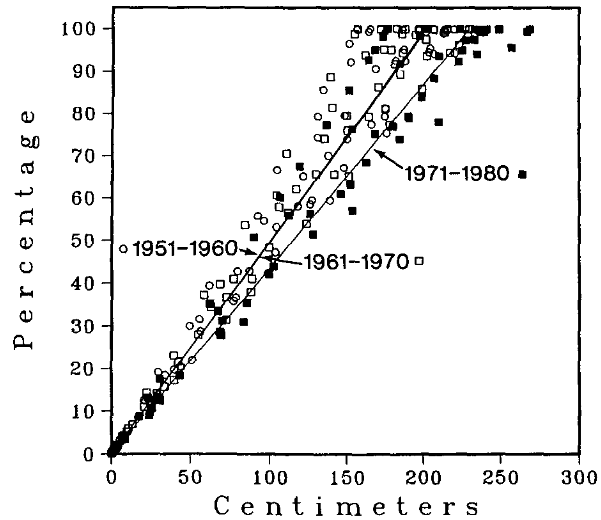

FIG. 8. Scatterplots with regression lines for cumulative monthly snowfall for the Great Lakes' drainage basin for the 1951–1960, 1961–1970, and 1971–1980 snow years.

a larger temperature difference with the lake surface. In winter, the greater the air–lake temperature difference the stronger the lake effect processes. Lower than normal temperatures have been more important in producing heavier snowfalls throughout the eastern United States than increases in antecedent moisture (Wagner 1979).

Snowfall in the region south and east of Lake Ontario was contoured for the 1971–1980 decade as its five-year components (Fig. 7). The same trends evident in the Lake Superior region were repeated. Lake effect zones received increased snowfall amounts and extended further inland, while more distant inland regions were essentially unchanged. This lake effect region received the greatest increase in snowfall amounts during the study period. This region is one of the most densely gauged in the study area; hence, the detail illustrated is very reliable. In order to further evaluate this region, a smaller window (Fig. 9) was established to quantify these changes that are discussed below.

Since basinwide changes are important hydrologically, monthly snowfall values for the land portion of the Great Lakes drainage basin were computed. These values were plotted in decadal groupings and regressed (Fig. 8). In this scatterplot the small difference between the first two decades versus the latter decade is quite evident. The scatter within each decadal dataset depicts strong interannual variability. The offset in the 1970s versus the 1950s and 1960s regression lines indicate

