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Great Lakes Air Temperature Trends For Land Stations, 1901–1987

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ABSTRACT. *An examination of gridded data developed from quality controlled land station temperature data for the 1901-1987 period for the Great Lakes basin reveals temperature trends not previously reported. On an annual basis, from early 1900 through the mid 1950s, a 5-year moving average shows that overall basin temperatures increased. A cooler regime prevailed for the remainder of the period of record. Seasonal 5-year moving averages show that spring temperatures increased throughout the period. Summer temperatures were highly variable, but with an early upward trend through the mid 1940s and a recent downward trend for the remainder of the period. Fall temperatures slowly warmed from the early 1900s until the mid 1960s, but have recently shown a cooling trend. Winter temperatures show an upward trend with intermittent wide swings from the early 1900s through the mid 1950s after which a lower temperature regime has prevailed. Temperature differences between a warm and a cool year and the long term mean show markedly varying patterns.*

INDEX WORDS: *Great Lakes, air temperature, climate change.*

INTRODUCTION

Until recently little has been published as to whether or not concrete indications of climate change are present in the Great Lakes region. Hanson *et al.* (1992) analyzed a long-term ice extent data set for the Great Lakes. They state "This suggests that the ice season on the Great Lakes has had, over the past 35 years, a tendency to end earlier and earlier." They use a 90-year Springtime temperature data base, for the U.S. side of the basin only, by Boden *et al.* (1990), for supporting evidence. In another recent paper, Ojala and Ferrett (1992) examined 90 years of temperature records at 45 stations in Michigan to determine evidence of global warming. They concluded that " . . . evidence was found to both support and refute today's global warming theory. When records for 45 stations were combined, there was a clear increase of almost 1 degree over the long term. . . . However, attributing such an increase to global warming is misleading because the highest average temperatures in Michigan occurred mainly from the 1930s to the 1950s. If data for only the past 40 years were analyzed, the obvious conclusion would be that Michigan is cooling rather than warming."

Land-based temperature records from 1901 to 1987, for the U.S./Canadian Great Lakes basin, on an annual basis and according to season, are examined in this paper. The seasonal analysis seems to resolve the apparent conflict between Hanson *et al.*'s (1992) and Ojala and Ferrett's (1992) studies. A subjective analysis of trends or lack of trends is also included. The data and analysis are not intended to imply either long-term climate warming or cooling, but to present a picture of past and recent trends as indicated by a spatially averaged and, hence, more representative data base.

Temperature isolines are shown as broken when they cross overwater surfaces to indicate that no overwater data (buoys, towers, ships) were used in this analysis. Overwater temperature patterns in the Great Lakes are often complex. An analysis of overwater temperatures similar to that conducted here for the land-based data would require a data set which is currently not available (long term, rigorously quality-controlled). During certain months of the year, temperature contours flow relatively smoothly across the some of the lakes while during other months relatively closed countours over the lakes prevail (see Saulesleja (1986) for excellent examples of both situations). The purpose of this report is to analyze the overall temperature patterns of the basin as determined from land station data to determine the existence of trends. A compatible analysis of air temperature patterns over the lakes would require a dense network of stations collecting a long-term data set that will take many years to develop. It is a subject area which has been, and will continue to be, under study by the Great Lakes research community for many years to come.

DATABASE

The database for this study was developed from monthly average air temperature records collected at land-based stations provided on magnetic tape from the Canadian Climate Centre for the Canadian side of the basin, and the Carbon Dioxide Information Analysis Center for the U.S. side. The U.S. data are known as the United States Historical Climatological Network Serial Temperature and Precipitation Data (Karl *et al.* 1990). The data used have been fully adjusted for all biases introduced by station moves, instrument changes, time-of-observation differences, and urbanization effects. The Canadian data were constructed by Atmospheric Environment Service, Environment Canada, Canadian Climate Centre to be compatible with these U.S. data.

Yearly files containing data for all reporting stations were constructed. Each line in a file has the station's number, most recent name, elevation, latitude and longitude, followed by 12 monthly temperature values. A number of these stations have data into the 1800s, but most station records commenced after 1900. Figure 1 illustrates the coverage of the air temperature stations in the Great Lakes region in 1901, 1931, and 1987. An obvious deficiency is the spatial coverage in Canada and certain portions of the United States. The lack of stations is due to the strict quality control of the all of the station data whereby few stations were able to meet all of the tests required (Karl *et al.* 1990). However, the lack of data in any portion of the basin is partly compensated for by the gridded mapping system, described below, which used all of the available data from those stations as well as the relationship of the data from those stations to other nearby stations.

It should be noted that the temperature data presented here are cooler than those presented in Boden *et al.* (1990) where only temperatures on the U.S. side were included as representative of the entire region. The trends of both data sets are the same, however, indicating that the differences are due to inclusion of higher latitude Canadian data in this study. Table 1 lists the annual and seasonal temperatures from which the 5-year running means were computed.

