

Digital Investigation of Great Lakes Regional Snowfall, 1951–1980

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ABSTRACT

A snowfall database for the Great Lakes region containing all available station data has been created. These data were previously translated to 240 high resolution (2 minutes Latitude by 2 minutes Longitude) monthly grids and 30 snow season grids of 198,000 cells for the 1951 - 1980 period. Using these grids, multiple seasonal snowfalls are presented, digitally compared, and computer contoured for the Great Lakes region. This paper introduces the concept of geographically-defined normals and new windowing techniques. The potential for incorporation of digital snowfall data into a Geographical Information System (GIS) for climate studies, forecasting, and management is presented.

INTRODUCTION

Maps have been used to depict the physical relationship between discrete physiographic (mountains, rivers) and/or distributed (vegetation, soil type) parameters over a defined geographic area. Man has strived to improve the quality of maps throughout time by making them more accurately illustrate these parameters. In these endeavors, a map has always been considered to be the end product. However, a map should not be viewed solely as an end product, but rather as one form of representing geographically keyed data.

Snowfall is a distributed parameter which lends itself to regional mapping. Previous Great Lakes snowfall studies have been carried out by Phillips and McCulloch (1972), Thomas (1964), and the U.S. Weather Bureau (1959). These studies all produced regional snowfall distribution maps. When trying to compare these studies with the data currently being processed, it was quickly determined that there was no way to make quantitative comparisons. Although these earlier maps represented significant effort in their production, they were cartographic end products and could not be further evaluated. Norton and Bolsenga (1991) produced a high resolution, digital snowfall climatology for the Great Lakes region. In that climatology the digital data were presented as snowfall distribution maps, but these data could be readily accessed for further evaluation. This study addresses what has been done as well as what can be done with this digital database.

DATABASE

The database used in this study is described in Norton and Bolsenga (1991) and in which monthly and seasonal gridded snowfall data were computed for the Great Lakes region for the period 1951 - 1980. The monthly grids were computed using all available station data from over 1200 snowfall stations/month. The station data were interpolated to cellular node values by the inverse of the distance squared. The monthly cellular values were smoothed along 2 columns and 2 rows. Snow-year grids were the sum of the October - May monthly grids. The 30-year average seasonal grid was the average of the 30 seasonal grids. Each grid was 600 x 330 cells for a total of 198,000 cells. This provided the author with a 30-year database, with seasonal and monthly grids, of high resolution data. The high resolution is obtained through the use of: all available station data, a monthly processing technique, and small size cells, 2 minutes Latitude by 2 minutes Longitude. These data reside on computer disk packs and computer compatible 9-track magnetic tape. All computing was accomplished on a networked system of Micro Vax computers.

The over-lake values in the database were objectively derived through the projection of overland station values and slopes over the lake. Although the regional cellular values in the database may represent the best objectively defined snowfall values possible, the quality of the cellular snowfall values do vary just as the quality of the station data used to generate them varies. The reader is cautioned to evaluate possible impacts on these cellular data from physical parameters (topography, vegetation, urbanization, lake-effect, etc.) not considered in the generation of these values.

METHOD

Three analysis methods were employed: inter-grid, intra-grid windows, and temporal-grid windows. The inter-grid method is representative of currently available GIS and can be used to answer simple questions about an entire grid. In this study the inter-grid method is used to change units, add additional information, and find maximum and minimum values. A GIS which contains other forms of data such as political, sociological, soils, vegetation, etc. can be used to answer a number of "set notation" type of questions. A typical question might be: "Which state-owned land has at least 150 cm seasonal snowfall, sandy soils, pine forests, and is located within 10 km of a major highway?" The intra-grid window method answers more in-depth questions than a GIS is currently capable of answering. The intra-grid method answers statistical questions about a sub-grid region of any shape. When these questions are sequentially asked of a number of grids, the statistical answers can be linked together and output tabularly or graphically. Thus, this method numerically defines both changes within a region and comparisons between regions. A typical question might be: "Is snowfall variability in the fruit growing regions of Michigan significantly different from that in New York?" The temporal-grid method delves into regional changes in yet another way. Through averaging along one dimension of a grid window and reassembling sequential averages, this method produces graphic output from which it is possible to see and directly measure temporal, spatial, and independent variable changes. A typical question might be: "What is the magnitude of snowfall variability between 1° Latitude increments?" The use of the three methods in this study is described below.

(1) Inter-Grid

Inter-grid methods are arithmetic computations based on grid to grid or grid and variable operations. Figure 1 was produced from the 30-year average snowfall grid converted from centimeters to inches and drawn using CA_DISSPLA (Computer Associates, 1991) software. The state and county borders shown are library functions of this software. A SURFACE III software package (Interactive Concepts Incorporated, 1991) was used to make numerical inter-grid evaluations. The package computes averages, differences, sums, quotients, etc. on inter-grid operations. These computations can be made over the entire grid or a grid subset defined by blanking-out portions of the grid along regular or irregular boundaries. CA_DISSPLA was used to produce Figures 1-7 from SURFACE III (Figures 1, and 4-7) and the author's Fortran software (Figures 2-3) produced grids. Separate Fortran software coded by the author was used to find cellular maximum and minimum values within the 30 seasonal snowfall grids.

(2) Intra-Grid Windows

Sub-areas can be defined, windowed, and compared. The Great Lakes Basin is a large and irregularly shaped area. In order to better understand and begin to measure snowfall variability within this basin, basin snowfall was compared with two windowed areas, one of continental climate, and a second which receives lake effect and orographically-induced snowfall. The three areas are of different size and shape (Figure 8). When comparing geographically-distributed parameters, the size and shape of the areas are not important. What is important is that they represent a "type" of whatever you desire to compare. For example, all north-south lake effect regions can be windowed, numerically combined, and compared with all east-west lake effect regions.

The SURFACE III package computes intra-grid statistics for grid and sub-grid window areas. Multiple SURFACE III computer runs were used to generate sets of seasonal statistical output for the 1951-1980 period for the three sub-grid regions. The seasonal mean values per windowed region were extracted and assembled into a file used as input into the author's Fortran software which utilized both STAT/LIBRARY (IMSL, Inc., 1991) and CA_DISSPLA for regression analysis and graphic output, respectively, to produce Figure 9. The data presented in Figure 9 were used to select the maximum and minimum snowfall years discussed above.

