Maximum Freezing Degree-Days as a Winter Severity Index for the Great Lakes, 1897–1977[1]

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ABSTRACT

General regional and temporal trends in maximum freezing degree-days (FDD's) are identified for the shore zone of the Great Lakes Basin for the 80 winter periods 1897–1977. The cumulative frequency distribution of FDD's at each of 25 locations is used to define winter severity for the 80 winters. Graphs, contour maps and tabulations are used to summarize and portray the spatial and temporal distribution of FDD's and mild and severe winter categories of winter severity.

1. Introduction

In some studies freezing degree-days are defined as the departure of the mean daily air temperature below 0°C, while departures above 0°C are defined as thawing degree days, e.g., Quinn *et al.* (1978). In this paper freezing degree-days are defined as the departure of the mean daily air temperature from 0°C. Temperatures below 0°C are given a positive algebraic sign and temperatures above 0°C are given a negative sign. The cumulative value of FDD's on a given date in the winter is dependent on the start date of the accumulation and mean daily air temperatures from that date. The convention used here is to start the accumulation on the first day after 1 October that the mean daily air temperature falls below 0°C and to continue the accumulation to 30 April of the following year, for a given winter season. If the cumulative FDD value becomes negative on a given date owing to a period of above 0°C temperature, the cumulative value is set to zero and a new FDD summation is started the next day.

Richards (1964) was one of the first investigators to use FDD's in ice-related studies for the Great Lakes. Later Snider (1974), Rogers (1976a) and Assel (1976) also employed the FDD concept in the development of ice prediction equations for the Great Lakes. FDD's have also been used as a measure of winter severity for a given winter season.

The maximum freezing degree-day value for each winter season is the maximum cumulative departure of the average daily air temperature from 0°C and is an index of winter severity. The annual maximum FDD's used in this study are from Assel (1980). For simplicity, a winter season will be designated by the calendar year in which most of it lies, i.e., 1897–98 will be called the winter of 1898. Rondy (1971) used FDD's to classify winter severity and then related winter severity class to ice extent on each Great Lake. Later, Assel and Quinn (1977), using a data base 10 years longer than Rondy's, revised his winter classification. In a more recent study on the 1977 Lake Michigan ice cover, Assel and Quinn (1979) calculated annual maximum FDD values at six locations on the perimeter of that lake for 80 winter seasons. In that study a new winter severity classification scheme was developed and used to identify the extreme winters for Lake Michigan from 1898 through 1977.

For this study, annual maximum FDD's were calculated for the same 80 winter base period at 19 additional stations, bringing the total to 25 stations (20 United States and 5 Canadian) for which long-term maximum FDD records exist (Fig. 1). The temporal and geographic characteristics of the maximum FDD's were investigated. Applying Assel and Quinn's (1979) winter severity classification results in the calculation of limits for each winter severity class. These were used to identify the geographic and temporal patterns for the severe and mild winters for the 80 winters.

2. Temporal trends in maximum FDD's

The general regional trend in annual maximum FDD's was calculated by averaging the annual maximum FDD values for all 25 stations for each of the 80 winters, 1898–1977, and analyzing the resultant time series. The regional average was used to provide an overall view of the Great Lakes. The 80 winter series had a mean value of 605 FDD's (°C) and a standard deviation (SD) of 153 FDD's. The

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FIG. 1. Air temperature station locations.

series was standardized (Fig. 2) and its cumulative departure from the mean calculated (Fig. 3). Fig. 2 shows that the extreme values in the series, i.e., values greater than ±2 SD, occurred in the first half of the series, while Fig. 3 shows a cooling trend between 1898 and 1918, followed by a long-term warming trend lasting until 1958 when a second cooling trend started and continued to the present.

These results are consistent with those of Diaz and Quayle (1978), who made a more detailed temporal analysis of temperature records. In their study a third-order polynomial was fit to regional temperature averages for various time periods. The Great Lakes fall into what they term the east-north-central and middle-Atlantic regions. Their polynomial equations for the average October–March temperature for these regions for the period from 1891 to 1977 show the same three general trends described above. The beginning and ending dates of each period are somewhat different due to differences in data bases and analysis methods.

