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Technical Report 162

SURVEY OF FROZEN PRECIPITATION IN URBAN AREAS AS RELATED TO CLIMATIC CONDITIONS

by
Michael A. Bilello

MAY 1967

U.S. ARMY MATERIEL COMMAND
COLD REGIONS RESEARCH & ENGINEERING LABORATORY
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DA Task 1VO14501B52A02

PREFACE

This report is an analysis of data on frozen precipitation compiled for LaGuardia Airport and Buffalo, New York.* The machine-tabulated data were processed and prepared by the U. S. Weather Bureau National Weather Records Center, Asheville, North Carolina. The survey ultimately included 24 locations within selected metropolitan areas, two of which are presented here as examples. The interpretations and graphs introduced in this report are intended to serve as application guides for the other sites.

Mr. Leonard Stanley assisted in the computer programming and Mr. Roy Bates graphed most of the data.

USA CRREL is an Army Materiel Command laboratory.

* The study was requested and funded by the U. S. Army Rocket and Guided Missile Agency.

CONTENTS

	Page
Preface	ii
Summary	v
Introduction	1
Data requirements	1
Frequency Table AI	2
Presentations of the data in Table AI	2
Recommended graphical interpretation for Table AI data	10
Frequency Tables AII and AIII	11
Presentation of the data in Tables AII and AIII	12
Frequency Table AIV	14
Presentation of the data in Table AIV	14
Presentations of supplemental data	16
Discussion	19
Instructions for using the recommended figures	19
Appendix A	27

ILLUSTRATIONS

Figure		
1.	Relationship between air temperature and frozen precipitation (annual)	3
2.	Relationship between air temperature and cat. a precipitation (monthly), LaGuardia, N.Y.	4
3.	Relationship between air temperature and cat. b precipitation (monthly), LaGuardia, N.Y.	4
4.	Relationship between air temperature and cat. c precipitation (monthly), LaGuardia, N.Y.	5
5.	Monthly distribution of frozen precipitation, cat. a, b and c, LaGuardia, N.Y.	6
6.	Probability of frozen precipitation occurring at specific temperatures (annual)	6
7.	Probability of cat. c precipitation occurring at specific temperatures (annual)	6
8.	Probability of cat. c precipitation occurring at specific temperatures (monthly)	8
9a.	Probability of frozen precipitation occurring at specific temperatures (annual), LaGuardia, N.Y.	9
9b.	Highest probability of frozen precipitation observed during the entire period of record for each month and the temperature at which it occurred, LaGuardia, N.Y.	9
10.	Probability of cat. a precipitation and specific temperatures occurring simultaneously (monthly)	10
11.	Number of 6-hr snowstorms per month during an 11-year period as related to wind speed	12
12.	Probability of a 6-hr snowstorm as related to temperature, wind speed, and amount of precipitation (monthly)	13
13.	Frequency of 6-hr snowstorms in terms of temperature, wind speed and amount (annual), LaGuardia, N.Y.	14
14.	Probability of a 6-hr snowstorm as related to temperature (monthly)	15

CONTENTS (Cont'd)

Figure		Page
15.	Probability of a 6- to 36-hr snowstorm if snow is occurring as related to air temperature (annual)	16
16.	Frequency of long-duration snowstorms in terms of temperature, LaGuardia, N. Y.	17
17.	Isolines of mean seasonal snowfall amounts, New York City and vicinity	17
18.	Monthly distribution of frozen precipitation, cat. a, b and c, Buffalo, N. Y.	20
19.	Relationship between air temperature and cat. a precipitation (monthly), Buffalo, N. Y.	20
20.	Relationship between air temperature and cat. b precipitation (monthly), Buffalo, N. Y.	20
21.	Relationship between air temperature and cat. c precipitation (monthly), Buffalo, N. Y.	21
22a.	Probability of frozen precipitation occurring at specific temperatures (annual), Buffalo, N. Y.	22
22b.	Highest probability of frozen precipitation observed during the entire period of record for each month and the temperature at which it occurred, Buffalo, N. Y.	22
23.	Frequency of 6-hr snowstorms in terms of temperature, wind speed and amount (annual), Buffalo, N. Y.	23
24.	Frequency of long-duration snowstorms in terms of temperature, Buffalo, N. Y.	25

TABLES

Table		
I.	Tabulation of total hours (by months)	15
II.	Mean monthly and seasonal snowfall	18
III.	Significant snow and freezing rain storms	24
IV.	List of stations in the study	24
AI.	Dry bulb temperature $\leq$39F vs frozen precipitation	27
AII.	Mean air temperature vs 6-hr precipitation amount	29
AIII.	Wind speed vs 6-hr precipitation amount	30
AIV.	Mean air temperature vs snowstorm duration	30

SUMMARY

This study investigates relationships between observed frozen precipitation and associated meteorological conditions in large cities, and develops procedures for presenting tabulated data on frozen precipitation in a readable and usable form. An explanation of several interpretations is included with methods of analysis, sample diagrams, advantages and disadvantages, and comparisons of the different interpretations. To avoid excessive bulk, only the diagrams for LaGuardia Airport and Buffalo, New York, are discussed in this paper. Similar figures for 22 other stations are on file at USA CRREL.

SURVEY OF FROZEN PRECIPITATION IN URBAN AREAS AS RELATED TO CLIMATIC CONDITIONS

by

Michael A. Bilello

INTRODUCTION

The purpose of this study was to investigate relationships between observed frozen precipitation and associated meteorological conditions in large cities, and to develop procedures for presenting tabulated data on frozen precipitation in a readable and usable form.

Data, naturally, can be interpreted and presented in several ways. Determination of the best method depends upon how, why, and by whom the data will be used. Questions which arise are: 1) What time periods should be used; that is, should the data be presented seasonally or for each month; 2) Should each precipitation type be shown separately; 3) For engineering purposes are bar graphs easier to interpret than smooth curves or isolines; and 4) For design purposes or forecasting, should the analysis be in terms of numerical frequencies, or probabilities?

An explanation of several interpretations is included, with methods of analysis, sample diagrams, advantages and disadvantages, and comparisons of the different interpretations.

One of the objectives of the study was to provide information on the frequency of frozen precipitation at a number of large cities. Unfortunately, inclusion of the diagrams for all the stations in this report would result in excessive bulk, so only the figures for LaGuardia Airport and Buffalo, New York, are discussed below. Similar figures for the other 22 stations are on file at USA CRREL.

DATA REQUIREMENTS

The basic problem was to determine climatological criteria which can be used to help solve problems in snow and ice control. The type of information requested of the Weather Records Center and the format of the tabulation were based on: 1) The climatic parameters which appeared important, 2) The data available on punched cards, and 3) Time-cost considerations. The tabulation was provided in four frequency tables. A sample tabulation (for LaGuardia Airport) is shown in Appendix A.

Initially, it was assumed that frozen precipitation would not occur above 39F. The LaGuardia data proved this assumption incorrect and the upper limit for the remaining stations was raised to 45F.

The period of record for LaGuardia Airport is October through December for the years 1949-1959 and January through May for the years 1950-1960. Since this 11-year record does not conform with established procedures, it was requested that the period of record for the remaining stations be 10 years instead (Jan 1951 to Dec 1960 incl.).

The tabulation consists of monthly and annual totals of the recorded data and for Table AI includes a count of the total number of cards (each an hourly observation).

Tables AI, AII and AIII include separate tabulations, one for each of the 6 to 8 winter months, October - May. (For some cities no frozen precipitation is observed during October or May.) Table AI also contains an annual summary. Table AIV contains one tabulation, which considers the winter period only.

A discussion of the contents of the tables and methods of presenting the data follows.

FREQUENCY TABLE AI

Table AI (Dry bulb temperatures and frozen precipitation) shows a count of the hours during which certain types of precipitation were observed at each temperature. These types are:

a. Snow and/or snow showers

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

c. Freezing rain and/or 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. When a and c or a, b and c were observed together, it was counted separately under a fourth category, d; category d did not occur frequently enough to justify its inclusion in this study.

Since hourly surface observation records were the source for Table AI, precipitation intensity is not reflected. Only frozen precipitation greater than a trace was counted in preparing this table. Temperatures were rounded prior to punching. For example, 32F includes from 31.5 through 32.4F.

Presentations of the data in Table AI

The information given in each of the columns of Table AI can be defined as follows:

N = total number of hours (of cards)

S = number of hours with frozen precipitation

T = number of hours with a certain temperature

C = number of hours with frozen precipitation occurring at a certain temperature (C refers to "combined")

A = number of hours with frozen precipitation occurring at temperatures below a certain value (A refers to "cumulative").

Two subscripts can be applied to the above symbols: first, a, b and c to designate the category of frozen precipitation; and second, O for October, N for November, etc., to define the particular month being analyzed. May is spelled out in order to differentiate it from M for March, and ann is used to denote an entire winter.

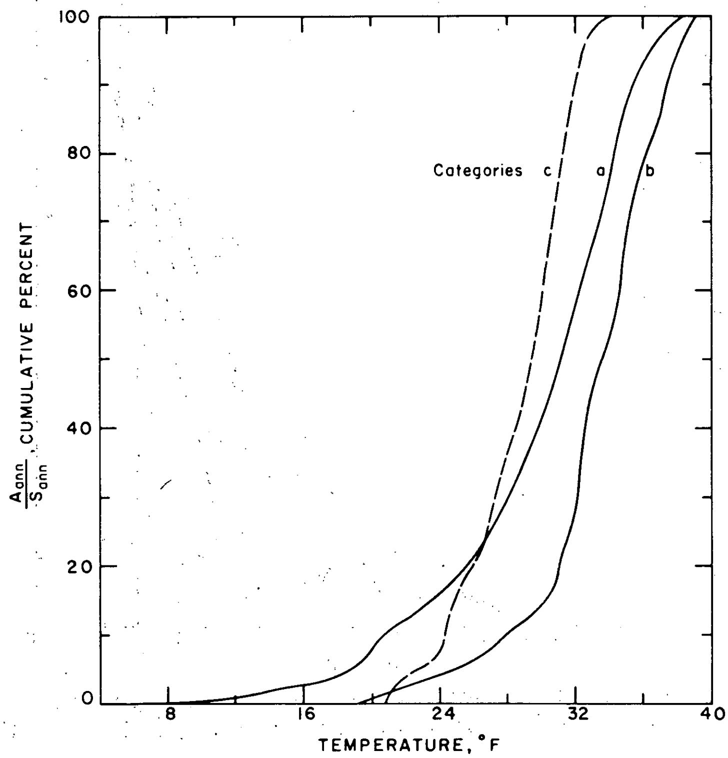

Figure 1. Relationship between air temperature and frozen precipitation (annual), LaGuardia, New York. See p. 2 for explanation and definition of symbols.

Cumulative percent. Figure 1 shows annual distribution of categories a, b and c as related to temperature, in terms of cumulative percent. The type of information obtainable from Figure 1, curve a, is, for instance: About 30% of the snow and/or snow showers observed at LaGuardia, New York, between 1949 and 1960 occurred at air temperatures at or below 28F. The figure also shows the temperature range within which categories a, b, and c occur. For example, between 10 and 90% (or 80% of the time) type b precipitation occurs from 28 to 37F whereas, in this same range, type c precipitation occurs from 24 to 32F. However, the presentation does not show monthly variations. A similar analysis was made for each category except that each month is considered separately (Fig. 2-4). From these figures, more detailed information may be obtained. For example from Figure 2 it can be said that: Of the snow and/or snow showers observed during April, 85% occurred at temperatures at or above 32F, whereas in January only 30% occurred at temperatures at or above 32F. However, the frequency or probable number of hours one might expect frozen precipitation to occur can not be extracted from these cumulative curves. Note that averaging the curves in Figures 2, 3 or 4 will not necessarily give the same results as the corresponding curve in Figure 1. The reason is that the greater frequency of occurrences reported during the mid-winter months biases the curves, especially the lower portions, in Figure 1 to the left.

