A UNITED STATES DEPARTMENT OF COMMERCE PUBLICATION

WEATHER BUREAU EASTERN REGION HEADQUARTERS
Garden City, New York
December 1969

A REVIEW OF USE OF RADAR IN DETECTION OF TORNADOES AND HAIL

R. E. HAMILTON

Technical Memorandum WBTM-ER-34

U.S. DEPARTMENT OF COMMERCE / ENVIRONMENTAL SCIENCE SERVICES ADMINISTRATION

ESSA TECHNICAL MEMORANDUM

Eastern Region Subseries

The Technical Memorandum series provides an informal medium for the documentation and quick dissemination of results not appropriate, or not yet ready, for formal publication in the standard journals. The series is used to report on work in progress, to describe technical procedures and practices, or to report to a limited audience. These Technical Memoranda will report on investigations devoted primarily to Regional and local problems of interest mainly to Eastern Region personnel, and hence will not be widely distributed.

The Eastern Region Subseries of ESSA Technical Memoranda, beginning with No. 23, are available from the Clearinghouse for Federal Scientific and Technical Information, U. S. Department of Commerce, Sills Building, Port Royal Road, Springfield, Virginia 22151. Price $3.00.

LIST OF EASTERN REGION TECHNICAL MEMORANDA

No. 1 Local Uses of Vorticity Prognoses in Weather Prediction. Carlos R. Dunn. April 1965

No. 2 Application of the Barotropic Vorticity Prognostic Field to the Surface Forecast Problem. Silvio G. Simplicio. July 1965

No. 3 A Technique for Deriving an Objective Precipitation Forecast Scheme for Columbus, Ohio. Robert Kuessner. September 1965

No. 4 Stepwise Procedures for Developing Objective Aids for Forecasting the Probability of Precipitation. Carlos R. Dunn. November 1965

No. 5 A Comparative Verification of 300 mb. Winds and Temperatures based on NMC Computer Products Before and After Manual Processing. Silvio G. Simplicio. March 1966

No. 6 Evaluation of OFDEV Technical Note No. 17. Richard M. DeAngelis. March 1966

No. 7 Verification of Probability Forecasts at Hartford, Connecticut for the Period 1963-1965. Robert B. Wassall. March 1966

No. 8 Forest-Fire Pollution Episode in West Virginia, November 8-12, 1964. Robert O. Weedfall. April 1966

No. 9 The Utilization of Radar in Meso-Scale Synoptic Analysis and Forecasting. Jerry D. Hill. March 1966

No. 10 Preliminary Evaluation of Probability of Precipitation Experiment. Carlos R. Dunn. May 1966

No. 11 Final Report. A Comparative Verification of 300 mb Winds and Temperatures Based on NMC Computer Products Before and After Manual Processing. Silvio G. Simplicio. May 1966

No. 12 Summary of Scientific Services Division Development Work in Subsynoptic Scale Analysis and Prediction - Fiscal Year 1966. Fred L. Zuckerberg. July 1966

No. 13 A Survey of the Role of Non-Adiabatic Heating and Cooling in Relation to the Development of Mid-Latitude Synoptic Systems. Constantine Zois. July 1966

No. 14 The Forecasting of Extratropical Onshore Gales at the Virginia Capes. Glen V. Sachse. August 1966

No. 15 Solar Radiation and Clover Temperature. Alex J. Kish. September 1966

No. 16 The Effects of Dams, Reservoirs and Levees on River Forecasting. Richard M. Greening. September 1966

No. 17 Use of Reflectivity Measurements and Reflectivity Profiles for Determining Severe Storms. Robert E. Hamilton. October 1966

No. 18 Procedure for Developing a Nomograph for Use in Forecasting Phenological Events from Growing Degree Days. John C. Purvis and Milton Brown. December 1966

No. 19 Snowfall Statistics for Williamsport, Pa. Jack Hummel. January 1967

No. 20 Forecasting Maturity Date of Snap Beans in South Carolina. Alex J. Kish. March 1967

No. 21 New England Coastal Fog. Richard Fay. March 1967

No. 22 Rainfall Probability at Five Stations, near Pickens, S. C., 1957-1963. John C. Purvis. April 1967

No. 23 A Study of the Effect of Sea Surface Temperature on the Areal Distribution of Radar Detected Precipitation Over the South Carolina Coastal Waters. E. Paquet. June 1967

No. 24 An Example of Radar As A Tool in Forecasting Tidal Flooding. Edward P. Johnson. August 1967.

(Continued on inside rear cover)

UNITED STATES DEPARTMENT OF COMMERCE
ENVIRONMENTAL SCIENCE SERVICES ADMINISTRATION
U.S. WEATHER BUREAU, EASTERN REGION
Garden City, New York

WEATHER BUREAU TECHNICAL MEMORANDUM ER-34

A REVIEW OF USE OF RADAR IN DETECTION OF TORNADOES AND HAIL

R. E. Hamilton
Weather Bureau Eastern Region, Garden City, N. Y.

Eastern Region
Eastern Region Headquarters
Scientific Services Division
Technical Memorandum No. 34

Garden City, New York
December 1969

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF FIGURES (contd)

LIST OF FIGURES (contd)

INTRODUCTION

The use of radar in detecting precipitation was first noted during World War II. After meteorologists began using radar they quickly learned how to distinguish between echoes associated with convective precipitation and echoes associated with stratiform precipitation. Although the need for a network of radars across the United States was recognized early, the first radars were installed along the Atlantic and Gulf Coasts for detection and tracking of hurricanes, and in the midwest for detection of severe storms especially tornadoes. It is felt that the use of radar in severe storm detection is probably the most dramatic application of radar, and a critical review of the many articles would be most helpful both to radar operators and forecasters. This review will be mostly limited to tornadoes and hail storms, since many of the radar characteristics are the same or similar for both phenomena.

The definition of severe weather can be quite arbitrary; however, in this paper the definitions of severe weather, tornadoes and funnel clouds as described by the Severe Storms Forecast Unit in Kansas City are used. A thunderstorm is severe if it produces hail three-quarters of an inch in diameter at the surface and/or winds of 65 mph or greater. A funnel must reach the ground to be classified as a tornado; if not, it is classified as a funnel cloud.

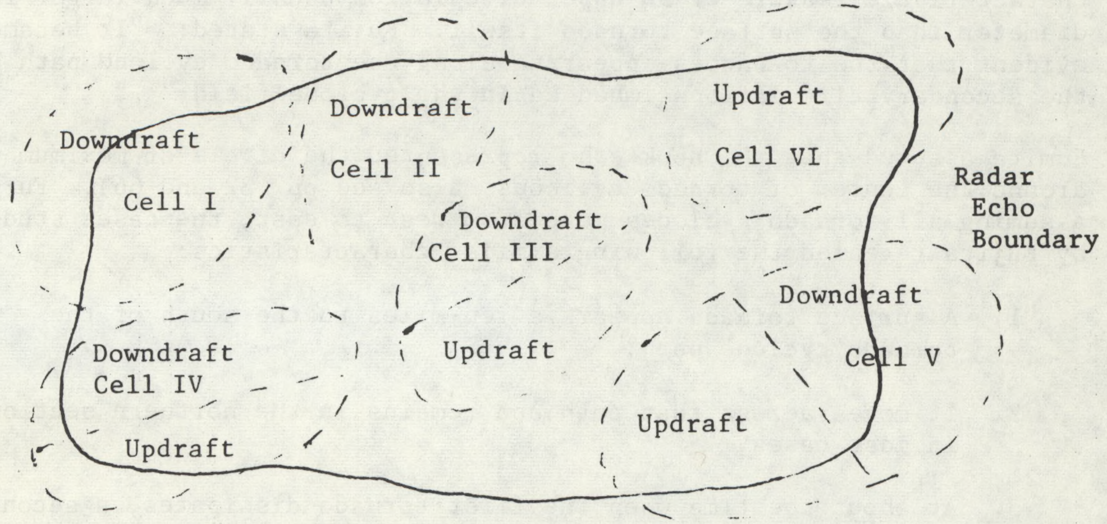
When severe weather is reported with a thunderstorm, it should indicate to the meteorologist that the convective process associated with this storm is unusually intense and may have a high degree of persistence. As will be shown in later sections, a severe storm and especially a tornado requires special air mass characteristics which are organized into a self-regenerative mechanism. The identification of a severe thunderstorm by radar so far has relied upon the determination of the convective intensity or organization of this process. Some of the most successful radar methods include echo reflectivity, echo tops, echo motion, and persistent echo configurations such as LEWP's, hooks and vaults.

Valuable research findings during the past 10 to 15 years have discovered many radar characteristics of hail storms and tornadoes and have helped provide storm models and contributed to a better understanding of the storms. A unique and completely reliable radar echo signature for severe thunderstorms is not available. However, a number of patterns have proved very reliable in detecting severe storms. Some stations have devised objective measures of echo height and tropopause penetration to indicate the probability of severe weather. Recent research on echo reflectivity has provided a highly reliable determination of which storms contain hail and which storms have the highest probability of large hail. The famous hook echo associated with tornadoes has been reinforced with discovery of the echo-free vault which has increased our understanding of these storms.

EVOLUTION OF SEVERE STORMS

In 1949, Byers and Braham classified three stages of individual thunderstorm cell evolution. These stages were: Cumulus or updraft; mature or both up and down drafts; and dissipating or down draft. Browning in 1965 stated that the above description was valid for nonsevere thunderstorm cells, but an additional stage was necessary for severe storm cells which he called SR Mature Stage. The S stands for Severe and the R for Right, since most severe local storms appear to travel anomalously to the right of the winds during this stage. It is his belief that this is the stage when tornadoes are most liable to occur.

The Byers-Braham classification of Mature Stage of an isolated nonsevere thunderstorm indicated that the cell lasts only 15 to 30 minutes before the Dissipating Stage occurs. It is well known, however, that most thunderstorms consist of a cluster of cells of different stages, as depicted in Figure 1a.



Radar Depiction of a Multicell Thunderstorm

Figure 1a

Browning believes that "a thunderstorm consists of a series of evolving sub-cells, effectively giving rise to a cell with a more persistent Mature Stage in which up and down drafts coexist in a pulsating fashion. However, given a favorable vertical distribution of temperature, humidity and wind field, the ordinary Mature Stage will evolve into a better organized Severe Mature Stage. This is a stage characterized by a very large convective cell that is devoid of significant sub-cell structure and can persist in a quasi-steady state for several hours before finally dissipating".

My own experience while living in the midwest and working with radar for eight years indicates there are many different types of thunderstorms. Some can be detected by radar in the early Cumulus Stage. The vertical motion is not unusually large and they may grow in the vertical to between 10,000 and 20,000 feet. Other thunderstorms develop more explosively. High vertical velocities associated with rapidly developing cumulus can be seen visually but not detected by radar. Then when there is enough moisture concentration and drop sizes are sufficiently large, a developing thunderstorm or cumulus congestus will suddenly appear on the radar screen. The top would in many cases first appear at 25,000 feet and continue to grow rapidly. The rapidly developing storms are most likely to contain severe weather.

Fujita in 1958 summarized the characteristics of tornado cyclones. The hook echo which appears in the vicinity of the surface tornado path is a characteristic feature of an upper circulation usually much larger in diameter than the surface tornado itself. Fujita stated: "It became evident that the tornadoes appearing along the tornado cyclone path are the secondary circulations imbedded in the cyclone field."

Fumita assumed that the hook echo represented the circle of maximum wind around the center of tornado cyclones (also see pp. 32 and 66). Further, assuming all tornado cyclones move from west to east, the cases studied by Fujita revealed the following similar characteristics:

"1. A surface tornado appears a few miles to the south of the tornado cyclone path.

2. It moves across that path and remains in the northern sections in most cases.

3. At about the time when the first tornado dissipates, a second one appears in the same manner as the first one.

4. Several tornadoes appear along the path of a tornado cyclone during its life. They form a tornado family.

5. Individual tornadoes, in many cases, are cone-shaped in their early stages and change into a rope-type funnel before dissipating.

6. There are chances that two or more tornadoes can be seen at one time inside a tornado cyclone circulation.

"It is natural from this evidence to assume that the strong cyclonic wind field of a tornado cyclone is most favorable to the initiation of the tornadoes."

ECHO ARRANGEMENT

Thunderstorms may first appear on the PPI radar scope as individual echoes or in some sort of echo pattern. There is a strong tendency to form organized clusters or lines. In severe weather situations, the forecaster is always looking for possible line formations since this indicates better organization of the parameters causing the thunderstorms.

In radar meteorology before a group of echoes can be classified as a line, it must be at least 20 miles long and have a length to width ratio of at least 5 to 1. There can be many causes of line formation such as topography, bodies of water, coast lines, upper-air phenomena, cold fronts and many others. For severe weather, the most important echo lines are associated with cold fronts and squall lines.

Squall lines are usually associated with cold fronts. Frequently they develop along or just ahead of a cold front, are oriented parallel to the front, but usually move faster than cold fronts. Therefore, they may be located hundreds of miles ahead of fronts. Our ability to detect tornadoes and hailstorms is important in that human lives and some movable property can be saved by accurate warnings. Warnings must be based on the radar operator's ability to distinguish between ordinary radar echoes and severe storms. Many times this capability depends upon the type radar used, special measurements and interpretation of the radar scopes. To an untrained operator, only the very obvious severe weather features would be detected.

The identification of most tornadoes or hailstorms by radar depend on storm features such as echo arrangement, configuration, vertical structure, reflectivity, and echo motion. These features reflect either the intensity or the persistent state of organization of the convective process.

A. Lines

Inman and Bigler in 1958 conducted a survey of midwestern severe storm situations by preparing composite echo patterns from nine ADC radars.[1] They tentatively defined two basic types of echo patterns associated with

[1] ADC Radars-Air Defense Command radars are used for the tracking of aircraft.

tornadoes. In one type the storm is isolated with clearly separated echoes. This will be discussed in detail in a later section. The second type of echo pattern was in the form of a precipitation band. Bigler in 1955 in a case study had noted that tornadoes and hail occurred during the organization of echoes into a line pattern which eventually extended over a length of 1000 miles.

In the 1958 study Inman and Bigler classified each echo pattern associated with tornadoes. They devised eight different categories of echo lines and their study revealed that echo lines were by far the most common echo distribution associated with tornadoes. Eighty-two percent of tornado-producing situations occurred with lines; however the 8 categories of echo lines described were too general to be of practical or operational value. The use of data from radar systems not designed or used for tracking weather echoes limited the total effectiveness of this study.[1] The most important finding was that most tornadoes occur with line formation. It is still highly important to carefully analyze all echo lines where conditions make severe storms possible. With the present sophistication of weather radars, it is more important to determine the precise location of a tornado or hailstorm, then forecast its movement and issue warnings, rather than classify line echo patterns. In some cases, echo lines extend up to 1000 miles in length, and it is apparent that the use of line classification for warning procedures is not operationally feasible.

(1) Line Echo Wave Pattern (LEWP)

One of the first persons to recognize the importance of echo line shape was Tepper in 1950. He reported the occurrence of a tornado at a bend in an echo line. Tepper believed the bend resulted from the intersection of two pressure jump lines.

Nolen in 1959 studied radar scope photographs of Weather Bureau WSR-1 and WSR-3[2] radars located in the plains states. He described a characteristic line echo wave pattern which he called LEWP. Nolen defined the LEWP as "a configuration of radar echoes in which a line of echoes has been subjected to an acceleration of the line immediately adjacent, with a resulting sinusoidal meso-wave pattern in the line". Nolen required that the lines and LEWPS be well defined. Figure 1 is an example of the development of a line echo wave pattern (LEWP) photographed at Oklahoma City. Of the LEWPS Nolen studied, tornadoes occurred near to the wave crest in three-fourths of the cases.

[1]ADC radars at the time of this study were not standardized; basically, there were 23 cm. and 10 cm. radars in use.

[2]WSR-1 and WSR-3 radars were aircraft detection radars modified by the Weather Bureau for weather detection. They are low powered, 50 KW., and have a wide beam width of 4°.

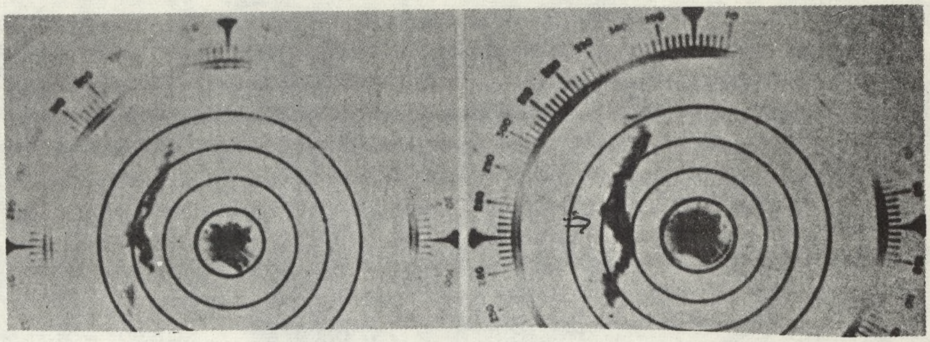


Fig. 1. Development of line echo wave pattern (LEWP) observed from Oklahoma City on 22 April 1957. Range marker interval is 20 miles. Tornado occurred at arrowhead in panel *d*. (From. Nolen, 1959.)

Cook in 1961 also studied the relationship of LEWPS to tornadoes; however, he went further in his study and also included funnels, windstorms, and hail three-quarter inch or larger in diameter. Again WSR-1 and WSR-3 radars were used in this study. Cook found "almost all LEWPS were formed by a segment of the line accelerating while other portions continued at about the same, or slightly slower, speed. Almost always, the echoes in the portion that accelerated seemed to intensify about the same time that the forward speed increased. Severe weather and/or funnels were reported with 40 of the 49 LEWPS. The majority of the severe weather was associated with or near the strongest cell as had been suggested by Bigler and was south of the crest of the LEWP. Most of the severe weather occurred after the LEWP was identifiable with a favorable distance of 10 to 40 nautical miles to the south of the crest".

Cook's study also revealed some other interesting characteristics about LEWPS. In 22 of the 49 cases there were more than one LEWP visible on the PPI scope at the same time and he felt they were near enough to be described as pairs. In all except one case, the northernmost LEWP developed first, but the occurrence of severe weather seemed to be varied and dependent on the synoptic situation. The speeds of the wave crests ranged from nearly stationary to 65 knots. The average speed of the LEWPS associated with severe weather was 30 knots while those without reports of severe weather averaged 28 knots.

Cook also investigated the coverage of echo lines as depicted by radar and this relationship to severe weather occurrence. He found that more tornadoes occurred with lines classified as scattered or broken more frequently than with solid lines.[1]

One interesting feature was that most of the hailstorms occurred with scattered lines while windstorms occurred with solid lines. He also indicated that severe weather occurred more with scattered and broken lines than with solid lines. The following table was taken from Cook's report:

TABLE I

	SCTD	BRKN	SOLID	TOTAL
Tornadoes	22	24	10	56
Funnels	5	15	3	23
Windstorms	5	1	9	15
Hailstorms	14	2	0	16
TOTAL	46	42	22	110

Mr. Cook's paper provided some very useful information which has practical application for all radar operators. There appears to be some shortcomings in his data which should be discussed. It is not clear in the report whether the LEWPS were looked for, by noting where and when severe weather had been reported, or whether the LEWPS were selected independent of severe weather occurrences. If severe weather reports were used to locate LEWPS, the data would be biased. Due to a fairly small number of cases, it appears that the risk of error of the second kind[2] would be fairly large and more data would be necessary to decrease this risk. Mr. Cook's statement, "If the line were solid, windstorms would be more likely" appears to be in error. About equal numbers of scattered and broken lines were evaluated while only half as many solid lines were analyzed. The probability of a tornado for different line coverage would be .48 for scattered; .57 for broken; and .45 for solid. If this sample were representative, then there would be around 20 tornadoes for 44 solid lines. This would compare reasonably well with scattered and broken lines and disagree with the above statement that wind storms would be more likely with solid lines.