3. Geographic trends in maximum FDD's

Statistics for maximum FDD values for the 80 winters between 1898 and 1977 at each of the 25 stations studied are summarized in Table 1. In addition, a contour analysis was performed on 1) the greatest value, 2) the smallest value, and 3) the mean value for the 80 winters (Fig. 4). Because of the sparsity of data (only 25 stations), there was some concern as to the representativeness of the contour analysis. However, the general pattern in the contour maps of Fig. 4 was, with a few exceptions, in good agreement with an isothermal contour map of mean daily January air temperature patterns based on much greater spatial resolution, over 400 stations, given in Phillips and McCulloch (1972).

The general pattern in Fig. 4 shows the effect of the Great Lakes, i.e., the largest FDD values are found at higher latitudes and along windward lake shores as would be expected. Lake effect is especially noticeable on Lake Michigan where the contour lines shift north as they cross the lake from

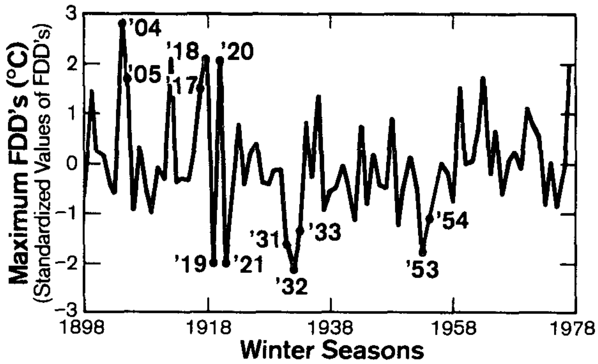

FIG. 2. Standardized values of maximum FDD's.

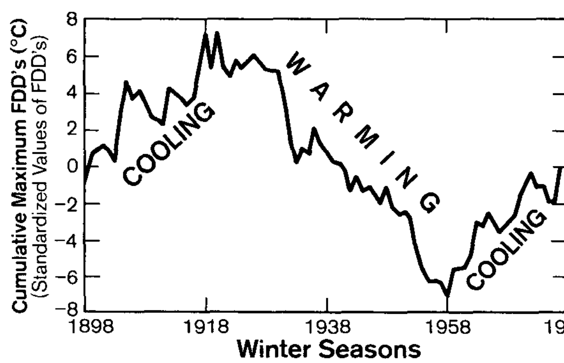

FIG. 3. Cumulative departure from mean (FDD − mean).

TABLE 1. Statistics on maximum annual FDD's (1898–1977) and lower boundaries of winter severity class.