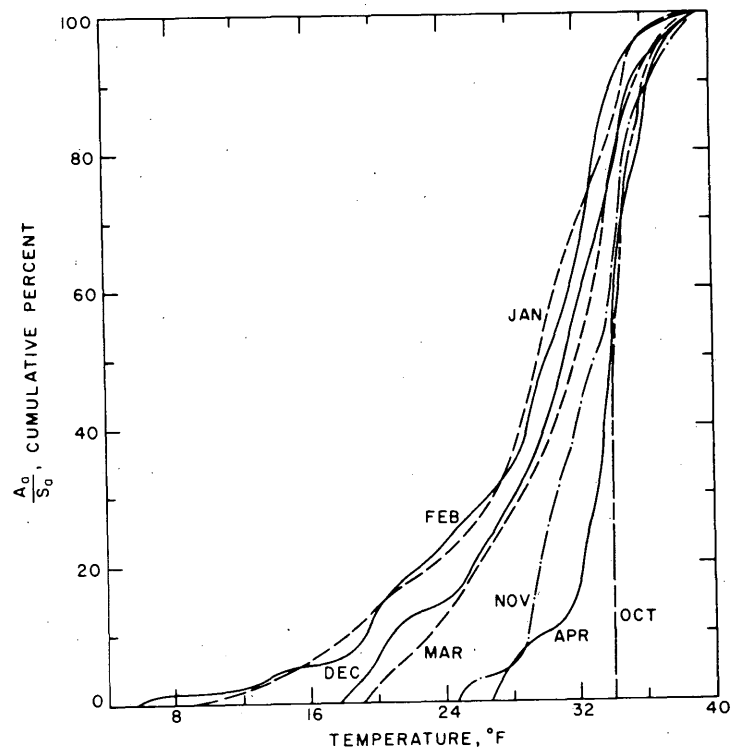

Figure 2. Relationship between air temperature and snow and/or snow showers (monthly), LaGuardia, New York.

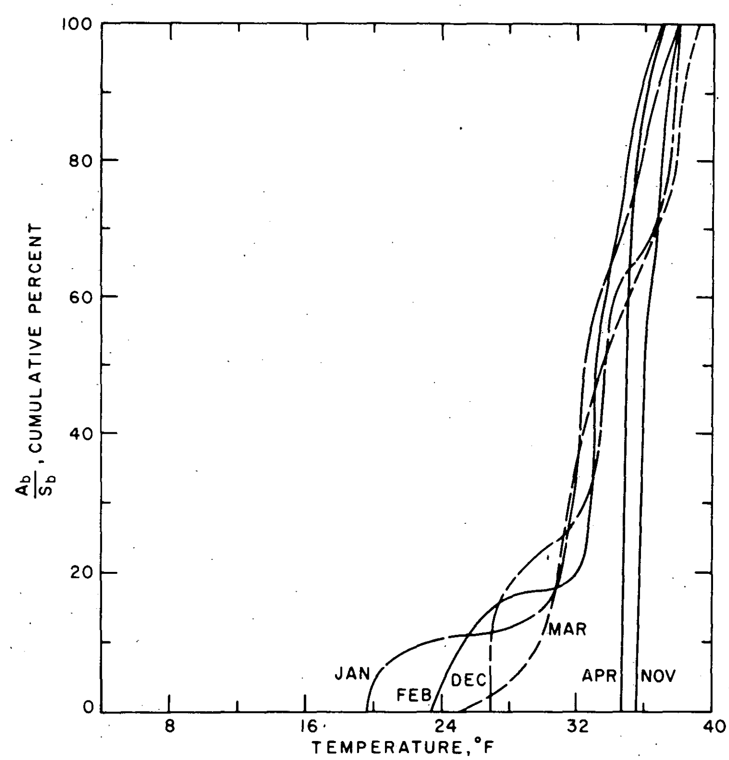

Figure 3. Relationship between air temperature and snow pellets, ice crystals, snow grains, soft hail and/or sleet (monthly), LaGuardia, New York.

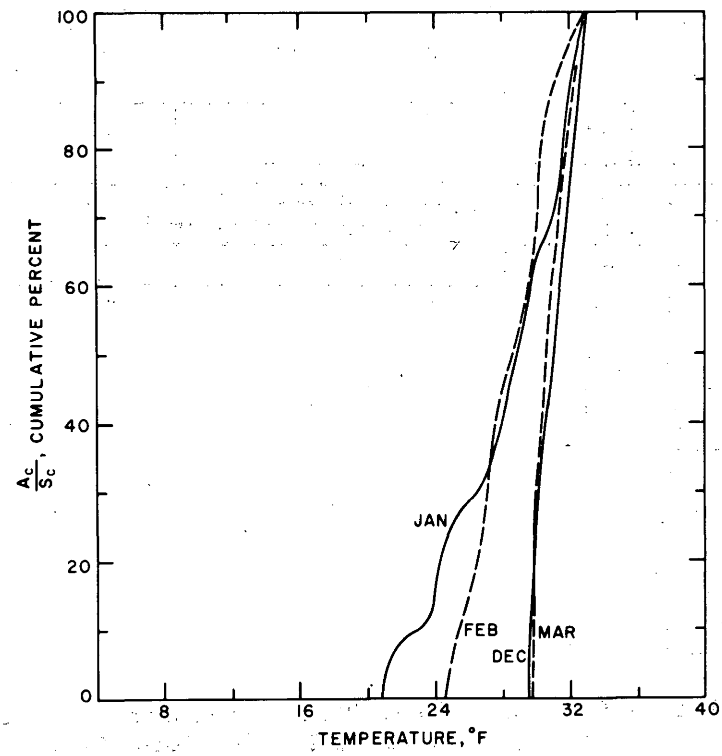

Figure 4. Relationship between air temperature and freezing rain and/or freezing drizzle (monthly), LaGuardia, New York.

The disadvantages, then, in using Figures 1 - 4 are: 1) They do not provide information on number of hours of frozen precipitation; 2) The presentation of curves for all months in one figure decreases readability, and 3) Figure 1 does not provide information on monthly distribution of frozen precipitation. The second disadvantage can be somewhat alleviated by combining some curves. In Figure 2, for example, the curves for January and February could be combined, as could those for December and March, with almost no appreciable loss in accuracy.

Probability of frozen precipitation occurring. A plot of S/N for each month was made for each category (Fig. 5). This "probability of occurrence" is shown as monthly bar graphs instead of curves because the data do not justify day-to-day interpretation.

Figures 1 - 5 can be used together as follows: assume the question, "Approximately how many hours of freezing rain or freezing drizzle can one expect at LaGuardia Airport during January if and when the temperature is equal to or less than 25F?" From Fig. 5, cat. c, the probability of freezing rain and/or freezing drizzle occurring in January is 0.73% or $\gtrsim$5.5 hr. Then, using Figure 4, we find that at temperatures of 25F or less, the phenomenon occurs 25% of that 5.5 hr, or 1.38 hr.

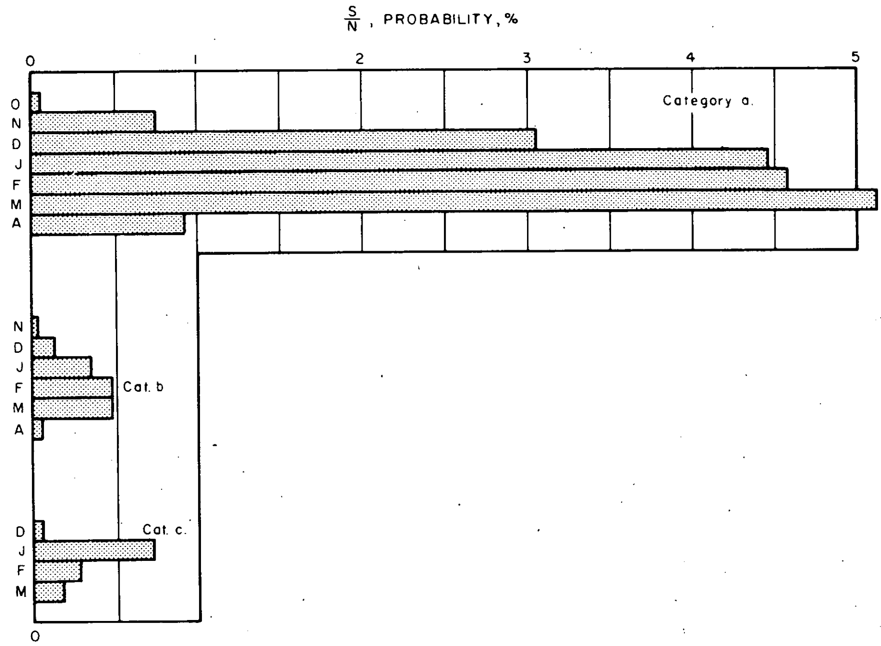

Figure 5. Monthly distribution of frozen precipitation, cat. a, b and c, LaGuardia, New York.

Figure 5, therefore, provides monthly frequency values for the occurrence of particular types of frozen precipitation. By itself, however, the presentation does not provide a relationship with any climatic parameters.

Probability of frozen precipitation occurring at specific temperatures. Dr. Andrew Assur of USA CRREL has offered the following approach: First, to avoid diagrams with many lines such as Figures 2-4, combine all months and then compute probable occurrence of frozen precipitation at specific air temperatures. This is actually the ratio C/T; some results are shown in Figures 6 and 7.

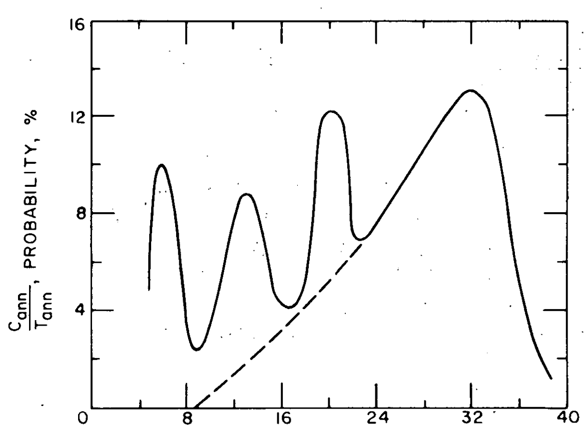

Figure 6. Probability of frozen precipitation occurring at specific temperatures (annual), LaGuardia, New York.

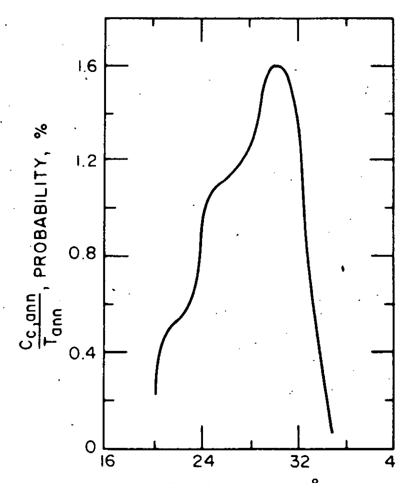

Figure 7. Probability of freezing rain and/or freezing drizzle occurring at specific temperatures (annual), LaGuardia, New York.

Incidentally, means overlapping over 3F were used on the data because of an obvious bias: i.e., a plot of observed temperatures showed that the 20F and 30F values were recorded far more often than 19 or 21 and 29 or 31F. The procedure was used for smoothing purposes also.

Figure 6 combines all months and categories. The distribution of points yielded a smooth curve at temperatures between 24 and 39F; but the curve becomes erratic at temperatures below 24F. It was reasoned that the deviations of the curve at the colder temperatures are due to insufficient data. Dr. Assur suggested that the curve in Figure 6 might approximate the dashed line if the period of record were 50 or more years instead of 11. It should be noted that similar plots for other locations provided smoother curves.

The analysis used to obtain Figure 6 can be carried further by considering the categories separately. For example, the results for freezing rain and freezing drizzle are shown in Figure 7. From this figure note, for example, that precipitation category c occurs most frequently at 30F at LaGuardia Airport.

The advantages gained by using Figure 7 are: 1) A direct association is provided between known or expected air temperatures and the probable occurrence of any type of frozen precipitation; 2) Smooth, individual curves permit easy reading.

Omitted from this type of presentation (Fig. 6 and 7) are monthly variations. This could be a serious omission, because temperatures between 20 and 35F (the range shown in Fig. 7) are observed during every winter month, but the frequency of frozen precipitation occurring at these temperatures varies from month to month. The magnitude of these variations is shown in Figure 8a, where the combined months of December, January, February and March used in Figure 7 were analyzed separately. The curves in this diagram are sufficiently uniform to permit smoothing and some combining for easier reading. The net result is shown in Figure 8b. The months, analyzed separately, show major departures in the end points and peaks when compared to Figure 7.