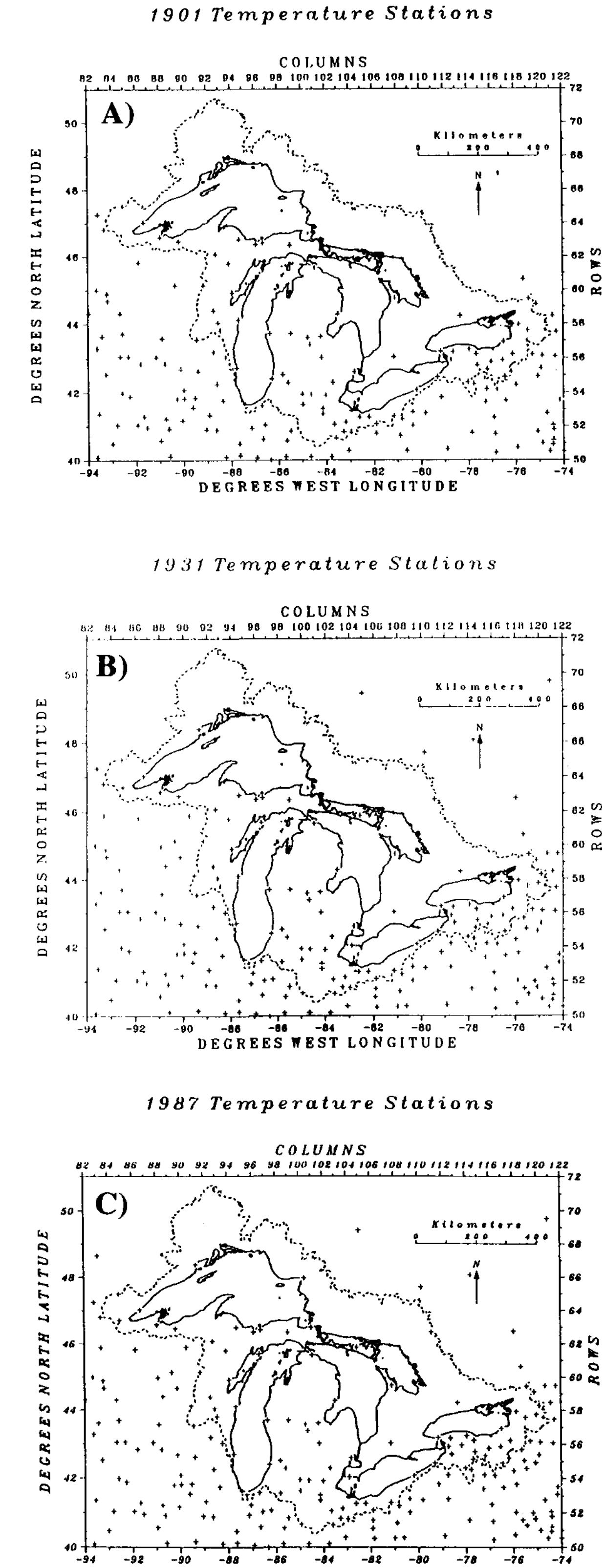

FIG. 1. Location of stations used in this study in (A) 1901, (B) 1931, and (C) 1987.

TABLE 1. Annual, winter (Dec., Jan., Feb.), spring (Mar., Apr., May.), summer (Jun., Jul., Aug.), and fall (Sep., Oct., Nov.) average air temperatures for the Great Lakes basin during the period 1901–1987 in degrees Celsius.

Year	Annual	Winter	Spring	Summer	Fall
1901	5.20	–8.36	3.95	18.82	6.93
1902	5.42	–7.83	5.37	16.28	7.77
1903	4.88	–7.72	5.51	15.77	6.87
1904	3.56	–12.12	2.59	16.42	6.94
1905	4.70	–10.20	3.26	17.23	7.25
1906	5.60	–5.90	3.00	17.99	8.10
1907	4.22	–8.73	1.64	16.79	6.49
1908	5.91	–7.01	3.97	17.86	9.24
1909	5.36	–6.62	2.83	17.93	7.53
1910	5.58	–8.10	5.98	17.97	7.02
1911	5.94	–7.52	4.87	18.25	6.27
1912	4.35	–9.77	2.77	16.49	8.38
1913	5.92	–7.05	3.76	17.92	8.32
1914	5.29	–6.93	3.90	17.82	8.39
1915	5.53	–7.20	4.44	15.72	8.40
1916	5.02	–7.64	2.78	18.66	7.05
1917	3.39	–10.50	2.46	16.76	5.76
1918	5.17	–11.81	5.13	17.46	7.35
1919	5.96	–4.69	4.29	19.30	7.36
1920	5.16	–11.34	3.32	17.37	9.13
1921	7.29	–4.98	6.69	20.04	7.97
1922	5.99	–7.71	5.66	17.80	8.75
1923	5.21	–9.02	2.02	17.91	7.92
1924	4.33	–7.02	2.90	16.60	7.62
1925	5.23	–8.53	4.39	18.14	6.03
1926	4.14	–7.62	1.64	16.90	6.04
1927	5.45	–7.79	4.66	16.05	8.55
1928	5.36	–7.47	3.05	17.31	7.35
1929	4.75	–8.49	4.89	17.05	6.90
1930	5.96	–7.85	4.35	18.46	8.17
1931	7.61	–5.46	4.69	19.12	10.95
1932	5.99	–3.20	3.05	18.40	7.02
1933	5.80	–6.06	4.40	19.13	6.53
1934	5.21	–9.38	3.43	18.15	8.42
1935	5.12	–8.40	3.62	18.44	6.83
1936	4.86	–10.55	4.10	18.37	6.44
1937	5.63	–6.08	3.59	19.15	6.86
1938	6.45	–7.63	5.50	18.81	8.37
1939	5.84	–7.20	3.36	18.75	7.72
1940	4.99	–6.94	2.33	17.90	7.30
1941	6.50	–6.93	5.21	18.66	8.66
1942	5.91	–6.66	6.29	18.08	7.55
1943	4.91	–8.75	2.49	18.73	6.68
1944	6.17	–6.03	3.89	18.72	8.29
1945	5.26	–8.90	5.75	17.20	7.30
1946	6.23	–8.35	6.13	17.32	8.84
1947	5.63	–7.22	2.46	18.61	8.97
1948	5.84	–9.03	4.33	18.25	9.19
1949	6.53	–5.65	4.64	19.56	7.65
1950	4.64	–6.64	1.98	16.81	7.46
1951	5.27	–7.72	4.95	17.10	6.32
1952	6.45	–6.46	4.68	18.68	7.57
1953	6.90	–4.77	4.71	18.71	9.30
1954	5.89	–5.49	3.41	18.03	8.16
1955	6.43	–7.08	5.71	20.19	7.73