(3) Temporal-Grid Windows

A diagrammatic technique used to illustrate atmospheric pressure as a function of time and latitude was developed by Hovmoller (1949) and is still in use today. This diagrammatic technique was expanded upon to evaluate temporal variability within a region through a form of windowing. Basically, four dimensional data (x, y, z, and time) are converted to averaged three dimensional data (averaged x or y, z, and time). Five rectangular windows were established 50 cells wide and of varying lengths (Figure 10). The author coded Fortran software to use SURFACE III generated seasonal snowfall grids which were averaged along the 50 cell axis, yielding a one dimensional numerical series for each of 30 seasons. The one dimensional arrays were then placed side by side to form a new two dimensional array for each window which was

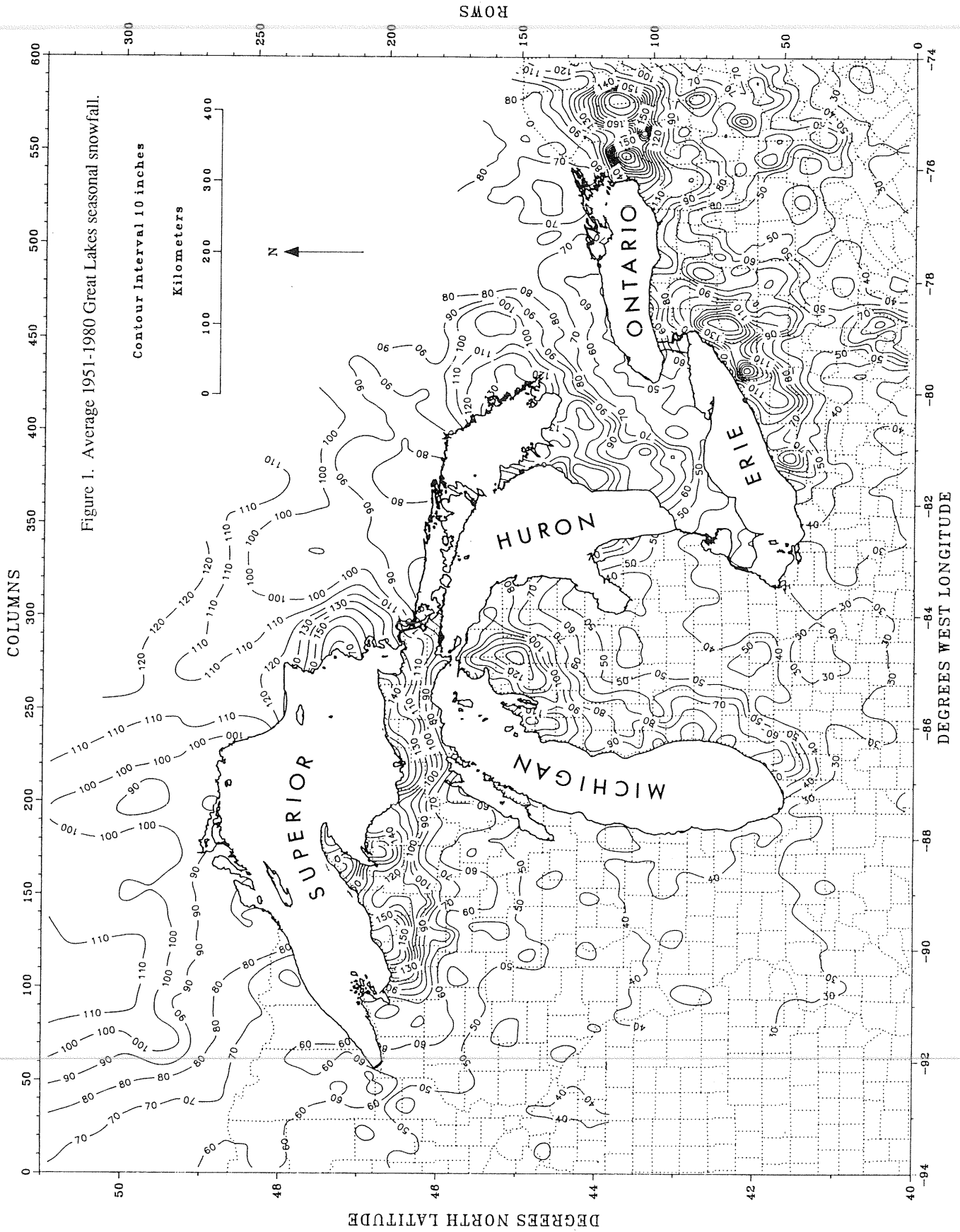
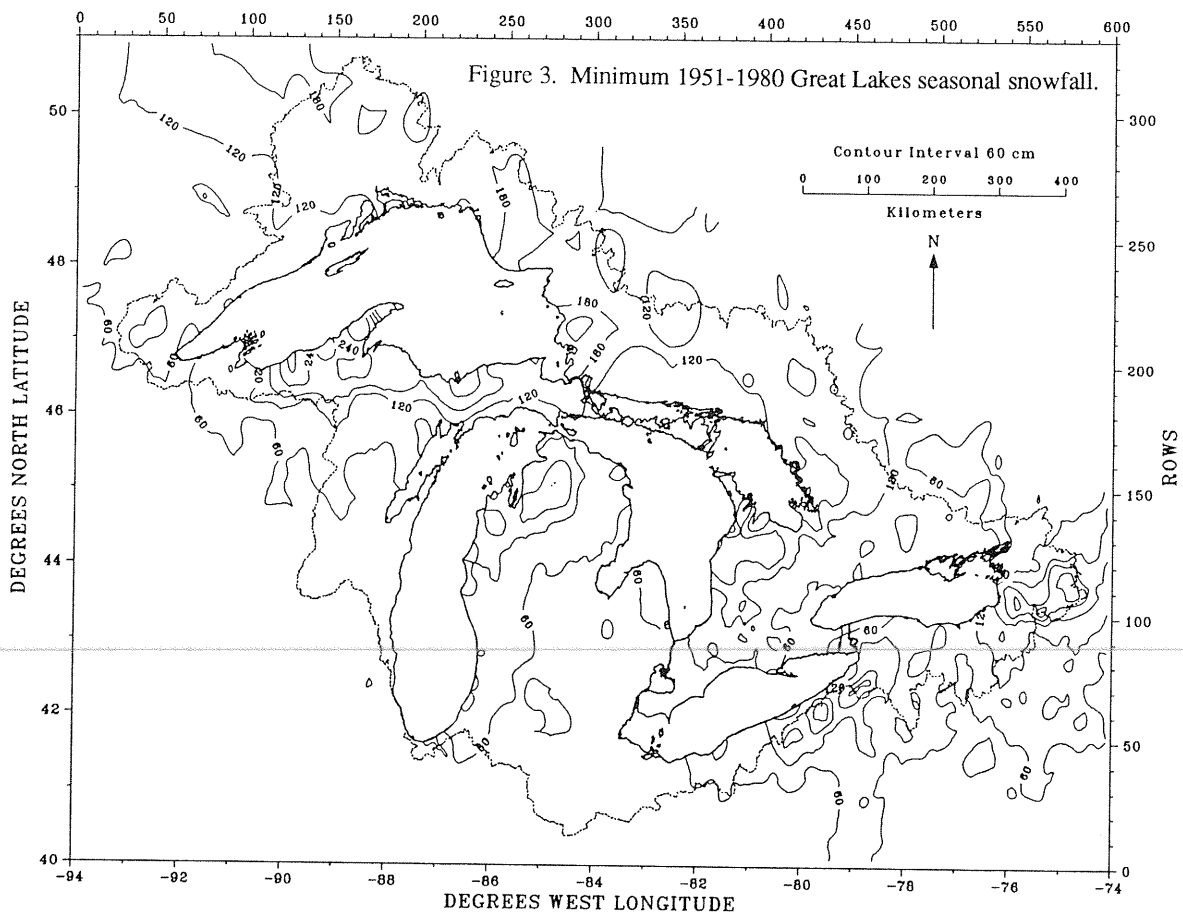
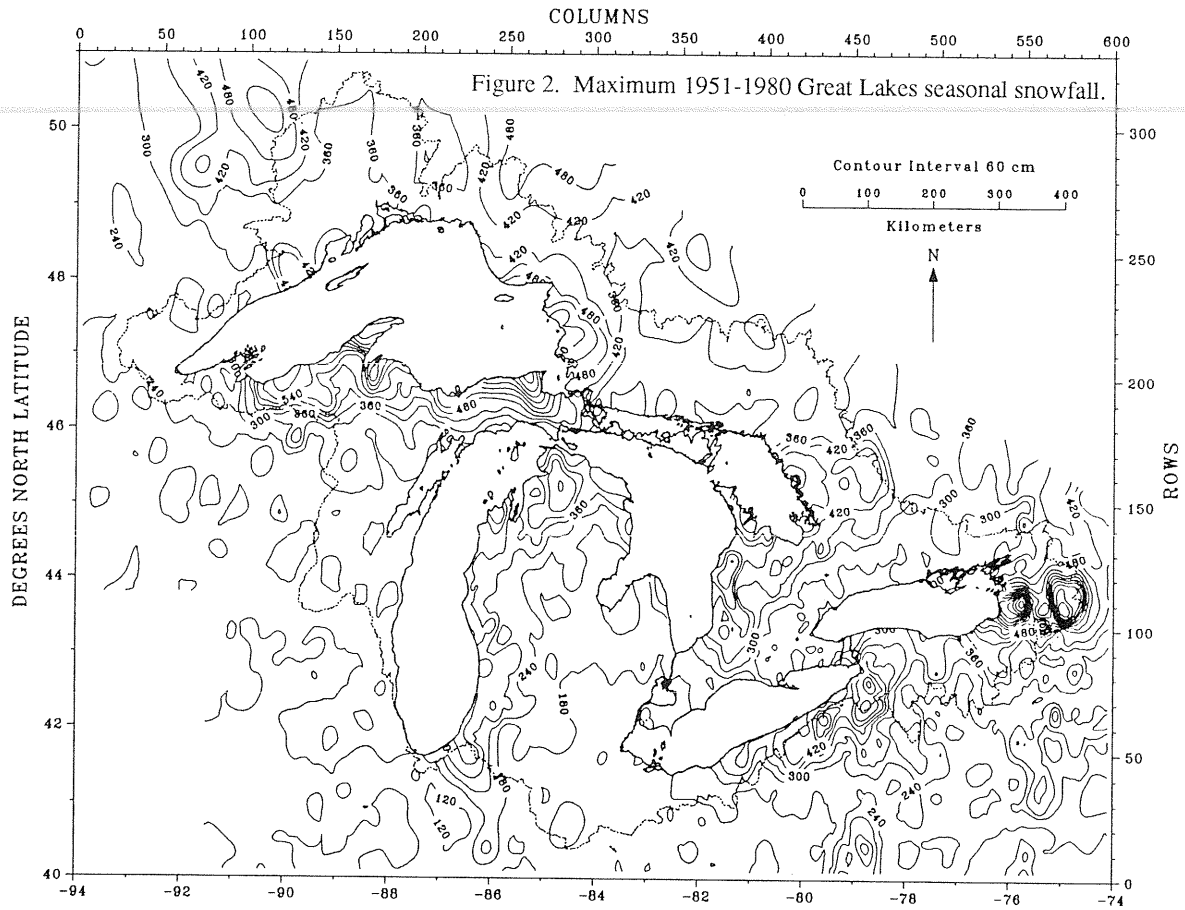
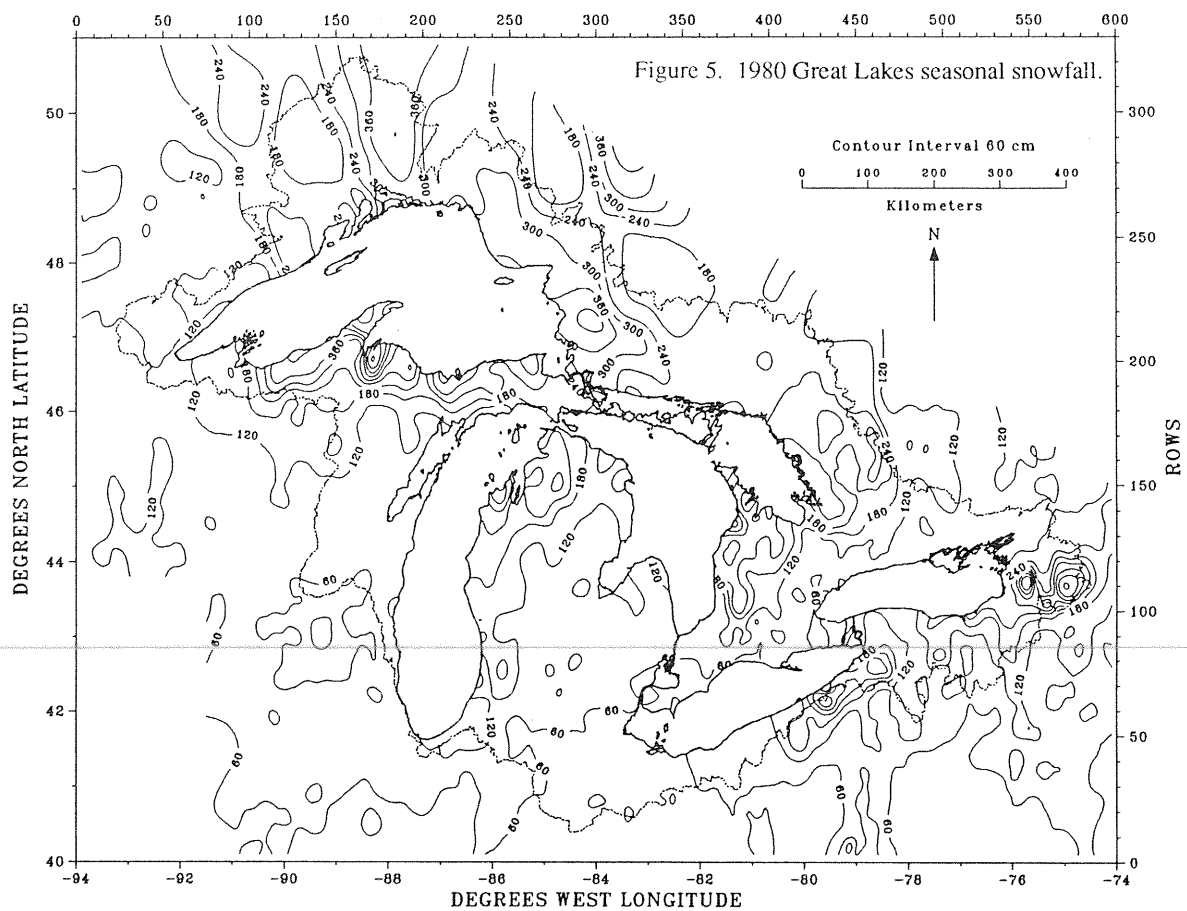
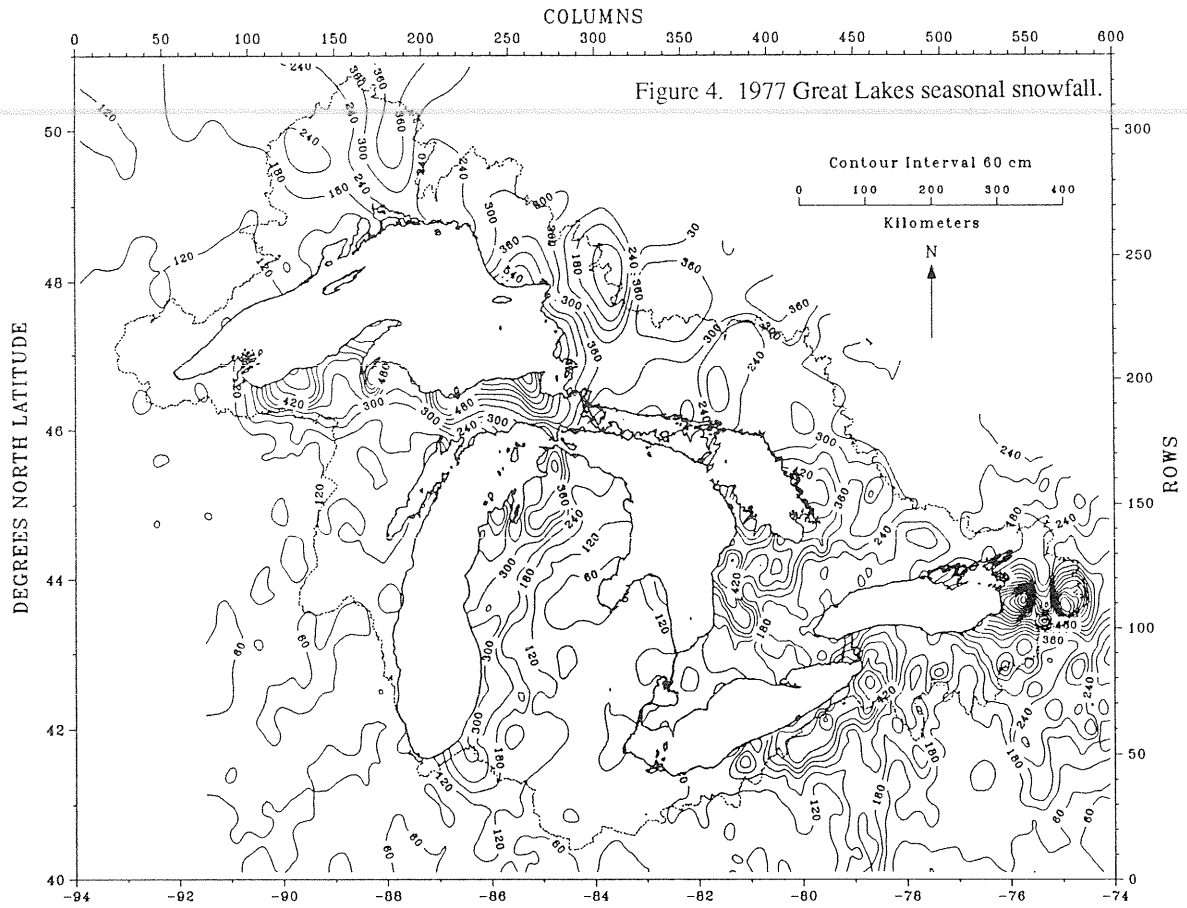
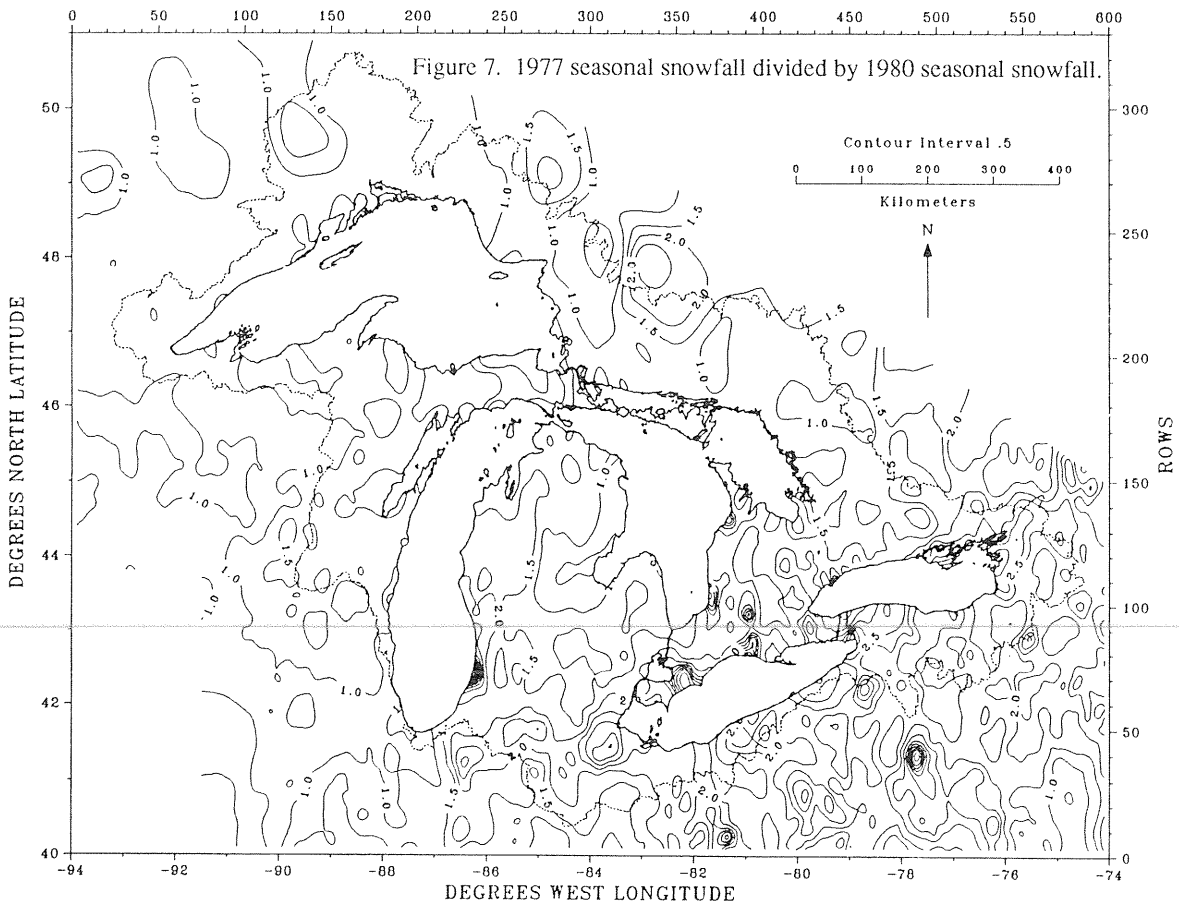
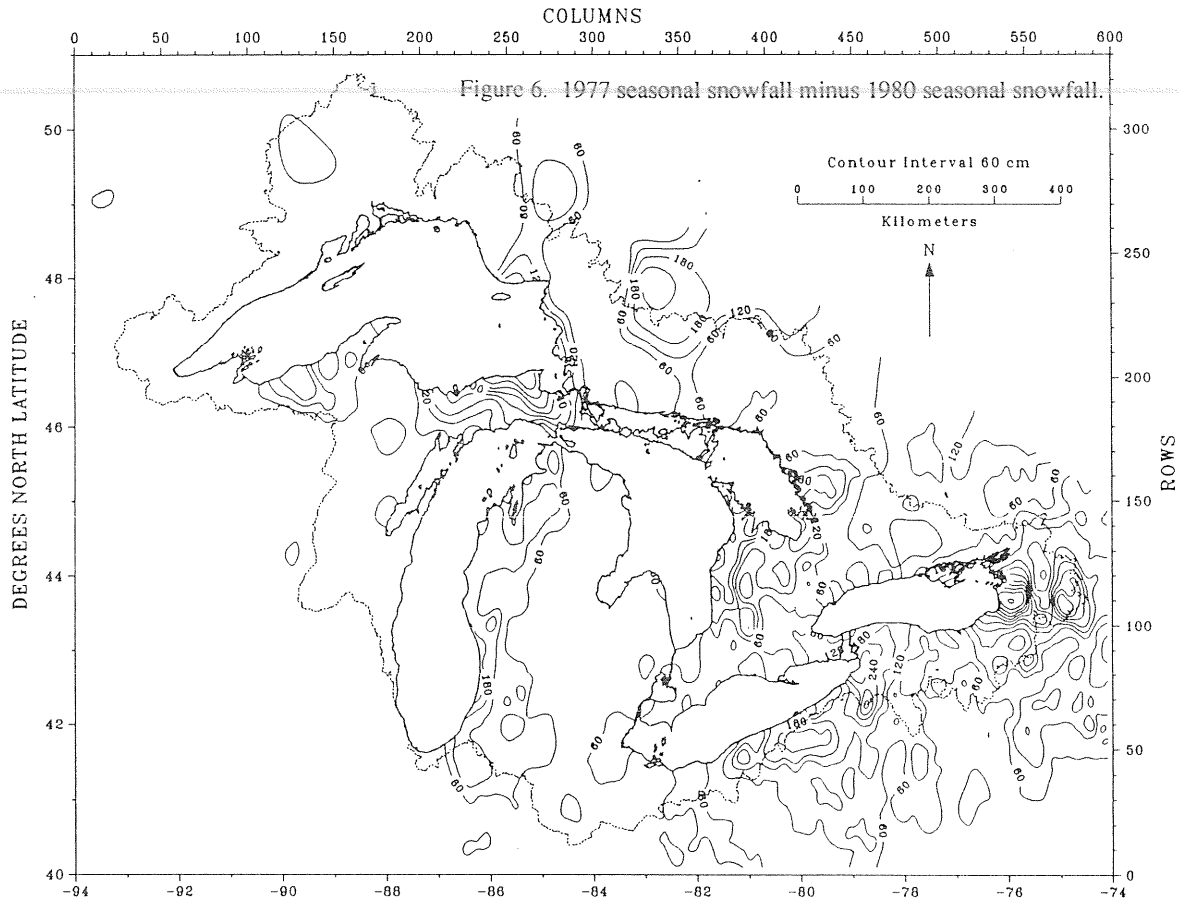