Since Figures 8a and 8b show significant differences in the maximum values, which do not appear in Figure 7, it was decided that the best presentation for C/T would be that given in Figure 7 plus an accompanying curve. The second curve would show the highest probability of frozen precipitation observed during the entire period of record for each month and the temperature at which it occurred. Such curves for each frozen precipitation type are shown in Figures 9a, b. Another reason for using annual curves is that the number of occurrences by months often is so small (e.g., Fig. 7) that the probability analysis becomes statistically unsound. In fact, for some cities, the number of observed counts for categories b and/or c were so few that any attempt to obtain probability values would be unreasonable. Annual curves in which all categories were combined (Fig. 6) were eliminated. The reason is that category a always showed much higher maximum probability values than did the other categories, and should be separated for maximum design purposes.

Dr. Assur also suggested studying the probability of frozen precipitation occurring at one specific temperature on a month to month basis. For a temperature of 32F, the results of such a study in which the combined values of three stations were used showed a probability increase from October to April.

Combined probability of simultaneous occurrence of frozen precipitation and specific temperatures (Fig. 10). Figures 6 through 9 are useful in providing probability values only when air temperatures are known or expected.

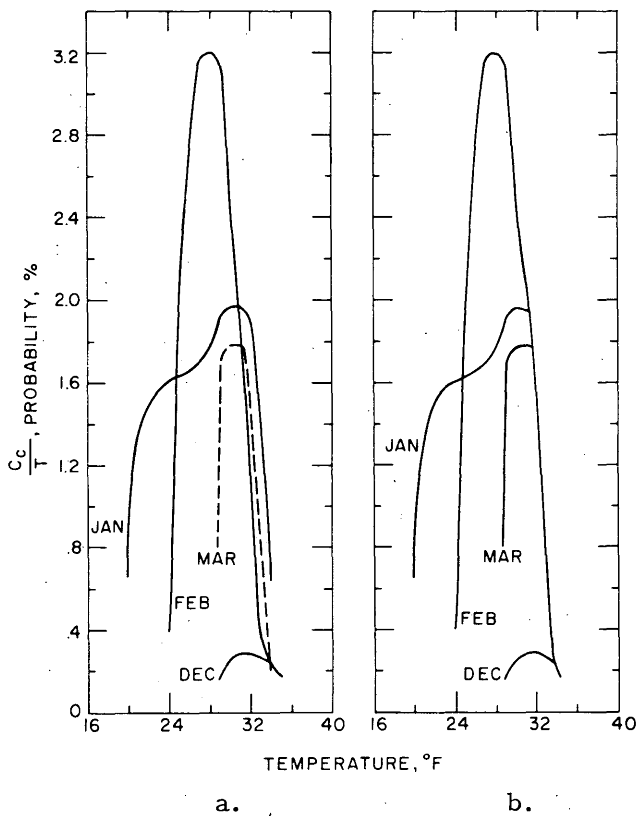

Figure 8. Probability of freezing rain and/or freezing drizzle occurring at specific temperatures (monthly), LaGuardia, New York. a. Monthly curves. b. Monthly curves simplified.

However, certain users, for example designers of special equipment for the control of snow or ice, may want information on how often specific temperatures occur in conjunction with a type of frozen precipitation. The next step, then, is to combine the probabilities of occurrence of frozen precipitation and specific temperatures. To compute the probability of both phenomena occurring simultaneously the ratio C/N is obtained, where N is the total number of hours in the month for the years of record (Table I, p. 15). The analysis of the probability of this simultaneous occurrence for category a, by months, is shown graphically in Figure 10.

Since Figure 10 considers both certain temperatures and the occurrence of frozen precipitation at those temperatures, the curves offer a multiple prediction. For example, such curves can provide the answer to the following question: For how many hours in January can one expect snow and/or snow showers to occur at LaGuardia at temperatures between 27 and 32F inclusive? Referring to Figure 10 and considering the total number of hours in January, we obtain:

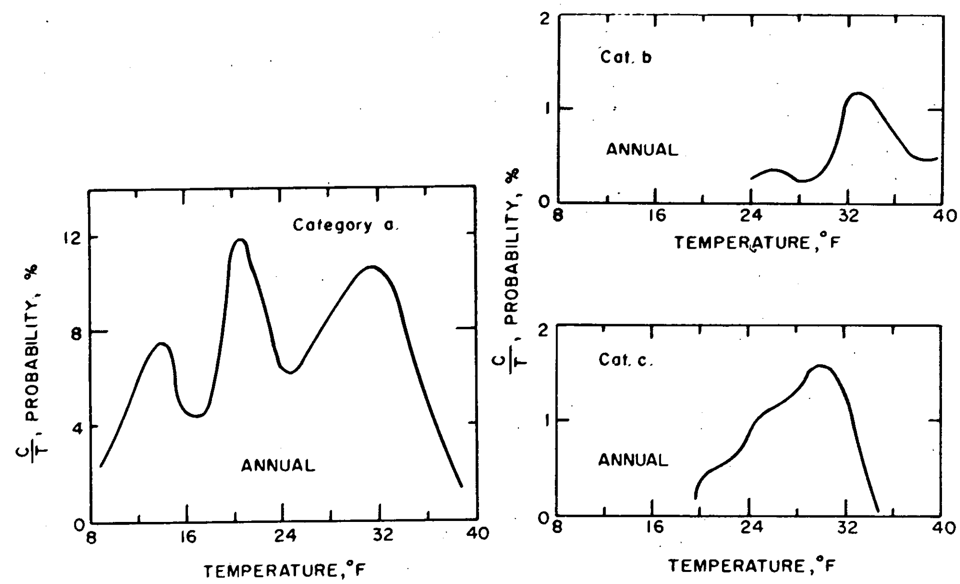

Figure 9a. Probability of frozen precipitation occurring at specific temperatures (annual), LaGuardia, New York.

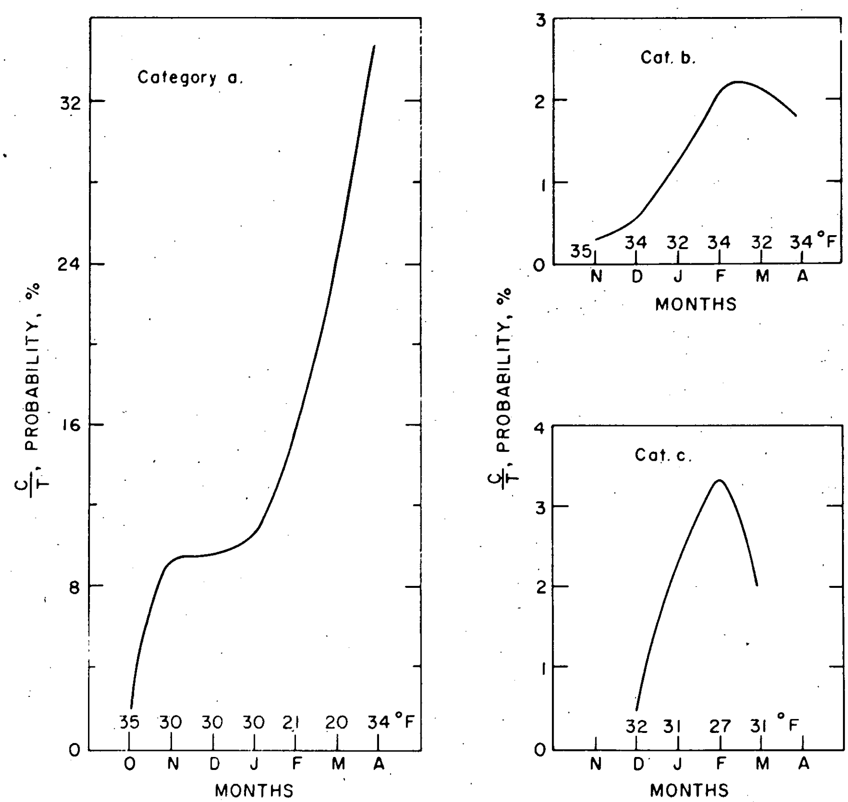

Figure 9b. Highest probability of frozen precipitation observed during the entire period of record for each month and the temperature at which it occurred, LaGuardia, New York.

Temp	No. hours in Jan	Probability	Probable no. of hours of snow and/or snow showers in Jan
27	744	.17%	1.3
28	744	.23%	1.7
29	744	.36%	2.7
30	744	.41%	3.0
31	744	.34%	2.5
32	744	.32%	2.4
		Total	13.6

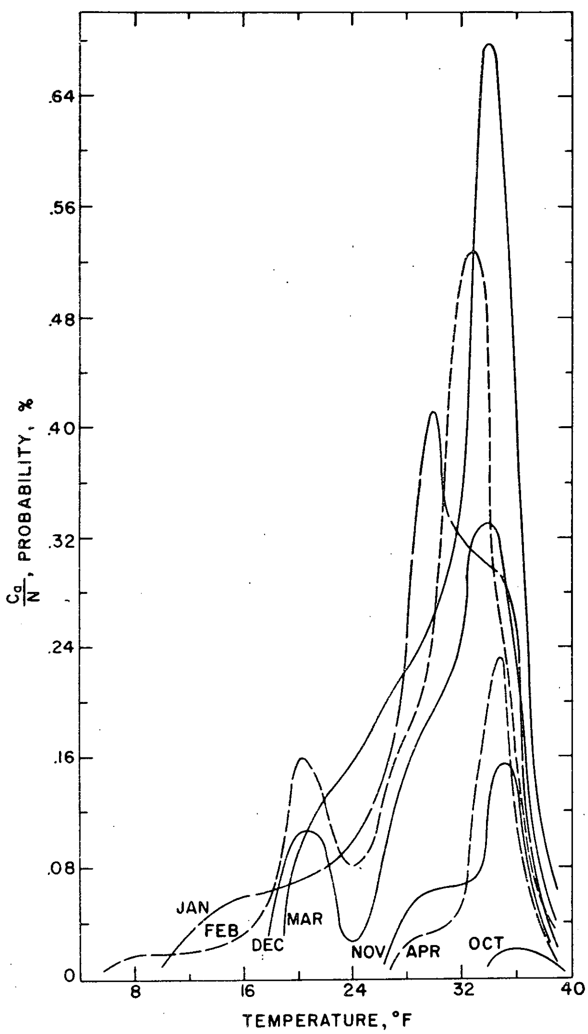

Figure 10. Probability of snow and/or snow showers and specific temperatures occurring simultaneously (monthly), La-Guardia, New York.

An annual curve for the above analysis in which all the categories are combined is not presented. The reason for this is that N, the total number of hours under consideration for a winter season, is difficult to determine. April, May and October, in particular, should be counted as winter months at one location but not at another.

The principal disadvantage in using Figure 10 is that considerable smoothing was used when drawing the curves, which may reduce accuracy.

Recommended graphical interpretation for Table AI data

The data in Table AI can be used by engineers, who require only broad knowledge of the parameters, calling for simple figures, and by forecasters, who require more detailed information and therefore more complex figures.

The next step is to determine the most useful graphical interpretation. The following example is given to show that Figures 2, 3, 4 and Figure 5 together provide the same information attainable from Figure 10.

Considering the ordinate symbols in Figures 2, 5 and 10, we have for one month (January) and for category a, the following:

$$\text{Figure 2} = \frac{A_{aJ}}{S_{aJ}}$$

$$\text{Figure 5} = \frac{S_{aJ}}{N_J}$$

$$\text{Figure 10} = \frac{C_{aJ}}{N_J} .$$

The product of the symbols on Figures 2 and 5 yields A_{aJ}/N_J and, if temperatures t_1 to t_2 (from lower to higher temperatures) are considered: $A_{aJ}(t_1 - t_2) = \sum_{t_1}^{t_2} C_{aJ}(t) = \int_{t_1}^{t_2} C_{aJ}(t)\,dt$. The latter expression describes the area under the January curve given in Figure 10. Thus, results approximating those obtained in the computations shown on page 10 are possible using Figures 2 and 5 as follows:

Temp range (Δt)	$\frac{A_{aJ}}{S_{aJ}\text{(for } \Delta t)}$	$\frac{S_{aJ}}{N_J}$	$\frac{A_{aJ}}{S_{aJ}} \times \frac{S_{aJ}}{N_J}$	No. hours in Jan	Probable no. of hours of snow and/or snow showers in Jan
27 to 32	69%-30%=39%	4.5%	39%x4.5% = .0176	744	13.1 hours

Several computations similar to the above were made to compare the methods. The results differed by ±5 to 10%; these variations were due mostly to the dissimilarity in drawing and smoothing procedures.

