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Maximum Snowfall at Long-Term Stations in the U.S./Canadian Great Lakes

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Abstract. Heavy snowfalls can pose natural hazards in the North American Great Lakes region. Maximum annual snowfalls are presented from an extensive data base at 82 long-period-of-record stations. In the absence of site-specific information, these data should be useful to designers, planners, and resource managers in the region. A relationship exists between maximum snowfalls and latitude because the northern Great Lakes climate is cooler and drier than the climate of the southern Great Lakes. A relationship between longitude and maximum snowfalls appears to be based on the longitudinal variation of precipitable water vapor aloft. No apparent relationship exists between maximum snowfall and elevation when station data are analyzed without regard to data from lake-effect zones. However, when one lake-effect region was analyzed in detail, an orographic effect was clearly evident in both maximum and average annual snowfalls.

Key words. Maximum snowfall, North American Great Lakes, snowfall.

1. Introduction

Heavy snowfalls can be natural hazards which result in loss of life or property damage. They pose severe problems for air and surface traffic and can damage structures such as power lines and building roofs. In order to minimize some of these problems, Landsberg (1984) proposed 'preventive climatology' which involves analysis of extreme values of weather records. He stated: "There is enough information on snowfalls on file that disastrous roof collapses could be forestalled by proper construction." There is also a possibility that underlying costs of adjusting to severe winter weather might be much larger than direct costs (Riebsame *et al.*, 1986).

In the Great Lakes, heavy snowfalls are common for a variety of reasons, including migratory low pressure weather systems which spawn severe storms; the extent of open water versus ice cover on the lakes (Richards and Derco, 1963; and orographic effects on precipitation (Richards and Derco, 1963; Hill, 1971; and Niziol, 1987). Hsu (1987) may be consulted for a review of climatological studies of Great Lakes snowfall and analyses of lake-effect snowfalls from observations. Mesoscale measurements are described by Agee and Hart (1990). Kelly

(1986) identified three different organizational patterns of lake-effect storms from satellite imagery to determine the pattern frequency. By mapping individual station deviations from a national composite, Harrington *et al.* (1987) identified positive snowfall deviations in the Great Lakes in early winter that are associated with lake-effect storms. Braham (1990) presented *in situ* snow particle size spectra near the downwind shore of Lake Michigan during lake-effect storms. Petersen and Hoke (1989) described problems with the regional analysis and forecast systems in predicting lake-effect precipitation.

An extensive amount of information has been published on all of the above subject areas which makes either an analysis of the many aspects of Great Lakes snowfall or an extensive literature review beyond the scope of this paper. The purpose of this study is to present, as suggested by Landsberg (1984), the results of an analysis of extreme values as one measure of the natural hazards of Great Lakes snows – maximum yearly snowfall at several long-term recording stations. In the absence of site specific information, such data should be useful for design standards and for prediction of catastrophic damages.

2. Data Base

Computerized records of snowfall for stations in the Great Lakes region were obtained from the U.S. National Climatic Data Center and from Environment Canada. The station data were reviewed for length and continuity of record. Stations having fewer than 55 yr of nearly continuous records were rejected on the first cut. After completing this procedure, we found that some areas, the lower portion of the State of Michigan for example, had few or no stations meeting these criteria. Stations with a shorter period of record were then added for those regions. The average period of record for the 82 stations selected was 57.4 yr ranging from 22 to 137 yr of record. Several Canadian stations had periods of record commencing in the 1800s. The earliest U.S. records began in 1900. The locations of most of the stations are within the boundaries of the Great Lakes basin as defined by the International Joint Commission. In some areas there were no suitable stations within the basin, in which case stations just outside of the basin boundary were included. A dense network of long-term stations exists in the southern portion of Ontario. Some long-term stations were deleted in that region. The data base was compiled to specifically provide information on maximum snowfall amounts from stations with a long-term period of record. It will be noted in the results below that a limitation of this nature often obscures certain characteristics of snowfall patterns not directly concerned with maximum annual snowfall.

