FROZEN PRECIPITATION - ITS FREQUENCY AND ASSOCIATED TEMPERATURES

by

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INTRODUCTION

Among the major winter problems in cities in the northeastern United States and southeastern Canada are those caused by frozen precipitation. Snow on roads and runways can paralyze transportation, and ice accretion on trees, wires and antennas can create excessive loads and cause costly damage (Austin and Hensel, 1956; Bennett, 1959; Pierce, 1969; Boyd, 1970).

To meet the increasing demand for uninterrupted winter operations, new methods such as thermal anti-icing systems and mechanical devices are being developed (Toms and Kidd, 1965; Kuroiwa, 1965). In designing such systems and determining their maintenance requirements, information on the frequency of various types of frozen precipitation and the air temperatures at which they occur is useful. Studies of the relationships between snow and ice occurrence and climatic parameters have previously been made in Canada (Boyd, 1955; McKay and Thompson, 1969); in the U.S. (Epstein, 1965); and in the USSR (Library of Congress, 1964; Zavarina and Borisenko, 1967). In this study, data on frozen precipitation at two Canadian and nine U.S. cities were analyzed and tables and graphs are presented for use in solving problems in design, construction and operation of snow and ice control equipment.

DESCRIPTION OF ORIGINAL DATA

The machine-tabulated data used for this study were compiled at the U.S. National Weather Records Center, Asheville, N.C. The cities studied and the specific locations of each of the sites are listed in Table I. The period of record for all sites is 10 years from January 1951 through December 1960 except for New York and Washington, D.C. An eleven-year record (October 1949 through December 1959 and January 1950 through May 1960) was used for the other two stations.

The tabulated data consisted of a count of the hours during each month when frozen precipitation occurred at specific temperatures. An hour was not counted if the precipitation amounted to a trace or less. The air temperatures are those observed at the time of the regular hourly observation and were rounded off so that 32°F, for example, includes 31.5° through 32.4°F.

The frozen precipitation types were divided into three categories:

Category a. Snow and snow showers

Category b. Snow pellets, ice crystals, snow grains, soft hail and sleet

Category c. Freezing rain and freezing drizzle.

Where categories a and b were observed together, the count was shown under a. Where b and c were observed together, the count was shown under c. The cases where categories a and c or a, b and c occurred together were negligible.

ANALYSIS OF THE DATA

In a previous report relationships between frozen precipitation and associated meteorological conditions in large cities were investigated (Bilello, 1967). However, only the results for LaGuardia Airport and Buffalo, New York, were discussed in the 1967 report. The information obtained from all 11 major cities (including N.Y. and Buffalo) in eastern U.S. and Canada form the contents of this paper. Although other climatic parameters, such as wind speeds during snowstorms, were investigated in the 1967 report, this paper considers only frequency of occurrence of various types of freezing precipitation and the air temperatures observed during the time of precipitation.

In the previous study, frequency of occurrence was determined by dividing the number of hours during which frozen precipitation was observed by the total number of hours in the period of record to obtain a probability value. For example, if snow and/or snow showers over a 10-year period were observed during 1488 hours in December (total hours = 31 x 24 x 10 or 7440), the probability of occurrence is 1488/7440 or 20% of the time. Another approach, and one which appeared more meaningful for this study, is to calculate the average number of hours per month that each precipitation type can be expected to occur. (This value is computed by dividing the number of hours of observed frozen precipitation for each month by the number of years of record.)

The results, computed monthly for each city, are shown in Tables II, III and IV for categories a, b and c respectively. In addition, the average air temperatures (°F) observed during the precipitation period are given. These temperatures were obtained by drawing cumulative frequency curves (from 0 to 100%) using the observed concurrent air temperature data given in the original computer tabulation; the average temperature is the value intersecting the 50% level on these curves.

From Table II note that snow and/or snow showers occur from October through April at most locations and briefly into May at Buffalo, Cleveland, Montreal, Pittsburgh, Toronto and Ypsilanti. Significant differences in snowfall occurrence are evident when stations like Buffalo and Montreal are compared with Philadelphia and Washington, D.C. For example, during January at Buffalo snow and/or snow showers, on the average, are observed during 255 hours, whereas at Philadelphia they occur during only 31 hours of the month.

