AREAL AND SPATIAL DISTRIBUTIONS OF PRECIPITATION IN NEW ENGLAND STORMS

by

MICHAEL JEFFREY KRAUS

SUBMITTED IN PARTIAL FULFILLMENT
OF THE REQUIREMENTS OF THE
DEGREE OF BACHELOR OF SCIENCE
at the
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

June, 1966

Signature of Author . . . .
Department of Geology and Geophysics, May 20, 1966

Certified by . . . .
Thesis Supervisor

Accepted by . . . .
Chairman, Departmental Committee on Theses

SPATIAL AND TEMPORAL DISTRIBUTIONS OF PRECIPITATION IN NEW ENGLAND STORMS

by

MICHAEL JEFFREY KRAUS

Submitted to the Department of Geology and Geophysics on 20 May 1966
in Partial Fulfillment of the Requirements for
the Degree of Bachelor of Science

ABSTRACT

The purpose of this study is to investigate the relation between mesoscale distributions of precipitation and the large scale weather patterns. All storms for two years, 1962 and 1963, were classified on the synoptic scale, according to the location and recent history of the low pressure center and/or frontal system with which the storm was associated. Mesoscale features were based on the precipitation which fell in an area on the order of 10^4 square miles. Hourly precipitation amounts from a network of recording rain gauges, radar observations, and U. S. Weather Bureau maps provided the basic data. The following quantities were compiled for each storm to depict the precipitation within a radius of 80 miles from Cambridge, Massachusetts: the duration, the total amount of water deposited, the hour during which the gauges recorded the maximum of rainfall and this amount, and spatial distributions within the area. These characteristics were analyzed for each of the synoptic groups and also for the individual storms within each group. Seasonal and diurnal variations were also considered.

Large scale precipitation producers were classified into seven groups. Three of them were cyclones which came towards the area over the water from the south, and overland from the southwest or west respectively. One group was a combination of overland and overwater (coastal) cyclones. The other three groups included stationary fronts with wave cyclones, cold fronts, and air mass storms.

It was found that coastal cyclones and low pressure centers from the southwest deposited the most precipitation over the area, not because of their frequency, but because of the intensity of the precipitation. The stationary fronts with waves were the most frequent storms. There was good agreement between the spatial distribution of precipitation and the paths which the storms took, the storms passing to the north depositing the most water in the northern sections, and the storms south of the area affecting the southern sections more. Seasonal distributions showed the cold fronts and air mass storms having maxima in total water during the summer months and the coastal and southwest cyclones having maxima in the fall and early winter.

Thesis Supervisor: Pauline M. Austin
Title: Research Associate

ACKNOWLEDGEMENTS

The author wishes to express his appreciation to Dr. Pauline M. Austin for her inspiration and guidance, without which this paper would not exist.

Special thanks go to Mr. Steven A. Ricci for the preparation of the figures.

Processing of the rain guage data was done by the Weather Radar Project in the Department of Meteorology at M. I. T. under the sponsorship of NSF Grant G-19230 and U. S. Army Electronics Command Contract no. DA 36-039 AMC-02225(E).

Machine computations were carried out at the M. I. T. computation center.

TABLE OF CONTENTS

ABSTRACT	ii
ACKNOWLEDGEMENTS	iv
TABLE OF CONTENTS	v
LIST OF FIGURES	vi
LIST OF TABLES	vii
INTRODUCTION	1
DATA AND METHODS OF ANALYSIS	4
A. Mesoscale Distribution of Precipitation	4
B. Large Scale (Synoptic) Features	10
RESULTS AND DISCUSSION	16
A. Distribution of Precipitation According to Storm Type	16
B. Variability Within Each Groups	17
C. Diurnal Variations of the Groups	24
D. Spatial Distribution of Precipitation	24
E. Geographical Location of Systems	30
F. Seasonal Variations	36
G. Representativeness of the Two Years, 1962 and 1963	36
CONCLUSIONS	39
APPENDIX: Storms Used in Study	42
REFERENCES	53

LIST OF FIGURES

Fig. 1. Map of rain-gauge stations reporting hourly amounts in New England.

Fig. 2. Computer output showing rainfall amounts for hour ending 1700 EST, 29 Sept., 1963.

Fig. 3. Histogram of hourly areal intensity for 23-24, Nov., 1963.

Fig. 4. Four sections within the 80 mile circle used to compute areal distributions.

Fig. 5. Typical examples of the seven classifications.

Fig. 6. Distributions of total water by group.

Fig. 7. Distributions of duration by group.

Fig. 8. Distributions of hourly areal maximum.

Fig. 9. Distributions of the hour of the areal maximum by group.

Fig. 10. Distributions of the location of systems by group.

Fig. 11. Distributions of number of storms per month by group.

Fig. 12. Distributions of total water per month by group.

LIST OF TABLES

Table 1. Number of storms, by group, for each year.

Table 2. Distribution of total water.

Table 3. Duration of storms and average water per hour.

Table 4. Total water: mean, median, and mode.

Table 5. Duration: mean, median, and mode.

Table 6. Maximum areal intensity: mean, median, and mode.

Table 7. Average depth (inches) of water deposited on each section for the two years.

Table 8. Frequency of maximum and minimum areal depths for each section (both years).

Table 9. Number of storms per month for two years.

Table 10. Monthly distribution of total water deposited by each type of storm ($m^3 \times 10^8$).

Table 11. Percentage above or below the normal monthly precipitation values (by section).

I. INTRODUCTION

The aim of this study is to investigate the relation between the distribution of precipitation, which exhibits small scale variability, and the large scale weather patterns. It seeks answers to such questions as: What is the relationship between the cyclonic and/or frontal systems and mesoscale spatial and temporal variations in the precipitation from these systems? Do all storms with a similar history have similar rainfall patterns and amounts, and do they affect similar areas? Are the details of precipitation predictable from the location of a system, its intensity, duration, moisture content, or combinations of these criteria? Answers to these questions would cast light on the problems of precipitation physics and dynamics of small scale circulations. In addition, they might help pave the way for better quantitative precipitation forecasts.

Most experienced meteorologists recognize that there are certain preferred routes by which storms approach New England: overland from the west or southwest, or up the cost from the south or southwest. Also, it is recognized that in the spring and summer there is often convective type rain associated with surface heating or passing cold fronts, while in the fall and winter widespread snow or rain storms occur. However, there have been no investigations concerning the actual numbers of the different types of storms, how much water they deposited, or precise localities where precipitation was heaviest.

A number of studies, including Mather, Adams, and Yoshioka (1964), and Jarvis (1965), have been made concerning cyclogenesis off the East Cost of the United States. They have studied tracks of these storms, and how to predict displacement and favorable times for development. However, none have considered the actual amounts and distributions of precipitation in a definite mesoscale area, nor have they compared the storms on an individual basis.

Nason (1965) investigated the relation of mesoscale patterns, as depicted by radar, with the macroscale features. He selected a number of storms on the basis of well defined radar pattern: areas, bands, and miscellaneous. He found that each of these patterns was associated with a predominant synoptic type and seasonal peak, finding that areas were mostly related to coastal lows in late winter, and that bands were associated with summer cold fronts. He also did much analysis on dimensions and durations of the areas and bands. He did not, however, determine the frequency of occurrence of the various types of patterns, nor the amounts of precipitation associated with them.

In this study, all storms for two years, 1962 and 1963, are classified on the synoptic scale, according to the location and recent history of the low pressure center and/or frontal system with which the precipitation was associated. The mesoscale features are characterized by the total amount of precipitation which fell in an area on the order of 10^4 square miles, its distribution within this area, the duration of the storm and the hourly rates of deposit. Seasonal and diurnal distributions are also considered.

All storms for a period of two years are included in order that an estimate of frequency of occurrence of the different types can be made. It is recognized that this is a small sample, statistically speaking, because the number and intensity of storms vary considerably from year to year. It is hoped, however, that the amounts and distribution of precipitation for these two years are reasonably representative.

II. DATA AND METHODS OF ANALYSIS

A. Mesoscale Distribution of Precipitation

Basic data for mesoscale patterns are rain gauge records and quantitative radar data.

The rain guage data for New England were obtained from Hourly Precipitation Amounts published by the U. S. Weather Bureau, which give the amount, in inches, of rainfall for each hour, day, and month. Data from 69 guages within 120 miles of Cambridge, Massachusetts were used in this study (see Fig. 1.). The rain gauge data used for quantitative purposes were limited to 37 guages within 80 miles of Cambridge. These ranges were selected to correlate with radar data for use on other projects. The range on the radar scope is 120 miles, but it is considered that quantitative radar data are rarely reliable beyond 80 miles.

A computer program was available which would plot data from the 120 mile network on hourly maps and compute the total volume of water that fell within the 80 mile circle for each hour, as shown in Fig. 2. In addition, similar maps were plotted, and total water volume computed for each 24 hour period.

Since the gauges are distributed unevenly over the area, in the computations of the total water, hourly amounts were weighted for each gauge by the area which the gauge best represents. Irregular polygons

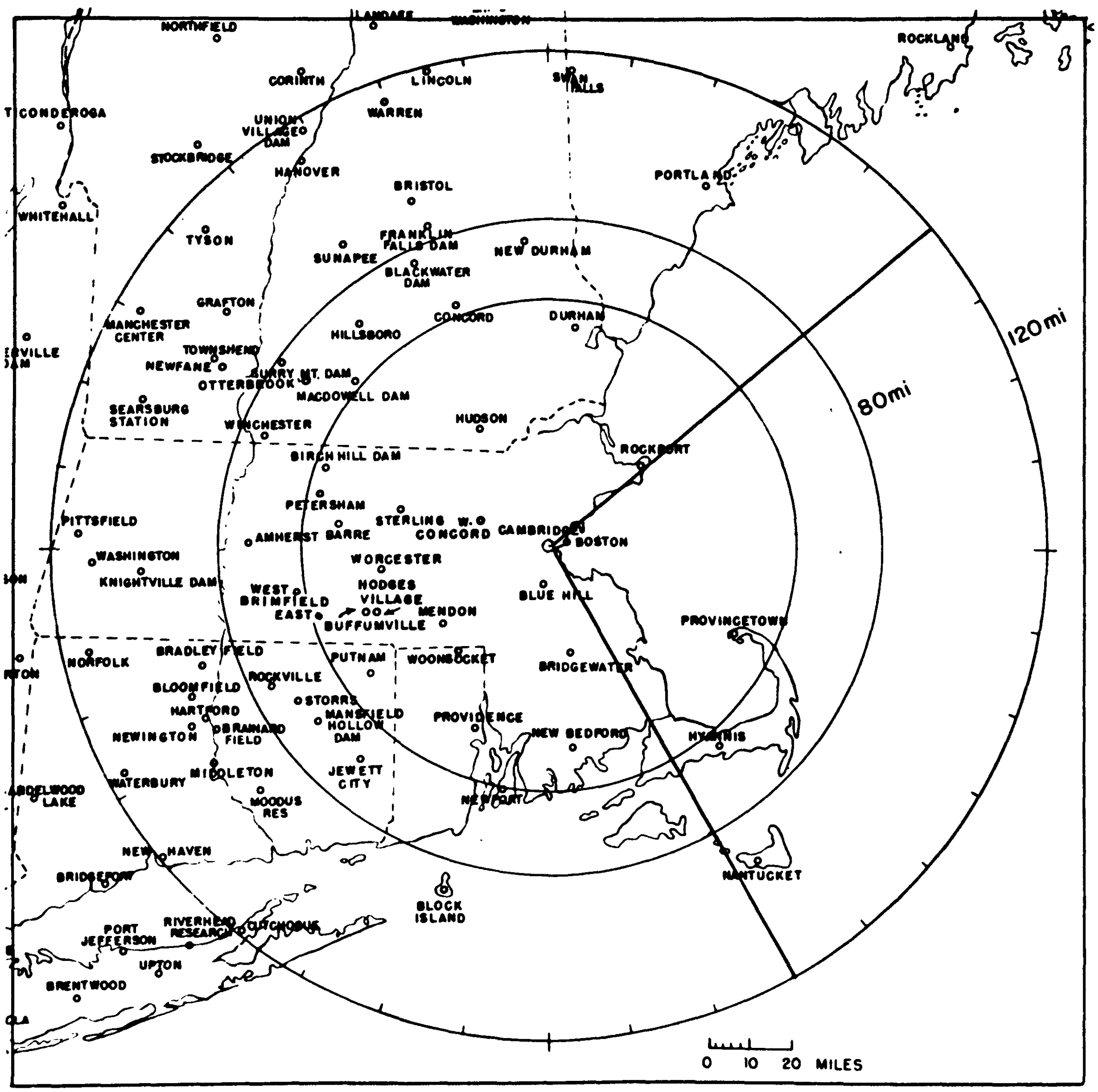


Fig. 1. Map of rain-gauge stations reporting hourly amounts in New England.