Figures 9a and b are needed to provide probability of occurrence at specific air temperatures. It has been shown that they provide all the essential information given by Figures 6-8. Figures 2, 3, 4, 5 and 9, therefore, are recommended as the best graphical presentation of the data contained in Table AI.

FREQUENCY TABLES AII AND AIII

The mean air temperatures in Table AII (mean air temperature, wind speed and 6-hr precipitation amount when snowfall was ≥ 1 in.) are for a 6-hr precipitation period and are grouped as 22-27F, 28-33F, 34-39F, etc. The term ≥ 1 in. per 6-hr snowfall refers to an inch or more of measurement, or the "catch." The precipitation amounts, however, are recorded in inches of water equivalent and grouped as .01-.09 in., .10-.19 in., etc.

The wind speeds in Table AIII are the values, in knots, recorded at the end of the 6-hr period. The values are grouped as 0-4, 5-9, 10-14, etc. The tabulation of the precipitation data in Table AIII is the same as that used in Table AII.

Presentation of the data in Tables AII and AIII

Tables AII and AIII provide monthly information on 6-hr snowstorms. The term "6-hr snowstorm" considers only regularly scheduled 6-hr observation periods. Therefore, the scheduled observations may divide a 6-hr period of heavy snowfall. The method also considers consecutive 6-hr periods in which 5 hr of no snow but 1 hr of $\geq$ 1 in. of snow was observed. Table AII correlates air temperatures with precipitation amount in inches of water equivalent. Table AIII correlates wind velocity and amount of precipitation.

An attempt was made to correlate temperature and wind for each particular storm with corresponding amounts of precipitation. This approach was not feasible because it was not possible to separate the storms. Attempts to extract information for a specific storm from a series of isoline charts (similar to Fig. 11) were also abandoned when it was found that no direct relationship existed between the charts and individual storms.

To obtain a complete diagrammatic interpretation of the data in Tables AII and AIII two precipitation conditions – monthly distribution and the number of 6-hr snowstorms – and three meteorological parameters – air temperature, wind speed, and amount of snow (water equivalent) – should be shown. Since it was not possible to combine all parameters, each meteorological parameter was associated with the precipitation conditions. Three diagrams were then required to present the data in this form.

Bar graphs were drawn depicting the conditions for each month. Such diagrams would show values of the probable occurrence of a 6-hr snowstorm in terms of the three meteorological parameters. The probability values are obtained by ExH/N, where E = number of observed snowstorms; H = number of hours per storm; and N = total number of hours. In this case, N refers to the number of hours for each month for the entire 10-year or 11-year record (Table I, p. 15).

The results, in which temperature, wind, and snow are shown separately, are presented in Figure 12. Presenting all three parameters on one figure permits direct comparison. The probability values unfortunately are extremely small because a long time period is being considered. The probability of a 6-hr

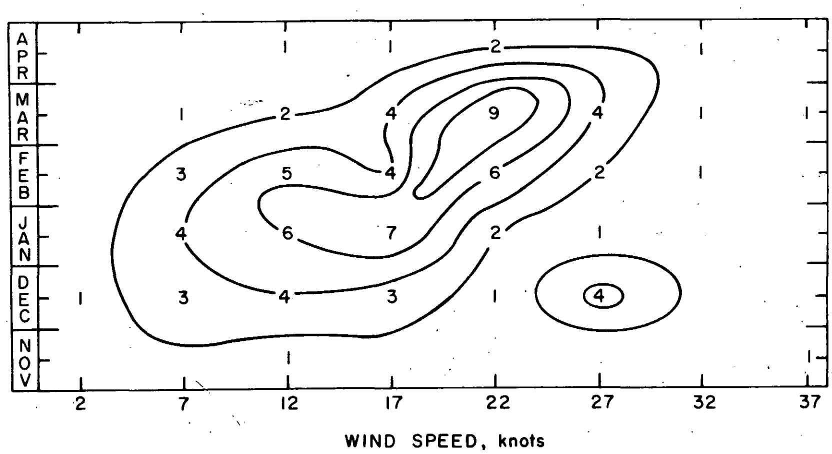

Figure 11. Number of 6-hr snowstorms per month during an 11-year period as related to wind speed, LaGuardia, New York.

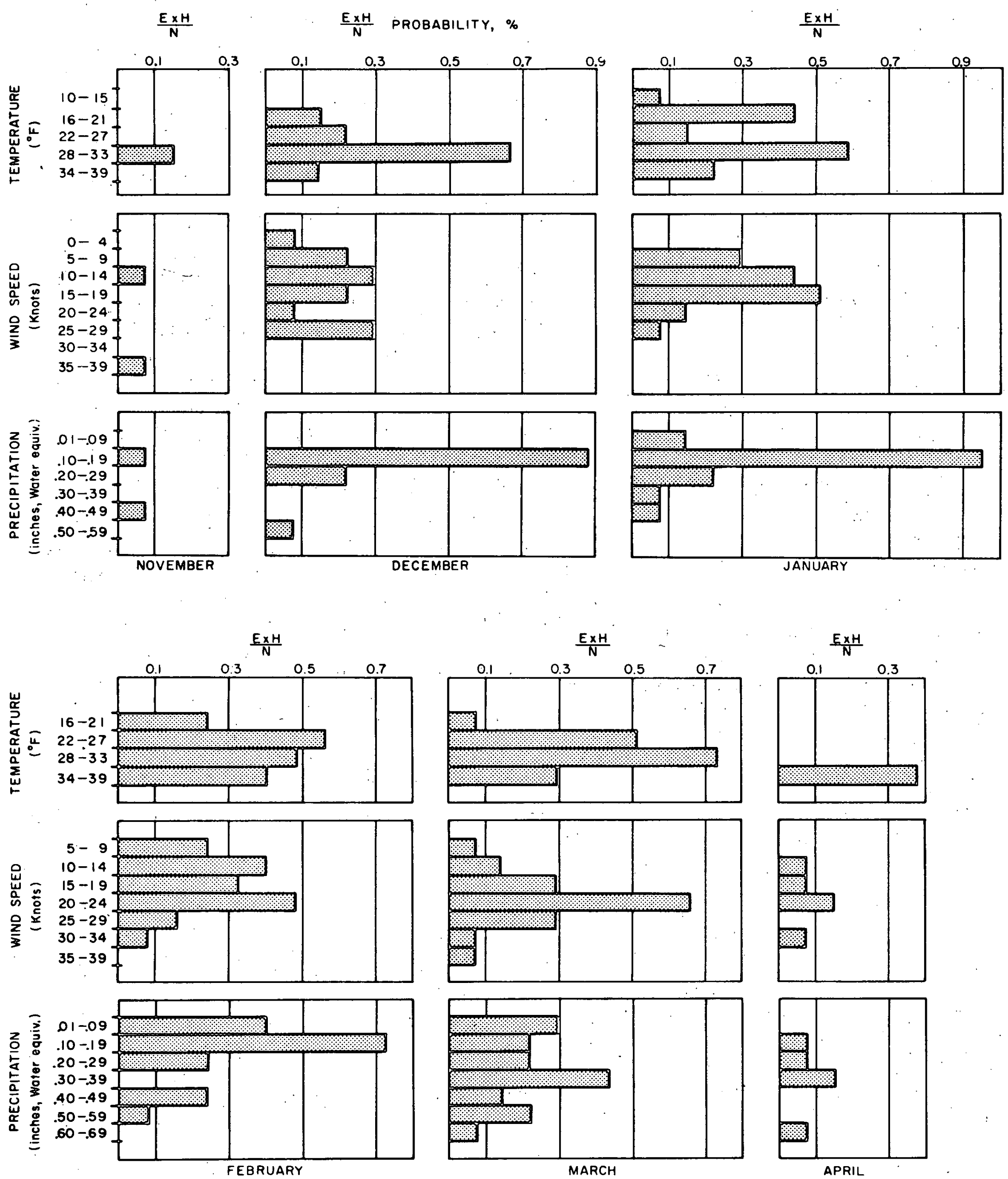

Figure 12. Probability of a 6-hr snowstorm as related to temperature, wind speed and amount of precipitation (water equivalent) (monthly), LaGuardia, New York. See p. 12-14 for explanation.

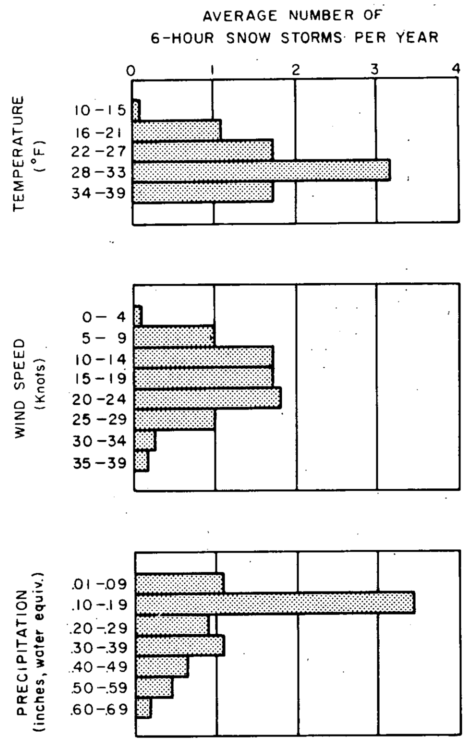

Figure 13. Frequency of 6-hr snowstorms in terms of temperature, wind speed and amount (annual), LaGuardia, New York.

snowstorm occurring at a time when snow is already falling can be determined by using the probability values obtained in Figure 12 and Figure 5. For example: the probability of a 6-hr snowstorm occurring at LaGuardia Airport, in January, in the temperature range of 28-33F is .0058 (from Fig. 12). Referring to Figure 5, we find the probability of any snow occurring in January to be .045. Dividing .0058 by .045 gives ≈.13, which is the probability that a 6-hr snowstorm will occur in January if and when snow is falling within the temperature range 28-33F. However, monthly breakdowns as shown in Figure 12 were not considered to be a sound approach, because of the small sampling. Therefore, annual summaries for each parameter were used and the frequency of occurrence expressed as the average number of 6-hr storms per year (Fig. 13).

Another way of presenting the data in Tables AII and AIII is shown in Figure 14. Here, bar graphs and probability values are utilized; the main difference is that the width of the bar is defined by the numerical limits of the parameters. This presentation, however, was rejected because the diagram appeared bulky, the probability ratios were too small and only one meteorological parameter could be shown on each figure.

The conclusion, therefore, is that the data given in Tables AII and AIII are graphically best represented by Figure 13.

FREQUENCY TABLE AIV

Mean air temperatures in Table AIV (mean air temperature and long-duration snowstorms when snowfall was ≥ 1 in. per 6-hr period) refer to the average temperatures observed during the last 6 hours of the snow period and are grouped as 22-27F, 28-33F, 34-39F, etc. The storm durations are for 6-, 12-, 18-, etc. hour periods when the snowfall amounted to ≥ 1 in. The term ≥ 1 in. snowfall per 6-hr period refers to an inch or more measurement of snowfall, or the "catch."

Presentation of the data in Table AIV

Since the data in Table AIV consider seasonal totals only, no monthly breakdown of the 10 or 11-year record was possible. The tabulation in Table AIV is as follows: A count of 1 is shown under the column marked 6 when the storm duration was 6 hr, under the column marked 12 when the storm duration was 12 hr, etc. As pointed out earlier, a 6-hr snowstorm does not necessarily mean that the snow fell continuously for 6 hr. If ≥ 1 in. of snow was recorded during the interval, the period was counted.