Figure 1. Average 1951-1980 Great Lakes seasonal snowfall.







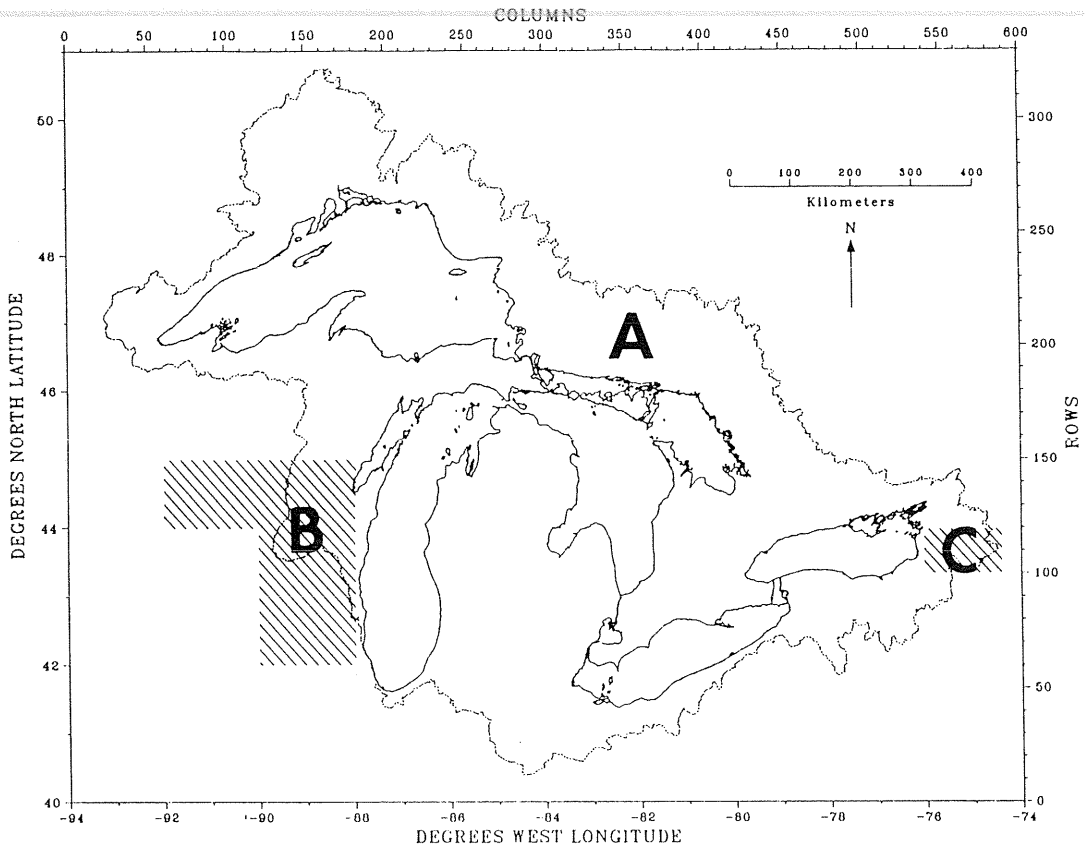


Figure 8. Three sub-grid windows: (A) The Great Lakes Drainage Basin, (B) a zone of continental climate, (C) a zone of lake effect and orographic precipitation.