A station location map and tabular listing of stations are given in Figure 1 and Table I. The period of record varies among the stations and no attempt was made to normalize the period of record by deleting or estimating data. The starting and ending dates for the period of record for each station are given in Table I. The

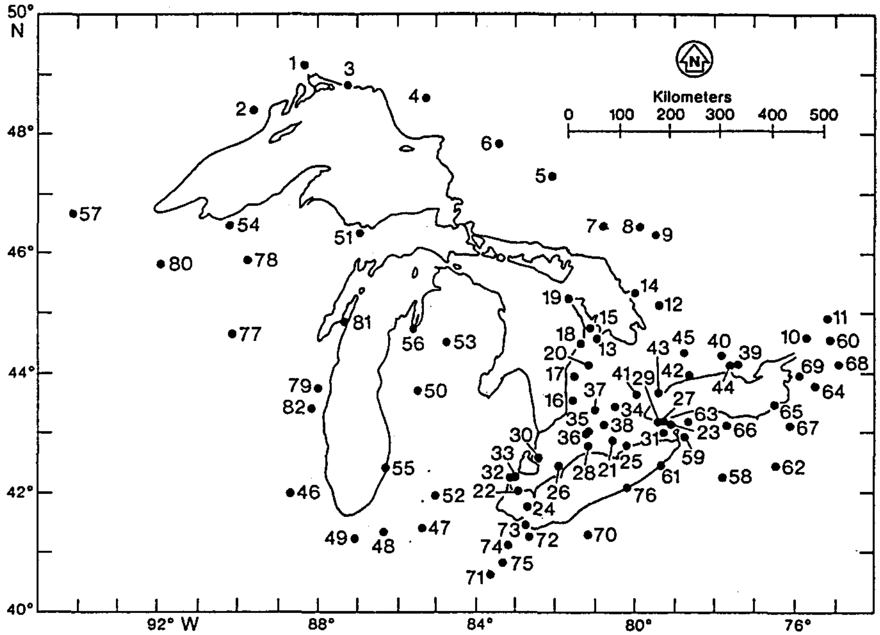

Fig. 1. Station locations. Location numbers refer to the station names listed in Table I.

years of record for each station in the table indicate the number of years of data with complete monthly records for a snow year (October through May) of data.

3. Results

Maximum snowfalls varied from 670.1 cm at Beatrice, Ontario to 115 cm at Albion, Indiana (Table I). For the 82 stations, nearly 30% of the maximum snowfalls occurred during the 1970s (1978, 9 occurrences; 1971, 6 occurrences; 1977, 5 occurrences; 1971, 4 occurrences).

Maximum snowfalls appear to be governed to some extent by station latitude (Figure 2). Decreased maximum snowfall amounts are to be expected at lower latitudes, where precipitation can occur as either snow or rain throughout the season. An upward trend in maximum snowfall amounts is shown as the latitude increases from 40.5 to 45.0°N. The relationship is obvious from Figure 2, but the statistical evidence is poor as indicated by the correlation coefficients from data for all stations ($R = 0.63$) and data only for stations not in lake-effect snow areas ($R = 0.64$) as described by Eichenlaub (1979). The highest maximum yearly snowfalls occurred at 43.5 to 46.5°N with all of those stations located in lake-effect snow zones. Annual snowfall normally decreases north of about 45°N in the Great Lakes region, because the average precipitable water vapor aloft decreases with increasing latitude manifested as a cooler, drier climate than in the southern Great Lakes. Above 45°N, when lake-effect stations were excluded from the regression

Table I. Location numbers corresponding to Figure 1, station latitude and longitude (degrees), station name, station elevation (m), period of record, maximum snow-year (Oct. thru May) snowfall (cm), year of maximum snowfall occurrence, and number of snow-years of record