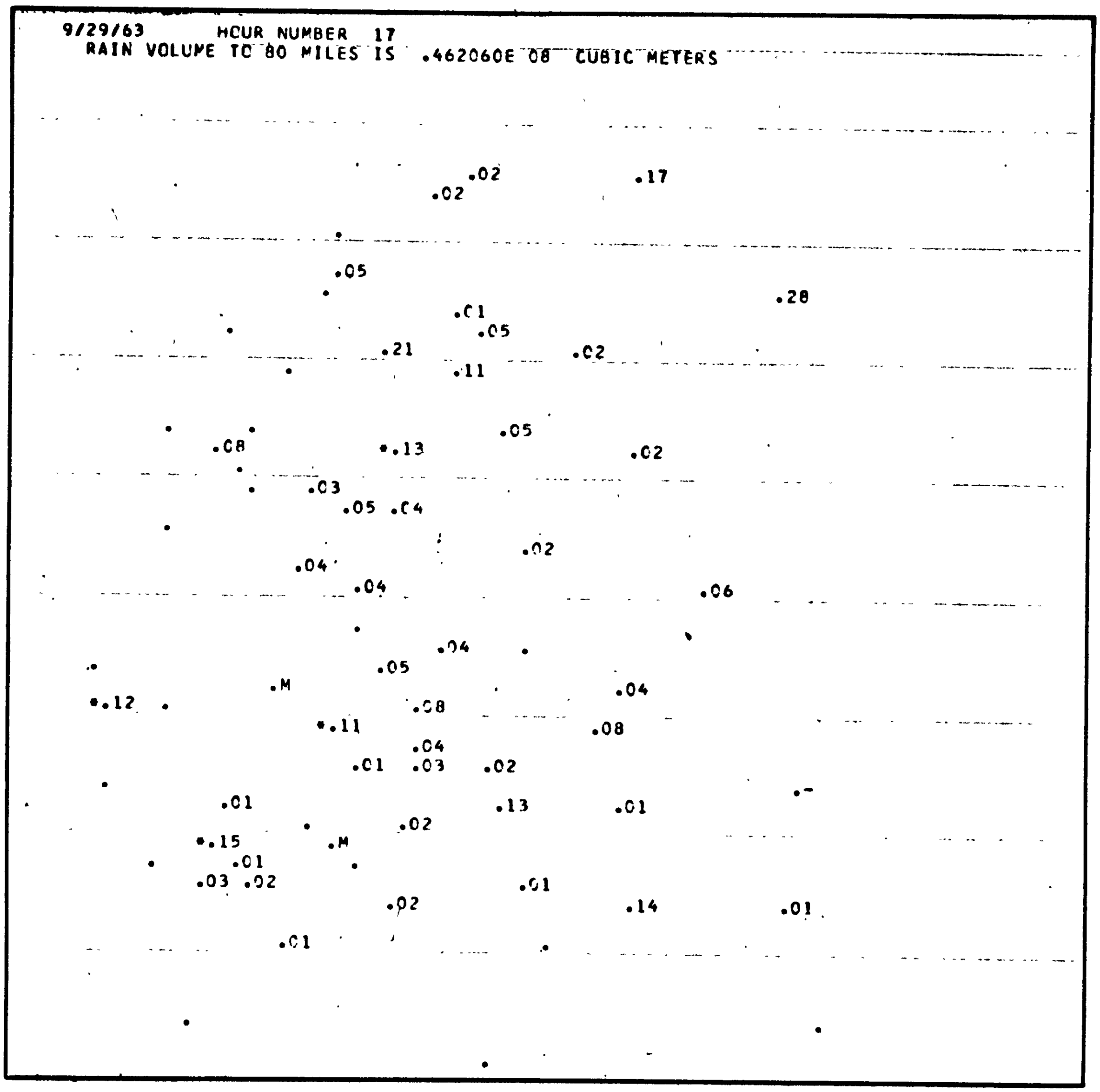


Fig. 2. Computer output showing rainfall amounts for hour ending 1700 EST, 29 Sept. 1963.

were used to determine this area. The polygons were formed from perpendicular bisectors of lines drawn between a station and all of the adjacent stations. A sector of the circle from 50° to 150° was omitted because there are no rain gauges over the ocean. The total area is 4×10^{10} m^2. Therefore, 1 $m^3 \times 10^8$ corresponds to an average areal depth of 2.5 mm or 0.1 inch.

A histogram of the hourly distribution of the total water was made for each day (Fig. 3.).

Areal distributions for each storm were computed by dividing the area into four equal sections as shown in Fig. 4. For each section, the average depth of water was obtained by adding the amounts of each gauge and dividing by the number of gauges. The sections were picked to coincide roughly with mountains, coastline, and general north-south directions. The number of sections was limited in order to facilitate data handling while enabling the results to be as meaningful as possible.

From the rain gauge data, the following information was tabulated:

a) The duration of each storm.

b) Total water within the 80 mile radius deposited by the storm. Units were in cubic meters times 10^8.

c) The hour of maximum amount of rainfall, and this amount for each storm as denoted by the peak in the histogram, Fig. 3.

d) Areal distributions.

In order to make a comprehensive survey it was desired to include all significant storms which occurred in 1962 and 1963, but, in the interests of saving time and labor in the analysis, to exclude ones

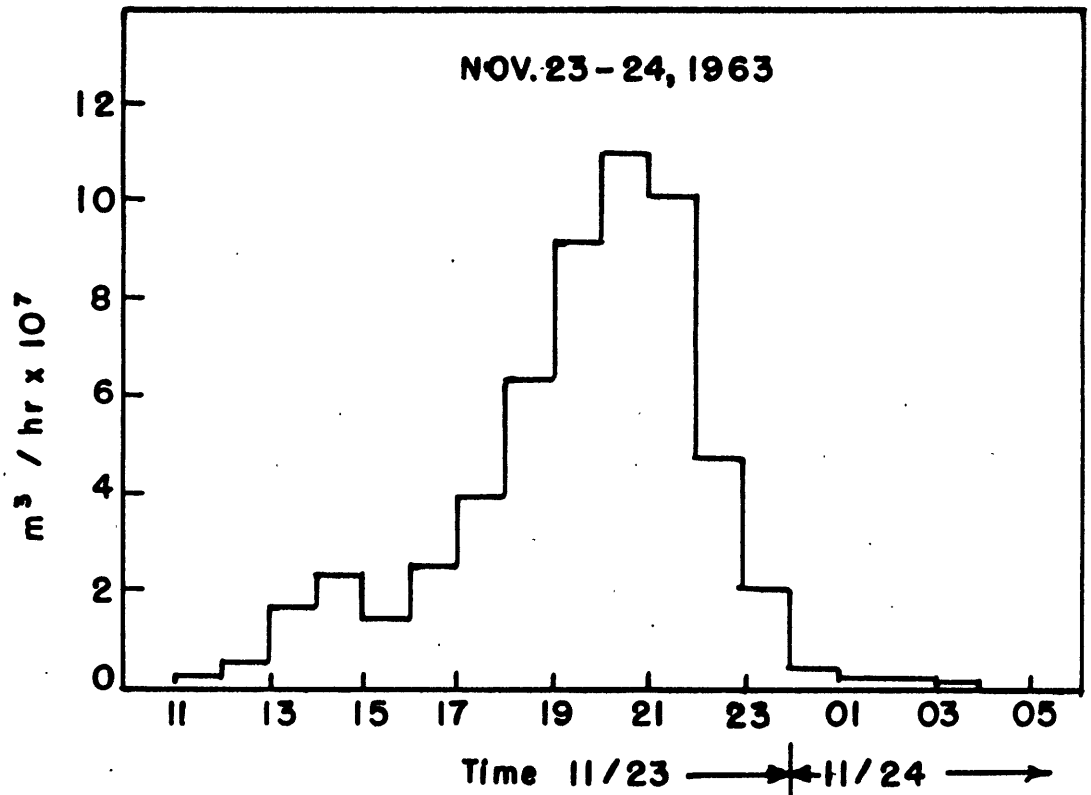


Fig. 3. Histogram of hourly areal intensity for 23-24, Nov., 1963.

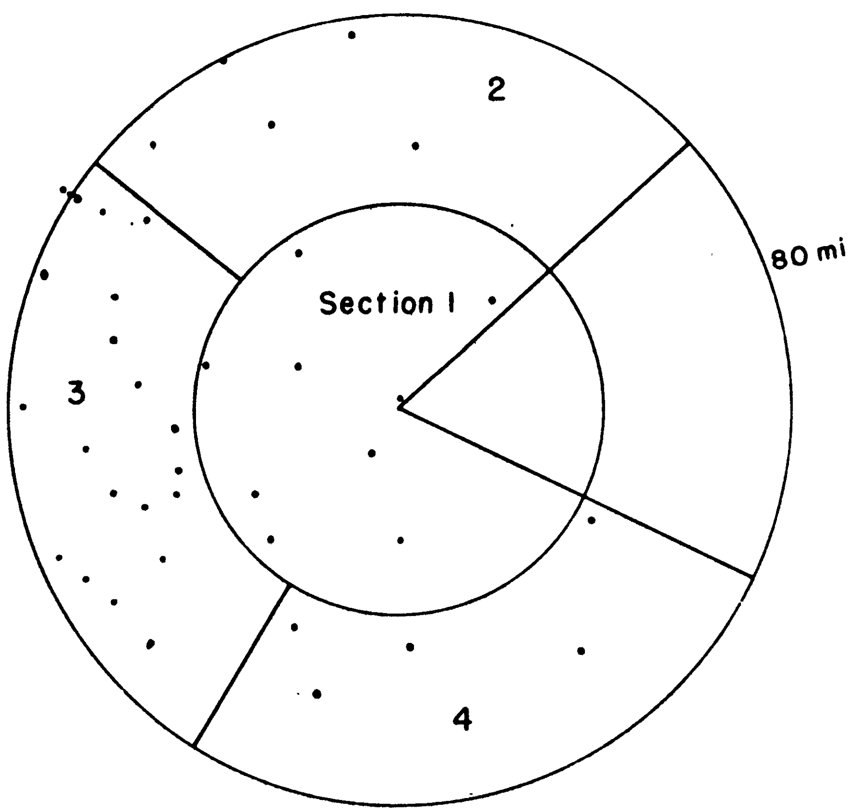


Fig. 4. Four sections within the 80 mile circle used to compute areal distributions.

which deposited very small amounts of water. For this reason, the following criteria were formulated. A storm was included in the survey if any one of three conditions was fulfilled:

1) 10 or more gauges (of the 69 within 120 miles) reported some precipitation and at least one had a 24 hour total of at least 0.2 inches or more.

2) 20 or more gauges reported some precipitation and at least one had a 24 hour total of as much as 0.1 inches.

3) 30 or more gauges reported some precipitation and at least one had a 24 hour total of at least 0.05 inches.

These criteria were chosen in order that a particular storm might be included or excluded on the basis of the rain gauge data. There is no particular value of total water below which a storm is excluded. If 10 gauges (15% of 69) report 0.2 inches, 0.03 inches of water fell over the entire area. When converted into units of total water, these criteria mean that the maximum value of total water a storm could have and not be included is about $0.3\ m^3 \times 10^8$, and any storm which was not included had less. A few storms which did have less than this amount were included on the basis of radar data or certain rain gauge data.

The major limitation of the rain gauge network is lack of sufficient coverage. The spacing of the gauges averages about ten to twenty miles and varies widely. As a result, convective cells can move between the gauges without hitting them in a representative way, or at all. Since the areas represented by different gauges are not equal, the gauges in less dense areas may make spuriously high contributions to the computed total water if one or more of them is hit hard by a small convective cell.

Errors may arise as a result of certain approximations made in the total water computation program. Symbols such as M (data missing), - (precipitation with no amount given), and * (amount given covers more than one hour) sometimes appear in the records. They are entered into the computation as 0 for M, .01 inches for - , and the average hourly amount for *. Although these approximations may result in distortions in the computed total water, they are better than making no approximations at all.

Two weather radars, AN/CPS-9 and SCR 615-B, located at M. I. T., have been recording quantitatively for a number of years. Several intensity levels of the range-normalized signal were used when recording storms on film. They show a good display of the small scale structure of storms, but the quantitative data are not in a convenient form for computation. Therefore, radar data were not used directly in this analysis.

B. Large scale (synoptic) features

U. S. Weather Bureau daily maps were used to determine the macroscale features which caused the precipitation in the 80 mile circle surrounding Cambridge. Gaps in the daily weather maps were filled in by regularly transmitted facsimile and teletype data. The maps were available at 12 hourly intervals only. Poor spatial resolution is inherent on large scale maps, and, therefore, there are some uncertainties on the order of a maximum of 100 miles, in the exact location of the systems being studied.

Storms were grouped according to the location and history of low pressure areas and/or frontal zones. Seven classifications were established. Typical maps for each group are shown in Fig. 5. The groups are:

1. Coastal Lows (CL). Cyclonic centers formed off the Atlantic Coast and moved up from the south or southwest over the ocean. They were usually occluded by the time they reached New England.