[1]Scattered - 1/10 to 5/10 echo coverage
Broken - 6/10 to 9/10 echo coverage
Solid - greater than 9/10 coverage or continuous without breaks.

[2]Error of second kind - the risk of missing real effects of variables.

Stout, Blackmer and Wilk in 1960 studied in detail two cases in which squall lines had a wave formation. They found: "The part of the line which was distorted in the direction of line movement corresponded closely with the areas of most hail and damaging winds. The upper wind field suggested a mid-tropospheric jet at 4-5 km. in the vicinity of both LEWPS."

The LEWP is a mesoscale disturbance which forms under many different conditions. I believe the most common pressure field at the surface associated with the phenomenon is illustrated in Figure 2.

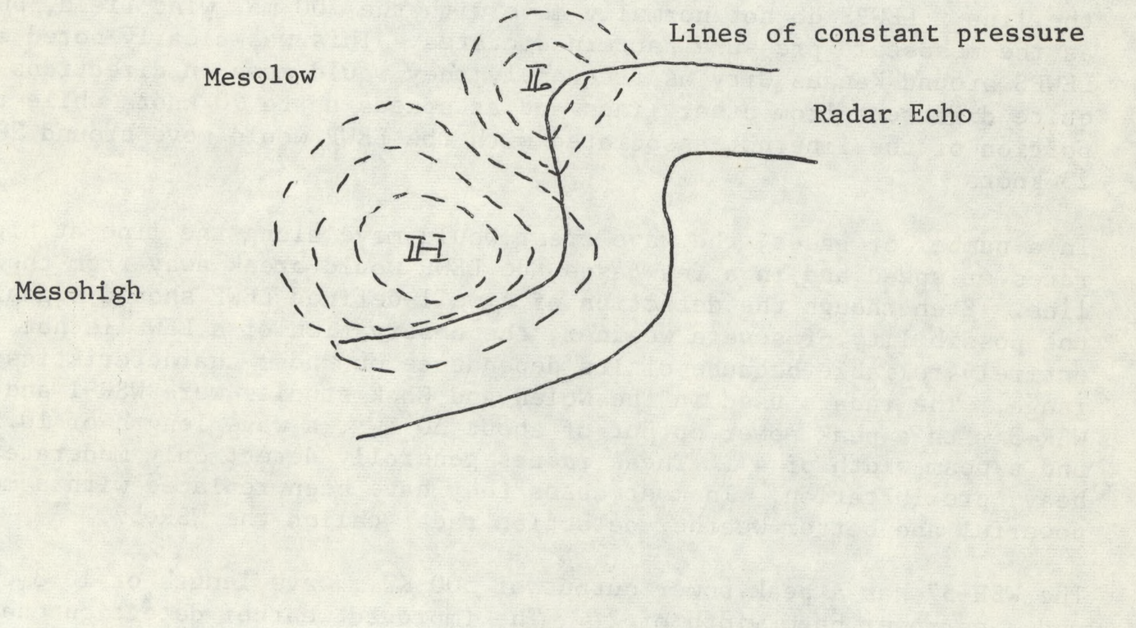


Figure 2

Illustration of a LEWP Formation and a Proposed Pressure Pattern Associated with it

In this illustration, a mesolow is associated with the wave crest and a mesohigh with the part of the line distorted in the direction of the line movement. The section of the line associated with the mesolow and mesohigh move at varying speeds, but usually faster than any other part of the line. Cook pointed out that the LEWPS usually moved from the southwest and the average speed of the LEWPS associated with severe weather was 39 knots, while those without reports of severe weather averaged 28 knots. A radar climatology conducted at Kansas City over a two-year period indicated an average line movement of around 22 knots. While at Kansas City, a number of well-defined LEWPS which moved at abnormally high speeds and usually in a direction different from the normal line movement were noted. In a number of instances, the LEWP moved at high speeds for an hour or two, then would slow down and lose its definition, then reintensify and increase its speed. These LEWPS seemed to move across the plain states in bursts of energy. In other situations, intense LEWPS would develop and remain strong and well defined throughout its lifetime which varied from less than an hour to up to four hours.

Boucher and Wexler in 1961 have shown that over a period of a few hours line motion is fairly persistent and rather conservative for any particular line and is close to the 700 mb. wind field in the vicinity of the line. LEWPS do not normally move with the 700 mb. wind field, but as the mesoscale pressure pattern dictates. This was clearly noted with LEWPS around Kansas City as frequently they would move in directions quite different from other lines and at speeds up to 70 knots while the portion of the line not associated with the LEWP would move around 20 to 25 knots.

In a number of cases, the wave crest would move along the line at high rates of speed and in a few cases the LEWP would break away from the line. Even though the detection of a well-defined LEWP should signal the possibility of severe weather, the observation of a LEWP is not entirely reliable because of its dependence on radar characteristics and range. The radars used in the Nolen and Cook studies were WSR-1 and WSR-3 with a peak power output of about 50 KW., a wave length of 10.5 cm. and a beam width of 4°. These radars generally detect only moderate or heavy precipitation. In most cases they have been replaced with a more powerful and better weather detection radar called the WSR-57.

The WSR-57 has a peak power output of 500 KW., wave length of 10.3 cm. and a narrower beam width of 2°. The improved weather detection characteristics of the WSR-57 allows the detection of some light and all other precipitation light and greater within 125 NM. radius of the radar. Because of this improved detection of lighter precipitation, there are times when phenomena such as LEWPS are masked by weaker precipitation surrounding it. It, therefore, becomes necessary for the radar operator to eliminate the obscuring precipitation by inserting attenuation into the receiver channel. This is a form of gain reduction and allows the signal to be progressively reduced so that the intensity of the inner core of targets may be determined. Since LEWPS are almost always composed of stronger echoes within the line, the use of a proper amount of attenuation will bring out the wave shape feature. In most cases, it does require a skilled radar operator to correctly operate the radar and accurately interpret the radar displays. Tracings of echo location made 5 and 10 minutes apart will reveal if the wave-like feature is likely to be a severe weather producer as discussed by Nolen and Cook or simply a small irregularity in the line pattern in which severe weather is not especially likely.

(2) <u>New Development Area</u>

It has been noted by a number of investigators and radar operators that frequently the first echo to develop in the formation of a squall line may be accompanied by severe weather. This is especially true if it develops rapidly in extent and intensity.

In the development of squall lines the northernmost cells frequently develop first with new development on the southern end of the line. Although any section of a squall line is dangerous, the area where new cells are developing frequently has the highest potential of severe weather. One apparent reason for this is the sudden release of instability as pulling the plug in a sink full of water which can sometimes help create a circular motion. High values of low level moisture and surface heating will help create very unstable air. When there is dry air in the middle levels, the instability is capped and a trigger mechanism such as a short wave trough or rapid cooling in the middle levels is required to release this instability.

I would like to provide a personal example of sudden echo development and the occurrence of severe activity on the southern and developing end of a squall line. One unusual feature of this example was the lack of the thermodynamic support in the low levels. The day prior to the outbreak of funnel clouds, a strong front had passed through the Kansas City area and a number of severe thunderstorms and squall lines with tornadoes and hail had occurred in the area. During the night, cooler air in the low levels had moved into the Kansas City area and at 500 mb a cold core low had cut off just to the west of Kansas City. With the front to the east of Kansas City, a squall line was not expected in our area. Around eleven A.M. echoes began developing rapidly just to west of Kansas City in a line oriented northeast-southwest. In a matter of a few minutes, tops increased to only about 25,000 feet, lasted 20 to 30 minutes, and then dissipated. New cells would form on the southwest end of the line, move northeastward along the line and dissipate. This squall line seemed to be associated with a small short wave at 500 mb that was moving around the cut-off low bringing with it cooler air in the middle levels that destabilized the sounding in that layer.

Shortly after the first echo was detected, a severe storm spotter noticed a small funnel cloud. During the lifetime of the line, other funnel clouds were reported; however, none of these funnels ever reached the ground and no damage was reported. After the first funnel was reported, careful analysis of the radar scope revealed a very small hook on a developing echo. It was necessary to go to short pulse, tilt the antenna to varying angles and insert attenuation to discern the very small hook. A number of hooks were detected during the morning, but they all lasted only a short time (30 minutes or less) and most of them were detected on developing storms on the southwest end of the line. As the short wave turned north around the cut-off low it moved away from the area and after about two hours, the line dissipated and was not detected again. If there had not been a dome of cold air in the lowest layers that helped prevent the funnels from reaching the ground, surely some small areas would have received some surface damage.

(3) Echo Line Intersections

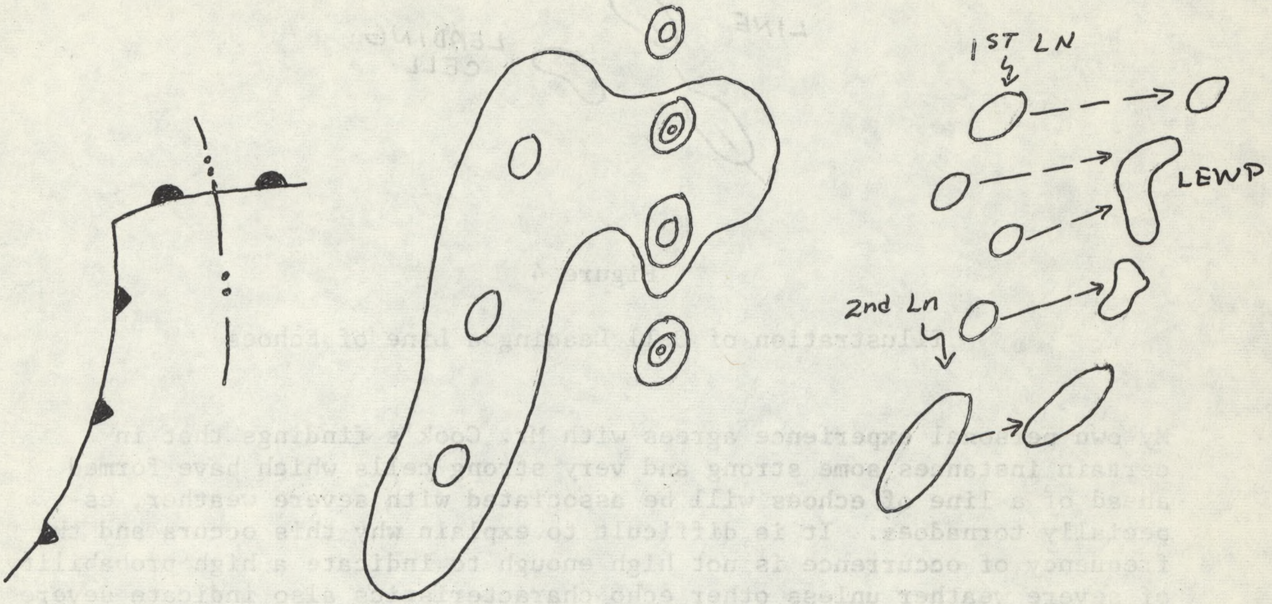
The Air Weather Service Manual on Severe Weather Forecasting has indicated that on some occasions one squall line will move faster than another, with the two lines merging sometimes. When the squall lines intersect, the intersection area is dangerous for a family of tornadoes to form. Rapidly falling pressures are typical prior to formation, but rapidly rising pressures indicate the bubble high pressure cell has materialized.

Thunderstorms are generally more severe at the intersection of a squall line with a warm front as in Figures 3a, 3b. This situation evolves into a micro-cyclone; the extreme and rapid rises in pressure found in bubbles are missing and, generally, so are vigorous wind shifts. Very rapidly falling pressures just north of the warm front and in line with the maximum low level winds presage formation of the micro-cyclone, which deepens rapidly with the approach of the squall line. The severe weather phenomena are normally confined to the immediate vicinity of the warm front.

The apparent reason for severe weather at the intersection of squall lines and at the intersection of a squall line and warm front is the increase of lift. The severe weather is triggered primarily by lift in micro-cyclones at the intersection and by overrunning of bubbles. Bubbles are precipitation and downrush induced micro-anticyclones within a general instability area.

In some situations where two squall lines intersect, it has been noted that a LEWP may develop with the crest at the intersection (Figure 3c). This formation of a LEWP is not as common as the formation on a squall line and literature describing this situation could not be found. A somewhat similar condition is the convergence of echoes in which echoes merge into a single larger echo mass. This special situation will be discussed in detail in the next section.

Tepper in 1950 suggested that the intersection of two unequal pressure jump lines in the atmosphere would produce a zone of wind shear favorable for tornado formation. He explained this by an analogy to the intersection of two unequal shock waves in gas dynamics.



3a
Synoptic Picture

3b
Radar Display

3c
Intersecting Squall Lines

B. Individual Echoes

(1) Cell Leading Line

Cook in 1961 in his study of LEWPS reported 19 cases where cells developed ahead of a line of echoes and were overtaken by the line as it moved eastward faster than the cell. In nine cases severe weather was not reported; however, the cells were small and only detected a few minutes when they were overtaken by the line. In two cases funnels were reported even though the cell was classified as weak in intensity. Tornadoes were reported with eight cases and the thunderstorms were considered moderate to strong in intensity. They were also larger in diameter and had a longer lifetime than the nonsevere cells--35 minutes to 1-1/2 hours. Cook's conclusions were: "These cases tentatively suggest that the intensity and size of the cell that is overtaken by the line is a clue not only to the probability of a tornado, but to its intensity also. Of course, much more data need to be checked before more definite conclusions can be made."

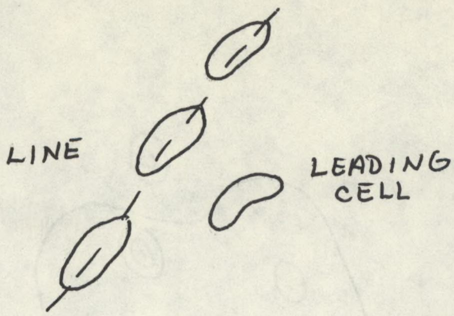


Figure 4

Illustration of Cell Leading a Line of Echoes

My own personal experience agrees with Mr. Cook's findings that in certain instances some strong and very strong cells which have formed ahead of a line of echoes will be associated with severe weather, especially tornadoes. It is difficult to explain why this occurs and the frequency of occurrence is not high enough to indicate a high probability of severe weather unless other echo characteristics also indicate severe weather. This condition should be used as an alerting mechanism for the radar meteorologist and forecaster to make a careful analysis of the situation. This and other parameters which highlight suspected echoes is important since on a radar scope there are usually hundreds of individual echoes all moving and changing shape and character.

It should also be mentioned that the WSR-57 radar now in use displays many more echoes than a WSR-3 or -4 making it more difficult to identify echoes capable of producing severe weather. Most echoes that develop ahead of lines are usually weak to moderate in intensity and are short-lived. Those that reach strong intensity and last for 30 minutes or longer should be suspected of severe weather and checked for other severe echo features.

(2) Converging Echoes

Many investigators in New England and the midwest have detected tornado development when separate echoes merge into a single larger echo mass. Stout and Hiser in 1955 revealed a high degree of association of echo convergence and vortex motion with tornadoes, severe winds and hail (Figures 5 and 6). Statts and Turrentine in 1965 studied the Blackwell, Oklahoma and Udall, Kansas tornadoes. They found a strong convergence of echoes toward the tornado producing storms (Figure 7).

Bailey in 1955 showed that a tornado occurred in a band of maximum vorticity of echo motion. Convective activity increased more noticeably and lasted longer in the area where echo speeds were greatest.

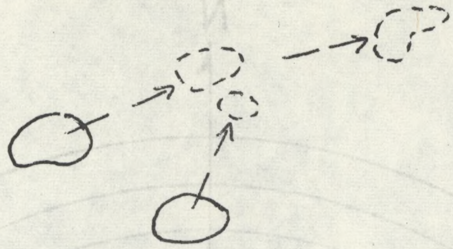


Figure 5

Converging Echoes

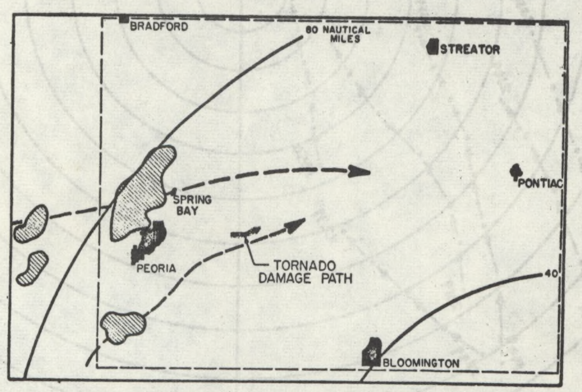


Figure 6

Echoes at 1649 CST, 28 May 1954, and paths of centers of converging echoes. Dashed rectangle corresponds to precipitation map. (From Stout and Hiser.)

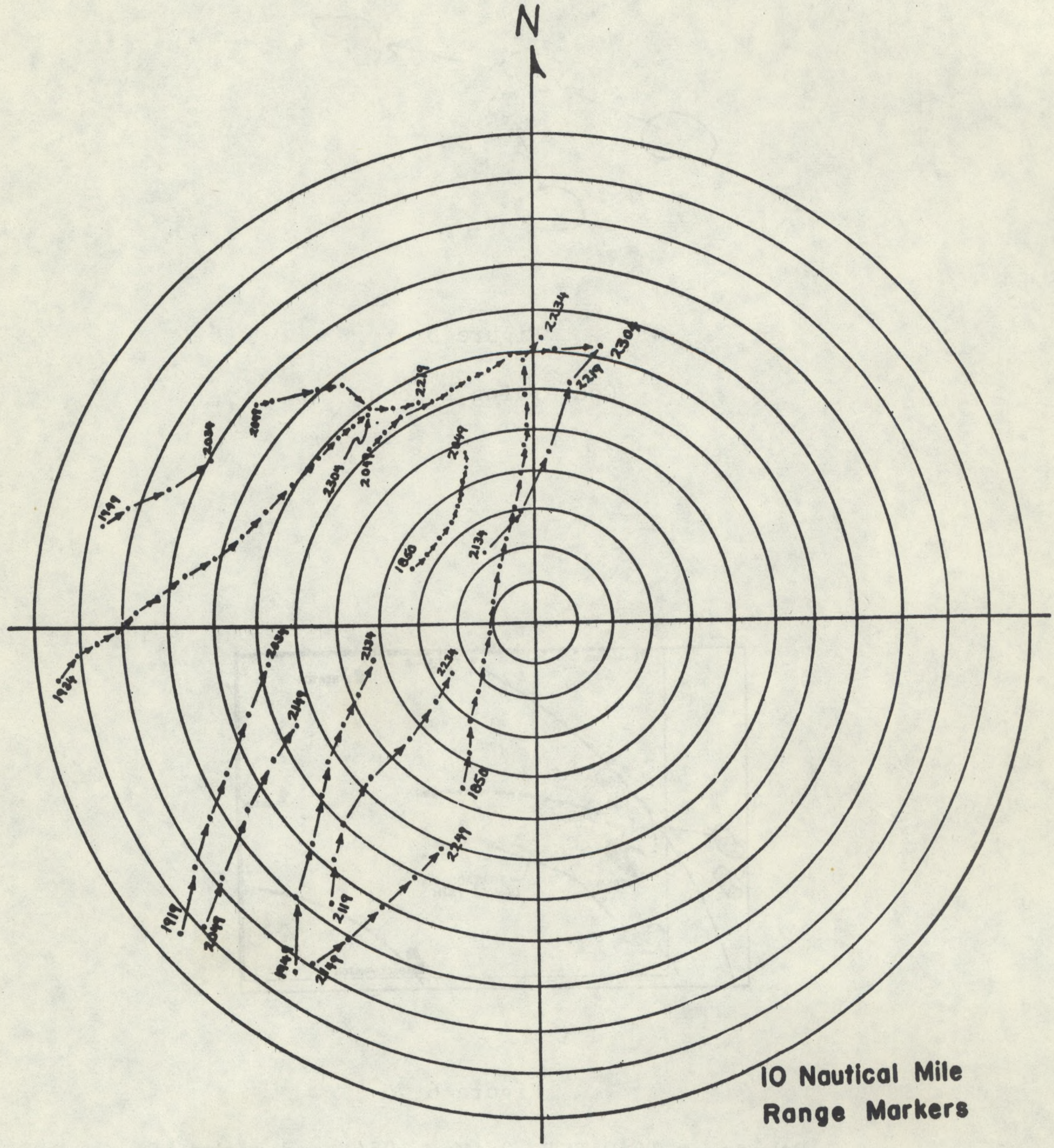


Figure 7

Trajectories of major echoes during evening of tornadoes.
From Statts and Turrentine.