	Value of FDD's (°C)					FDD dates		Severity class boundaries*			
Stations	High	Low	Mean	SD	SD/ Mean	Mean	SD	MN (5%)	N (20%)	SN (80%)	S (95%)
Lake Ontario											
Kingston, Ont. (KIN)	1134	250	675	184	0.27	22 Mar	11	370	524	827	996
Toronto, Ont. (TOR)	854	120	406	156	0.38	13 Mar	13	164	278	524	745
Oswego, NY (OSW)	792	92	397	149	0.38	14 Mar	13	160	276	500	679
Rochester, NY (ROC)	712	83	364	143	0.39	12 Mar	14	124	250	491	623
Lake Erie											
Buffalo, NY (BUF)	683	92	361	142	0.39	12 Mar	13	118	259	484	642
Port Dover, Ont. (PTD)	997	93	445	175	0.39	15 Mar	13	199	322	547	813
Detroit, MI (DET)	745	60	325	146	0.45	7 Mar	15	104	224	441	615
Erie, PA (ERI)	620	30	271	139	0.52	11 Mar	37	61	164	374	565
Toledo, OH (TOL)	757	53	307	155	0.50	5 Mar	37	73	187	417	583
Cleveland, OH (CLV)	671	30	246	145	0.59	5 Mar	51	57	124	371	535
Lake Huron											
Parry Sound, Ont. (PAS)	1403	520	914	196	0.21	28 Mar	11	581	751	1070	1287
Alpena, MI (ALP)	1117	284	670	179	0.27	26 Mar	12	377	524	823	1005
Bay City, MI (BCI)	914	134	457	178	0.39	12 Mar	14	184	326	588	829
Port Huron, MI (PHR)	882	114	402	158	0.39	13 Mar	13	159	282	521	740
Lake Michigan											
Escanaba, MI (ESC)	1326	448	818	195	0.24	29 Mar	11	506	690	974	1193
Traverse City, MI (TVC)	1109	201	563	180	0.32	23 Mar	11	335	408	706	899
Green Bay, WI (GB)	1288	369	790	202	0.26	21 Mar	11	418	639	977	1163
Muskegon, MI (MSK)	800	103	370	150	0.41	12 Mar	12	166	258	462	681
Milwaukee, WI (MIL)	915	160	500	175	0.35	12 Mar	13	245	367	677	827
Chicago, IL (CHI)	779	86	338	166	0.49	28 Feb	17	104	198	479	620
Lake Superior											
Thunder Bay, Ont. (THB)	1851	879	1425	230	0.16	4 Apr	9	982	1250	1657	1778
Houghton, MI (HOU)	1362	513	976	199	0.20	2 Apr	10	621	802	1158	1298
Duluth, MN (DUL)	1738	690	1267	232	0.18	1 Apr	10	877	1052	1468	1653
Marquette, MI (MQT)	1391	403	823	228	0.28	29 Mar	11	469	631	1020	1239
Sault Ste. Marie, MI (SSM)	1467	575	1008	196	0.19	2 Apr	11	679	877	1171	1327

* MN, milder than normal; N, normal; SN, severer than normal; S, severe.

west to east. In areas of little or no data, such as the northeastern shore of Lake Superior, the eastern shore of Lake Huron and the northern shore of Lake Erie, the representativeness of the contour pattern is suspect. Phillips and McCulloch (1972) show contours of mean daily January temperatures paralleling the shore line in the vicinity of the shore and it is probable that the true FDD pattern in the shore zone would approximate this pattern if additional stations had been available for use in the analysis.

4. Winter severity classification

The winter severity classification based on annual maximum FDD accumulations developed by Assel and Quinn (1979) for Lake Michigan is used in this study. Winters are classified into five categories of severity on the basis of the cumulative frequency distribution (CD) of the maximum FDD's for the 80 winter periods. The eight winters with maximum FDD's in the upper and lower 5% of the CD are classified as severe (S) and mild (M), respectively. Winters in the next 15% interval on either side of these extremes, 12 each, are classified as severer (SN) and milder than normal (MN), respectively. And those 48 winters with maximum FDD's in the 60% mid-range of the CD, i.e., between 20 and 80% of the CD, are classified as normal (N). Limits of the five winter classes are given in Table 1.

a. The distribution of the severe and mild winters

The distribution of the severe and mild winters is given in Fig. 5 as a function of the stations shown in Fig. 1 and the 80 winter seasons. Severe winters occurred at one or more stations during 17 of the 80 winters under study. These winters and the number of stations experiencing a severe winter, expressed both as a number and as a percentage of the total stations, are also given in Fig. 5.

Of the $4 \times 25 = 100$ severe winters, 68 occurred in the 22 years from 1899–1920, or 27.5% of the

