Radar Measurements of Severe Storms in New England

Weather Radar Research

Department of Meteorology

Massachusetts Institute of Technology

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RADAR MEASUREMENTS OF SEVERE STORMS IN NEW ENGLAND

by

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ABSTRACT

Two investigations concerning severe storms are presented in this
report. The basic data for both are iso-echo contours of the averaged,
range-corrected signal, photographed from the PPI of a 10-cm radar. These
quantitative measurements at a wavelength unaffected by rain attenuation
are particularly suitable for the study of severe storms.

A numerical investigation of New England squall lines was undertaken
for the purpose of providing a quantitative description which can be used
for statistical analysis and as a basis for formulating and testing dynamic
models. Eight squall lines are analyzed and three charts are plotted for
each one: a total intensity chart which shows the rate at which water is
being precipitated in the whole line as a function of time; a space composite
showing the distribution of rain in a moving grid attached to the squall
line; a time-space composite showing the distribution of rain along the line
as a function of time. The use of a coordinate system attached to the line
permitted investigation of changes in internal structure while eliminating
effects produced by the motion of the line as a whole. There were large
differences from storm to storm in overall intensity and areal coverage.
The time scale was roughly the same for all the lines as were the motions
and orientation with respect to the prevailing wind. Strong similarities
in internal structure were noted with most of the lines being very narrow
and well defined and all of them having persistent groups of intense storms
spaced 25-35 miles apart. Two distinct modes of development were observed
with four storms in each group.

The second investigation is concerned with the reflectivity of
hailstorms at a 10-cm wavelength. Comparison is made between occurrence
and size of hail and radar reflectivity for a large number of storms on

six days in 1961. Over 800 reports of hail occurrences were received on those days. They were reduced to 275 by grouping together those from any single town at approximately the same time and by excluding those which were not observable by the radar because of either location or time of occurrence.

On four days when the thunderstorms were in squall lines, 95% of the reported hail occurrences were located in echoes whose equivalent Z values exceeded $10^{5.5}$ mm^6/m^3. Also, on those days, except for a few spots which were very small in area and of short duration, reports of hail were received from all regions where reflectivity factors exceeded $10^{5.5}$ unless they were located entirely over the ocean or swamp areas. It is clearly shown that, for this type of storm, reflectivity is related to the size of hailstones. In the Boston area if $Z_e \sim 10^{5.5} mm^6/m^3$, the storm contains hail probably 1/4" to 1/2" in size. If $Z_e \sim 10^{6.0}$ the largest size hailstones are likely to be nearly 1" in diameter; while for $Z_e \sim 10^{6.5}$ hailstones the size of golf balls may be expected.

On two days when there were scattered air mass thunderstorms, 80% of the reported hail occurrences were in storms where $10^{5.0} \leq Z_e \leq 10^{6.0}$. On these days the storms were generally of brief duration and were small in both horizontal and vertical dimensions. Measured reflectivities were closely related to the ranges of the storms, suggesting that in many cases the radar beam was not adequately filled with intense precipitation.

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INTRODUCTION

The Weather Radar Research project at Massachusetts Institute of
Technology is especially suited for radar studies of severe storms because in-
strumentation is available which provides quantitative measurements of radar
reflectivity at a wavelength unaffected by rain attenuation. Data are in
the form of averaged, range-corrected iso-echo contours presented directly
on the PPI and may be interpreted as lines of equal Z value ($Z = \sum D^6$ where
D represents diameters of scattering particles in a unit volume) or of equal
rainfall rate.

Two investigations concerning severe storms and based on intensity-
contour data have been carried out, the results of each are presented sepa-
rately in this report. One is a study of the internal structure of squall
lines, and the other an analysis of reflectivities of hailstorms. Although
they are based on somewhat limited data (long records of signal-intensity
contours are not yet available), both investigations produced interesting
and significant results. One conclusion which may be drawn is that the
importance of accurate quantitative observations can scarcely be overempha-
sized.

Recommendations for future research include: continuation of the
investigations described here to cover considerably larger data samples;
extension of the numerical study of squall lines to include a quantitative
description of the vertical structure of thunderstorms; and development of
dynamic models for squall lines to explain the observed precipitation patterns.

A NUMERICAL INVESTIGATION OF NEW ENGLAND SQUALL LINES

A. Introduction

The purpose of this investigation is to provide a numerical descrip-
tion of squall lines which can be used both for statistical analysis and as
a basis for formulating and testing dynamic models of squall lines and the
small-scale circulations which produce them.

A preliminary investigation of the statistics and linear predicta-
bility of patterns in widespread precipitation areas has been made by Noel
and Fleisher (1960) and Noel (1961). A similar investigation is proposed
for the precipitation patterns associated with squall lines. Hence the
basic techniques for data processing which were employed by Noel and Fleisher
have also been used in this study but with certain modifications which make
them more suitable for the different storm type and the improved quantita-
tive data.

An adequate dynamic model should explain both the dimensions and
intensities of the individual convective elements and also the pattern which
they form. It has been shown by Newell (1959) that the patterns formed by
small convective cells in relatively shallow layers of the atmosphere are
compatible with Rayleigh's theory of Benard cells in a layer of fluid
heated from below, but the dimensions and spacing of larger cells fail to
agree with the theory. This result is not surprising since radar observa-
tions show that deep convective cells do not generally appear in a more or
less uniform two-dimensional array but tend to form one or several lines.
The most intense and highly organized lines are the squall lines which
appear in advance of cold fronts. It is hoped that the investigation of
such lines will provide further insight into the factors which control the

modes of overturning in an unstable atmosphere.

In most previous radar studies of squall lines attention has been focused either on individual convective storms or on the behavior of the squall line as a whole; for example, Donaldson (1961), Wilk (1961), Boucher and Wexler (1961). The distribution of precipitation within the line and the behavior of individual areas of heavy precipitation have received little consideration largely because conventional radar data are not suitable for such types of analysis. Data are now being taken in the form of iso-echo contours of the averaged range-corrected signal from precipitation with instrumentation described by Kodaira (1959). These data display clearly and quantitatively the internal structure of the squall lines.

The present study is a survey of eight squall lines observed during the summers of 1958, 1959 and 1960. It has been summarized in a paper by Austin, Cochran and Patrick (1961). Some aspects of the investigation are described more fully by Swisher (1959) and Cochran (1961).

B. Data and Methods of Analysis

In this study a squall line is defined as a narrow band of precipitation parallel to and associated with a surface cold front which is advancing into New England from the northwest or west. Eight cases were chosen where radar records of fairly well-defined lines were available for periods of several hours. A summary of the synoptic weather aspects of the various storms is on page 19.

The data are of averaged range-corrected signal intensity contours as they appear on the PPI of the SCR-615-B radar, which operates on a wavelength of 10.7 centimeters. The iso-echo contours represent lines of equal radar reflectivity. Since the observations were taken at an elevation angle
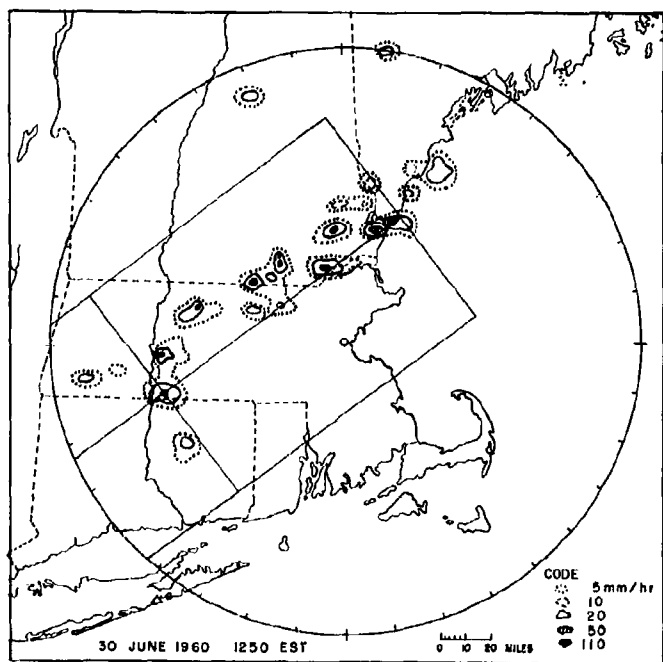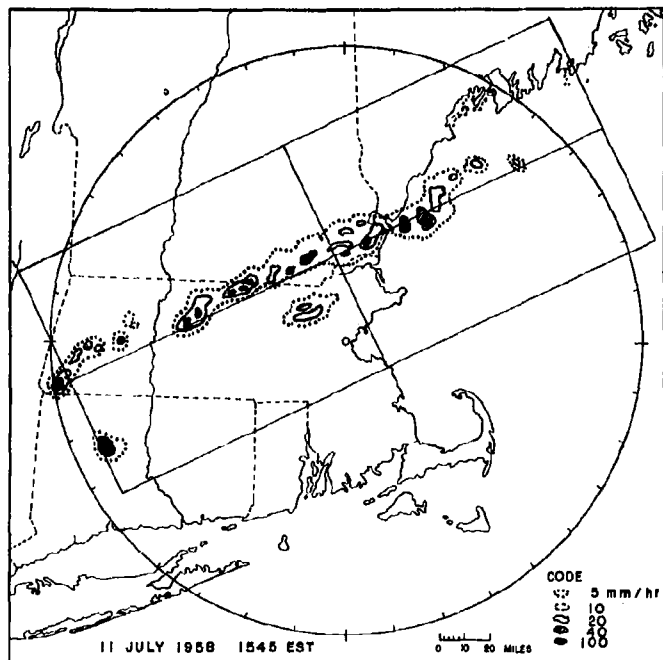
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FIG I . Examples of squall line contours expressed
in equivalent rain intensity. (mm / hr)