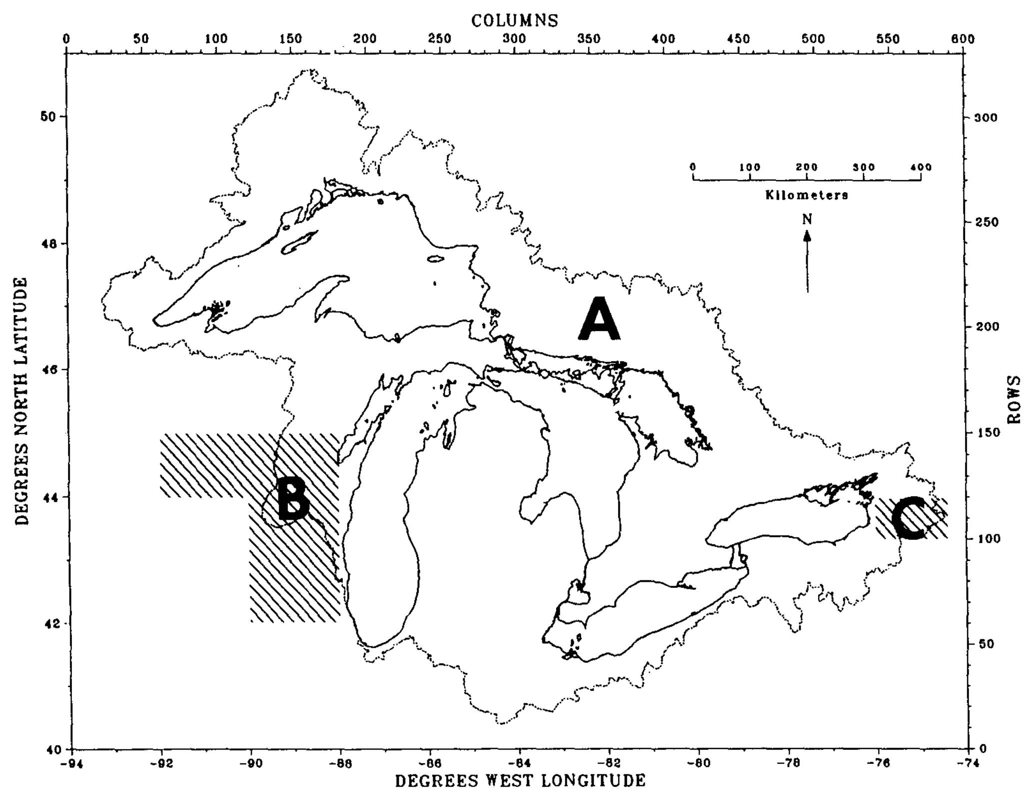

FIG. 9. Three subgrid windows: (a) The Great Lakes drainage basin, (b) a zone of continental climate, (c) a zone of lake effect and orographic precipitation (from Norton 1991).

that a greater percentage of snowfall occurred late in the season in the latter decade.

Seasonal average values were generated for the Great Lakes drainage basin, a lake effect zone, and an area of continental climate (Fig. 9). Although the lake effect zone and the continental climate zone were subjectively defined, they represent areas typical of those climates (Eichenlaub 1979). The snowfalls in these three regions do not have the same trends (Fig. 10). The snowfall over the Great Lakes drainage basin increased slightly, continental snowfall decreased slightly, and the lake effect zone increased substantially. These results are consistent with those shown in Figs. 3–5, namely that the general increase in snowfall for the Great Lakes drainage basin was principally due to increases in lake effect snowfall, not continental snowfall. The variability of Lake Ontario winter precipitation distributions was investigated in an eigenvector analysis for the period 1947–1982 (Weinbeck 1983). The spatial variations within the precipitation patterns were thought to be linked to large-scale climate changes. It was suggested that pattern changes might relate to the occasional redirection of precipitation from coastal storms back into New York.

Figure 11 presents an overview of snowfall variations within the Great Lakes drainage basin throughout the period under study. Here, trends are identified within and between monthly, seasonal, and long-term periods. In these three-dimensional plots, *b* is base plot, *s* is side plot, and *r* is rear plot. The overall increase in seasonal snowfall described earlier is also evident in the monthly snowfall [Fig. 11a (*b*)]. The 1971 maximum and the 1958 minimum snowfall years are readily identifiable. These two years along with constructed cumulative sums of monthly maximum and minimum values, that is, worst case scenarios, illustrate the snowfall range in the region [Fig. 11c (*s*)]. The difference in the percentage distribution of snowfall between the maximum, minimum, 1971, and 1958 seasons [Figure 11b (*s*)] was small. This indicates that the Great Lakes drainage basin is sufficiently large to greatly smooth even large localized variations. The 1971 seasonal maxima snow year began with moderate snowfall [Fig. 11a (*b*), 11c (*b*, *s*)] that constituted a small percentage of the total [Fig. 11b (*b*, *s*, *r*)]. The December snowfall was somewhat above average [Fig. 11c (*s*)]. January reported the most snowfall [Fig. 11c (*b*)] that year. The cumulative sum then accounted for almost 60% of the 1971 seasonal sum [Fig. 11b (*r*)], which was not an uncommon percentage [Fig. 11b (*r*, *s*)]. February and March snowfalls [Fig. 11a (*b*), b (*r*)] were also above average. None of the 1971 snow-year monthly values

