

CHARACTERISTICS AND DEVELOPMENT OF MESOSCALE
PRECIPITATION AREAS IN EXTRA-TROPICAL CYCLONES

by

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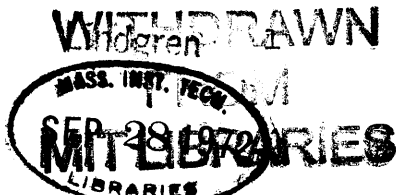
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Submitted to the Department of Meteorology on August 14, 1972
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ABSTRACT

Eight New England cyclones, in various stages of development, were studied in order to determine the nature and behavior of the larger mesoscale precipitation features that they contained. Quantitative radar pictures, the basic data, were supplemented by rain gauge and radiosonde data. All of the storms exhibited a marked banded precipitation structure. Three types of bands, distinct in terms of size, shape, and structure, were identified. Type 1 bands were composed of elongated large mesoscale areas (LMSA's) which were about 4,000 km² in area. Type 2 bands were larger and not composed of LMSA's, and type 3 bands were about the size of LMSA's but highly elongated. Virtually all of the cells and heavy rain were concentrated into the bands and LMSA's, which in turn were organized into one or more "belts." These belts maintained a fixed position with respect to the cyclone, extending from the cyclone center to approximately 500 km ahead of the center. The LMSA's and bands, which had lifetimes of about four hours, moved through the belts, dissipating at the leading edge. There was, therefore, a recursion of mesoscale precipitation features. The mesoscale features were found to move with the 700 mb wind, despite the fact that they were varied in vertical development. The bands were oriented nearly perpendicular to their directions of motion, with the exception of the type 1 bands and LMSA's, which were oriented about 50° to the right of their directions of motion.

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I. INTRODUCTION

A. The General Problem

A look at radar or high-resolution rain gauge data reveals that several scales and intensities of precipitation occur simultaneously in extra-tropical cyclones. At one end of the spectrum is the synoptic scale precipitation, which is associated with the large-scale upglide motions which are part of the cyclonic circulation itself. At the other extreme is the more intense precipitation of convective cells, which are characterized by buoyant parcels of air with rather large vertical velocities. Areas of precipitation which occur between these extremes of scale and intensity are termed mesoscale precipitation areas.

Because synoptic-scale disturbances, by definition, are of the size which permits their study by data from stations which have the density of the regular synoptic reporting stations, investigators have been able to study them in great detail. Cellular activity, likewise, has received considerable attention, especially through the application of numerous numerical and physical models. It is desirable to obtain a knowledge of mesoscale precipitation features, as well. Such a knowledge is the first step in achieving an understanding of mesoscale precipitation areas and their relationship to the larger and smaller scales of activity. Because of the scale involved, radar offers virtually the only means of performing an extensive and detailed study of these phenomena. It has been only recently, however, that quantitative radar data has been available from radars which have the sensitivity,

accuracy, and resolution that are required for this type of study.

B. Background

Austin and Houze (1972) compared the different scales of precipitation activity in terms of size, intensity, duration, and movement. For this purpose, they divided mesoscale precipitation areas into two classes, large mesoscale areas (LMSA's) and small mesoscale areas (SMSA's). These areas were defined as shown in Table 1, which was derived from their results.

Table 1. Characteristics of precipitation areas of different scales.

Parameter	Synoptic	Mesoscale		Cells
		LMSA	SMSA	
Definition	$> 10^4 \text{ mi}^2$	500-5000 mi^2	25-5000 mi^2	$< 25 \text{ mi}^2$
Preferred size range	*	900-1800 mi^2	100-150 mi^2	**
Duration	days	1-12 hours	1/3-1 hour	$\sim 1/4 \text{ hr}$
Rainfall rate increase over the next larger scale	--	2 X	2 X	2-10 X

* areas too large for determination by radar

** areas near the resolution capability of the radar

The fact that LMSA's and SMSA's tended to have preferred sizes that were well within the pre-defined limits reinforces the contention that the two are different and distinct entities. Austin and Houze found evidence that the SMSA's were closely related to cellular activity, while they could offer no hypothesis concerning the existence of the LMSA's.

The precipitation areas have been found to be highly organized. Austin and Houze (1972) noted that in cyclones each scale of precipitation area almost always contains each of the smaller areas. Furthermore, areas of a given scale rarely existed outside of areas of the next larger scale. Elliott and Hovind (1964) and Browning and Harrold (1969) also found, in cyclones, precipitation bands of the size of LMSA which enveloped smaller convective elements.

Several investigators have discovered band-shaped precipitation areas, or "bands," in extra-tropical cyclones. Austin (1960) found large north-south oriented bands across the warm frontal area in two storms over New England. The bands were about 250 miles long and 40-50 miles wide, and contained small areas of heavier precipitation. Ligda, Serebreny, and Nagle (1961) found spiral-banded precipitation areas in cyclones, usually ahead of the warm front. In fact, they reported finding three different scales of banded structure. They concluded that the spiral-banded structure is characteristic of cyclones during the occluded stage. Elliott and Hovind (1964) studied four storms on the California coast. Each contained precipitation bands that were 20-40 miles wide and 30-60 miles apart (between centers), and were oriented along the shear vector between the winds in the convective cloud layers and the adjacent layer above. These bands contained all the cells, and were trackable for up to three hours or 100 miles. Browning and Harrold (1969) analyzed one cyclone over England in great detail. They found bands ahead of the warm front which were parallel to it, and bands in the warm sector which were

parallel to the winds there. Austin and Houze (1972) observed that of seventeen New England cyclones, all contained band-shaped precipitation areas. They noted that these bands tended to line up parallel to the surface isobars, with the angle between the bands and isobars rarely exceeding 30 degrees. They also noted that some of these bands were much larger than the large mesoscale areas as previously defined.

The movement of mesoscale precipitation areas has received a fair amount of attention. Ligda and Mayhew (1954) discovered that the movement of mesoscale precipitation echoes in cyclones was most closely approximated by the 700 mb wind field. Other investigators, including Boucher and Wexler (1960), have also found that 700 millibars represents the steering level for precipitation areas. Elliott and Hovind (1964), however, observed that bands moved in the direction of the shear vector between the winds in the convective cloud layers and the layer below. Austin and Houze (1972) found that irregularly-shaped LMSA's moved approximately with the cells within them, which in turn moved with the winds at mid-cell level, while the band-shaped LMSA's moved more slowly and almost perpendicular to the movement of the cells.

C. Specific Statement of the Problem

In this study, then, advantage will be taken of the improved quantitative radar data that has recently become available in order to determine the nature and behavior of the LMSA's and bands found in extra-tropical cyclones, and to determine how they are related to the

cyclonic circulation. Specifically, the direction, speed, and orientation of the bands and LMSA's are to be compared to the wind field and to the movement of the cyclone. Also, the configuration of the areas and/or bands relative to the cyclone itself and to the synoptic scale area of light rain which accompanies the cyclone will be studied. The final objective is to gain evidence concerning the relationship, if any, between LMSA's as defined and observed by Austin and Houze, and bands, which have been noted by a number of authors and which are sometimes much larger than the LMSA's.

II. DATA AND METHODS OF ANALYSIS

A. Data

The basic data for this study are Plan Position Indicator (PPI) displays from the WR-66 weather radar that is operated by the Department of Meteorology at the Massachusetts Institute of Technology. These data are supplemented by tipping-bucket rain gauge traces from gauges at West Concord, Massachusetts, and at M. I. T., by hourly precipitation amounts from other stations in New England and New York, and by wind data obtained from the nearest regular radiosonde stations.

The characteristics of the WR-66 radar at M. I. T. are given in Table 2. This radar is superior in accuracy, sensitivity, and resolution to radars in use at M. I. T. prior to 1967. The radar's scopes display an averaged and range-normalized signal which has been quantized into intensity levels that are 4.5 db apart. Each intensity level corresponds to an increase in rainfall rate of approximately a factor of two over the preceding level. The entire sequence of intensity levels on the PPI is photographed every two to four minutes, depending on the number of intensity levels that are needed to describe the precipitation that is occurring or is expected to occur. This automatic process is occasionally interrupted in order to manually photograph a sequence of intensity levels from the Range-Height Indicator (RHI). Thus vertical cross-sections through features of interest are obtained as well as horizontal depictions of the area that is surveyed by the radar.

Table 2. Characteristics of the WR-66 radar

Wavelength	10.5 cm
Beam width (degrees between half-power points)	1.35 deg
Pulse length	1.0 μ sec
Transmitted power (approximate)	600 kw
Range (approximate)	200 km

The tipping-bucket gauges at West Concord, Massachusetts, and M. I. T. utilize 80 and 60-inch catches, respectively. They are capable of time resolutions that are on the order of a few seconds in heavy rain and one minute in light rain. Both gauges are routinely compared to other gauges for accuracy. Agreement is generally within five percent. West Concord is located 28 km west-northwest (290°) from M. I. T.

Hourly precipitation amounts for New England and New York stations are published monthly by the National Weather Service. There are approximately 70 reporting stations within 200 km of the radar site.

Upper level winds were obtained from soundings from the following radiosonde stations: Portland, Maine (PWM); Albany, New York (ALB); New York City Airport (JFK); and Nantucket, Massachusetts (ACK), which was replaced by Chatham, Massachusetts (CHH) during 1971.

B. Selection of Storms

Four of the storms used in this study were among the 17 storms which were studied by Austin and Houze (1972). The storms for that study were chosen because of their cyclonic nature, their stage of development (mature, but not occluded), and the adequacy of radar and

rain gauge coverage. (From that study, it was known that these storms all contained elongated or band-shaped precipitation patterns. However, since only instantaneous precipitation patterns were studied, it was not known how these features behaved.) The four storms selected from that group were the most recent of the seventeen; therefore they had been observed with the superior WR-66 radar. Also, radar coverage was more continuous during this later period.

Four other storms were added to the study. These were picked from 1970 and 1971 data, the primary considerations in their selection being that they were cyclonic storms with a considerable amount of rain and that there was adequate radar coverage. The stage of the storm was a factor only in that an attempt was made to select at least one cyclone that was occluded during the period of observation.

The storms selected for study are listed in Table 3. They are listed in the order that they will be considered, rather than chronologically.

Table 3. Storms selected for study. The central pressure of the system is used as a measure of its intensity.

<u>No.</u>	<u>Date</u>	<u>Stage of Development</u>	<u>Intensity Characteristic</u>
1	5 Nov 69	mature, not occluded	deepening rapidly
2	14 Nov 69	almost occluded	filling slowly
3	8 Dec 69	very weak	filling slowly
4	11 Dec 69	becoming occluded	deepening
5	3 May 71	occluded	deepening
6	8 May 71	very weak	deepening slowly
7	30 Dec 71	mature, not occluded	deepening slowly
8	2 Apr 70	occluded	deepening

C. Methods of Analysis

The 35-mm films of the PPI displays were placed in a Richardson viewer, thus allowing the nature and evolution of the storm's precipitation pattern to be observed. At approximately one half hour intervals, instantaneous tracings, such as that shown in Figure 4, were made of the entire PPI at all intensity levels. These were used, along with direct viewing of the films, to track identifiable precipitation features in time. From these tracks, the speed, direction of motion, orientation, and evolution of the precipitation areas were determined. The tracks were determined by tracing the area at the intensity level that was found to best define the area. Although the determination of this level is necessarily subjective (at least at present), observers with experience in interpreting quantitative radar data would usually agree on the choice of level for any particular area. It was found that for a given storm the same level would serve to identify or define all of the larger mesoscale features, i.e., the LMSA's and bands.

Hourly precipitation data for New England and New York were used to supplement the radar data in determining the character and extent of the heavy rain and to determine the extent of the light rain which did not meet the radar's intensity threshold. For each storm, the time of the beginning of light and of heavy rain were plotted for all stations, thus allowing the advancement of these rain areas to be determined as well as their extent. For the first two storms, the hourly rainfall amounts were plotted in the form of histograms and used, but with only partial success, to track mesoscale precipitation areas that moved into

or out of radar range. The procedure was to compare hourly rainfall maxima with the extrapolated paths of the precipitation areas.

Traces from the high-resolution rain gauges were compared to the tracks of precipitation areas in order to identify features of the gauge trace with the different precipitation areas that were tracked. In this manner the gauge and radar data were compared to insure consistency.

Next the vertical extent of the mesoscale precipitation areas was determined. The tops were determined from the films of the RHI displays. The bases were assumed to be at one km.

Upper level winds for the storms were determined from soundings from the four nearest radiosonde stations. Because the mesoscale precipitation areas of the storms were so close together in time and space, and because it was found that the winds at a given level, in most cases, did not change drastically during the 12-hour period between soundings, one set of winds was determined for comparison with all of the mesoscale features of a given storm. Simple time and space averaging were used to determine these winds.

The mesoscale area motions were compared to the wind field, particularly to the 700 mb wind and to the wind at the center of vertical development of the mesoscale precipitation areas. It was then determined how these two levels were related to the level where the wind most nearly approximated the velocity of the mesoscale precipitation features. The movements of the mesoscale features were also compared to the movement of the cyclone itself. The comparisons consisted of

simply finding the difference between the respective speeds and directions. In order to test the findings of Elliott and Hovind (1964), the orientations of the precipitation areas were compared to the vertical wind shear between the upper regions of the precipitation areas and the adjacent layer above.

III. DESCRIPTIONS OF INDIVIDUAL STORMS

A. Explanation of Figures and Tables

In this chapter the synoptic situation, synoptice scale precipitation, and mesoscale precipitation of the eight storms are discussed. Several figures and tables, in common to the corresponding eight sections, require explanatory remarks. To avoid repetition, these remarks are presented here.

The symbols S, D, and O are used in tables to represent the speed, direction, and orientation of the mesoscale precipitation areas. The orientation is defined as being to the right of the direction of forward motion, while the direction is taken as the direction from which the area is moving. S_{xxx} and D_{xxx} denote the speed and direction of the wind at xxx mb, and S_c and D_c represent the speed and direction of movement of the cyclone. The expression $(D-O)-90^\circ$ is a measure of how close the precipitation area comes to moving in a direction perpendicular to its orientation.

PPI presentations of the precipitation patterns are given for each storm. For ease of interpretation, only four intensity levels are represented in the figures. Thus higher levels, representing higher rainfall rates, were omitted in many cases. Thin and heavy lines denote the thresholds of the first two levels, while the next two levels are depicted by hatching and shading, respectively. The two outer circles represent ranges of 100 and 200 km, while the next smaller circle (20-25 km radius) outlines the area that is effectively obscured by ground clutter.

B. Storm of 5 November 1969

1. Synoptic Situation. A coastal cyclone was moving northward towards New England, as shown in Figure 1. The system, which was deepening rapidly, was associated with a closed circulation which extended above 500 mb. At 1227 EST, the time of the most marked banded precipitation structure, the cyclone was still south of Nantucket, Massachusetts. At this time the warm front, which was oriented approximately in a N-S direction, was located just east of Portland, Maine, and across Cape Cod. The movement of the cyclone, which was virtually constant during the period of radar observations, was from 155 degrees at a speed of 15 m/sec. The system later slowed drastically, however, and caused precipitation in New England during the day on 6 November. The region of the storm that was observed by the radar is depicted in Figure 2.

2. The general precipitation pattern. An extensive area of precipitation preceded the cyclone as it approached New England. Hourly precipitation data for New England stations indicates that the rain was continuous for at least 12 hours and for as long as 20 hours for some stations. Rainfall accumulations were typically one to two inches, though values both above and below this range were experienced. Maine experienced larger rainfall amounts than the rest of New England, which suggests the importance of the warm front as a precipitation mechanism.

Light rain began in the northern parts of Vermont, New Hampshire, and Maine at about 0100 EST, apparently the result of a terrain

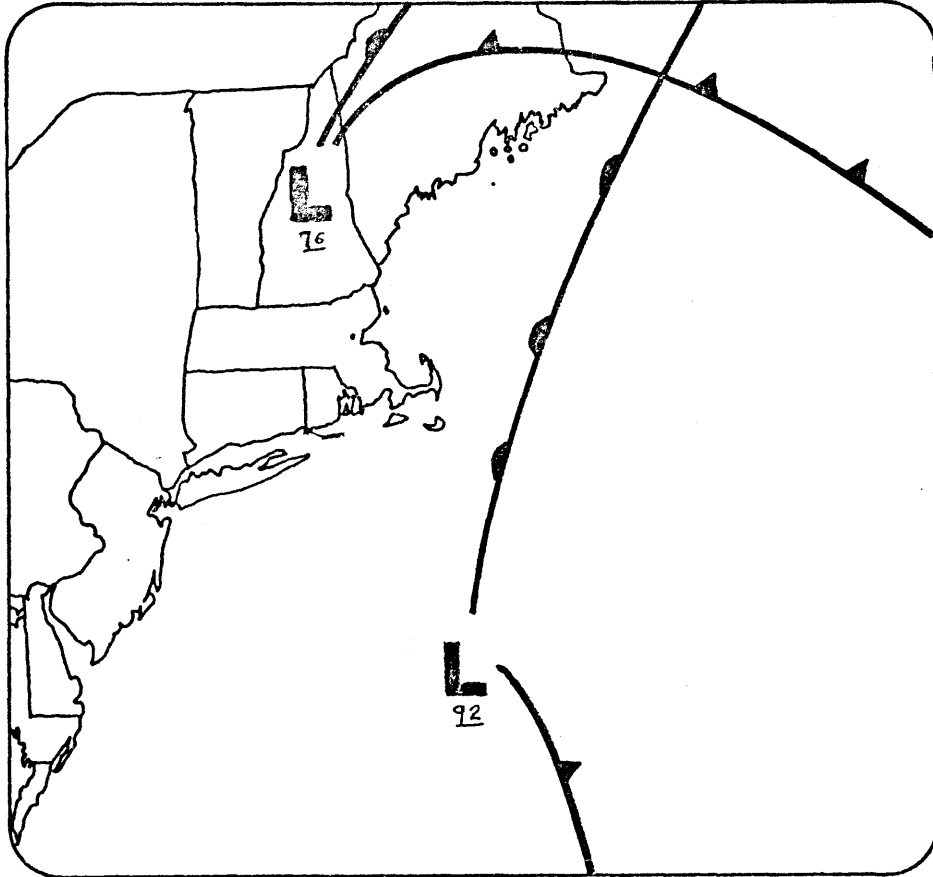


Figure 1. The synoptic situation on 5 November 1969. The cyclone is shown at 0700 and 1900 EST.

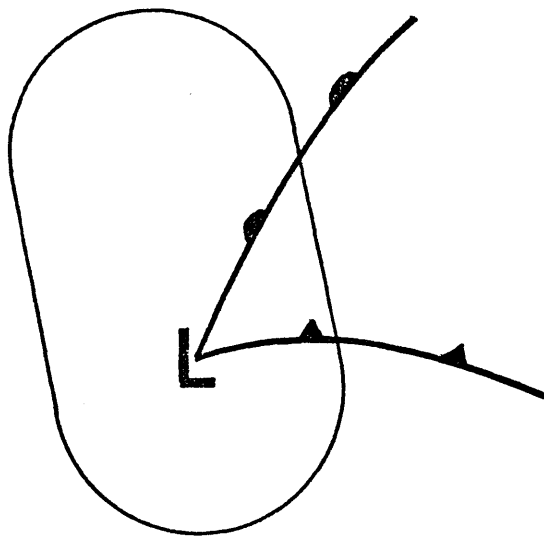


Figure 2. The part of the 5 November storm that was observed by radar. Radar range is 200 km.

influence. At about 0200 EST, light rain, which is believed to have been caused by the warm front, commenced along the coast of Maine. Southern New England first experienced light rain at about 0300-0500 EST, after which the rain moved steadily northward. The northern edge of this light precipitation preceded the cyclone by approximately 500 km. Its intensity varied from .01 to .05 inches per hour, and it lasted for about 4-6 hours, depending on the location. The light rain was followed by a period of heavier rain, during which hourly precipitation amounts generally exceeded .1 inch and occasionally reached .3 inches. This heavy rain reached New England at about 08-0900 EST, preceding the cyclone by about 250 km. For most areas the heavy rain lasted for about five hours. It ended with the passage of the storm center. The east-west extent of the heavy rain was well over 400 km, reaching from the eastern edge of Maine to the Hudson River.

3. The mesoscale precipitation pattern. Most of the heavy rain was observed by the radar as it moved through New England. That which was observed consisted of seven rather distinct LMSA's, which were spawned as the cyclone and accompanying warm front moved northward. Each area, in turn, moved toward the northwest as it developed and dissipated. These areas are designated A through F. Their paths are depicted in Figure 3.