Continued

TABLE 1. Annual, winter (Dec., Jan., Feb.), spring (Mar., Apr., May.), summer (Jun., Jul., Aug.), and fall (Sep., Oct., Nov.) average air temperatures for the Great Lakes basin during the period 1901–1987 in degrees Celsius, (continued).

Year	Annual	Winter	Spring	Summer	Fall
1956	5.42	-7.43	2.54	17.61	7.98
1957	5.71	-7.63	4.61	17.95	7.56
1958	5.35	-6.93	5.09	16.88	8.52
1959	5.70	-10.36	4.70	19.31	6.79
1960	5.52	-5.86	3.20	17.57	8.76
1961	6.01	-7.93	4.13	18.00	9.11
1962	5.27	-8.98	5.23	17.50	7.76
1963	5.19	-10.64	4.26	17.99	9.87
1964	6.03	-7.24	5.18	17.73	7.70
1965	5.11	-8.64	3.65	16.67	7.26
1966	5.43	-6.77	3.83	18.67	7.23
1967	5.13	-7.95	3.38	17.60	6.90
1968	5.77	-8.03	5.44	17.54	8.80
1969	5.61	-7.08	4.15	17.74	7.48
1970	5.53	-9.05	4.07	18.64	8.63
1971	5.67	-8.49	3.24	17.62	9.52
1972	4.45	-7.98	3.25	17.01	6.47
1973	6.67	-7.22	5.79	19.05	8.82
1974	5.34	-8.18	3.84	17.89	6.91
1975	6.16	-5.57	3.96	18.79	8.36
1976	5.03	-7.28	4.92	18.50	5.54
1977	5.80	-10.78	7.43	17.34	7.83
1978	4.80	-9.70	3.69	17.59	7.63
1979	4.94	-10.63	4.21	17.47	7.55
1980	5.15	-7.06	4.73	18.02	6.58
1981	5.92	-7.89	5.19	18.25	7.06
1982	5.22	-9.29	4.38	16.65	8.08
1983	6.20	-4.39	3.90	19.60	8.45
1984	5.95	-8.13	3.39	18.56	7.98
1985	5.40	-7.75	6.13	16.95	7.93
1986	6.09	-8.50	6.52	17.49	7.02
1987	7.31	-5.05	6.99	19.20	7.71

METHODOLOGY

In order to overcome limitations due to inconsistent station records and to include all available monthly data, a computer-generated graphics system based on gridded data was used. Gridded data have the advantage that the grids can be summed, averaged, and compared. If, for example, the best possible monthly temperature map for a region was desired, it is reasonable to assume that it should include all available data. If a second map for the following month was desired, it should again include all available data. However, if a map of a 2-month average was desired, one might find that the stations reporting in the first month are not the same as those reporting in the second month. If only those stations which report during both months are used, the map produced is not as representative as a map which composites the "information" presented in the two monthly maps. When monthly station data are gridded, the grids can be averaged to incorporate detail available in each of the monthly maps. A software package designated as Surface III (Interactive Concepts Inc., 1990) was used for processing station data to grids. A cell size of 30 minutes latitude by 30 minutes longitude was used from 94.0° to 74.0°W Longitude by 40.0° to 51.0°N Latitude (170 by 90 cells).