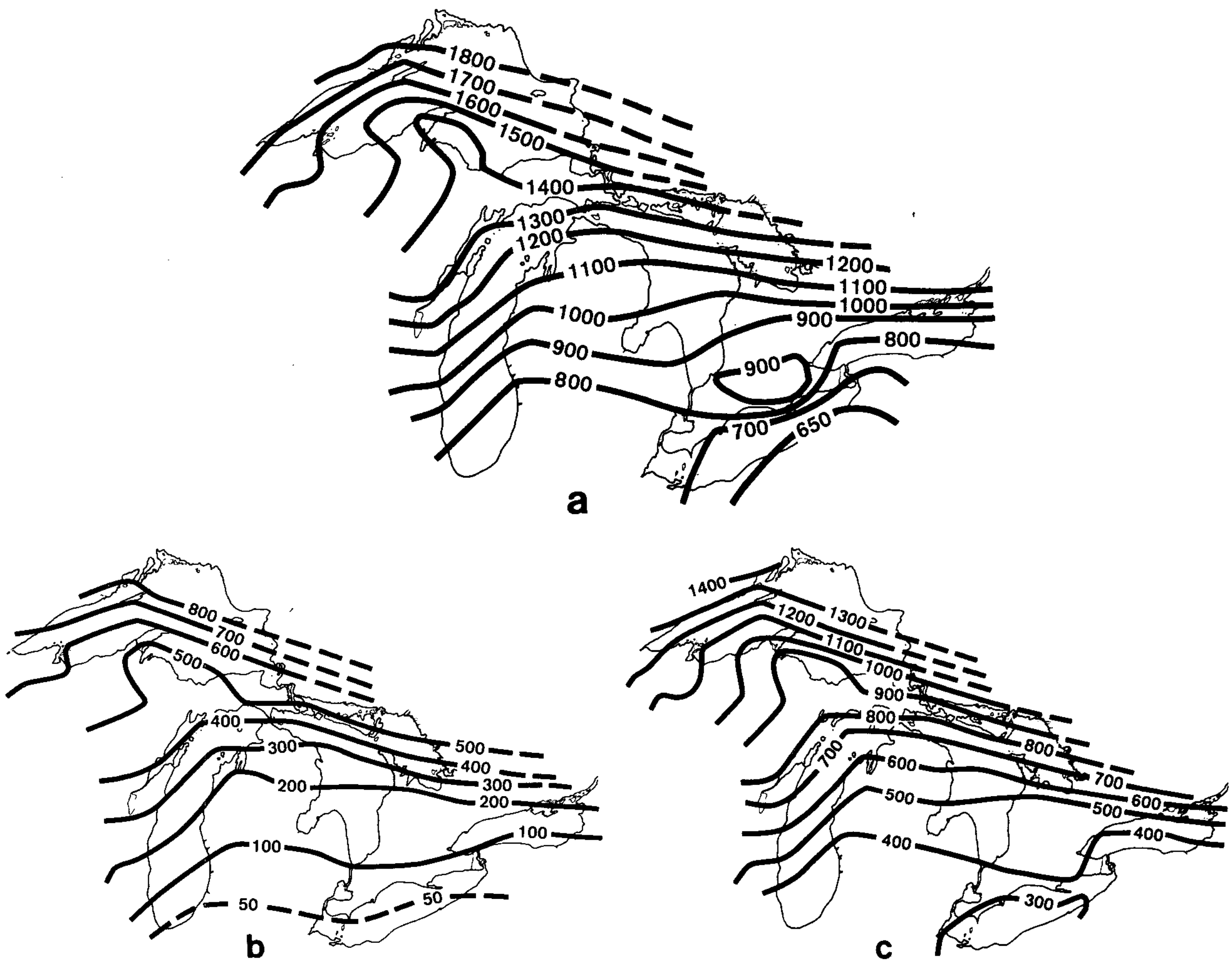

FIG. 4. General patterns of geographic distribution of (a) highest maximum FDD's, (b) lowest maximum FDD's and (c) average maximum FDD's.

80 winter periods. Two major geographic patterns appear:

1) During the winters 1899, 1912 and 1920 when 5, 8 and 8, respectively, of the 25 stations had severe winters, the locations of stations experiencing severe winters expanded farther eastward each succeeding winter; 1920 had at least one severe winter station on every Great Lake. 2) During the winters of 1905 and 1918, 6 and 15 of the 25 stations experienced severe winters, all in the eastern part of the basin, i.e., east of 81°W in 1905 and east of 85°W in 1918.