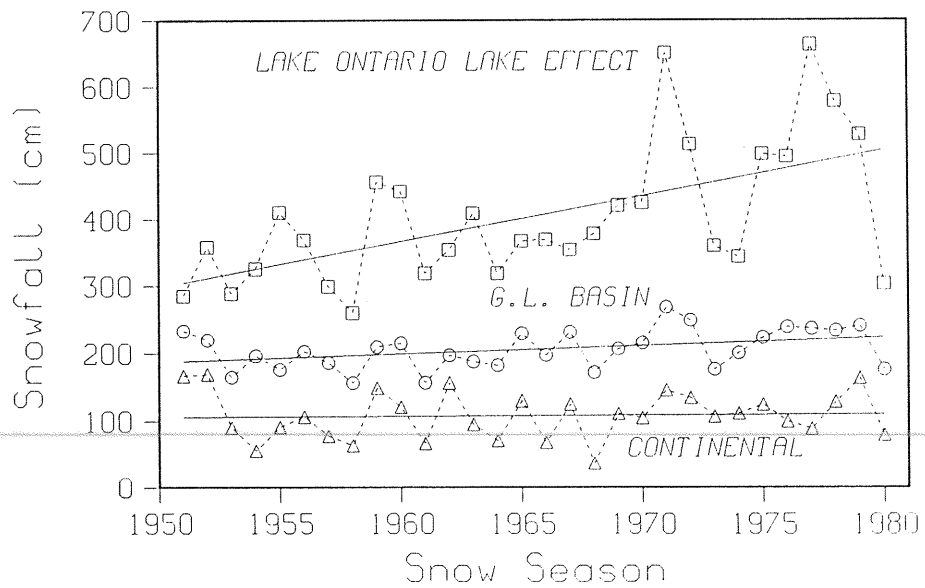


Figure 9. An intra-grid comparison of three sub-grid windows defined in Figure 8 for the 1951-1980 snow seasons.

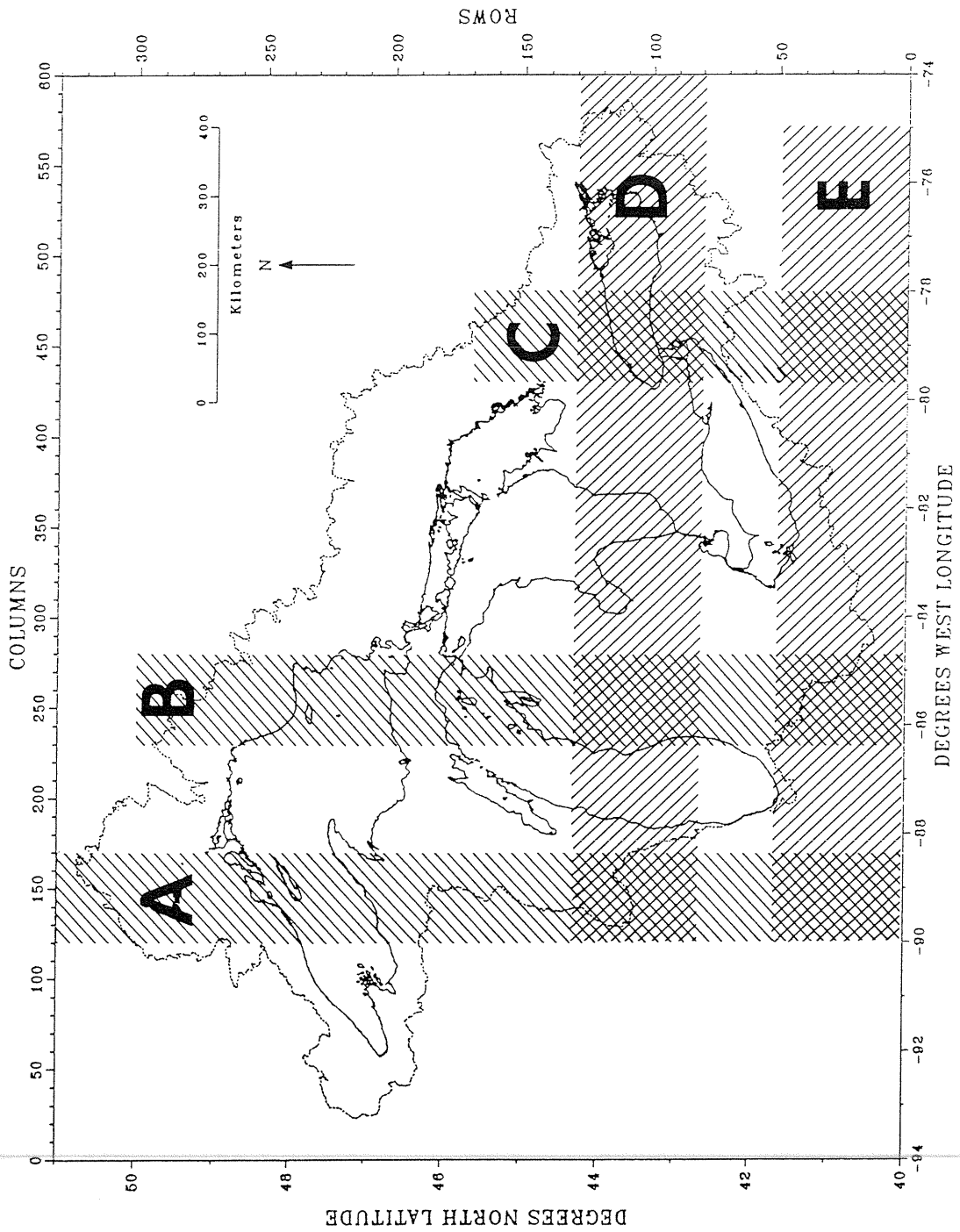


Figure 10. Five temporal-grid windows. Each window is 50 cells wide.