Table I. Tabulation of total hours (by months).

LaGuardia, Oct1949 to May 1960		Buffalo, Oct 1950 to May 1960	
Month	Total hours	Month	Total hours
October	8184	October	7440
November	7920	November	7200
December	8184	December	7440
January	8184	January	7440
February	7392 (+72) = 7464	February	6720 + 72 = 6792
March	8184	March	7440
April	7920	April	7200
May	8184	May	7440

Some of the diagrams introduced to represent the data given in Tables AII and AIII were tried for the Table AIV information. Bar graphs and probability values as related to air temperature and storm duration were tested. Since the data in Table AIV were seasonal totals, attempts to use the entire period of record produced impractical probability values. Instead, only the hours when snowfall actually was observed were used. This value, obtained from Table AI for the 11-year record, is 1514 hr for LaGuardia. The probability of a long-duration storm occurring if and when snow is falling is defined as:

$$\frac{E \times H}{S_a}$$

where E = number of observed storms; H = number of hours per storm and S_a = total number of hours with snow. The results, for the data given in Table AIV, are shown in Figure 15.

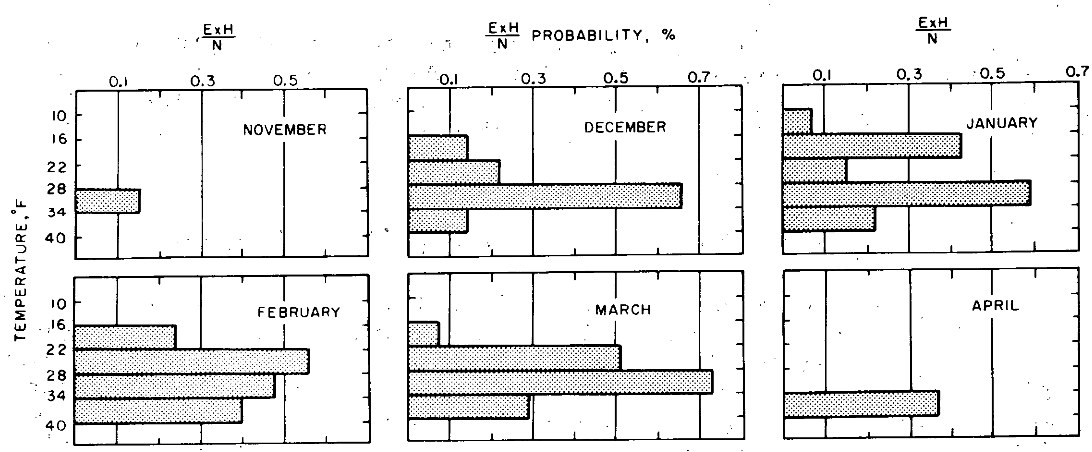

Figure 14. Probability of a 6-hr snowstorm as related to temperature (monthly), LaGuardia, New York.

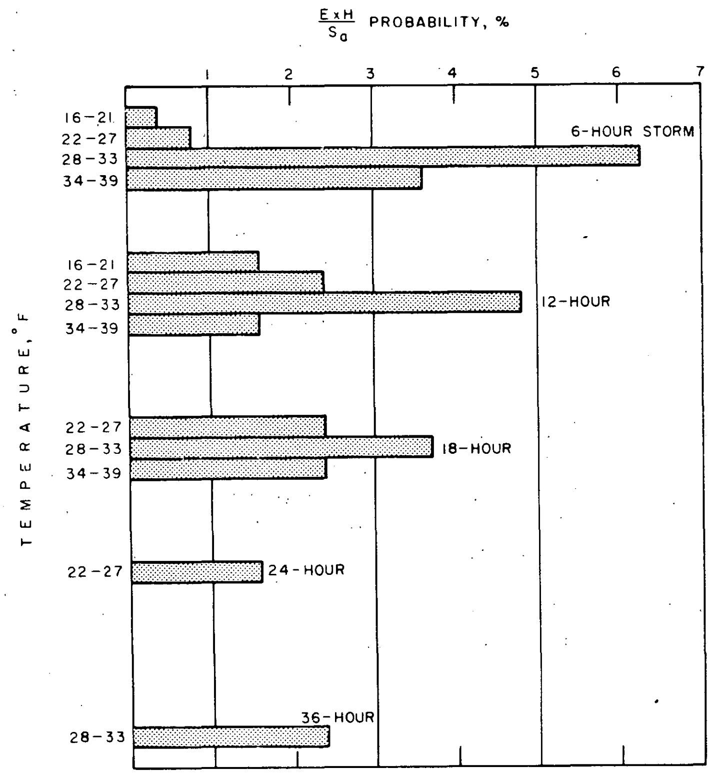

Figure 15. Probability of a 6- to 36-hour snowstorm if snow is occurring as related to air temperature (annual), LaGuardia, New York.

This approach was considered unfavorable because the presentation would be of little value for engineering purposes. As an alternative, still using bar graphs, the frequency of long-duration snowstorms was expressed in terms of average number per 10-year period and this was related to air temperature (Fig. 16).

PRESENTATIONS OF SUPPLEMENTAL DATA

Besides machine-tabulated data such as those given for LaGuardia in Tables AI through AIV, other frozen precipitation information was received for some stations. For example, the question whether data collected at one location such as LaGuardia Airport are representative of all of New York City and its suburbs was asked. Mean monthly and seasonal snowfall amounts (in inches) for 12 stations in and around New York City were therefore requested (Table II), and isolines of seasonal snow amounts were drawn (Fig. 17). No analysis was possible south and southwest of LaGuardia Airport, due to the lack of information. From this diagram we note that a variation of as much as 14.4 in. of snow a year occurs within 20 miles in New York City and its suburbs.

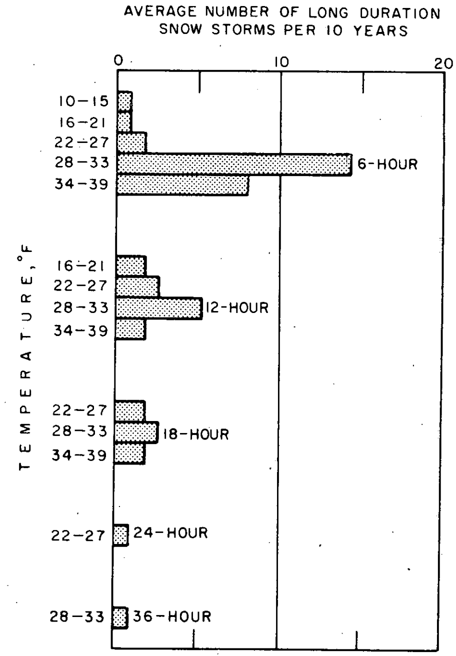

Figure 16. Frequency of long-duration snowstorms in terms of temperature (10 years), LaGuardia, New York.

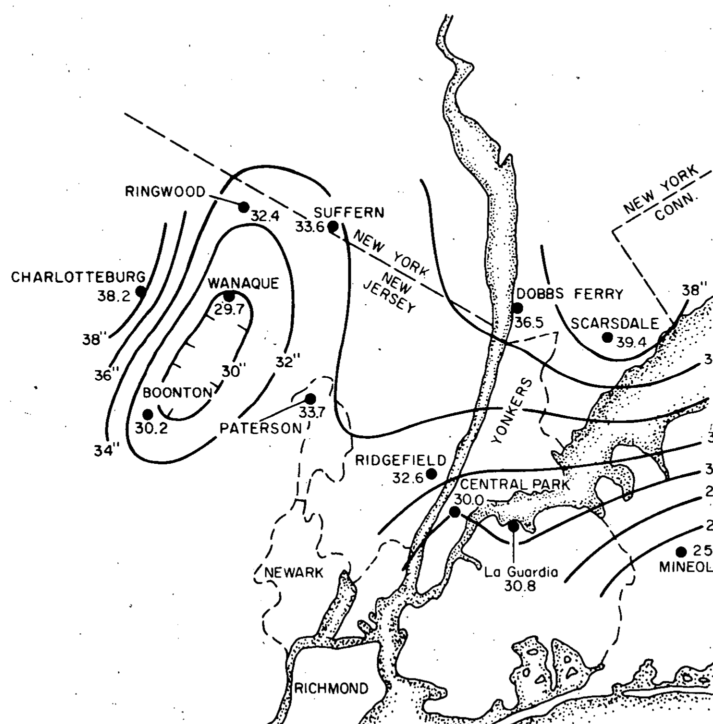

Figure 17. Isolines of mean seasonal snowfall amounts (inches), New York City and vicinity.

Table II. Mean monthly and seasonal snowfall (inches).

	Station	Sept	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Seasonal
(17)	Mineola, L.I.	0	T	1.0	6.2	5.9	6.8	4.0	1.1	0	25.0 (1955)
(16)	LaGuardia, N.Y.	0	T	0.6	8.3	6.5	7.8	6.5	1.1	0	30.8 (1960)
(92)	Central Park, N.Y.	0	T	1.1	6.2	7.6	8.5	5.5	1.1	0	30.0 (1960)
(38)	Ridgefield, N.J.	0	0.1	1.2	7.0	8.3	9.8	5.2	1.0	T	32.6 (1955)
(59)	Paterson, N.J.	0	T	1.4	6.8	8.4	10.5	5.2	1.4	T	33.7 (1955)
(29)	Boonton, N.J.	0	T	1.0	5.3	6.8	10.4	5.3	1.4	T	30.2 (1955)
(6)	Wanaque, N.J.	0	0	0.5	9.6	6.1	9.3	4.2	0	0	29.7 (1952)
(59)	Charlotteburg, N.J.	T	0.1	2.1	7.4	10.2	11.0	5.9	1.5	T	38.2 (1955)
(45)	Scarsdale, N.Y.	T	T	1.9	7.7	9.6	11.5	7.1	1.6	T	39.4 (1955)
(10)	Dobbs Ferry, N.Y.	0	0.1	1.8	10.6	8.8	10.1	4.6	0.5	T	36.5 (1955)
(7)	Suffern, N.Y.	T	0	1.0	7.4	8.1	12.6	2.7	1.8	0	33.6 (1952)
(5)	Ringwood, N.J.	0	0	0.3	9.9	8.8	9.5	3.9	0	0	32.4 (1952)

1. Figures (in parentheses) at left show number of years of record used.
2. Figures (in parentheses) at right show latest year used.

Requests also were received for information on maximum 6-hr snowfall amounts and the longest period of freezing rain and/or freezing drizzle during the 11- (or 10-) year record. These data were transcribed from the Local Climatological Data sheets published by the U. S. Weather Bureau; Table III (p. 24) gives the data for LaGuardia Airport.

DISCUSSION

After a study of several possible methods of data presentation, certain ones were found to be better than others.

These presentations consequently were prepared for 23 other locations in Canada and the U. S. (including Alaska) (Table IV). The probability values used in these diagrams were obtained through a Bendix G-15 computer. Some significant facts concerning the phenomenon of frozen precipitation may be obtained from the study. It was noted, for example, that freezing rain and freezing drizzle in almost all cases are confined to a rather small and definite temperature range.

The relationships between temperature, wind and the occurrence of frozen precipitation should provide the answers to some engineering problems in ice and snow removal or control.

Instructions for using the recommended figures

A sample station (Buffalo, New York) will be used to show how each of the recommended figures may be used. The order of the figures has been changed for more convenient use.