To show the regional variation in snow occurrence the average number of hours per month (given in Table II) for each city was plotted on a map of the area under study (Fig. 1). The marked difference in snowfall frequency between the coastal and inland stations is apparent. The inland locations have snow much more often than the cities along the coast. Although the relative locations of these places with respect to latitude account for part of these differences the ameliorating effects of the Atlantic Ocean are undoubtedly of major importance. The average temperature observed during the time of snowfall in January for each station (Table II) is shown in Figure 1 to point out this oceanic influence. The highest average temperature for the inland stations is at Pittsburgh (24°F). This is colder than the lowest temperature at the coastal stations (25°F at Chicopee Falls), despite the fact that the latter station is about 2 degrees further north.

Another unique feature is that the seasonal bar graphs for the inland stations in general show a normal distribution, whereas snow occurrence at the coastal stations does not peak in mid-winter but remains rather uniform from December through March. Attempts to explain this difference would be speculative and will consequently be avoided. However, it should be stressed that other factors such as topography (e.g. the Appalachian Mountains) and local effects naturally create snow frequency and temperature patterns different from those shown in Figure 1, especially on a storm-to-storm or year-to-year basis.

From Tables III and IV we find that frozen precipitation categories b anc c occur significantly less often than category a. In fact, on an average annual basis snow is observed about nine times more often than either of the other two categories. The season for b and c also is shorter, extending mainly from November through March and briefly into April. Category b precipitation types generally occur most often at the inland stations, Montreal in particular. The concurrent air temperatures (Table III) vary greatly because of the many types of frozen precipitation in this category.

Table I. List of stations in the study.

City	Location	State or Province
Bedford	Hanscom Field	Massachusetts
Buffalo	W.B.*Airport Station	New York
Chicopee Falls	Westover AFB	Massachusetts
Cleveland	W.B.*Airport Station	Ohio
Montreal	Dorval Airport	Quebec
New York	La Guardia Airport	New York
Philadelphia	W.B.*Airport Station	Pennsylvania
Pittsburgh	Greater Pittsburgh Airport	Pennsylvania
Toronto	Malton Airport	Ontario
Washington	Washington National Airport	D.C.
Ypsilanti	Willow Run Airport	Michigan

* Now National Weather Service

Table II. Average number of hours per month with snow and the average air temperature observed during the precipitation period.

Station	Oct		Nov		Dec		Jan		Feb		Mar		Apr		May	
	No. of hr	Avg temp	No. of hr	Avg temp	No. of hr	Avg temp	No. of hr	Avg temp	No. of hr	Avg temp	No. of hr	Avg temp	No. of hr	Avg temp	No. of hr	Avg temp
Bedford	1	35	9	34	42	26	74	26	66	27	67	31	15	33	0	
Buffalo	6	34	86	31	191	25	255	22	196	25	151	28	40	33	2	37
Chicopee Falls	2	36	8	31	40	27	68	25	54	27	60	30	11	33	0	
Cleveland	7	36	85	31	133	26	191	23	139	25	130	28	33	33	1	38
Montreal	3	35	48	29	162	23	167	18	156	22	103	27	13	33	1	35
New York	<1	35	5	33	23	31	33	30	31	30	38	32	7	34	0	
Philadelphia	<1	36	7	32	22	31	31	29	21	29	32	32	3	34	0	
Pittsburgh	8	33	73	30	142	26	180	24	124	25	122	28	29	33	<1	40
Toronto	3	34	53	29	129	26	174	22	119	26	97	28	22	34	1	35
Washington, D.C.	0		7	32	13	33	22	30	14	31	22	32	2	34	0	
Ypsilanti	2	36	73	29	116	25	153	23	107	26	101	28	26	34	1	35