Other winters in which 5 or more of the stations experienced severe winters were 1904, 1963 and 1977. During 1963, seven stations were on or south of 45°N and during 1977 all but one of the 10 stations experiencing a severe winter were south of a northwest-southeast diagonal from Toronto, Ontario, to Marquette, Michigan. In terms of basinwide extent, the winter of 1904 was the severest: all 25 stations had severe winters. It was followed by 1918 with 15 stations and finally 1977 with 10 stations.

The distribution of the mild winters is also given in Fig. 5. Mild winters occurred in 12 of the 80 winters in the base period. Three general geographic patterns are observed for winters in which 5 or more of the 25 stations experienced mild winters. During the winters of 1919, 1921 and 1932, 18, 16 and 21 of the 25 stations, respectively, had mild winters. There was a random pattern to the distribution of these mild winters, partly because of the large number of stations experiencing mild winters. During the winter of 1931, there was a bias for mild winter in the western part of the Great Lakes Basin as all eight stations having mild winters were west of 85°W. The opposite trend was observed in 1953 when 14 of 16 stations with mild winters were east of 85°W. Finally, during the winters of 1933 and 1949, when 6 and 5 of the stations, respectively, had mild winters, there was a strong geographic bias for the southeastern section of the Great Lakes Basin.

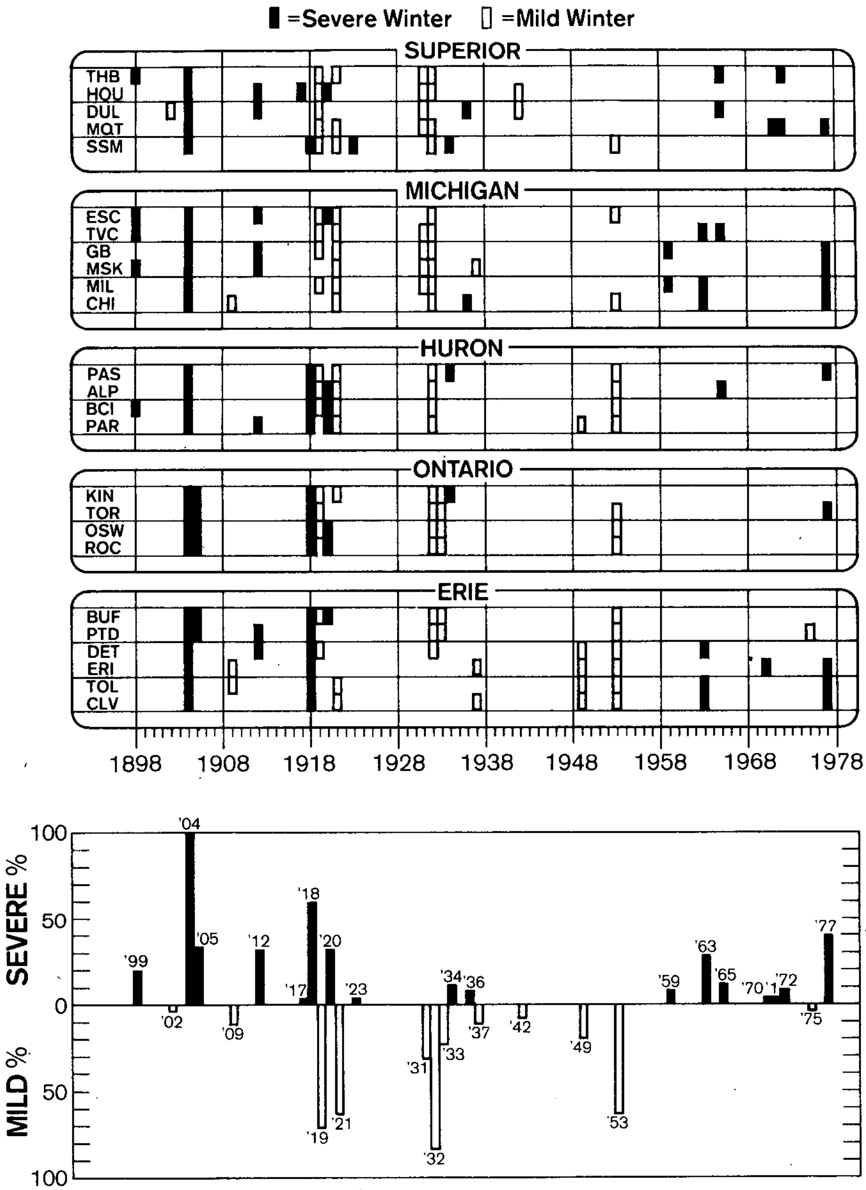

FIG. 5. Distribution of severe and mild winters.

During the winter of 1933, all mild winter stations were located south of 45°N and east of 81°W and during the winter of 1949 all mild winter stations were south of 43°N and east of 84°W. In terms of basin-wide extent, the 1932 winter, during which 21 of 25 stations had mild winters, was the mildest, followed by the 1919 winter with 18 and then 1921 and 1953 with 16 each.

b. Distribution of extreme winters during period of well-documented ice cover on the Great Lakes

The distribution of mild and severe winters from about 1960 to 1977 deserves further comment as it is only during this time that we have well-documented records of large-scale patterns of ice-cover concentration and distribution on the Great Lakes. Also, this period includes the years of a feasibility study and demonstration program to extend the navigation season on the Great Lakes and the St. Lawrence Seaway. Therefore the severity of these winters relative to the 80 winter data base is of particular importance.