Monthly distribution of frozen precipitation categories (Fig. 18). Using Figure 18, category a, we find snow and/or snow showers occurring from October through May. The maximum amount is observed in January, the probability of occurrence being 34.3%. The period N under consideration (January) is 744 hr. From the ordinate S/N we obtain .343, which when multiplied by N will give S (number of hours with snow and/or snow showers), i.e., (.343) x (744 hr) = 255 hr. Similar computations can be made for each month and category. If such detail is not required, the probability values for all months for all or each category can be combined. For example: to find the seasonal total hours for occurrence of freezing rain and/or freezing drizzle at Buffalo, simply add the S's for this category (computed as shown above) for each month, as follows:

November:	S	=	(720) x (.001)	= 0.72
December:	S	=	(744) x (.005)	= 3.72
January:	S	=	(744) x (.012)	= 8.93
February:	S	=	(672) x (.004)	= 2.69
March:	S	=	(744) x (.006)	= 4.46
			Total	= 20.5 hr

Association of frozen precipitation occurrence with air temperature (Fig. 19-21. Figures 19-21 are used in conjunction with Figure 18. Let us assume that only snow occurring at 22F and above is critical for a particular design or structure problem at Buffalo in January. From Figure 19, January curve, we find that 42% of the snow observed at Buffalo occurs at temperatures less than

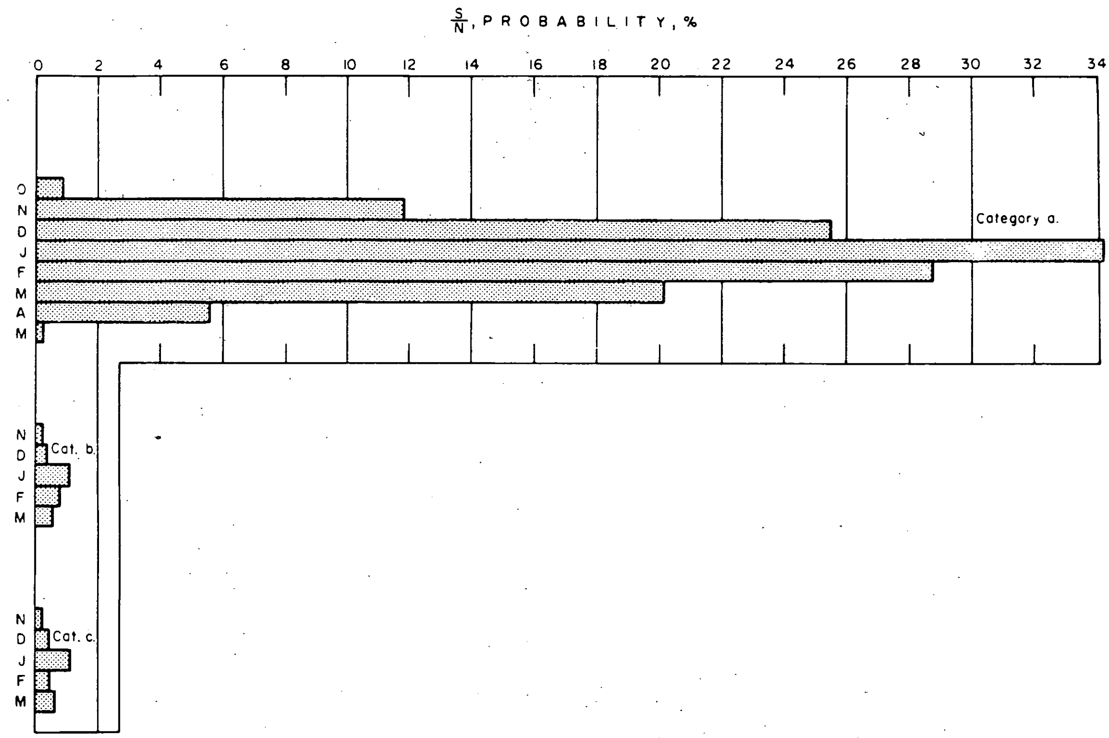

Figure 18. Monthly distribution of frozen precipitation, categories a, b, and c, Buffalo, New York.

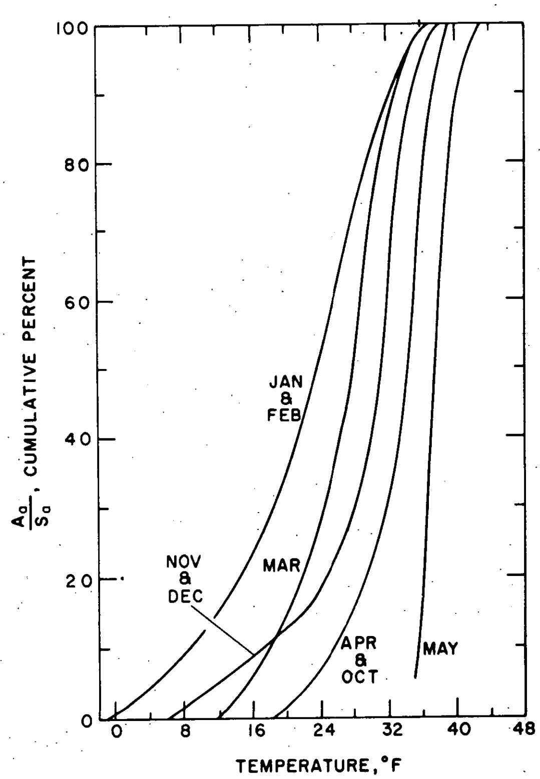

Figure 19. Relationship between air temperature and cat. a precipitation (monthly), Buffalo, New York.

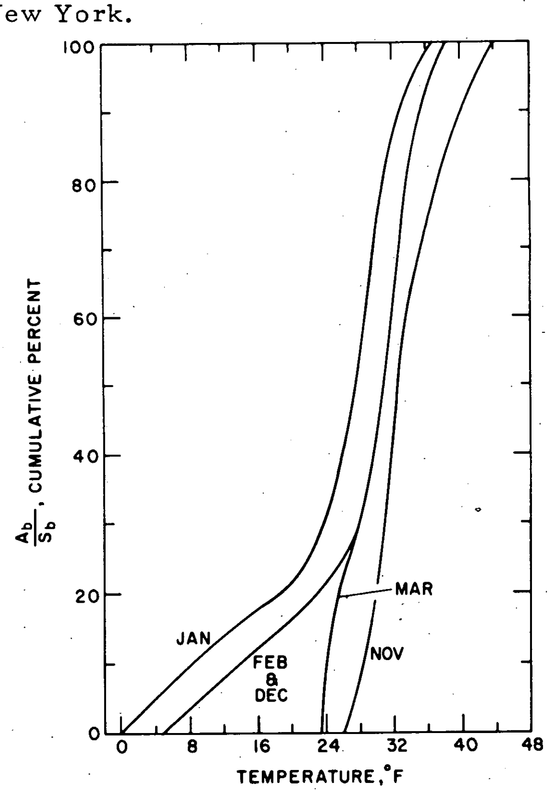

Figure 20. Relationship between air temperature and cat. b precipitation (monthly), Buffalo, New York.

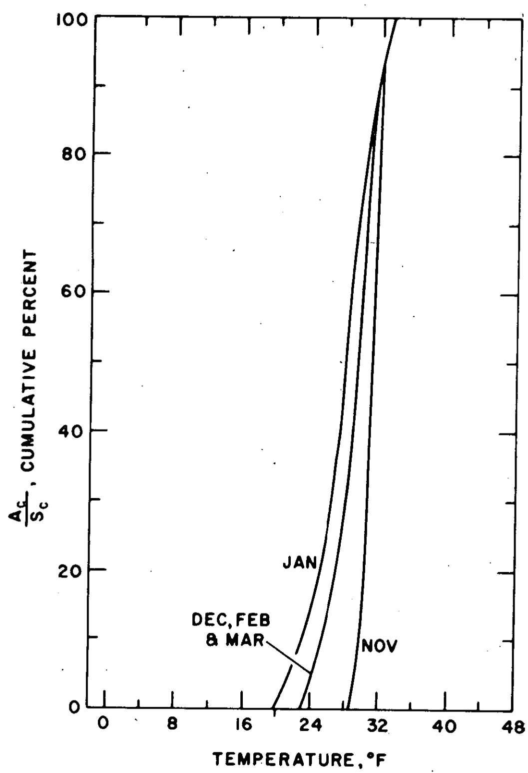

Figure 21. Relationship between air temperature and freezing rain and/or freezing drizzle (monthly), Buffalo, New York.

22F. Therefore, 58% of the snow occurring in January is observed at 22F or above. Using the probable number of hours (255) that snow will occur in Buffalo in January (from Fig. 18), we compute as follows: (255) x (.58) = 148 hr.

Similar computations can be accomplished for a group of months and for all or individual categories.

Probability at specific temperatures (Fig. 22a, b). These figures provide probability values for the occurrence of each frozen precipitation type at known or expected temperatures.

For example: from the annual curve in Figure 22a the probability of snow and/or snow showers occurring if the temperature is 12F is 39.3%. Note that for temperatures from 13 to +33F the probability ranges between 32 and 42% and then decreases rapidly. A companion curve (Fig. 22b) shows monthly maximums. We find from this curve, for example, an absolute maximum (53.8%) occurring at 22F in January.

Since categories b and c occur less frequently, their ordinate scales in Figure 22 had to be expanded. For some locations the probability of occurrences was so small for these categories that part or all of the curve was omitted. For category c we note on the annual curve that the greatest probability (2.1%) of freezing rain and/or freezing drizzle occurs at 30F and the maximum curve shows that the peak for any month lies between 28 and 31F.

Average number of 6-hr snowstorms to be expected per year (Fig. 23). Six-hr snowstorms were associated with temperature, wind velocity and amount of snow. From Figure 23, we find that most of the 6-hr snowstorms at Buffalo occur between 28 and 33F during 10 to 14-knot winds and the snow accumulation in inches of water equivalent is between .10 and .19 inches. Fractional frequencies, for example 0.9 for the temperature range 40-45F, indicate that, on the average, one 6-hr snowstorm can be expected to occur between these temperatures within a 10-year period. It should be noted that the 6-hr snowstorm information given here considers a 24-hr storm, for example, as four 6-hr storms.

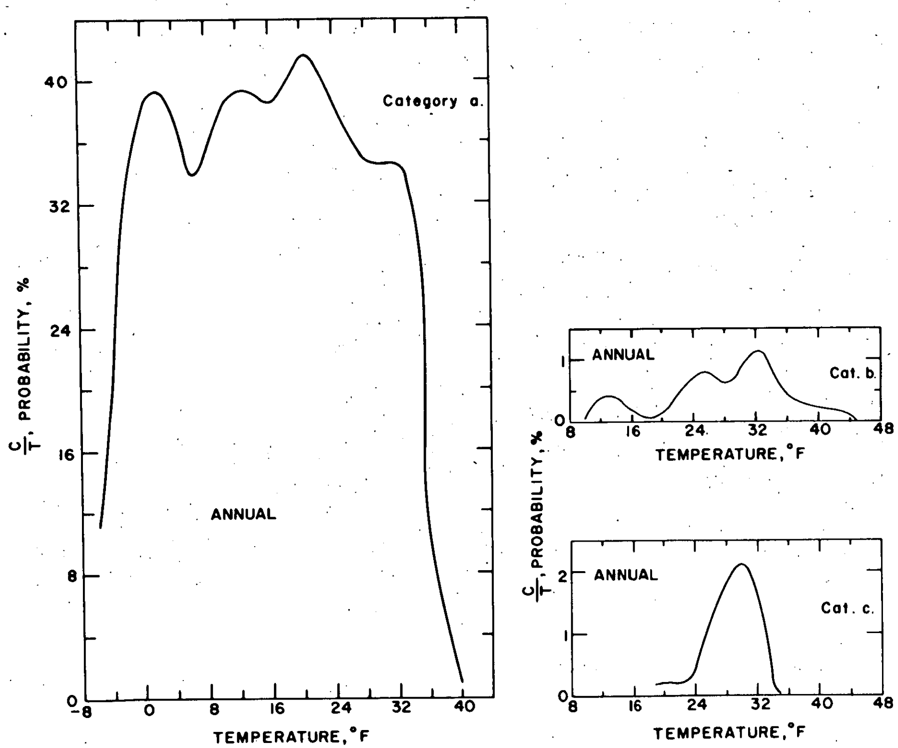

Figure 22a. Probability of frozen precipitation occurring at specific temperatures (annual), Buffalo, New York.