Location	Lat.	Long.	Name	Elev. (m)	Period of record	Maximum snowfall (cm)	year	Snow-years
Ontario								
1	49.150	88.350	Cameron Falls	229	1924–1987	355.8	1982	55 yr
2	48.400	89.617	Kakabeka Falls	278	1908–1977	337.2	1950	62 yr
3	48.817	87.267	Schreiber	302	1893–1975	438.3	1975	56 yr
4	48.600	85.283	White River	379	1886–1976	446.6	1934	82 yr
5	47.300	82.100	Biscotasing	407	1914–1987	362.3	1954	51 yr
6	47.833	83.433	Chapleau 2	432	1886–1966	328.6	1924	36 yr
7	46.467	80.817	Coniston	237	1921–1976	348.7	1938	49 yr
8	46.450	79.867	Crystal Falls	227	1922–1987	381.4	1951	58 yr
9	46.317	79.467	North Bay	201	1887–1982	304.8	1975	49 yr
10	44.600	75.700	Brockville	91	1871–1980	418.1	1879	67 yr
11	44.917	75.183	Morrisburg	82	1913–1987	405.1	1926	70 yr
12	45.133	79.383	Beatrice	290	1876–1979	670.1	1883	101 yr
13	44.567	80.917	Owen Sound	182	1879–1962	649.1	1899	60 yr
14	45.333	80.000	Parry Sound	194	1874–1976	541.9	1959	99 yr
15	44.750	81.133	Wiarton	182	1883–1936	507.9	1928	45 yr
16	43.550	81.550	Brucefield	259	1903–1987	367.5	1971	63 yr
17	43.950	81.500	Lucknow	290	1885–1987	576.9	1977	95 yr
18	44.500	81.367	Southampton	186	1872–1982	535.2	1943	98 yr
19	45.250	81.667	Tobermory	183	1888–1983	327.3	1928	41 yr
20	44.133	81.150	Walkerton	244	1902–1971	414.2	1934	56 yr
21	42.867	80.550	Delhi CDA	232	1934–1987	242.4	1939	49 yr
22	42.033	82.900	Harrow CDA	191	1917–1987	229.0	1982	67 yr
23	43.133	79.083	Niagara Falls	183	1902–1987	257.0	1960	47 yr
24	41.750	82.683	Pelee Isand	175	1888–1987	209.5	1895	59 yr
25	42.783	80.217	Port Dover	186	1874–1983	276.6	1917	87 yr
26	42.450	81.883	Ridgetown	206	1883–1987	203.7	1954	72 yr
27	43.200	79.250	St. Catharines	91	1882–1987	178.2	1971	48 yr
28	42.783	81.167	St. Thomas	236	1882–1980	252.1	1978	59 yr
29	43.183	79.400	Vineland Station	79	1924–1987	219.4	1960	56 yr
30	42.583	82.400	Walaceburg	177	1905–1987	187.5	1912	55 yr
31	43.000	79.267	Welland	175	1872–1987	404.4	1901	87 yr
32	42.350	83.100	Windsor	191	1866–1929	257.3	1873	44 yr
33	42.267	82.967	Windsor A	190	1940–1987	199.6	1970	46 yr
34	43.433	80.500	Kitchener	343	1914–1977	245.2	1924	54 yr
35	43.033	81.150	London A	278	1940–1987	343.4	1971	45 yr
36	42.983	81.217	London South	246	1883–1932	427.0	1911	47 yr
37	43.383	81.000	Stratford	363	1865–1959	381.9	1883	72 yr
38	43.133	80.767	Woodstock	282	1870–1987	374.4	1883	105 yr
39	44.150	77.400	Belleville	76	1866–1987	413.6	1873	71 yr
40	44.300	77.800	Campbellford	146	1915–1987	286.1	1947	60 yr
41	43.650	79.950	Georgetown	274	1882–1966	265.3	1904	71 yr
42	43.967	78.617	Orono	148	1923–1987	365.3	1941	56 yr
43	43.667	79.400	Toronto	111	1840–1987	314.4	1870	137 yr
44	44.133	77.600	Trenton Ont. Hydro.	88	1915–1987	292.0	1947	65 yr
45	44.350	78.750	Lindsay	267	1880–1971	404.5	1908	77 yr
Illinois								
46	41.983	88.683	Sycamore	256	1901–1965	167.1	1926	46 yr