of 1° it may be reasonably assumed that the major portion of the beam is below the melting level and that the scattering particles were composed of water except where hail may have occurred. With this assumption the measured reflectivity values have been converted to equivalent Z values and then to isohyets based on the relation $Z = 200 R^{1.6}$ where Z is the reflectivity parameter in mm^6/m^3 and R the rainfall rate in mm/hr. The contours are separated by an interval of 5 db in signal intensity which corresponds to a factor of two in rainfall rate. Contours for 10-minute intervals have been traced from the film onto maps of New England. From such maps the location and motion of areas of intense precipitation within the line can be observed. Examples of a compact solid line and a fairly loose line are shown in Fig. 1.

For statistical analysis the data were converted to digital form, each number representing the equivalent rainfall rate in a 5x5 mile square. The grid of squares was moved with the squall line, the motion of the origin being the velocity of a selected intense storm and the y-axis lying along the front edge of the line. The position of the line was determined by eye and the axis was subsequently maintained on the line even if it was necessary to rotate as well as translate the grid. The origin of the grid was placed on the southernmost storm in the line when it could first be identified as a line. When the origin cell dissipated, the translation of the origin was continued by moving it parallel to the apparent velocity of some other strong storm which had the same motion as the origin storm when the latter was still present. A moving grid was used so that the precipitation could be kept in the center of the grid and the number of squares with no precipitation reduced as much as possible. The result is that the changes in internal structure can be investigated while effects produced by the motion of the line as a whole are eliminated.

Three charts have been made to describe the behavior and structure of each line:

1. The sum of the computed rainfall rates for all the grid points at a given time (total equivalent rainfall intensity) is used as a measure of the general intensity of the line at that time and represents the rate at which water is being precipitated. It depends both upon the magnitude of the rainfall rates and the areal extent of the line.

2. By adding the rainfall rate in each of the grid points separately over the entire period of observation, a space composite chart for the squall line is computed. The units are adjusted so that the numbers represent total depth of precipitation, in mm, for each grid square. Since the grid is moving, they do not, of course, represent depths of rainfall on the ground. The space composite shows the relative intensities and areas of storms or groups of storms (i.e., areas distinguished by the contours as having heavier precipitation), and the amount of scatter or organization of precipitation along the line. It also serves to determine the spacing between the precipitation maxima.

3. A time-space composite for each squall line is obtained by adding the rainfall rates in each row of grid points perpendicular to the squall line for each time of observation. The numbers thus obtained represent total rainfall rate in gm/sec for each 5-mile interval of distance along the line. No account is taken of the distribution across the line and storms which lie ahead or behind the line itself are included in the total. The chart is plotted with time as abscissa and distance along the line as ordinate. Contours on these charts indicate the times and locations of heavier precipitation and hence demonstrate the life cycles of storms and their motions relative to the origin.

The accuracy of the data is believed to be within the limits of resolution which were selected, intervals of 5 miles in space and 5 db in radar reflectivity. The SCR-615-B radar has a beam width of 3° between half-power points, which is 5 miles across at a range of 95 miles. The maximum range used in this investigation is 120 miles and most of the observed storms were within 100 miles. Hence for most of the observations the resolution of the radar is better than that required for the grid, and is at least equal to it for all of them. Austin and Geotis (1960) have shown that when short-period fluctuations are averaged electronically and when the radar is carefully and frequently calibrated, measurements of radar reflectivity are accurate to about 2 db. Marshall et al, (1955) have shown that the scatter in observed drop size distributions indicates a standard deviation of 3 db in the empirical equation relating rainfall rate and radar reflectivity. Because of the exponent involved ($Z = 200 \ R^{1.6}$) the uncertainty in the rainfall rate deduced from the radar reflectivity is only about 2 db. It appears, then, that at worst the overall error in the rainfall rates assigned to each grid point may be 4 db. Since it is unlikely that all the errors will be cumulative, an uncertainty of 3 db (a factor of 2) is considered a reasonable estimate.

C. Results and Discussion

Intensity curves, space composites and time-space composites for the eight storms are in Figs. 2, 3, and 4, pages 8-12.

From the time variation of the total intensity, three periods in the life of a squall line can be identified: the early period, when the line is recognizable as a squall line but remains at a relatively low intensity as compared with its peak value; the period of peak intensity, taken as
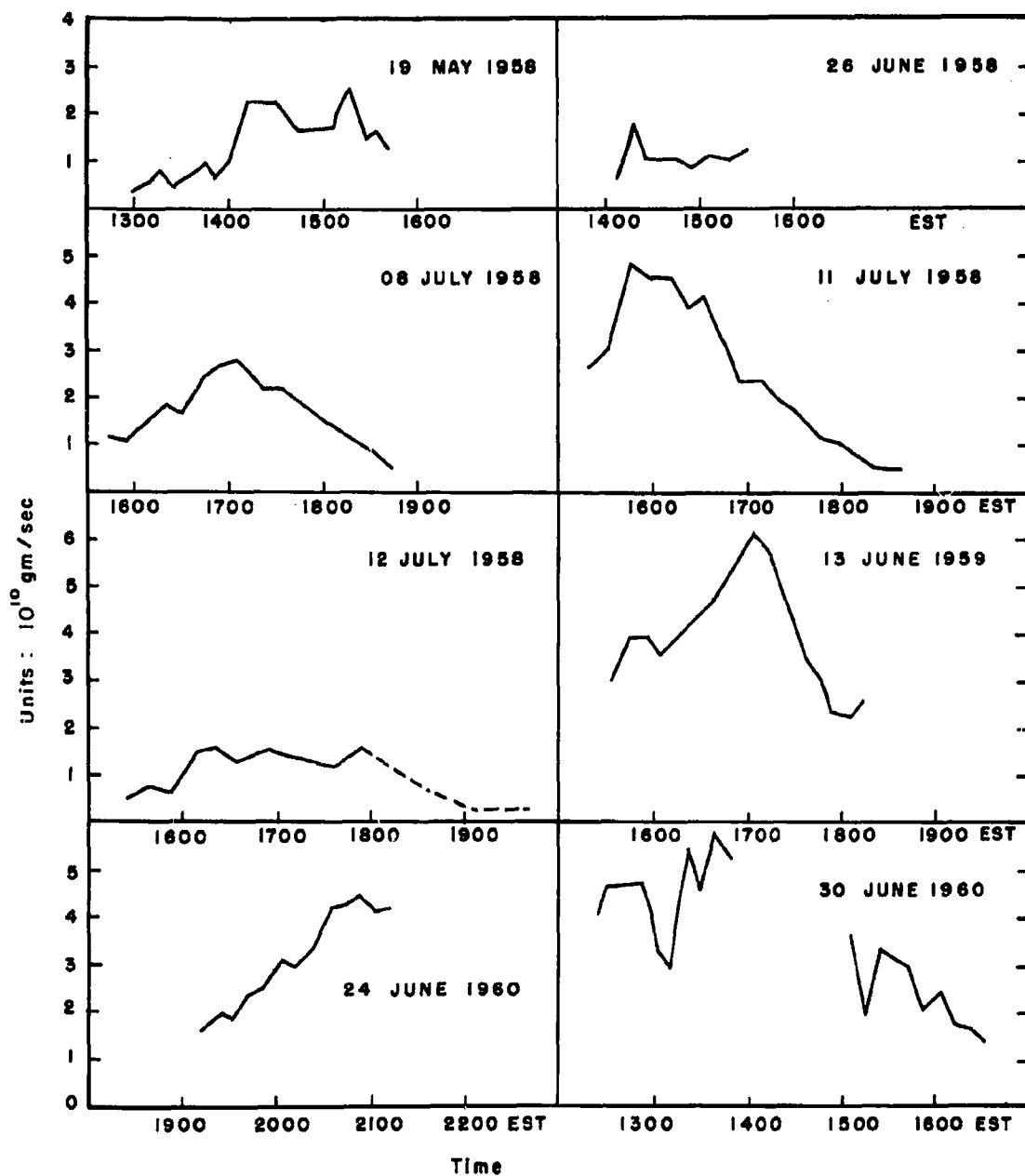
Fig. 2 Total intensity charts (equivalent rainfall rate for the whole line as a function of time).