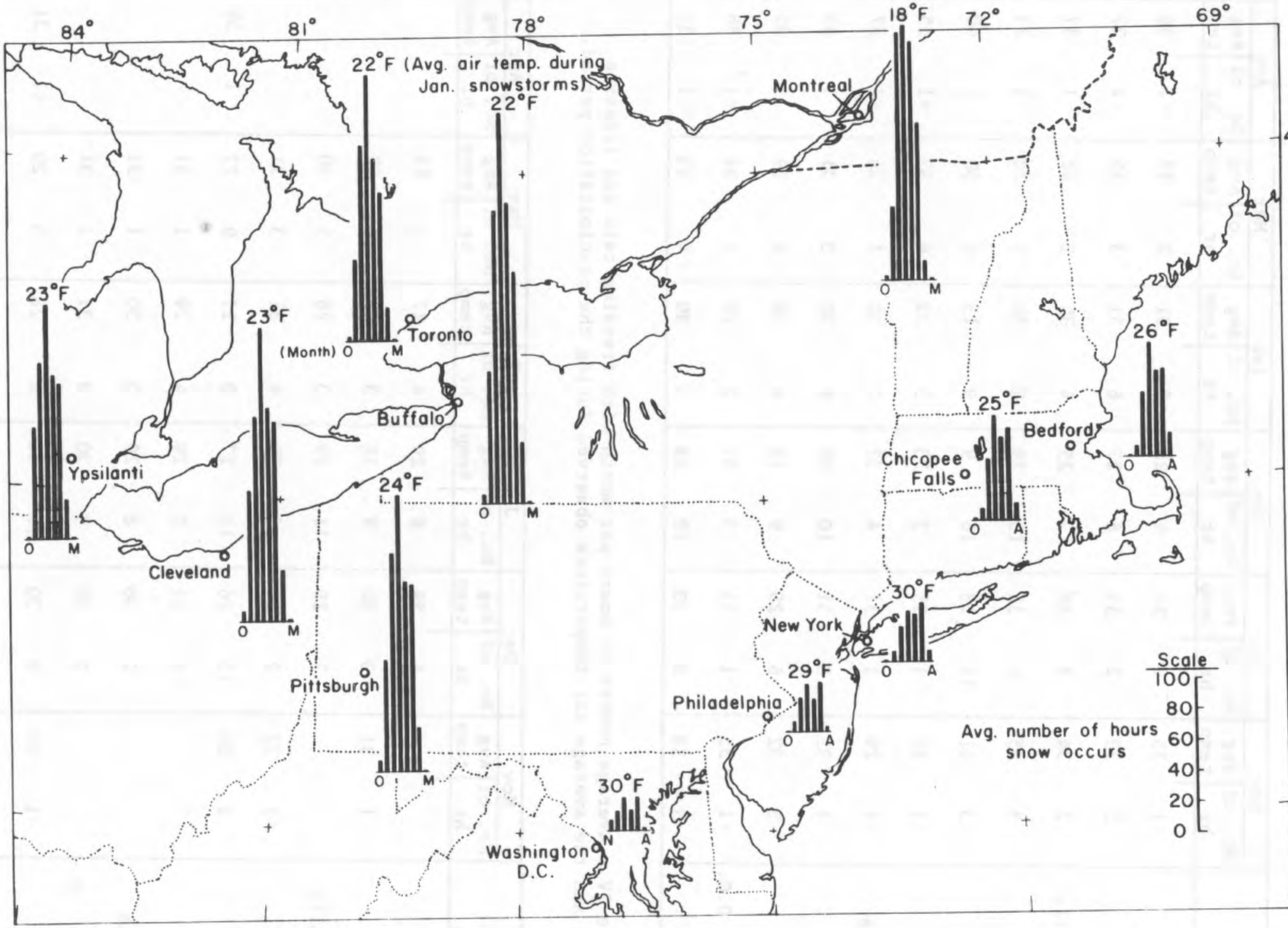

Figure 1. Average number of hours of snow observed per month and concurrent air temperatures during the January storms.

Table III. Average number of hours per month with snow pellets, ice crystals, snow grains, soft hail and/or sleet and the average air temperature observed during the precipitation period.

Station	Nov		Dec		Jan		Feb		Mar		Apr	
	No. of hr	Avg temp	No. of hr	Avg temp	No. of hr	Avg temp	No. of hr	Avg temp	No. of hr	Avg temp	No. of hr	Avg temp
Bedford	1	35	3	31	4	28	3	31	2	33	<1	36
Buffalo	2	33	2	33	8	27	6	31	3	33	<1	37
Chicopee Falls	2	34	2	30	7	25	4	30	3	32	1	37
Cleveland	3	35	4	32	15	29	9	30	5	32	1	33
Montreal	3	31	12	13	16	9	9	13	6	30	1	40
New York	<1	36	1	35	3	33	3	33	4	33	<1	35
Philadelphia	<1	29	1	31	4	32	2	32	1	34	<1	37
Pittsburgh	1	33	5	31	10	28	6	30	3	31	1	37
Toronto	3	32	6	25	9	15	6	28	4	29	1	35
Washington, D.C.	<1	35	1	35	3	32	2	28	1	34	<1	38
Ypsilanti	3	33	8	30	12	28	7	30	4	33	1	35

Table IV. Average number of hours per month with freezing rain and freezing drizzle and the average air temperature observed during the precipitation period.