Table I. *Continued.*

Location	Lat.	Long.	Name	Elev. (m)	Period of record	Maximum snowfall (cm)	year	Snow-years
Indiana								
47	41.400	85.333	Albion 5E	299	1916–1972	115.0	1952	39 yr
48	41.333	86.317	Plymouth Pwr. Substa.	241	1905–1986	246.9	1977	51 yr
49	41.233	87.067	Wheatfield 2 NNW	198	1916–1986	115.5	1957	41 yr
Michigan								
50	43.700	85.483	Big Rapids Waterworks	283	1900–1986	292.9	1952	57 yr
51	46.350	86.933	Chatham Exp. Farm	268	1901–1986	576.6	1984	51 yr
52	41.950	85.000	Coldwater State Schl.	299	1900–1986	215.3	1978	56 yr
53	44.517	84.750	Higgins Lake	363	1908–1978	233.3	1951	22 yr
54	46.467	90.183	Ironwood	436	1901–1986	647.8	1971	64 yr
55	42.400	86.283	South Haven Exp. Farm	192	1926–1986	257.8	1967	36 yr
56	44.732	85.583	Traverse City FAA AP	189	1900–1986	347.7	1985	77 yr
Minnesota								
57	46.667	94.117	Pine River Dam	381	1901–1986	236.7	1971	49 yr
New York								
58	42.250	77.783	Alfred	543	1926–1986	322.5	1970	48 yr
59	42.933	78.733	Buffalo WFSO AP	216	1922–1986	506.6	1977	52 yr
60	44.567	75.117	Canton 4 SE	134	1922–1986	430.0	1971	40 yr
61	42.450	79.300	Fredonia	232	1926–1986	361.1	1977	45 yr
62	42.450	76.450	Ithaca Cornell Univ.	293	1926–1986	292.3	1958	48 yr
63	43.183	78.650	Lockport 2 NE	158	1926–1986	350.5	1978	50 yr
64	43.783	75.483	Lowville	271	1926–1986	637.6	1971	48 yr
65	43.467	76.500	Oswego East	107	1926–1986	638.5	1972	54 yr
66	43.117	77.667	Rochester WSO AP	168	1926–1986	410.8	1960	54 yr
67	43.117	76.117	Syracuse WSO AP	128	1922–1986	409.5	1978	54 yr
68	44.150	74.900	Wanakena Ranger Schl.	460	1926–1986	580.8	1943	39 yr
69	43.967	75.867	Watertown	152	1926–1986	570.3	1977	45 yr
Ohio								
70	41.300	81.150	Hiram	375	1900–1986	265.6	1914	57 yr
71	40.633	83.600	Kenton	299	1900–1986	155.2	1978	55 yr
72	41.267	82.617	Norwalk Sewage Plant	204	1900–1986	209.7	1910	64 yr
73	41.450	82.717	Sandusky	186	1936–1986	150.6	1982	33 yr
74	41.117	83.167	Tiffin	232	1936–1986	154.4	1978	41 yr
75	40.833	83.283	Upper Sandusky	262	1936–1986	180.1	1978	42 yr
Pennsylvania								
76	42.083	80.183	Erie WSO AP	223	1926–1986	362.7	1978	44 yr
Wisconsin								
77	44.650	90.133	Marshfield Exp. Farm	381	1913–1986	224.9	1962	48 yr
78	45.883	89.733	Minocqua Dam	485	1905–1986	411.0	1969	64 yr
79	43.750	87.983	Plymouth	265	1910–1986	233.3	1974	62 yr
80	45.817	91.883	Spooner Exp. Farm	335	1911–1986	236.2	1969	36 yr
81	44.867	87.333	Sturgeon Bay Exp. Farm	201	1905–1986	301.8	1909	60 yr
82	43.400	88.183	West Bend	287	1924–1986	241.5	1979	34 yr

equation computations, the correlation coefficient was 0.47. When lake-effect stations were included in the computations, R was only 0.01.