Fig. 3   Space composite charts. Numbers represent computed rainfall
depth (mm) in the moving grid for indicated time periods.

FIG. 3 continued. Space composite charts.

Fig. 4 Time-space composites. Units: 2×10^7 gm/sec per 5-mile interval of length along the squall line.

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Fig. 4 continued. Time-space composites.

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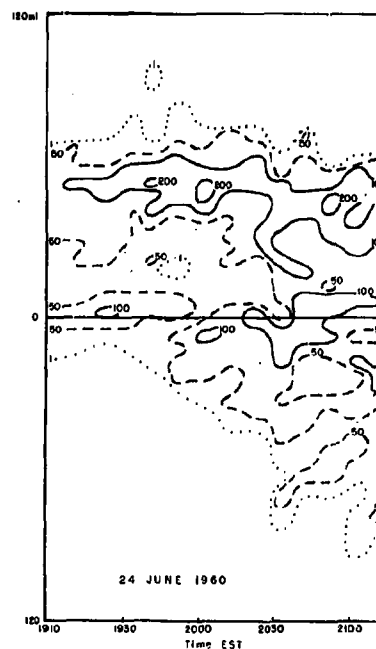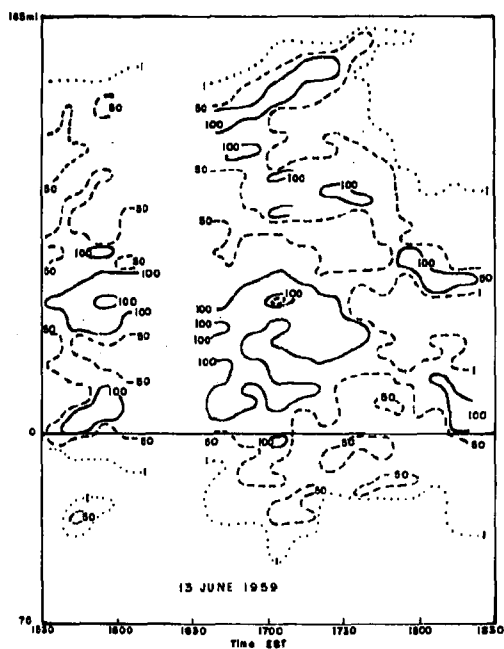
Fig. 4   continued.   Time - space composites.