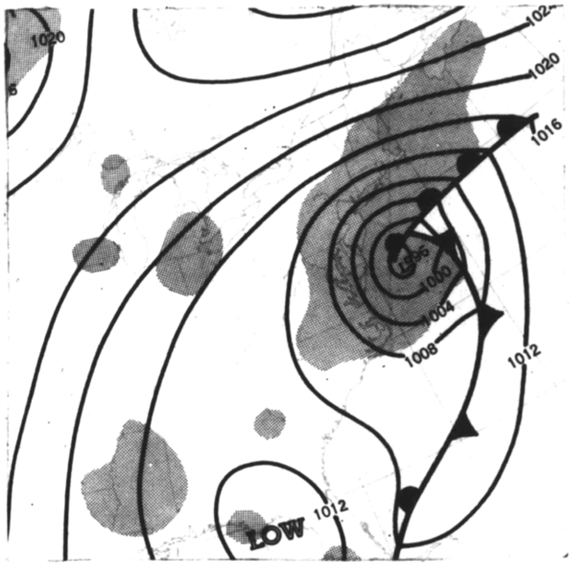
2. Southwest Lows (SW). These systems originated somewhere to the southwest of Boston, forming anywhere from Texas to Pennsylvania. They stayed overland and passed to the west of the area.

3. Great Lakes Lows (GL). These low pressure areas came from the west or northwest from points of origin west of the Great Lakes. Theirpaths brought them over, or near, the lakes, and they continued over New England or to the north.

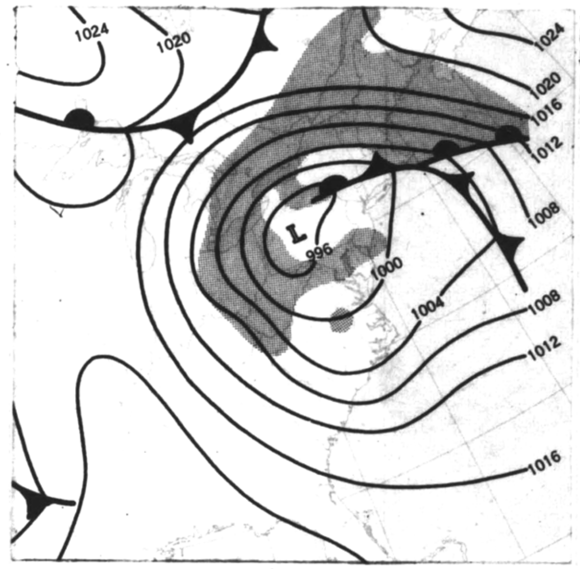
4. Overland Lows plus Coastal Lows (OL&CL). This is a group of storms each formed by a combination of two separate systems, or by an overland low together with a secondary coastal cyclone which formed on the warm front extending from the overland center. In most cases, the overland cyclone was of the GL variety. Usually the GL filled and the secondary took over the circulation. Sometimes the secondary died out and the GL held its own.

5. Stationary Fronts with Waves (SFW) includes all cases of lows forming, either over land or sea, on stationary fronts. All of these low pressure centers formed on stationary fronts which were south of the area.

6. Cold Fronts (CF). Cold fronts were associated with cyclones which were usually located in Canada, too far away to have any direct

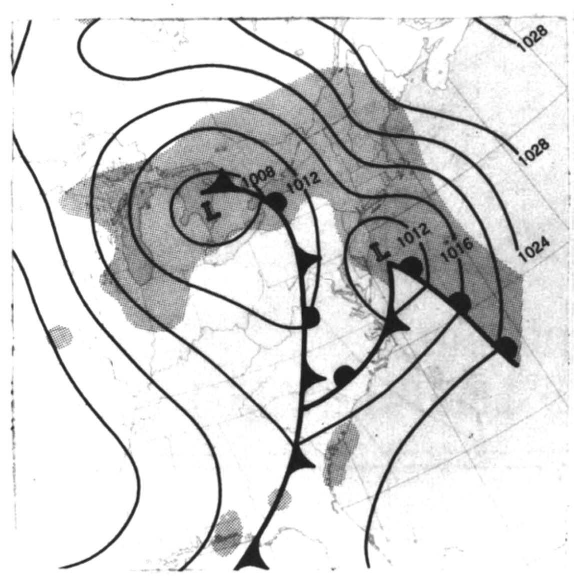


Coastal Low November 3, 1962



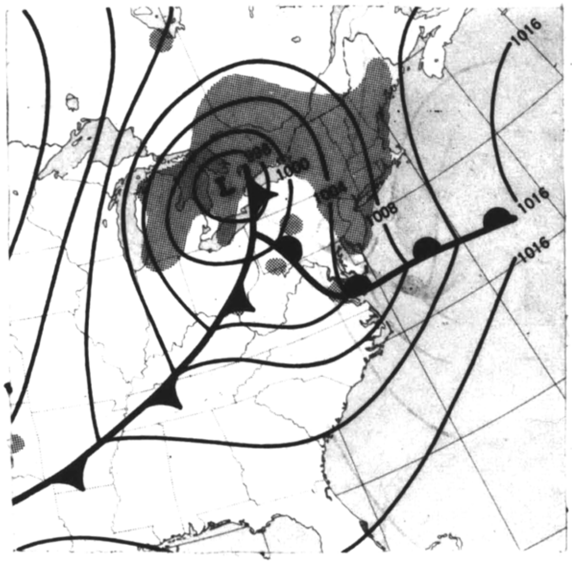
Southwest Low November 10, 1962

Overland Low plus Coastal Low
February 24, 1963

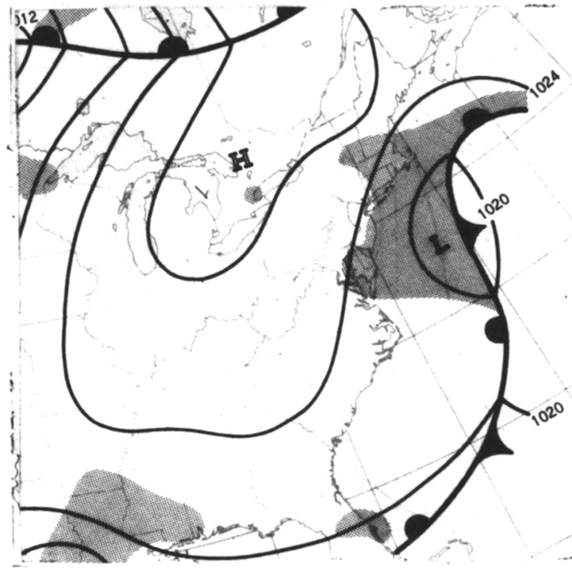


Overland Low plus Secondary
Coastal Low Feb. 19, 1962

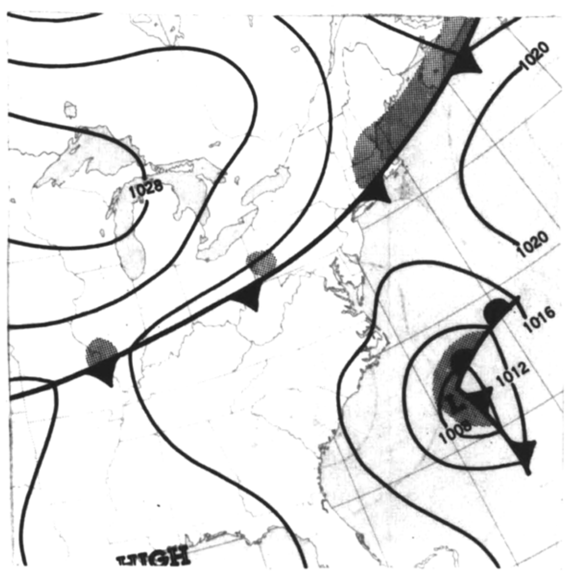
Fig. 5. Typical examples of the seven classifications



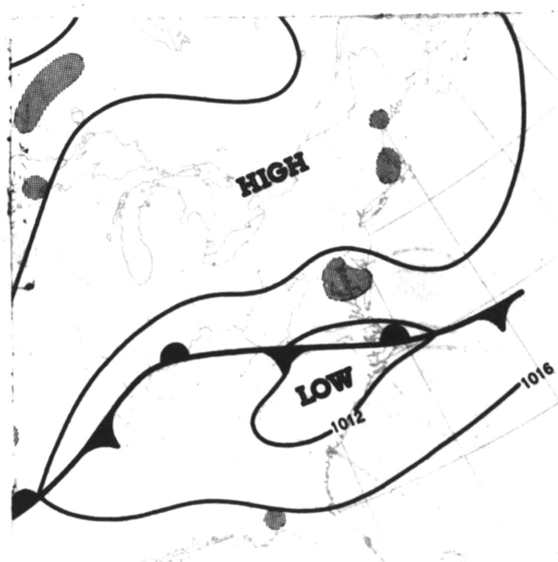
Great Lakes Low August 13, 1963



Stationary Front with Wave
September 17, 1963



Cold Front May 5, 1963



Air Mass ~~January~~ July 18, 1962

Fig. 5. (continued)

influence on the observed precipitation, which was of the frontal types in all cases.

7. Air Mass (AM). All of the storms in this category were caused either by local heating or uplift over certain widespread areas. No low pressure area or frontal system was in the vicinity of the area.

Each storm was classified according to its appearance on the weather maps. Originally the classifications had included warm fronts, occluded fronts, and the seven final groups, along with many combinations of fronts and cyclones, or fronts and fronts. It was realized, however, that many of these features represented the subjective opinion of the map analyst. So, in order to make the statistics more meaningful, the classification system was based primarily on the positions and paths of the low pressure centers. A storm was classified as frontal only if there was no cyclonic center near the area on the map. In order to distinguish between GL's which went far to the north, so that the precipitation in the area under observation was associated with warm fronts or occluded fronts, the maps were used to locate the position of the low pressure centers at the time of the maximum hourly amount of precipitation. This was also done for the cyclones or fronts in the other six groups. The location included direction and distance in miles. The position of a system was deduced through an interpolation of its position assuming constant speed and direction throughout the 12 hours separating succeeding maps.

There was some uncertainty as to the distinction between coastal low pressure centers and waves on stationary fronts when the latter formed over the ocean. Therefore, a rule was established that no storm classified as SFW was to have occluded by the time it reached New England. Coastal low pressure centers formed farther to the south than did the waves. They developed more and were generally quite mature systems once they reached the area.

III. RESULTS AND DISCUSSION

A. Distribution of Precipitation According to Storm Type

Tables 1 - 3 show the distribution of the groups with respect to the number of storms of each type, the total amount of water deposited, and duration.

Table 1. Number of Storms

Group	1962	1963	Total	%
CL	13	8	21	11.2
SW	6	7	13	6.9
GL	17	18	35	18.6
OL&CL	9	10	19	10.5
SFW	16	26	42	22.4
CF	12	17	29	15.2
AM	17	12	29	15.2
Total	90	98	188	100.0

Table 2. Total Water Deposited Within The Area Under Observation ($m^3 \times 10^8$)

Group	1962	1963	Total	%
CL	115.5	67.9	183.4	25.7
SW	67.3	46.1	113.4	15.9
GL	44.4	63.8	108.2	15.2
OL&CL	52.8	48.0	100.8	14.1
SFW	62.5	56.8	119.2	16.7
CF	23.0	33.0	56.0	7.9
AM	20.6	11.3	31.9	4.5
Total	386.1	326.9	712.9	100.0

Table 3. Duration and Average Water Per Hour

	Hours of Precipitation				Average Water Per Hour ($m^3 \times 10^8$)		
Group	1962	1963	Total	%	1962	1963	Avg. For Both Years
CL	369	285	654	17.9	.313	.238	.280
SW	190	159	349	9.8	.354	.290	.325
GL	269	364	633	17.3	.128	.175	.171
OL&CL	207	224	431	11.8	.255	.214	.234
SFW	397	481	860	23.6	.165	.118	.139
CF	117	194	311	8.8	.196	.170	.182
AM	252	154	406	11.1	.082	.073	.079
Total	1783	1861	3644	100.3	.216	.176	.196

The storms which deposited the greatest amount of total water (CL) were by no means the most frequent. They were, however, of long duration and had heavy areal precipitation rates. Stationary front waves deposited a large percentage of the total water because they occurred more frequently than any other type and lasted for the most hours. The areal precipitation was, however, very light. The southwest lows were wetter than the coastal lows, but, because they were so infrequent, they did not deposit as much water.

B. Variability Within Each Group

Distribution within the various synoptic groups with respect to amount, duration, and intensity are summarized in Tables 4 - 6 and Figs. 6 - 8.