Station	Nov		Dec		Jan		Feb		Mar		Apr	
	No. of hr	Avg temp	No. of hr	Avg temp	No. of hr	Avg temp	No. of hr	Avg temp	No. of hr	Avg temp	No. of hr	Avg temp
Bedford			5	29	9	29	4	27	3	29		
Buffalo	1	31	3	30	9	28	3	29	4	29		
Chicopee Falls			7	29	11	29	3	26	5	30		
Cleveland	<1	32	2	29	6	30	4	31	3	31		
Montreal	2	30	15	26	13	27	9	27	9	27	1	30
New York			<1	31	5	29	4	29	1	31		
Philadelphia			2	30	6	29	3	30	1	31		
Pittsburgh			2	30	9	30	3	31	1	31		
Toronto	<1	32	6	30	12	30	6	28	5	29	<1	31
Washington, D.C.	<1	33	2	30	5	29	2	31	<1	32		
Ypsilanti	1	31	4	30	12	30	6	29	4	30		

The regional variations for category c (freezing rain and freezing drizzle) shown in Figure 2 differ considerably from those for category a. The data used for the bar graphs in Figure 2 appear in Table IV; note that the scale given in Figure 2 is one-tenth of that used in Figure 1. There are no marked regional differences for freezing rain and drizzle as there were for snowfall occurrence. The frequencies reported in Massachusetts for example equal or exceed those of the inland stations. The greatest differences in frequency are found when New York, Philadelphia and Washington, D.C., are compared with Montreal.

The average temperatures observed during the time of freezing rain and freezing drizzle in January for each station (Table IV) are shown in Figure 2. In contrast to the regional variations in temperature found in Figure 1, the temperatures for category c precipitation are very uniform for all regions (between 27° and 30°F). Maximum frequency values occur mostly in January, the only exception being Montreal where the maximum month is December.

Naturally, these average values should be used with caution because they mask the occasional long, severe ice storm. Frequency and specific storm studies on icing and glaze have been conducted by other investigators; for example, Bennett (1959), Ackley and Itagaki (1970), Downs (1938) and Metcalfe (1949).

AIR- AND PRECIPITATION-TEMPERATURE RELATIONSHIPS

An interesting aspect of the study, useful in practical applications, is the comparison of these storm temperatures with the mean* monthly air temperatures for corresponding stations. These comparisons were made for all but three stations in the study during snow and snow showers (Fig. 3). Bedford, Chicopee Falls and Ypsilanti were omitted in the analysis because mean air temperatures for these locations were not immediately available. As expected, the results of these temperature relationships show good correlation.

Two estimated best-fit straight lines are shown in Figure 3. One incorporates the points below the mean monthly air temperature of about 35°F, the second the points above that temperature. The equation for the former line is $y = 2x - 24$ (y = the mean monthly air temperature and x = the average air temperature during snowstorms) so that, at a temperature of 24°F the x value equals that of y. When the mean monthly temperature is above 24°F the average air temperature when it is snowing is less than 24°F; at temperatures below 24°F the reverse is true. The change in the slope of the best-fit line for the second set of points shows that the difference between the mean monthly air temperature and the temperature observed when it is snowing is even greater when the mean monthly value is above 35°F. Note that most of the points in Figure 3, with respect to the average air temperature during snowstorms, lie between 25° and 35°F. This means that few snowstorms are observed at temperatures above and below this range and that the best-fit lines mainly refer to the 25° to 35°F range on the x-axis.

A similar analysis was conducted for the various forms of frozen precipitation listed under category b (Fig. 4). Two best-fit straight lines are shown in Figure 4. The values for line A may possibly be associated with air temperatures observed during periods of ice crystal occurrence, when an extremely cold environment is required. The values pertaining to line B show considerable scatter, perhaps due to the variety of frozen hydrometeors in this category.

* For convenience, <u>mean</u> is used to define the long-term monthly air temperature and <u>average</u> to define the air temperature observed during the occurrence of each of the freezing precipitation types.