the time during which the total intensity is as much as 70% of the maximum recorded value; the period of weakening or dissipat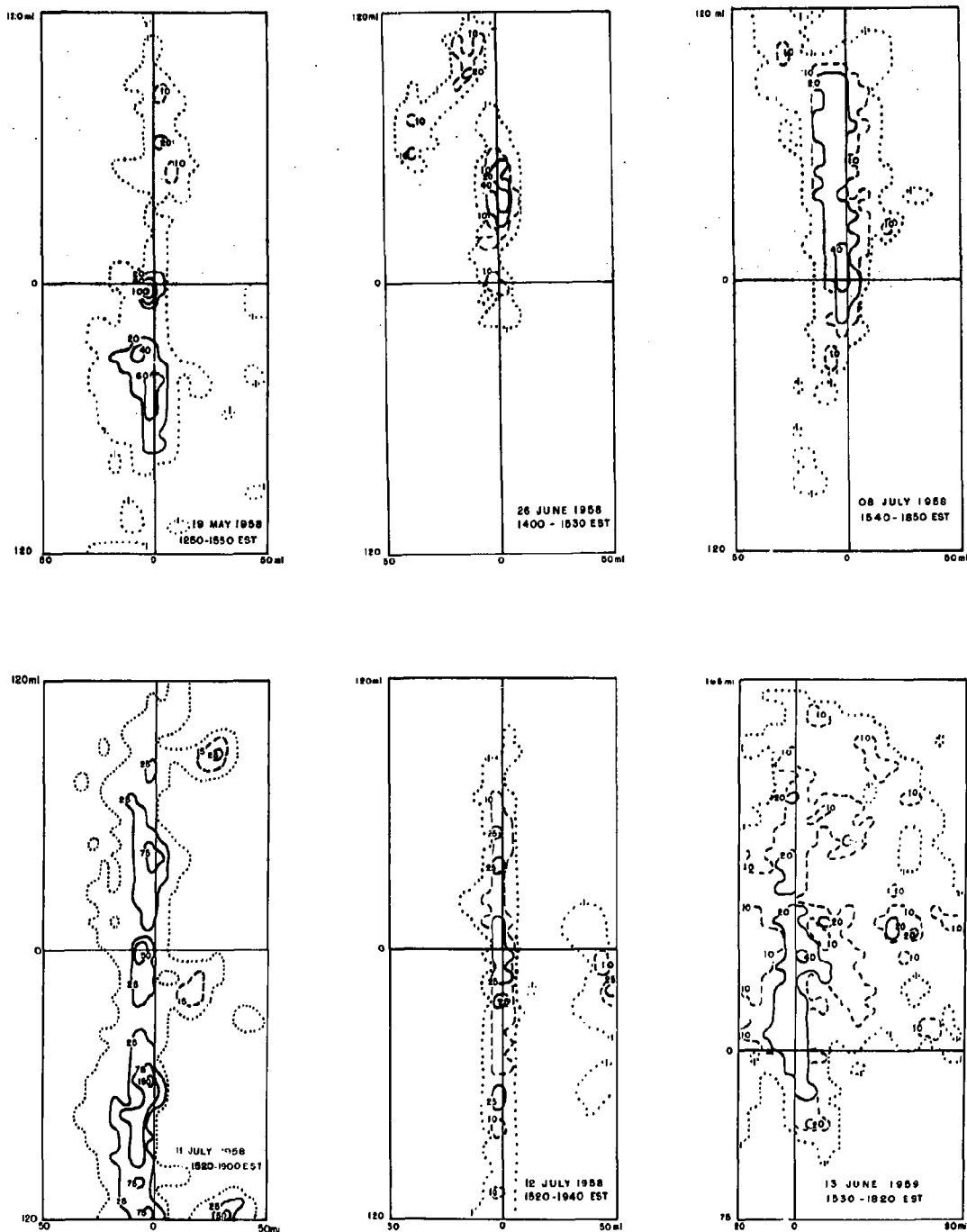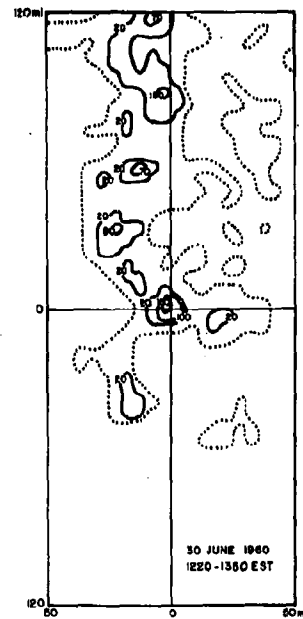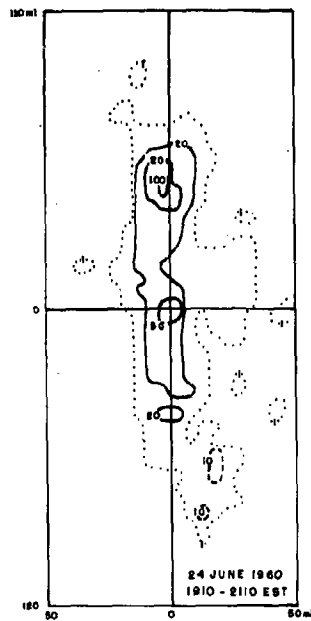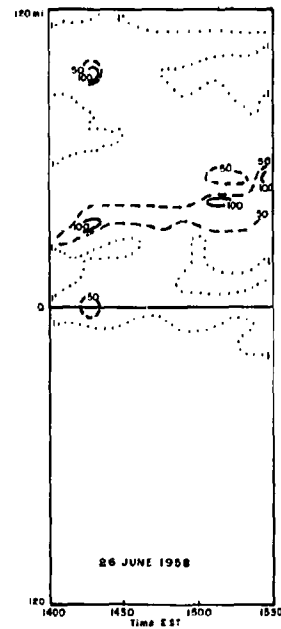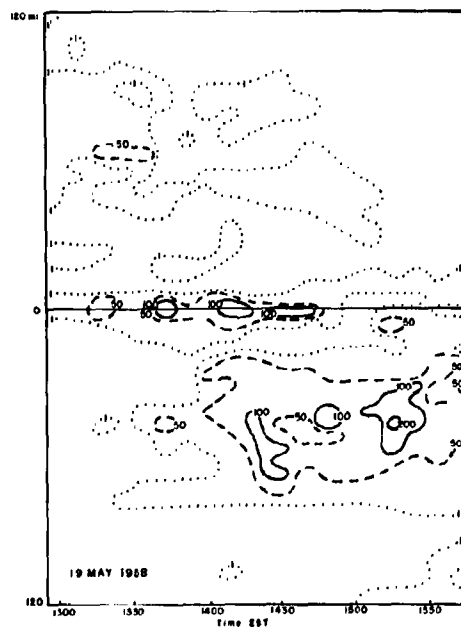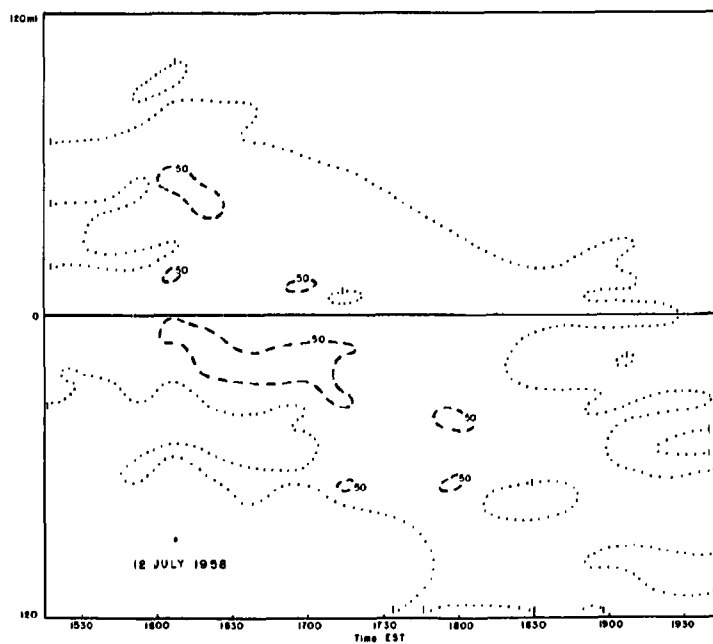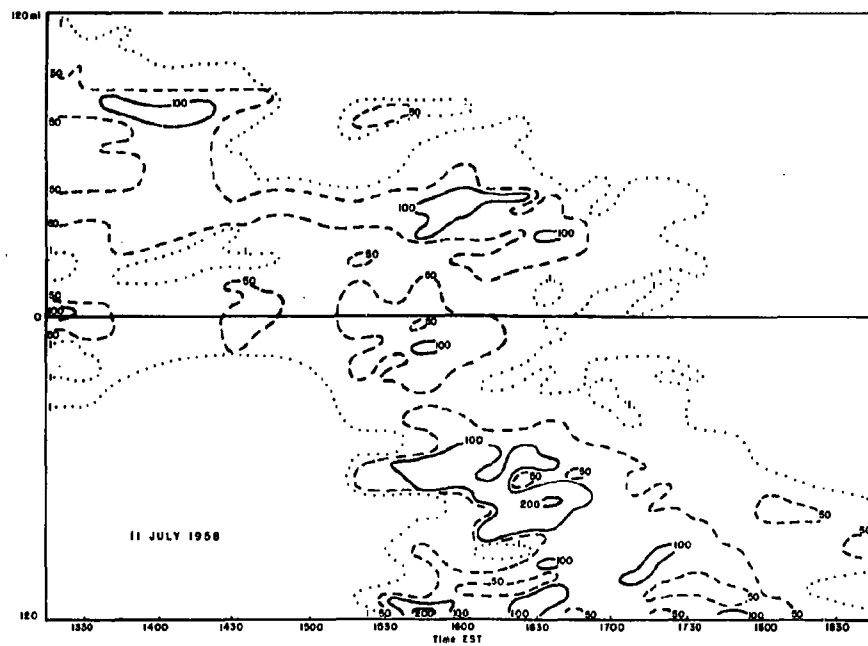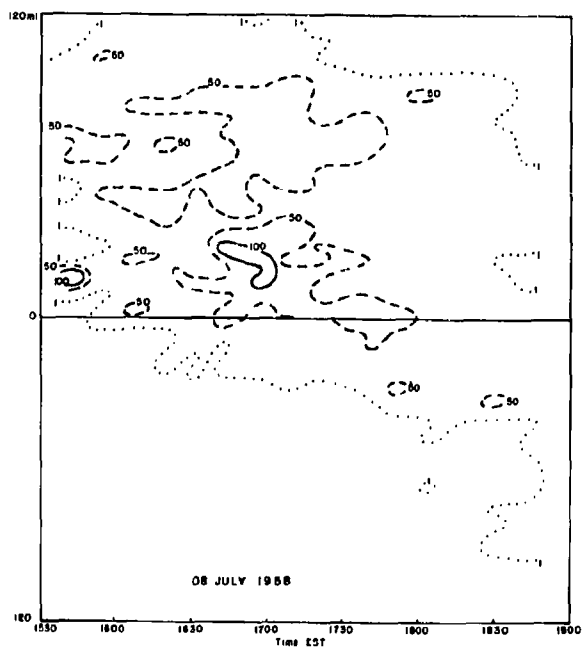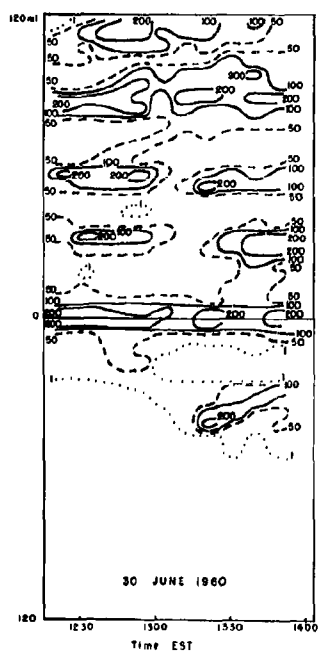ion. The 70% level was selected simply because for the particular squall lines in this study most of the sharp rises or falls in intensity, which would be the natural limits for the periods of maximum intensity, cross this level while most of the smaller fluctuations in intensity were entirely above or below it. Little can be said regarding the duration of the early and late periods because the observed durations are influenced by the time the radar was turned on or off and the range at which the line developed. The period of peak intensity usually lasted between one and two hours, as shown in Fig. 5. The peak rainfall rates and areal coverages are given in the Table on page 14. Spatial distributions of rainfall rates are in Fig. 6. At the time of peak intensity the most frequently observed rainfall rate is about 20 mm/hr. During the dissipating stage lighter rain occurs over larger areas.