Longitudinal variations are much less prominent than latitudinal variations. Nevertheless, the pattern shown in Figure 3 is similar to patterns of precipitable

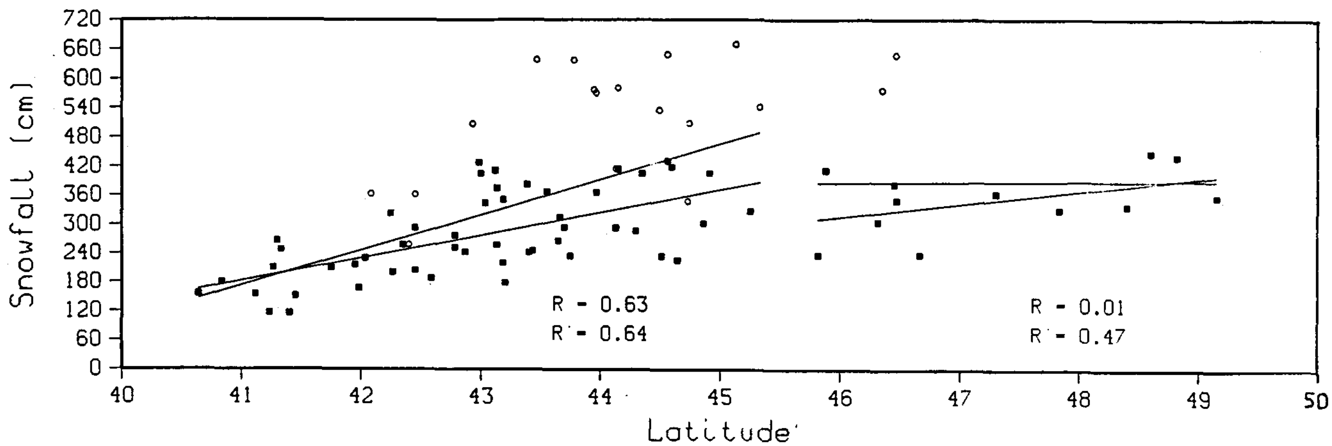

Fig. 2. Scattergram of maximum yearly snowfall amounts (cm) versus North Latitude (degrees). Data from stations in areas defined by Eichenlaub (1979) as lake-effect zones are shown by open circles. Lines of regression and regression coefficients are calculated for data from 40.5 to 45.0°N and for data from 45.0 to 50.0°N, for all data in each category (*R*) and for only non-lake-effect data (*R′*).