Table 4. Total Water Deposited In The Area By Individual Storms ($m^3 \times 10^8$)

Group	Mean	Median	Mode
CL	8.7	4.2	1.5
SW	8.7	6.1	---
GL	3.1	1.9	0.2
OL&CL	5.4	5.4	---
SFW	2.8	2.1	0.4
CF	1.9	1.2	0.4
AM	1.1	0.7	0.6

Table 5. Duration Of Individual Storms (hours)

Group	Mean	Median	Mode
CL	31.1	23	22
SW	26.8	29	--
GL	28.1	14	14
OL&CL	22.7	22	16
SFW	20.5	18	19
CF	10.7	10	9
AM	14.0	11	11

Table 6. Maximum Areal Intensity ($m^3 \times 10^7$)

Group	Mean	Median	Mode
CL	6.60	5.3	---
SW	10.89	7.8	---
GL	4.27	3.7	---
OL&CL	6.56	5.0	---
SFW	4.59	3.4	---
CF	4.99	3.4	---
AM	2.38	1.85	1.4

In all of these quantities, the ranges within each group appear considerably larger than the differences from group to group. Therefore, there is no clear distinction. However, sometimes the wide range results from only one or two storms with extremely high values, such as two coastal lows which deposited 31.6 $m^3 \times 10^8$ and 51.3 $m^3 \times 10^8$

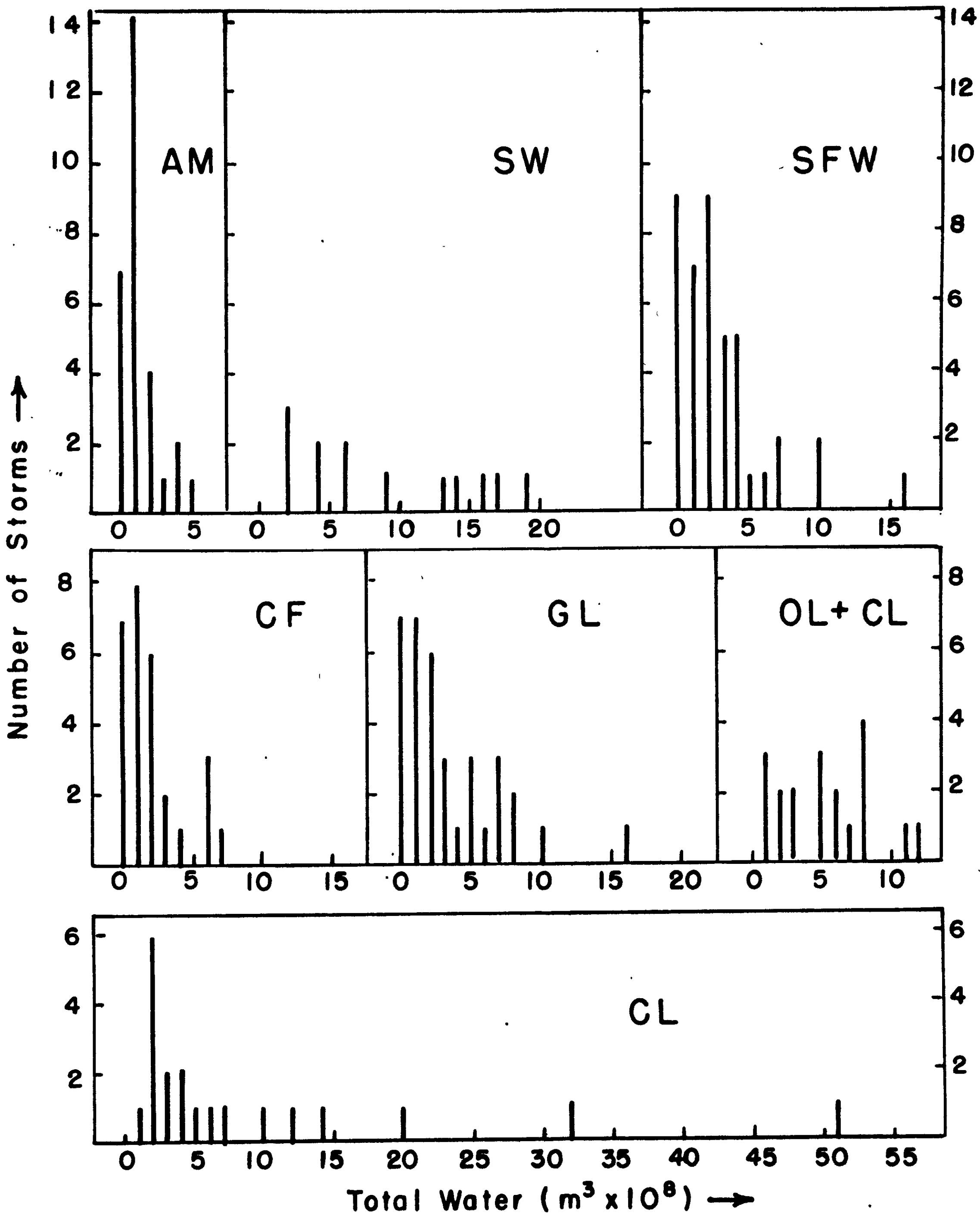


Fig. 6. Distributions of total water by group.

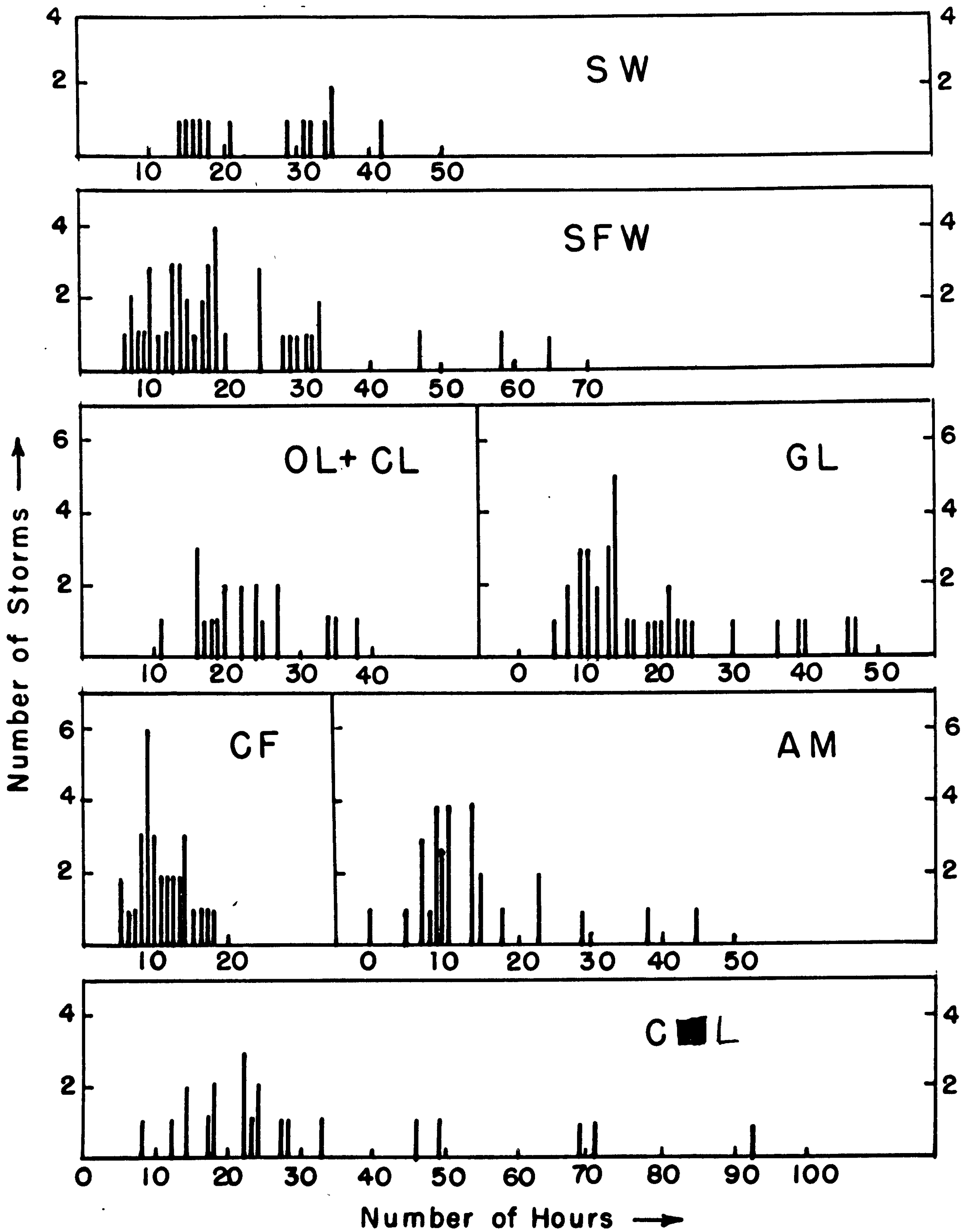


Fig. 7. Distributions of duration by group.

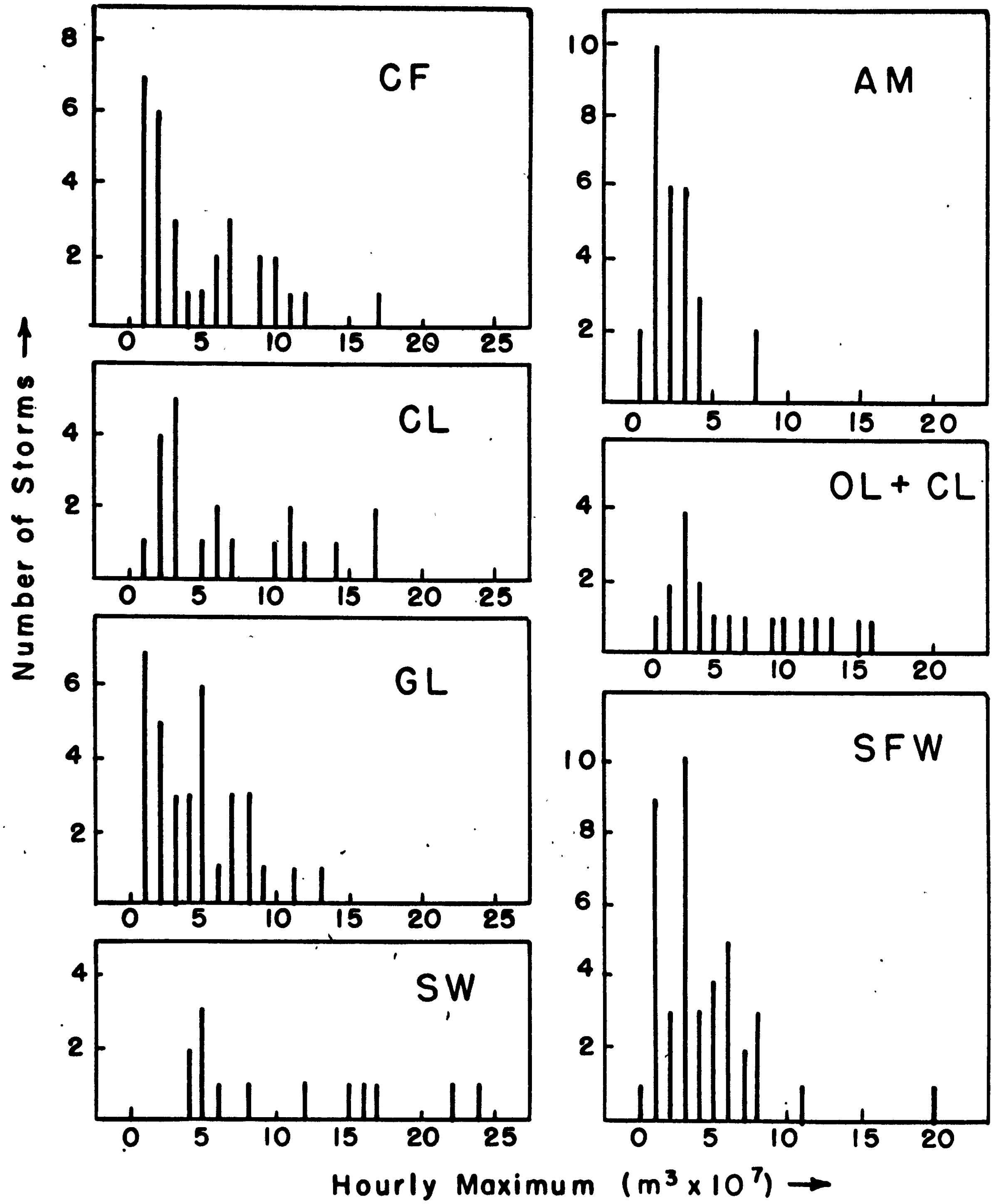


Fig. 8. Distributions of hourly areal maximum.

of total water respectively, two air mass storms which lasted 38 and 45 hours, or a stationary front wave with a maximum areal intensity of 19.8 $m^3 \times 10^7$ of water. Trends reflected in median and mode values are generally indicative of the different groups. In many cases, the mode is very poorly defined. Rather than being a result of the small sample size, this is probably indicative of a lack of preference for a definite value, or a certain range of values.