During all periods of the squall lines, heavy showers occur in groups rather than uniformly spread along the line. Both space composites and time-space composites (Figs. 3 and 4) clearly demonstrate this tendency. The groups of intense showers are spaced irregularly but average 25 to 35 miles apart for all of the lines at the time of peak intensity. This tendency for intense storms to develop in the immediate activity of existing storms is expected from certain dynamic considerations. An investigation by Patrick (1960) of the role of released latent heat in the development and maintenance of squall lines showed that perturbations due only to the heat sources produced vertical velocities of sufficient magnitude to serve as a triggering mechanism for new storms. Moreover, the preferred positions for upward vertical velocities were quite close to existing storms, while at points midway between them there was a tendency for downward motion. Newton (1959)

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Table. Summary of characteristics of lines at peak intensity and average motion and orientation

Date	Time	Total	Area	R_{max}	R_{av}	Length	Interval	Motion	700-mb Wind	Orien-tation
5/19/58	1410	2.4	1800	110	15	100	25	250/20	240/40	045-225
6/26/58	1420	1.8	1100	90	20	100	35	250/13	240/30	040-220
7/8/58	1710	2.8	2400	45	15	75	25	265/14	250/35	050-230
7/11/58	1545	4.8	2600	95	25	140	23	275/16	260/35	065-245
7/12/58	1610	1.5	1400	30	15	75	25	260/18	240/30	045-225
6/13/59	1605	6.1	4100	30	12	130	32	245/18	240/35	050-230
6/24/60	2050	4.4	3000	90	18	115	28	250/28	240/25	055-235
6/30/60	1250	5.8	2900	115	25	115	35	290/19	260/30	055-235

Time: Time of peak intensity, EST
Total: Total intensity, gm/sec x 10l0
Area: Area, sq. miles
R_{max}: Maximum rainfall rate, mm/hr
R_{av}: Average rainfall rate, mm/hr
Length: Length of line, miles
Interval: Average distance between intense rain areas in miles
Motion: Motion of origin, °/kts
700 mb Wind: 700 mb wind, °/kts
Orientation: Line orientation, °
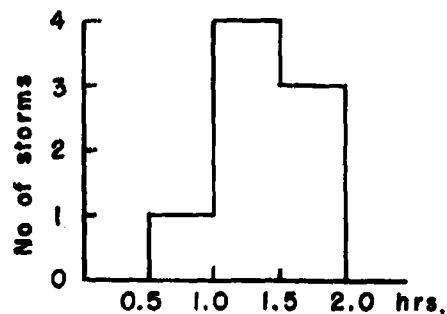
FIG. 5. DURATION OF PERIOD OF PEAK INTENSITY

TOP ROW: EARLY PERIOD

CENTER ROW: PEAK INTENSITY

BOTTOM: PERIOD OF WEAKENING

KEY

1	0 - 4 mm/hr
2	4 - 8
3	8 - 17
4	17 - 35
5	35 - 70
6	70 - 140
7	> 140 mm/hr
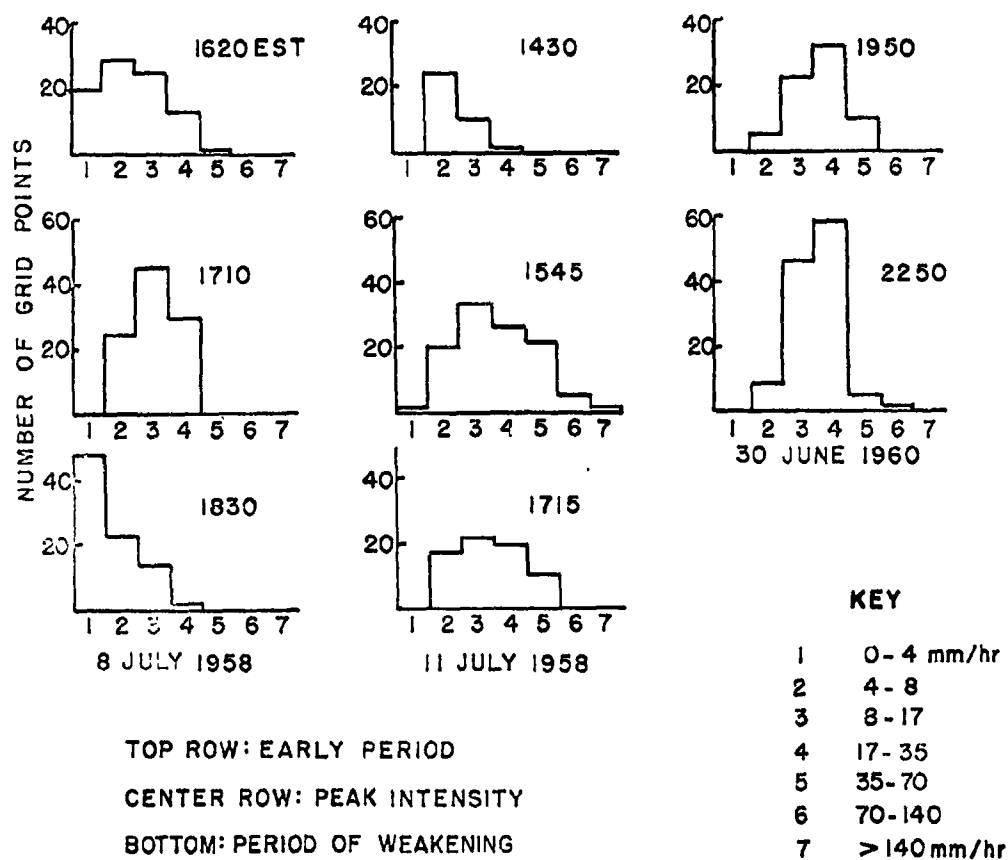
FIG. 6   EXAMPLES OF RAINFALL DISTRIBUTION AT DIFFERENT PERIODS IN LIFE CYCLE OF SQUALL LINES

in considering the interaction between large convective clouds[o] and an environment with vertical shear, showed that pressure forces also tend to encourage the development of new cells in certain areas in the immediate vicinity of existing convective storms.

With respect to the manner of development and maintenance, the eight storms fall into two groups. Four of them, group B, showed a continual development of storm areas on the southern end of the line with simultaneous dissipation on the northern end. The other four, group A, simply intensified and filled in within the area where the line was first delineated on the grid. The respective tendencies can be best observed from the space composite charts where the storms in group B show significant amounts of precipitation below the x-axis. For those in group A most of the echoes are above the x-axis. The grouping is as follows:

Group A	Group B
26 June 1958	19 May 1958
08 July 1958	11 July 1958
13 June 1959	12 July 1958
30 June 1960	24 June 1960

Since the storms were selected on the basis of being well-defined lines, the compactness of the structure in most of the space composite charts is not surprising. It is interesting to note, however, that the two which do not exhibit such highly organized linear structure, 13 June 1959 and 30 June 1960, are the most intense storms in the group. It may be that extremely vigorous convective activity tends to disrupt the organization of the line, but there are far too few cases in this study to justify recognition of such a tendency.

The total intensity curves, Fig. 2, show that the storms in group A tend to intensify to a single peak value and then to decline steadily. The

curve for 30 June 1960 is an exception. Its rather erratic behavior is explained by the fact that at about 1300 EST and again a half-hour later very intense storm areas moved off the northern end of the grid and were suddenly lost, producing sharp and artificial minima in the intensity curve. The group B storms, on the other hand, tend to have a rather sharp increase in intensity followed by a broad plateau which contains several maxima and minima. The dissipation period is complete for only two of the storms, but they show a gradual tailing off in intensity. No consistent differences were noted between the two groups with respect to environmental parameters (stability and moisture content), wind field or line orientation. In fact, all of these quantities were remarkably similar for the eight lines.

Comparison of the motion of the origin (the velocity of a selected intense storm area), the 700-mb winds and the orientation of the lines is in the Table. The difference in the motion of the origin and the 700-mb wind is of interest because it has been found that the motions of the smallest closed contours agree closely with the 700-mb wind. Therefore there appears to be a southwest to northeast motion of the intense cores within the slightly larger-scale storm areas. This relative motion cannot be deduced from the time-space composites because the 5x5 mile squares do not provide sufficient resolution for tracking the intense cores.

D. Summary

Certain characteristics in pattern and development which appear to be common to all New England squall lines have been observed. Although the lines are generally narrow and well defined, the precipitation is not spread uniformly along the length but is concentrated in relatively persistent (lasting one to three hours) intense storm areas spaced at intervals of 25-35 miles.