At 1227 EST, all seven areas existed, as shown in Figure 4. At this time, four bands can be observed. Band E-F formed because area F became elongated (part of the area moved out of radar range) and area E moved up below area F. The band was continuous, but disappeared

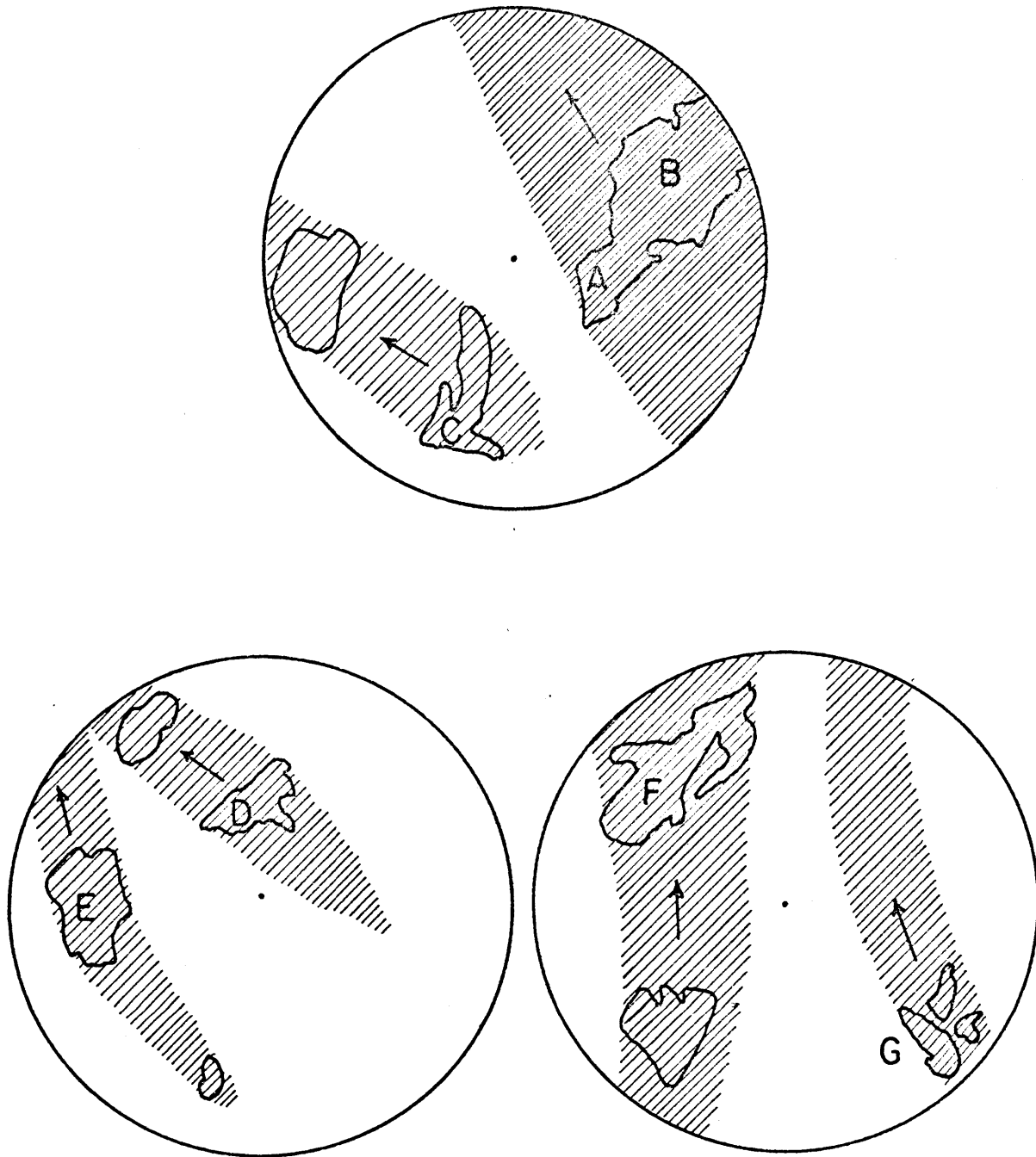


Figure 3. The paths of the mesoscale precipitation features of the 5 November storm. The features are shown at intensity level 4 (rainfall rate ≥ 5 mm/hr), which was also used to determine their paths. The areas are labeled at 1227 EST. Areas C, D, E, and F are also shown at 1518, 1346, 1031, and 0947 EST, respectively. Arrows indicate the directions of motion. The circle radius is 200 km.

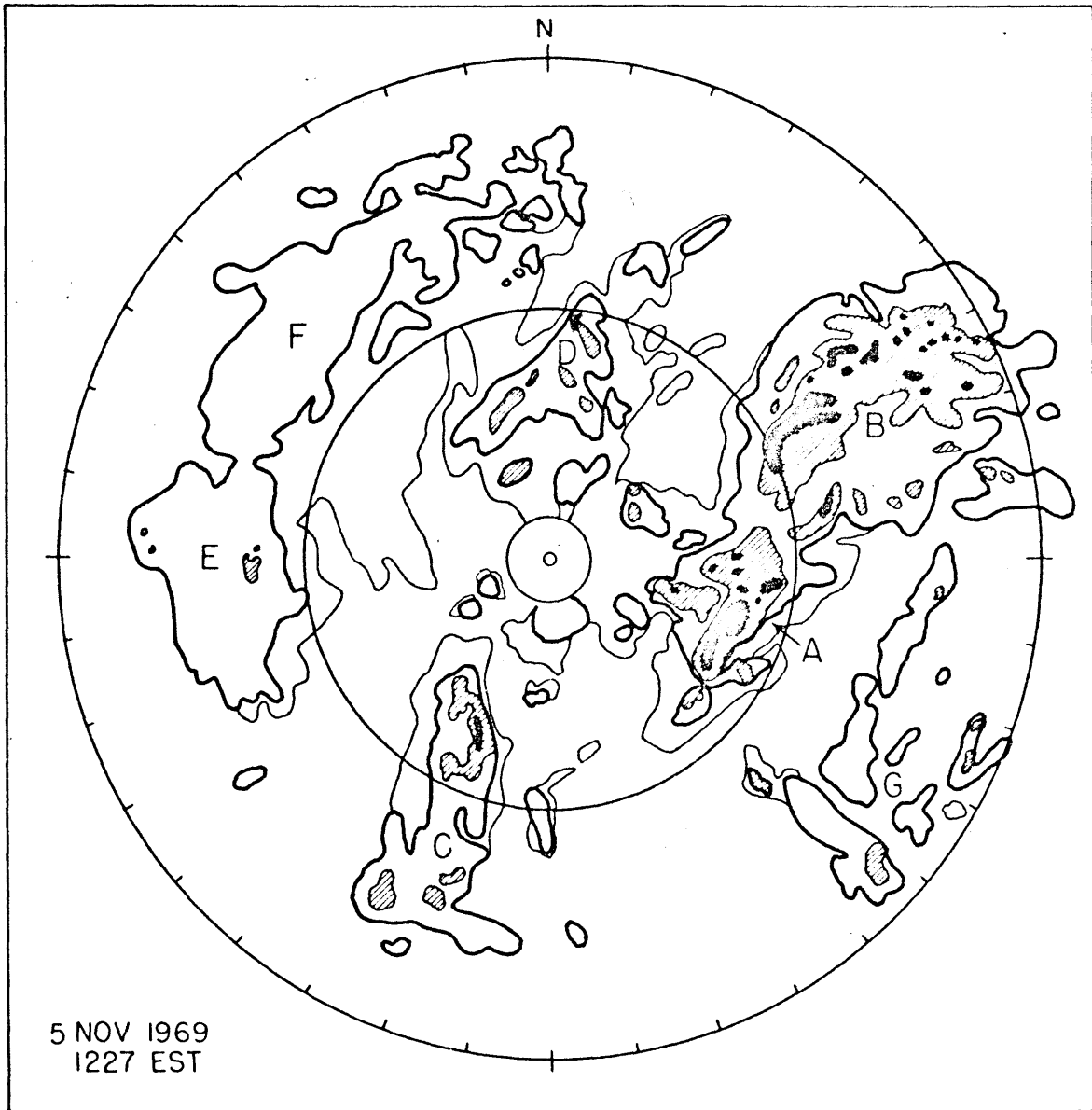


Figure 4. Precipitation pattern of the storm of 5 November 1969. Areas A through G are labeled. Intensity levels 3-6 are depicted. Threshold values correspond to rainfall rates of approximately 3, 5, 9, and 17 mm/hr. The radius of the outer circle is 200 km.

when the two areas moved out of view of the radar. Band C-D formed when area C lined up with area D. This band was never continuous. It broke up because the two areas, which had slightly different speeds and directions of motion, drifted apart, and because area C became irregular in shape as area D began to dissipate. Band A-B formed as areas A and B became more elongated. These two areas, though fairly distinct, stayed together during their entire lifetime as viewed by the radar. The band was the longest lived of the bands, existing until it finally moved northward off the radar scope. Band G formed to the southeast of band A-B and was composed of area G and a thin band of small areas extending to the northeast. It dissolved because the thin band became remote from area G and merged with area B.

4. Discussion. Analysis of the mesoscale precipitation patterns yields several interesting results. Several parameters describing the behavior of the mesoscale areas are listed in Table 4.

The orientations of the areas are strikingly similar. The orientations of the four northermost areas (areas A-B, D, F, and G) were within a 14-degree interval. The other two areas differed in orientation by 14 degrees, also, but the two 14-degree intervals were about 30° apart.

The spacing of the areas is also notable. The distances between the centerlines (axes) of the areas ranged from 65 to 115 km, with an average of 90 km. If the distances are measured parallel to the velocity of the "following" area, then the separations ranged from 75 to 117 km and averaged 97 km. These correspond to time separations of

Table 4. Mesoscale precipitation area statistics for the storm of 5 November 1969. See section A, Chapter III for definition of symbols.

<u>Parameter (Units)</u>		<u>Area</u> <u>A-B</u>	<u>Area</u> <u>C</u>	<u>Area</u> <u>D</u>	<u>Area</u> <u>E</u>	<u>Area</u> <u>F</u>	<u>Area</u> <u>G</u>	<u>Average</u>	<u>Range</u>
S	(m/s)	21	20	24	25	20	29	23	9
D	(deg)	149	126	132	165	175	158	151	49
O	(deg)	36	12	41	358	37	27	25	43
S-S ₇₀₀	(m/s)	8	7	11	12	7	16	10	9
D-D ₇₀₀	(deg)	-3	-26	-20	13	23	6	-1	49
S-S _c	(m/s)	6	5	9	10	5	14	8	9
D-D _c	(deg)	-6	-29	-23	10	20	3	-4	49
D-O-90°	(deg)	23	24	1	77	48	41	36	76
Time Tracked by Radar	(hrs)	5	4	3	2½	3	3	3½	2½

0.74 hours, 1.5 hours, and 1.2 hours. These areas did not pass over precisely the same regions because they had somewhat different directions of movement. But they did pass over many of the same regions, since their paths intersected at relatively small angles.

The most clear-cut case of recursion of precipitation areas involved areas E and F. Area E followed area F northward over western Massachusetts, but it was moving faster than area F so it eventually merged with it. Analysis of hourly rainfall data revealed that a mesoscale area had preceded area F, before radar coverage began. Thus three areas moved over the same region.

The average direction of motion of the areas was very close to the 700-mb wind direction, closer than to the direction of the wind at any other level. The speed of the areas, however, was much greater than the wind speed at 700 mb. It agreed best with the winds at the 550-mb level. The rain areas were found to have a vertical extent of approximately 7 km, which is close to 400 mb. Thus the 550 mb level was somewhat higher than the midpoint of the vertical development of the mesoscale areas.

The precipitation areas were tracked by radar for an average of three and one half hours. However, several of the areas existed at the commencement of radar coverage, and some of the areas continued to exist after moving out of range of the radar. Thus the lifetimes are greater than that which is indicated by the $3\frac{1}{2}$ -hour figure. Area A-B, for example, was determined to have existed as a mesoscale feature for at least six hours.

During much of the time that the mesoscale areas existed within radar range there seemed to be a slight banded appearance. This is because the areas were somewhat elongated and because the lighter rain, which barely reached the radar's threshold, tended to line up with the mesoscale areas in some cases. The bands, however, were not obvious until approximately 1230 EST. Even then, the LMSA's were the more basic mesoscale entity. Of the rain which was of sufficient intensity to be observed by the radar, relatively little occurred outside of the LMSA's.

All of the LMSA's were within the size range of LMSA's as defined by Austin and Houze (1972). Area A-B, if considered as one area, was one and one third times as large as the upper limit of that definition.

C. Storm of 14 November 1969

1. Synoptic situation. A coastal cyclone was approaching New England from the south-southwest, as shown in Figure 5. The cyclone was not associated with a closed circulation at 850 mb or above. It filled slightly during the 12 hours depicted by the chart, and by the end of this period it had become occluded. At the time of the maximum precipitation activity, however, the storm was located well south of New England and was not yet occluded. The accompanying warm front maintained a relatively fixed position with respect to the cyclone center, which was found to be moving from 203 degrees with a speed of 14 m/sec. Figure 6 depicts the part of the storm that was surveyed by the radar.

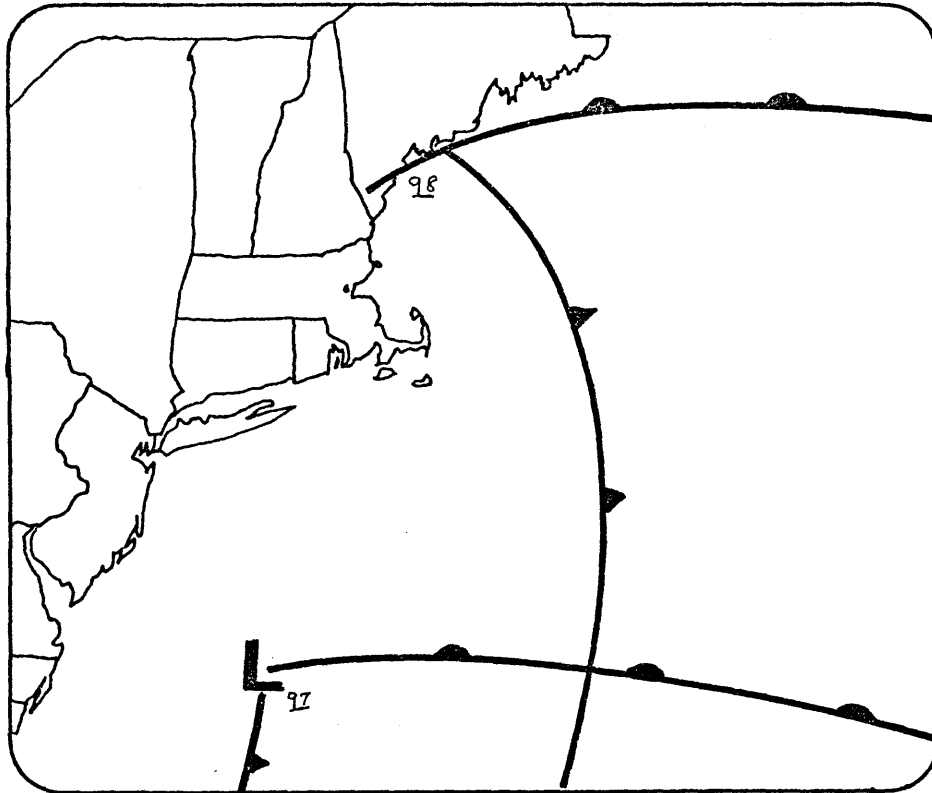


Figure 5. The synoptic situation on 14 November 1969. The cyclone is shown at 0700 and 1900 EST.

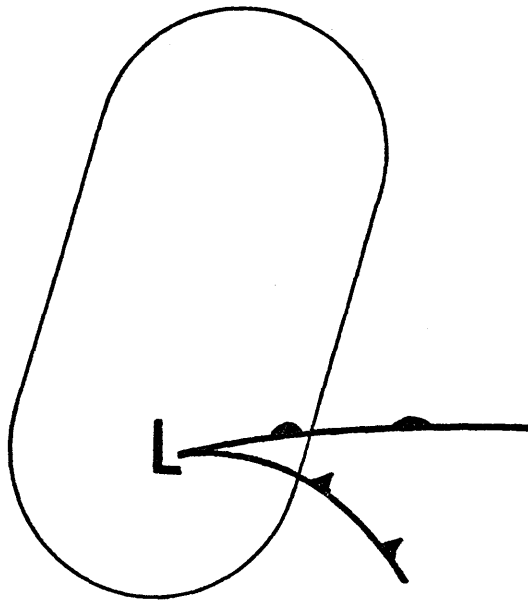


Figure 6. The part of the 14 November storm that was observed by radar. Radar range is 200 km.

2. The general precipitation pattern. Most New England stations received 7 or 8 hours of continuous precipitation as the storm approached. Total amounts were not large and were quite variable, ranging from .15 to .60 inches in Massachusetts alone.

Light rain began in southern New England at about 0400 EST, approximately 450 km ahead of the warm front. Precipitation began early in the valley along the New York-Vermont border (possibly the result of some local terrain-related convergence phenomenon), but in general the light rain moved steadily northward. This rain, whose typical intensity was .01 to .03 inches, lasted for about two hours at most stations.

A belt of heavier rain followed the light rain, beginning at about 0600 EST in southern New England. Hourly precipitation amounts ranged from .06 inches to more than .2 inches, but values near .1 inch were typical. The heavy rain lasted for somewhat less than 3 hours, on the average. The front edge of the heavy rain belt preceded the cyclone by about 350 km, while the trailing edge was about 200 km ahead of the cyclone center.

The heavy rain belt extended eastward at least through most of Maine, but no farther westward than the Hudson River. The stations in extreme northern Vermont, New Hampshire, and Maine did not encounter such an intense and sharply defined precipitation belt as that experienced by the rest of New England, though the cyclone continued its northward progress.

The belt of heavy rain was followed by a period of light rain

that lasted for about two hours. At 1400 EST, rain had ended in all parts of Massachusetts, but the cyclone center was just entering the southeastern part of that state.

3. The mesoscale precipitation pattern. The region of heavy rain was observed by the radar and found to be composed of several large mesoscale areas which formed into bands. The paths of these areas are illustrated in Figure 7. At the beginning of radar coverage, about 0800 EST, four large mesoscale areas were observed. All were moving northward. Area A was the most intense and was in the latest stage of development, while area B, which followed area A, was just beginning to grow. Area E, the least intense, was just beginning to develop. The last area was the largest of the four, and from it areas C and D developed.

At 0900 EST the banded structure of the precipitation pattern, shown in Figure 8a, was very apparent. Areas A and B were elongated, and two additional bands had formed. Area D became elongated and merged with area E to form band 1. Area C, still composed of two parts, lined up with a less distinct and un-named area to form band 2.

At 1000 EST the banded structure was equally striking, as can be seen in Figure 8b. Area A had dissipated, and band 3 had formed from an elongated area B and the remains of band 1 (area E had either dissipated or moved out of radar range). Band 2 was over the radar site and was more elongated because of the addition of several smaller areas. Both bands broke up during the next hour. From then on, the precipitation consisted of small, disorganized areas of relatively light rain.

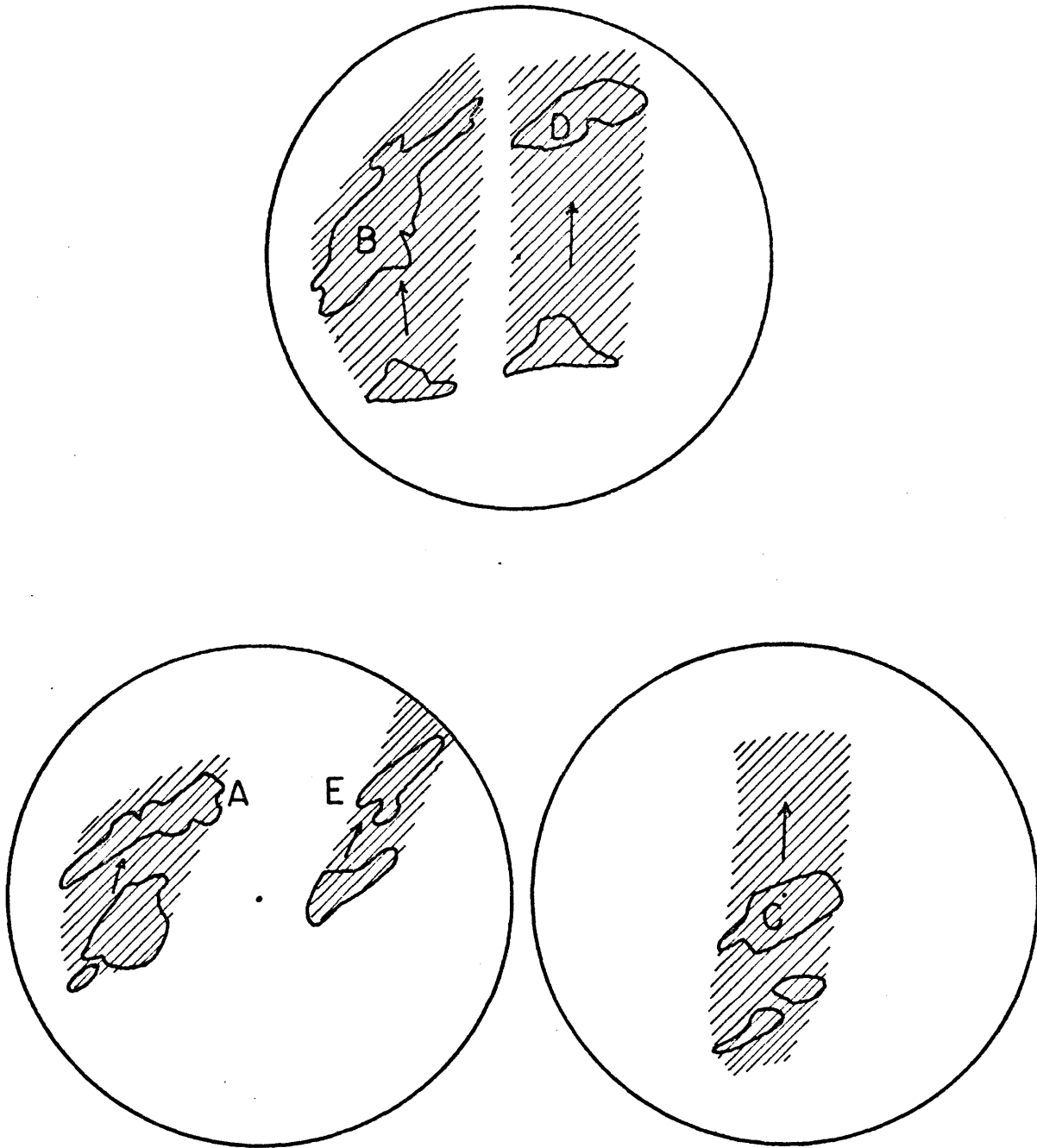


Figure 7. The paths of the mesoscale precipitation features of the 14 November storm. The features are shown at intensity level 4 (rainfall rate $\geq 5\text{mm/hr}$), which was also used to determine their paths. Areas B, C, and D are labeled at 0959 EST. Areas A and E are labeled at 0900 EST. Areas A, B, D, and E are also shown at 0804 EST, the beginning of radar coverage. Area C is shown additionally at 0900 EST. Arrows indicate the directions of motion. The circle radius is 200 km.