The coastal cyclones deposit more total water than any of the other groups, the reason being their tendency to produce, from time to time, storms with extremely high values of total water. The tendency for the CL's, on the average, is to produce between 1.0 and 7.0 $m^3 \times 10^8$ of total water. The total water for the southwest lows is very evenly distributed. The overland low plus coastal low groups is also very evenly distributed throughout their entire range of total water values. The nature and interaction of these systems is very complex. Each storm is different from all others in its stage of development and the balance of power between the two causes. Although they deposit less water in total than the more frequent coastal cyclones, the SW's and the OL&CL's have relatively more storms with values greater than 7.0 $m^3 \times 10^8$.

The Great Lakes lows generally deposit around 3.1 $m^3 \times 10^8$ or less, with a small group between 6.5 and 7.0 $m^3 \times 10^8$. Stationary front waves are capable of depositing large amounts of water. However, these cases are rare and the cluster between 0.1 and 4.0 $m^3 \times 10^8$ seems representative of this group. Cold fronts and air mass storms have similar distributions. The mean total water for air mass storms is affected by three storms with very large values and the median or mode values are more typical for this group as a whole. The CF's deposit a slightly greater amount of water over the area than the AM's.

The small duration of the cold front storms is understandable in view of the fact that they are associated with narrow and steadily moving areas of precipitation. Air mass storms are short since they are generally caused by daytime heating. Great Lakes cyclones tend to pass by fairly rapidly, but coastal cyclones may linger for very long periods of time. The storms which had very high values of total water were the longest lasting storms, showing that they were produced by a nearly stationary system rather than a very intense system. Stationary front waves travel at moderate speeds along the frontal boundary. Most of them pass by fairly rapidly, even though the front remains stationary for long periods of time. The longer storms are a result of series of waves with overlapping areas of precipitation, or just the general effects of the close proximity of a stationary front. The durations of the southwest lows depend on the size of the rainfall area, since they tend to travel at moderate speeds. The even distribution of duration also points up their variability. The overland low plus coastal low group generally last as long as the CL's, without having the extreme values, that sometimes occur in the latter group.

Most of the distributions for areal maxima are very even. The lowest hourly maximum value for the southwest lows is 3.5 $m^3 \times 10^7$, which is rather high since only four air mass storms have higher values than this. The maximum values for the SW's are higher than for any other groups. This gives support to the conclusion that these storms tend to precipitate more heavily. Nearly half of these storms had hourly areal maxima in excess of 10 $m^3 \times 10^7$. Only one fourth of the storms involving coastal cyclones (CL and OL&GL groups) had areal maxima which were higher than this value, while in the other groups they were extremely rare (no AM, 2 CF, 1 SFW, and 1 GL). The Great Lakes lows were distributed nearly the same as the stationary front waves with most storms within the range between 0.3 and 8.7 $m^3 \times 10^7$. Of all groups, the air mass storms showed the greatest tendency, to group between two close values. The OL&CL's and the cold fronts showed the greatest variability.

C. Diurnal Variations of the Groups

The distributions of the hour of the areal maximum for each group are shown in Fig. 9. An analysis of these distributions failed to yield any significant positive results except for the air mass and cold front storms, which both showed afternoon peaks. The AM peak was more pronounced, and the CF storms had a secondary peak in the early morning. None of the other groups showed definite tendencies for a certain time of day. Minor peaks did occur, but no overall pattern was noted.

D. Spatial Distribution of Precipitation

The 80 mile circle was divided into four equal sections as explained before and illustrated in Fig. 4. An analysis was made of the average depths (inches) of water deposited over these four sections. For each storm, one or more of the sections received a maximum amount, and one or more received a minimum.

Table 7 shows the average depth of water deposited over each section by each group. Definite maximum values are underlined by a solid

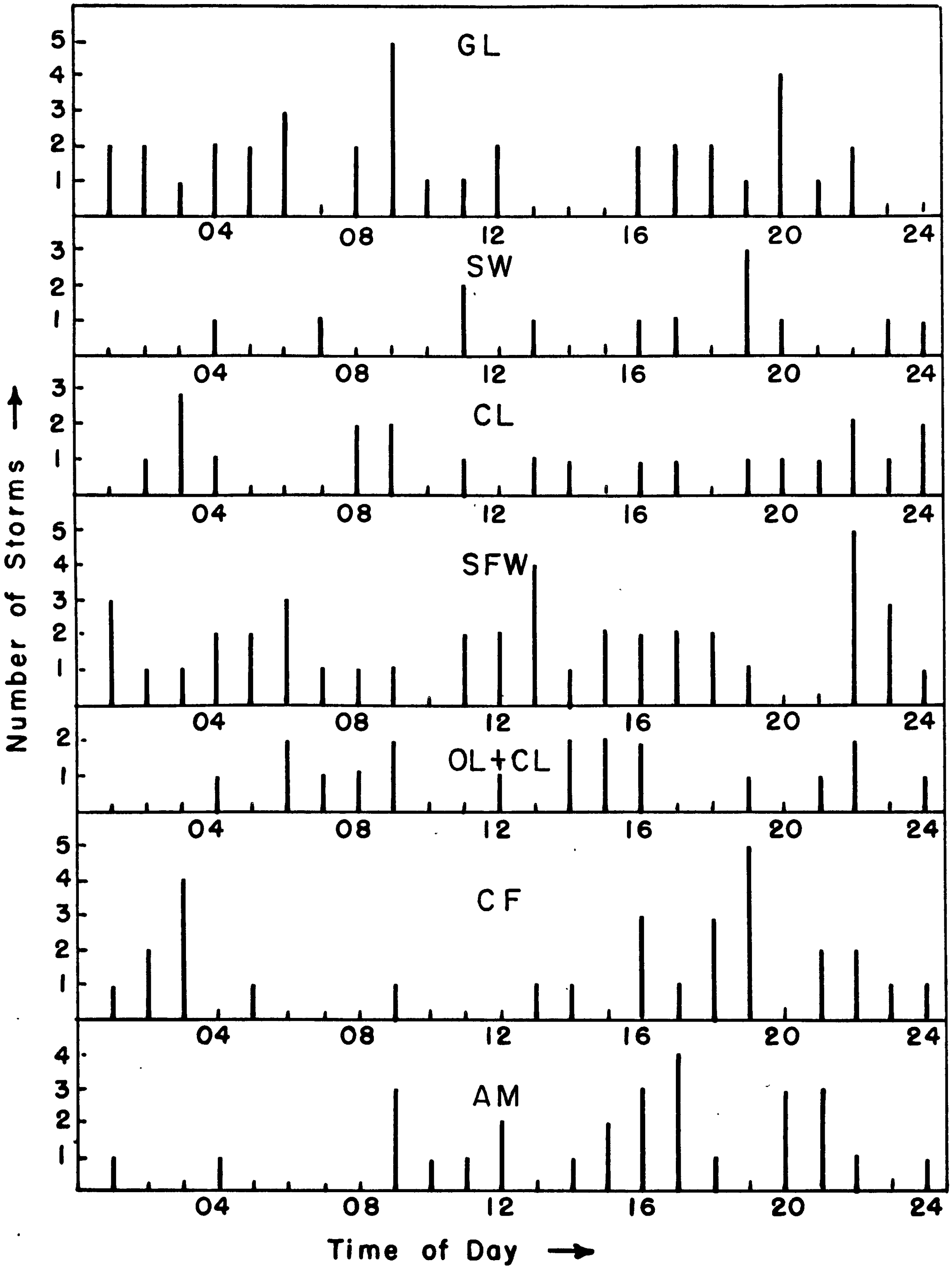


Fig. 9. Distributions of the hour of the areal maximum by group.

line, and definite minimum values are underlined by a dashed line.

The biggest contrast occurred for the coastal cyclones, where the western portion, section 3, had a definite minimum, and section 1, the center, had a clear maximum. These cyclones always passed to the east of the area, a fact with which explains the minimum in section 3. Cyclones from the Great Lakes, whose paths are generally north of New England, deposited the greatest amount of precipitation in the northerly section, 2, and least in the southerly section, 4. The combination of overland and coastal cyclones reflects the pattern shown by the CL's, but in a much less pronounced manner.

Table 7. Average Depth of Water (Inches) Deposited On Each Section For The Two Years

Group	Section 1 (Center)	Section 2 (North)	Section 3 (West)	Section 4 (South)	Total
CL	23.51	19.38	15.36	20.96	79.21
SW	13.22	12.34	11.28	11.68	48.47
GL	10.09	12.69	11.36	9.88	44.02
OL&CL	11.88	10.91	9.37	10.36	42.82
SFW	13.21	11.66	13.30	14.55	52.72
CF	6.51	4.29	6.56	6.52	23.88
AM	4.42	3.60	3.81	2.43	14.26
Total	82.84	74.87	71.04	76.63	305.38

All sections receive an almost equal amount of precipitation from the southwest cyclones. Air mass storms show a maximum in section 4 and cold fronts deposit a nearly equal amount of water on all sections except for the northern section, 2, which receives less. The stationary front waves have a minimum over section 2 and a maximum over section

4, just the opposite of the GL's. This is understandable since all of the SFW's were to the south.

Table 8. shows the number of times individual storms had maxima and minima in each section. The purpose of this analysis is to determine whether the distributions noted in the previous paragraph for groups of storms are indicative of the distributions for most of the individual storms as well, or whether they were unduly influenced by a few storms in the group which deposited large amounts of rain and had pronounced areal distributions.

In general, the trends which appear in Table 8. are similar to those in Table 7., though there are some exceptions. Individual Coastal cyclones tend to deposit maximum depths on either section 4 or 1, depending on how far south of the area the storm goes out to sea. They most frequently deposit minimum depths on section 2. This is not in agreement with the results shown in Table 7., which indicates a minimum depth for section 3. This is explained by the fact that on the average, whenever section 2 received a minimum depth, the difference in depth between sections 2 and 3 was not great, whereas, usually, whenever section 3 received a minimum depth, it fell well below the depth for section 2. Also, whenever section 4 received the minimum depth (5 times), section 2 had a greater depth than section 3. Precipitation from the southwest cyclones was pretty evenly distributed, agreeing with Table 7. The frequent occurrence of maxima for the Great Lakes cyclones in section 2 and the minima in section 4 supports the data in Table 7. This pattern results from the fact that most of these lows move to the north of the area. The overland low plus

Table 8. Number of Times (During the Two Years) That Individual Storms Showed Maximum or Minimum Areal Depths in the Indicated Sections

MAXIMUM

Group	1 (Center)	2 (North)	3 (West)	4 (South)
CL	8	4	2	7
SW	2	3	5	3
GL	2	17	10	6
OL&CL	6	4	0	9
SFW	9	14	7	14
CF	6	5	11	7
AM	9	10	6	4
Total	42	57	41	50

MINIMUM

Group	1 (Center)	2 (North)	3 (West)	4 (South)
CL	0	10	6	5
SW	2	4	1	6
GL	4	7	3	21
OL&CL	1	7	6	5
SFW	2	15	8	19
CF	1	12	1	15
AM	0	8	5	16
Total	10	63	30	87

coastal low group had more maxima in section 4 and more minima in section 2. This shows that the majority of times the coastal cyclone takes over the circulation from a filling overland low. Section 3 never receives a maximum depth and section 1 never receives a minimum. This also points out the tendency for the coastal system to dominate.

Stationary front waves have both maxima and minima in sections 2 and 4. Section 4 had more minima than section 3, yet Table 7 showed that Section 4 had the greatest depth. The conclusion is that there is no preferred pattern. Further analysis of individual storms might show whether or not the section where the most rain is deposited is related to the position of the front.

There are a large number of cold front minima in sections 2 and 4, the former is caused by a drying effect of downslope motion, the latter being caused by the fact that the temperature of the ocean has less contrast with the air temperature in the spring and summer. In the case of the air mass storms, there is an infrequency of occurrence in section 4. These storms were caused by surface heating and they tended to dissipate as they reached the coast. Since section 1 had the most maxima and no minima it may be concluded that part of this area is well enough inland to escape the coastal effects on these storms.

Examination of the totals for all the groups showed that the four sections displayed little variation in the number of maximum areal values they received. Investigation of minimum values showed that section 1 rarely received the minimum depth. It is in a position where it is in the center of different cyclone paths. Storms from the west pass to the north of this area. Storms from the south pass either to its east or west. All of these storms contribute to the rainfall of this area, in its northern, southern, eastern, or western portions. It is a favored region by its very nature of availability to these different systems. The highest frequency of minima occurs in section 4 from storms which pass to the north and storms which dissipate as they reach the coast. However, the large value for the total depth tend to reduce the importance of these types as water producers. Section 3 is least affected by producers of large amounts of water, mainly the coastal cyclones. The minimum of depth in this section from these storms accounted for its low value of total depth. Section 2 received most of its minima from CL's and SFW's which travel out to sea well to the south of the region.