There are usually four or five such areas at the time of maximum intensity of the squall line. These intense storm areas move more slowly than the 700-mb wind and in a direction somewhat to the right of the prevailing wind direction, but the intense cores (small closed contours) within them appear to move with the velocity of the 700-mb wind. The orientation of the line itself is to the left, usually 15°-20°, of the 700-mb wind direction.

The time scale was roughly the same for all the squall lines with the period of peak intensity lasting one to two hours. The development and dissipation stages were slightly longer. There were large differences from storm to storm in overall intensity and areal extent. The maximum intensities varied from a total computed precipitation rate of 1.5×10^{10} gm/sec to 6.1×10^{10} gm/sec, the maximum lengths from 75 to 140 miles, and the areas from 1100 to 4100 square miles.

With respect to mode of development two distinct patterns were observed. In half of the squall lines new storm areas developed successively at the southern end of the line while those at the northern end dissipated. In the other four there was no systematic extension of the line, merely a filling in and intensification.

Since generalizations cannot be drawn from such a small number of cases it is desirable that the investigation be continued. With analysis of more squall lines the significance of tendencies which have been observed can be evaluated, and similarities and differences between storms and groups of storms can be more clearly depicted.

SYNOPTIC WEATHER SUMMARY

1. 19 May 1958. A surface cold front moved into New England in the afternoon. Flow aloft was from the west-southwest at both 700 and 500 millibars, and no change in direction occurred during the period of observation.

2. 26 June 1958. A northeast-southwest cold front advanced into New England during the day. Two short squall lines of differing orientation were observed by radar, the most southern of the two lines being considered the primary line. Upper air flow was from the southwest.

3. 08 July 1958. Two cold fronts were identified at 1300 EST, the two merging along the western New England border prior to squall line formation. Flow aloft was west-southwest during the time of squall line activity.

4. 11 July 1958. A northeast-southwest cold front with an extensive squall line moved into New England during the afternoon. Upper air flow was southwest at 0700 EST and veered to west by 1900 EST. The squall line was observed from 1315 EST to 1845 EST, the longest period of observation of a line in this study.

5. 12 July 1958. The cold front of the previous day became stationary through Massachusetts on this date, while a new cold front moved into New England from the northwest causing a short squall line in the afternoon. Flow aloft was southwesterly throughout the day.

6. 13 June 1959. A cold front with a north-south orientation entered New England in the late morning, and the associated squall line moved ahead of the front in the early afternoon. Considerable precipitation occurred in the warm moist air throughout the day. Winds aloft were west-southwest during the day, but the winds along the New England coast backed to south-southwest by 1900 EST.

7. 24 June 1960. A weak cold front advanced into New England in the late afternoon. The squall line developed about 1900 EST. Upper air flow was west-southwest at 700 millibars and westerly at 500 millibars.

8. 30 June 1960. The cold front and associated squall line entered New England at noon and progressed eastward rapidly. Flow aloft was westerly throughout the day.

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REFLECTIVITY OF HAILSTORMS AT 10 CENTIMETERS

A. Introduction

On the basis of the scattering characteristics of precipitation
particles it may be expected that storms containing hail would, because of
the presence of larger particles, have higher reflectivities than those which
contain only rain. This difference would be more pronounced for a wave-
length of 10 cm than for 3 cm because at the longer wavelength Rayleigh
scattering would still be effective for reasonably large hailstones. Experi-
ments conducted by Donaldson (1961) and a preliminary survey made at M.I.T.
under a previous contract (Weather Radar Research, 1961) support this ex-
pectation, but do not yield a definite relationship between storm reflec-
tivity and the occurrence and size of hail.

Donaldson (1961) measured vertical profiles of radar reflectivity
in 130 separate thunderstorms during the summers of 1957 and 1958; 51 of
the storms were hailstorms. Surface weather conditions were reported by
an extensive network of cooperating observers. Selection of storms for
study was based on availability of both radar and surface data. Donaldson's
measurements were made with an AN/CPS-9 radar ($\lambda = 3.2$ cm). It has been
amply demonstrated both by theory (Hitschfeld and Bordan, 1954) and obser-
vation (Austin, 1961) that X-band radiation is significantly attenuated
by moderate to heavy rain and severely attenuated by intense rain of 50-
100 mm/hr. Since most hail observed in New England is accompanied by very
heavy rain, many of Donaldson's measurements are doubtless affected by
large but unknown amounts of attenuation. His most consistent results were

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from data taken at an altitude of 30,000 ft. At such heights the scattering particles might well be composed almost entirely of ice, in which case the attenuation might not be significant. The 30,000 ft data showed much higher reflectivities in hailstorms than in rainstorms and still higher values when the hailstones were large.

In the preliminary M.I T. study (Weather Radar Research, 1961) the radar data were in the form of averaged, range-corrected signal-intensity contours on the SCR-615-B radar ($\lambda = 10.7$ cm). The hail information was the same as Donaldson's, from the volunteer observer network of the Geophysical Research Directorate, AFCRL. For three squall lines in 1957 and 1958, reported hail occurrences were generally associated with values of Z_e, equivalent Z computed on the assumption of Rayleigh scattering and water particles, of 10^5 mm^6/m^3 or higher. Measurements on several days in 1960 indicated that hailstorms have Z_e values of at least $10^{5.5}$. There were, however, a number of storms reaching the critical Z_e value in intensity for which it was not possible to ascertain whether or not hail occurred because there were no observers in their paths. It was evident that more complete coverage in the hail observations would be required for an adequate survey.

During the summer of 1961, the number of hail reports was greatly increased through the cooperation of Don Kent, Bob Copeland and Norman Macdonald, meteorologists of Station WBZ-TV in Boston. On days when the radar had measured reflectivities in the vicinity of $Z_e = 10^{5.5}$ mm^6/m^3 or greater, they requested their listeners to send in postcards giving the time, place and size for any hail which had been observed. The results were extremely gratifying with hundreds of mutually confirming reports in several

storms. Some of the results have been discussed by Geotis (1961). This report presents a more complete analysis of the data.

B. Data and Methods of Analysis

During almost all storms where moderate to heavy rain occurs, continuous records are taken of the signal intensity contours on the PPI of the SCR-615-B radar. Occasionally storms which develop unexpectedly during the night or on weekends are missed. The signal is averaged electronically and corrected for normal range attenuation with instrumentation described by Kodaira (1959). The contours as they appear on the scope represent lines of equal radar reflectivity per unit volume, η. When the scattering particles are small compared with the wavelength, λ, and are composed entirely of ice or water, η is related to the reflectivity factor Z (ΣD^6, where D refers to the diameters of the scattering particles) by the formula for Rayleigh scattering:

$$\eta = \frac{\pi^5 |K|^2 Z}{\lambda^4}$$

where $|K|^2 = 0.93$ for water particles and 0.197 for ice. Values of Z computed from measured reflectivities by means of the Rayleigh formula for water particles are called equivalent Z values and designated by Z_e. For a wavelength of 10.7 cm, when the scatterers are raindrops Z and Z_e are the same within the limits of experimental error. For hailstones the Rayleigh approximation is good within 2 db for diameters up to 3 cm, but the suitability of using the relation for water particles depends upon the distribution of water and ice in the hailstone. When Rayleigh scattering does not apply values of Z_e are dependent upon the wavelength of the radiation used for observing. All values of Z_e in this discussion are based on a wavelength

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of 10.7 cm. The units of Z_e are mm^6/m^3.

For high reflectivities the intensity contours are separated by intervals of approximately 4 db with thresholds corresponding to the following values of Z_e: $10^{5.3}$, $10^{5.7}$, $10^{6.1}$, $10^{6.5}$. The accuracy of the radar measurements is estimated to be 2 db (Austin and Geotis, 1960).

During the summer of 1961, there were seven days when a number of storms were observed to have Z_e values in excess of $10^{5.7}$. On those evenings requests for hail reports were made by the meteorologists of Station WBZ-TV; nearly 900 reports were received. On one day a delay in commencing radar operations caused most of the hail observations to have no associated reflectivity measurements. Hence this day was excluded and the analysis is based on data from six days.