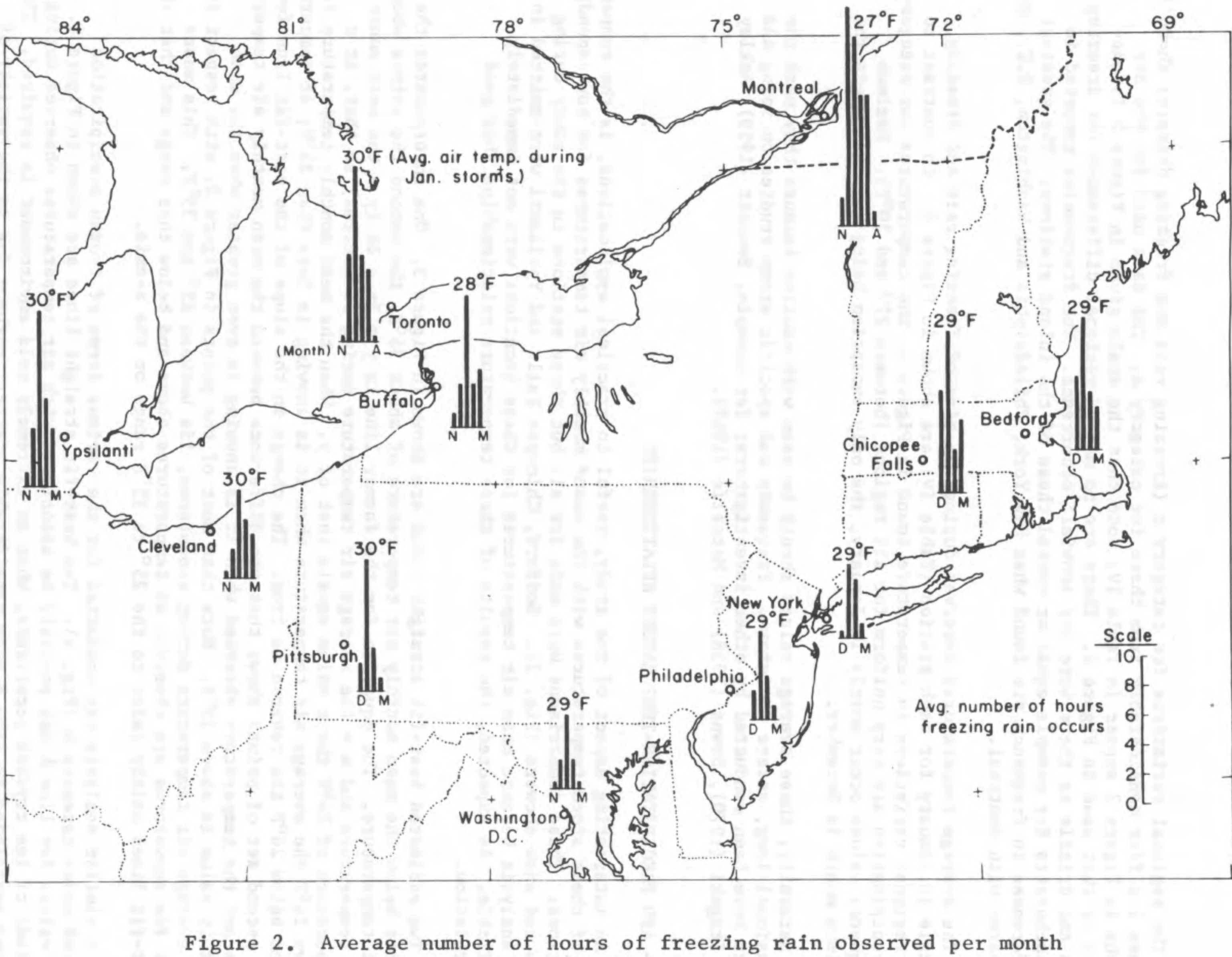

Figure 2. Average number of hours of freezing rain observed per month and concurrent air temperatures during the January storms.