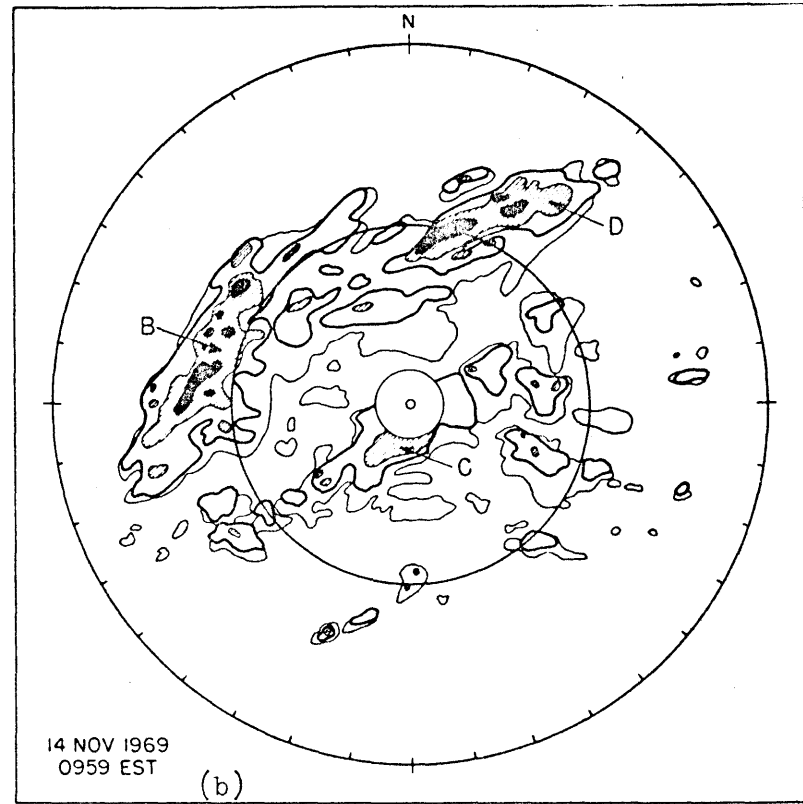
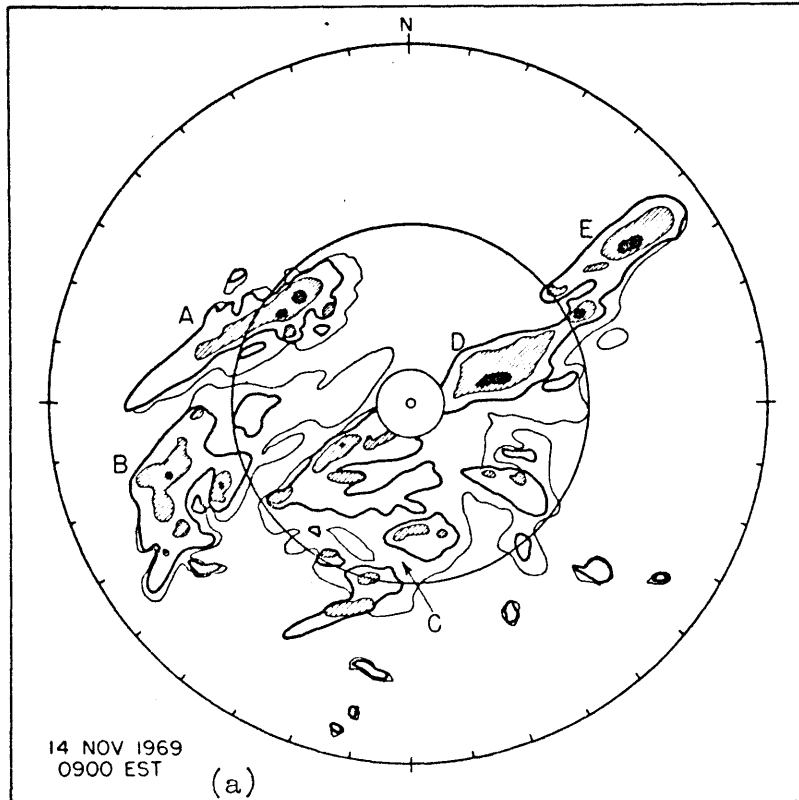


Figure 8 (a), (b). Precipitation patterns of the storm of 14 November 1969. Intensity levels 3-6 are depicted. Threshold values correspond to rainfall rates of approximately 3, 5, 9, and 17 mm/hr. The radius of the outer circle is 200 km. In (a) areas A through E are labeled. Band 1 lies across the radar site with band 2 to the south. In (b) areas B, C, and D are labeled. Band 3 (to the north) and band 2 (now across the radar site) are apparent.

4. Discussion. The banded nature of the precipitation pattern is its most striking characteristic. The bands are clearly a more integral part of the precipitation pattern than was the case for the 5 November storm. However, the LMSA's still seem to be the more basic mesoscale entity, since they transcend the banded structure. Area B, for example, existed before band 3 was formed, and was observed to exist after the band had broken up. There is somewhat more precipitation of moderate intensity that is not within the LMSA's than was the case for the previous storm. Most of this rain, however, lined up with the bands. The areas of all the LMSA's are within the limits of the definition proposed by Austin and Houze (1972).

In Table 5, several characteristics of the precipitation areas are tabulated. It can be seen that the speeds, directions, and orientations of the areas were very similar. The speed of the areas was found to agree best with the 700 mb winds, though the directions of motion of the areas were approximated better by the winds in the 800-750 mb layer. The maximum vertical extent of the precipitation was about 6 km, which was just above 500 mb.

There are two instances of one precipitation area following another over nearly the same regions. Area B followed area A, trailing by about 60 km or .93 hours. Band 2 follows band 1, maintaining a separate distance of about 85 km (1.1 hours).

Table 5. Mesoscale precipitation area statistics for the storm of 14 November 1969. See section A, Chapter III for definition of symbols.

Parameter (Units)	Area	Area	Area	Area	Area	Average	Range
	A	B	C	D	E		
S (m/s)	25	18	21	24	23	22	7
D (deg)	198	172	186	182	205	188	33
O (deg)	56	40	56	63	54	54	23
S-S ₇₀₀ (m/s)	2	-5	-2	1	0	-1	7
D-D ₇₀₀ (deg)	-3	-29	-15	-19	4	-13	33
S-S _c (m/s)	11	4	7	10	9	8	7
D-D _c (deg)	-5	-31	-17	-21	2	-15	33
D-O-90° (deg)	52	42	40	29	61	44	32
Time Tracked by Radar (hrs)	1½	3½	3½	2½	1½	2½	2

D. Storm of 8 December 1969

1. Synoptic situation. A weak cyclone was approaching New England from the southwest at a speed of about 8 m/sec. The circulation was very weak at the surface and entirely absent aloft. The system was filling slowly, as is indicated in Figure 9. Figure 10 depicts the section of the storm that was observed by the radar.

2. The general precipitation pattern. The precipitation caused by the approaching system was virtually continuous for about 30 hours over most New England stations. Total rainfall amounts, depicted in Figure 11, were small considering the rainfall duration.

The first light rain began in southeastern New England at about 2100 EST on 7 December. At this time the leading edge of the light rain was 450 km ahead (northeast) of the low center and over 300 km north of the warm front. The rain spread gradually toward the east-northeast, more in agreement with the movement of the low center than with the movement of the warm front. Rainfall rates ranged from .01 to .07 inches per hour. The light rain lasted for two to four hours, depending on the location.

The first heavy rain began in eastern New England at about 2300 EST on the 7th. This rain preceded to move eastward for 75 to 100 km before dissipating. Similarly, several other areas of heavy rain developed and dissipated while moving over limited regions of New England. The advancement of the three important heavy rain areas is depicted in Figure 12. The heavy rain areas were separated by time intervals of two to ten hours for a given region. The situation is in contrast to

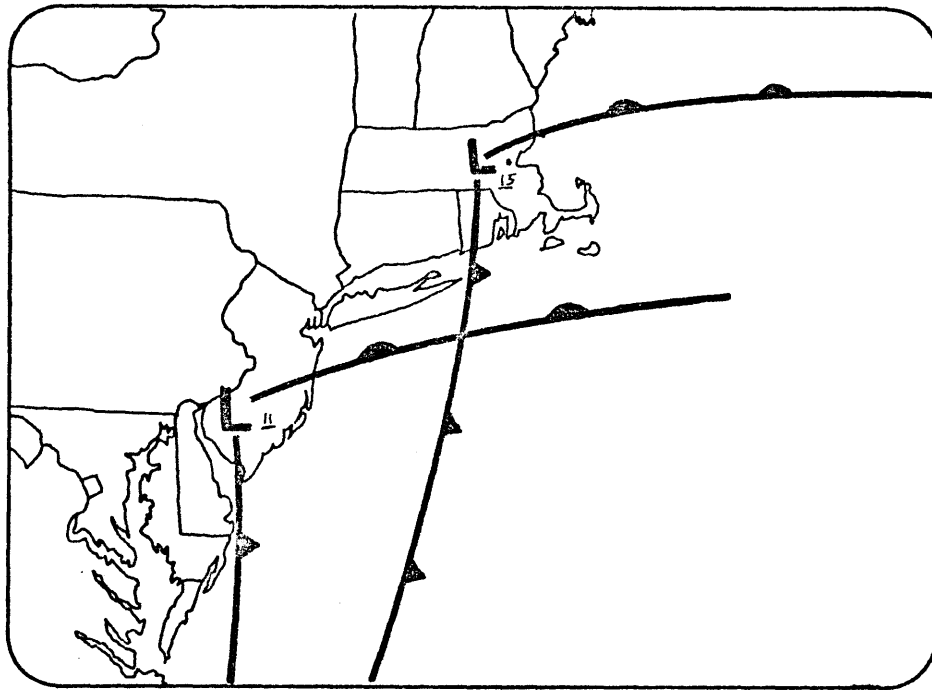


Figure 9. The synoptic situation on 8 December 1969. The cyclone is shown at 0700 and 1900 EST.

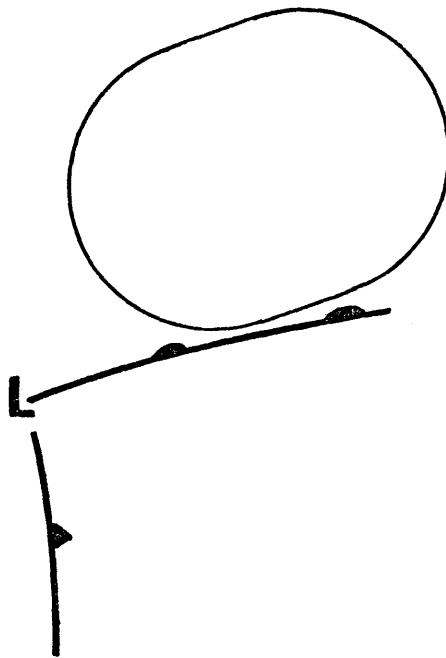


Figure 10. The part of the 8 December storm that was observed by radar. Radar range is 200 km.

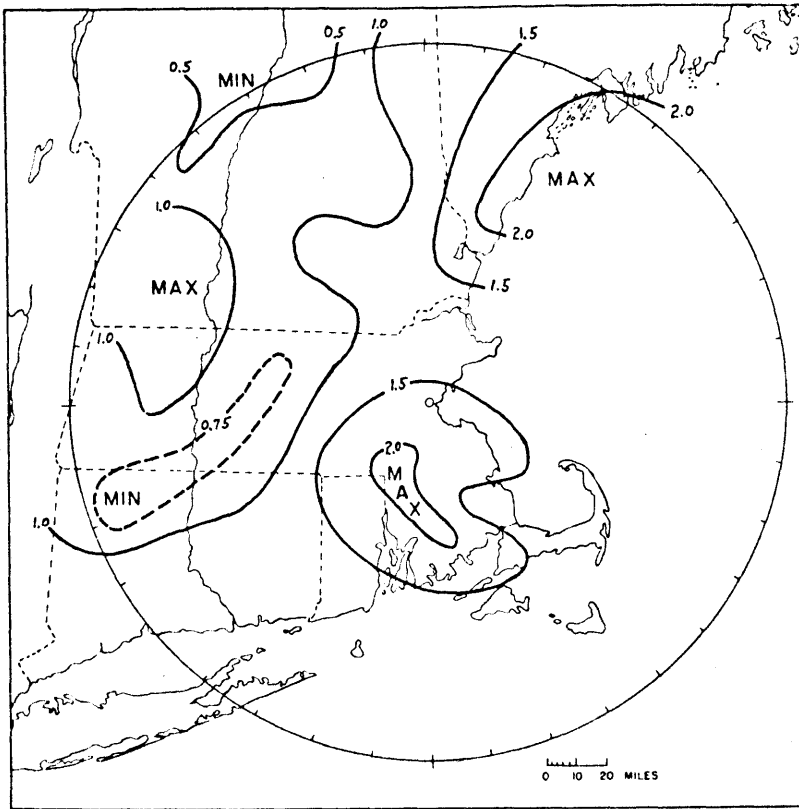


Figure 11. Isohyetal map for the storm of 8 December 1969. Contours are labeled in inches.

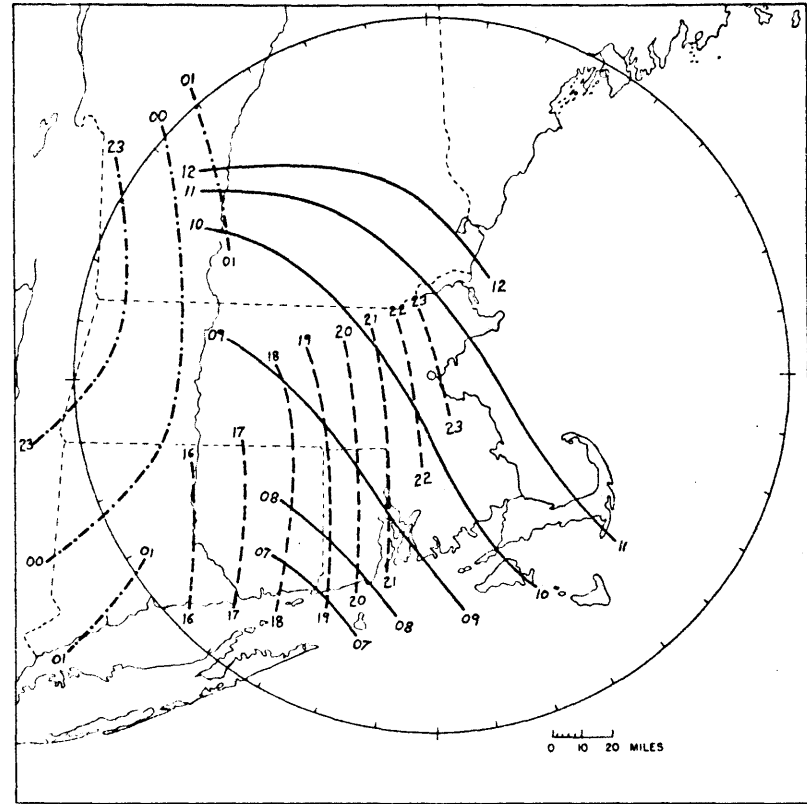


Figure 12. Advancement of three separate areas of heavy rain during the storm of 8 December 1969. The contours represent the position of the front edge of the heavy rain, and are labeled in hours, EST. The heavy rain that was observed by the radar is represented by the solid lines.

the first two storms, in which the heavy rain was concentrated into precipitation areas which were very close to each other in time and space and were organized into a single belt of heavy rain.

All of the heavy rain that occurred within a given region did so within a 20-hour period. Some stations accounted for all of their heavy rain in a shorter period because they did not experience one or more of the mesoscale precipitation areas that were experienced by other stations. When the last heavy rain ended at Boston, at about 0200 on the 9th, the cyclone center was 50 km to the west. The heavy rain was followed by a period of light rain which lasted for at least two hours.

3. The mesoscale precipitation pattern. Only one of the major areas of heavy rain was observed by radar. At the beginning of radar coverage, it consisted of three long, thin, discontinuous precipitation bands, shown in Figure 13a. Areas A, B, and C are identified, all of which moved toward the northeast. The lower band developed into the band of intense precipitation seen in Figure 13b. The top part of the band, which later broke off from the rest of the band, is termed area D. The center of the band, with its precipitation maximum, is termed area E for the purpose of tracking. Area F developed along the right forward section of area E as the latter was dissipating. They had slightly different directions of motion. Area G formed from the end part of the band, and dissipated quite rapidly, while area H developed separately. Area I, which was much later in time than the other areas, was just becoming a LMSA when radar coverage was discontinued. The paths of the areas are shown in Figure 14.

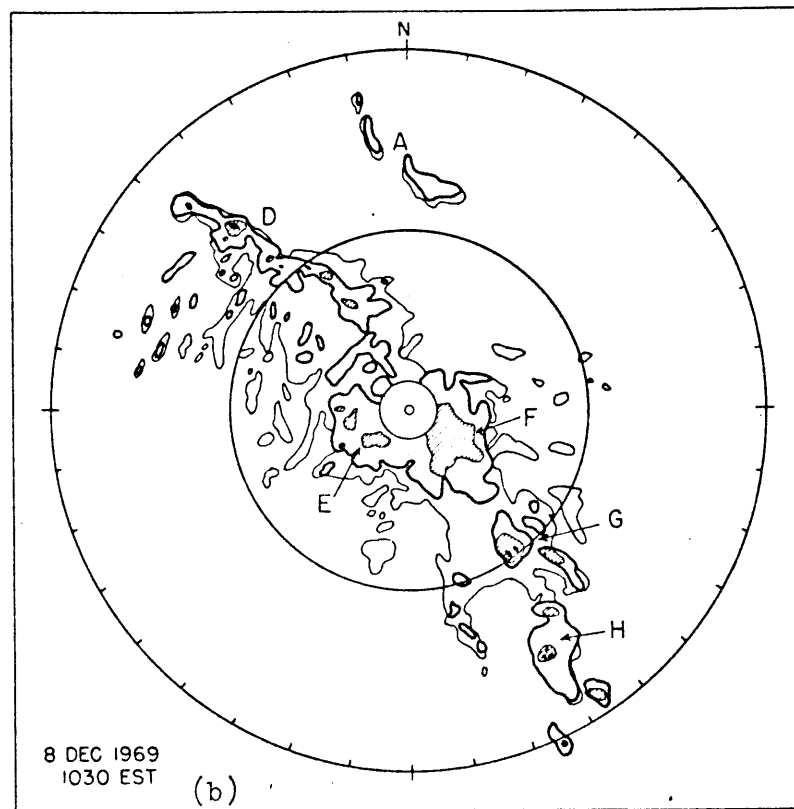
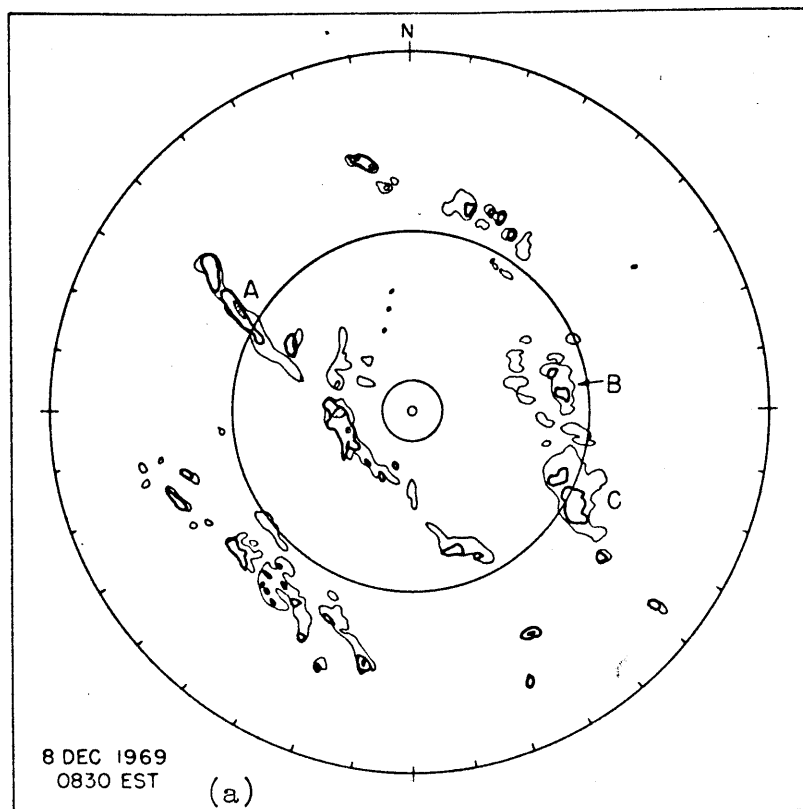


Figure 13 (a), (b). Precipitation patterns of the storm of 8 December 1969. Intensity levels 3-6 are depicted. Threshold values correspond to rainfall rates of approximately 3, 5, 9, and 17 mm/hr. The radius of the outer circle is 200 km. In (a) three bands are apparent. Areas A, B, and C are labeled. In (b) one large band is seen. Areas A, D, E, F, G, and H are labeled.