In contrast to the above findings, Hiser in 1958 reported that echo convergence in Florida occurs frequently but was not generally associated with tornadoes or destructive winds although intense rains often occur. One possible reason for this is that Florida is considered to be in the subtropics where the dynamics are considered to be weaker than in the tornado belt. The convergence of echoes could result from thermodynamics or water-land contrasts which may have greater controlling effects in the subtropics than in the mid-latitudes.

A phenomenon closely related to converging echoes and echoes in close proximity to each other was described by Browning in 1964. This same interaction of severe storms is also likely in a line of thunderstorms where they are close together. Browning had derived an air flow model to account for the three-dimensional structure of severe storms which display a hook feature when viewed by a horizontally-scanning radar. The principal features of the model are summarized by Browning in Figure 8. In his summary, SR stands for a severe storm which travels to the right of the winds in the middle troposphere.

The interaction between two severe local storms both with hook echoes traveling side-by-side, with their hooks separated by only 15 mi., will be discussed and illustrated in detail. A discussion of the Browning-Ludlam model will be delayed until a later section (see page 2). Figure 9 is a schematic of the PPI view of two severe storms A and B as described by Browning.

Note that some of the precipitation falling ahead of storm B was detected by radar to be drawn toward the hook echo of storm A. "Relative streamlines are drawn for air approaching the updrafts at low levels and leaving them at high levels. Parts of the echo believed to be associated mainly with downdrafts are stippled more lightly. The protrusion from storm B is thought to be due to light rain which enters the inflow toward A's updraft."

The part of storm B which seems to be pulled out of its rain area toward the echo-free region just ahead of A's hook echo can be explained as particles that descend from storm B into the area of moist air which is moving rapidly into the updraft region of storm A. Browning describes the connecting finger as a "tilted curtain of echo, inclined upward from west to east". The detailed 3-dimensional radar study together with nearby wind data implies that an updraft was present at low levels within the area without echoes just ahead of the hook echo as well as the "echo free" vault (also see p. 2). These echo characteristics, converging echoes, leading cell theory and storm interaction cannot be used as a positive indication of severe weather. However, the knowledge that echoes have any or all of these features can help to identify severe storms. Frequently severe weather spotters call the radar operator on special spotter telephones and report severe weather. By knowing the location of each spotter he can check all echoes in that vicinity, locate any storms with severe weather features, and put out warnings for other areas in the path of the storm so people can take necessary precautionary measures.

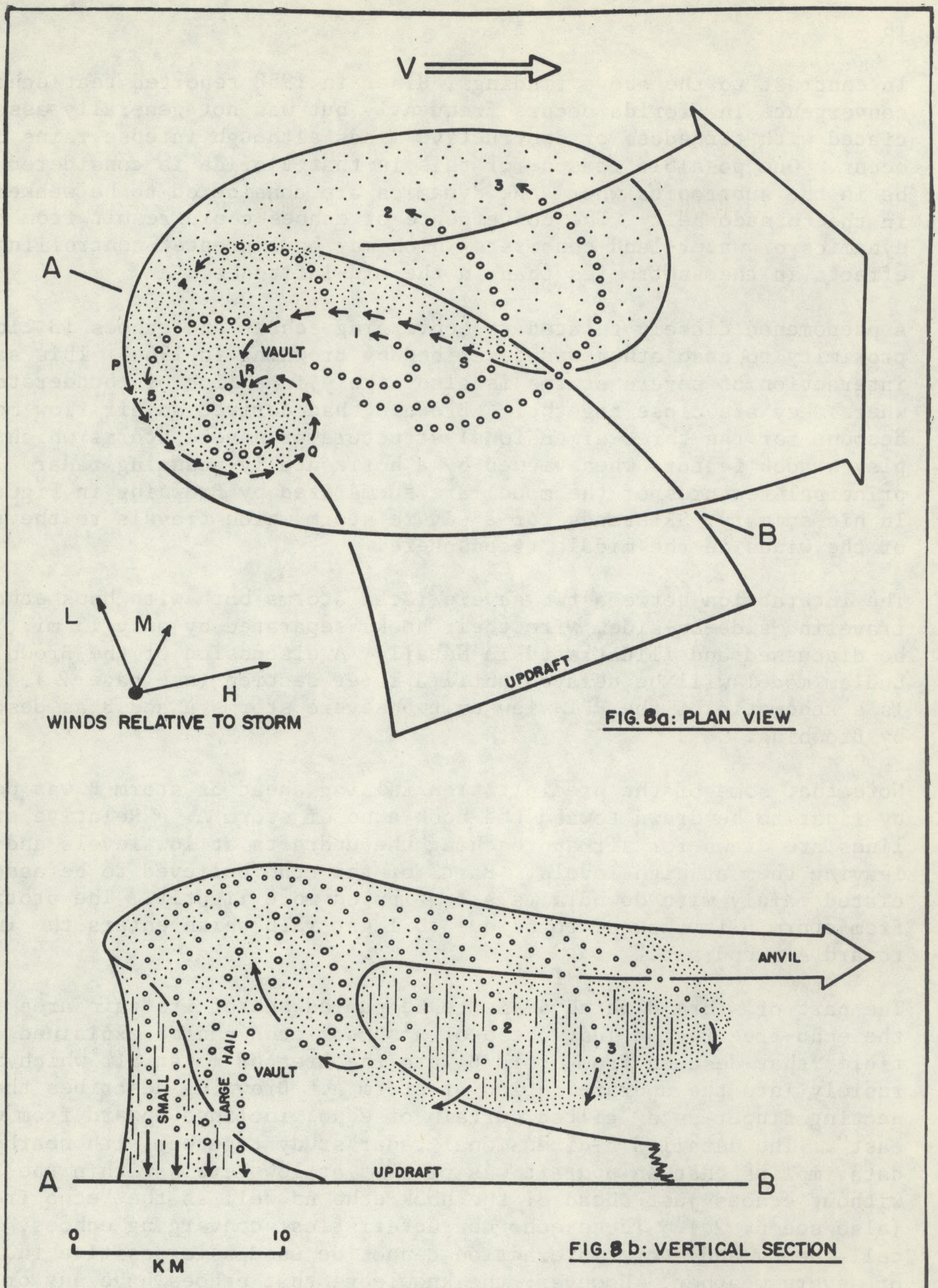


Fig. 8 Schematic horizontal (Fig. 8a) and vertical (Fig. 8b) sections qualitatively illustrating precipitation trajectories in different parts of an SR storm traveling at a velocity V. In both figures the extent of the updraft is represented by solid curves and precipitation trajectories are represented by dotted curves. In the horizontal section the extents of rain and hail close to the surface are represented by light and heavy shading, respectively, and the arrows around PQRS indicate the direction of motion of protuberances on the edge of the low-level radar echo. The vertical section along AB is oriented in the direction of the mean wind shear, into which the updraft is inclined at low and medium levels. In the vertical section the presence of downdrafts with strong normal components of motion is indicated by broken vertical hatching. On the downshear side of the updraft (right side of page) these components are directed into the page; beneath the updraft, on its upshear side, they are directed out of the page

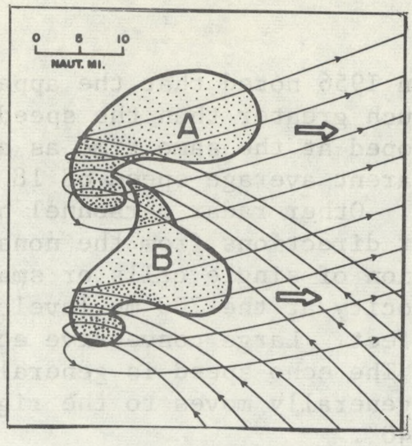


Fig. 9 Schematic diagram showing a low-level plan view of the radar echoes from two neighboring severe local storms A and B ($z = 10^2$ $mm^6 m^{-3}$). Relative streamlines are drawn for air approaching the updrafts at low levels and leaving them at high levels. Parts of the echo believed to be associated mainly with downdrafts are stippled more lightly. The protrusion from storm B is thought to be due to light rain which enters the inflow toward A's updraft. (From Browning)

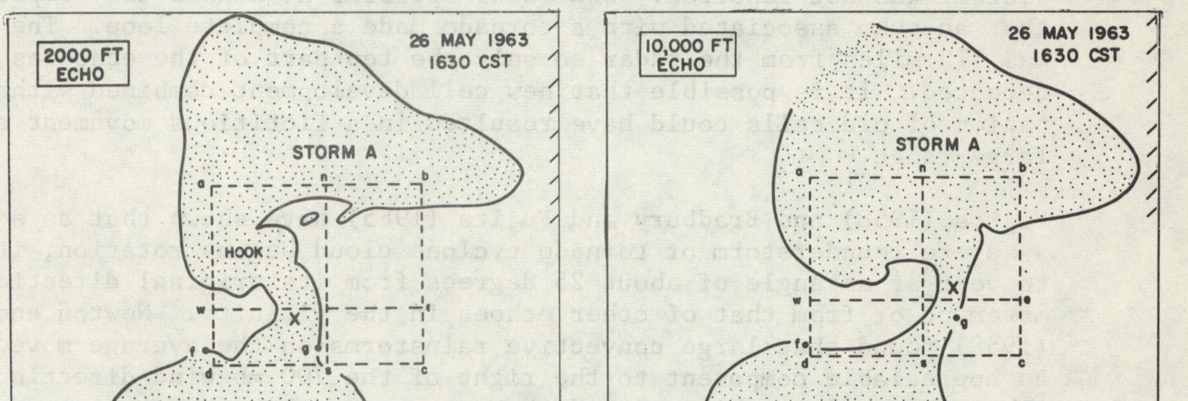


Fig. 10 Extent of echo ($Z = 10^2 mm^6 m^{-3}$) at 2,000 and 10,000 ft. (above MSL) within storms A, B, and C. Locations of radars are indicated: To the south of positions f and g the WSR-57 data were employed, while, to the north, the high resolution FPS-6 data were used. X is the curtain of precipitation being drawn from B toward A. (From Browning)

(3) Echo Motion

Staats and Turrentine in 1956 noted that the apparent speed of movement of certain echoes was much greater than the speed of others. A non-severe echo which developed at the same time as a tornado and in the same general area had an apparent average speed of 18 knots, while the tornado had a speed of 33 knots. Other radar personnel have reported that severe storms move in different directions from the nonsevere storms. Newton in 1963 found that the motion of single cells or small clusters is closely related to the wind velocity at the 700 mb level and to the mean wind between 5,000 and 20,000 feet. Large convective echoes do not move with the wind at any level. The echo speed is generally less than the wind speed at 700 mb and it generally moves to the right of the upper winds, varying between 0° and 40°.

When storms move in different directions from surrounding echoes, it may mean that the echo extends to greater heights than the other storms and higher level winds are steering the storm. It could also result from the formation of new convective cells, predominately on the right flank and down wind from the echo. This process can cause the large echoes to propagate to the right. While at Kansas City a number of storms were noted that moved in strange and erratic paths and frequently these storms were associated with severe weather. However, there were cases when severe weather was not reported. One radar operator at Kansas City reported that an echo associated with a tornado made a complete loop. The echo was 175 miles from the radar so only the top part of the echo was being detected. It is possible that new cell development combined with dissipation of old cells could have resulted in a fictitious movement at that large range.

Fujita (1958) and Bradbury and Fujita (1965) have shown that as soon as a severe thunderstorm or tornado cyclone cloud begins rotation, it tends to veer at an angle of about 25 degrees from its original direction of movement or from that of other echoes in the vicinity. Newton and Katz (1958) found that large convective rainstorms on the average moved with an appreciable component to the right of the 700 mb wind direction. Others have also substantiated that severe weather phenomena tend to follow a path to the right of the direction of the middle tropospheric winds.

On Palm Sunday 1965, Fujita and Bradbury found that all tornado producing echoes moved to the right of the direction of the 500-mb winds, but the degree of veering was not the same in all cases. The maximum angle of veer was approximately 22 degrees. Those echoes which did not produce tornadoes or intense damage-producing thunderstorms moved generally in the direction of the stream lines of the 500-mb. winds.

Stout and Hiser in 1955 reported that high echo speeds were associated with severely damaging winds. They also found that pivoting squall lines appear to produce destructive winds when the end opposite to the pivot point moves rapidly and has well-developed thunderstorms. This appears frequently in squall lines. One part of the line, usually the northern part, will move faster than another part of the line. It has been my experience that strong gusty winds are more common with this feature, but if the echoes associated with the rapid moving line are in the strong to very strong category, then hail and tornadoes may result, especially if other severe features are noted.

In summary, an echo or echo complex that moves erratically and significantly different from nearby or surrounding echoes should be suspected of producing severe weather, especially if the storms are strong in intensity. Pivoting squall lines where one end moves rapidly should also be an alerting feature of possible severe weather. These features are not as reliable as other features and require constant and sometimes prolonged surveillance. Propagation must be subtracted from echo movement to obtain the true echo movement.

ECHO CONFIGURATION

A. Hook Echo

The first report of an unusual radar echo associated with a tornado was made at Maxwell Air Force Base, Alabama in 1945. Although radarscope photographs were not made, there was visual observation of a precipitation area shaped like a "6" associated with a tornado that passed near the base. The first photograph of the echo pattern now referred to as a hook echo was made in 1953 by the Illinois State Water Survey staff and is shown in Figure 11. Some important findings were: (1) a large thunderstorm was present before the tornado developed; (2) the tornado was not directly under the thunderstorm but to the southwest of it; and (3) the tornado was associated with the hook echo on the rear right side of the thunderstorm cloud.

Fujita in 1958 made a detailed analysis of echo motion associated with the Illinois tornado. He combined the radar data with a mesoanalysis of the surface pressure and wind field as shown in Figure 12. Fujita found a tornado cyclone which had a small circulatory system of about 3 miles in diameter, while the tornado had a much smaller diameter and was located one to two miles south of the cyclone center at the ring of maximum winds. The hook echo appeared to rotate and revealed a cyclonic motion with inward-spiralling surrounding echoes. This system was called a "tornado cyclone" by Brooks in 1949, who discovered the phenomena by studying surface observations of pressure in great detail. Fujita's mesoanalysis of the wind and pressure fields for the Illinois tornado also revealed an intense meso-high in the northwest portion of the thunderstorm cell.

Time lapse movies of 10 or 12 classic hook echoes detected by the Kansas City Weather Bureau's WSR-57 were reviewed. A definite inward spiralling and cyclonic motion was clearly visible and in a few cases circulation bands appeared. Most of the tornadoes viewed on film were damaging tornadoes. It is believed that if a well defined hook is visible, there is a high probability that a damaging tornado will be associated with it.

Fig. 11 Hook echo of Champaign, Illinois, tornado photographed on APS-15 radar scope by Donald A. Staggs of Illinois State Water Survey, Urbana, Ill., on 9 April 1953. This is the first occasion in which a tornado hook echo was recognized and photographed. At this time, 1715 CST, the tornado was about 10 miles to the NNE of the radar, in the southern end of the hook. (Photograph courtesy of Mr. Glenn E. Stout.)

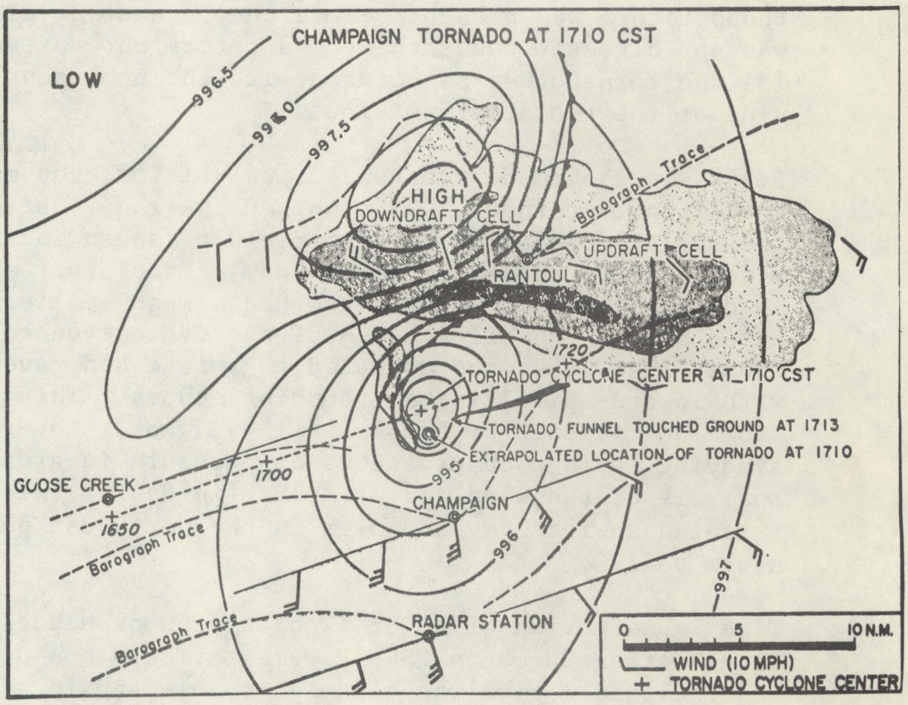


Fig. 12 Mesoanalysis of the wind and pressure field and radar echo of the Champaign, Illinois, tornado cyclone at 1710 CST, 9 April 1953. (From Fujita, 1958.)

It should be pointed out that some hooks have been observed where no reports of tornadoes or severe weather have been reported and these hooks have been classified as false hooks. It takes an experienced radar operator to properly evaluate a questionable hook echo. The features of the hook are fairly small in scale and their observation depends on range, beam width of the radar, on surrounding echoes, and on the angle of view of the radar. The shorter the range between tornado and radar and the narrower the antenna beam in both azimuth and elevation the better the chances are of observing the hook echo. Most hook echoes are observed within 60 miles of the radar. However, Statts and Turrentine in 1956 found a hook echo associated with the devastating Blackwell, Oklahoma tornado, clearly discernible at 80 miles. Detection at this range is not common and, it is believed, will only occur with very large tornadoes.

The Weather Radar Manual lists the following distinctive features of a bona fide hook echo:

"(1) The hook is located in the trailing half of the main echo with respect to its motion and occurs most often in the right rear quadrant.