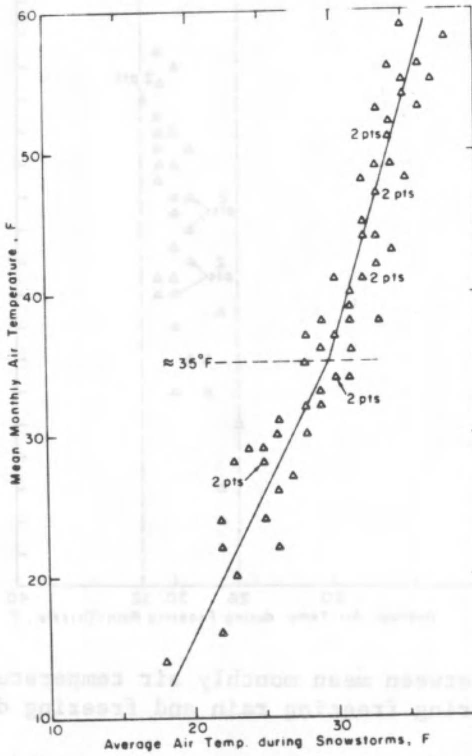

Figure 3. Relationship between mean monthly air temperature and average air temperature during snow or snow showers.

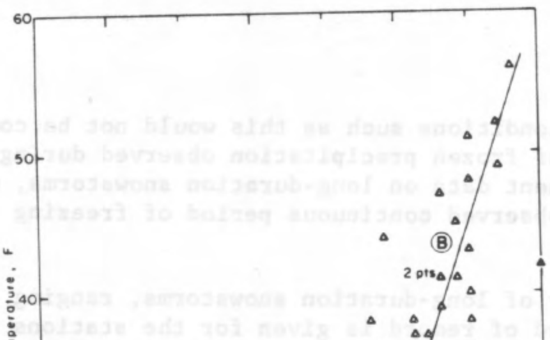

Figure 4. Relationship between mean monthly air temperature and average air temperature during category b frozen precipitation.

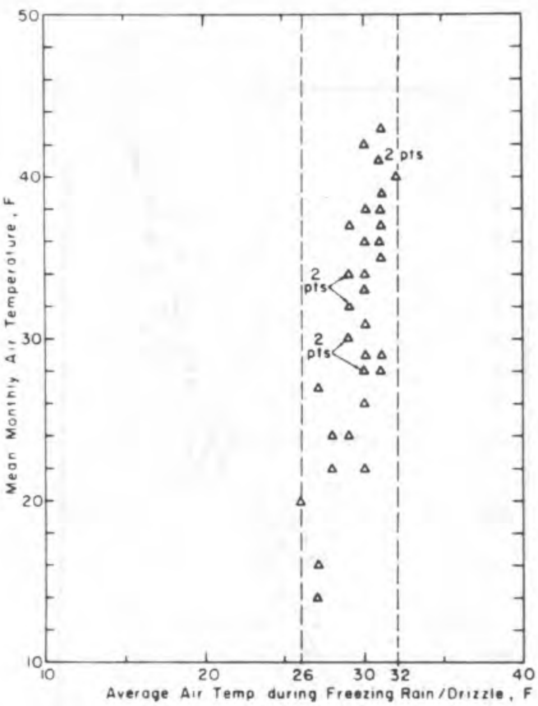

Figure 5. Relationship between mean monthly air temperature and average air temperature during freezing rain and freezing drizzle.

The same temperature investigation for category c precipitation (freezing rain and drizzle) revealed no correlation (Fig. 5). As noted earlier, this particular frozen precipitation occurs persistently at air temperatures between 27° and 32°F. According to the distribution shown in Figure 5 this is true regardless of the range of mean monthly air temperatures.

SUPPLEMENTAL DATA

A study on climatic conditions such as this would not be complete without some information on extremes of frozen precipitation observed during the period of record. Consequently, some pertinent data on long-duration snowstorms, maximum 6-hour snowfall amounts and the longest observed continuous period of freezing rain and freezing drizzle were investigated.

In Table V the number of long-duration snowstorms, ranging from 6 to $\geq$ 36 hours, observed during the period of record is given for the stations studied. Each duration period has been broken down into three temperature ranges. These temperatures are those observed during the last hour of the extended snowstorm. All cities show a majority of 6-hour snowstorms at air temperatures ranging between 28° and 39°F. The most (67 cases in 10 years) were reported at Buffalo and the least (13 cases in 11 years) at New York. Montreal observed most storms of long duration at temperatures between 4° and 15°F (37 in all), and it is surprising to find that Bedford exceeds all stations with 18-hour snowstorms between temperatures of 28° and 39°F. Incidentally, Montreal and Buffalo (one case only) had the only snowstorms in which the air temperature during the last hour ranged between -8° and +3°F. Only five locations (Bedford, Buffalo, Chicopee Falls, Montreal and New York) of the eleven reported snowstorms of 36 hours duration or longer.