E. Geographical Location of Systems.

Fig. 10., which shows the location of the various systems with respect to Boston at the time of maximum areal precipitation rate, was set up in order to explore the possibility that there are preferred paths for storms or areas of deepening, so that any particular type of storm is likely to be in a particular region at the time the area gets the heaviest rain from it.

Nothing can be said about the air mass storms, since in these cases, no definite system was involved. The distance of the cold fronts ranged from 0 to 150 miles from Boston. Most of the precipitation

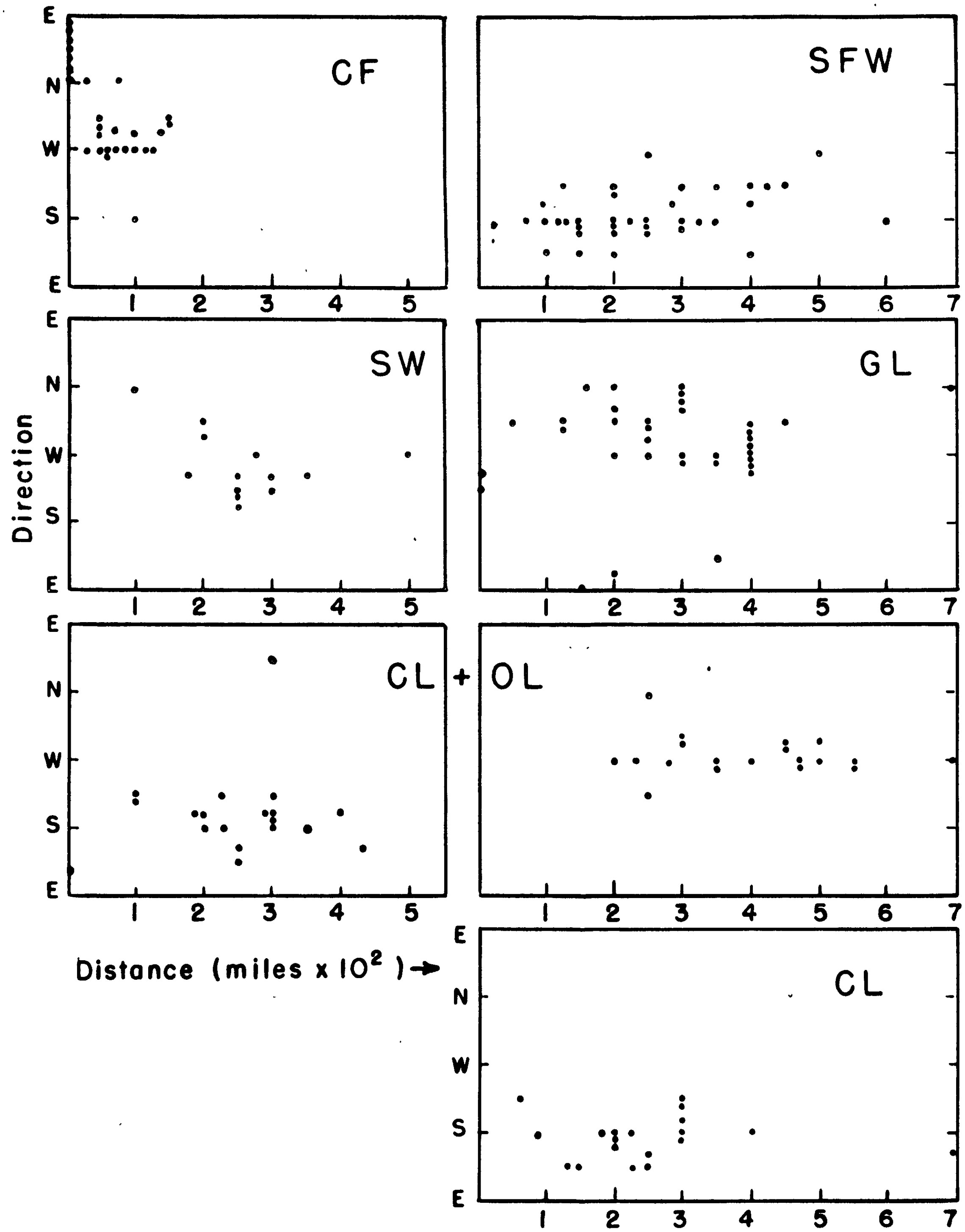


Fig. 10. Distributions of the location of systems by group.

was pre-frontal, the front being to the west or north of Boston or in the immediate vicinity. In three storms, the precipitation appeared to be slightly behind the front, but two of these are easily within the realm of measurement errors, from interpolation, or the large map scale. One front was 100 miles south, and the precipitation was definitely post frontal. The stationary front waves were mostly less than 400 miles away, this distance being a measure of the distance of the wave, not necessarily the nearest point of the front itself. All of them were south of the Boston latitude. The coastal cyclones were usually between 100 and 300 miles away. Most of the storms were located to the south or southeast of Boston. All but two southwest lows were between 200 and 350 miles away. All but one were between the southwest and northwest axes, most being southwest or west-southwest. Most of the Great Lakes lows were between 200 and 400 miles away. All but three storms were between the north and west axes. The coastal lows involved in the OL & CL group were between the southeast and southwest, some 100 to 400 miles away. The overland lows in this group were mostly GL's, being anywhere from 200 to 700 miles away and between the north and west. One SW in this OL & CL group was 250 miles northwest.

A figure similar to Fig. 10, was made which included the amounts of total water for each storm. It showed that within each group the amount of rain received in the area was not dependent on the particular path or position of the cyclonic system. Therefore, other factors such as stability, moisture content, and the vigor of the circulation, must be more important.

Table 9. Number of Storms Per Month For Two Years

Group	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
CL	1	1	1	2	0	2	0	1	3	3	2	5
SW	3	0	2	1	0	0	0	1	1	0	3	2
GL	3	3	1	2	10	2	2	4	1	3	3	3
OL&CL	2	7	4	1	1	0	2	0	0	0	0	2
SFW	4	4	3	5	5	5	5	6	3	0	3	1
CF	0	0	1	1	4	5	4	6	4	3	1	0
AM	0	1	1	1	4	5	6	3	2	1	5	1
Total	13	16	13	13	24	19	19	21	14	10	17	14

Table 10. Monthly Distribution of Total Water Deposited by Each Type of ~~Sotmr~~ Storms ($m^3 \times 10^8$)

Group	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
CL	1.7	9.8	1.5	4.9	0	3.6	0	12.2	27.4	68.1	36.3	17.9
SW	24.7	0	8.2	4.1	0	0	0	1.9	13.8	0	37.4	23.3
GL	6.3	7.3	0.9	7.3	21.0	4.9	10.6	12.6	2.1	18.0	7.7	9.4
OL&CL	14.5	28.2	30.3	5.9	7.6	0	10.4	0	0	0	0	3.9
SFW	9.6	14.5	3.7	24.4	11.3	22.0	6.1	13.5	9.9	0	3.9	0.4
CF	0	0	0.4	1.7	4.8	8.7	13.5	11.2	6.1	1.3	5.6	0
AM	0	0.7	1.4	0.6	4.2	7.3	5.4	3.2	2.0	1.5	4.7	0.1
Total	56.8	60.5	46.4	49.9	48.9	46.5	47.8	54.6	61.3	88.9	96.6	55.0

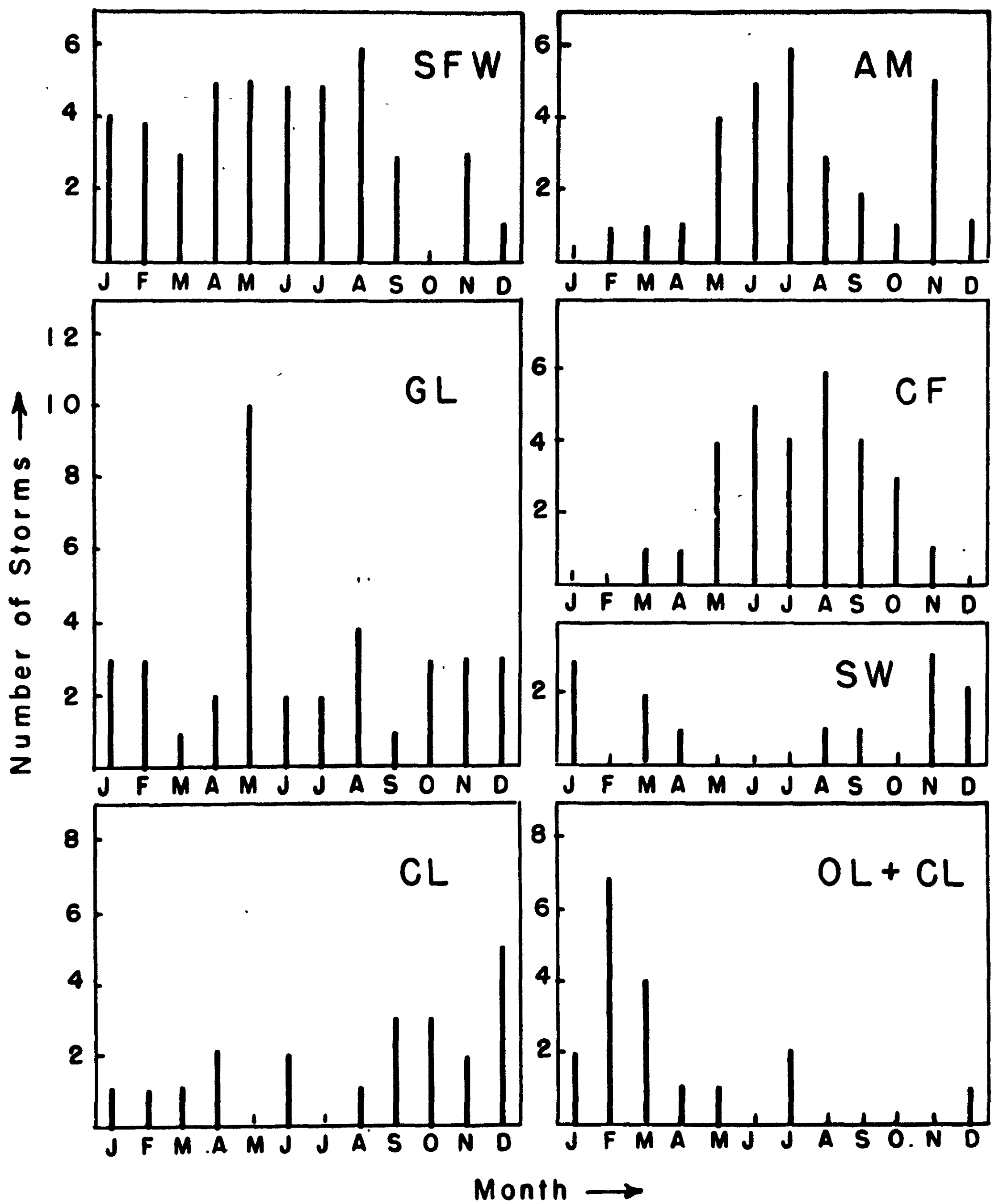


Fig. 11. Distributions of number of storms per month by group.