Estimates for temperatures at grid nodes by Surface III was by linear projection (Davis 1986). As defined by the Surface III user manual (Sampson 1988), linear projection is:

> ". . . a two-part procedure in which a weighted average of slopes projected from the nearest neighboring data points around each grid node

are used to estimate the value at the node. Initially, the slope of the surface at every data point must be estimated. The nearest n neighboring observations around a data point are found and each is weighted inversely to its distance from the data point. A linear trend surface is then fitted to these weighted observations... The second part of the algorithm estimates the value of the surface (temperature) at the grid nodes. A search procedure finds n' nearest neighboring data points around the node to be estimated. The X,Y coordinates of the grid node are substituted into each of the local trend surface equations associated with these data points, in effect projecting these local dipping planes to the location of the node. An average of these estimates is then calculated, weighting each slope by the inverse of the distance between the grid node and the data point associated with the slope."

The function used in this study was the inverse distance squared, scaled to extend from from 1 to 0 with increasing distance. Each value was also weighted to account for cell size differences due to longitudinal convergence. Smoothed monthly grids were summed to produce annual grids and the annual grids averaged to form period of record averages. All maps and plots were created with CA-DISSPLA (Computer Associates 1992).

RESULTS

Figure 2 shows a 5-year moving average and a regression line for annual temperatures during the period of record for this study. The slope of the regression line indicates an upward trend in temperatures (correlation coefficient r = 0.403). However, a subjective analysis of the data indicates that fitting a regression line through this time series is likely misleading. From early 1900 through mid 1950, overall basin temperatures increased substantially. A cooler regime prevailed from the mid 1950s through the 1970s with temperatures approximating the average of the previous 50-year period. Temperatures dipped abruptly from the late 1970s through the early 1980s after which they rose quite rapidly.

Analysis of the 5-year moving averages by seasons presents more detail than that indicated by the annual values. For the spring season (Fig. 3), an upward trend has prevailed over the period of record as indicated both by the slope of the regression line (correlation coefficient r = 0.614) and by subjective analysis.

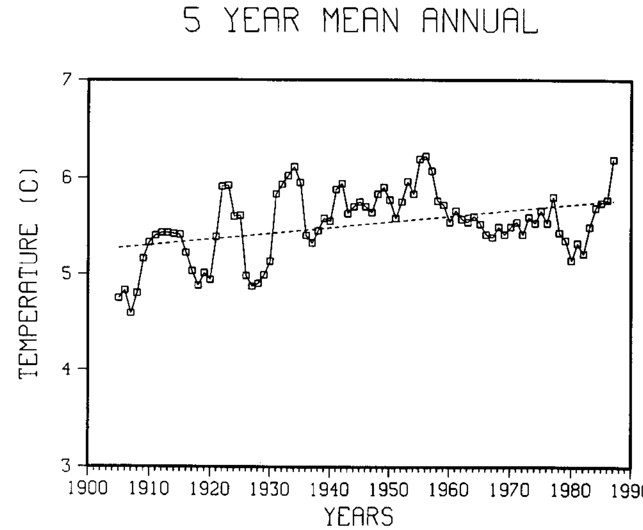

FIG. 2. Five-year moving average of annual temperatures (°C) in the Great Lakes basin.

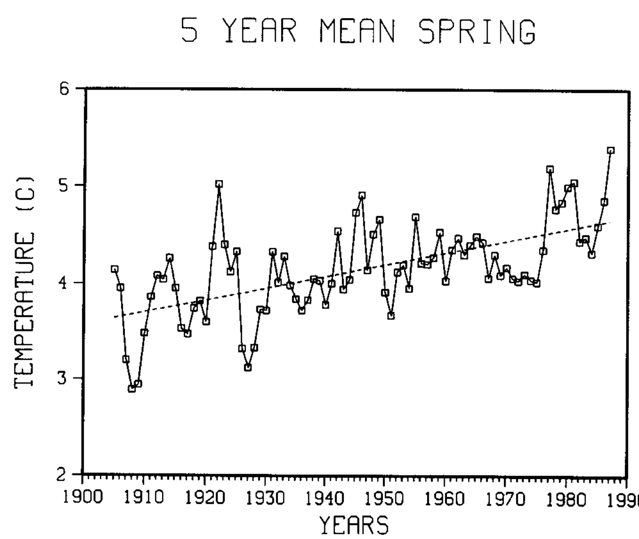

FIG. 3. Five-year moving average of spring temperatures (°C) in the Great Lakes basin.

For the summer season (Fig. 4) the slope of the regression line is also upward, but the correlation coefficient is weak (r = 0.332). Subjective analysis indicates a relatively low temperature regime with an upward trend from the beginning of the period of record until the mid 1910s. A sharp temperature increase occurred from that point until the mid 1920s. Temperatures moved sharply downward from the mid 1920s until about 1930, then sharply upward until the mid 1940s. From the mid 1940s, there has been a slow downward trend in summer temperatures through the end of the period of record.

For the fall season (Fig. 5), the slope of the regression line is also upward, but the correlation coefficient is again weak (r = 0.212). A subjective analysis of the temperatures indicates a slow upward trend from the beginning of the period of record until the mid 1960s at which time a moderate downward trend commenced.