A graphical presentation of the total number of storms observed for each duration interval for five cities is given in Figure 6. The values were plotted on semilog paper and the results show a relatively straight-line pattern of uniform slope. If the frequency of 6-hour snowstorms in 10 years at a location is known, a good approximation of the frequency of longer duration storms can be made from the relationship shown in Figure 6.

Table V. Number of long-duration snowstorms observed in 10 years with associated temperatures (^{o}F).

	6 hr			12 hr			18 hr			24 hr			30 hr			≥ 36 hr		
Avg temp range	39-28	27-16	15-4	39-28	27-16	15-4	39-28	27-16	15-4	39-28	27-16	15-4	39-28	27-16	15-4	39-28	27-16	15-4
Station																		
Bedford	37	17	3(1)*	21	7	3	11	6	1	2	1							
Buffalo	67	49	10	28	16	4	9	5	3	1	4		1	1	1	1		
Chicopee Falls	42	23	4	20	10	3	3	3	1		4					1		
Cleveland	51	31	5	16	9	1	3	3			1			1				
Montreal	47	42	18(3)	16	23	13(6)	10	7	4(1)	2	3	1	2		1(1)	2	1	
New York†	13	3	1	7	4		4	2		2	1					1		
Philadelphia	15	6		8	2		2	1		3								
Pittsburgh	30	14		14	7		2	3										
Toronto	44	29	5	18	11	2	2	2	1		1	1		1				
Washington, D.C.†	22	2		7	3		3											
Ypsilanti	50	23	2	10	7			3										

*Numbers in parentheses are storms during which air temperatures ranged between -8^{o} and $+3^{o}F$.

†Period of record – 11 years.

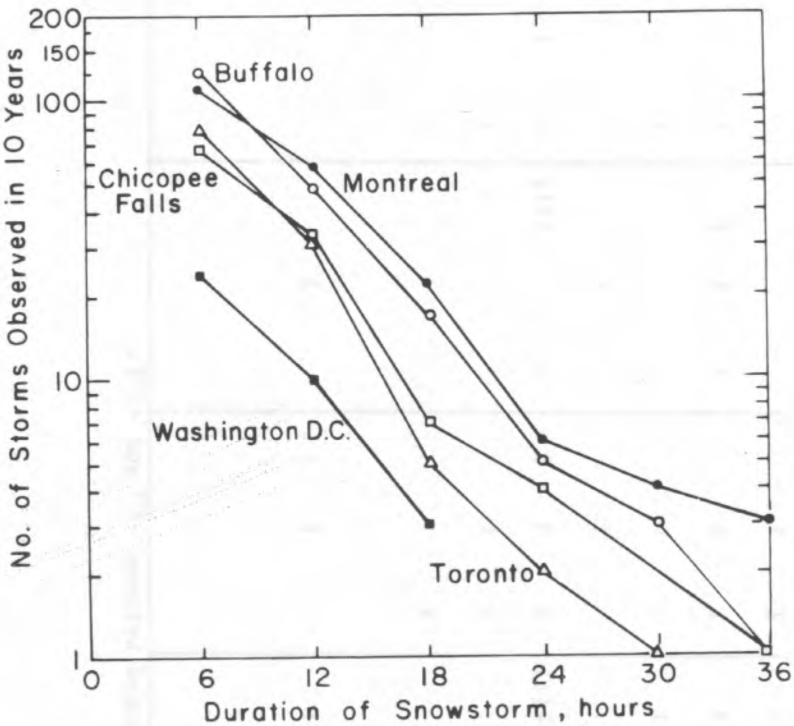

Figure 6. Number of snowstorms observed for specific durations.