(2) The hook is formed by a cyclonic swirl of a part of the main echo into a hook-shaped appendage.

(3) The hook is a small scale feature having a dimension of about 10 n. miles or less from the main body of the echo to the farthest extremity of the hook.

(4) On occasions, the hook has preceded the formation of a tornado.

(5) The few RHI cross-sections that have been measured through a hook show it to extend as high as 35,000-40,000 ft. Thus, it appears to be the echo from a high level vortex.

(6) The hook forms in a short time; usually only a few minutes are required.

(7) The duration of an identifiable hook varies greatly from a few minutes to an hour, or even more in some cases. The fluctuations in the hook display, from clear-cut to indistinct, appear to be related to corresponding vigor of the tornado and width of its track. Thus, a crisp, clear hook appears to be related to a narrow funnel with an unmistakably clear track on the ground whereas a large diffuse hook may be associated with a funnel aloft or with a wide and more diffuse damage path on the ground. Many more observations are needed to confirm these speculations, however."

There is good agreement between most researchers and radar operators on the first four features of a bona fide hook echo. There is some small disagreement as to whether the hook or tornado cyclone is a low level or high level feature, however.

Garret and Tice in 1957 reported on a series of RHI observations of a tornado which showed an appendage which developed at about 20,000 feet and extended downward to the ground with time. Bigler in 1955 also detected hook echoes at levels above 30,000 feet when the tornado cyclone was developing and then found that the hook had built downward to 10,000 feet later in the tornado cyclone's life cycle. Prosser in 1967 reported on the devastating tornado that struck Topeka in 1966. He found a definite life cycle to the hook echo associated with the tornado cyclone. The hook developed at high levels early in the storm's life and built downward with time. He also described a singular feature of great reflectivity called an "asc" which was associated with the tornado vortex and damage path. The high reflectivity is believed due to debris in the tornado vortex.

Fujita in 1965 studied dual hook echoes using antenna-tilt step photographs. He found the hook echo up to about 15,000 feet, but above 25,000 feet the cloud overhang obscured the hook echo. From these results, he concluded that the hook feature was a low level phenomenon.

My own experience has been limited to a few observations of hook echoes mostly using the PPI display. Hook echoes at high levels and also low levels have been observed. The very clear-cut hooks associated with tornadoes seemed to display the hook echo from near the surface to at least 25,000 feet. There were cases, however, where it was necessary to tilt the antenna to detect the hook. Except in the case of very large tornadoes which frequently were associated with individual echoes and had the classic hook shape, it was necessary to use attenuation (to reduce the signal) to bring out the hook.

It appears that a hook may either be a high or low level feature depending on the storm. The hook may develop at high levels and build down with time; however, it is felt that there are insufficient cases to prove this point at this time. It is apparent that surveillance procedures must include checking the upper and middle levels of suspected storms and reduce the receiver gain to enhance the detection capability.

Not mentioned as a criteria for distinguishing a true hook echo is intensity. As discussed in the section on reflectivity, most tornadoes are associated with strong echoes and only a few with moderate intensity echoes. From my experience and from findings of others, it seems very likely that the stronger the echo associated with the hook, the higher the probability it is a bona fide hook and not just due to chance echo positioning or configuration.

Due to a high probability that a tornado will be associated with a bona fide hook, forecasters presently issue alerts or warnings of possible tornadoes even before reports of a tornado have been received. Frequently reports of tornadoes are received too late to provide warnings to communities in its path since the life of the tornado is frequently short except for the very large and devastating tornadoes which may last for hours.

The hooked echo has been observed without tornadoes but usually some type of severe weather has been reported. Donaldson stated that Lintner and Atlas in 1956 reported hailstorms and windstorms associated with a hook, and in 1960 Schaefer reported severe weather, but no tornado associated with a hook echo. Other radar operators have reported detecting a hook echo without severe weather; however, in many of these cases, they had seen false hooks which frequently occur on the radar. This type echo does not have the appearance of a spiral band wound around a cyclonic vortex and usually exceeds 10 n. miles in diameter.

Many tornadoes have occurred without the characteristic hook. Frequently tornadoes that are associated with line formations do not exhibit hooked echoes. Some reasons why a hook may not be discernible are: (1) excessive range from the radar; (2) excessive beam width to detect such a small scale phenomenon; (3) attenuation of 3 cm and 5 cm radar signals; and (4) improper use of the radar to detect the hook.

Many hook echoes will go undetected unless the operator frequently tilts the antenna to find the level where detection of the tornado cyclone is best. Most hooks are also masked by precipitation and unless the receiver gain is reduced to eliminate the obscuring feature, it will not be seen. Therefore, unless the radar operator has a good radar, the tornado cyclone is close to the radar and the operator can devote his full attention to operating the radar properly, most hooked echoes will go undetected.

In conclusion, the bona fide hooked echo is associated with the well-organized tornado cyclone in which tornadoes frequently, but not always, occur and large hail is likely.

B. Echo Pendant

Echoes with protrusions usually on the southwest portion of a thunderstorm cell may be associated with severe weather (Figure 13). This type echo might have a hook shape with a cyclonic circulation if examined more closely. However, because of the small scale of this feature, it is possible that the radar resolution is not sufficient to reveal the circulation. As example of a tornado associated with this type echo will be discussed in more detail later in this section. This type echo is more difficult to identify than the "6" shaped echo and not as reliable an indication of severe weather.

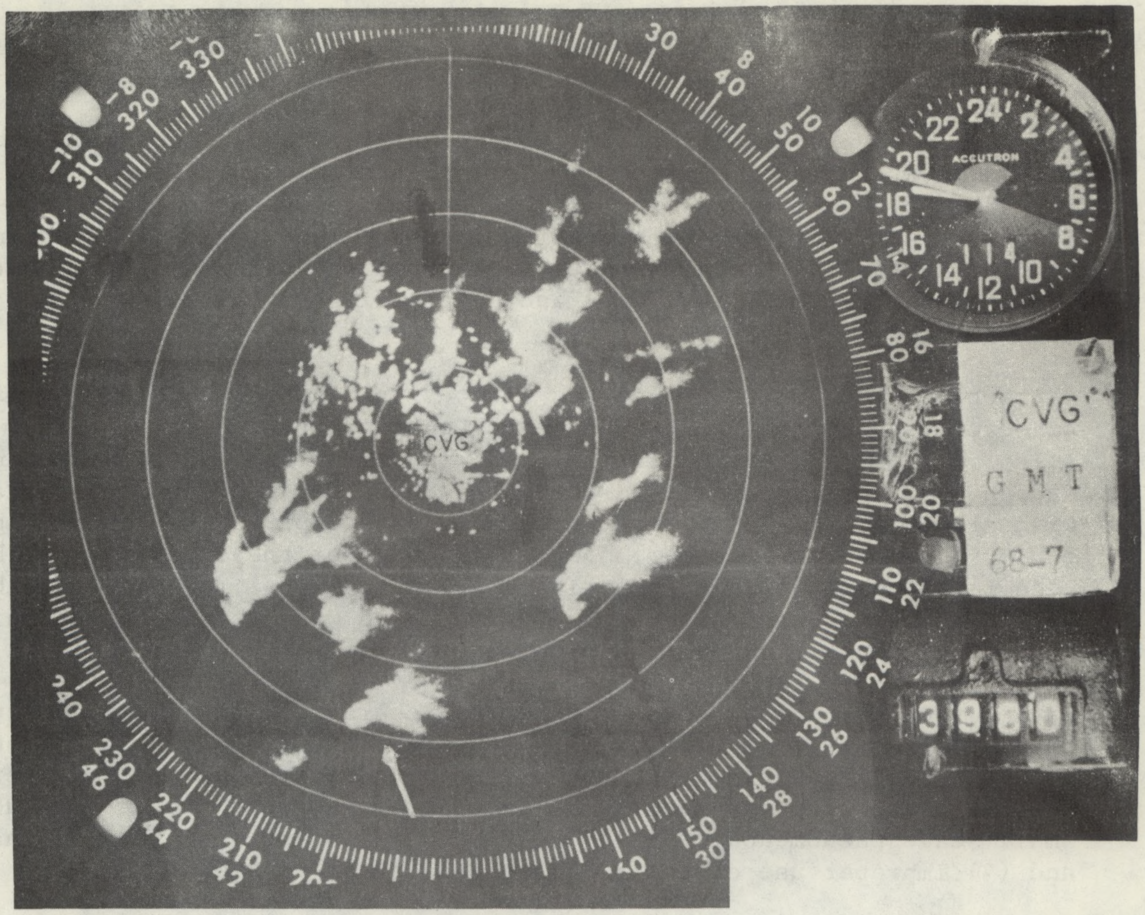


Fig. 13 - Echo Pendant 200/35

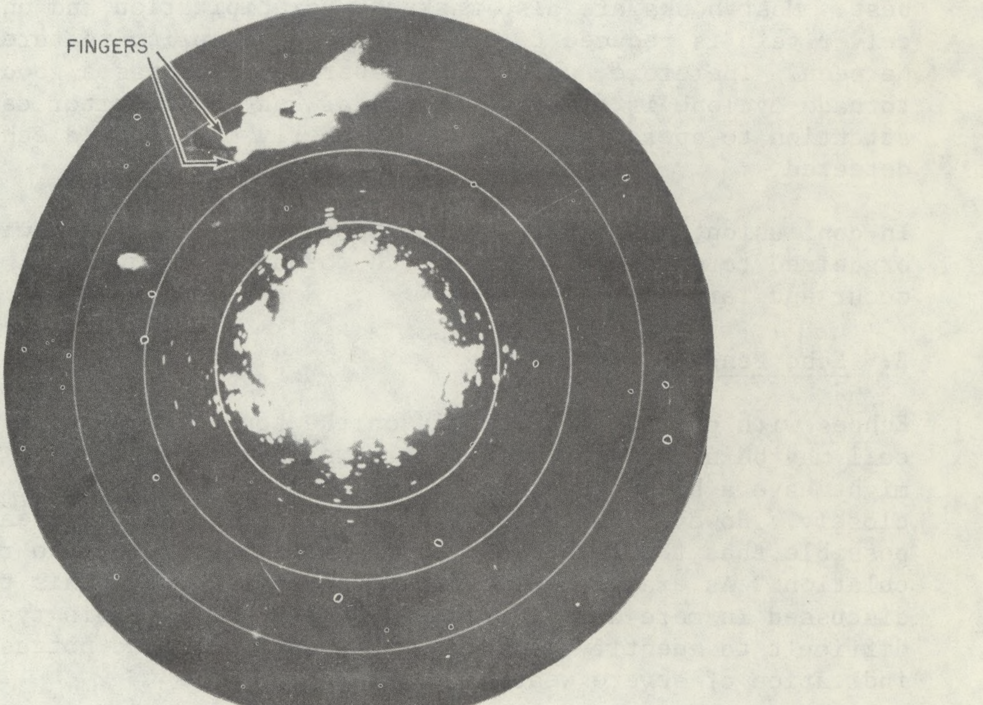


Fig. 14 WSR-57 (10 cm) PPI Showing Intense Thunderstorm Echo NNW of Radar Site and Characteristic "Fingers" Usually Associated With Hail. U.S. Weather Bureau Radar, Kansas City, Missouri. 100 n. mi. Range.

C. Fingers

Harrison and Post in 1954 found that thunderstorm echoes with fingers protruding generally from the upwind side were frequently associated with hail of one-half inch or more in diameter (Figure 14). These fingers are believed to be hail shafts falling on the fringes of the storm. The fingers would change shape rapidly and at times give a scalloped edge appearnce. This sudden change in shape was believed to indicate that hail falls in bursts. Most of Harrison's data was obtained from 5 cm aircraft radars which have different detection characteristics from most ground based radars. Their research was conducted on the eastern slopes of the Rockie Mountains, where there is a high hail-to-thunderstorm ratio. In other areas of the country where the ratio is much lower and where different types of ground radars have been used, the relationship between echo fingers and scalloped edges and hail has not been as good.

D. "V" Notch

Investigators have noted that thunderstorm echoes may collide and merge into a single large echo mass (Figure 15). This merger may form a "V" notch, and when this occurs a tornado may occur at the "V" notch.

"V" notches have also occurred with very strong echoes when a 3 cm radar was used. The notch is caused by precipitation or hail attenuation. With the 10 cm WSR-57 radar, attenuation is very small; therefore, a "V" notch cannot be caused by precipitation attenuation. However, "V" notches have been detected on the WSR-57 radar as illustrated in Figure 16.

The "V" notch is usually associated with hooked echoes and echoes with protrusions and may be a result of the inward-spiralling and cyclonic motion of precipitation and hail particles toward the tornado cyclone center. A rather poor comparison might be drawn to the hurricane and the precipitation bands that are drawn toward the storm center with dry areas interspersed with these rain bands.

An example of echoes that possess many of these severe characteristics was photographed by the Cincinnati WSR-57 during a tornado outbreak on April 23, 1968.

On April 23, at 1752Z, the first of four tornado watch areas for Michigan, Ohio and Kentucky was issued by National Severe Storms Forecast Center (NSSFC) at Kansas City, Mo. The 1745Z radar reports indicated thunderstorm activity increasing in intensity through eastern Indiana, western Kentucky and extreme western Ohio. A line of strong thunderstorms extended from near Lansing, Michigan to the Indiana-Ohio border and south-southwestward to just south of Fort Wayne, Indiana. This line produced numerous tornadoes in southern Michigan and northern Ohio. Further south a very strong storm 43 n. miles southwest of Cincinnati was increasing in intensity and had developed protruding hail fingers.

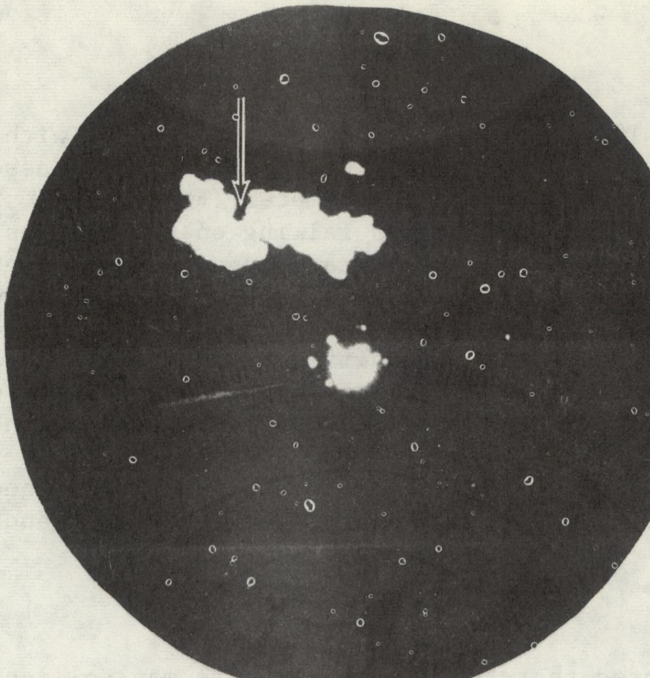


Fig. 15

AN/FPS-77 (5.4 cm) PPI Showing V Notches Resulting from Recent Merger of Two Thunderstorm Echoes. A Severe Hail and Windstorm Occurred at Location Indicated by Arrow. AWS Radar, Hanscom Field (Mass.) 30 n. mi. Range, 5^{o} Elevation.

Fig. 16 - "V" notch at 140/22

By 1835Z, the storm had moved east 40 n. miles to 25 south-southeast of Cincinnati and had developed a hook-shaped appendage located in the trailing half on the southwest portion of the main echo (Figure 17). Note the hook is a small scale feature with dimensions less than 10 n. miles from the main body of the echo to the farthest extremity of the hook. Also note the V-shaped notch on the forward or northeast part of the main echo. Mr. Dill, Cincinnati radar operator, indicated the hook was detected best at one-half degree antenna tilt, 33 dB (decibels) attenuation, STC on and with the scope on 50 n. miles range. In this storm, the hook had already built down to a very low level and was probably on the ground. Mr. Dill alertly reported the hook echo and possible tornado in his radar reports. Special RAREPS and narratives were routinely transmitted to keep everyone informed. Public reports received later confirmed that a tornado had touched down near Falmouth, Kentucky, around 1830Z, the time the hook was first noted on radar. The tornado moved eastward at 40 knots and remained on the ground for over an hour.

Figure 18 illustrates the same activity four minutes after Figure 17 with the radar operating on long pulse, normal gain, one-half degree elevation, 0 dB attenuation and STC on. Note that the hook is more discernible than in Figure 17. This is a little unusual since hooks are frequently masked by surrounding precipitation and require some attenuation and tilt of the antenna for optimum detection.

In Figure 19, 33 dB has again been inserted with the other settings remaining the same as in Figure 18. The hook southeast of the station is still visible. The public reported the tornado still on the ground and near West Union, Ohio at this time. The echo at 195/35 (195 degrees, 35 n.mi. from the radar) has a protrusion on its southwest portion and fingers on the eastern or leading edge. A hook is not visible, but the echo has all the features of a severe storm. The echo northeast of CVG (65/11) has a finger extending to the south of the echo, although no hook is visible. A tornado associated with this echo was reported near Bativa around 1900Z. Numerous funnel clouds were reported about this time in eastern Cincinnati suburbs. Baseball-size hail from the storm at 360/22 was reported around 1840Z.

In Figure 20 there are 3 severe storms on the scope. Hook echoes are located at 70/18 and 130/30. The echo at 190/32 has a pronounced protrusion on the trailing side and a "V" notch in its eastern portion. Hail was reported with this echo about this time and 50 minutes later a tornado was reported at Dover, Kentucky. Radar settings remain the same except 15 dB attenuation has been inserted.

Figure 21 shows a classic hook at 120/35. The echo at 65/30 has a pendant echo on the southwest side of the echo although a cyclonic swirl is not evident on the photograph. The tornado that had been associated with the echo has either lifted or dissipated by this time. The storm

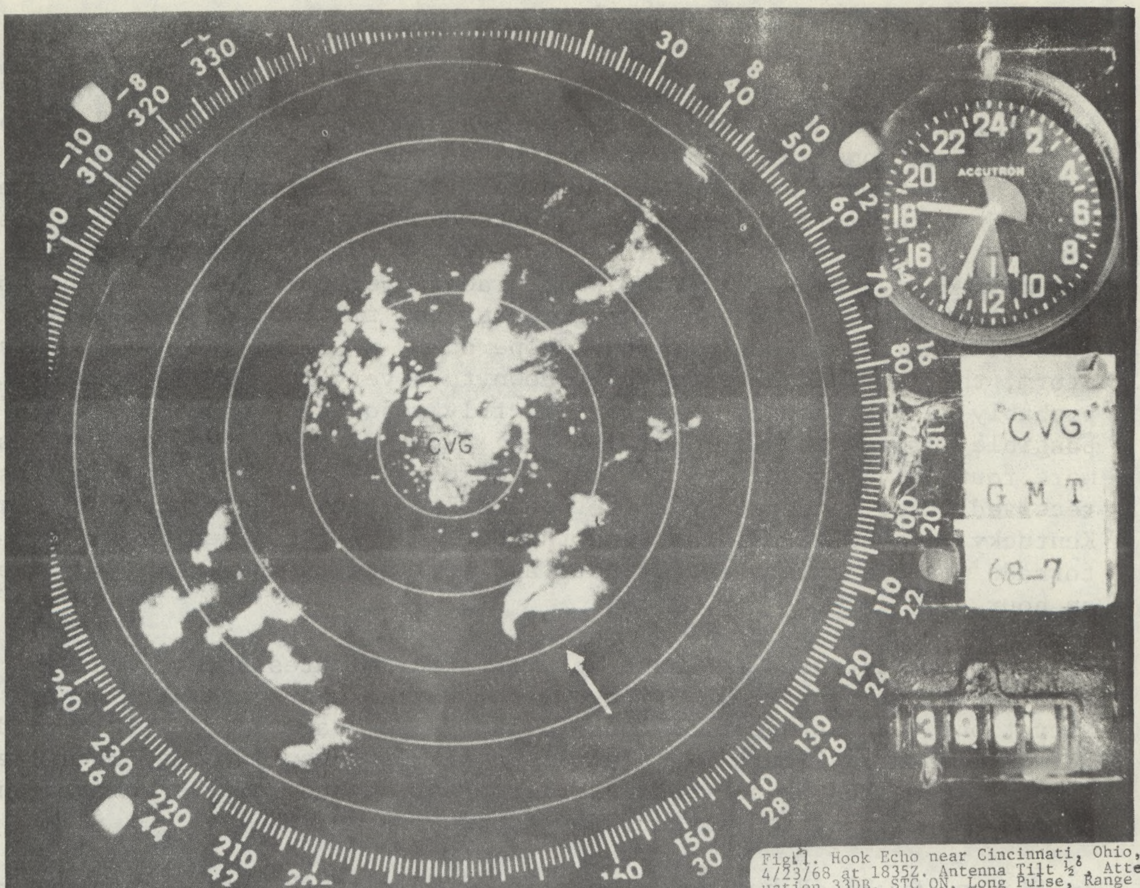


Fig.17. Hook Echo near Cincinnati, Ohio, 4/23/68 at 1835Z. Antenna Tilt ½°, Attenuation 33DB, STC ON, Long Pulse, Range 50NM, Range Circles 10NM.