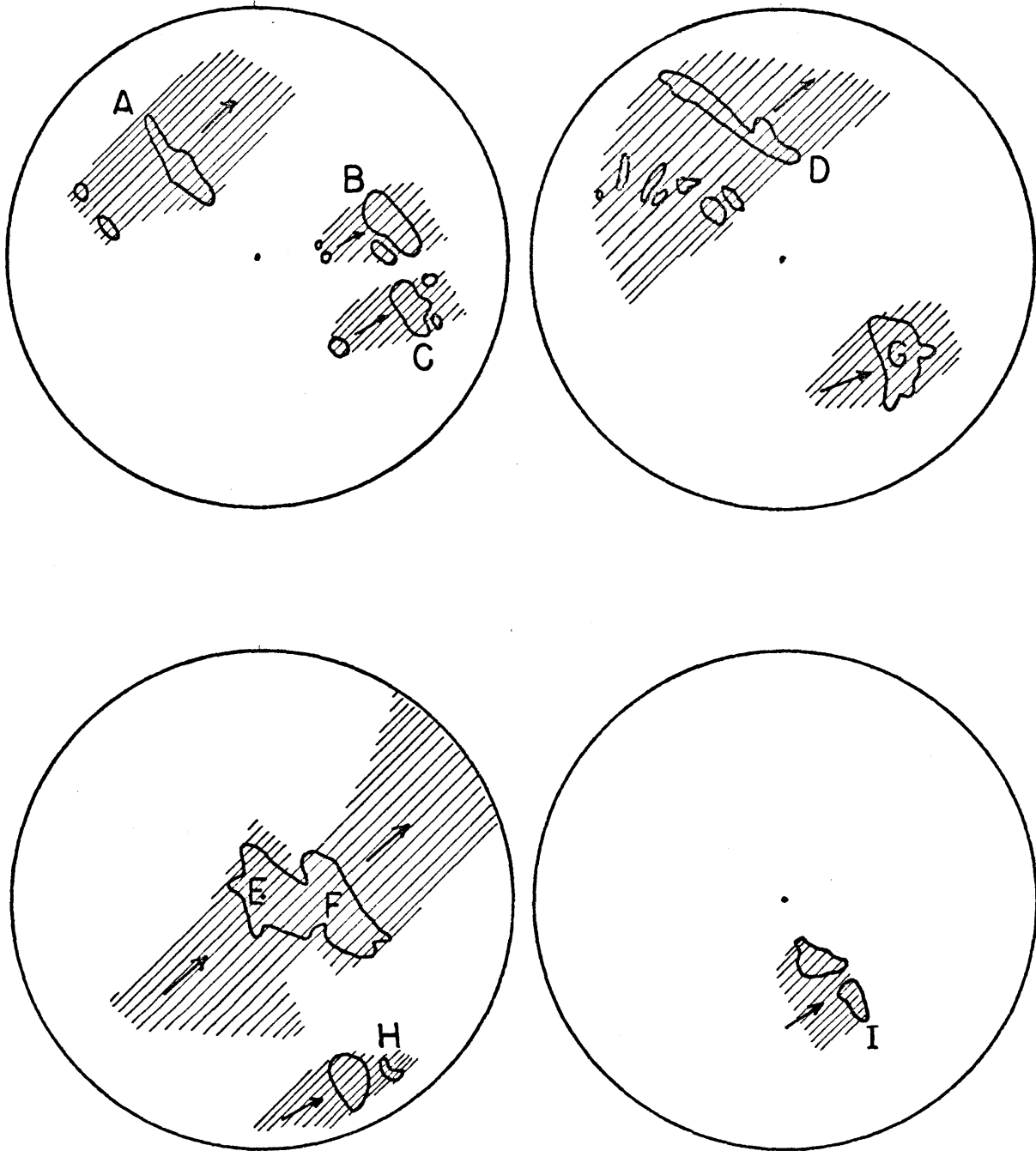


Figure 14. The paths of the mesoscale precipitation features of the 8 December storm. The features are shown at intensity level 4 (rainfall rate ≥ 5 mm/hr), which was also used to determine their paths. Areas A, B, and C are labeled at 0900 EST. Areas D through H are labeled at 1100, and area I is labeled at 1500 EST. Areas A, B, and C are also shown at 0800 EST. Areas D and H are shown additionally at 1000 and 1030 EST, respectively. Arrows indicate the directions of motion. The circle radius is 200 km.

Table 6. Mesoscale precipitation area statistics for the storm of 8 December 1969. See section A, Chapter III for definition of symbols.

<u>Parameter (Units)</u>		<u>Area</u>	<u>Area</u>	<u>Area</u>	<u>Area</u>	<u>Area</u>	<u>Area</u>	<u>Area</u>	<u>Area</u>	<u>Area</u>	<u>Average</u>	<u>Range</u>
		A	B	C	D	E	F	G	H	I		
S	(m/s)	18	16	17	17	16	15	17	16	14	16	4
D	(deg)	227	242	239	235	234	238	258	232	236	238	31
O	(deg)	145	139	163	122	142	158	---	155	140	145	41
S-S ₇₀₀	(m/s)	2	0	1	1	0	-1	1	0	-2	00	4
D-D ₇₀₀	(deg)	-7	8	5	1	0	4	24	-2	2	4	31
S-S _c	(m/s)	10	8	9	9	8	7	9	8	6	8	4
D-D _c	(deg)	-8	7	4	0	-1	3	23	-3	1	3	31
D-O-90°	(deg)	-8	13	-14	23	2	-10	---	-13	6	00	31
Time Tracked by Radar	(hrs)	2½	1	1½	2½	2½	3	2	2	1	2	2

4. Discussion. The bandedness of the mesoscale precipitation pattern is quite apparent. Three bands were observed, one of which developed into a very intense band of precipitation. Areas D, E, F, and G seemed to have developed from the band, or at least as part of the band. The band is the primary mesoscale feature.

A striking feature of the precipitation pattern is the existence of a series of tiny bands which are attached and perpendicular to the northern half of the main band. These tiny bands, which can be observed in Figure 13b, were prominent for over two hours.

As for the previous storms, the band or area orientations and directions were remarkably similar, as shown in Table 6. The areas were determined to have moved in very close agreement with the 700 mb wind. Vertical development of the precipitation was to 5 km, or about 550 mb.

The three bands were found to be separated by 125 and 85 km. They therefore were separated by periods of 2.0 and 1.4 hours.

E. Storm of 11 December 1969

1. Synoptic situation. A well-developed cyclone, shown in Figure 15, was moving northward through Virginia, Pennsylvania, and New York. It was occluding and intensifying, the lowest pressure having fallen to approximately 990 mb by 0700 EST. The surface low was associated with a closed low at 850 mb, but a closed circulation at 500 mb was just beginning to develop. The cyclone was moving from 196 degrees at a speed of approximately 13 m/sec. Figure 16 depicts

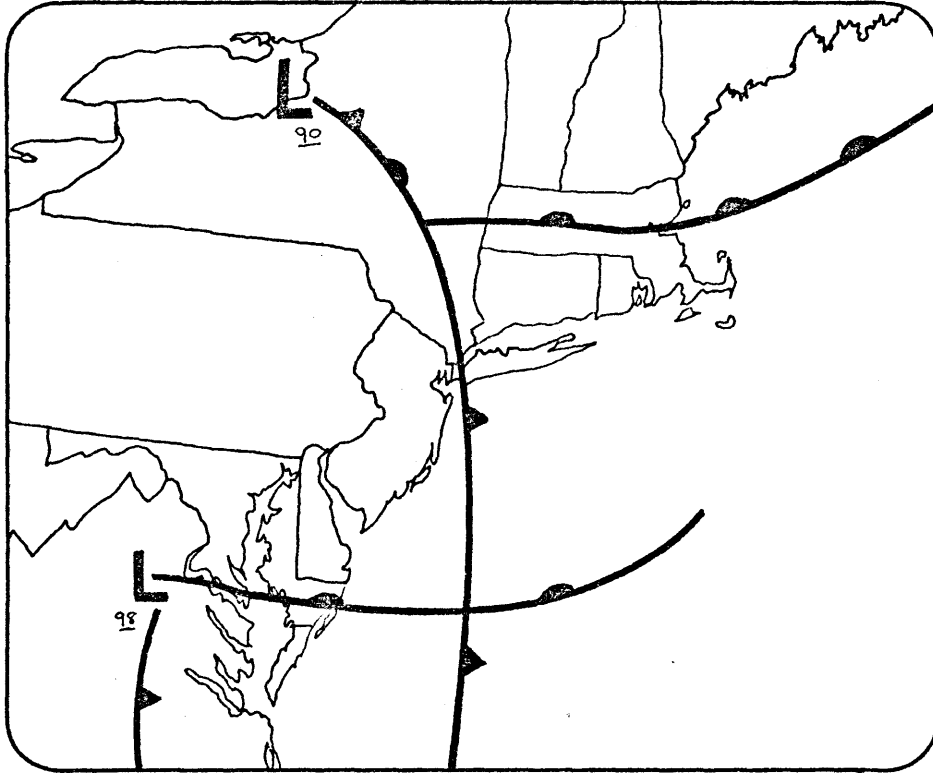


Figure 15. The synoptic situation on 11 December 1969. The cyclone is shown at 1900 EST on the 10th and at 0700 EST on the 11th.

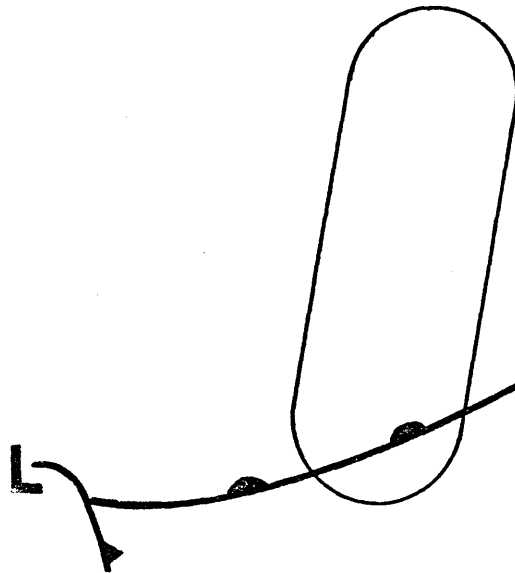


Figure 16. The part of the 11 December storm that was observed by radar. Radar range is 200 km.

the part of the storm that was surveyed by the radar.

2. The general precipitation pattern. Rain fell for approximately 18 hours on the tenth and eleventh of December. Total rainfall amounts were quite variable in space, as shown in Figure 17. Maine experienced smaller amounts of rain because it was farther from the path of the storm. Northern New England received less rain than did southern New England, though each area had the same relationship to the storm's path.

Light rain began by 1600 EST on December in southwestern New England and moved steadily northward. At this time the cyclone center was in Virginia and the warm front was 400 km south of New England. Typical rainfall intensities were .02 to .04 inches per hour, though values up to .06 inches per hour were occasionally experienced. At each location the light rain lasted for about three hours (actually, 2-5 hours) before the onset of the first heavy rain.

The first heavy rain began at about 1900 EST in western Connecticut, at which time the cyclone was 480 km to the southwest and the warm front was 320 km to the south. This rain worked its way north-eastward through most of New England (excluding Maine) before dissipating. At any given location the heavy rain lasted for about two hours. Typical hourly rainfall amounts were between .08 and .15 inches.

The first period of heavy rain was followed by a period of from one to two hours of light rain, after which a second area of heavy rain began to move through New England. This rain took five to six hours to pass over a given station and was characterized by hourly rainfall

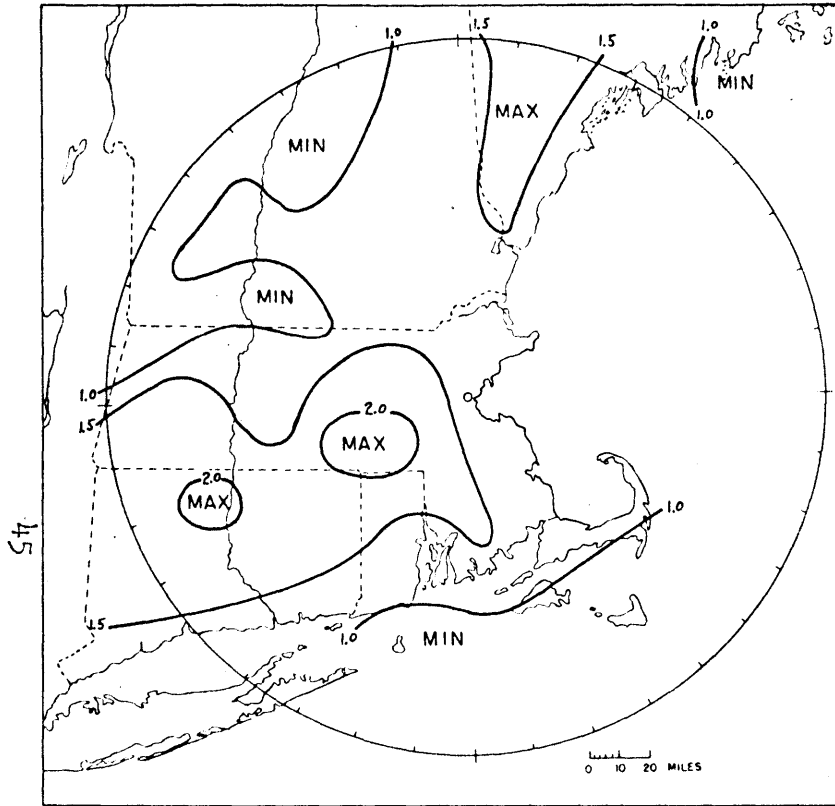


Figure 17. Isohyetal map for the storm of 11 December 1969. Contours are labeled in inches.

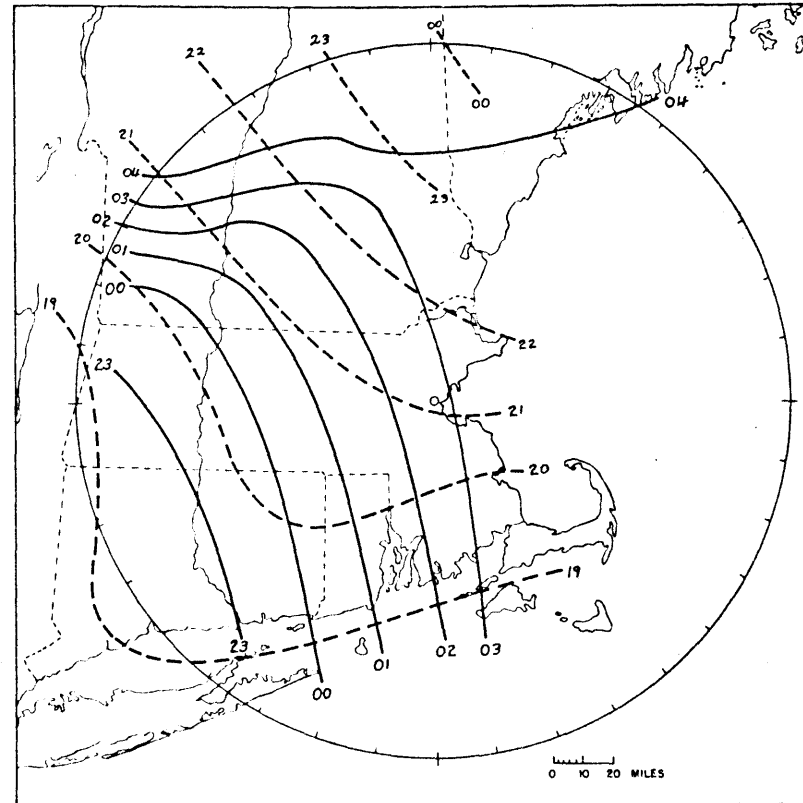


Figure 18. Advancement of two separate areas of heavy rain during the storm of 11 December 1969. The contours represent the position of the front edge of the heavy rain, and are labeled in hours, EST.

amounts of .09 to .4 inches. For most of New England, this was the last heavy rain that occurred, though Maine experienced other periods of heavy rain. The heavy rain ended in the immediate vicinity of the warm front, and was followed by a four or five hour period of light rain. The advancement of the two areas of heavy rain is depicted in Figure 18.

3. The mesoscale precipitation pattern. Radar observations were taken only during the period in which the second heavy rain area existed. They showed that this area was composed of three bands, each moving toward the north-northeast. The bands followed each other so closely that they were not resolved in the hourly precipitation data. Band 1 formed at the edge of the 200-km radar circle, while band 2 formed directly behind band 1 and well within radar range. See Figure 19a. Both dissipated shortly after passing over Boston. Band 3 followed band 2, as shown in Figure 19b, but had a somewhat larger velocity component toward the north. It did not dissipate near Boston, but continued to move northward until it went out of range of the radar. The paths of the bands are depicted in Figure 20.

The bands did not extend northwestward into extreme northern Vermont or New Hampshire. Also, they did not seem to extend southeastward outside of the radar circle, although this could not be definitely determined.

4. Discussion. The bands are the basic mesoscale entities of the mesoscale precipitation pattern for this storm. In general, the band center contained the most intense precipitation, while lighter

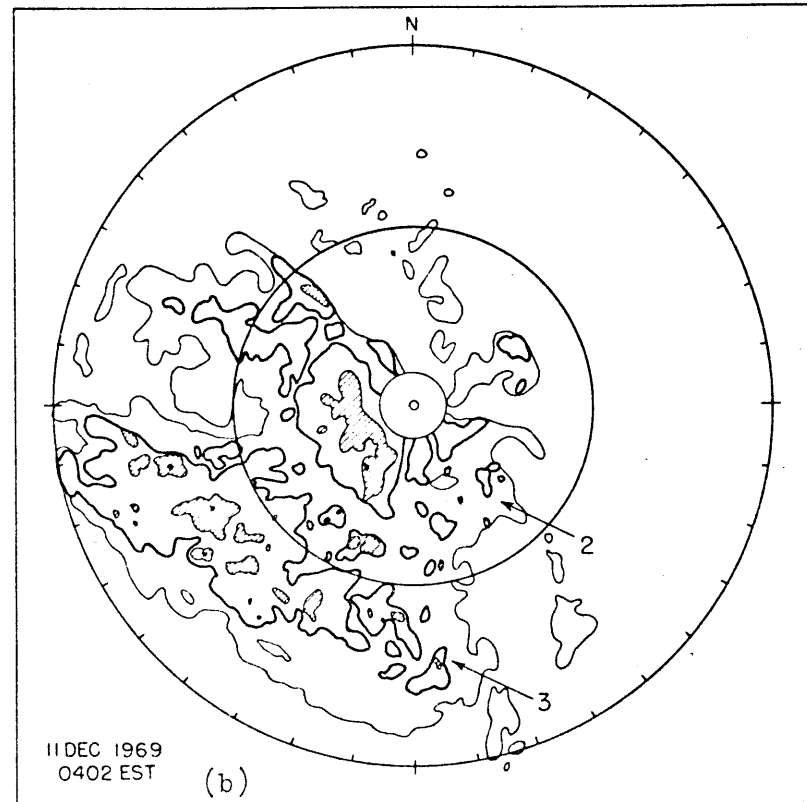
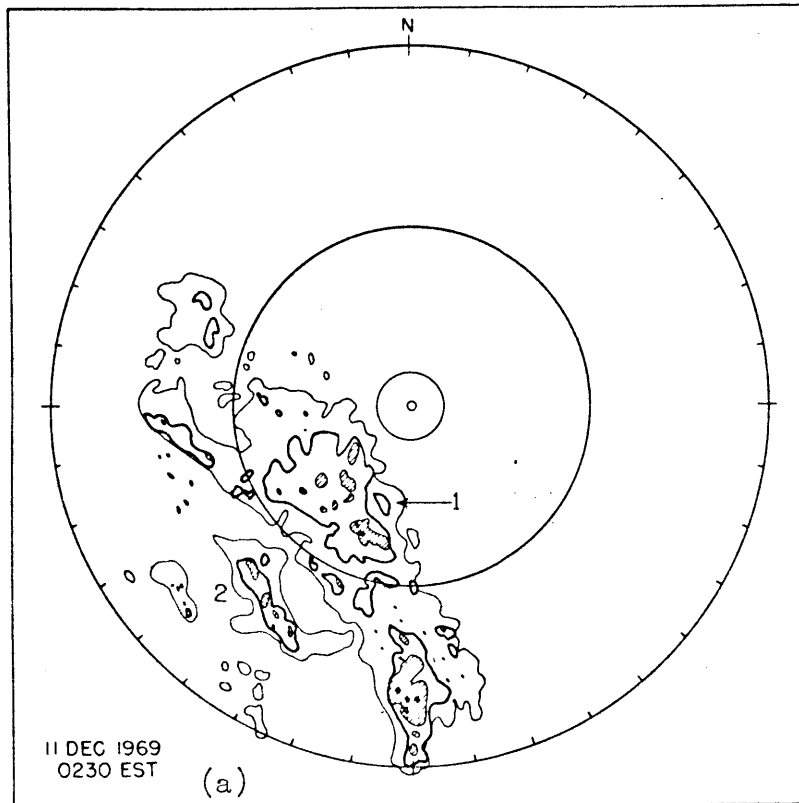


Figure 19 (a), (b). Precipitation patterns of the storm of 11 December 1969. Intensity levels 4-7 are depicted. Threshold values correspond to rainfall rates of approximately 5, 8, 17, and 30 mm/hr. The radius of the outer circle is 200 km. In (a) bands 1 and 2 are labeled. Band 2 is just beginning to develop. In (b) bands 2 and 3 are labeled.