During only one winter (1975) and at only one site (Port Dover, Ontario) was the winter classified as mild. During this same period, severe winters occurred at seven sites in 1963, three sites in 1965, one site each in 1970 and 1971, two sites in 1972 and ten sites in 1977. Expressed as a percentage of the total number of severe winters at all sites, 24% of all severe winters between 1898 and 1977 occurred during 18.75% of this period, the 15 winters between 1963 and 1977. Ice and weather conditions for the particularly noteworthy 1977 winter are described by Quinn *et al.* (1978). Thus, in terms of the winter severity index, the period of well-documented ice cover for the Great Lakes contains winters representative of one extreme, i.e., severe winters, but not of the other, mild winters.

5. Summary

The geographic and temporal trends identified in this study are primarily confined to the nearshore zone of the Great Lakes and are representative of lake effect thermal regimes. Lake effect boundaries have been identified in other studies, such as those of Eichenlaub (1979), Kopec (1965) and Leighly (1947). In the nearshore zone, maximum FDD values are likely to be smaller compared to sites farther inland because of the moderating effect of the Great Lakes on winter air temperature. This moderating effect is greater along lee lakeshores owing to warming of air as it crosses the lake, as illustrated by the northward shift of the contours of maximum FDD's crossing from western to eastern shores of Lake Michigan.

On a regional basis, three temporal trends in maximum FDD distribution were identified: a cooling period from 1898 to 1918, a long-term warming period from about 1920–58, and a second cooling period from 1958 to the present. This was reflected in the distribution of the mild and severe winters: a majority of the severe winters occurred in the two cooling periods and a majority of the mild winters occurred in the warming period. On a subregional basis, strong patterns in the geographic distribution of extreme winters were observed at times; for example, the 1905 winter showed that all stations experiencing a severe winter were located in the southeastern portion of the region. The examination of general circulation patterns over North America and associated sea surface temperatures as was done by Rogers (1976b) and Namias (1969, 1971, 1978) might help explain these patterns and is an area where further study may prove fruitful.

Finally, the winter severity classification presented here can be used to put the severity of the last 80 winters, i.e., between 1898 and 1977, into proper perspective. One application of this is the comparison of the period of well-documented ice cover with the 80 winter base period. This comparison shows that the last 15–20 winters have contained severe winters but, with the exception of one occurrence at one station, no mild winters.

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