Fig. 17

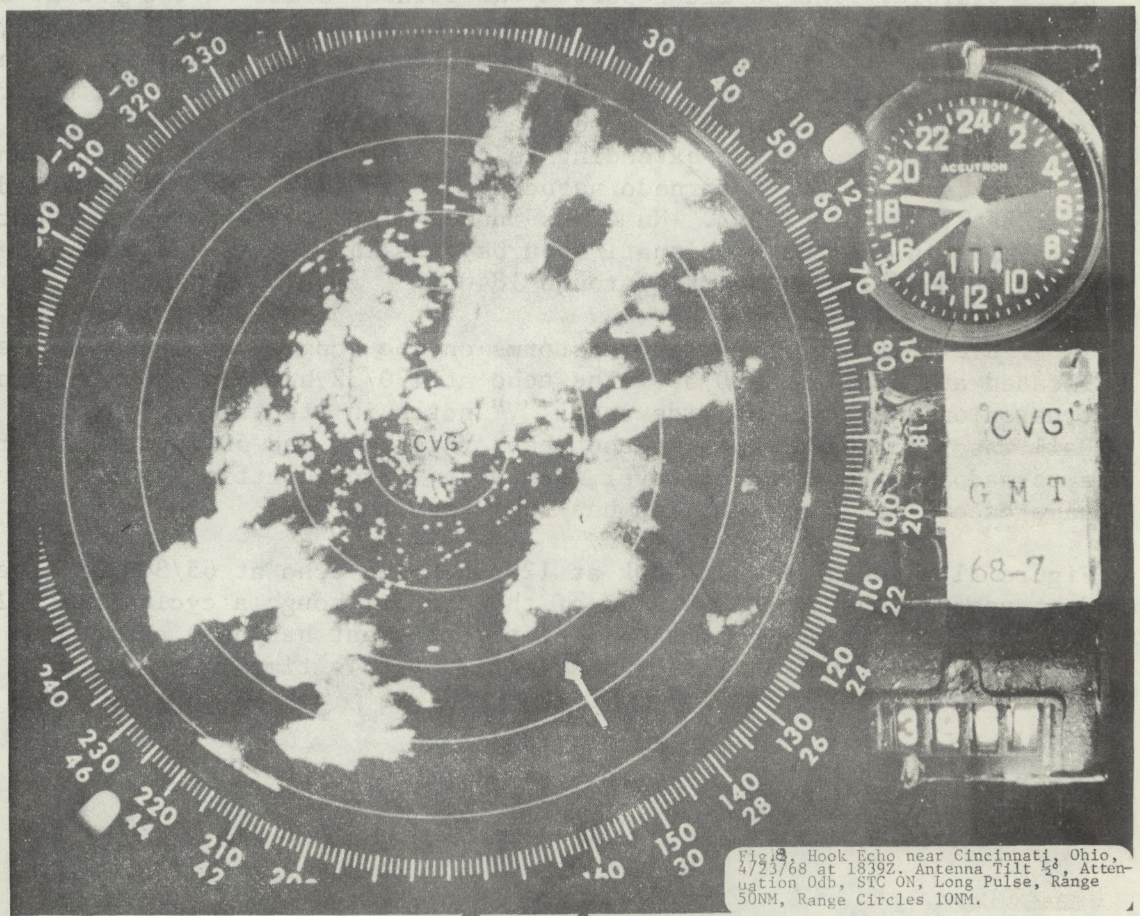


Fig.18. Hook Echo near Cincinnati, Ohio, 4/23/68 at 1839Z. Antenna Tilt ½°, Attenuation 0db, STC ON, Long Pulse, Range 50NM, Range Circles 10NM.

Fig. 18

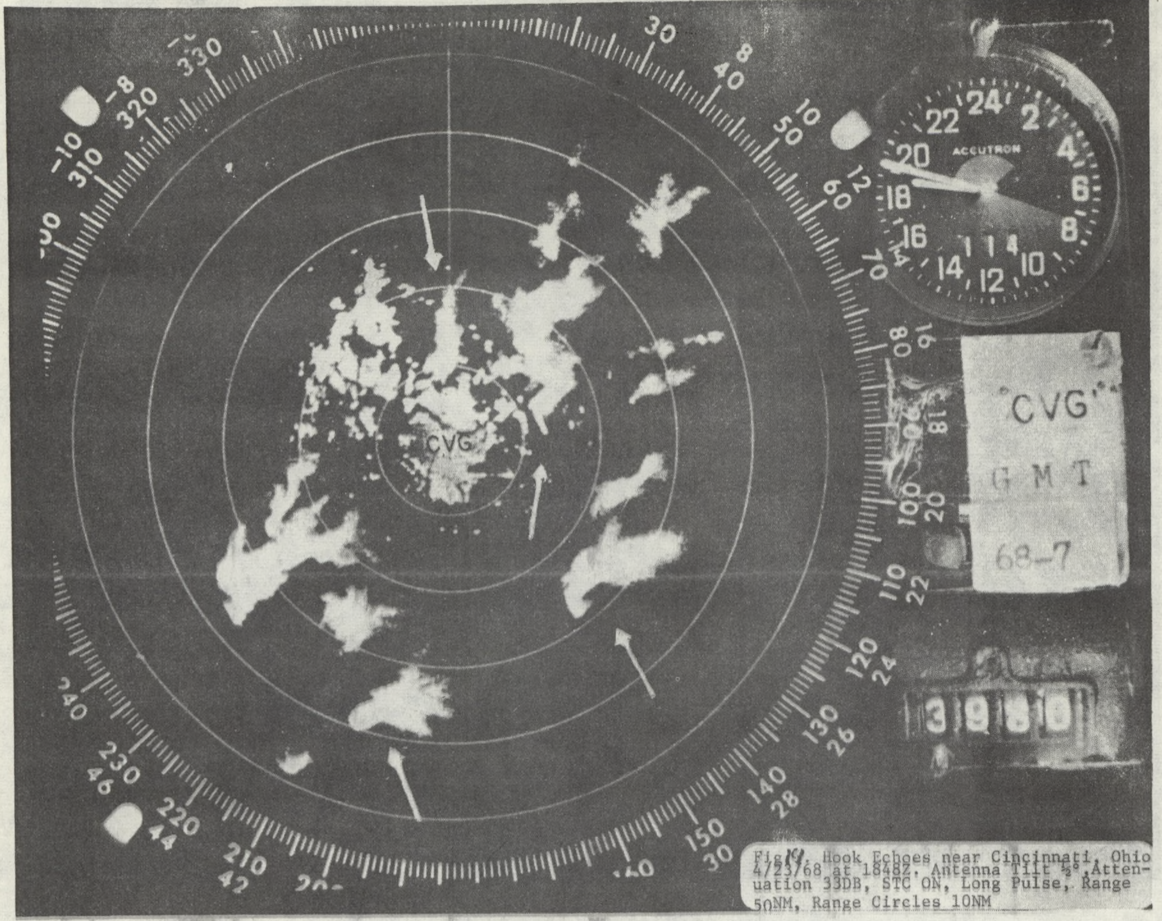


Fig 19. Hook Echoes near Cincinnati, Ohio 4/23/68 at 1848Z, Antenna Tilt ½° Attenuation 33DB, STC ON, Long Pulse, Range 50NM, Range Circles 10NM

Fig. 19

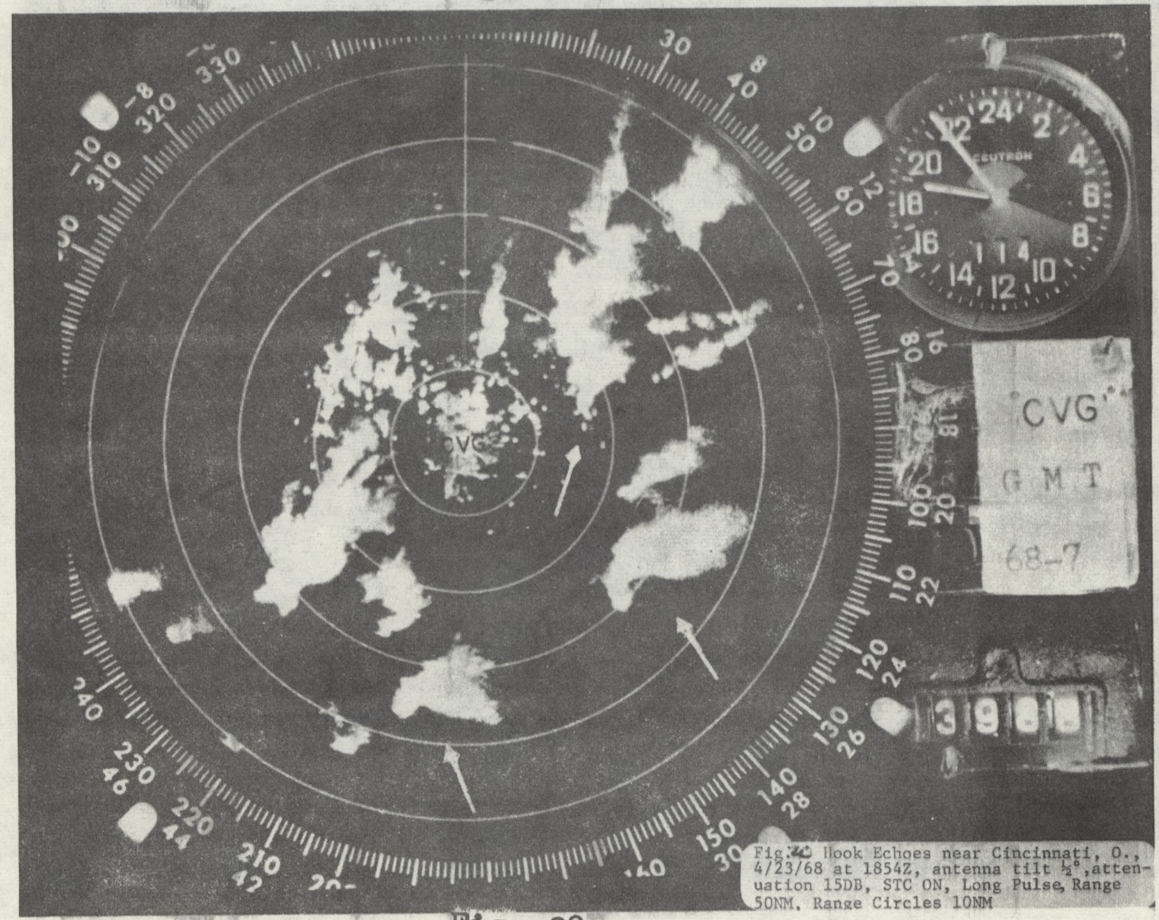


Fig 20 Hook Echoes near Cincinnati, O., 4/23/68 at 1854Z, antenna tilt ½°, attenuation 15DB, STC ON, Long Pulse, Range 50NM, Range Circles 10NM

Fig. 20

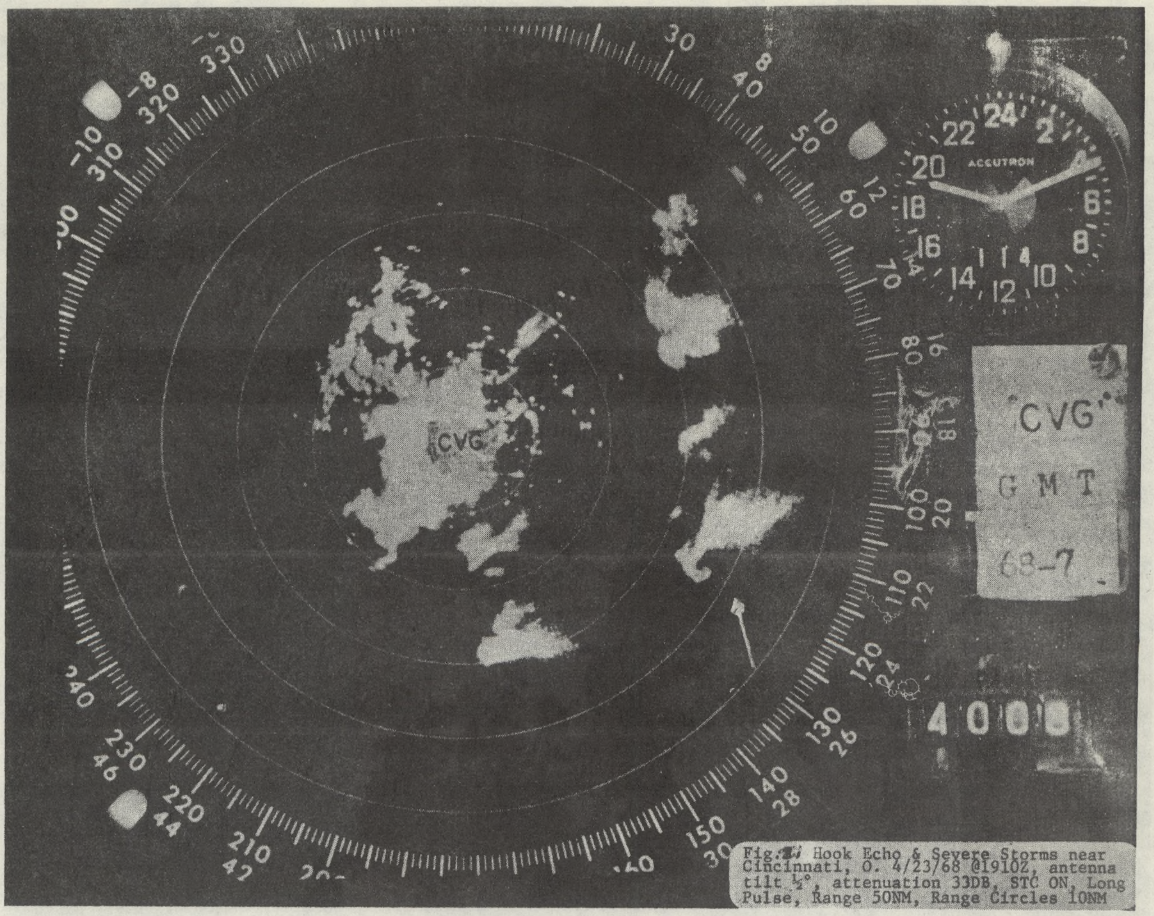


Fig.[illegible] Hook Echo & Severe Storms near Cincinnati, O. 4/23/68 @1910Z, antenna tilt ½°, attenuation 33DB, STC ON, Long Pulse, Range 50NM, Range Circles 10NM

Fig. 21

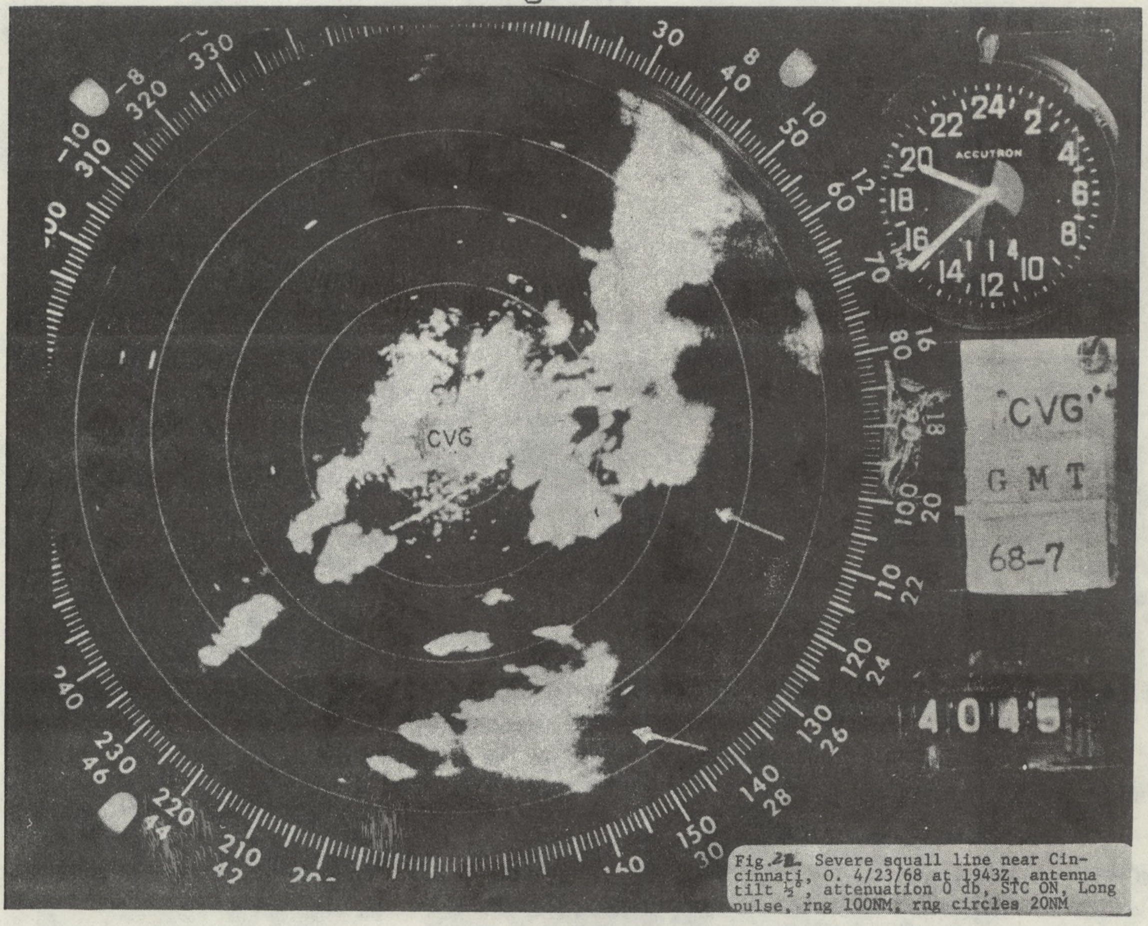


Fig.22 Severe squall line near Cincinnati, O. 4/23/68 at 1943Z, antenna tilt ½°, attenuation 0 db, STC ON, Long pulse, rng 100NM, rng circles 20NM

Fig. 22

remained very strong and 3/4 inch hail and funnel clouds were reported south of Columbus around 2030Z. The storm at 165/28 was still dangerous with large hail reported at Falmouth, Kentucky. Radar settings remain the same except the attenuation has been increased to 33 dB.