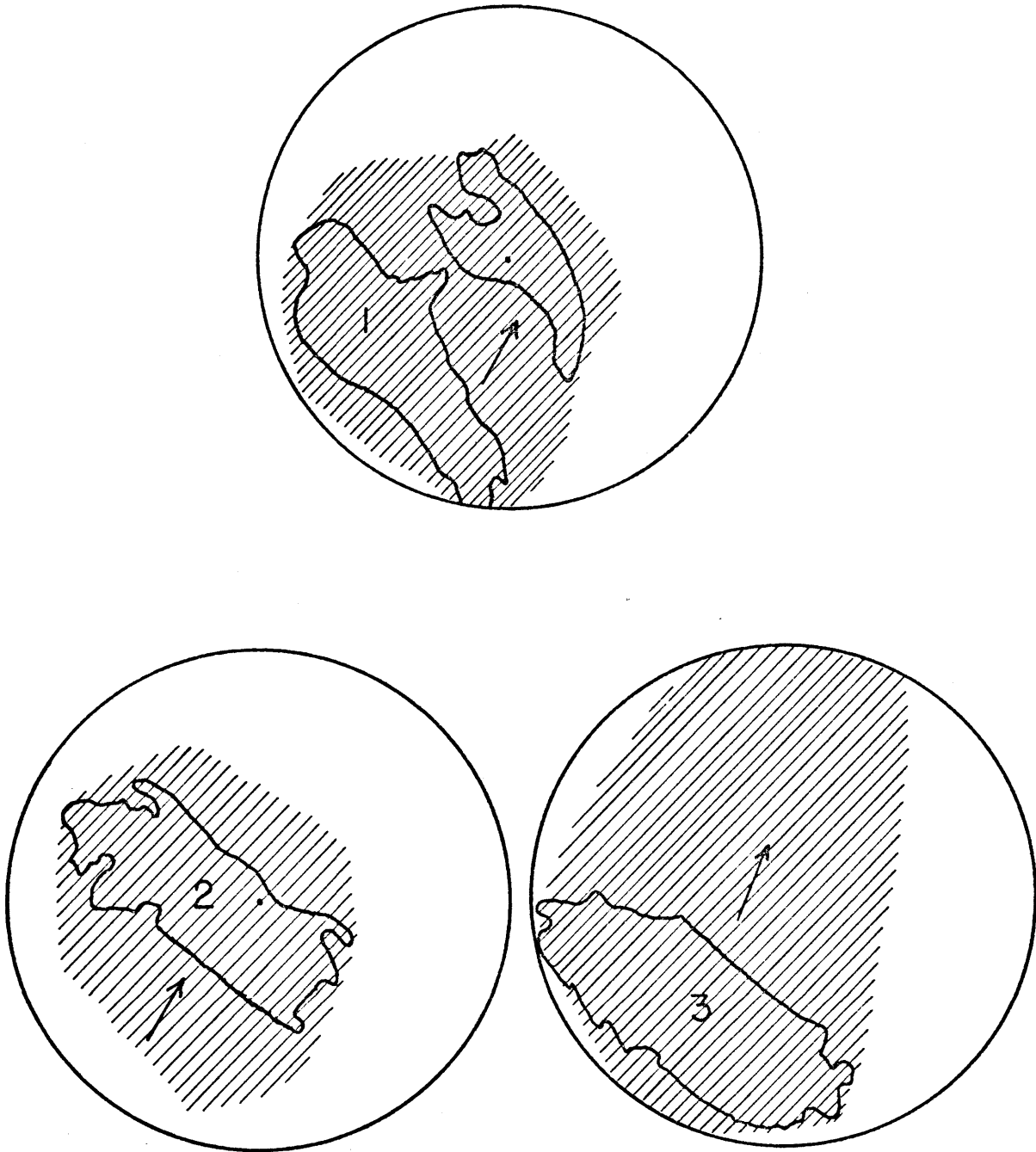


Figure 20. The paths of the mesoscale precipitation features of the 11 December storm. The features are shown at intensity level 4 (rainfall rate ≥ 5 mm/hr), which was also used to determine their paths. Band 1 is shown at 0200 and at 0330 EST. Bands 2 and 3 are shown at 0402 EST. Arrows indicate the directions of motion. The circle radius is 200 km.

Table 7. Mesoscale precipitation area statistics for the storm of 11 December 1969. See section A, chapter III for definition of symbols.

<u>Parameter (Units)</u>	<u>Band 1</u>	<u>Band 2</u>	<u>Band 3</u>	<u>Average</u>	<u>Range</u>
S (m/s)	26	20	28	24	8
D (deg)	208	209	202	206	7
O (deg)	146	158	116	140	42
S-S ₇₀₀ (m/s)	1	-5	3	-.3	8
D-D ₇₀₀ (deg)	0	1	-6	-2	7
S-S _c (m/s)	13	7	15	12	8
D-D _c (deg)	12	13	6	10	7
D-O-90° (deg)	-28	-39	-4	-24	35
Time Tracked by Radar (hrs)	2½	2½	3	2½	½

precipitation, sometimes enclosing smaller areas of more intense rain, formed the outer regions of the bands. LMSA's, as such, could not be detected as part of the bands. The bands had lengths that were three to six times their widths. At their maximum size they were about two times as large as the upper limit of the LMSA definition of Austin and Houze (1972).

The distances separating the band centers, perpendicular to their axes, were 99 and 82 km. In the direction of motion, the bands were separated by 117 km (1.2 hours) and 92 km (1.3 hours).

As shown in Table 7, the directions and orientations of the bands were quite similar. The bands moved in remarkably close agreement with the 700 mb winds. Vertical development of the precipitation was to about 7 km or about 400 mb.

F. Storm of 3 May 1971

1. Synoptic situation. An occluded cyclone was traveling northward through central New England at a speed of about 7 m/sec. The system was deepening and becoming more occluded with time, as shown in Figure 21. A closed circulation existed at least through the 500 mb level. Figure 22 depicts the section of the storm that was observed by the radar.

2. The general precipitation pattern. New England received rain from this storm, intermittently, for nearly 48 hours, with rainfall accumulations ranging from one half to over two inches for the two-day period.

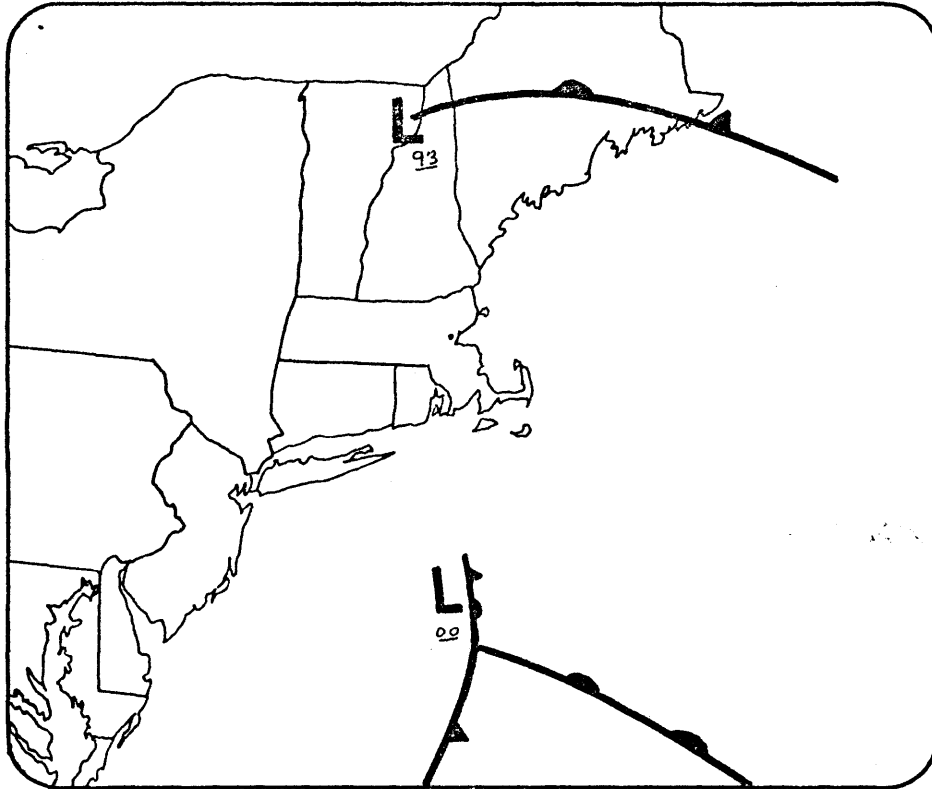


Figure 21. The synoptic situation on 3 May 1971. The cyclone is shown at 0700 and 1900 EST.

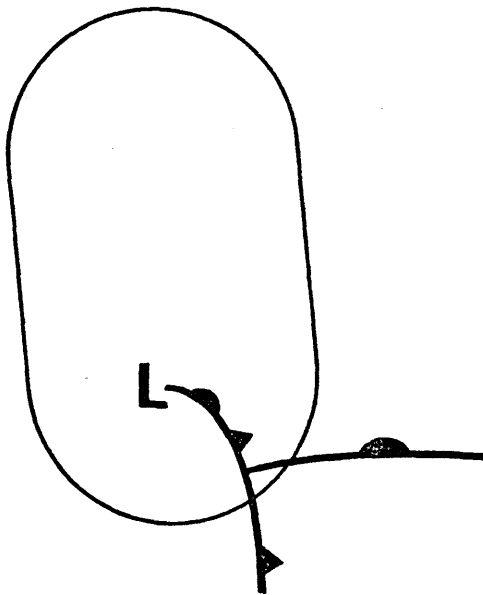


Figure 22. The part of the 3 May storm that was observed by radar. Radar range is 200 km.

The first light rain occurred in western New England at about 1500 EST on the second day of May. This light rain advanced in an irregular manner toward the northeast, and by 2100 EST had covered all of New England with the exception of Maine. The rain was not continuous, however. In fact, many stations reported no rain for periods of three to six hours or more. It is possible that this rain was associated with a front which had previously washed out. The cyclone was about 500 km to the southwest at this time.

Continuous light rain began at about 0400 EST in southern New England, 300 km in advance of the cyclone. The rain progressed northward and slightly westward through New England. Typical intensities were between .01 and .05 inches per hour.

Although there were isolated instances of heavy rain earlier, most of the heavy rain began from one to three hours after the onset of the continuous light rain, and advanced toward the north. This heavy rain, which was not continuous in time or space, was characterized by hourly amounts ranging from .07 to .2 inches. The leading edge of the heavy rain preceded the cyclone center by about 250 km, or ten hours. The last heavy rain ended just ahead of the cyclone center. The heavy rain extended westward only to the New York border, and eastward through most of Maine.

3. The mesoscale precipitation pattern. The principal part of the heavy rain area, which contained almost all of the heavy rain, was viewed by the radar and found to be composed of at least 13 mesoscale precipitation areas. These areas formed in many different parts of the

New England area, as shown in Figure 23, but all moved in a northward direction. Areas B, F, and H became elongated enough to resemble bands, though none were as large as the major bands found in previous storms. Other bands formed because the areas lined up with each other. For example, area H formed a continuous band with area D, then formed a discontinuous band with area E when the latter replaced area D. Finally, area H formed a continuous band with area G when area G moved up next to area H at one end and area E dissipated at the other. These areas are shown in Figure 24.

It should be noted that some of the banded appearance is due, at least in part, to the intersection of the freezing level by the radar beam at a height of about 1.5 km and a range of 100 to 150 km. Thus the echoes are enhanced due to the melting layer effect.

Area F was observed to behave in a manner that was different from that of the other mesoscale areas. At first it had a large component of motion toward the east, but it developed to the north and slowed drastically at approximately the same time.

4. Discussion. The mesoscale areas, which are seen as the predominant mesoscale entities, were generally smaller than their counterparts in the other storms. Although they were within the size range of the LMSA definition suggested by Austin and Houze, many were close to the lower limit of that definition.

Table 8 lists several parameters which describe the behavior of the mesoscale areas. The orientations of the areas are more varied than was the case for previous storms. There are some notable

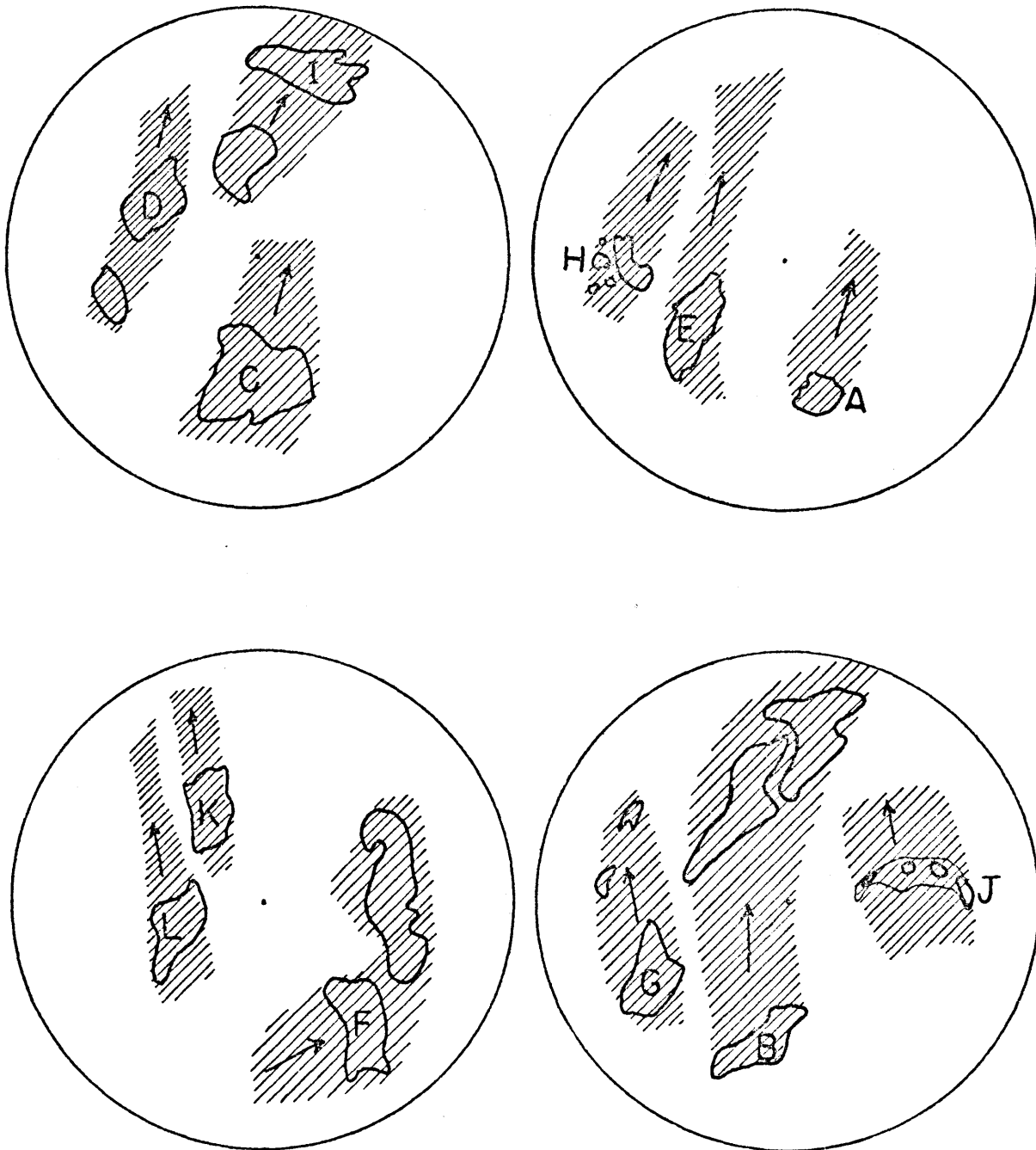


Figure 23. The paths of the mesoscale precipitation features of the 3 May storm. The areas are shown at intensity level 4 (rainfall rate ≥ 3 mm/hr), which was also used to determine their paths. Area J is also shown at level 3. Areas A through L are labeled at 0727, 0727, 0840, 1030, 1000, 1130, 1130, 1030, 1306, 1101, 1430, and 1430 EST, respectively. Areas B, D, F, G, and I are also shown at 1000, 0931, 1430, 1402, and 1130 EST, respectively. Note that the areas shown in a given circle do not necessarily coexist. Arrows indicate the directions of motion. The circle radius is 200 km.

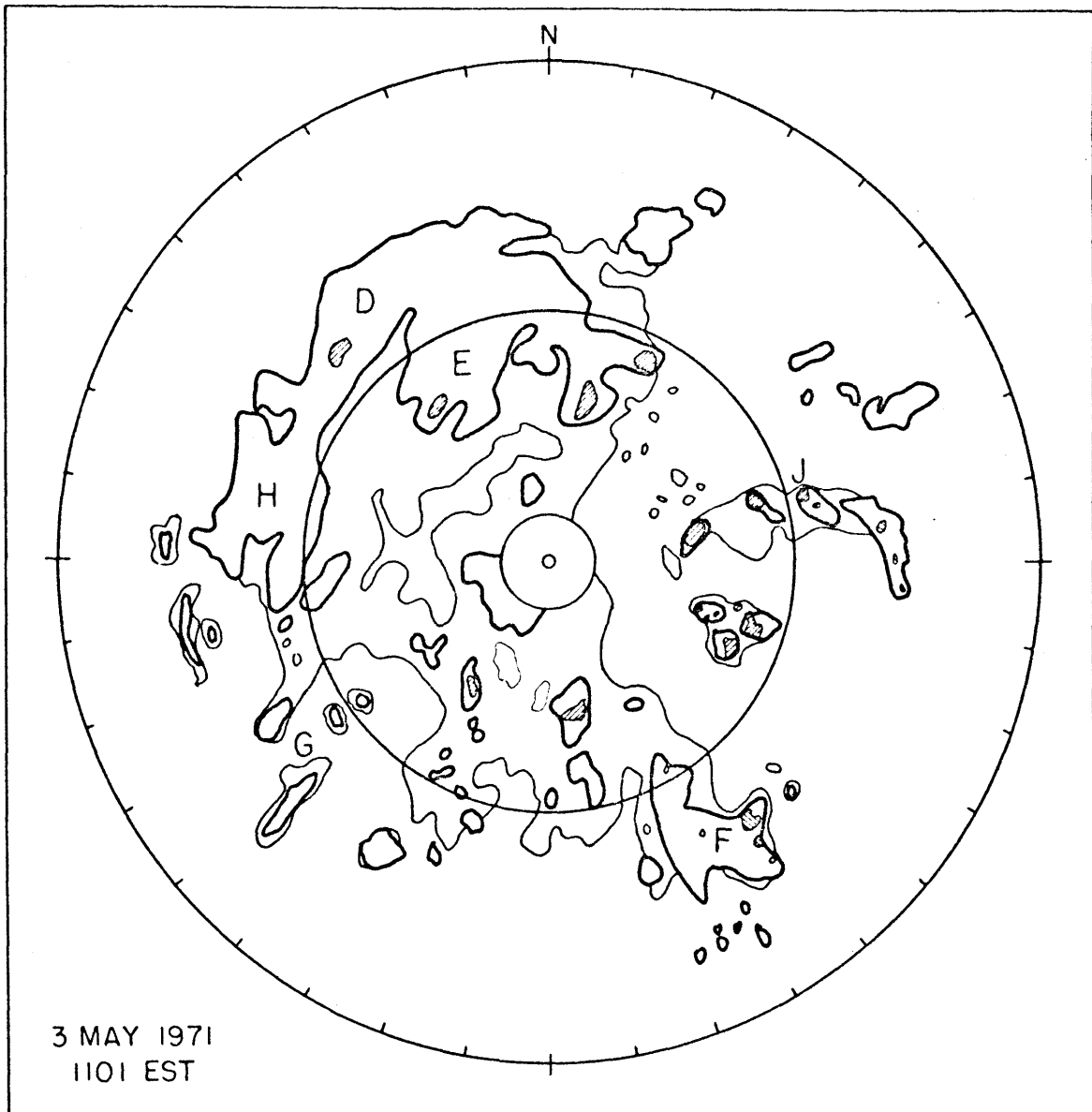


Figure 24. Precipitation pattern of the storm of 3 May 1971. Intensity levels 3-5 are depicted. Threshold values correspond to rainfall rates of approximately 1, 3, and 6 mm/hr. The radius of the outer circle is 200 km. Areas D, E, F, G, H, and J are labeled.

Table 8. Mesoscale precipitation area statistics for the storm of 3 May 1971. See section A, Chapter III for definition of symbols.

Parameter (Units)		Area A	Area B	Area C	Area D	Area E	Area F	Area G	Area H	Area I	Area J	Area K	Area L	Average	Range
	S (m/s)	22	21	15	29	35	14	13	13	15	26	18	13	18	22
	D (deg)	196	180	190	193	193	205	166	202	223	168	172	171	188	57
	O (deg)	---	46	---	35	35	175	17	22	105	88	---	15	60	160
95	S-S ₇₀₀ (m/s)	14	13	7	21	27	6	5	5	7	18	10	5	10	22
	D-D ₇₀₀ (deg)	11	-5	5	8	8	20	-19	17	38	-17	-13	-14	3	57
	S-S _c (m/s)	15	14	8	22	28	7	6	6	8	19	11	6	12	22
	D-D _c (deg)	16	0	10	13	13	25	-14	22	43	-12	-8	-9	8	57
	D-O-90° (deg)	---	44	---	68	68	-60	59	90	28	-10	---	66	39	150
	Time Tracked by Radar (hrs)	2	3	1½	2½	2	6	3½	3	2½	1½	2	4½	2.8	4½

exceptions to the preferred orientation.

The direction of area motion agreed closely with the 700 mb wind field, though the rain areas have a vertical extent of only 4 km or about 600 mb. The speeds of the areas, however, averaged almost 10 m/sec faster than the 700 mb wind, and were even faster than the wind at 500 mb.

G. Storm of 8 May 1971

1. Synoptic situation. A cyclonic storm located to the south of New England was moving toward the northeast, as shown in Figure 25. The low was weak, and had no closed circulation at 850 mb, though it was deepening. The actual movement of the system was from 230 degrees at approximately 8 m/sec. Figure 26 illustrates the part of the cyclone that was observed by the radar.

2. The general precipitation pattern. The storm produced rain in New England for 12 to 15 hours, though the rain was immediately followed by precipitation produced by a second disturbance. Total rainfall amounts ranged from .4 to 1.4 inches in southern New England. Northern New England experienced much less precipitation because that area was farther from the storm's path.

Light rain began at 0900 EST in southwestern Connecticut, 400 km north of the cyclone. It progressed slowly and steadily northeastward into northern New Hampshire and southern Maine, reaching Portland, Maine, by 2000 EST. The light rain was characterized by rainfall intensities of .01 to .04 inches per hour.