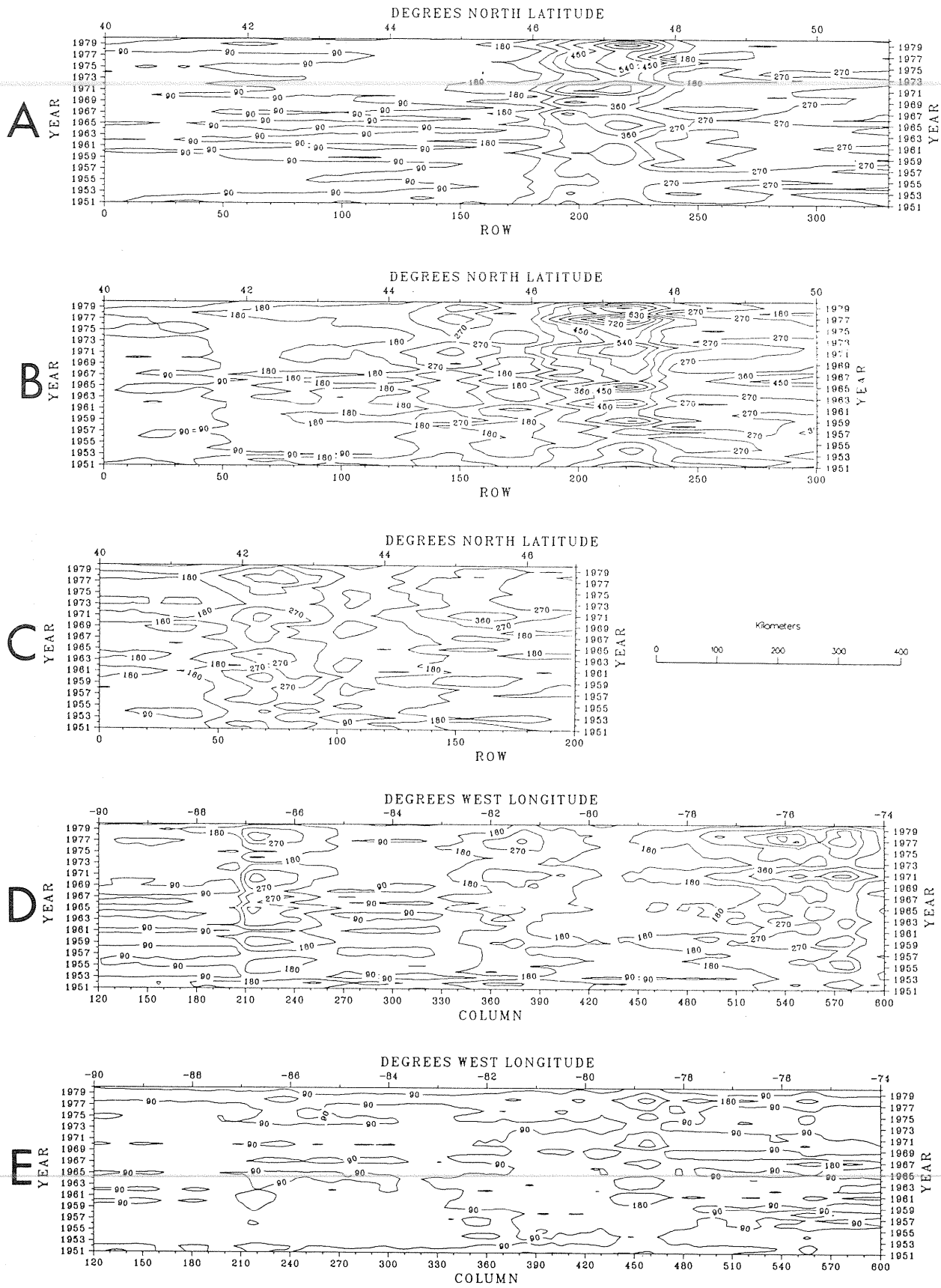


Figure 11. Three longitudinally averaged temporal-grid windows (A, B, and C), and two latitudinally averaged temporal-grid windows (D and E), contour interval 90 cm. See Figure 10 for the location of each window within the region.

then contoured. Where these windows contain cells over the lakes, the over-lake values were used in the cellular averages. Figure 11 illustrates the three north-south and two east-west windows created using this technique.

These computed and assembled arrays depict regional snowfall variability in a new way and were graphically output using CA_DISSPLA. Distinct increases in snowfall within these windows that extend through several years are here referred to as "pulses." The data in these temporal windows may be directly measured for regional extent (kilometers), timing of events (years), and magnitude (cm). The magnitudes can be estimated on the plots or extracted from tables (not presented) used to generate the plots.

RESULTS AND DISCUSSION

Data which exist in digital form can be easily output as different map types. Figure 1 was constructed from the same 30-year average seasonal snowfall grid as that presented by Norton and Bolsenga (1991). Although the original grid was in centimeters, it was easily converted to inches. The cellular data utilized in creating this map are similar to station data in terms of how they were created and how they can be used. Each cell value was computed using all available monthly snowfall data from the surrounding stations. A cell containing a station which reported 100% of the time has essentially the same value as an average of the station data. If a station did not report for a any given month, the surrounding stations were used to create an interpolated value for that location. Cells which contain no reporting stations have interpolated values for every month based on all surrounding reporting stations for all 240 months in the 30-year study period. The 30-year average cellular values are therefore geographically-defined "normal" values. Obviously, a cell "normal" containing a 100% reporting station is superior to less well defined cells. However, even with station data, all normals are not created equally. The Canadian Climate Program (1982) published snowfall normals which are the arithmetic average at full-period stations (20-30 years of record), and adjust short-period stations (5-19 years of record) using a single nearby station. The grid processing technique employed by Norton and Bolsenga (1991) uses all available snowfall data and a monthly time step (8 monthly grids summed for each yearly grid, 30 yearly grids summed and averaged for a "normal" grid). This grid technique generally produces a superior estimate of snowfall at a non-reporting station site, or any cell site, than an adjustment based on simple correlations. This grid technique does not work as well as some statistically derived adjustments when the reporting stations are significantly different (in elevation, lake-effect vs. non lake-effect, nearshore vs. inland, etc.) from the location being approximated. Overall, the grid "normal" values represent the most accurate data set that can be objectively, computer generated at this time. The normal value of any cell can be extracted from the grid. Thus, for the first time, access to continuous geographically-defined snowfall normals is possible. Such data is important to a wide range of users such as highway departments and regional planners.

Political boundaries, drainage basins, cities, and highways in digital form are readily addable to digitally-based maps. These types of additional data are frequently available in GIS. Unfortunately, GIS are not currently able to accept and maintain high resolution data (ie., large floating point arrays) as presented here. If high resolution data products are desired, having digital data enables a user without a GIS to perform compromise solutions such as generating high resolution snowfall overlay maps to match existing highway and resource maps of any size or map projection.

Having snowfall data in gridded form enables a user to ask questions not possible with either station data or traditionally-produced maps. For instance, a climatologist might be asked to produce maps depicting maximum and minimum snow seasons for a particular region. He would be able to produce maps of those years which he thinks represent maximum and minimum snowfalls using station data. Gridded data, however, will normally produce higher resolution maps than the climatologist can produce from selected seasonal station data. The higher resolution is inherent in the grid processing techniques use of "all available data" through monthly time steps which combines and averages snowfall distributions and not simply contouring selected station data. Moreover, a database in grid form can also be searched to find the "cellular" maximum and minimum values for any given period of time, and maps can be produced from these computed grids. These climatic extremes over a given base period are of interest to forecasters, highway departments, planning agencies, and snow-related businesses.