For the winter season (Fig. 6) the slope of the regression line is also upward, but the correlation coefficient is the lowest of all seasons computed (r = 0.064). Subjective analysis indicates a greater complexity than with a single regression line where an upward trend with intermittent wide swings in temperatures is evident from the beginning of the period of record through the mid 1950s after which a lower temperature regime prevailed through the remainder of the period of record. An abrupt increase in temperatures occurred near the end of the period of record, but this rise commenced from low temperature levels in the early 1980s.

A contour plot of the annual temperatures for the basin is shown in Figure 7. The isolines run across the land areas of the basin in a fairly smooth, west to east pattern. Temperature gradations occur mostly on a latitudinal basis with slight increases from east to west due to the influence of the lakes. Isoline values vary from 10°C in the southern portion of the basin to 1°C in the most northern portion of the basin. The contours indicate warmer temperatures over the basin as opposed to the temperatures of the plains to the west and the mountainous regions to the east likely due to the moderating influence of the lakes. However, as shown below, iso-

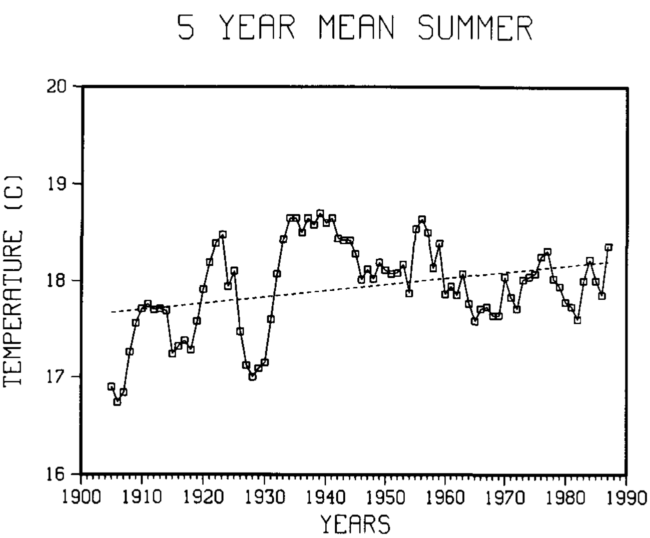

FIG. 4. Five-year moving average of summer temperatures (°C) in the Great Lakes basin.

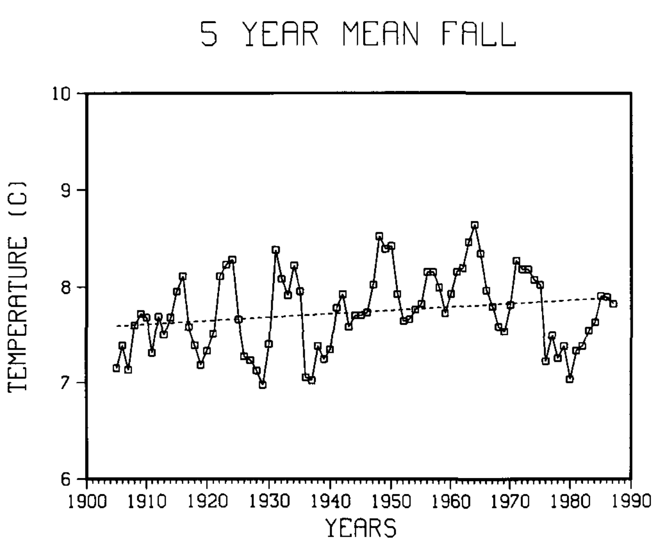

FIG. 5. Five-year moving average of fall temperatures (°C) in the Great Lakes basin.

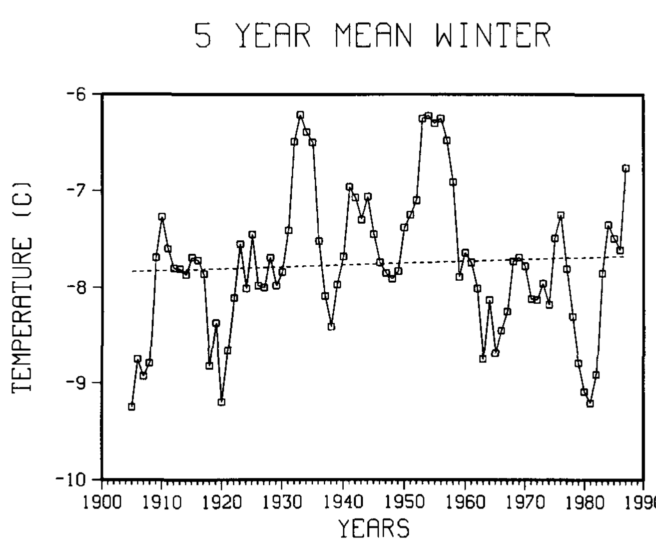

FIG. 6. Five-year moving average of winter temperatures (°C) in the Great Lakes basin.