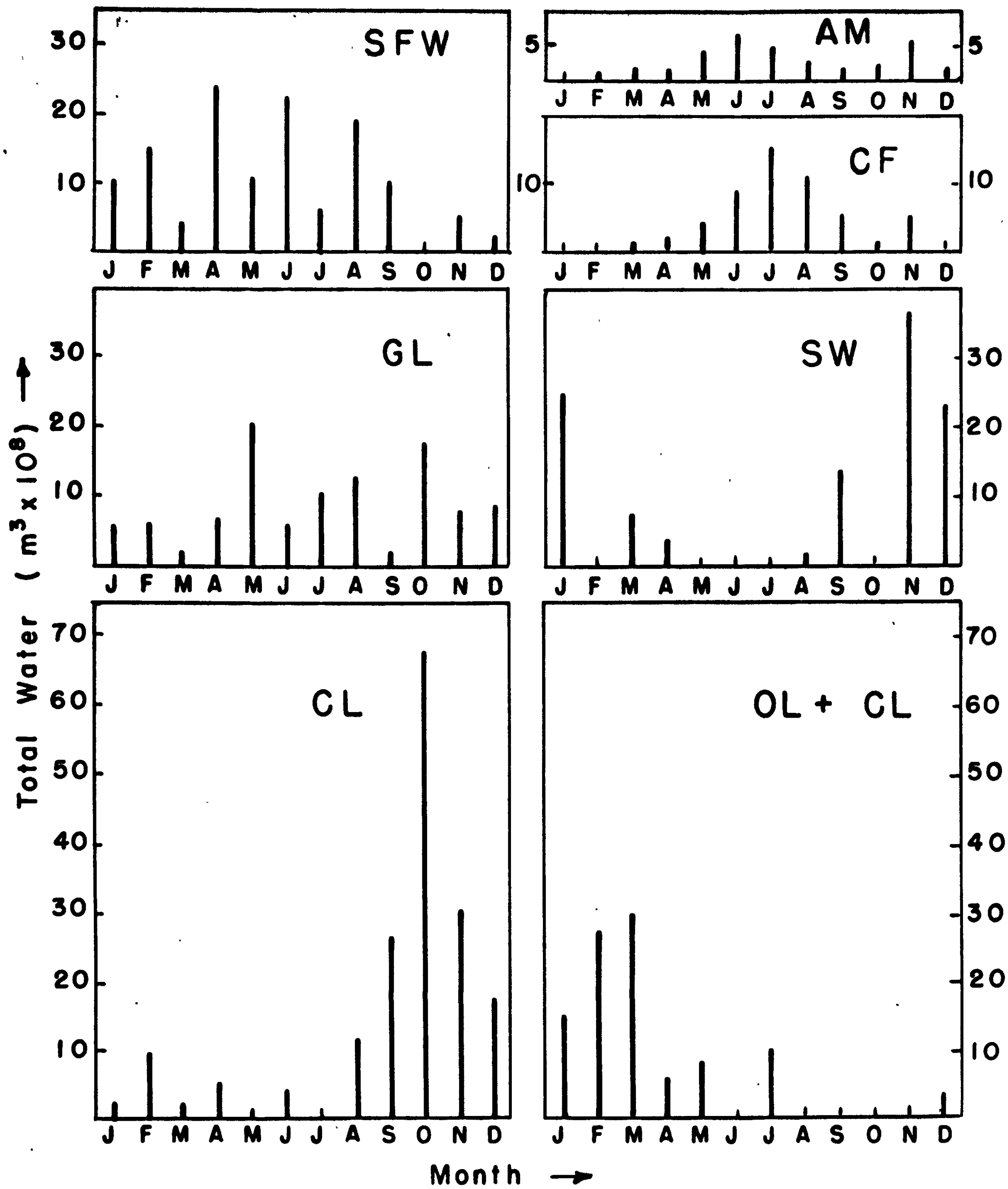


Fig. 12. Distribution of total water per month by groups.

F. Seasonal Variations

Tables 9. and 10. give the distribution of storms per month and water per month for each group. Figs. 11. and 12. illustrate these tables.

Although seasonal variation is slight when all storms are grouped together, each synoptic type shows pronounced seasonal tendencies. Coastal cyclones predominate during the fall, with low pressure centers from the southwest becoming important in the winter. The major source of precipitation in the spring is the overland low plus coastal low group, while in the late spring air mass storms and cold fronts begin, the cold fronts being most frequent in the summer. Stationary front waves and Great Lakes cyclones appear equally likely to occur in almost any time of the year.

G. Representativeness of the Two Years, 1962 and 1963

Table 11 shows, for each section, how close the monthly precipitation for these two years came to the normal values. The U. S. Weather Bureau Annual Summary of Climatological Data for New England lists, for certain gauges, the values recorded for each month of the year and their departures from the normal values based on data from 1931 to 1960. Two or three gauges were used to represent each section. Values in the table are percentages above or below the normal amounts.

The total amount of rain for each of the two years is below normal. The average precipitation for 1962 was nearly normal. However, the

TABLE 11. PERCENTAGE ABOVE OR BELOW THE NORMAL MONTHLY PRECIPITATION VALUES (BY SECTION)

Month	Section 1 1962	Section 2 1962	Section 3 1962	Section 4 1962	Entire Area 1962
Jan.	-8.5	-26.7	-1.5	+18.0	-4.4
Feb.	-45.7	+9.2	+28.9	+55.9	+35.8
March	-58.7	-44.7	-59.8	-67.4	-58.4
April	+18.3	-12.8	-12.7	-9.4	-3.4
May	-35.6	-20.5	-19.7	-55.6	-30.1
June	-28.2	+0.3	-23.0	+59.2	-8.5
July	-43.1	-4.7	-40.6	-28.7	-33.6
Aug.	+17.3	-25.0	-7.5	-14.5	-4.6
Sept.	-19.0	-38.2	-11.3	-8.5	-7.1
Oct.	+163.2	+231.0	+62.0	+186.1	+142.5
Nov.	-1.3	-13.0	-8.3	+2.1	-4.9
Dec.	+19.5	+21.4	-14.1	-27.4	-0.6
Total	+10.0	-2.9	-11.8	+4.9	-0.2

Month	Section 1 1963	Section 2 1963	Section 3 1963	Section 4 1963	Entire Area 1963
Jan.	-23.8	-34.9	-18.2	-5.2	-20.3
Feb.	-9.8	+0.2	-6.0	+0.5	-5.3
March	-0.8	-21.0	-8.4	-7.7	-8.3
April	-63.4	-64.5	-57.4	-47.6	-58.5
May	-10.0	-9.5	-31.7	+21.2	-13.0
June	-47.7	-63.2	-19.2	-21.4	-35.4
July	-42.0	-20.0	-38.9	+3.7	-30.2
Aug.	-26.0	-0.8	-46.0	-38.0	-32.5
Sept.	-1.4	-22.4	-8.5	-4.3	-3.6
Oct.	-58.4	-38.8	-82.6	-52.8	-61.8
Nov.	+91.5	+116.5	+46.3	+36.2	+81.5
Dec.	-19.8	-47.8	-36.2	-28.4	-32.0
Total	-15.8	-15.8	-24.5	-9.6	-17.5

largest storm in the survey gave the month of October an exceedingly great amount of precipitation. Its effect was to decrease the percentage below normal by a very large amount. The average amount of precipitation for 1963 was further below the normal. A large storm in November gave this year its only positive departure. In toto, all of the months except for February, October, and November have below normal precipitation amounts, with the greatest negative departures occurring from March to July.

It is rare for a given month to receive exactly the normal amount of precipitation for that month. It has been found that the standard deviation is approximately a departure of 40 to 50% from the normal.* Therefore, these two years, taken together, may be considered to be reasonably representative, although the amounts are slightly on the low side.

*Based on computations by J. Prohaska, 1966, at the Massachusetts Institute of Technology.

IV CONCLUSIONS

The courses of storms and rain clouds are very erratic and their effects are considerably varying. No two storms are alike. Yet, when properly classified, a large number of storms will yield a variety of facts which will, statistically, reduce the individuality of each storm. In this study, storms were grouped according to the nature and path of large scale system. Individual storms in the various groups can be recognized to be either different from or coincident with the group norm.

As groups, the coastal cyclones, low pressure systems from the southwest, and stationary fronts with waves deposited the most water. The large values of total water from the CL's and SW's were caused by high intensities, whereas the SFW's deposited their large values as a result of high frequency of occurrence and long duration. Air mass storms and cold fronts deposited the least amount of total water, and lasted for the shortest periods of time.

The spatial distribution of total water showed good relationships between the path of the storms in a group and the sections receiving the most total water. Northern sections received more precipitation than any other section from the Great Lakes Cyclones, which passed to the north of the area. Southern sections received a maximum of water from the stationary fronts with waves which passed to the south of the area, and western sections received a minimum of water from coastal cyclones, which passed to the east of the area.

Seasonal distributions indicated that most of the cold fronts and air mass storms occurred from May through August, while the cyclone groups occurred mostly in the fall and winter months.

Geographical locations of the systems showed no apparent relation between the distance of a storm center from Boston and the total water the area received. Each group did have a certain "preferred" range of distance at the time it deposited the greatest hourly amount of water. This range was between 200 and 400 miles for the cyclonic groups, and about 50 miles or less for the cold fronts.

The results in this study were based entirely upon the distributions of the total water deposited over the area. It is relatively simple to obtain a mean value of total water, deposited by individual storms in any group. It is easy to obtain a frequency distribution from which can be obtained the probability of a given value of total water occurring in that group. This has some value for predicting the amount of water that will fall from a storm belonging to any of the groups. However, the distributions are so broad that the assistance they give in arriving at a prediction for such a storm is limited.

Each group had a wide range of total water values. Undoubtedly, the differences in these values may be attributed to such factors as moisture content and the vigor of the circulation. It is desirable, therefore, to classify these factors in conjunction with the total water amounts. Once these factors, moisture content and intensity of the circulation, are compared with the total water it would be possible to distinguish between different storms in the same group, to describe why they were different. Instead of just concluding that the coastal cyclones deposit more total water than any other groups, meteorologists would be able to see why this was true and why the storms in this group varied the way they did. All of these factors must be combined with the total water figures in order to determine as closely as possible, the relationships between the mesoscale precipitation patterns and large scale circulations.

The results of a purely statistical analysis are limited because of the large number and high degree of variability of the factors involved. It is hoped, however, that these results will provide a basis for understanding the dynamical relationships between the large and small scale circulations. Radar data are available which depict the character of the precipitation patterns on an even smaller scale. When these data are used in the analysis a more complete picture of the precipitation processes will be obtained.

APPENDIX A

Storms Used In Study

1962 Date	Time	Duration (Hours)	Total Water ($m^3 \times 10^8$)	Cause & Location (mi.)	Hr. of Areal Max.	Amount of Areal Max. ($m^3 \times 10^7$)
Jan 1 2	22 11	14	1.7	CL 250 SE	.03	1.6
5 6 7	23 09	35	17.1	SW 400 W	24	11.8
15	05.22	18	5.5	SW 200 NW	19	15.0
22	07.15	9	1.2	GL 200 W	10	2.6
26 27	16 05	14	2.8	GL 300 N	20	5.2
30	02.17	16	2.3	GL 250 W	09	4.9
Feb 3	02.19	18	0.7	AM	15	1.0
9 10	16 10	19	2.1	SFW 250 S	22	2.5
14 15	07 09	27	6.4	GL 300 WNW CL Sec 300 S	24	3.3
16 17	18 04	11	0.5	GL 300 NNW CL 350 S	22	0.9
19 20	09 11	27	5.4	GL 475 W CL Sec 275 SSW	14	6.5
21 22	24 16	17	2.2	GL 550 W CL Sec 300 SSW	04	3.6
23 24	24 19	20	7.8	OL 225W CL Sec 300 SW	06	14.7
26 27	10 03	18	4.6	GL 400 W CL Sec 300 SSW	15	5.6
27	09.18	10	0.4	SFW's 400 SE & 600 SW	13	0.8
28	02.21	20	2.0	SFW 250 S	09	3.1
Mar 4 5	18 24	33	1.5	CL 700 SSE	13	1.2

1962 Date	Time	Duration (Hours)	Total Water ($m^3 \times 10^8$)	Cause & Location (mi.)	Hr. of Areal Max.	Amount of Areal Max. ($m^3 \times 10^7$)
Mar12	05	25	11.8	GL 700 W	21	8.6
13	05			CL Sec 100 SW		
26	19	29	1.4	AM		
27	23				10	1.6
31	16	33	15.8	SFW 350 SW		
Apr 1	24				06	19.8
6	23	31	4.1	SW 200 WNW		
7					20	5.4
8	05					
9	15.23	9	1.7	CF 150 W	19	5.8
12	18	38	5.9	GL 500 W		
13				CL 200 SSW	09	4.4
14	07					
15	11	22	2.0	CL 225 SE		
16	08				03	2.0
19	09.22	14	0.6	AM	16	1.2
29	07	47	4.9	SFW 125 SW		
30					18	5.0
May 1	05					
2	03	39	5.2	GL 400 W		
3	17				04	4.7
3	21	13	0.3	GL 400 NW		
4	09				02	0.9
6	10.20	11	0.8	GL 300 N	18	1.9
14	02.19	18	3.7	SFW 300 S	11	5.8
15	22	14	0.4	AM		
16	11				01	1.1
18	17.24	8	0.6	AM	20	1.9
19	13.21	9	1.1	SFW 200 S	17	5.7
20	19	10	1.2	GL 200 N		
21	04				01	4.1
24	03.13	11	3.1	GL 300 W	08	7.8

1962 Date	Time	Duration (Hours)	Total Water ($m^3 \times 10^8$)	Cause & Location (mi.)	Hr. of Areal Max.	Amount of Areal Max. ($m^3 \times 10^7$)
24 25	17 02	10	1.6	CF over Boston	24	4.6
31 June 1	17 01	9	3.2	AM	20	8.0
1	14.18	5	0.1	CF 150 W	16	0.5
5 6	09 09	25	10.0	SFW 100 E	06	7.2
6	16.24	9	1.1	AM	21	2.4
11 12 13 14	16 08	65	6.9	SFW 300 SW	08	8.1
19	01.06, 16.23	14	1.0	GL 400 NW	17	2.4
20 21	17 17	25	2.2	SFW's 300 NE & 150 S	01	2.2
24 25	11 04	18	5.0	AM	18	8.4
26	11.21	11	2.2	CF over Boston	18	8.6
July 9	10.19	10	7.3	CF 100 W	14	17.2
12	14.22	9	1.7	AM	17	4.1
13	03.17	15	1.1	GL 120 NW	08.09	3.0
15 16	16 06	15	1.0	AM	21	2.9
18	10.19	10	0.3	AM	16	1.4
21	15.22	8	1.2	CF over Boston	19	4.1
22	13.21	9	1.3	AM	17	3.3
23 24	13 12	24	8.2	GL 300 W CL sec over Boston	19	11.7