The planned method of analysis was to prepare maps showing the locations and times of occurrence for storms with Z_e values in excess of $10^{5.5}$ Actually $Z_e = 10^{5.7}$ was used as the critical value because $10^{5.5}$ was not a contour threshold. On other maps the times and places of reported hail would be plotted. By overlaying the maps one could determine: (a) the percentage of high reflectivity storms for which hail was reported; and (b) the distribution of reflectivities for storms in which hail was observed. Such a simple procedure was not feasible, however. Some storms remained at an intensity above the critical value for periods of several hours and left extensive and well-defined tracks as they moved across the area under observation. In other storms the critical value was exceeded for only a few minutes over a very small area. Clearly the probability of receiving reports verifying the occurrence of hail differs greatly for these two cases and they should not be given equal weight in any survey. Neither

is it feasible to regard each report of hail occurrence as equally significant. When a hailstorm passes over a city or town numerous reports are received; from rural regions reports are relatively few; while from ocean, swamp or forest areas there are usually no reports at all. Therefore, in plotting the data all reports of hail occurrence within a single town at approximately the same time (within an interval of about 15 minutes) were considered as a single observation.

In order to apply a weighting factor to the radar data, areas from which high reflectivity echoes were received were divided into two categories, "tracks" and "spots". A "track" was left by a storm whose Z_e value remained close to or above $10^{5.7}$ for at least 15 minutes and which moved enough to cover a path at least 10 miles in length. If either or both of these requirements were not fulfilled the storm echo was a "spot". The probability of a confirming hail report is relatively small for "spots" and lack of such evidence is not considered significant. When "tracks" have no supporting hail reports an explanation is sought.

Lack of knowledge as to the exact location of an observer within a given town and distortion of the scope in the processes of photographing and projecting its image caused uncertainties in plotting the maps which might be as large as several miles. Therefore, if a strong echo was within three miles of a plotted hail report they were considered to be coincident.

C. Results and Discussion

Results of the analysis are summarized in Tables 1-5, pages 26-27, and illustrations of "tracks" and "spots" with associated hail reports are in Figs. 7-9, pages 28-29.

Table 1. Summary of Hail Observations. Number of hail reports in each category is given.

Date	Total	Adjusted	Associated echo intensity				
			No echo	$Z_e < 10^{5.3}$	$10^{5.3} \leq Z_e < 10^{5.7}$	$Z_e \gtrless 10^{5.7}$	Not observable by radar
5-22	128	81	5	13	13	3	47
6-6	205	50	1	2	1	44	2
6-24	24	12	0	0	0	4	8
6-30	226	89	3	0	6	66	14
7-3	51	28	0	0	3	18	7
7-10	201	110	14	24	36	19	17
Total	835	370	23	39	59	154	95

Table 2. Summary of radar storm tracks*

Date	Number of tracks			Echo heights (Thousands of feet)		No. of hail reports	
	Total	With hail reports	Over ocean	Max	Ave	In tracks	In spots+
5-22	0	0		30	20-25	0	21
6-6	12	9	2	40	35	44	2
6-24	2	2		30	20-25	4	0
6-30	7	6	1	40	30	72	0
7-3	3	3		35	30	16	5
7-10	10	9	1	30	20-25	36	42
Total	34	29	4				

* A "track" represents the path of a storm for which $Z_e \gtrless 10^{5.7}$, path length $\gtrless$ 10 miles, duration $\gtrless$ 15 min.

+ A "spot" has $Z_e \gtrless 10^{5.0}$ and is not sufficiently large and intense to be a "track".

Table 3. Range and intensity distribution for echoes associated with hail reports on May 22 and July 10. Number of cases in each category is given.

Range (miles)	<20	20-30	30-40	40-50	50-60	60-80	80-100
No echo	2	0	1	3	1	7	5
$Z<10^{5.3}$	1	3	5	6	12	6	2
$Z>10^{5.3}$	11	19	18	10	6	5	1

Table 4. Comparison of hail stone size with radar reflectivity, all days. Number of cases in each category is given.

Diameters of Hailstones

$\log Z_e$	2"	1"	$\frac{1}{2}$"	$\frac{1}{4}$"	No size reported	Total
5.3-5.6	0	4	18	31	6	59
5.7-6.0	0	5	40	35	11	91
6.1-6.4	2	6	23	3	3	37
6.5-6.8	9	10	8	0	0	27
Total	11	25	89	69	20	214

Table 5. Comparison of hailstone size with radar reflectivities, omitting May 22 and July 10. Omitted Number of cases in each category is given.

Diameters of Hailstones

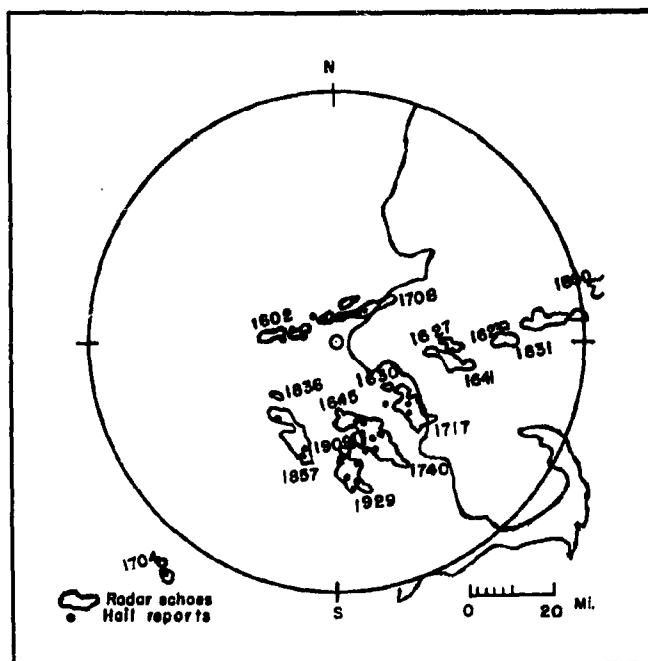| $\log Z_e$	2"	1"	$\frac{1}{2}$"	$\frac{1}{4}$"	No size reported	Total
5.3-5.6	0	0	4	5	1	10
5.7-6.0	0	1	32	25	11	69
6.1-6.4	2	6	23	3	3	37
6.5-6.8	9	10	8	0	0	27
Total	11	17	67	33	15	143

FIG. 7   HAIL TRACKS AS DETECTED BY RADAR AND REPORTED BY GROUND
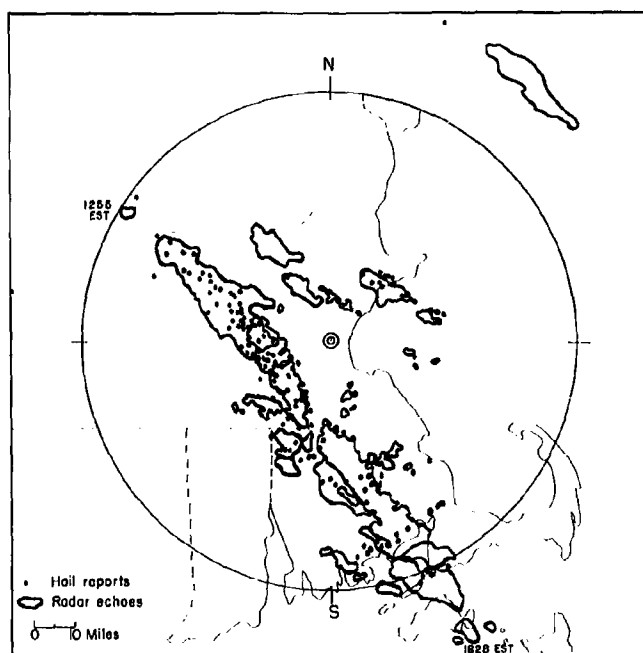OBSERVERS   6 JUNE 1961.