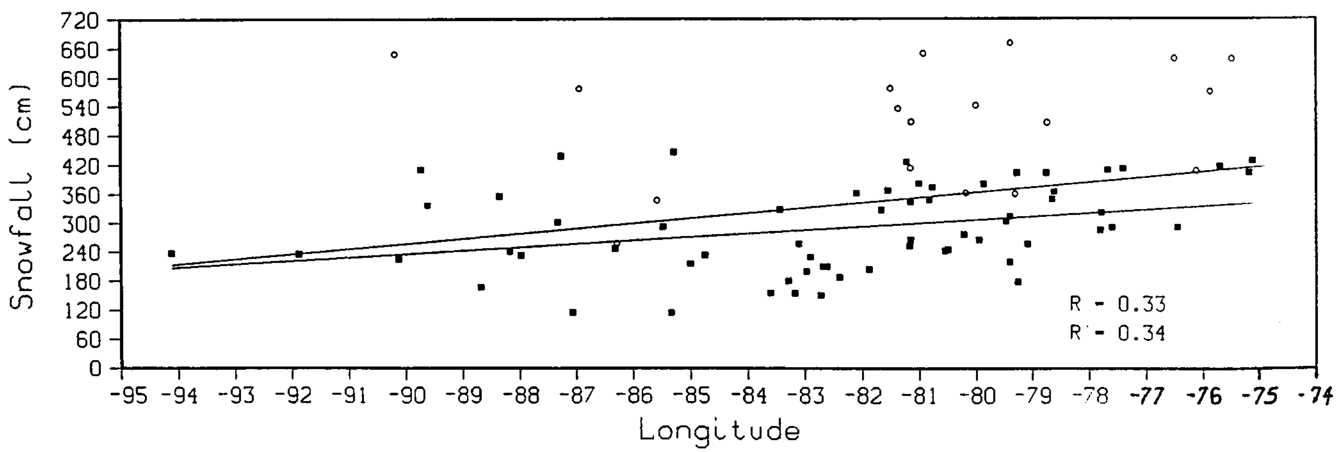

Fig. 3. Scattergram of maximum yearly snowfall amounts (cm) versus West Longitude (degrees). Data from stations in areas defined by Eichenlaub (1979) as lake-effect zones are shown by open circles. Lines of regression and regression coefficients are calculated for all data (*R*) and for only non-lake-effect data (*R*′).

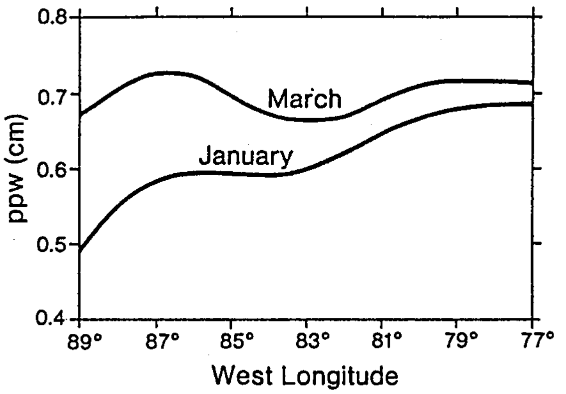

Fig. 4. January and March average precipitable water vapor aloft (ppw) for the period 1956–65 (from Bolsenga, 1967).

water vapor aloft which, during the winter months, rises abruptly from 89 to 87°W longitude (roughly the north-south centerline of Lake Michigan). Moving eastward over the basin, precipitable water vapor drops to minimum values at approximately 84°W longitude (roughly a line passing through the lower peninsula of Michigan). Precipitable water vapor slowly rises again further eastward in the basin from 84 to 77°W longitude. Figure 4 shows data from 89 to 77°W longitude for January and March from data in Bolsenga (1967). Correlation coefficients for Figure 3 are 0.34 and 0.33, excluding and including lake-effect stations in the computations, respectively.

Maximum yearly snowfalls versus elevation are shown in Figure 5. No apparent pattern is demonstrated by the scatter of the points and high maximum snowfall amounts are distributed relatively evenly at elevations ranging from 76 to 543 m. Richards and Derco (1963), Hill (1971), and Niziol (1987) have reported snowfall increases of 25–50 cm for every 100 m of elevation "at the very least". Others disagree and state rates that are significantly different (Lansing, 1963; McMullen, 1963). The wide variance of rates might possibly be due to geographical differences in control factors, such as distance from the shoreline and the direction of a storm's traverse across a slope. However, if the station data in Figure 5 are supplemented to include groups of stations in lake-effect zones located both near the shoreline and at various elevations downwind, the orographic effect is clear as shown in the following example.

Hill (1971) stated:

> As an example of how both the lake and higher terrain operate together to enhance snowfall: Oswego on the eastern end of the lake (elevation 107 m) receives about 90 inches (229 cm) per year while Bennett's Bridge at an elevation of 660 feet (201 m) and 15 miles east of the shore receives 190 inches (483 cm) per year. Further east, Boonville, with an elevation of 1500 feet (457 m) and 50 miles from the shore, receives an average of 209 inches (531 cm) per year.