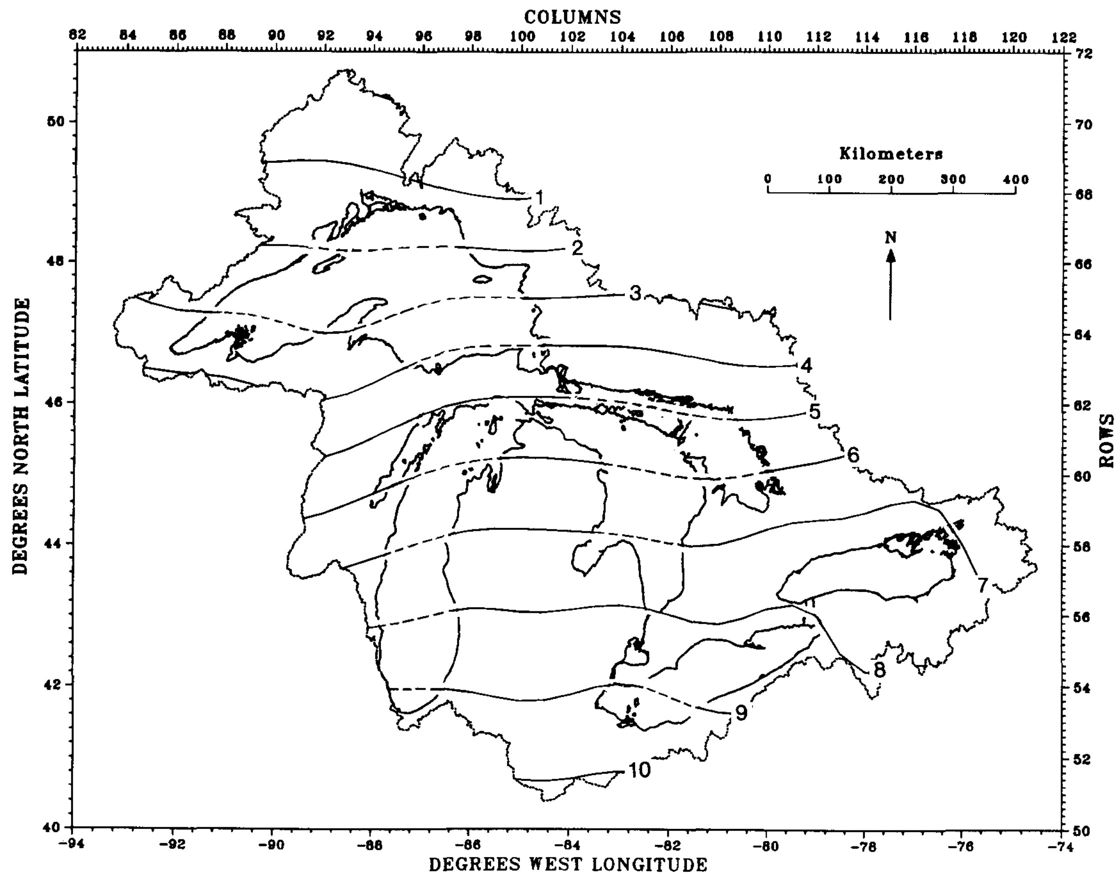

FIG. 7. ***Isolines of average annual temperatures (°C) for the 1901–1987 period. Dotted lines indicate no data.***

lines of differences between long-term mean temperatures and particularly warm or cool years present quite different patterns.

During the recent portion of the period of record, 1987 represents an unusually warm year and 1972 an unusually cold year. Figures 8 and 9 are isolines plots of differences of the grid cell values of those years minus the grid cell values of average temperatures for the period of record. In 1987 (Fig. 8), temperature differences varied from over 3°C higher than the long-term average (1901-1987) in the northwestern portion of the basin to about 1°C higher in the Lake Erie-Ontario area. Those isolines lie generally on a plane tilted from the northwest to the southeast. The fact that the northwestern areas of the basin were impacted the most is likely due to the moderating effect of the lakes on the eastern portion of the basin combined with the predominant westerly flow of air masses over this region. The differences for the cooler than normal year, 1972 (Fig. 9), range from over -1.5°C in the northern portion of the basin to less than -0.8°C in the southern portion of the basin. Note that the contours trend from north to south during this cooler than average year possibly due to the movement into the region of cooler air masses from the north.

DISCUSSION

It appears that, in terms of temperature, the climate in the Great Lakes basin has shown and continues to show appreciable change. Regression analysis indicates an upward trend in temperatures on an annual basis and during each of the seasons. We feel that, except for the spring season, that trend is misleading and that a subjective description of the multiple trends contained within each of the seasons more adequately describes the data. Descriptively, seasonal temperatures indicate a persistent