The thunderstorm activity in Figure 22 was well organized into a very intense squall line which extended from 40/100 to 170/100. The radar is now operating on standard gain, no attenuation, and the range on the photographic repeater has been increased to 100 n. miles. Numerous severe storms were reported along this line with extensive damage occurring later at Wheelersburg, Ohio, where 6 deaths and 43 injuries were reported. A tornado was reported with the echo (125/38) at Dover, Ky. destroying 90 percent of the buildings in the town. Also note the very large storm 80 n. miles south of Cincinnati. Hail up to two inches in diameter was reported with the echo at 1900Z. The apparent fine line just southeast of the ground clutter is actually a line of telephone poles displayed in a few photographs due to super-refraction of the radar beam.

In summary, it should be made clear that echo shape is one more feature which plays an important part in alerting the radar operator and forecaster to the possibility of severe weather. The most important pattern is the hook echo which is characteristic of a well-organized tornado cyclone in which large hail and tornadoes are likely but do not always occur. Other patterns indicative of severe weather are echo pendants, echo fingers and a "V" notch.

VERTICAL INDICATIONS

All weather radars allow examination of echoes in the vertical by tilting the antenna. Some radars have an automatic vertical scan with the echo displayed on an RHI, range height indicator, which usually is next to the PPI or horizontal plan position indicator. By using both these scopes, individual echoes can be surveyed in detail.

A. High Echo Tops

The height of a convective echo is an indication of whether the echo is a rain shower, thundershower, or hail storm. The use of top data, together with other indicators, can be very helpful in locating possible tornadoes. Although you cannot determine by radar alone if an echo is a thunderstorm, most radar operators use a top of at least 25,000 feet to indicate a thunderstorm. Some radar operators have detected lightning in thunderstorms; however, this is infrequent and cannot be routinely used in determining thunderstorms. Donaldson in 1965 reported that a Russian named Kotov found the altitude of the -22°C isotherm to be the height dividing shower and thunderstorm echo tops. Ninety-three percent of the thunderstorm echoes extended above the height of -22°C. Ninety percent of rain showers did not reach the -22°C level. These data were collected at high latitudes in Russia and have not been followed up with similar research in the United States.

Echo tops of hailstorms and tornadoes are generally higher than rainshowers and thundershower echoes. Studies conducted in different areas of the United States have revealed a good relationship between the probability of hail and high tops. Donaldson in 1958, using a GPS-9 radar in New England, found that the probability of hail at the surface has a good correlation with the maximum height. He also found that most severe weather occurred with the highest echo tops. Donaldson indicated that the probability of hail at the surface increased from zero with echo top heights below 20,000 feet to 48% for tops above 50,000 feet. The median for echo tops associated with hail was 43,000 feet, while thunderstorms without hail ran around 38,000 feet.

Douglas in 1960 and 1961 also found a good relationship between echo height and the probability of hail in Alberta, Canada; however, hailstorms in Canada had top heights lower than New England hailstorms. This is not unexpected since air masses in Canada would not normally have vertical velocities as large as the warmer air masses further south. Tropopause heights would normally be much lower in Canada than in the United States, further reducing average echo tops in that region. The Canadian data were obtained in the lee of the Canadian Rockies where hail should be more common. Even with the added lift of the mountains, echo top heights associated with hailstorms ran about 10,000 feet lower than in New England.

Schlewsener and Marwitz in 1963 conducted similar research on hailstorm echo tops in the lee of the United States Rockies and had results similar to Douglas. When you move away from the mountains and go further south where the air masses are quite different in thermal structure, maximum echo heights are also different. In Texas, Inmann (1961) also noted that the tallest echoes produced the largest hail sizes. In Texas the average height of thunderstorm echoes was higher than in other more northern parts of the country and average tops of hailstorms was above 50,000 feet. This is not unexpected since the tropopause is higher in this region thereby allowing kinetic energy of the rising air of a thunderstorm to go much higher before the loss of kinetic energy in the stratosphere reduces the vertical motion and limits the top of the echo. Douglas in 1963 compared three sections of North America, Alberta, New England and Texas summarizing the hail probability as a function of the maximum echo height. For the probability of hail to reach 50%, the echo top should reach 58,000 feet in Texas, 50,000 feet in New England and only 22,000 feet in Alberta. These data were obtained using a 3 cm radar similar to the CPS-9. It is generally agreed that the characteristics of this radar will result in slightly higher tops than with the 10 cm WSR-57 radar.

Data collected by WSR-57 radars at Minneapolis, Minn. and St. Louis, Mo. also indicated that higher echo tops especially those approaching the tropopause had the highest probability of hail. At Minneapolis in 1963 Whalen found that approximately 80% of the hail occurrences were associated with echo heights above 40,000 feet with an average echo height of 46,000 feet. Conte at St. Louis, Mo., using data collected in 1961 and 1962, found 45,000 feet to be the significant threshold level for hail. When tops were 45,000 feet or greater, hail occurred 79% of the time. Williams at St. Louis in 1965 used data collected in 1963 to substantiate the earlier findings. In 1963, hail occurred in 81% of the cases with echo tops above 45,000 feet. The combined data of 1961, 1962 and 1963 had a positive correlation of echo tops and hail occurrence of 0.73.

The St. Louis data appear to be very reliable since the storm echoes used were selected on the basis of intensity and height as observed on radar, and not on the basis of hail reports. Their procedure was to select the strongest echoes with tops 30,000 feet or higher, then obtain as much data as possible from the area near the selected echoes from 500 volunteer severe weather spotters. It is not clear how Whalen collected his data therefore the reliability is uncertain. There does seem to be general agreement that once an echo reaches 45,000 feet in height, there is a good probability of hail. It should be pointed out that at St. Louis no hail was reported when echo tops were less than 39,000 feet, while at Minneapolis no hail occurred when tops were below 30,000 feet.

Geotis in New England reported 1-1/2 inch hail one day with an echo top of only 25,000 feet and Donaldson found 20,000 feet to be the lower limit for hail. In Canada, Douglas reported some hail with tops less than 10,000 feet. It is therefore apparent that the relationship of hail and echo tops is a function of latitude and location. Surely air mass properties which are a function of the time of year would also show a variability in echo tops and hail probability.

Tornadoes are usually associated with the tallest echoes but not always. Many persons have given examples and made case studies that demonstrate this feature. However, there are also examples of tornadoes that occurred with echoes that were not the tallest. Therefore, other indications are needed to accurately identify a tornado.

B. Tropopause Penetration

The use of echo heights in determining the probability of hail is very helpful, but with the range in echo heights which varies with latitude, location, and time of year, an additional criteria is needed. Douglas in 1961 found that large hail occurred only when echo tops reach or penetrate the tropopause. Donaldson, Chmela, and Shackford in 1960 studied echo penetration of the tropopause in New England. Of the storms that penetrated the tropopause, two-thirds had hail reported by ground observers and 80% of the storms with 3/4 inch or larger hail had echo tops higher than the tropopause. Generally, the greater the tropopause penetration the larger the hail size. The median tropopause penetration associated with 3/4 inch or larger hail was 5,000 feet, while the maximum penetration during the study was 15,000 feet.

Tropopause penetration is a measure of the storm's energy since strong buoyant forces would be necessary for the storms to exceed the tropopause by a very large amount. After the above results were published, several WSR-57 stations in the Weather Bureau also compared the amount of tropopause penetration with the occurrence of hail. Conte at St. Louis in the same study on maximum echo heights, found the tropopause penetration to be a more reliable indication of hail. For data collected for 1961 and 1962, hail occurred 31 times out of the 37 cases, or 84% of the time when echoes penetrated the tropopause. Williams using data for 1963, found hail occurred in only >7% of the cases when echo tops were below the tropopause but occurred in 52% of the cases when echo tops were above the tropopause. He found the biserial correlation coefficient for the tropopause penetration parameter was 0.53 and significant at the 0.001 level. Whalen at Minneapolis found that 86% of 90 hail echoes reached or penetrated the tropopause. Most of his cases had tropopause penetration of 4,000 to 15,000 feet with an average penetration of 5,400 feet. Whalen did not find that a larger tropopause penetration meant a larger hail size as others had.

The above statistics are somewhat conservative since it is certain that not all the hail was reported. There is no reliable way of obtaining reports from every storm since they rely on widely-spaced volunteer observers. Also, there is no way of obtaining reports from sparsely settled or uninhabited areas.

Pautz and Doloresco in 1963 studied the relationship of severe weather to tropopause penetration. This was an extensive study since the severe weather logs at SELS (Severe Local Storms Center at Kansas City) and the RADU radar charts were used to correlate the storms with the severe weather occurrences. Tropopause heights were obtained from a Jet Stream Tropopause Chart prepared every 6 hours in areas where severe weather is suspected.

Special Rawinsondes are taken by upper air stations when requested by SELS; therefore, it is likely that the tropopause estimates in this study were more accurate than in other studies. The area of study was limited to east of the Rockies since this is where almost all of the Weather Bureau radars are located. Their results indicated that echoes which penetrate the tropopause have a much better chance of producing tornadoes. Of the thunderstorms that produced tornadoes or large hail, their average height exceeded the tropopause by 10,000 feet. These results agreed with a more limited study by Donaldson, Chmela and Shackford in 1960 where tornadoes occurred on five days when echoes exceeded the tropopause by 10,000 feet. On four of the five days the tallest echoes and therefore the storms which exceeded the tropopause by the greatest heights produced tornadoes. Some very great penetrations into the stratosphere exceeding 20,000 feet were reported by Pautz and Doloresco, and by Browning, Donaldson and Lamkin in 1963.

The above information can be very useful in detecting hailstorms and tornadoes. Since severe weather varies with the location, season and time of day, the above research findings must be used with caution. It appears that climatological data for each part of the country--Northeast (east of the Appalachians), Midwest, and South, which would relate the probability of hail and tornadoes to echo tops and tropopause penetration for each season of the year--is needed to better identify severe storms. It should be made clear that hail and tornadoes can occur with echoes that have low tops and do not approach the tropopause height, but their frequency is low and the severity of the storm is usually not as great.

The probability of hail and tornadoes increases as the height of the echo increases. In the average, hail is probable (greater than 50%) when heights reach 22,000 feet in Alberta, Canada; 40,000 feet in the northern plains (Minnesota area); 45,000 feet in the Midwest and New England; and 55,000 feet in Texas. The probability becomes even greater when the echo equals or exceeds the tropopause and the greater the penetration the better the chance for hail. When storms exceed the tropopause by 10,000 feet, the storms will be severe with a tornado likely. The use of both echo tops with tropopause penetration will result in more accurate storm detection. These parameters used with echo reflectivity and echo configuration will result in very accurate storm detection.

C. Vault

RHI photographs taken by Bigler and others at Texas A&M in 1958 and visual observations by Garrett and Tice (1957) associated an echo free region within a thunderstorm echo with a tornado. Garrett and Tice reported that on their RHI scope a pronounced anvil-shaped echo extended from the southern edge of a thunderstorm echo around 1800 CST (Figure 23A). An appendage developed on the end of the anvil-shaped cloud and extended rapidly down to the ground (Figures 23B and 23C). A clear area was evident between the main echo and the newly-formed echo. The clear area lasted for at least 90 minutes and the location and time the appendage touched the ground was very close to the time and place the tornado touched down. After the appendage formed, the main echo and the clear space seemed to shrink in size. The sketches below were reproduced from rough drawings made by the radar operator and some were constructed from memory after the tornado.

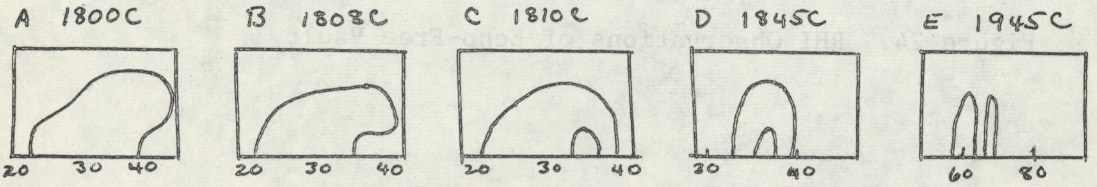


Fig. 23 - Sketches of a thunderstorm echo which developed an appendage that lowered to the ground creating an echo free area. A tornado was associated with the echo free area.

Bigler in 1958 obtained some unique RHI photographs through the center of the hook-shaped echo which revealed a vault structure (Figure 24). Bigler and others believed that the open center of the hook-shaped echo is the center of the tornado cyclone as described by Brooks. They further believed that the center of this cyclone could be relatively free of hydrometeors due to centrifugal force of the rotating cyclone removing them from the center.

Bigler indicated that based on the assumption that the echo-free region was the center of the tornado cyclone, then the echo-free region near the farthest edge on the photographs show the cyclone extends vertically to at least 36,000 feet while the thunderstorm top was about 54,000 feet.

Browning did not feel that centrifugal force is the only reason for the lack of precipitation in the center of the hook or tornado cyclone. Browning pointed out that very excessive tangential velocities over a much larger area than the tornado cyclone usually covers would be necessary to create the echo-free area by centrifugal force. Browning and Ludlam in 1962 called the echo-free area a vault and explained it as a result of both rotation and the very strong updrafts. They suggested that cloud particles that form within the vault do not have sufficient time to grow to radar-detectable size until they are carried to great heights in the high-velocity core of the updraft.

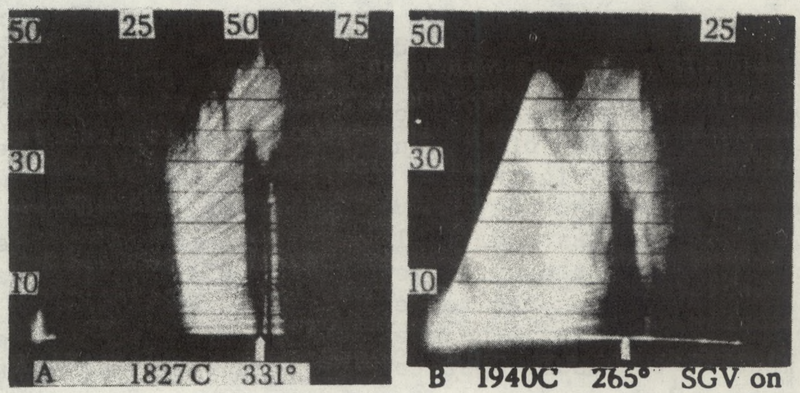


Figure 24. RHI Observations of Echo-Free Vault

Browning and Ludlam proposed a storm model which explained their observations of the echo vault, other radar structures and other meteorological observations (Figures 25 and 26). The model proposes the entry of warm moist air in the lower levels from ahead and the right forward quadrant. The warm air then rises within the updraft and leaves within the overhang or anvil cloud in the general direction of the storm movement. The vault is adjacent to the intense updraft and Browning believes that it tilts toward the rear and left side of the storm in the vertical, opposing the wind shear. The potentially coldest air which becomes the downdraft is generally located in the middle levels. This agrees with SELS techniques and the theory proposed by Fawbush and Miller in 1954. For the nonsevere storms which travel with the middle level winds, the amount of air entering at this level is not great hereby hindering the formation of a strong downdraft.

Newton in 1963, however, pointed out that severe storms frequently travel with an appreciable component to the right of the middle level winds and this would increase the amount of middle level air entering the storm. The middle level air is very dry and is cooled by evaporation of precipitation from above. The precipitation formed in the updraft diverges in the upper levels and becomes heavy enough to fall. The cooling in the middle levels makes the air negatively buoyant, and a vigorous downdraft is induced within the middle level air which falls through the region of precipitation descending on the downshear side of the updraft. When the downdraft air reaches the surface, it diverges in all directions but leaves the storm toward the rear. The most intense part of the downdraft is within the heaviest precipitation which is usually in the rear left part of the storm.

Browning also indicated, in storms with strong gust fronts, the downdraft air diverges strongly in all directions when it reaches the surface but spreads mostly beneath the updraft toward the storm's right flank. The edge of the cold outflow develops into a gust front and is frequently seen on radar as a fine line. The low level warm air inflow overruns the gust front as it moves toward the updraft flow creating a strong shear zone. The gust front can be severe, and has been known to actually tear aircraft apart due to the violent up and down drafts of the warm and cold air. Radar can detect and determine their rate of movement which is a fair estimate of the wind gust associated with the gust front. Their movement can be from 25 kts to 75 kts, with the more rapid movements associated with more severe storms and stronger downdrafts.

There are at least two theories on what the radar is detecting in the gust front. One theory indicates the strong temperature gradient refracts the lower part of the radar beam to the ground and returns a weak signal. The other theory is that the temperature gradient is strong enough that it reflects a part of the radar energy back to the radar and a fine line is visible.

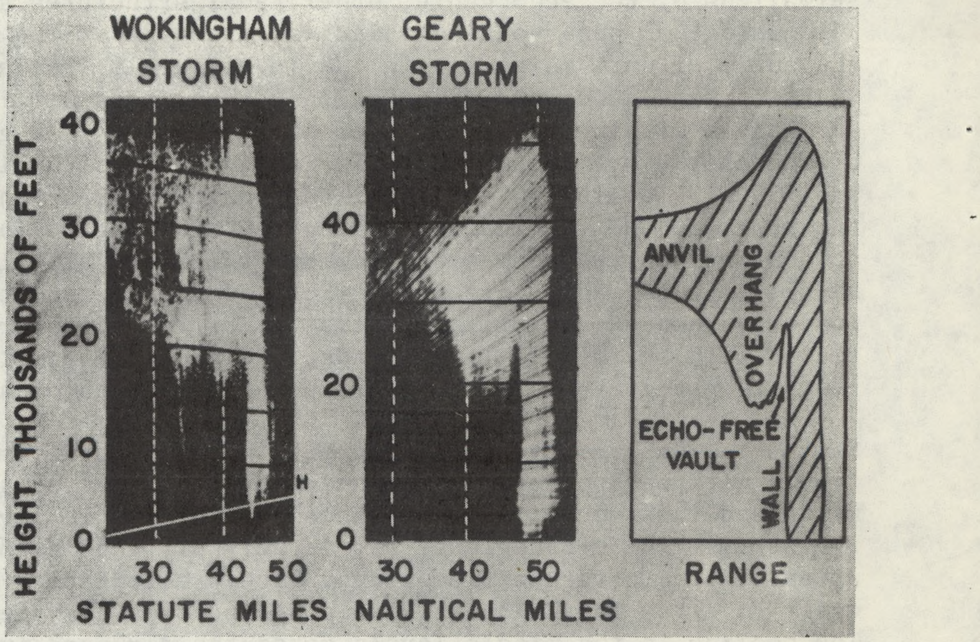


Fig 25 RHI photographs illustrating the similarity of the echo structure of the Wokingham, England, and Geary, Oklahoma, storms during their most intense phases, with a sketch illustrating the key features. Storm motion in both photographs is from *right to left*. (From Browning and Donaldson, 1963.)