Data for Bennett's Bridge and Boonville were not included in the maximum yearly

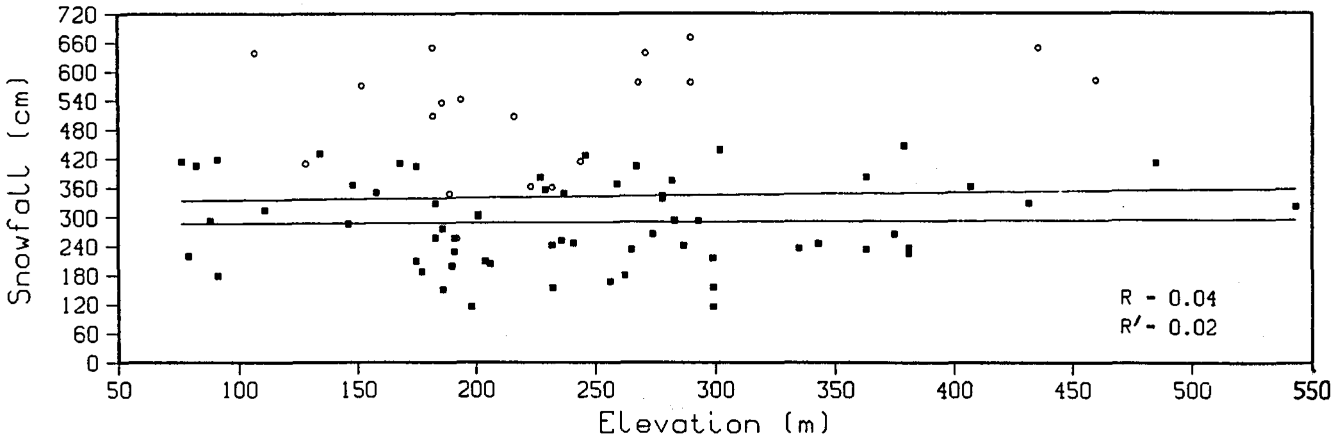

Fig. 5. Scattergram of maximum yearly snowfall amounts (cm) versus elevation (m). Data from stations in areas defined by Eichenlaub (1979) as lake-effect zones are shown by open circles. Lines of regression and regression coefficients are calculated for all data (R) and for only non-lake-effect data (R').

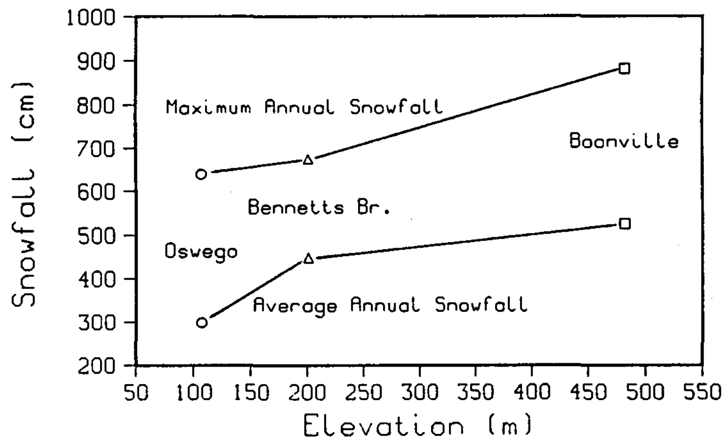

Fig. 6. Maximum annual snowfall and average annual snowfall at Oswego, Bennett's Bridge and Boonville, NY. Both maximum annual and average annual snowfall increase with elevation.

snowfall data set due to missing data and insufficient length of record. However, with the data available (Oswego East, elev. 107 m, 54 yr; Bennett's Bridge, elev. 201 m, 28 yr; Boonville 2 SSW, elev. 482 m, 33 yr), maximum annual snowfall amounts were 638 cm at Oswego, 674 cm at Bennett's Bridge, and 879 cm at Boonville (Figure 6). Average yearly snowfalls at the three stations between 1950 and 1986 for 20 yr in which all of the stations reported data during the same year, were: Oswego, 299 cm; Bennett's Bridge, 448 cm; Boonville, 525 cm (Figure 6). It appears that the changes in annual snowfall with elevation found in the data set presented here are consistent with those reported by both Hill (1971) and Niziol (1987).