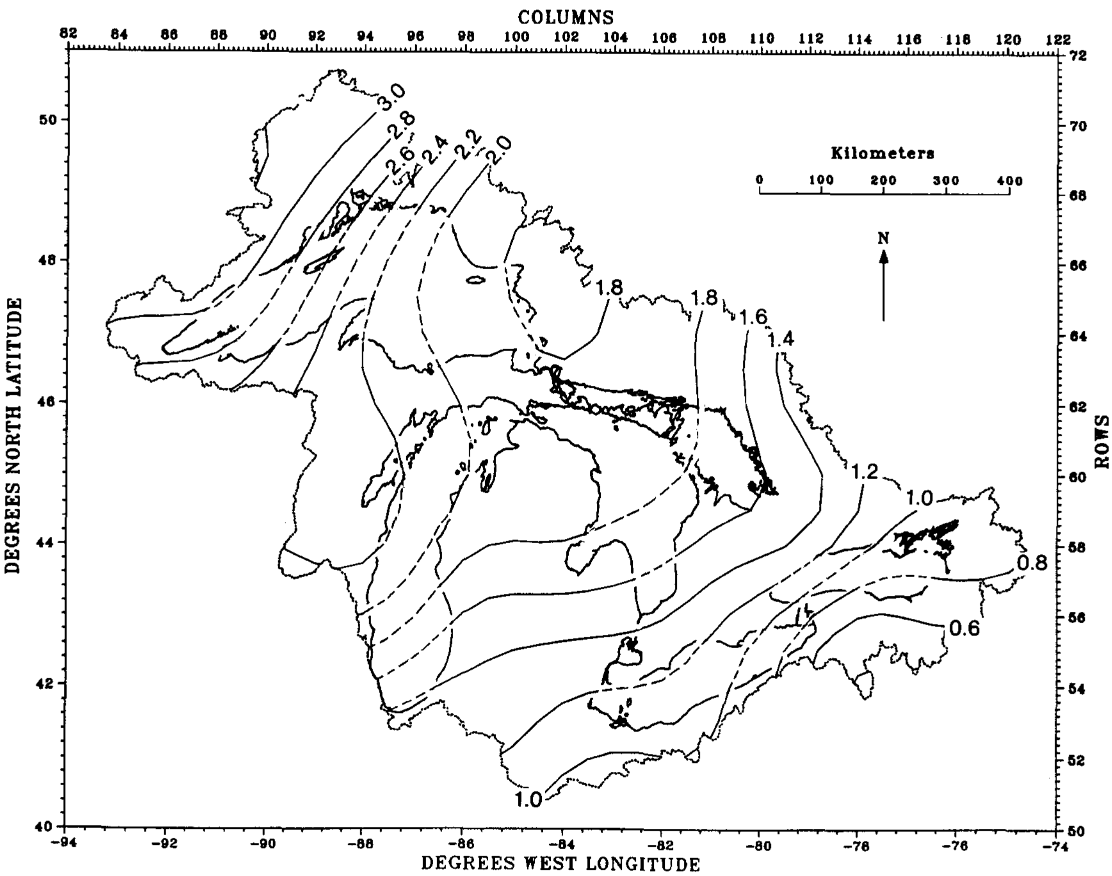

FIG. 8. Isolines of differences, 1987 temperatures minus average annual temperatures (°C) for the 1901–1987 period (1987 was an unusually warm year in the Great Lakes basin). Dotted lines indicate no data.

spring warming, a slow downward trend during the summers since the 1940s, a downtrend in fall temperatures since the 1960s, and a recent lower temperature regime in the winter since the late 1950s. Diaz (1986) speculated that longer-term temperature fluctuations might be ascribed to southward and northward shifts in the storm track that runs from the Midwest/Great Lakes region along the St. Lawrence River Valley toward the North Atlantic. The results here seem to agree with Ojala and Ferrett (1992) who found a recent cooling trend at stations in Michigan. It is noteworthy that Karl and Riebsame (1984) found relatively large spatial temperature gradients between adjacent U.S. climate divisions with opposite climate fluctuations.

At the present time it is impossible to determine whether or not the changes noted here will have a significant positive or negative economic effect on the region. The general slow, but steady, warming of springtime land station temperatures is the most easily recognizable trend and has possibly influenced the extent of the ice season as noted by Hanson *et al.* (1992). The data for Hanson *et al*'s. (1992) study also only included land-based stations, but overwater/ice, or at least shoreline, air temperature data are probably critical for an accurate analysis of ice cover variability. However, if this trend is actual and if it persists, earlier openings of the St. Lawrence Seaway System would be possible, netting increased economic activity in the region. Persistence of the cooler trend in summer temperatures would likely benefit agriculture and hydropower interests due to lower evaporation rates from lake and land surfaces. Cooler fall temperatures would shorten the growing season and tend to be counterproductive to many agricultural interests. When the cooler fall temperatures are combined with cooler winter temperatures, winter recreation interests