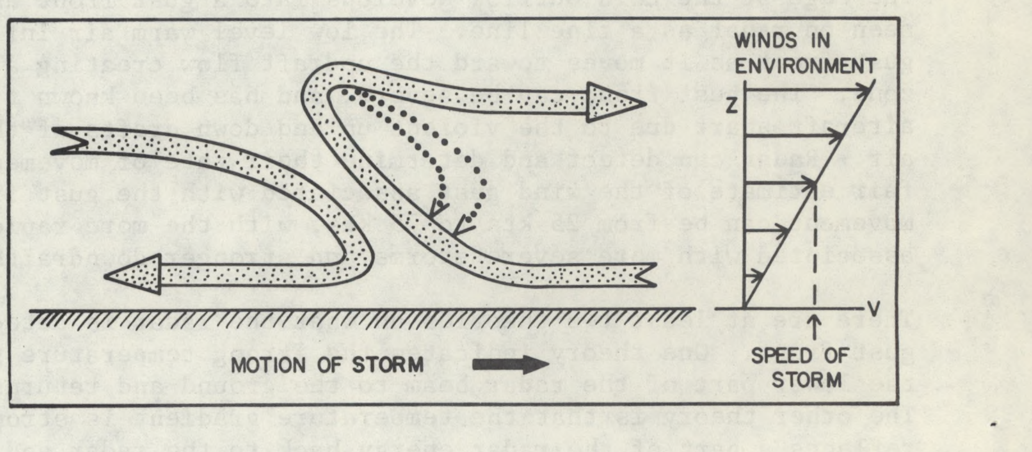


Fig 26 Simplified Browning-Ludlam model of airflow in organized storm and environmental winds, projected into the vertical plane of storm motion. Dotted paths indicate trajectories of hailstones falling out of top of updraft and re-cycling into foot of updraft for a second trip. (Sketch courtesy of Dr. Keith A. Browning.)

Since this is a low level phenomenon, its detection is usually limited to around 60 or 70 miles from the radar. Tornadoes that occur will frequently form to the right rear in the region of strong cyclonic shear where the axis of the updraft inflow overruns the gust front. Hailstones which develop in the updraft are thrown out of the overhang region, and since the updraft tilts toward the rear of the storm, some of the stones are caught in the updraft and taken aloft again where they grow to large hail. Figures 27 and 28 taken from Browning illustrate the above discussion.

Browning and Ludlam in 1962 detected a vault structure in a severe hailstorm near Workingham, England. Donaldson in 1962 also discovered a similar vault structure in a severe storm near Geary, Oklahoma. Tornadoes occurred beneath the vault which extended vertically to about 40,000 feet. Browning, Donaldson and Lamkin in 1963 detected a similar vertical echo structure in a tornado echo near Oklahoma City. Donaldson in 1965, after evaluating the Browning/Ludlam model and his observations of the vault structure, stated the following: "Under proper conditions of buoyancy, wind shear, and low-level moisture, convection may proceed to an advanced state where the updraft is intense, persistent, and organized with the downdraft into a continuously self-regenerative mechanism, in which large hail is produced by the re-cycling of small hail. Such a form of organization is favorable for the generation of tornadoes, though the manner in which this comes about is not yet known. This state of organized convection may be recognized by means of radar as a tornado hook echo or completely-enclosed echo hole in plan view, or a vault and wall configuration in vertical section".

Donaldson also believed that most present-day radars have too wide an antenna beam to resolve the vault and hook echo phenomena except at ranges less than 50 miles and except for unusually large vaults and well developed hook echoes. Donaldson and Browning firmly believe that when a persistent vault is observed, the storm is well organized, hail is very likely and there is a good chance of a tornado and damaging wind near the vault.

Very few vaults have been reported by Weather Bureau radar operators. Perhaps one of the reasons is that when a hook echo is detected, the Weather Bureau operator is so busy tracking the severe echo, issuing warnings and statements, and checking with severe storm spotters that he normally does not have time to make extensive RHI measurements of the storm as can be made by research operators. Another possible reason for the limited detection of the vault is the rather wide 2° beam width of the WSR-57 radar which does not have the resolution of other more narrow beam radars. Unless the vault was very near the radar or was unusually large, it would probably be necessary to use attenuation and the shortest pulse possible to improve the resolution.

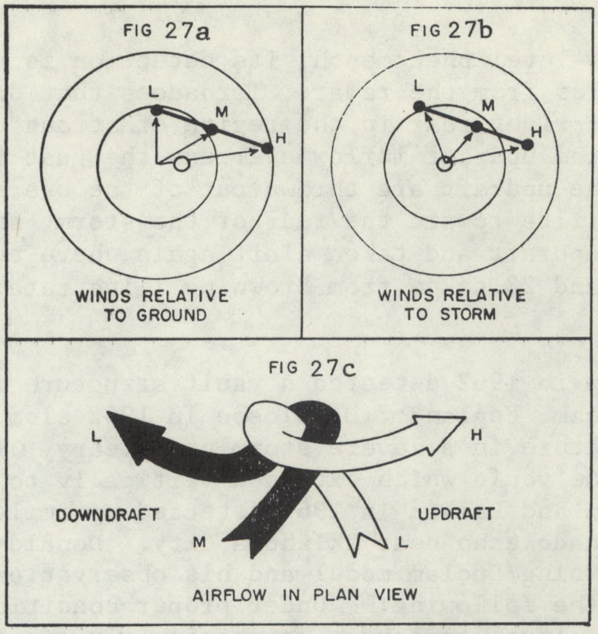


FIG 27 Diagrams illustrating how the airflow within an SR storm is governed by the environmental wind field and its own direction of travel. Wind directions in the hodographs are represented as directions toward which the winds are blowing. In each case the velocity of the storm is denoted by an open circle. For details see the text.

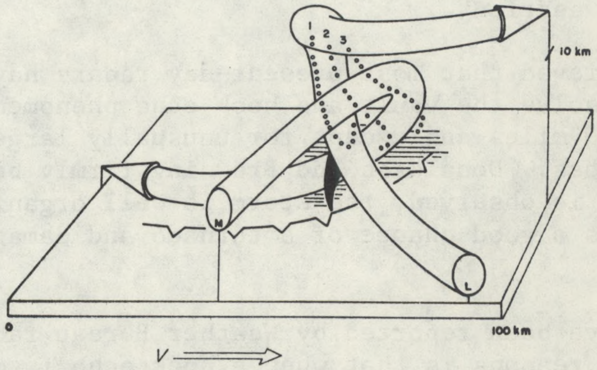


FIG. 28 ***Three-dimensional model of the airflow within an SR storm*** **(i.e., a severe storm which travels to the right of the winds in the middle troposphere). Updraft and downdraft circulations are depicted *relative to the storm itself*, being represented schematically without regard to convergence. L (low) and M (middle) refer to the predominant levels of origin of the updraft and downdraft, respectively. Also shown are some precipitation trajectories (cf. Fig. 5), the approximate extent of precipitation at the surface (hatched area), and the positions of the surface gust front and the tornado (when present). Finally, note the five-fold exaggeration of the vertical scale.**

D. Vertical Echo Protrusions

A phenomenon which has been noted by a few Weather Bureau radar operators is the occurrence of spire-like echo protrusions from the tops of echoes which have produced severe weather. Apparently, this occurs more frequently with the WSR-57 since other researchers who use other types of radars have not reported protrusions.

The first report of protrusions from storms associated with severe weather was by Parrish in 1962 at Charleston, South Carolina. Parrish reported these echo protrusions from four storms, three in which severe weather was verified. The first occurred in the morning with a cell about 40 miles west of Charleston from which two tornadoes were reported. The top of the cell was 35,000 feet, but the spire extended to the top of the RHI or 70,000 feet. The base of the spire was about 5 n.mi. across and tapered toward the top. A second echo with a protrusion was observed that same morning 34 miles southeast of Charleston. Winds of 100 mph were reported with this storm. The third observation of an echo protrusion occurred at a range of about 85 n.mi. from Charleston (Fig. 29). Hail one-half inch in diameter and winds of 64 mph were reported. The fourth echo with a protrusion occurred over a sparsely settled swamp area where no investigation was made.

Yates in 1963 studied 12 cases of vertical echo protrusions in Iowa and related this phenomenon to hail occurrence. In 10 of the 12, or 83%, of the cases hail was verified, indicating that echoes with protrusions should be suspected of having hail. Smith in 1962 reported similar phenomena in Florida, but did not relate them to severe weather. He explained the protrusions as nonreal echoes caused by side lobe radiation.

Figure 30 illustrates the vertical radiation pattern of the WSR-57 radar at Apalachicola, Florida which is representative of all WSR-57's. Note the main lobe of energy at zero degrees. However, peak power points of significant side lobes beneath the main lobe are at 4-1/2°, 8°, 13° and 22°. Only echoes with high reflectivity will produce side-lobe echo protrusions since these side lobes are -26-1/2db, -26db, -32db and -33-1/2db, respectively, below the peak power point of the main beam. Since echoes with hail and tornadoes usually have the highest reflectivities, these storms would be more likely to have echo protrusions than rainstorms. This does not mean that echoes without protrusions will not produce hail, but echoes with protrusions should be carefully checked for other features that may show the echo has a high probability of hail. Due to the limited data sample, additional research is necessary before definite conclusions can be made.

It appears at this time that vertical echo protrusions will best be used as an alerting mechanism that an echo is suspected of being a producer of severe weather. The use of reflectivity criteria should prove more useful than protrusions, but it is possible that a severe storm could be missed when a very strong maximum is aloft in the storm and the operator does not tilt the antenna. The detection of a vertical echo protrusion should alert the operator to check the echo very carefully for other severe characteristics.

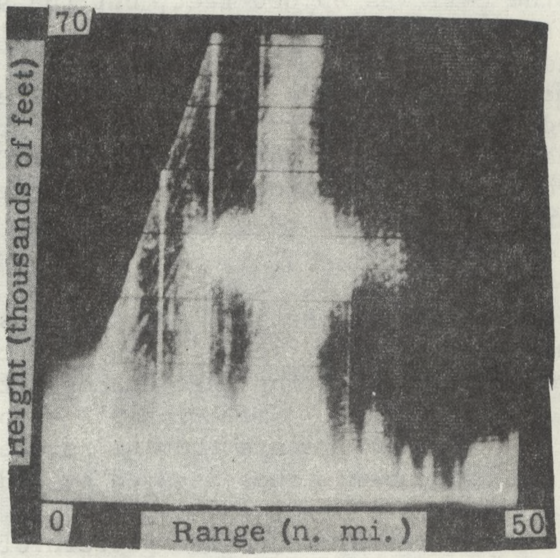


Figure 29. RHI Display of Echo Protrusion near Charleston, S.C. July 2, 1961. The WSR-57 Radar was on 50 n.mi. Range at an Azimuth of 277.

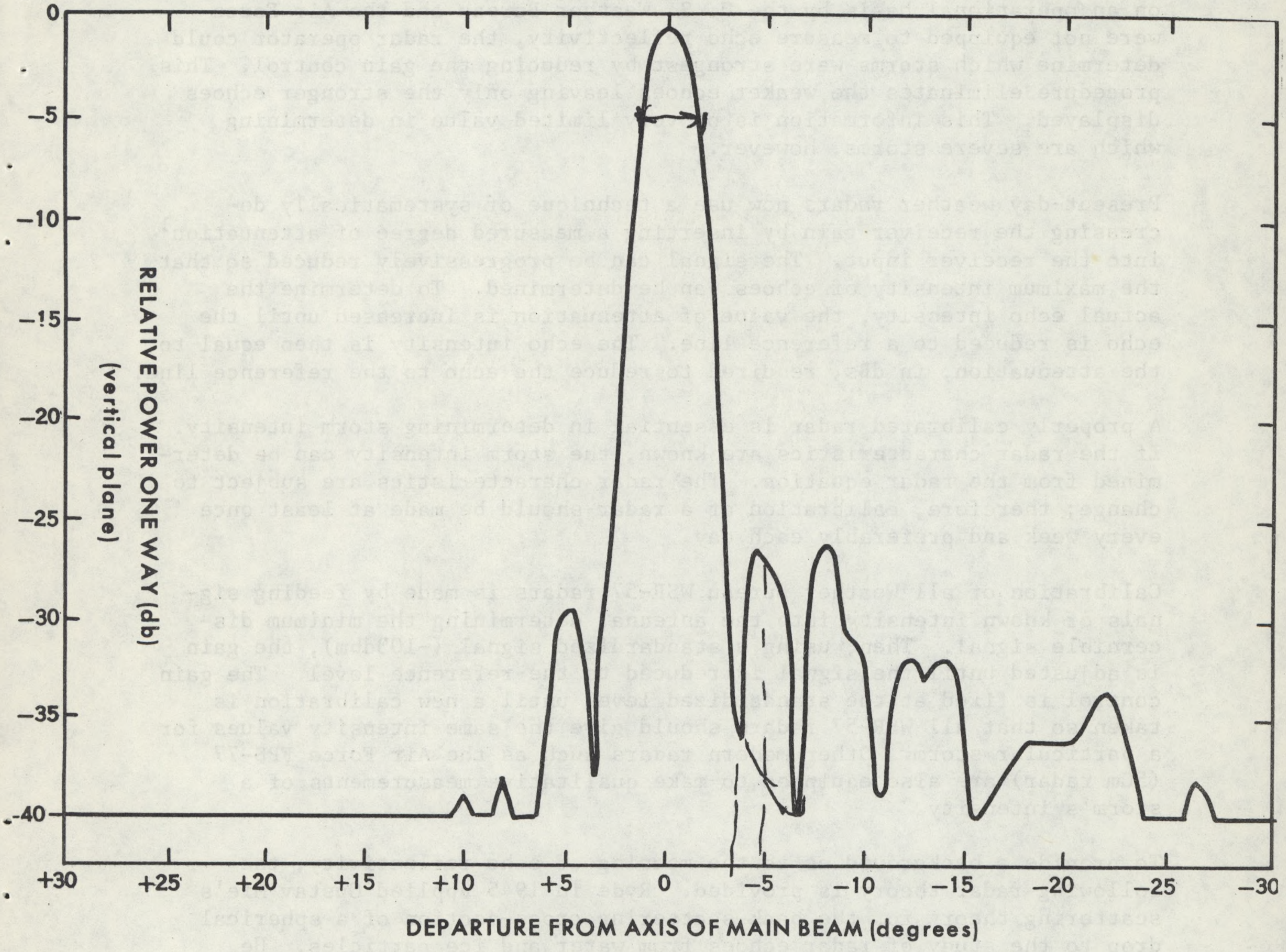


Figure 30 Radiation Pattern of WSR-57 Radar - Apalachicola, Florida

REFLECTIVITY MEASUREMENTS AND REFLECTIVITY PROFILES

It has been known for some time that storms with very high reflectivity values more frequently have severe weather than storms with low reflectivity values. Even though the first radars used for weather detection on an operational basis by the U. S. Weather Bureau and the Air Force were not equipped to measure echo reflectivity, the radar operator could determine which storms were strongest by reducing the gain control. This procedure eliminates the weaker echoes leaving only the stronger echoes displayed. This information is of very limited value in determining which are severe storms, however.

Present-day weather radars now use a technique of systematically decreasing the receiver gain by inserting a measured degree of attenuation[1] into the receiver input. The signal can be progressively reduced so that the maximum intensity of echoes can be determined. To determine the actual echo intensity, the value of attenuation is increased until the echo is reduced to a reference line. The echo intensity is then equal to the attenuation, in dBs, required to reduce the echo to the reference line.

A properly calibrated radar is essential in determining storm intensity. If the radar characteristics are known, the storm intensity can be determined from the radar equation. The radar characteristics are subject to change; therefore, calibration of a radar should be made at least once every week and preferably each day.

Calibration of all Weather Bureau WSR-57 radars is made by feeding signals of known intensity into the antenna, determining the minimum discernible signal. Then, using a standardized signal (-103dbm), the gain is adjusted until the signal is reduced to the reference level. The gain control is fixed at the standardized level until a new calibration is taken so that all WSR-57 radars should give the same intensity values for a particular storm. Other modern radars such as the Air Force FPS-77 (5Cm radar) are also equipped to make qualitative measurements of a storm's intensity.

To provide a background as to the meaning of echo reflectivity, the following radar theory is provided. Ryde in 1945 applied Gustav Mie's scattering theory for the back-scattering cross-section of a spherical drop to the study of radar echoes from water and ice particles. He

[1]Attenuation is a reduction of the energy defined by the equation $10 \log P_r/P_{ro} = -2\int_0^r k\,dr$ where P_r is the power that would have been received had there been no attenuation over the range o to r. The reduction of power is expressed in db and the attenuation coefficient K is expressed in db/n.mi.

demonstrated that the back-scattering cross-section of a single particle was:

(1)
$$\sigma i = \frac{64\Pi^5}{\lambda^4} |K|^2 \; A_i^6$$

where $K = (m^2-1)/(m^2+2)$ the complex index of refraction, λ is the wave length, and A is the drop diameter. This equation is very similar to the Rayleigh scattering formula and is usually referred to as the "Rayleigh Approximation." When the drop diameter is less than about $.04\lambda$ the approximation can be used without correction. Otherwise, the more complex Mie formula must be used. In the Mie scattering region, the back-scattered power is a complex function of particle size with numerous maxima and minima and an over-all increase at a rate considerably less than the sixth power of particle diameter.

Among the pioneers in investigating the use of radar for extimating precipitation were Marshall, Longille and Palmer. In their studies, they reported that average power reflected from precipitation was proportional to the summation of the back-scattering crossection.

(2)
$$\overline{P}_r = \frac{P_t A_e h}{8\Pi r^2} \eta$$

where

$\overline{P}_r$ = average power received

P_t = peak transmitted power

A_e = effective cross-sectional area of the antenna

h = pulse length (WSR-57 long pulse = 4 μsec)

r = range

η = reflectivity

For this equation, it is assumed that the scatterers fill the pulse volume. Because the particles are not uniformly illuminated throughout the beam width, the intensity across their beam is averaged. The reflectivity $\eta = \Sigma\sigma$ is the summation of the back-scatter cross sections of the particles per unit volume averaged over the pulse volume.

Since it is common to specify drop sizes in terms of their diameters, then

(3)
$$\overline{P}_r = P_t \left(\frac{\Pi^5 \theta\phi A_p^2 h}{72\lambda^6} |K|^2 \right) \sum_{vol} \frac{N D_i^6}{r^2}$$

The average radar echo power from a host of scatters is proportional to the summation of the diameter sixth powers of all the raindrops illuminated by the volume of the radar beam. The summation is the radar reflectivity factor Z.

The echo from a host of discrete scatterers is the combination of echoes from each. The droplets will change positions due to vertical and horizontal motions of the air. This movement of the particles results in a changing interference pattern and a resultant amplitude which varies between very wide limits at a rate closely related to the variance of the wind speed in the illuminated volume.

Since many hailstones are larger than the Rayleigh limits, the scattering properties of hail in the Mie region were studied by Atlas, Harper, Ludlam and Macklin in 1960. Measurements of the back-scattering cross sections of large ice spheres were obtained through experiments. When hail sizes are in the Mie region, a measure of the radar reflectivity should be taken and the equivalent reflectivity factor Z_e computed. Z_e is defined as the summation per unit volume of the sixth power of the diameters of spherical water drops in the Rayleigh scattering region which would scatter back the same power as the measured reflectivity. For most water drops, $Z_e = Z$ and is related to rainfall intensity by the empirical relationship $Z = aR^b$. For thunderstorm rainfall, Jones in 1956 found

$$Z = 486\ R^{1.37}$$

, where R is in mm hr^{-1}. This relationship is quite variable from storm to storm, but the values of "a" and "b" appear fairly stable within storms.