Fig. 8   Hail tracks as detected by radar and reported by ground observers. 30 June, 1961.
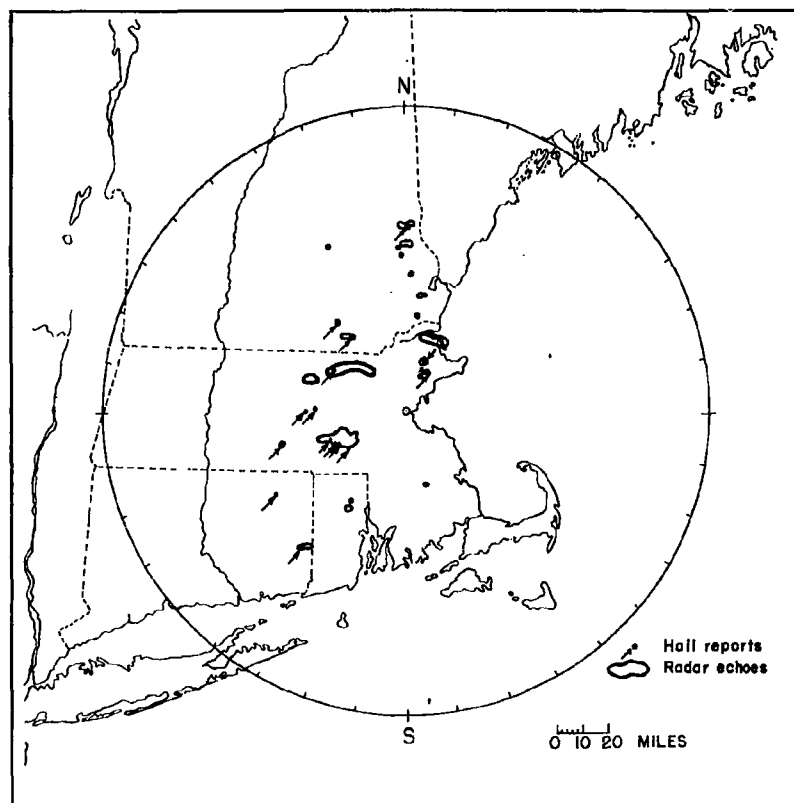
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Fig. 9   Hall tracks as detected by radar and reported by ground observers
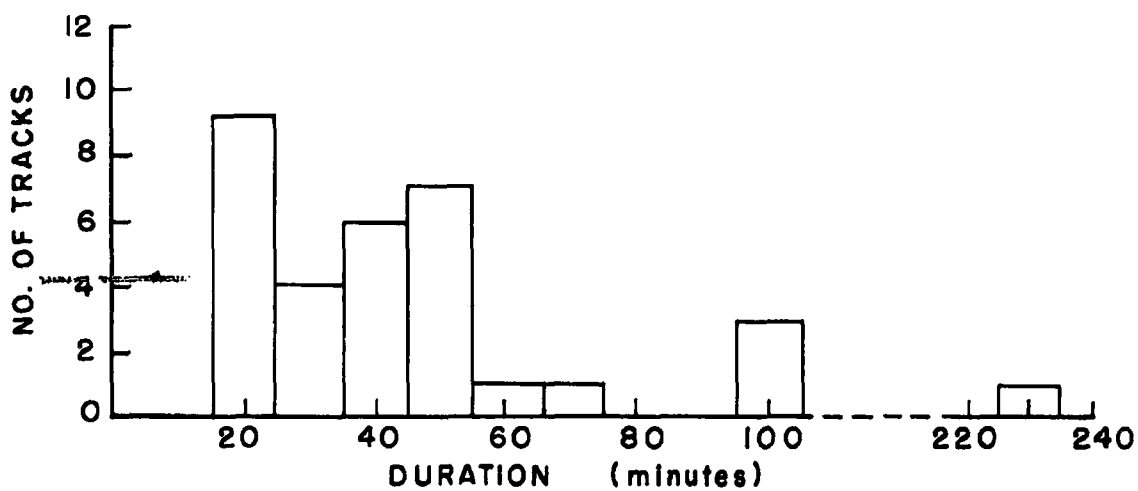10 July 1961   1345-1500 EST

FIG. 10   Duration of storms leaving high intensity
echo tracks.

In Table 1 the adjusted number of hail reports is obtained from the total number by grouping together all reports from a single town at approximately the same time. The reports labelled "not observable by radar" include hail which occurred when the radar was not turned on or at places which were beyond the range of the radar, in the ground clutter or in shadow areas.

From the results summarized in the tables it can be seen that the occurrences on May 22 and July 10 differed from those on the other four days in several respects. On those two days the radar echoes were very spotty with many storms appearing in random positions, then building and dissipating rapidly. The heights of the storms were generally less than 25,000 ft with the tallest reaching only 30,000 ft. Many hail reports were associated with echoes whose Z_e values were less than $10^{5.3}$. It may be that except at close ranges some of the showers were not large enough to fill the beam so that the observed radar reflectivities were less than the actual maximum values within the storms. Range and intensity relationships for echoes associated with hail reports on those two days support this supposition (Table 3).

On June 6, 24, 30 and July 3, squall lines moved across the area, the high-reflectivity areas left well-defined tracks, and practically all the hail reports were from locations within the tracks (Table 2). Also, there was at least one reported hail occurrence within every track observed by the radar except for four which were entirely over the ocean and one short one which was over a swamp area. The duration of the observed tracks varied from 15 minutes (the minimum, by definition) to nearly four hours. As shown in Fig. 10, the most frequently observed duration was the shortest (approximately 20 minutes), the next most frequent was 50 minutes, and very few lasted over an hour.

A complete count of "spots" was not made because it was apparent that even with the great improvement in coverage of hail reporting, one still cannot tell whether lack of a hail report from such a small area means no hail or no observer. Two partial counts were made, however, with the following results. On May 22 between 1130 and 1330 EST, 27 "spots" were observed and 11 had associated hail reports. On July 10, over 20 "spots" were tabulated and about one-third of them had hail reports.

The relationship between size of hail stones and storm reflectivity is in Tables 4 and 5. Hail sizes which were reported qualitatively were tabulated as follows: pea or bean, 1/4"; marble or mothball, 1/2"; walnut, 1"; golf ball, 2". When a range of sizes was reported from a single location, the largest size was used for the analysis. In general, the tables show a definite tendency for large hail to be associated with the higher Z_e values and smaller hail with lower reflectivities. This tendency shows more clearly in Table 5, where the data for May 22 and July 10 are omitted. The strong dependence between range and observed reflectivity on those days, Table 3, apparently overshadowed any relationship between hailstone size and reflectivity. There are 8 cases where Z_e values in excess of $10^{6.5}$ appear to be associated with 1/2" hail and 3 cases where Z_e values greater than $10^{6.1}$ have only 1/4" hail reported. It is suspected that the observers were close to rather than actually in the areas of highest reflectivity, but it is not possible to pinpoint the locations with sufficient precision to be certain of it.

Most of the intensities in excess of $Z_e = 10^{6.5}$ were observed on June 30 and this was the only day on which hail of the 2" category was reported. All of the reports of 2" hail and most of the areas whose

reflectivity exceeded $10^{6.5}$ were in the long track which lasted nearly four hours. On other days, also, the largest hail and highest reflectivities were found in the longer tracks. The only other day when Z_e values greater than $10^{6.5}$ were recorded was June 6. There was a very small area covered by such intense echoes and reports of hail the size of half-dollars were received from that locality. Hail as large as this was not observed at any other place on that day.

In Fig. 8 it appears that the long track lasted over five hours. Actually, however, the southeasterly end of the track area represents two storms, the second one following almost the same path as the first but about an hour later. There were at least two other occasions when the path of a hailstorm was almost identical to that of one which had occurred about an hour earlier. There also appear to be certain geographical areas where hail occurred on several days, a surprising frequency for such a small number of samples. These apparent tendencies are interesting but cannot be adequately investigated on the basis of one summer's data.

D. Conclusion

We conclude that a 10-cm radar equipped with instrumentation to make accurate reflectivity measurements over the area it observes can identify hailstorms and also provide an estimate of the hail size. In the Boston area any storm whose reflectivity parameter Z_e exceeds $10^{5.5}$ mm^6/m^3 may be assumed to contain hail, probably 1/4" to 1/2" in size. If $Z_e \sim 10^6$, the hailstones are likely to be greater than 1/2" but smaller than 1". If $Z_e \sim 10^{6.5}$, the hailstones are at least 1" in diameter and probably the size of golfballs.

Acknowledgment

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> Austin, P.M., H. B. Cochran and G. O. Patrick: Investigations Concerning the Internal Structure of New England Squall Lines, pp 193-198.

> Geotis, S.G.; Some Radar Measurements of Hail, pp 133-138.

Thesis

> Cochran, H.B., 1961: A Numerical Description of New England Squall Lines, Master's degree thesis, Department of Meteorology, M.I.T.