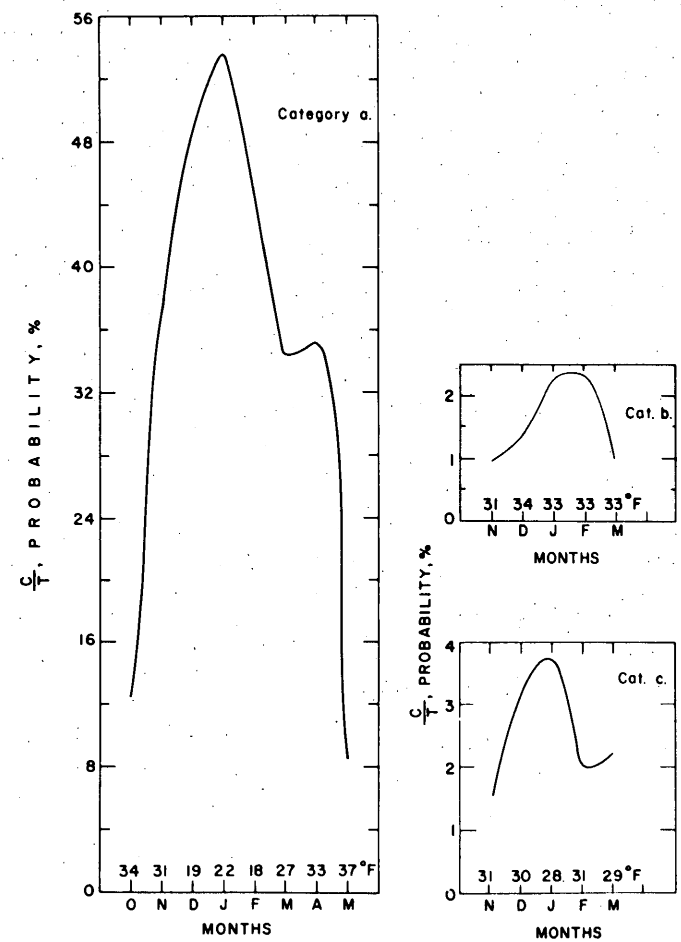

Figure 22b. Highest probability of frozen precipitation observed during the entire period of record for each month and the temperature at which it occurred, Buffalo, New York.

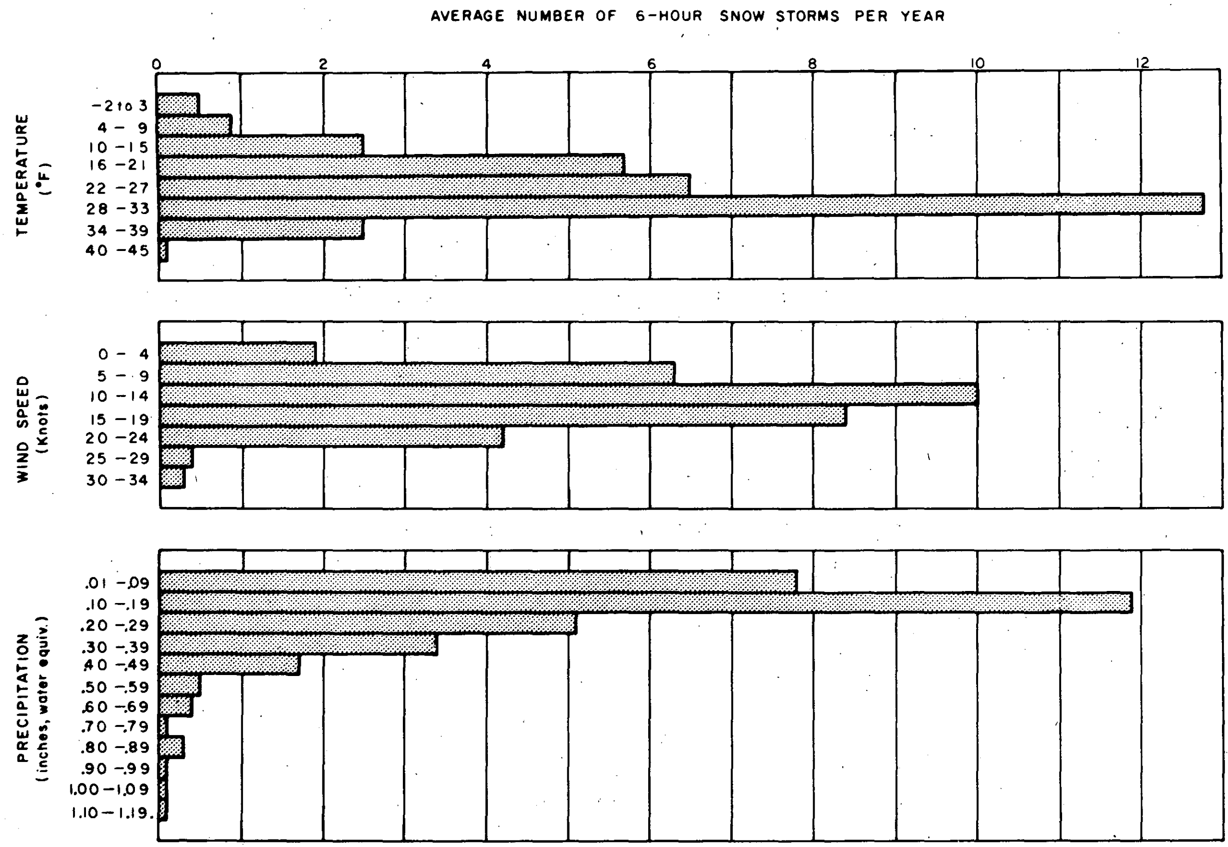

Figure 23. Frequency of 6-hr snowstorms in terms of temperature, wind speed, and amount (annual), Buffalo, New York.

Average number of long-duration (6 through 42-hr) snowstorms to be expected during a 10-year period (Fig. 24). These snowstorms of long duration were associated with the mean temperature observed during the final 6-hr of the storm period.

From Figure 24 we find that 6, 12, 18, 24, 30 and 42-hr snowstorms have been observed in Buffalo. The greatest number of 6-hr storms per 10-year period (54) occur at a temperature between 28 and 33F. An average of one 42-hr snowstorm can be expected every 10 years, with a temperature between 28 and 33F during the last 6 hr. of the storm.

Table III. Significant snow and freezing rain storms, LaGuardia, New York.

(Record: October 1949 through May 1960)

A. Greatest consecutive 6-hr snowfall amount (water equivalent, inches).

March 3, 1960. Hour ending at:

1400	1500	1600	1700	1800	1900
.10	.10	.10	.12	.13	.04

Total "catch" of snowfall 6.5 in. City Office, Battery Place, N.Y., reported 0.15 in. during 1 hr of this period.

B. Longest continuous period of freezing rain and/or freezing drizzle (water equivalent, inches).

February 22, 1950. Hour ending at:

1300	1400	1500	1600	1700	1800	1900	2000	2100	2200	2300	2400
.01	.01	.01	.02	.04	.03	.01	.01	.02	.01	.01	.01

Continued February 23, 1950:

0100	0200	0300	0400	0500	0600	0700
Trace	.03	.03	.02	.01	.01	.02

Table IV. List of stations in the study.

City	Location	State or Province
Anchorage	Merrill Field	Alaska
Barrow	Weather Bureau Office	Alaska
Bedford	Hanscom Field	Massachusetts
Buffalo	W.B. Airport Station	New York
Chicago	W.B. Airport Station	Illinois
Chicopee Falls	Westover AFB	Massachusetts
Cleveland	W.B. Airport Station	Ohio
Denver	W.B. Airport Station	Colorado
Fairbanks	International Airport	Alaska
Kansas City	W.B. Airport Station	Missouri
Kotzebue	Weather Bureau Office	Alaska
Milwaukee	W.B. Airport Station	Wisconsin
Minneapolis	W.B. Airport Station	Minnesota
Montreal	Dorval Airport	Quebec
New York	LaGuardia Airport	New York
Omaha	W.B. Airport Station	Nebraska
Philadelphia	W.B. Airport Station	Pennsylvania
Pittsburgh	Greater Pittsburgh Airport	Pennsylvania
Seattle	Seattle-Tacoma Airport	Washington
St. Louis	Lambert Airport	Missouri
Toronto	Malton Airport	Ontario
Vancouver	Abbotsford	British Columbia
Washington	Washington National Airport	D. C.
Ypsilanti	Willow Run Airport	Michigan

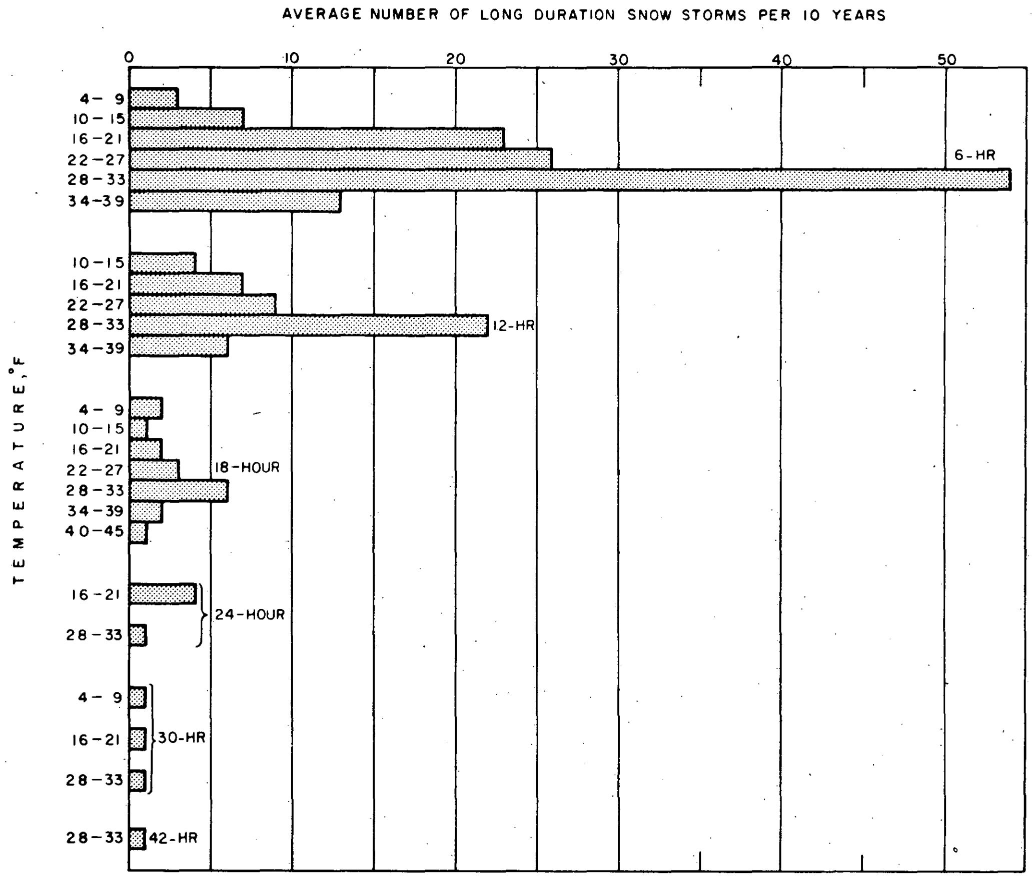

Figure 24. Frequency of long duration snowstorms in terms of temperature (10 years), Buffalo, New York.

Table AI. Dry bulb temperature ≤ 39F vs frozen precipitation. Period of record: Oct-Dec for the years 1949-1959; Jan-May for the years 1950-1960. (Source: WB NWRC Card deck 144, hourly surface observations.)

Station = WBAN station no. 14732 = LaGuardia, N.Y.
Mo = Month 01=Jan, 02-Feb, etc., Ann=Annual
DB Temp = Dry bulb temperature in whole °F
Tot=Total frequency count of each frozen precipitation group
Under the heading "Frozen precipitation":
A = Snow and/or snow showers
B = Snow pellets, ice crystals, snow grains, soft hail and/or sleet
C = Freezing rain and/or freezing drizzle
D = A+C or A+B+C observed together

Tot A-D = Total of A+B+C+D
Tot Cds = Total number of cards surveyed
Where A is observed alone a count of 1 is shown under A.
Where B is observed alone a count of 1 is shown under B.
Where C is observed alone a count of 1 is shown under C.
Where A+B are observed together a count of 1 is shown under A.
Where B+C are observed together a count of 1 is shown under C.
Where A+C or A+B+C are observed together a count of 1 is shown under D.