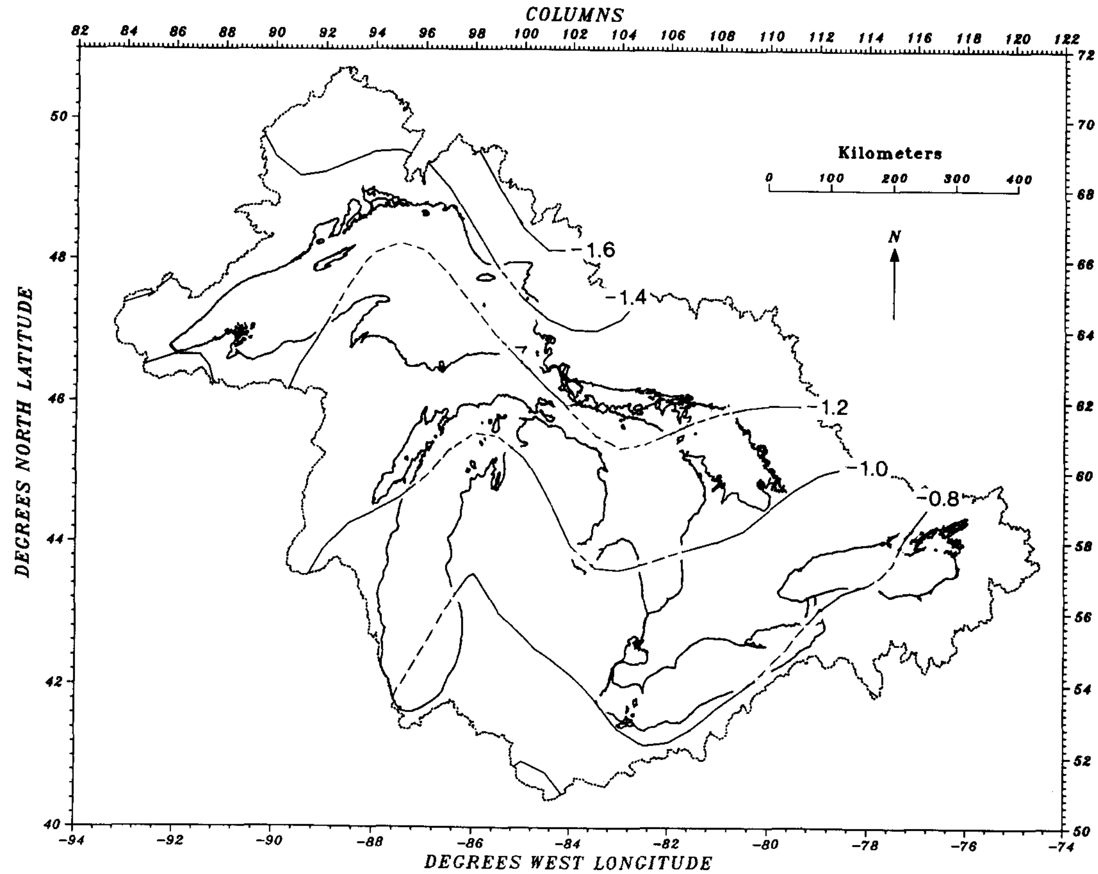

FIG. 9. Isolines of differences, 1972 temperatures minus average annual temperatures (°C) for the 1901–1987 period (1972 was an unusually cold year in the Great Lakes basin). Dotted lines indicate no data.

would benefit, and ice covers on both the Great Lakes and inland lakes within the basin would be more extensive and thicker at least until the springtime period. A thicker and more extensive ice cover would also tend to balance the effect of an earlier springtime warming and shorter extent of the ice season as mentioned above. A possible answer to this apparent conflict between thicker wintertime ice covers and Hanson *et al.*'s (1992) earlier spring ice breakup observations is provided by the fact that the winter cooling appears weaker than the springtime warming. We strongly emphasize, however, that any analysis involving the Great Lakes ice cover should include nearshore and/or offshore air temperature data.

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REFERENCES

Boden, T. A., Kanciruk, P., and Farrell, M. P. 1990. In *Trends '90, A Compendium of Data on Global Change,* pp. 242-243. Carbon Dioxide Information Analysis Center. Oak Ridge National Laboratory, Oak Ridge, TN.

Computer Associates. 1992. CA-DISSPLA Software. San Diego, CA.

Davis, J. C. 1986. *Statistics and Data Analysis in Geology,* 2nd. ed. New York: John Wiley & Sons, Inc.

Diaz, H. F. 1986. An analysis of twentieth century climate fluctuations in Northern North America. *J. Climate and Appl. Meteor.* 25:1625-1657.

Hanson, H. P., Hansen, C. S., and Yoo, B. H. 1992. Recent Great Lakes Ice Trends. *Bull. Am. Meteor. Soc.* 73:577-584.

Interactive Concepts, Inc. 1990. SURFACE III Software, Lawrence, KS.

Karl, T. R., and Riebsame, W. E. 1984. The identification of 10- to 20-year temperature and precipitation fluctuations in the contiguous United States, *J. Climate and Appl. Meteor.* 23:950-966.

_______, Williams Jr., C. N., and Quinlan, F. T. 1990. *United States Historical Climatological Network (HCN) Serial Temperature and Precipitation Data.* ORNL/CDIAC-30, NDP-019/R1. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, Oak Ridge, Tennessee.

Ojala, C. F., and Ferrett, R. L. 1992. Global Warming?, A Case Study of Michigan. *Michigan Academician* 24:467-484.

Sampson, R. J. 1988. *Surface III.* Interactive Concepts, Inc. Lawrence, KS.

Saulesleja, A. 1986. *Great Lakes Climatological Atlas.* Canadian Government Publishing Centre, Ottawa.

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