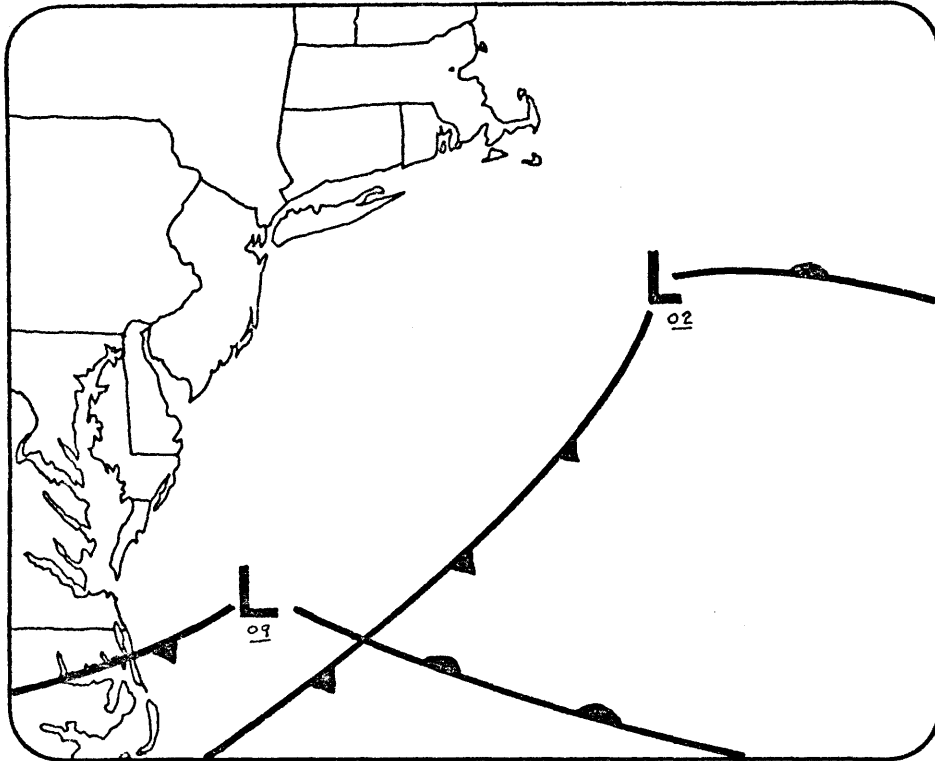


Figure 25. The synoptic situation on 8 May 1971. The cyclone is shown at 0700 EST on the 8th and at 0700 EST on the 9th.

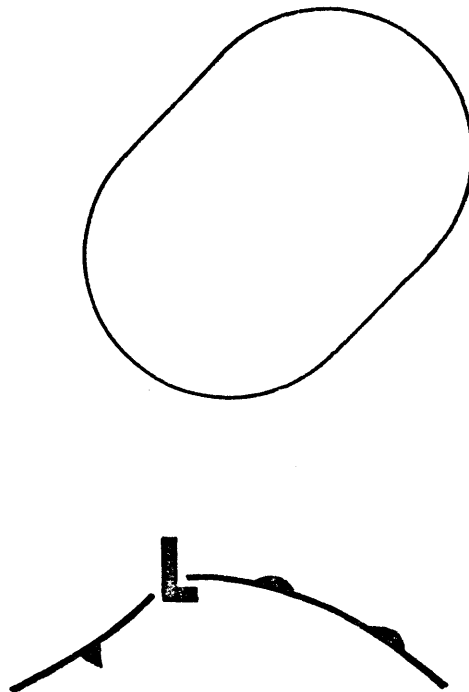


Figure 26. The part of the 8 May storm that was observed by radar. Radar range is 200 km.

Heavy rain began about an hour after the onset of the light rain. Hourly rainfall amounts ranged from .06 to .3 inches, though values near .1 inch were more typical. It took about 8 hours for all of the heavy rain, which was moving toward the northeast, to pass a given station. The heavy rain did not penetrate into extreme northern New Hampshire or Vermont. Thus its maximum northern displacement from the northeastward-moving cyclone was about 580 km.

3. The mesoscale precipitation pattern. Radar observations revealed that the heavy rain was organized into two bands, each of which moving toward the northeast. Band 1, which seemed to be composed of two parts (labeled A and B), is shown in Figure 27a. Band 1 dissipated rapidly, though area A, which was the largest part of the band, took longer to do so.

Band 2, which followed band 1, was much broader, as shown in Figure 27b. It was resolved into two parts for the purpose of tracking only. Radar coverage was discontinued as the band, still intense, was reaching Boston. The paths of the bands are illustrated in Figure 28.

4. Discussion. The two bands are seen as the primary mesoscale features of the storm. Though band 1 could be viewed as two separate LMSA's the band still behaves as a single entity. Areas A and B were identical with respect to both speed and direction of movement. Also, the areas were not always as distinct as they appear in Figure 27a. The areas comprising band 2 seemed to be little more than precipitation maxima, though area C, at times, resembles a LMSA. Like areas A and B,

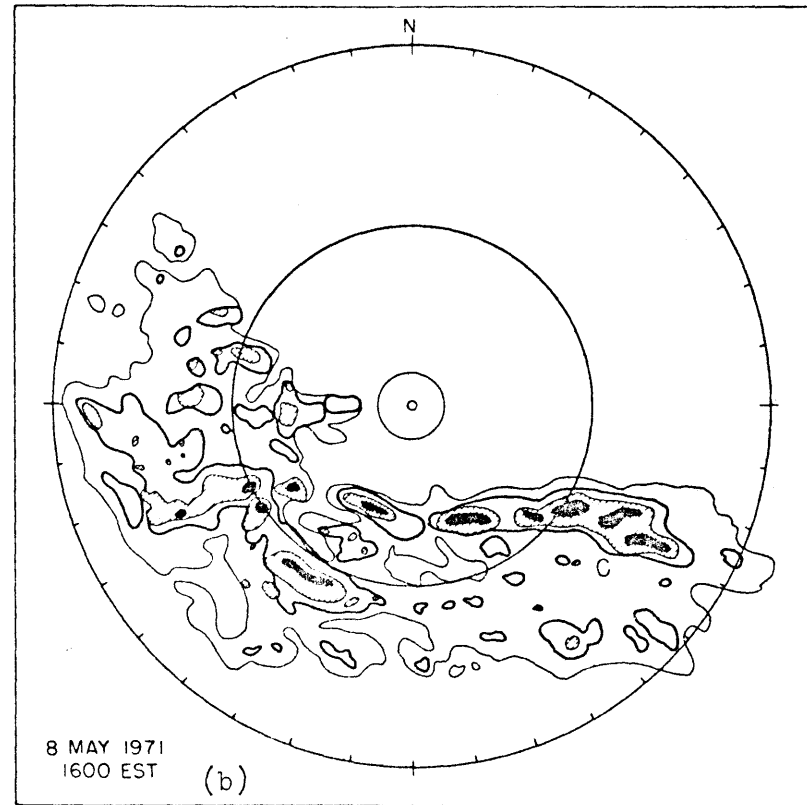
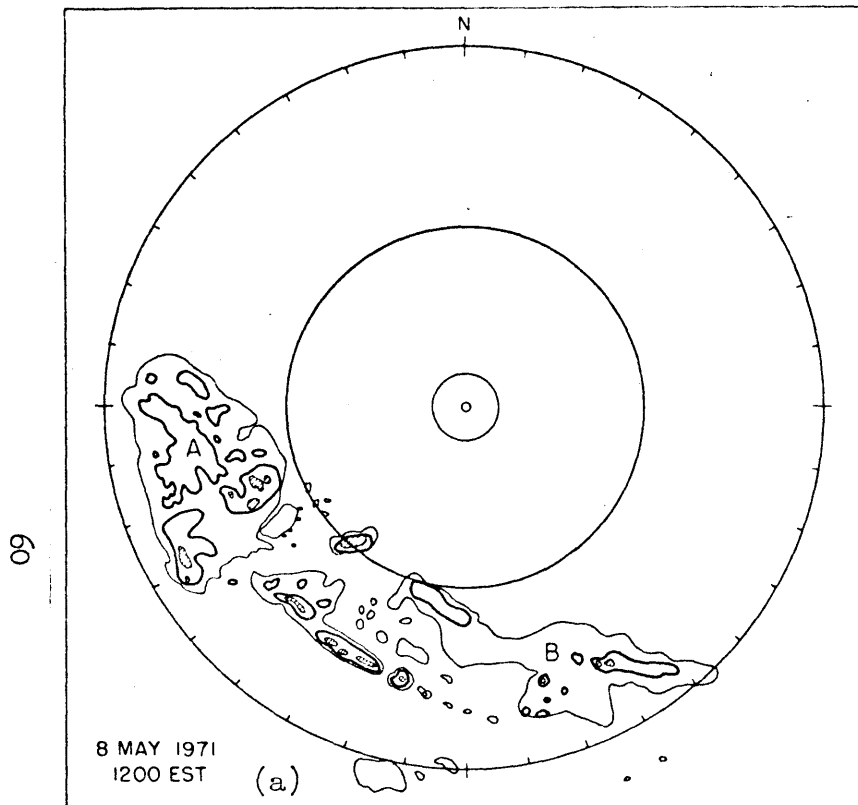


Figure 27 (a), (b). Precipitation patterns of the storm of 8 May 1971. Intensity levels 4-7 are depicted. Threshold values correspond to rainfall rates of approximately 3, 6, 10, and 19 mm/hr. The radius of the outer circle is 200 km. In (a) band 1 is shown, with areas A and B labeled. In (b) band 2 is shown.

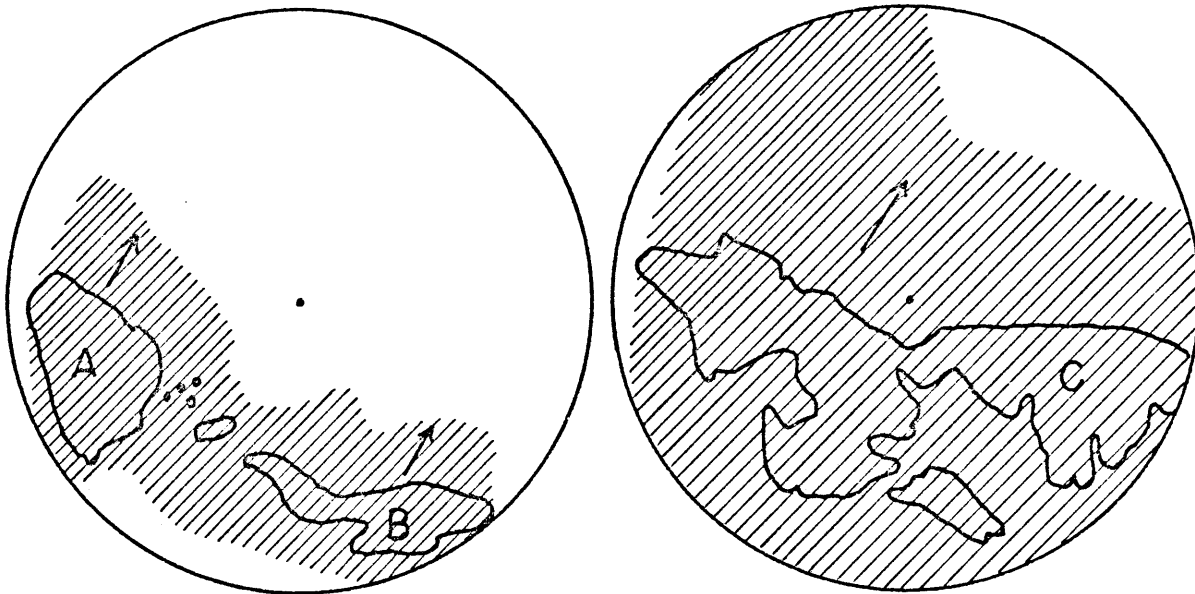


Figure 28. The paths of the mesoscale precipitation features of the 8 May storm. The bands are shown at intensity level 4 (rainfall rate ≥ 3 mm/hr), which was also used to determine their paths. Areas A and B of band 1 are shown at 1200 EST. Band 2 is shown at 1600 EST. Arrows indicate the directions of motion. The circle radius is 200 km.

Table 9. Mesoscale precipitation area statistics for the storm of 8 May 1971. See section A, Chapter III for definition of symbols.

Parameter (Units)	Area	Area	Area	Area	Average	Range
	A	B	C	D		
S (m/s)	6	5	12	13	9	8
D (deg)	207	207	219	214	212	12
O (deg)	129	106	100	128	116	29
S-S ₇₀₀ (m/s)	-2	-3	4	5	1	8
D-D ₇₀₀ (deg)	-11	-11	1	-4	-6	12
S-S _c (m/s)	-2	-3	4	5	1	8
D-D _c (deg)	-23	-23	-11	-16	-18	12
D-O-90 ^o (deg)	-12	11	29	-4	6	41
Time Tracked by Radar (hrs)	5	3	5	2½	4	2½

areas C and D have identical speeds and directions. Bands 1 and 2 were two and four times larger, respectively, than the LMSA's defined by Austin and Houze (1972). Areas C and D, by themselves were larger than the upper limit of that definition.

Table 9 gives the different parameters that were calculated for the four areas. It can be seen that the movement of the areas approximated the 700 mb wind field fairly well. The average direction was halfway between the winds at 750 and 700 mb, while the average speed was equal to that of the 750 mb wind but differed by only 1 m/sec from the 700 mb wind. The maximum vertical development of the bands was only to 4 km (about 600 mb). It is also noted that the orientations of the areas were quite similar, and that they were very close to being perpendicular to the directions of motion.

Band 2 was found to follow band 1 by about 1.7 hours.

H. Storm of 30 December 1971

1. Synoptic situation. A well-developed cyclone, shown in Figure 29, was moving eastward along a path that took it south of New England. The system, which was deepening slowly, was found to be moving almost directly eastward at a speed of 21 m/sec. The part of the storm that was surveyed by the radar is illustrated in Figure 30.

2. The general precipitation pattern. The storm caused continuous rain for approximately 18 hours over New England stations. Total rainfall amounts were not large, ranging from .5 to 1.5 inches.

Light rain began in southwestern Connecticut at 0500 EST, almost

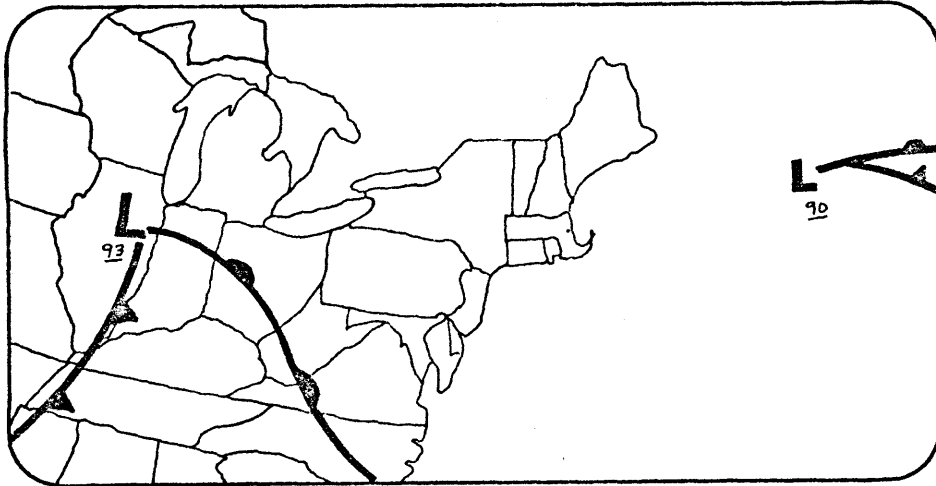


Figure 29. The synoptic situation on 30 December 1971. The cyclone is shown at 0700 EST on the 30th and at 0700 EST on the 31st.

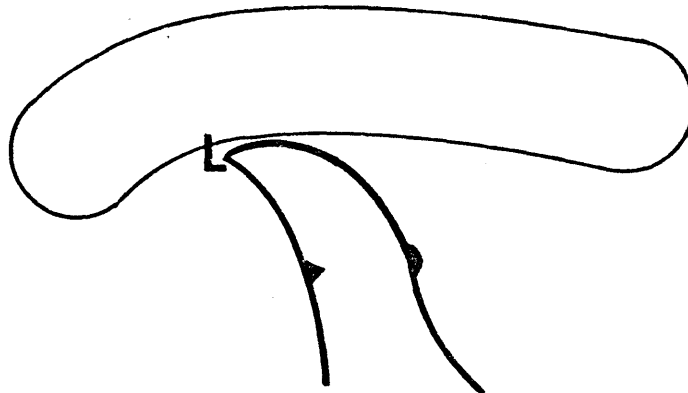


Figure 30. The part of the 30 December storm that was observed by radar. Radar range is 200 km.

1400 km ahead of the cyclone center. The rain progressed slowly toward the northeast, with intensities ranging from .01 to .05 inches per hour.

The major part of the heavy rain began in New England at about 0900 EST, some 970 km ahead of the cyclone. The rain proceeded to move northward, and then eastward, through New England. The heavy rain lasted for 4 to 6 hours at southern New England stations, but only for 2 to 3 hours at stations in northern New England. When its trailing edge finally passed north of Boston, the cyclone, then 280 km to the south-southwest, had almost reached Boston in longitude.

The main heavy rain area was preceded and followed by shorter periods of heavy rain which lasted for about one hour for a given station, but were experienced by only some stations. These two smaller heavy rain areas were separated from the main heavy rain by approximately two hours of light rain. The last of the small heavy rain areas was approximately 280 km behind (to the west of) the cyclone center.

3. The mesoscale precipitation pattern. The entire period of heavy rain was viewed by the radar as it passed through New England. It was thus determined that the first short period of heavy rain was actually composed of two parallel bands which moved toward the northeast. These bands, termed band 1 and band 2, are seen in Figure 3la just before they dissipated. The first part of the main heavy rain area is also shown in this figure, and it too was quite banded in structure. As it moved northward, area A, the largest part, broke off and moved eastward. The original area then became stationary.

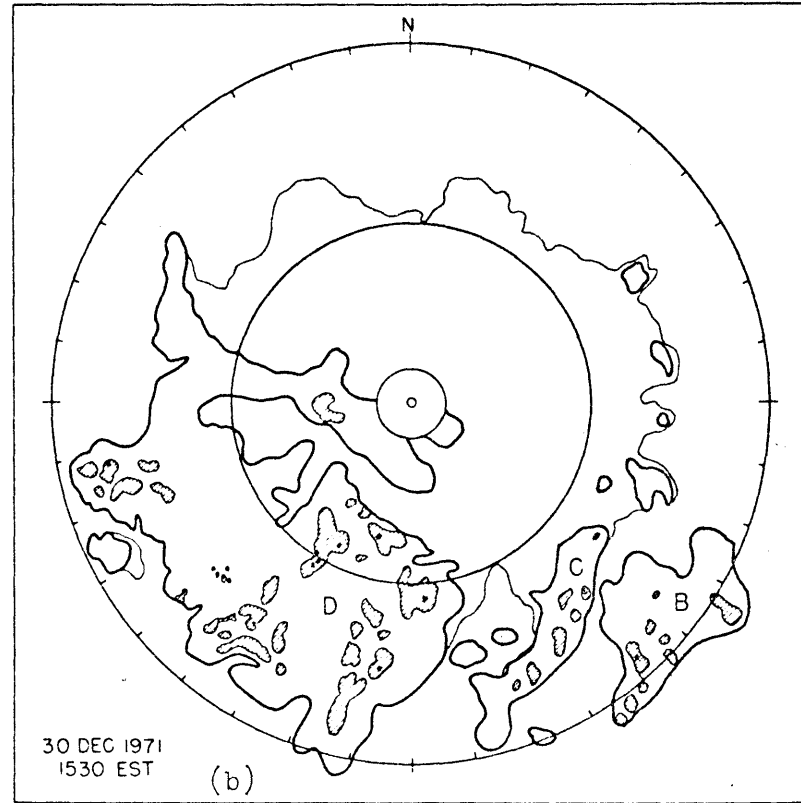
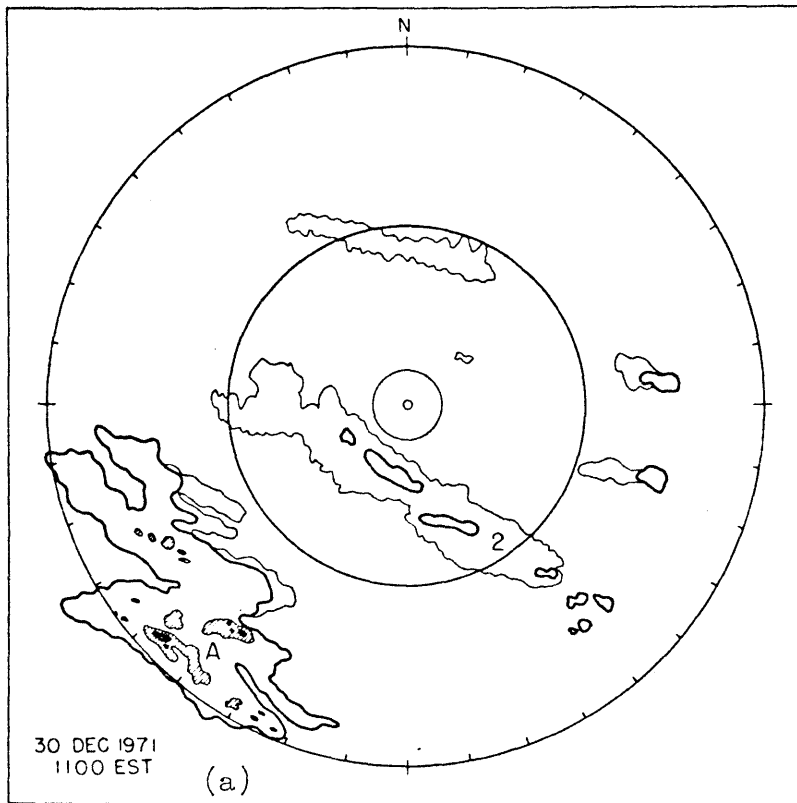


Figure 31 (a), (b). Precipitation patterns of the storm of 30 December 1971. Intensity levels 3-6 are depicted. Threshold values correspond to rainfall rates of approximately 1, 2, 4, and 7 mm/hr. The radius of the outer circle is 200 km. In (a) area A and band 2 are labeled. In (b) areas B, C, and D are labeled.

It is believed to have continued to exist because of the enhanced echo from the melting layer.

Areas B and C, like area A, broke off from the original area and moved toward the east. In doing so, area B joined with a smaller area, which broke off to the north at about the same time, to form a rather large north-south oriented band. Next, area D, which was much larger than the other areas, moved eastward, leaving nothing of the original area behind it. At times, area D seemed to have an internal banded structure, with a north-south orientation similar to that of areas B and C. Areas B, C, and D are shown in Figure 31b.

The final part of the main heavy rain was composed of areas E, F, and G. These areas were smaller than their predecessors, and their eastward paths were farther to the north. Area F behaved in an interesting manner. As it moved eastward, the largest part began to dissipate, while its southernmost part, denoted F', intensified somewhat and continued its eastward progress for at least an hour after the rest of area F had dissipated.