Some of the problems in ascribing patterns to the data set are also due to the fact that the measurements were not collected continuously during identical time periods. This deficiency is partially emphasized in Figure 7, which shows an upward trend in maximum snowfall amounts according to increases in the data collection period.

The variability in snowfall amounts, even at stations in close geographic proximity, can be considerable. Certain stations were included in the network to highlight that variability: Stations 32 and 33 (257.3 and 199.6 cm, respectively); Stations 35 and 36 (343.4 and 427.0 cm, respectively); Stations 23, 27, and 29 (257.0, 178.2, and 219.4 cm, respectively); and Stations 39 and 44 (413.6 and 292.0 cm, respectively). Such differences can also be due to factors such as topography, gage exposure, gage error, and variations in observer technique as well as to natural differences in snowfall.

4. Conclusions

The extensive database of snowfall records in the Great Lakes summarized in this report provides information for engineering design and prediction in the absence

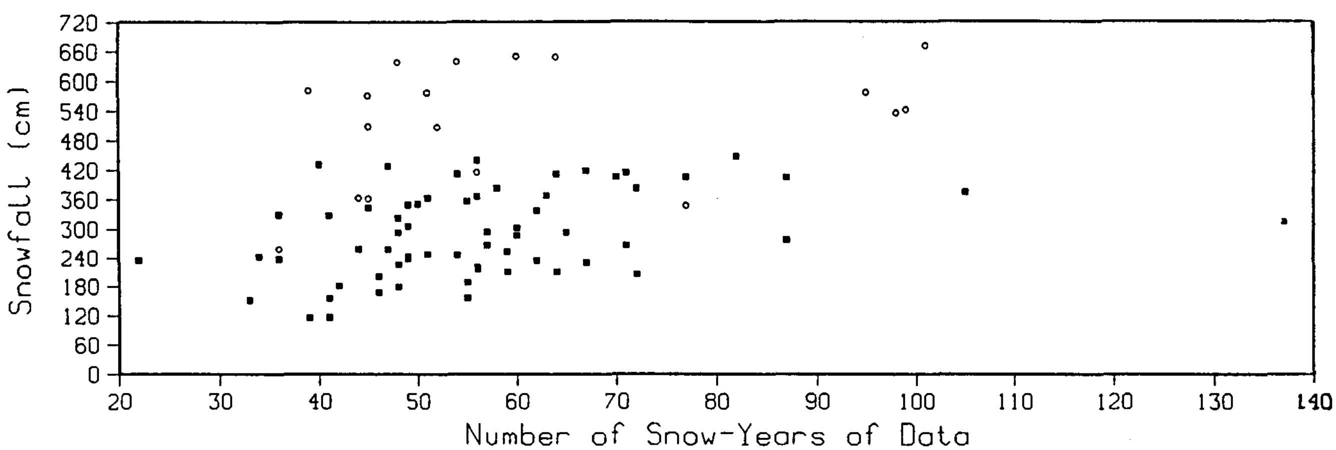

Fig. 7. Scattergram of maximum yearly snowfall amounts (cm) versus number of snow-years of record.

of site-specific information. The value of extensive data analysis is, however, severely limited because the data were not collected over the same period of record nor were all station data continuous. Users of the data for design purposes must be aware of the possibility of extreme spatial variability of snowfall and of the attendant risks when extrapolating these data to sites other than those at which the measurements were actually taken.

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