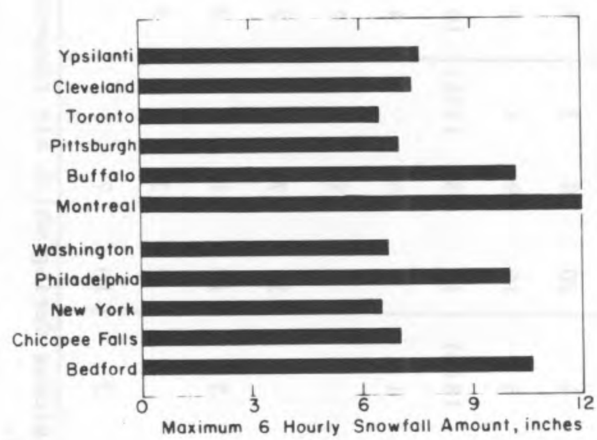

Figure 7. Maximum snowfall amount observed during 6-hour snowstorms.

In Figure 7 the maximum snowfall amount (in inches) observed during a 6-hour snowstorm for the period of record is given for each city. The six inland stations (top of diagram) have been purposely separated from the five coastal stations (lower portion of diagram) in order to compare the two regions. The amounts range from 6½ to 12 inches, but in contrast to the frequency of snow occurrence (Fig. 1) the variations in maximum amount are not regionally dependent. Three of the maximum values at the coastal stations almost match the amounts observed at four of the inland sites, and two of the coastal cities approach the maximums reported at the inland locations. This phenomenon again can be attributed to the oceanic effect: although the sea moderates the winter temperatures along the coast it also provides more moisture to any particular snowstorm.

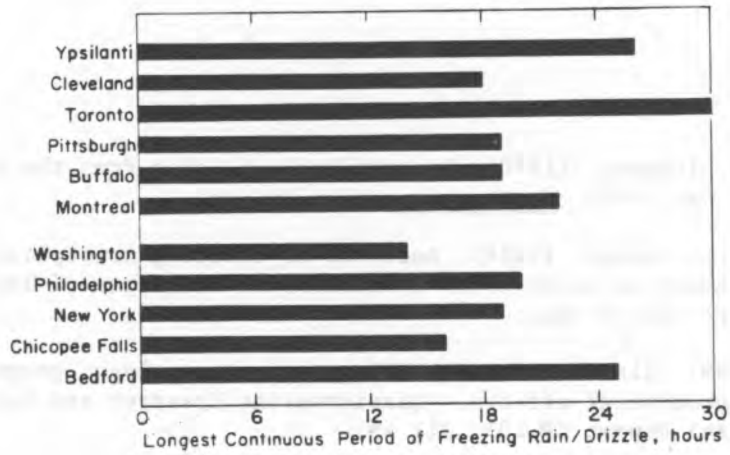

Figure 8. Longest continuous period of freezing rain and freezing drizzle.

It would appear that locations such as Cleveland, Toronto and Buffalo would produce heavier snowstorms because they have suitable temperatures and moisture available from the Great Lakes, especially in early winter when the lakes are not ice-covered. This fact is true when monthly or seasonal snow amounts for these and coastal stations are compared. However, for individual 6-hour storms, Figure 7 shows that the moisture sources and temperature regimes for both regions provide similar snow amounts.

In Figure 8 the longest continuous period of freezing rain and freezing drizzle (in hours) observed during the period of record is given for each city. This particular information was obtained by carefully scanning the hourly weather observations and tabulating the duration of each of these storms. In all cases, those hours when only a trace of precipitation was recorded were counted as part of the continuous period of the storm.* As in Figure 7 the inland and coastal stations were separated for comparison. Washington, D.C. reported the briefest continuous freezing rain and drizzle storms (14 hours) and Toronto the longest (30 hours). In general, the inland stations observe longer storms than the coastal cities, although the storm at Bedford exceeded all but those observed at Toronto and Ypsilanti.

SUMMARY

Frozen precipitation is observed in various forms and its frequency varies by month and by region. Graphs showing the probable occurrence of frozen precipitation at eleven locations in the U.S. and Canada are presented as possible aids in devising methods for improving winter operations. Average temperatures observed at the time of precipitation occurrence are also given and related to long term mean air temperatures. These temperatures as well as some information on extremes in frozen precipitation may be helpful in determining the specifications required for developing heating systems for the control of ice and snow in large cities. For example, the information extracted from Figures 5 and 8 provides a potential user with knowledge of the maximum duration and probable concurrent air temperatures for freezing rain and/or freezing drizzle storms.

* The data for Montreal and Toronto were kindly provided by the Canadian Meteorological Service, Toronto, Canada, and pertain to the period between 1957 and 1966. They also provided the values given in Figure 7 for these two stations for the record between 1951 and 1960.

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