The heavy rain which followed the main rain area was composed of bands 3 and 4. These bands moved across New England in a manner similar to areas A through G. Band 4 developed directly behind band 3, after which the latter dissipated. The paths of the mesoscale areas and bands are depicted in Figure 32.

4. Discussion. The numbered bands observed in this storm were not equivalent to the much larger bands of some of the storms discussed above. They were about the size of IMSA's, but they were very thin.

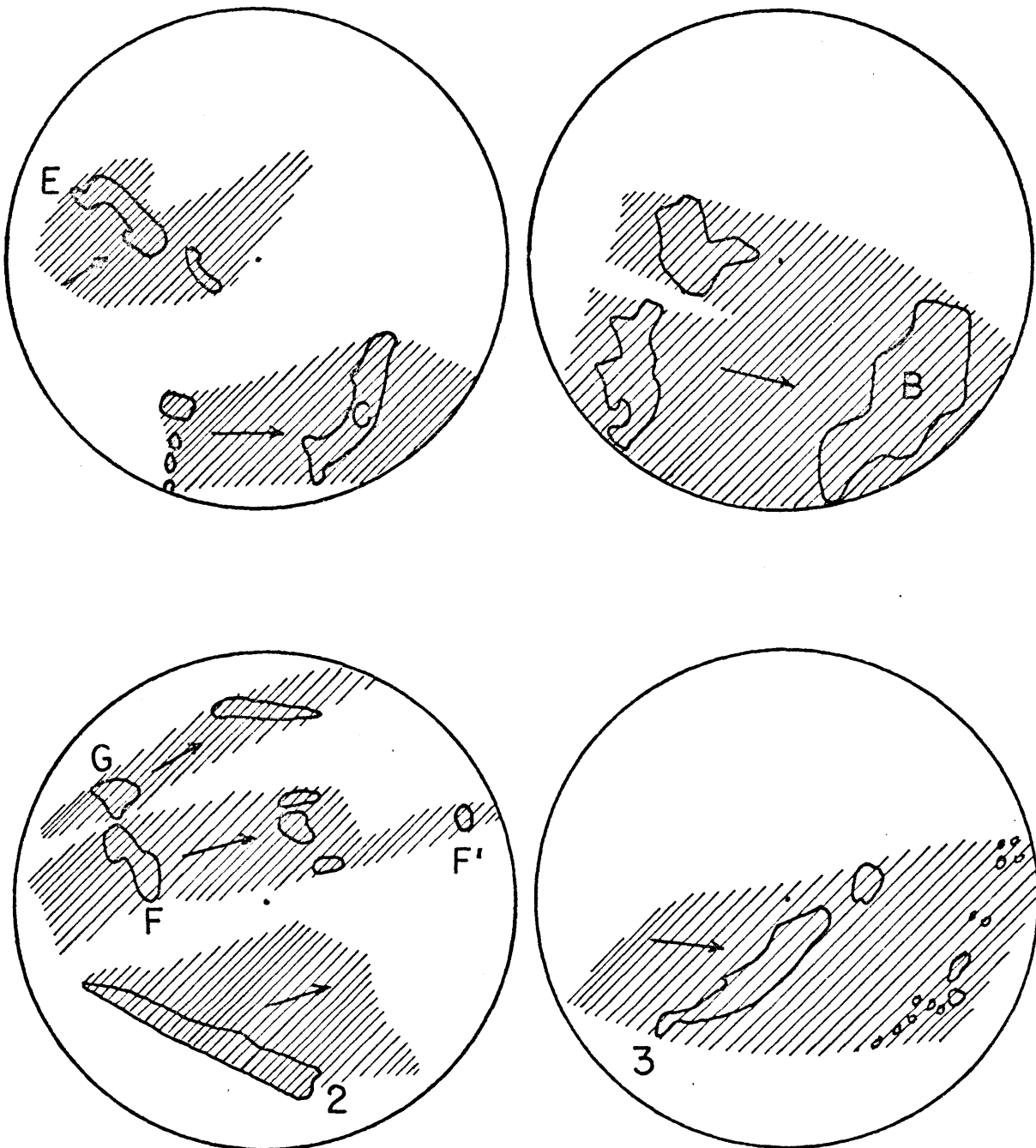


Figure 32. The paths of the mesoscale precipitation features of the 30 December storm. The areas and bands are shown at intensity level 4 (rainfall rate ≥ 2 mm/hr), which was used to determine their paths. Features B, C, E, F, F', G, 2, and 3 are labeled at 1501, 1530, 1653, 1730, 1902, 1730, 0907, and 2100 EST, respectively. B, C, F, G, and 3 are shown also at 1301, 1431, 1800, 1800, and 2230 EST, respectively. Note that the areas shown in a given circle do not necessarily coexist. Arrows indicate the direction of motion. The circle radius is 200 km.

Table 10. Mesoscale precipitation area statistics for the storm of 30 December 1971. See section A, Chapter III for definition of symbols.

Parameter (Units)	Band 1	Band 2	Area A	Band B	Area C	Area D	Area E	Area F	Area F'	Area G	Band 3	Band 4	Average	Range
S (m/s)	20	20	26	34	37	27	23	34	38	33	21	21	28	18
D (deg)	244	258	262	288	269	260	236	255	253	243	284	267	260	52
O (deg)	118	118	126	197	199	134	130	148	---	96	227	237	157	141
S-S ₇₀₀ (m/s)	-10	-10	-4	4	7	-3	-7	4	8	3	-9	-9	-2	18
D-D ₇₀₀ (deg)	-23	-9	-5	21	2	-7	-31	-12	-14	-24	17	0	-7	52
S-S _c (m/s)	-1	-1	5	13	16	6	2	13	17	12	0	0	7	18
D-D _c (deg)	-26	-12	-8	18	-1	-10	-34	-15	-17	-27	14	-3	-10	52
D-O-90° (deg)	36	50	46	1	-20	36	16	17	---	57	-33	-60	13	117
Time Tracked by Radar (hrs)	1½	2½	2½	2	1½	4	3	1½	1	2	3	2½	2½	3

Area B, for a short period, formed a rather broad band. Areas B and D were about twice as large as the IMSA's defined by Austin and Houze (1972), but the other areas fell within the limits of their definition.

Several examples of recursion are obvious. Band 2 followed band 1 by 50 km or .7 hours. Area B followed area A by 275 km or 2.2 hours, and was followed by area C by about 100 km or .75 hours. Area D followed area C, but its axis could not be determined for the purpose of computing the separation distance. Areas F and G followed area E by about 100 km or .82 hours, while band 4 followed band 3 by 50 km or about .66 hours.

From Table 10 it can be observed that the areas moved in close agreement with 700 mb wind field. Closer agreement was observed with the winds in the layer between 750 and 700 mb. Vertical development of the precipitation was to 6 km (about 500 mb). It is noted that the areas moved in a direction that was nearly perpendicular to their orientation.

I. Storm of 2 April 1970

1. Synoptic situation. A mature cyclone, depicted in Figure 33, moved northeastward across northern New York, becoming occluded well before entering New England. The actual movement of the system, which was still deepening, was from 240 degrees at a speed of 15 m/sec. Figure 34 illustrates the part of the storm that was observed by the radar.

2. The general precipitation pattern. Large amounts of precipitation fell in New England as the storm approached. Extreme northern

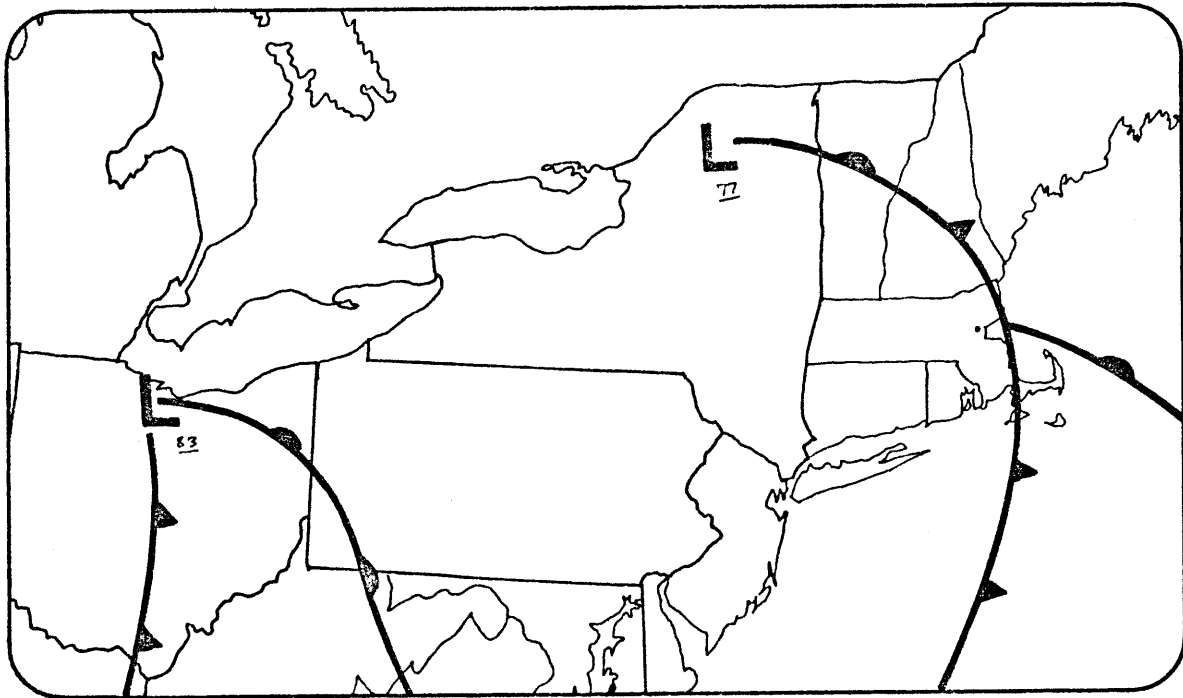


Figure 33. The synoptic situation on 2 April 1970. The cyclone is shown at 0700 and 1900 EST.

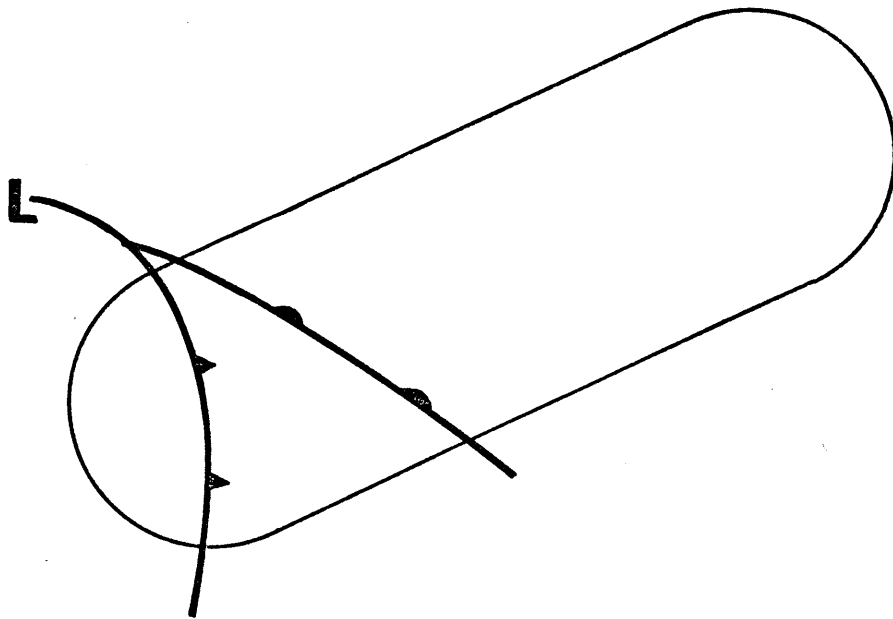


Figure 34. The part of the 2 April storm that was observed by radar. Radar range is 200 km.

New England received accumulations of about one inch, while the remainder of the area received total amounts ranging from two to three and a half inches. For most stations the rain fell continuously for 17 or 18 hours.

Light rain entered southwestern New England at about 2200 EST on 1 April, and advanced rapidly toward the northeast. Intensities ranged from .02 to .08 inches per hour. For most stations the light rain lasted for about 4 hours.

Heavy rain first entered New England at about 0200 EST, almost 950 km ahead of the cyclone center. The rain proceeded to move toward the northeast, taking 12 hours, on the average, to pass a given station. Hourly rainfall amounts ranged from .1 to .3 inches, and averaged about .2 inches. The trailing edge of the heavy rain passed Boston just ahead of the occluded front. After the heavy rain, most stations reported several hours of light rain.

3. The mesoscale precipitation pattern. The heavy rain was studied in detail with the aid of the radar. It was found to consist of several distinct precipitation areas and bands which were well organized and behaved in a consistent manner. However, there were also some intense rain areas, in the northern part of the radar circle, whose behavior was difficult to determine. Since the freezing level dropped rapidly with latitude, it is believed that the problem was due, at least in part, to the enhanced echo resulting from the radar beam intersecting the melting layer. Because of the resulting complications, these precipitation areas, which were few, are not considered in this study.

The main part of the heavy rain was composed of seven large precipitation areas which moved across New England toward the east. Many of these areas, such as area B in Figure 35a, were quite elongated and could be considered as bands. Others, such as area D, shown in Figure 35b, were very large. Figure 36 shows the paths of these areas.

One interesting occurrence concerned areas E and E'. Area E' was originally ahead of the southern end of area E, but moved across ahead of area E and eventually merged with it at the latter's northern end.

4. Discussion. Several of the precipitation areas of this storm were more like bands than LMSA's. Areas B, C, E, and G were all very elongated. Each, at some time, was much larger than the LMSA's defined by Austin and Houze (1972). Areas D and F, which were not bands, were 2 to 3 times larger than the LMSA's of Austin and Houze.

In this storm an excellent example of recursion is seen. Areas A, B, C, D, E, F, and G all move eastward across New England along the same path. The areas were separated by distances (times) of 85 km (.57 hours), 85 km (.54 hours), 125 km (.97 hours), 150 km (1.2 hours), 250 km (3.6 hours), and 280 km (2.5 hours).

From Table 11 it can be seen that, with the exception of area J, the orientations of the areas were very similar. The speeds, also were not very dissimilar, with two notable exceptions. The areas moved in rough agreement with 700 mb wind field. The speeds of the areas agreed best with the wind at 650 mb, while the directions were

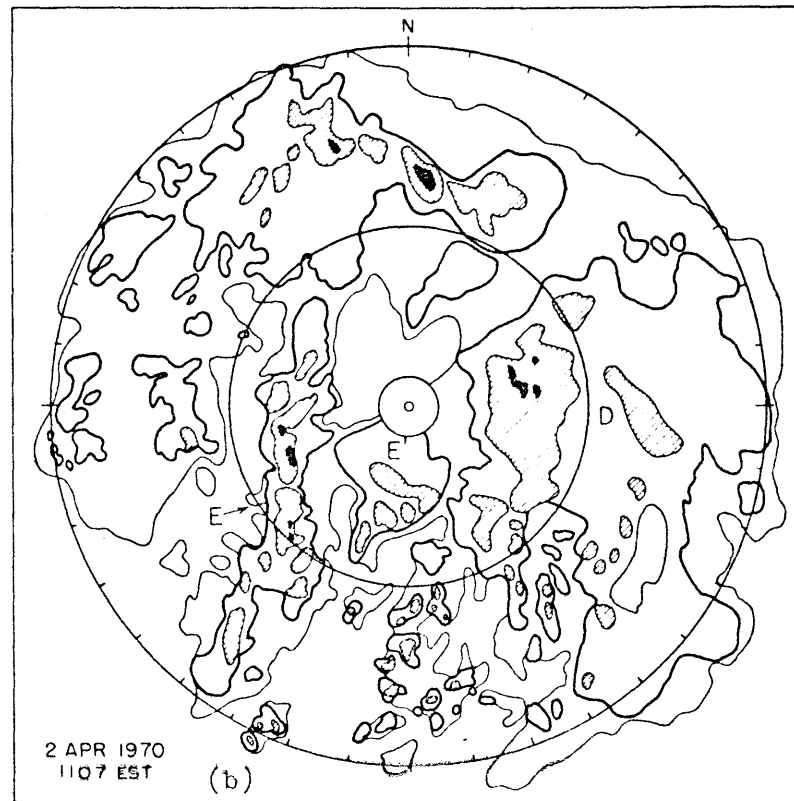
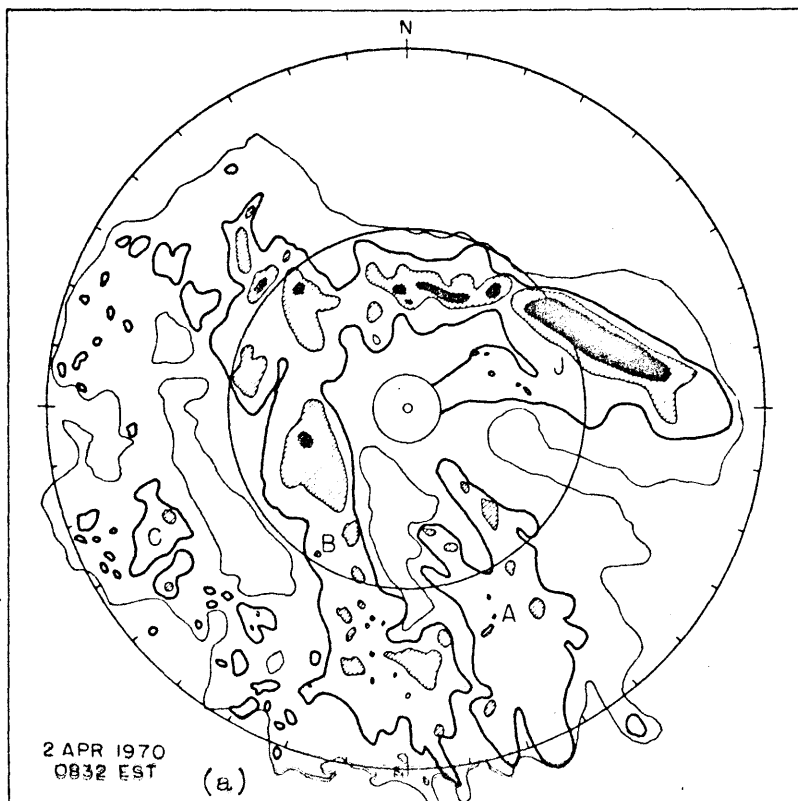


Figure 35 (a), (b). Precipitation patterns of the storm of 2 April 1970. Intensity levels 4-7 are depicted. Threshold values correspond to rainfall rates of approximately 3, 6, 13, and 24 mm/hr. The radius of the outer circle is 200 km. In (a) bands A, B, C, and J are labeled. In (b) areas D and E' and band E are labeled.

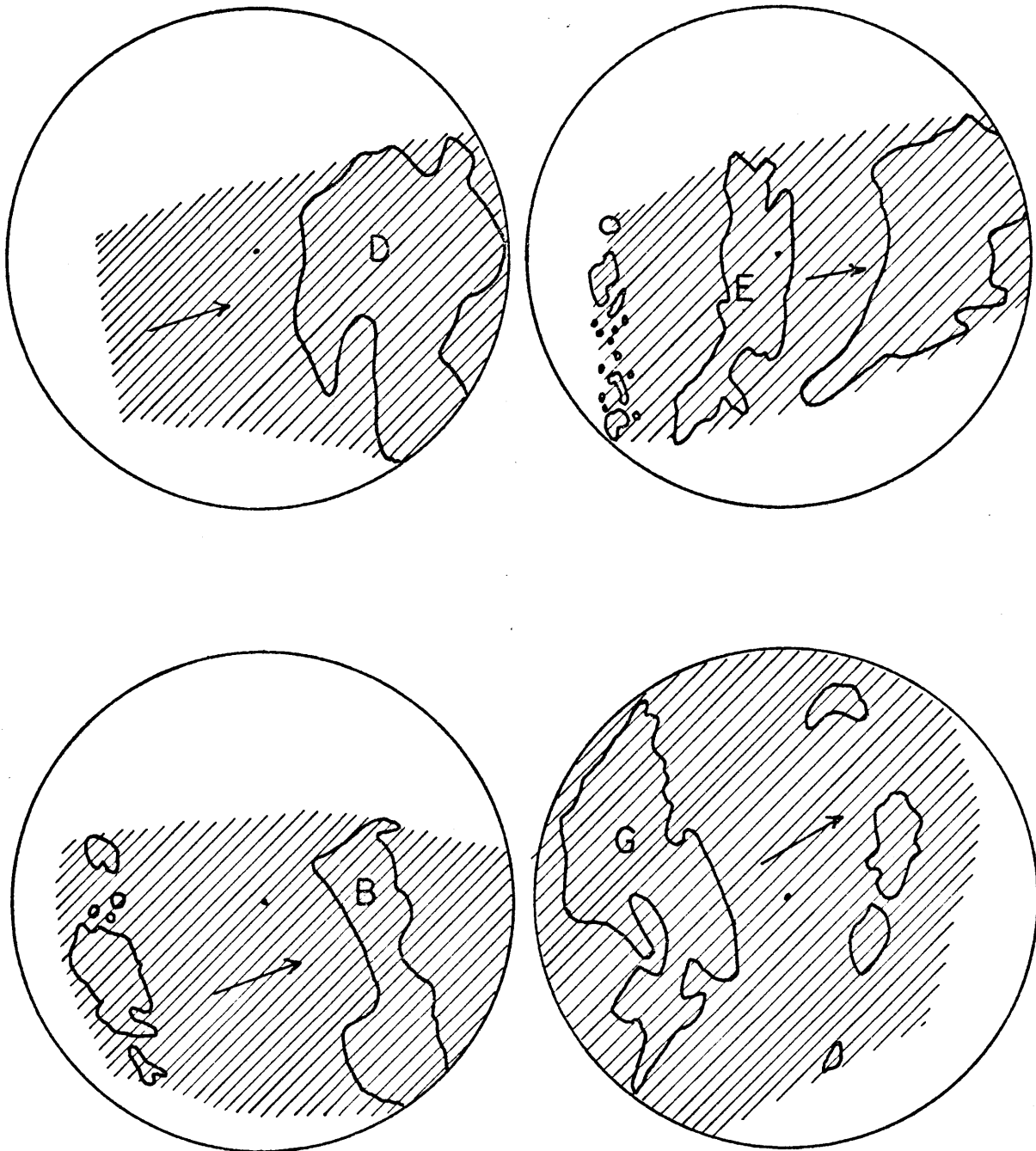


Figure 36. The paths of the mesoscale precipitation features of the 2 April storm. The features are shown at intensity level 5 (rainfall rate ≥ 6 mm/hr), which was also used to determine their paths. Features B, D, E, and G are labeled at 0930, 1107, 1130, and 1700 EST, respectively. B and G are also shown at 0800 and 1900 EST. Band E is shown additionally at 1030 and at 1258 EST. Arrows indicate the directions of motion. The circle radius is 200 km.