Station	Mo	DB temp	Frozen precipitation A	B	C	D	Tot A-D	Tot Cds	Mo	DB temp	Frozen precipitation A	B	C	D	Tot A-D	Tot Cds
14732	10	39	1				1	29	11	39	2				2	240
		38						25		38	3	1			4	251
		37						8		37	2				2	209
		36						8		36	6	1			7	136
		35	2				2	9		35	13				13	168
		34	1				1	1		34	4				4	107
		Tot	4				4	80		33	6				6	77
										32	5				5	85
										31	5				5	55
										30	8				8	82
										29	3				3	34
										28	1				1	49
										27						33
										26	2				2	21
										25						20
										24						17
										23						9
										22						9
										21						2
										20						3
										19						7
										18						2
										17						2
										Tot	60	2			62	1618
14732	12	39	3				3	377	01	39	2				2	302
		38	9	3			12	375		38	4	2			6	334
		37	6	1			7	363		37	4	3			7	425
		36	17				17	316		36	26	3			29	398
		35	28	4			32	347		35	33	4			37	523
		34	23				23	250		34	20				20	375
		33	20		2		22	231		33	25	7	8		40	358
		32	26	1			27	269		32	26	3	10		39	352
		31	19		1		20	217		31	29	2	4	2	37	284
		30	17		1		18	240		30	34	1	7		42	375
		29	8			1	9	179		29	31		6	2	39	281
		28	12	1			13	187		28	20		6		26	255
		27	8	1			9	178		27	14		2		16	222
		26	13				13	139		26	11		2		13	190
		25	6				6	152		25	7	1	6		14	227
		24	1				1	91		24	9		3		12	164
		23	3				3	103		23	4		1		5	166
		22	5				5	81		22	5		3		8	143
		21	10				10	73		21	8	1	2		11	99
		20	7				7	103		20	14	1			15	120
		19	7				7	74		19	4				4	83
		18	2				2	73		18	6				6	102
		17						43		17	5				5	88
		16						36		16	6				6	44
		15						37		15	4				4	44
		14						17		14	5				5	35
		13						16		13	2				2	21
		12						8		12	4				4	22
		11						9		11	1				1	10
		10						4		10	2				2	15
		9						3		9						5
		8						5		8						5
		7						5		7						4
		6						3		6						1
		Tot	250	11	4	1	266	4604		5						2
										4						1
										3						2
										1						3
										Tot	365	28	60	4	457	6080

Table AI (Cont'd).

Station	Mo	DB temp	Frozen precipitation A	B	C	D	Tot A-D	Tot Cds
14732	02	39	3				3	403
		38	2				2	415
		37	6	1			7	420
		36	11	6			17	363
		35	20	6			26	410
		34	33	6	2		41	340
		33	45	10			55	337
		32	33	1	2	1	37	308
		31	24		9		33	198
		30	30		5	1	36	255
		29	16		4		20	151
		28	13	2	6	1	22	159
		27	10		5		15	155
		26	6	1	3		10	98
		25	12	3	3		18	117
		24	6				6	107
		23	6				6	90
		22	10				10	92
		21	11				11	69
		20	15				15	91
		19	7				7	87
		18	3				3	63
		17						53
		16	1				1	45
		15	3				3	47
		14	7				7	40
		13	2				2	37
		12	1				1	29
		11						11
		10						22
		9						18
		8						14
		7	4				4	24
		6	1				1	7
		5						4
		4						3
		3						2
		2						1
		Tot	341	36	39	3	419	5085
14732	04	39	1				1	94
		38	2				2	94
		37	10	1			11	83
		36	6				6	51
		35	18	2			20	72
		34	15				15	32
		33	10				10	16
		32	4				4	13
		31	1				1	10
		30	1				1	16
		29	2				2	5
		28	3				3	10
		27	1				1	3
		26						3
		25						5
		24						4
		Tot	74	3			77	511
	05	39						2
		38						1
		Tot						3
	03	39	6	6			12	448
		38	10	5			15	462
		37	24	2			26	433
		36	22	3			25	320
		35	50	2			52	376
		34	58	3			61	264
		33	35	5	2		42	244
		32	42	5	3		50	243
		31	20	4	5		29	168
		30	21	3	4		28	197
		29	14				14	137
		28	20				20	149
		27	18	1			19	113
		26	14				14	91
		25	13				13	91
		24	12				12	58
		23	11				11	79
		22	7				7	61
		21	15				15	49
		20	8				8	33
		19						14
		18						7
		17						6
		16						5
		15						5
		14						5
		13						4
		12						4
		11						4
		Tot	420	39	14		473	4070
	Ann	39	18	6			24	1895
		38	30	11			41	1957
		37	52	8			60	1941
		36	88	13			101	1592
		35	164	18			182	1905
		34	154	9	2		165	1369
		33	141	22	12		175	1263
		32	136	10	15	1	162	1270
		31	98	6	19	2	125	932
		30	111	4	17	1	133	1165
		29	74		10	3	87	787
		28	69	3	12	1	85	809
		27	51	2	7		60	704
		26	46	1	5		52	542
		25	38	4	9		51	612
		24	28		3		31	441
		23	24		1		25	447
		22	27		3		30	386
		21	44	1	2		47	292
		20	44	1			45	350
		19	18				18	265
		18	11				11	247
		17	5				5	192
		16	7				7	130
		15	7				7	133
		14	12				12	97
		13	4				4	78
		12	5				5	63
		11	1				1	34
		10	2				2	41
		9						26
		8						24
		7	4				4	33
		6	1				1	11
		5						6
		4						4
		3						4
		2						1
		1						3
		Tot	1514	119	117	8	1758	22051

Table AII. Mean air temperature °F (for 6-hr period) vs 6-hr precipitation amount (water equivalent) when the 6-hr snowfall was ≥ 1 inch. Period of record: Oct-Dec for the years 1949-1959; Jan-May for the years 1950-1960. (Source: WB NWRC Card deck 344, 6-hr surface observations.)

Station = WBAN station no. 14732 = LaGuardia, N. Y.
Mo = Month 01=Jan, 02=Feb, etc., 12=Dec.
Pcp = 6-hr precipitation amount in inches to hundredths
1.40 = Precipitation from 1.40 - 1.49; 1.30 = Precipitation from 1.30 - 1.39, etc.
T = Trace
Tot = Total frequency count of each temperature group.

Temperatures:
From 39-34. A frequency count of 1 is shown when the 6-hr mean temperature was between 39 and 34F.
From 33-28. A frequency count of 1 is shown when the 6-hr mean temperature was between 33 and 28F, etc.
Tot = Total count for each precipitation interval, for each temperature group.

		Temperature From: 39	33	27	21	15	9	3	-3	-9	-15	-21	-27	-33	-39	-45	-51	
Station	Mo	Pcp To: 34	28	22	16	10	4	-2	-8	-14	-20	-26	-32	-38	-44	-50	-99	Tot
14732	11	.40		1															1
		.10		1															1
		Tot		2															2
	12	.50		1															1
		.30	1	1	1														3
		.10	1	7	2	2													12
		Tot	2	9	3	2													16
	01	.40			1														1
		.30		1															1
		.20	1	1		1													3
		.10	2	6	1	3	1												13
		.01				2													2
		Tot	3	8	2	6	1												20
	02	.50	1																1
		.40		1	2														3
		.20	1		1	1													3
		.10	3	4	1	1													9
		.01		1	3	1													5
		Tot	5	6	7	3													21
	03	.60			1														1
		.50		3															3
		.40	2																2
		.30		3	2	1													6
		.20	2		1														3
		.10		2	1														3
		.01		2	2														4
		Tot	4	10	7	1													22
	04	.60	1																1
		.30	2																2
		.20	1																1
		.01	1																1
		Tot	5																5

Table AIII. Wind speed, knots (at end of 6-hr period) vs 6-hr precipitation amount (water equivalent) when the 6-hr snowfall was ≥ 1 inch. Period of record: Oct-Dec for the years 1949-1959; Jan-May for the years 1950-1960. (Source: WB NWRC Card deck 344, 6-hr surface observations.)

Station = WBAN station no. 14732 = LaGuardia, N. Y.
Mo = Month 01=Jan, 02=Feb, etc., 12=Dec.
Pcp = 6-hr precipitation amount in inches to hundredths
Tot = Total frequency count of each wind speed group

From 0 to 4 = A frequency count of 1 is shown when the wind speed was between 0 and 4 knots.
From 5 to 9 = A frequency count of 1 is shown when the wind speed was between 5 and 9 knots, etc.
Tot = Total count for each precipitation interval for each wind speed group.

		From:	0	5	10	15	20	25	30	35	40	45	50	55	60	65	70	75	
Station	Mo	Pcp To:	4	9	14	19	24	29	34	39	44	49	54	59	64	69	74	+	Tot
14732	11	.40								1									1
		.10			1														1
		Tot			1					1									2
	12	.50						1											1
		.30			1	1	1												3
		.10	1	3	3	2		3											12
		Tot	1	3	4	3	1	4											16
	01	.40				1													1
		.30						1											1
		.20			2	1													3
		.10		4	4	3	2												13
		.01				2													2
		Tot		4	6	7	2	1											20
	02	.50					1												1
		.40			1			1	1										3
		.20					2	1											3
		.10		2	1	3	3												9
		.01		1	3	1													5
		Tot		3	5	4	6	2	1										21
	03	.60					1												1
		.50				1	1			1									3
		.40					2												2
		.30			1	1	3	1											6
		.20						2	1										3
		.10		1		1	1												3
		.01			1	1	1	1											4
		Tot		1	2	4	9	4	1	1									22
	04	.60			1														1
		.30				1	1												2
		.20					1												1
		.01							1										1
		Tot			1	1	2		1										5

Table AIV. Mean air temperature °F vs duration (hours), when snowfall was ≥ 1 inch (8-month seasonal only). Period of record: Oct-Dec for years 1949-1959; Jan-May for years 1950-1960. (Source: WB NWRC Card deck 344, 6-hr surface observations.)

Station = WBAN station no. 14732 = LaGuardia, N. Y.
Mean temperature = Mean air temperature °F for the last 6-hr snow period.
39-34 = The mean air temperature was between 39 and 34F for the first 6-hr snow period.
33-28 = The mean air temperature was between 33 and 28F for the first 6-hr snow period.

Tot = The total frequency of each duration group.
6 = A count of 1 is shown under 6 when the duration was 6 hours.
12 = A count of 1 is shown under 12 when the duration was 12 hours, etc.

	Hours duration					
Mean temperature °F	6	12	18	24	30	36
39-34	9	2	2			
33-28	16	6	3			1
27-22	2	3	2	1		
21-16	1	2				
15-10	1					
Tot	29	13	7	1		1

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1. ORIGINATING ACTIVITY *(Corporate author)*	2a. REPORT SECURITY CLASSIFICATION
U. S. Army Cold Regions Research and Engineering Laboratory, Hanover, N.H.	Unclassified
	2b. GROUP

3. REPORT TITLE

SURVEY OF FROZEN PRECIPITATION IN URBAN AREAS AS RELATED TO CLIMATIC CONDITIONS

4. DESCRIPTIVE NOTES *(Type of report and inclusive dates)*

Technical Report

5. AUTHOR(S) *(Last name, first name, initial)*

Bilello, Michael A.

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
May 1967	33	0

8a. CONTRACT OR GRANT NO.	9a. ORIGINATOR'S REPORT NUMBER(S)
b. PROJECT NO.	Technical Report 162
c. DA Task 1VO14501B52A02	9b. OTHER REPORT NO(S) *(Any other numbers that may be assigned this report)*
d.	

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	U. S. Army Cold Regions Research and Engineering Laboratory

13. ABSTRACT

This study investigates relationships between observed frozen precipitation and associated meteorological conditions in large cities, and develops procedures for presenting tabulated data on frozen precipitation in a readable and usable form. An explanation of several interpretations is included with methods of analysis, sample diagrams, advantages and disadvantages, and comparisons of the different interpretations. To avoid excessive bulk, only the diagrams for LaGuardia Airport and Buffalo, New York, are discussed in this paper. Similar Figures for 22 other stations are on file at USA CRREL.

DD FORM 1 JAN 64 1473

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14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Snow precipitation--Distribution--U. S. Climatology--U. S. Precipitation--Meteorological factors Precipitation--Statistical analysis						

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