1962 Date	Time	Duration (Hours)	Total Water ($m^3 \times 10^8$)	Cause & Location (mi.)	Hr. of Areal Max.	Amount of Areal Max. ($m^3 \times 10^7$)
July26	02.19	18	1.8	SFW 100 SE	14	4.4
29 30	18 08	15	0.3	AM	04	1.4
Aug 1	6.10, 13.16	11	0.3	AM	09	1.5
7 8	08 04	21	4.5	GL 160 N	20	8.6
10 11	01 08	32	6.5	SFW 320 S	13	4.5
14	11.24	14	0.5	CF 20 E	17	2.1
17	11.24	14	5.9	CF over Boston	19	8.5
20	02.07	6	0.3	SFW 250 W	04	0.8
20 21	18 07	14	0.7	CF 120 W	19	2.2
28 29 30	06 03	46	12.2	CL 200 SE	04	10.2
Sep 1	17.23	7	0.5	AM	17	1.4
5 6	06 09	28	2.1	SFW 200 S	22	3.3
17 18	15 02	12	5.6	CL 60 SW	23	1.2
19 20	20 04	9	0.4	CF 60 W	23	1.2
25 26	18 03	10	2.1	GL 250 NW	22	4.5
26 27 28	24 24	49	19.5	CL 300 SW	21	10.9
Oct 4 5 6 7	22 20	71	51.3	CL 300 S	22	16.6

1962 Date	Time	Duration (Hours)	Total Water ($m^3 \times 10^8$)	Cause & Location (mi.)	Hr. of Areal Max.	Amount of Areal Max. ($m^3 \times 10^7$)
9 10	04 17	38	1.5	AM	11	1.1
12	07.11	5	0.2	GL 450 NW	09	1.4
12	15.19	5	0.4	CF 50 NW	16	2.0
23	07.20	14	1.9	GL 300 N	12	3.7
25 26	22 20	23	3.3	CL 140 SE	09	2.9
28 29	23 06	8	0.9	CF 90 W	02	3.4
30 31 Nov 1	16 13	46	15.9	GL 300 W	16	7.4
3 4	07 06	24	4.7	CL 200 S	19	6.3
10 11	04 14	35	12.9	SW 350 WSW	11	23.5
13 14	13 11	23	0.8	AM	21	1.2
17 18	20 07	12	0.3	SFW 420 SW	01	0.9
18	11.24	14	2.9	SFW 350 S	16	3.2
21 22	20 24	29	8.6	SW 300 SW	07	7.8
24	07.15	9	0.3	GL over Boston	09	1.1
Dec 5 6	05 22	42	19.1	SW 250 SW	16	16.4
9 10	14 06	17	1.6	CL 200 S	17	2.6
15 16	23 12	14	0.7	GL 50 S	03	0.8

1962 Date	Time	Duration (Hours)	Total Water ($m^3 \times 10^8$)	Cause & Location (mi.)	Hr. of Areal Max.	Amount of Areal Max. ($m^3 \times 10^7$)
Dec21 22	21 18	22	6.6	CL over Boston	11	6.5
25 26	18 07	14	1.1	CL 300 S	02	2.1
29 30	09 06	22	4.4	CL 400 S	22	5.8
1963						
Jan11 12	15 03	13	3.0	SFW 150 S	18	7.8
12	08.21	14	3.6	SFW 200 S	12	6.3
13	05.19	15	2.5	SFW 400 SW	13	4.0
17 18	22 17	19	0.5	SFW 600 S	06	1.0
19 20	22 13	16	6.7	GL 460 W CL 480 SSE	06	9.7
23 24	17 06	14	2.1	SW 100 N	19	3.5
26 27	21 16	20	7.8	OL 250 SW CL 150 SSW	07	12.6
Feb 2 3	10 07	22	6.7	GL 200 NNW	18	7.1
11	02.15	14	0.4	GL 400 W	05	1.0
11 12 13	22 04	31	10.0	SFW 400 SW	11	7.9
14 15	16 04	13	0.2	GL 350 SE	22	0.5
19 20	14 07	18	9.8	CL 80 S	20	10.8
24	08.23	16	1.3	GL 200 W CL 400 SSW	16	1.9

1963 Date	Time	Duration (Hours)	Total Water ($m^3 \times 10^8$)	Cause & Location (mi.)	Hr. of Areal Max.	Amount of Areal Max. ($m^3 \times 10^7$)
Mar 1 2	14 10	21	6.1	SW 250 SSW	23	5.7
4 5	10 03	18	0.4	SF 250 S	02	0.5
6	06.21	16	10.8	GL 450 WNW CL Sec 100 SW	15	15.6
10	02.19	18	0.9	GL 300 NNW	12	1.7
11 12	24 18	19	3.3	SFW 200 SSE	07	3.5
13 14	14 05	16	2.1	SW 250 WSW	17	5.1
17	01.22	22	3.2	GL 500 WNW CL Sec 200 S	08	3.2
20 21	03 12	34	4.5	GL 450 WNW CL Sec 250 SSE	09	2.5
26 27	23 07	9	0.4	CF 60 W	05	1.2
Apr 2 3	21 04	8	0.9	SFW 125 S	23	2.8
3 4	21 09	13	0.7	GL 700 N	06	1.9
17 18	18 10	17	1.7	SFW 200 SW	23	3.4
19 20	23 14	16	1.6	SFW 200 SW	01	5.5
23 24	10 09	24	2.9	CL 200 S	16	2.7
30 May 1	03 08	30	6.6	GL 400 W	20	5.3
2	04.22	19	3.1	GL 150 E	11	3.6
5	12.20	9	0.2	CF over Boston	13	0.7

1963 Date	Time	Duration (Hours)	Total Water ($m^3 \times 10^8$)	Cause & Location (mi.)	Hr. of Areal Max.	Amount of Areal Max. ($m^3 \times 10^7$)
May 8 9	18 03	10	0.4	SFW 80 SSW	23	1.3
10 11	12 11	24	6.1	SFW 150 SE	24	11.1
13 14	23 07	9	0.4	GL 450 NW	02	1.2
14	15.24	10	2.0	GL 400 NW	16.17	5.4
18 19	06 03	22	7.6	GL 550W CL Sec 225 SW	14	10.8
20 22	14.19 06	6	1.8	CF 50 WNW	03	3.1
28	0	0	0	AM	0	0
29 30	06 02	21	4.9	GL 400 NW	20	7.5
June 3 4	20 03	8	1.5	CL 300 SSW	24	3.0
6 7	14 06	17	0.6	CF 75 N	22	1.0
9	11.22	12	2.6	CF 30 N	18	12.1
10	09.15	7	0.1	SFW 150 S	13	0.3
11 12	06 22	41	3.9	GL 350 W	01	3.3
14	13.19	7	0.7	AM	15	2.3
15	02.19	18	2.1	CL 225 S	08	2.8
17	14.24	11	0.5	AM	17	2.7
20 21	19 07	13	3.2	CF 100 WNW	03	6.7
28 29	15 20	30	2.8	SFW over Boston	17	5.6

1963 Date	Time	Duration (Hours)	Total Water ($m^3 \times 10^8$)	Case & Location (mi.)	Hr. of Areal Max.	Amount of Areal Max. ($m^3 \times 10^7$)
July 2	20	8	0.4	CF 140 WNW		
3	03				01	1.7
5	08.21	14	0.7	AM	16	3.2
7	24	24	9.5	GL 400 NW		
8	23				04	7.5
14	13	19	2.2	GL 350 W	16	5.0
15	07			CL Sec over Boston		
16	22	10	0.9	SFW 60 S		
17	07				03	0.3
18	09.21	13	0.9	SFW over Boston	16	1.9
19	18	15	2.1	SFW 100 S		
20	08				04	2.5
21	02.18	17	0.4	SFW 275 SSW	15	1.1
30	01.13	13	6.4	CF 30 W	09	10.3
Aug 1	15	29	3.5	SFW 80 W		
2	19				05	5.0
4	02.08	7	1.5	GL 400 NW	06	6.3
7	15.21	11	1.9	CF 150 NW	19	10.0
8	13.19	7	0.9	AM	14	3.0
9	21	7	0.3	CF 50 WNW	22	0.8
10	03					
11	15.24	10	2.0	AM	22	3.9
13	02	36	6.4	GL 250 WNW	19	10.5
14	13					
17	20	12	1.9	CF 70 WNW		
18	07				03	6.0
20	01.11	11	2.4	SFW 450 SW	05	7.0
23	17	13	0.5	SFW 200 NNW	22	1.7
24	01					
24	06.42	7	0.2	GL 50 NW	06	0.4

1963 Date	Time	Duration (Hours)	Total Water ($m^3 \times 10^8$)	Case & Location (mi.)	Hr. of Areal Max.	Amount of Areal Max. ($m^3 \times 10^7$)
Aug29	08.22	15	1.9	SW 275 W	13	4.5
30	18.24	7	0.3	SFW 100 S	22	1.2
Sept 4	01.09	9	0.1	CF over Boston	03	0.9
5 6 7	24 03	28	2.3	CL 240 SE	08	1.9
12 13	19 10	16	4.3	CF over Boston	21	7.0
15 16 17 18	23 08	58	4.0	SFW 300 S	12	2.7
19 20	19 09	15	1.2	CF 100 S	03	2.7
20 21	10 03	18	3.8	SFW 225 S	19	5.2
21 22	20 18	23	1.5	AM	09	3.0
29	04.20	17	13.8	SW 175 WSW	11	17.4
Oct 3	12.21	10	0.9	CF over Boston	18	2.2
27 28 29 30	21 17	69	13.5	CL 150 SE	03	11.8
Nov 1 2	02 24	47	7.7	GL 125 NW	09	7.2
5 6 7 8 9	23 19	93	31.6	CL 300 SW	14	17.3
11 12	01 21	45	3.9	AM	19	3.5

1963 Date	Time	Duration (Hours)	Total Water ($m^3 \times 10^8$)	Case & Location (mi.)	Hr. of Areal Max.	Amount of Areal Max. ($m^3 \times 10^7$)
Nov13	12.16	5	0.1	AM	20	0.9
14 15	18 03	10	0.4	AM	24	0.6
18 19	17 11	19	0.7	SFW over Boston	22	3.4
21	08.18	11	0.5	AM	12	1.6
23 24	11 04	18	5.6	CF 75 W	21	11.0
29 30	07 14	32	15.9	SW 250 SW	19	21.9
Dec 2 3 4	20 05	34	4.2	SW 300 WSW	04	3.6
6	05.15	11	0.1	AM	12	0.3
8 9	22 17	20	6.7	GL 250 NW	05	12.7
12 13	06 16	35	2.5	GL 350 W CL Sec 22 SS	12	2.5
18 19	09 07	23	2.0	GL 200 ESE	21	1.5
23 24	18 20	27	4.2	CL 200 S	24	5.3
26	11.24	14	0.4	SFW over Boston	15	0.9
27 28	05 04	24	1.4	GL 275 W CL Sec 250 SE	22	1.6

REFERENCES

Bergeron, T., 1960: Problems and methods of rainfall investigations, Physics of Precipitation, Geophysical Monograph 5, 5-30.

Brown, M. J., and Peak, & L., 1962: Reliability of precipitation measurements as related to exposure, JAM 1, 203-207 .

George, J. J., 1960: Weather forcoasting for Aeroneutics: Academic Press, N. Y., Ch. 15, 18.

Jarvis, E. C., 1965: A grid method for predicting the displacement and central pressure of East Coast Cyclones, JAM 4, 38-46.

Mather, J. H., Adams, Henry III, Yoshioka, Gary, 1964: Coastal Storms of the eastern U. S., JAM 3, 693-706.

Miller, James E., 1946: Cyclogenesis in the Atlantic coastal region of the U. S., J. of Met. 3, 31-44.

Nason, C. K., 1965: Mesoscale precipitation patterns in central New England, S. M. Thesis, Dept. of Meteor., Mass. Inst. of Technology, Cambridge, Mass., 99 pp.

Reiss, G., 1955: A composite analysis of cyclonic precipitation in the eastern U. S., N. Y. U. of Eng. Research Div. Technical Paper #3

Tweedy, D. L., 1965: The distribution of heavy precipitation associated with extratropical cyclones in New England, S. M. Thesis, Dept. of Meteor., M. I. T., Cambridge, Mass., 98 pp.

Vergas, K. W., and Ostby, F. P., Jr. 1963: Application of a moving coordinate prediction model to East Coast cyclones, JAM 1, 24-38.