Table 11. Mesoscale precipitation area statistics for the storm of 2 April 1970. See section A, Chapter III for definition of symbols.

Parameter (Units)	Band A	Band B	Band C	Area D	Band E	Area E'	Area F	Band G	Band H	Band I	Band J	Average	Range
S (m/s)	35	41	44	36	36	40	19	31	43	43	16	35	28
D (deg)	264	247	241	255	261	230	234	237	223	214	230	240	50
O (deg)	168	164	154	177	191	---	180	183	180	---	115	168	76
S-S ₇₀₀ (m/s)	5	11	14	6	6	10	-11	1	13	13	-14	5	28
D-D ₇₀₀ (deg)	39	22	16	30	36	5	9	12	-2	-11	5	15	50
S-S _c (m/s)	20	26	29	21	21	25	4	16	28	28	1	20	28
D-D _c (deg)	24	7	1	15	21	-10	-6	-3	-17	-26	-10	00	50
D-O-90° (deg)	6	-7	-3	-12	-20	---	-36	-36	-47	---	25	-14	72
Time Tracked by Radar (hrs)	1	2	2	2	3½	2½	4	4	2½	1½	2	2½	3

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closest to the wind direction at 500 mb. However, the wind veered very slowly with height. Vertical development of the mesoscale areas was to almost 8 km (about 350 mb).

IV. SYNTHESIS AND DISCUSSION

A. Bandedness

A banded precipitation structure was found to be characteristic of all eight storms. Each storm was extremely banded at times, and each was at least somewhat banded in structure for most of the time that it was studied by the radar.

Three distinct types of bands were found in the storms. These types are based on the observed characteristics of size, shape, and structure. Type 1 bands are composed of LMSA's; type 2 bands are very large, but are not composed of LMSA's; and type 3 bands are small and thin. The behavior differences of the three types of bands were found to be statistically significant in only one respect. This aspect will be discussed in section C, below.

Type 1 bands were usually composed of two LMSA's, though some were composed of one or three LMSA's. These LMSA's, in general, had somewhat different speeds and directions of motion, and they had lifetimes that were greater than those of the bands. The LMSA's were usually connected by light rain, though in some cases they were either partially merged or entirely separate. The average length and width of the LMSA's, based on six cases (11 LMSA's, 6 bands) and three storms, were 120 km and 41 km, respectively. The LMSA's thus fit into the definition proposed by Austin and Houze (1972). The ratio of length to width of the LMSA's averaged 2.9. The total band length averaged 240 km. Examples of type 1 bands were found in storms 1, 2, and 5.

Type 2 bands were large, broad bands which usually contained a single absolute precipitation maximum. There were frequently one or two relative precipitation maxima present, also. If the band contained two absolute precipitation maxima, the two had identical speeds and directions of motion. The bands, therefore, behaved as a single entity. They could not be resolved into, nor did they develop from or break up into, separate and distinct LMSA's. Based on eight bands in three storms, the average length and width of the bands were 320 and 71 km, respectively. The average length was actually somewhat longer, since four of the bands extended beyond radar range. The average ratio of length to width was 4.4. These bands were about twice as large as the LMSA's defined by Austin and Houze (1972). Storms 4, 6, and 8 provide examples of the type 2 bands.

Type 3 bands were small and highly elongated. The average length and width, based on six bands in two storms (storms 3 and 7), were 200 and 21 km, respectively. The bands were therefore of LMSA size. The ratio of length to width averaged 9.5. Bands 1, 2, 3, and 4 of storm 7 were the best examples of this type of band.

There was a tendency for one type of band to dominate a particular storm. However, no relationship could be found between a given band type and any of the characteristics of the storm that contained it. The bands in storms 1, 2, and 5 were all type 1 bands, and the bands in storms 4, 6, and 8 were type 2 bands. The four type 3 bands in storm 7, however, were only four of twelve mesoscale features which existed in that storm. The remaining mesoscale features included one

type 2 band and seven LMSA's, four of which were elongated.

The three band types were quite distinct in terms of size and shape. There were very few borderline cases where it was difficult to categorize a specific mesoscale feature. It should be noted, however, that there were two types of mesoscale features that did not fall into one of the above band types, though they were few in number. First, two of the storms contained LMSA's that were not part of bands. Five of the twelve LMSA's in the 3 May storm were never part of a band and did not resemble bands themselves. Of the twelve mesoscale features in the 30 Dec storm, four were LMSA's which were clearly never part of a larger band. The LMSA's, however, did tend to be elongated. Of approximately 40 that were studied, only seven did not have a predominant orientation. Second, three mesoscale features were observed which were as large as or larger than the largest bands and yet were not band-shaped. Area D of storm 7 and areas D and F of storm 8 were the specific areas. Two of these areas, however, had a slightly banded internal structure.

B. Organization of the Bands

It was observed that the bands were organized into one or more "belts" of heavy precipitation which contained all of the mesoscale features. Five of the storms contained only one such belt. The other three storms contained two or three belts, separated by light rain. However, in these storms one of the belts was much greater in width (took longer to pass a given station) and in precipitation intensity

than the others. Thus each storm had a "main belt," while some had one or two additional "minor belts."

The main belts averaged 300 km in width (perpendicular to the direction of motion). The times required for the main belt to pass over a given station averaged about 7 hours. The average length of the belts was at least 450 km, though the exact value could not be determined because of lack of data beyond radar range over the ocean. The minor belts were parallel to the main belt and separated from it by about two hours of light rain. The overall belt widths, including the minor belts and separating light rain, when present, averaged 450 km.

The belts were found to maintain a relatively fixed position with respect to the cyclone. The leading edge of the first (or only) belt averaged 500 km ahead of the cyclone center. The trailing edge of the belt(s) averaged about 50 km ahead of the storm center. In only one case did a heavy rain exist behind the cyclone center, and this case involved one of the minor belts only, not the main precipitation belt.

C. Behavior of Mesoscale Precipitation Features

The mesoscale precipitation areas behaved in a manner that was quite consistent. Table 12 summarizes the parameters that were derived for the individual storms. In this section a bar will be used to denote an average for the mesoscale precipitation features of a given storm.

Table 12. Summary of mesoscale precipitation statistics for the eight storms. See section A, Chapter III for definition of symbols.

Parameter (Units)	5 Nov 69	14 Nov 69	8 Dec 69	11 Dec 69	3 May 71	8 May 71	30 Dec 71	2 Apr 70	Average
\bar{S} (m/s)	23	22	16	24	18	9	28	35	22
Range of S (m/s)	9	7	4	8	22	8	18	28	13
\bar{D} (deg)	151	188	238	206	188	212	260	240	210
Range of D (deg)	49	33	31	7	57	12	52	50	36
\bar{O} (deg)	25	54	145	140	60	116	157	168	108
Range of O (deg)	43	23	41	42	160	29	141	76	69.4
$\overline{S-S_{700}}$ (m/s)	10	-1	0	0	10	1	-2	5	3
$\overline{D-D_{700}}$ (deg)	-1	-13	4	-2	3	-6	-7	15	-1
$\overline{S-S_c}$ (m/s)	8	8	8	12	12	1	7	20	9.5
$\overline{D-D_c}$ (deg)	-4	-15	3	10	8	-18	-10	0	-3
$\overline{D-O-90^\circ}$ (deg)	36	44	0	-24	39	6	13	-14	12.5
Avg Time Tracked by Radar (hrs)	3 $\frac{1}{2}$	2 $\frac{1}{2}$	2	2 $\frac{1}{2}$	3	4	2 $\frac{1}{2}$	2 $\frac{1}{2}$	2.8

1. The steering level. The steering level is defined as the level at which the direction of the wind best approximates the average direction of motion of the mesoscale precipitation areas of a given storm. The 700 millibar level was found to best represent the steering level for the mesoscale areas of the eight storms. The average value of $(\bar{D}-D_{700})$ was -1 degree, while the average value of $(\bar{S}-S_{700})$ was +3 m/sec. Thus there was no significant tendency for the mesoscale features to move either to the right or the left of the 700 mb wind, while there was a slight tendency for the areas to move faster than the 700 mb wind. The average value of $|D-D_{700}|$ was 12.5 degrees, and the average value of $|S-S_{700}|$ was less than 7 m/sec. Thus the deviations from the 700 mb wind direction were relatively small, while the deviations from the 700 mb wind speed were somewhat more significant.

While the directions of motion of the mesoscale features never deviated radically from the 700 mb wind direction, there were mesoscale areas with speeds which were significantly greater than the speed of the 700 mb wind. The precipitation areas of storms 1 and 5 moved faster than the 700 mb wind by 10 m/sec. In the latter storm the mesoscale areas were moving faster than the winds 100 mb above their tops.

The upper wind data was available for levels 50 mb apart. In two of the eight storms the direction of movement of the mesoscale precipitation features was best approximated by the 700 mb wind, and in three other storms the 700 mb level was very close to the steering level. In two of the three remaining storms the center of vertical development of the precipitation areas was farther from the actual

steering level than was the 700 mb wind. In terms of speed, the 700 mb level was closest to the actual steering level in three storms and was very close to the steering level in another. Of the four remaining storms, in only case was the midpoint of the vertical development of the areas closer to the steering level than was the 700 mb level. The center of vertical development of the areas was determined to the nearest 50 mb. It was at 700 mb in only one of the eight storms. Thus, in general, the 700 mb level was quite close to the steering level, and was almost always closer than was the center of vertical extent of the precipitation areas.

2. Mesoscale velocity vs cyclone movement. The average mesoscale feature moved with a speed that was 9.5 m/sec faster than the speed of the cyclone. Of 60 mesoscale features tracked, only four had speeds that were less than that of the cyclone. The precipitation areas moved in relatively close agreement with the direction of movement of the cyclone. The average values of $(D-D_c)$ and $|D-D_c|$ were +3.25 and 13.4 degrees, respectively.

3. Direction vs orientation. It was found that the mesoscale precipitation features had a tendency to be orientated perpendicular to their direction of motion. The average value of $(\bar{D}-0-90^\circ)$ was +13 degrees, indicating that the areas were oriented in directions that averaged 77 degrees to the right of their directions of motion. The average absolute deviation, given by $|\overline{D-0-90^\circ}|$, was found to be 28 degrees.

A distinction was found between the values of $(\overline{D-O-90^\circ})$ for the storms containing type 1 bands and the remaining storms. The average value of this parameter for the three "type 1" storms was +39.7 degrees, while the remaining five storms averaged -3.8 degrees. This difference was found to be statistically significant at the 99% confidence level.

4. Orientation vs wind field. The orientations of the bands and LMSA's in these storms did not agree with the direction of the shear vector between the winds in the convective cloud layer and the adjacent layer above, as was the case for the storms studied by Elliott and Hovind (1964). The average deviation of the shear vector from the orientations was 41 degrees. Though the winds in each storm were found to veer with height, the change of direction with height was very gradual above the 700 mb level. In fact, the winds occasionally backed slightly from 500 to 300 mb. The shear vector, therefore, was approximately parallel to the winds near 500 mb, which did not differ greatly from the 700 mb winds. Since the precipitation areas moved with the 700 mb wind and perpendicular to their orientations, the orientations were not close to that of the shear vector.

The areas and bands were found to be oriented roughly along the surface isobars, as was found by Austin and Houze (1972), though there were several exceptions. For the four storms not studied by Austin and Houze, the average deviation $(\overline{O_{\text{isobars}}-\overline{O}})$ was +22 degrees, while the absolute deviations $|O_{\text{isobars}}-\overline{O}|$ averaged 26 degrees. O_{isobars} represents the average orientation of the surface isobars during the period of radar observation.

5. Recursion of mesoscale areas. There were many examples, several in each storm, of mesoscale precipitation areas following other precipitation areas and therefore moving over the same region. The average separation time was found to be about 1.3 hours, though the separation times ranged from .54 hours to 3.6 hours. For each storm the average separation time was between 1.0 and 1.8 hours.

There was a tendency for the trailing mesoscale area to develop behind the leading area and then to travel beyond the place where the leading area had dissipated. There were, however, some exceptions, and many cases where such behavior could not be verified because the areas moved into or out of radar range.

6. Time tracked by radar. The average mesoscale feature was tracked by radar for about 2.8 hours. However, radar coverage frequently began or ended during the life of a mesoscale entity, and many precipitation areas moved into or out of radar range. Thus the average lifetime of the mesoscale features was greater than the time it was tracked by radar, and probably was close to four hours. Several areas were found to have existed for 5 or 6 hours.

7. Other parameters. Several parameters were found to have variations that were related to the storm intensity, as determined by the central pressure of the system. They are listed in Table 13, below.

Table 13. The mean values of parameters that were categorized according to storm intensity.

<u>Parameter</u>	<u>Mean value for the four most intense storms</u>	<u>Mean value for the four least intense storms</u>
Range of (D-0-90°)	104 degrees	35 degrees
Range of O	105 degrees	34 degrees
Range of S	19.3 m/sec	6.8 m/sec
Range of D	52 degrees	21 degrees

Each of these differences was found to be significant statistically at the 95% confidence level, or better. Thus the more intense storms had mesoscale precipitation features that were more varied in behavior.

D. The Composite Storm

A composite or "average" storm is shown in Figure 37. The cells and heavy rain are concentrated into the LMSA's and bands, which in turn are organized into a main precipitation belt and a single minor belt. The main precipitation belt is composed of three bands, each of which is in a different stage of development. The leading band is dissipating, the second band is in its most developed stage, and the third band is just beginning to develop. There is, then, a recursion of mesoscale precipitation areas within the belt.

The bands are moving with the 700 mb wind, which is in agreement with the direction of movement of the cyclone. They are moving faster than the cyclone. However, because they dissipate at the leading edge of the precipitation belt, the belt maintains a relatively fixed

position with respect to the storm center. The bands are oriented approximately perpendicular to their direction of motion and in rough agreement with the orientation of the surface isobars.

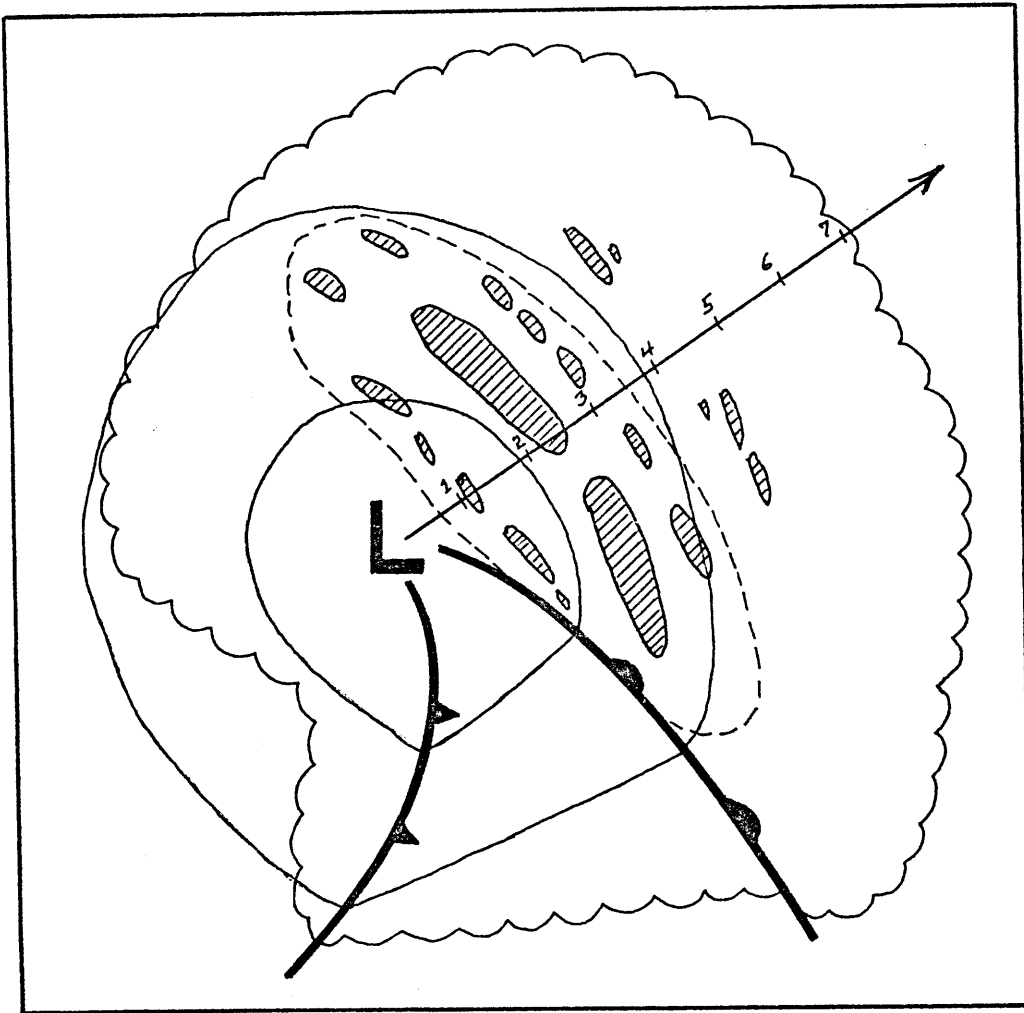


Figure 37. The composite storm. The arrow indicates the direction of motion of the cyclone. The distance scale is labeled in hundreds of kilometers. The hatched areas represent mesoscale areas and bands, while the scalloped line indicates the edge of the light precipitation. The "main belt" is outlined by the dashed line. Two isobars are shown.

V. SUMMARY AND SUGGESTIONS FOR FURTHER STUDY

A. Summary

All eight of the storms studied had quite banded precipitation structures. This result lends strong support for the contention of several investigators that such bandedness is characteristic of extra-tropical cyclones as well as of tropical cyclones.

Three distinct types of bands were identified, based on their characteristics of size, shape, and structure. Type 1 bands were composed of large mesoscale areas (LMSA's) which averaged 120 km in length and 41 km in width, and had a length to width ratio of 2.9. The bands averaged 240 km in length. Type 2 bands were large, broad bands that were not composed of LMSA's. The average length, width, and ratio of length to width were 320 km, 71 km, and 4.4, respectively. Type 3 bands were small and thin, with average length and width of 200 and 21 km, respectively. They were of LMSA size, but had a ratio of length to width of 9.5. Six of the eight storms were dominated by a single band type, while the other two storms contained two or three types of bands. LMSA's were found outside of bands in two of the storms.

It was verified that virtually all of the cells and heavy rain were concentrated into the LMSA's and bands. Other investigators have found the same organization. It was determined, in addition, that these mesoscale features were organized into one or more "belts" which preceded, and maintained a relatively fixed position with respect to,

the cyclone center. Each storm had a "main belt," and some had one or two "minor belts," in addition. The main belts averaged 300 km in width, while the overall belt widths averaged about 450 km. Belt lengths averaged at least 450 km. Thus the bands and belts could be viewed as two different scales of bandedness. Ligda, Serebreny, and Nagle (1961), however, suggested that three scales of bandedness existed in cyclones.

The bands were found to develop in the back part of the belts and to move toward the leading edge of the belt, where they dissipated. Since each belt contained two or more bands, there was a recursion of mesoscale precipitation features. The period of recursion was quite variable, but averaged somewhat over one hour.

The mesoscale areas had lifetimes that averaged at least three hours and probably close to four hours. They were steered by the 700 mb wind, in agreement with the results of several other investigations. It is significant that the steering level for the mesoscale areas was much closer to the 700 mb level than to the midpoint of vertical development of the areas. The mesoscale areas of all of the storms moved in rough agreement with the direction of the 700 mb wind, though the areas in two of the storms moved significantly faster than the winds at 700 mb or the midpoint level. The speeds of the areas of the remaining storms agreed closely with the speed of the wind at 700 mb.

The type 2 and type 3 bands were found to be oriented in a direction that was nearly perpendicular to their directions of motion. The type 1 bands and IMSA's, however, had orientations that were 50 degrees to the right of their directions of motion.

Some general comments can be made, based on these findings, about the causes of mesoscale precipitation. The similarity in band structure of storms with different paths rules out topographical causes, though such effects were important in the storm studied by Browning and Harrold (1969). Mesoscale features are certainly related to cellular convection, since they contain virtually all of the cells within a storm. However, the fact that the features move with the wind field of the storms suggests that they are related to the synoptic circulation, as well.

B. Suggestions for Further Study

There is still much to be determined about the nature and behavior of mesoscale precipitation features. A larger amount of observational data should be obtained in order to eventually determine the causes of mesoscale areas and their relationship to the larger and smaller scales of activity.

Radar data offers the best possibility of studying a large number of storms and mesoscale areas in great detail. A study with similar data but including a larger number of storms would be likely to uncover distinctions between types of mesoscale features and also between the storms that contain them. The determination of such distinctions is difficult and uncertain when a small number of storms are used.

An investigation of the cellular nature of the mesoscale areas could be instrumental in determining the relationship between convective cells and the mesoscale areas which contain them. Determination

of how the cellularity of mesoscale features varies during their lifetimes would shed light on the nature of this relationship.

Finally, detailed studies, such as those by Browning and Harrold (1969) and Elliott and Hovind (1964), should be performed. Their studies were too limited in terms of number of storms for any general conclusions to be drawn. The addition of radar data would make the study more complete.

It is realized that the recommended extensive studies require the analysis of large amounts of data. Thus automatic data processing methods would be extremely helpful. Such methods may depend on an objective and precise definition/description of mesoscale areas. Therefore, attention should be directed toward this goal.

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