The author coded Fortran software to determine maximum and minimum cellular snowfall amounts for the 1951-1980 period. These computed grids were not smoothed, but the maps produced (Figures 2 and 3) have contours that look like they were generated from smoothed data. This smoothness is due to the grid processing procedure reproducing the geographic distribution of snowfall as opposed to discrete station data points. If this type of data were combined with highway data (via GIS, overlays, or new software), inch-miles of snow removal could be estimated, volumetric computations would be possible, and optimum locations of supplies such as salt stockpiles could be determined. When these data are combined with state and federal land information, areas suitable for winter recreation development can be defined and compared.

Individual monthly or snow year snowfalls are often of importance to reevaluate snowfall forecasts, snow removal problems, etc. Digital data offer great flexibility in these areas. Figures 4 and 5 depict the last regional maximum (1976-77) and minimum (1979-80) snow seasons occurring during the study period. These snow seasons were not subjectively determined maximum and minimum snow seasons, but numerically selected as described later. These two snow seasons can be compared against the cellular maximum and minimum cellular values, individual previous snow years, the 30-year average snow year, an average of the last three maximum and minimum snow seasons, etc.

In order to measure inter-seasonal variability, the numerical difference between the two snow season grids (Figure 6) was produced which showed that the greatest differences were in the lake effect zones, and the least difference in the areas of primarily continental climate. The lake effect region east of Lake Ontario had the greatest difference, and the southwest portion of the region had the least difference.

An inter-seasonal variability quotient was also produced by dividing the 1976-77 grid by the 1979-80 grid (Figure 7). Overall, the lake effect region east of Lake Ontario was more variable than the lake effect regions around the other lakes. All areas of greatest differences (Figure 6) were not the same areas as the areas of maximum variability (Figure 7). As measures, differences are most sensitive to maximum values, and quotients are most sensitive to minimum values. Indirectly, over seasonal and shorter time spans these measures are measures of composite storm frequency and storm intensity. Inter-seasonal variability could be examined in greater temporal detail by comparing monthly and cumulative monthly snowfall grids.

Sub-region variability may be evaluated and compared with other sub-regions using intra-grid methods. In Figure 8, three areas were defined for intra-grid comparison using seasonal grid data. In this example (Figure 9), the three regions do not portray the same trends. Seasonal snowfall in the Great Lakes Basin is increasing slightly, while continental snowfall is decreasing slightly. The seasonal snowfall in the lake effect area of Lake Ontario is increasing significantly as is the inter-seasonal variability. These results indicate that the general increase in snowfall in the Great Lakes Basin was due principally to increases in lake effect snowfall, not continental snowfall. These results are in agreement with those found by Norton and Bolsenga (1991) when evaluating 5- and 10-year regional snowfall trends.

In order to evaluate regional snowfall latitudinal and longitudinal variability through time, five temporal-grid windows were established (Figure 10). The most westerly north-south window (Figure 11A) shows moderate variation in the continental zone south of 46° Latitude. Between 46° and 47.5° Latitude, stronger lake effect pulses are evident. These lake effect pulses tended to increase over time and are sometimes evident as far south as about 45° Latitude. In the region north of Lake Superior (49° - 51° Latitude), a diminution trend in the snowfall is evident. The middle north-south window (Figure 11B) also exhibits a diminution in snowfall north of Lake Superior except for a large pulse in the mid 1960's. The eastern end of Lake Superior (46° - 48° Latitude) shows a strong increase in snowfall through time. Although that portion of the grid is mostly over lake and hence was projected from near shore station data, this trend coincides with the pulse in the Lake Michigan lake effect zone around 45° Latitude. South of 44° Latitude, the snowfall was variable with regional maxima occurring in the late 1970's. The pulses observed east of Lake Michigan do not always coincide with the pulses north of Lake Superior. In the eastern window strong lake effect pulses are observed east of Lake Erie (Figure 11C, 42° to 43°). These pulse maxima do not coincide with the pulses east of Georgian Bay (Figure 11D, -82° to -81°). The lower lake pulses have tended to increase over the period, while the more variable Georgian Bay pulses peaked around 1971.

The east-west window that cuts across three of the Great Lakes (Figure 11D) readily defines the lake effect zones of each lake with abrupt pulses. Each of the three lake effect zones identified is of a different shape pulse. The shape differences in each zones' "pulse" is related to the topography and roughness of each land surface. The over-lake extent of these lake effect pulses are computed projections of inland data. The eastern shore of Lake Michigan with its steep bluffs and wooded nearshore area created strong asymmetrical pulses. The eastern shore of Lake Huron with its very low relief and farm lands created broad and gentle pulses. The eastern shore of Lake Ontario with its woods and highlands created large and distributed pulses. Although the Lake Ontario-induced pulses are somewhat consistent in eastward extent throughout the period, there was a doubling (Figure 11D, 270 to 540 cm) and westward extension of the pulse maxima (Figure 11D, -74.8° to -76.0°) during the period. The east-west window at the southern limit of the study area (Figure 11E) lies mostly outside the region which is normally considered to receive lake effect snowfall (Eichenlaub, 1979). This window just catches the tip of the Lake Michigan snowbelt. However, there is a small lake effect pulse in that window in the late 1970's aligned with all of the more northerly pulses observed in Figure 11D. Snowfall throughout the window increased somewhat during the late 1970's. Pulses occurring east of 79° Longitude (Figure 11E) are in a highland region of the Appalachian Mountains. The times of the Appalachian pulse maxima are inversely related to the eastern Lake Ontario snowbelt pulses (Figures 9 and 11B) except for the 1977 snow season maxima pulse. The 1977 pulse (Figure 11E) had significantly expanded eastward and westward extent.

SUMMARY

Maps in digital form offer many new opportunities to the researcher, planner, and administrator. When gridded data are combined with the proper questions, very informative answers are obtained. This study addresses some regional snowfall questions and presents new digital methods to answer them. It is demonstrated that inter-regional and intra-regional snowfall can be examined spatially and/or temporally. It is shown that seasonal snowfall throughout the Great Lakes Basin has increased during the 1951-1980 period, and that the increase is due to increases in lake effect snowfall. Cellular maximum and minimum distributions are generated and mapped to produce climatic extremes. Recent high snowfall and low snowfall snow years are compared to quantitatively determine seasonal variability. Sub-regions were defined for the Great Lakes Drainage Basin, lake effect, and continental climate. The temporal variability within and between these regions is presented. Temporal and spatial variability within windowed regions is presented illuminating the geographic extent, magnitude, and times of snowfall maxima.

The digital examination of the snowfall data presented here is reproducible as well as enhanceable. When research on a subject is suspended an immediate "loss of knowledge" occurs. However, if that research was encapsulated into digital products and digital methods, the knowledge lives on and can itself be further enhanced by succeeding researchers.

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