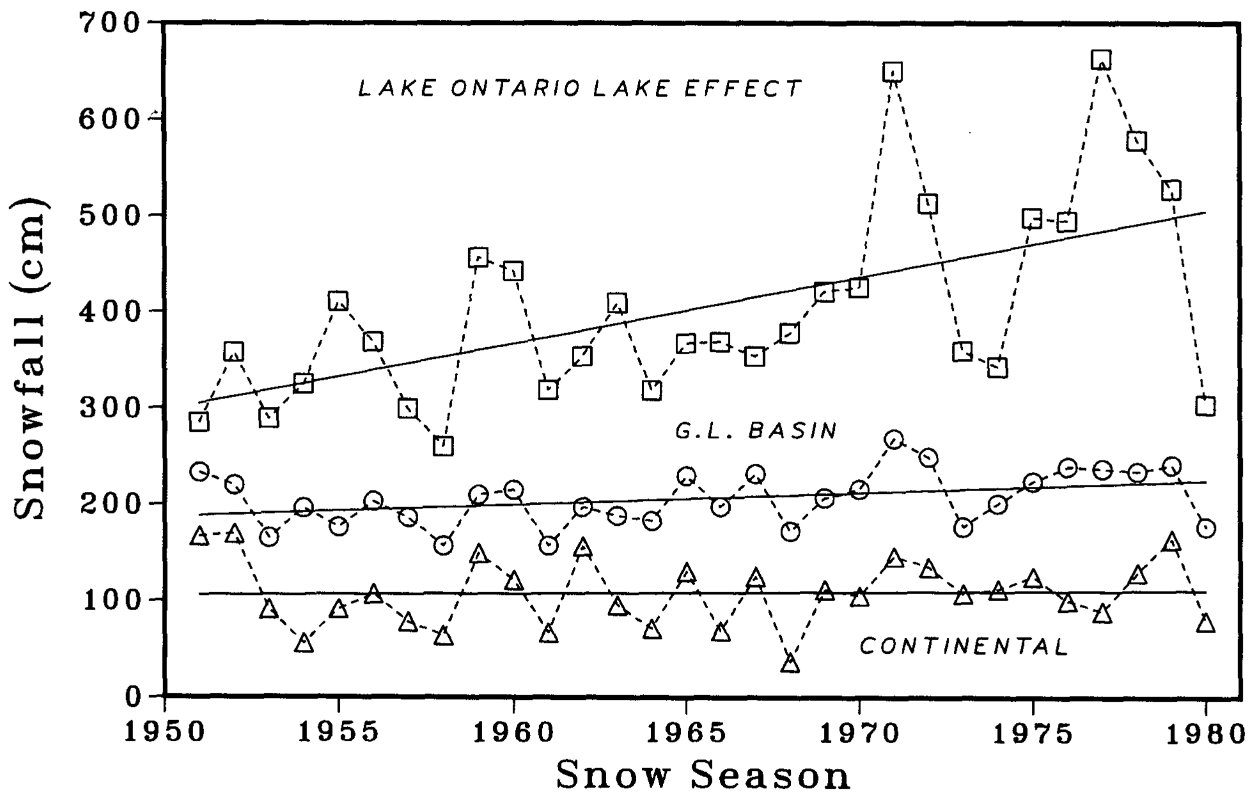

FIG. 10. An intergrid comparison of three subgrid windows defined in Fig. 9 for the 1951–1980 snow seasons (from Norton 1991).

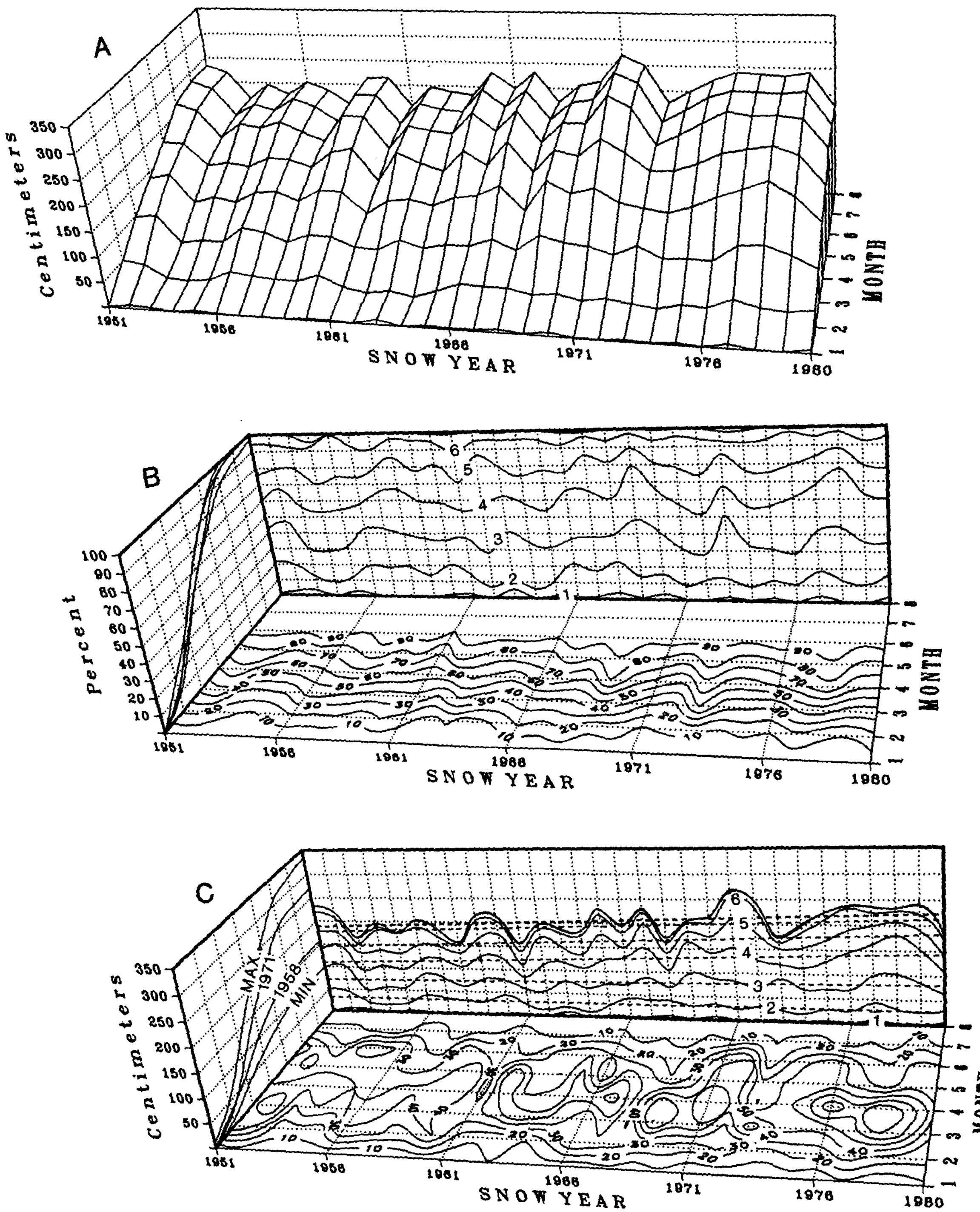

FIG. 11. Multiple aspects of monthly snowfall for the Great Lakes drainage basin during the 1951–1980 period. (a) Cumulative monthly snowfall; (b) cumulative monthly snowfall expressed as a percent of the seasonal sum, "Bb" contour interval 10%, "Bs" curves are in the same order as "Cs"; (c) cumulative monthly snowfall (cm) on side and back plots with monthly snowfall on the base plot, "Cb" contour interval 10 cm, "Cs" curves are: MAX = monthly maximums, 1971 snow year, 1958 snow year, and MIN = monthly minimums. Months are numbered as: 1, October; 2, November; 3, December; 4, January; 5, February; 6, March; 7, April; and 8, May.

[Fig. 11c (*s*)] were maximum monthlies for the 1951–1980 period, nor was the snowfall distribution [Fig. 11c (*b*), b (*b*)] unusual that year. The 1958 minimum snow year was similarly undistinguished. The regressed cumulative monthly values [Fig. 11c (*r*)] show January snowfall as increasing the most during the study period. The December through March regressions indicate increasing snowfall during the study period [Fig. 11c (*b*, *r*)], while the October, November, April, and May values were somewhat constant. These regressions identify an increasing regional snowfall trend during the 1951–1980 period associated with high interannual variability. In the Great Lakes region, winter and spring air temperatures generally declined during the 1951–1980 period (Bolsenga and Norton 1993).

A decreasing trend has been observed in North American, Eurasian, and Northern Hemisphere snow covers during the 1980s. The decrease has been most striking in the spring (Robinson 1993). Global spring air temperatures have been rising in recent years (Robinson and Dewey 1990). Winter and spring air temperatures have increased over the Great Lakes Basin during the 1980s (Bolsenga and Norton 1993). The midwinter to early spring period accounted for most of the snowfall increase in the Great Lakes region during the 1970s. In the years since 1980, snowfall in the Great Lakes region has diminished from the 1970s record levels, returning to a regime more reminiscent of the 1960s.

5. Conclusions

The three 10-year and one 30-year maps represent an objective presentation of average snowfall conditions for the Great Lakes region. They include all available monthly data combined with high resolution computer processing techniques. There were decadal increases in regional snowfall and these increases were not spatially uniform. By windowing the spatiotemporal database, the increases shown in the maps were identified as increases in lake effect snowfall and not increases in continental snowfall. Cooler antecedent air temperatures rather than an increased moisture availability appears responsible for the increase in lake effect snowfall. Annual snowfall increases were primarily the result of December through March increases. These increases correspond to cooler winter and spring air temperatures. There were increases in lake effect and regional snowfall throughout the 1951–1980 period, particularly during the 1970s. The boundaries of lake effect zones during this period were not static but did migrate further inland as snowfall increased. Neither the 1971 maximum nor the 1958 minimum snow years contained a single maximum or minimum monthly snowfall value. Assembled worst-case snowfalls for maximum and minimum snow years were more than 10% worse than the natural extremes. McKay (1972) enumerated a number of the problems associated with snowfall maps. He felt that current information could be exploited to much greater advantage through the use of computerized mapping. Since that time, computer hardware and software have vastly improved. This study represents a logical implementation of computer mapping and graphical analysis that narrows the gap identified by McKay.

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