When hail sizes are larger than the Rayleigh limits, a measure of the radar reflectivity should be taken and the equivalent reflectivity factor Z_e computed. It is felt that radar measurements in terms of Z_e are best since they are more conservative with respect to radar wavelength than reflectivity. For particle sizes larger than .04λ, the back-scattered power is no longer proportional to the sixth power of the particle size. This size particle is in the Mie scattering region, where the back-scattered power is a complex function of particle size and has an over-all increase at a rate considerably less than the sixth power of the particle diameter. Wilk and Kulshvestha in 1965 calculated Z_e values of hail stones for 3, 5, 10 and 23 cm wavelengths (Figure 31). Note the variances in Z_e when the hail size exceeds 1-cm diameter for the 3-cm wavelength and 3-cm diameter for 10-cm wavelength.

It is obvious that hailstones will remain in the Rayleigh scattering region for the 10-cm radar longer than for a 3-cm radar. In this case, the Z_e computed for the 10-cm radar would be greater than the Z_e value for the 3-cm radar. Another difficulty in interpreting measurements of Z_e in hail is complexity of scattering properties of nonspherical shapes and mixtures of water and ice associated with hailstones.

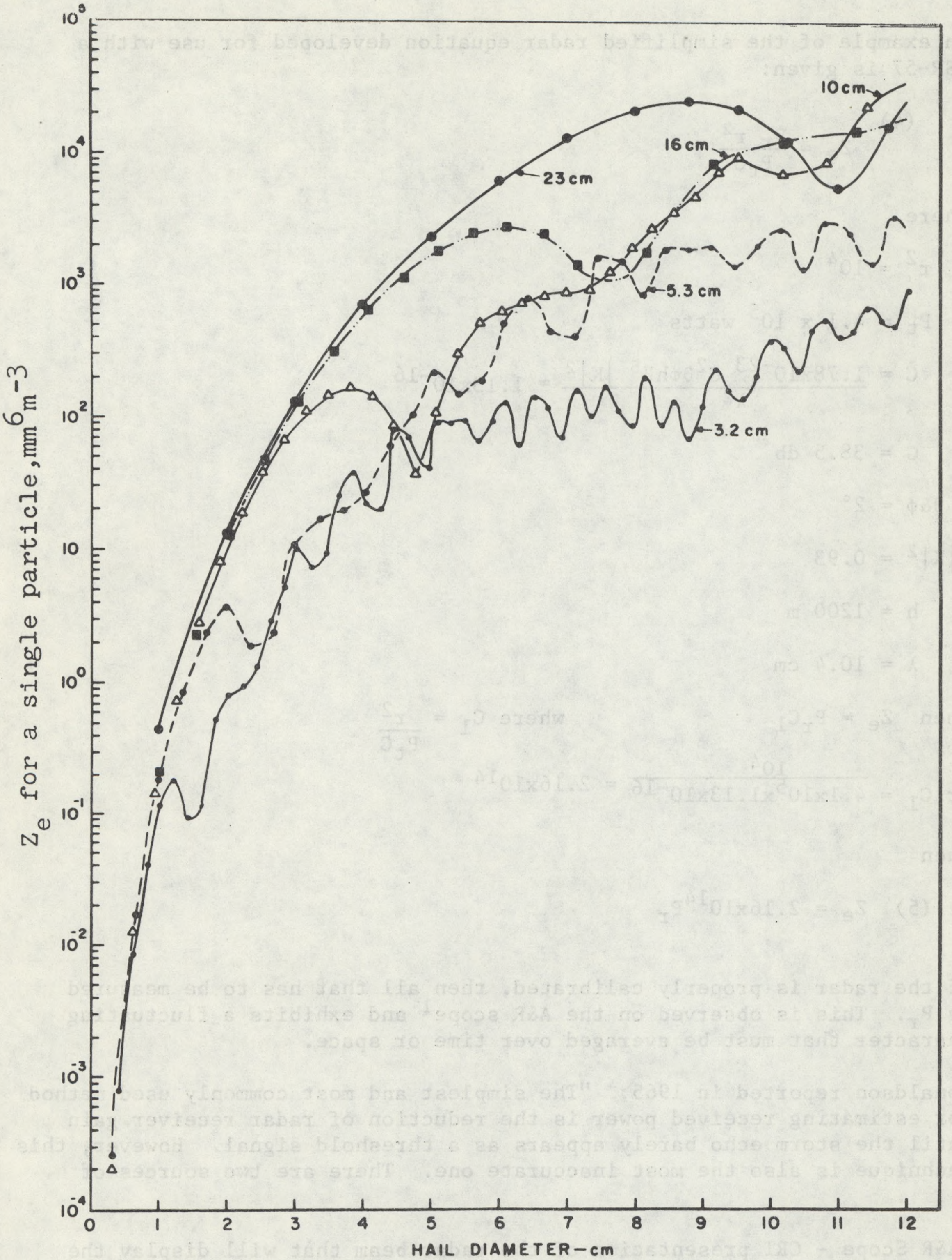


Figure 31 - Equivalent radar reflectivity for wavelengths in the range $3.2 \le \lambda \le 16$ cm., as a function of hail diameter (0°C). **From Wilk and Kulshvestha**

An example of the simplified radar equation developed for use with a WSR-57 is given:

$$(4) \quad Z_e = \frac{P_r\, r^2}{P_t C}$$

where

$r^2 = 10^4$

$P_t = 4.1 \times 10^5$ watts

$C = \frac{1.78\text{x}10^{-23}\ G^2 \theta \phi h \Pi^5\ |K|^2}{\lambda^2} = 1.13\text{x}10^{-16}$

$G = 38.5$ db

$\theta \& \phi = 2°$

$|K|^2 = 0.93$

$h = 1200$ m

$\lambda = 10.4$ cm

when $Z_e = P_r C_1$ where $C_1 = \frac{r^2}{P_t C}$

or $C_1 = \frac{10^4}{4.1\text{x}10^5 \text{x} 1.13\text{x}10^{-16}} = 2.16\text{x}10^{14}$

then

$$(5) \quad Z_e = 2.16\text{x}10^{14} P_r$$

If the radar is properly calibrated, then all that has to be measured is P_r. This is observed on the A&R scope[1] and exhibits a fluctuating character that must be averaged over time or space.

Donaldson reported in 1965: "The simplest and most commonly used method for estimating received power is the reduction of radar receiver gain until the storm echo barely appears as a threshold signal. However, this technique is also the most inaccurate one. There are two sources of

[1]A&R Scope - CRT presentation of the radar beam that will display the presence of a target, measure its range and is now used with other radar components to determine intensity of an echo.

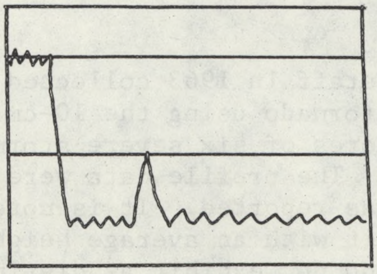
error which are specific to the thresholding technique. First, radar receivers generally have a response curve in which the signal output is least sensitive to signal input in the vicinity of the threshold. Thus a small error in estimating the threshold signal means a rather large error in determination of the received power. Second, a threshold signal implies a minimum of integration; ideally, one pulse exceeding the threshold power may be sufficient to give a detectable signal. In such a limited sample, the variance of the probability distribution of signal power about its true value is likely to be very large. As the antenna beam scans across the measured storm, several pulses of transmitted power will, in general, illuminate the most reflective part of the storm. There is a good chance that the returned power in one of these pulses may considerably exceed the true average power. If this returned pulse is detected as a threshold signal, the echo reflectivity will be systematically overestimated."

There is some disagreement as to the over-all error of the thresholding technique. Dr. Austin in 1964 reported discrepancies of 10 db, but Donaldson estimated the errors of his measurement to be around 5 db. The threshold error depends on radar characteristics and on individual operator techniques in evaluating the threshold level.

The Weather Bureau now uses a technique that will help reduce the error of thresholding and standardize all WSR-57 radar intensity measurements. The technique reduces by attenuation the echo being evaluated to a reference level presently set for -103 dbm, while the MDS of most WSR-57 radars is -108 to -112 dbm. A diagram of the above technique is illustrated below.

Precipitation echo reduced to the reference level

Ground Clutter



-103 reference level

noise level

Figure 32. RHI Display

A new Video Integrator Processor developed by the National Severe Storms Laboratory will be installed on all WSR-57 radars thereby giving an integrated presentation of all echoes within 125 n. miles of the radar. This will provide a much better estimate of the true echo intensity with a more reliable average power returned determination.

The first attempt at classifying thunderstorms by their reflectivity was attempted by Donaldson in 1958. He used a step gain device which reduced the reflected signal in predetermined steps and elevation angles to threshold values which were recorded on film. The reflectivity profiles of maximum reflectivity were correlated with rain, thunderstorm, hailstorm and tornado reports (Figure 33).

The intensity of an echo is an indication of the size and concentration of precipitation droplets. Echoes with especially intense reflectivity values may indicate large updrafts which are associated with large water drops and hail. Donaldson, using a 3-cm radar, found reflectivity characteristics which distinguish hail storms and tornadoes from ordinary rainstorms in New England. Figure 33 shows the median vertical profiles of the equivalent reflectivity factor in the echo core of storms producing rain, hail and tornadoes. Note that the median rain profile shows the smallest reflectivity values at all altitudes and the values decrease with height. The severe storm shows higher reflectivity values which increase upwards to a maximum near 20,000 feet and then decrease. Donaldson found that the Z_e maximum aloft increases with the severity of the weather; that is, hail, large hail and tornadoes. Donaldson also suggested using 30,000 feet as the best level to measure Z_e values for determining storm type.

Inman and Arnold in 1961, also using a 3-cm radar, reported that storms in Texas had reflectivity maxima aloft similar to the New England storms; however, certain exceptions were noted. The differences in the median rainstorm and the severe storm reflectivity are not nearly as great in Texas as in New England. Although some severe storms indicated Z_e maximums aloft, the median Z_e did not indicate this distinct maximum. It should be remembered that the data collected by Donaldson, Inman and Arnold was for a 3-cm radar with different characteristics than a 10-cm radar.

Hamilton and the Kansas City staff in 1963 collected reflectivity data for five hail storms and one tornado using the 10-cm WSR-57 radar. Vertical profiles of Z_e in the cores of six severe storms using the WSR-57 are illustrated in Figure 34. The profile data were collected at the precise time severe weather was reported. It is noted here also that reflectivity maxima occur aloft with an average height of about 19,000 feet. However, the profiles do not exhibit as distinct a maxima as occurred with the 3-cm radar for severe storms. Z_e ranged from 10^5 to about 10^6 except for profile No. 6 which was associated with the largest hail. The range to this storm was less than for other storms and could account for a slight increase in Z_e. Normally, the more intense storms are greater in horizontal extent with a higher probability that they fill the beam; also, the beam may be more nearly filled by the hail shafts of the unusually intense storms. The tornado profile No. 4 has a relatively constant reflectivity profile and the maximum value is less than for most of the hail values. This does not agree with Donaldson or Inman and Arnold's 3-cm tornado profiles.

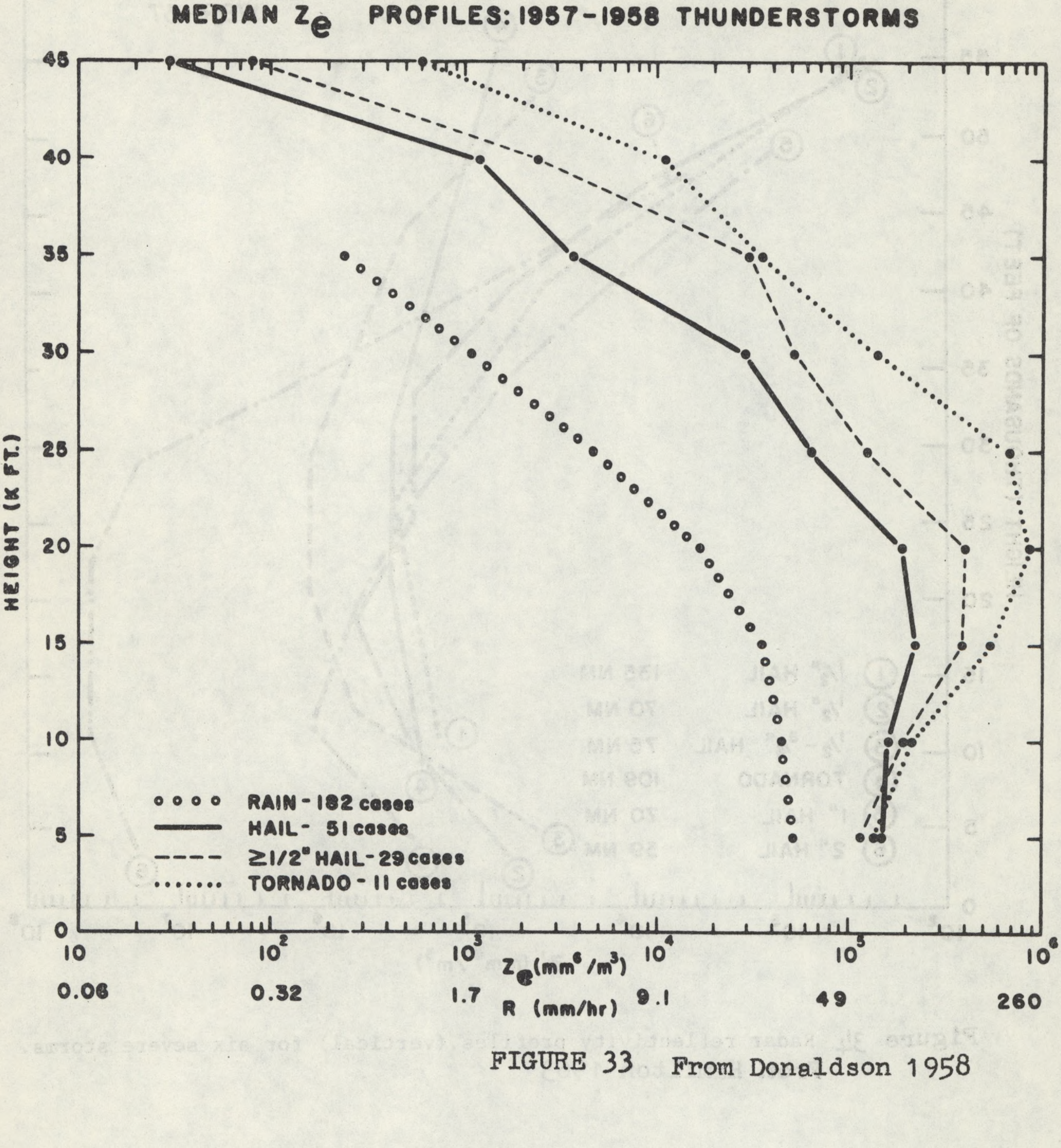


FIGURE 33 From Donaldson 1958

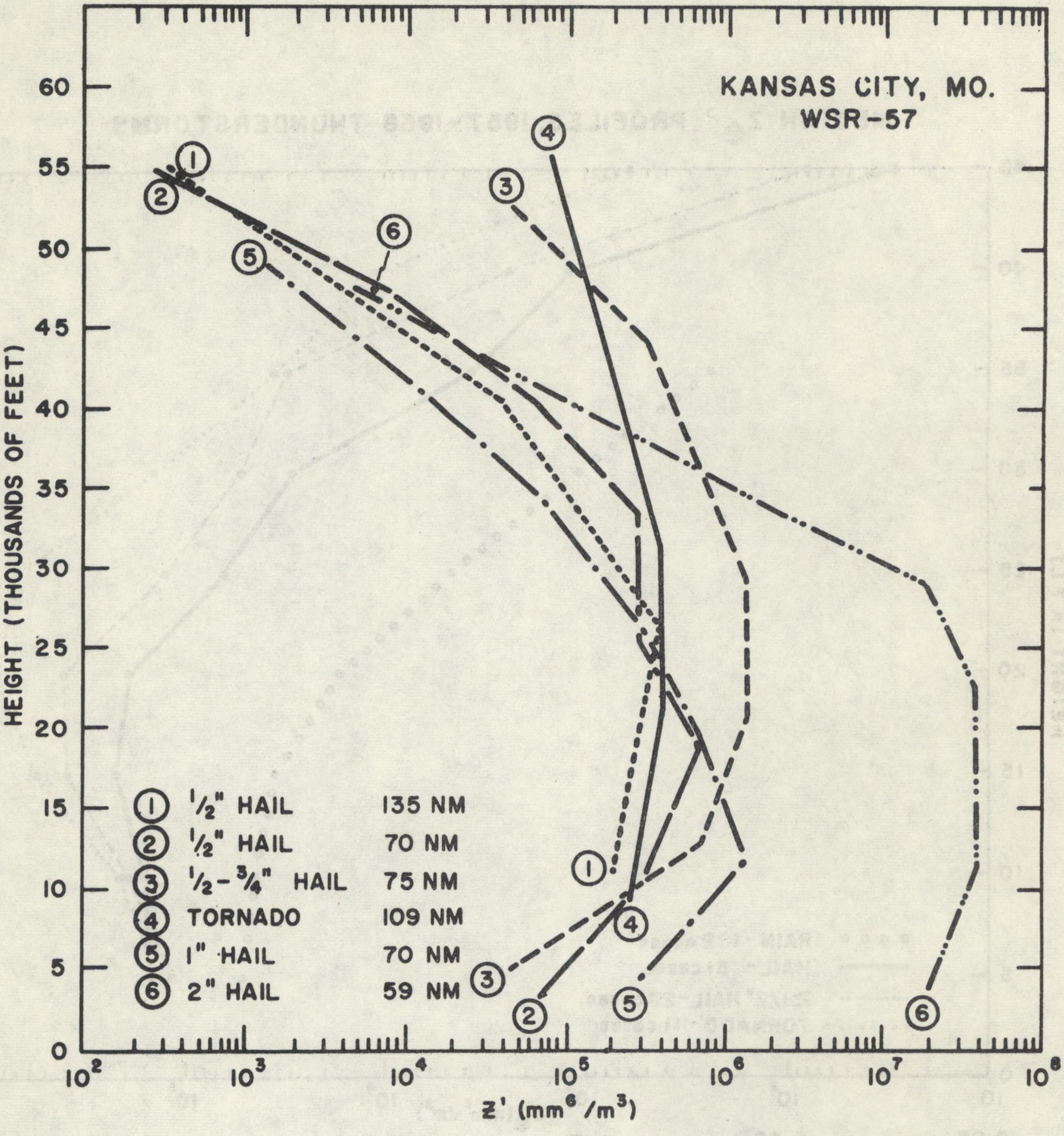


Figure 34 Radar reflectivity profiles (vertical) for six severe storms. From Hamilton 1963

Conte in 1964 and Williams in 1965 at St. Louis, and Whalen in 1963 at Minneapolis, using 10-cm WSR-57 radars, also indicated that reflectivity maxima may occur aloft but the maximum is usually not as sharply defined as for the 3-cm radar. The height of the maximum may vary with the radar location and decrease with increasing latitude.

The relationship of high reflectivity near the surface to severe weather was investigated by Copeland in 1958. He used integrated contours from his 10-cm radar and found a good relationship between hail occurrence and areas of high reflectivity at the surface. Donaldson in 1958, using a 3-cm radar, did not find significant low level reflectivity differences between thunderstorms with hail and those without hail. Geotis in 1963, using a 10-cm radar, reported the following relationship of Z_e at low levels to maximum hail size:

$10^{5.5} < Z_e < 10^6$ 1/4" <hail size <3/8"

$Z_e \approx 10^6$ 1/2" <hail size <1"

$Z_e \approx 10^7$ 1" hail size

These specific values have not been verified by other 10-cm radars.

Investigators at NSSL (Ward, Wilk and Herrman in 1965) studied the relationship of storm Z_e to hail size. Figure 35 shows how the hail occurrences reported with certain Z_e values are distributed with size.

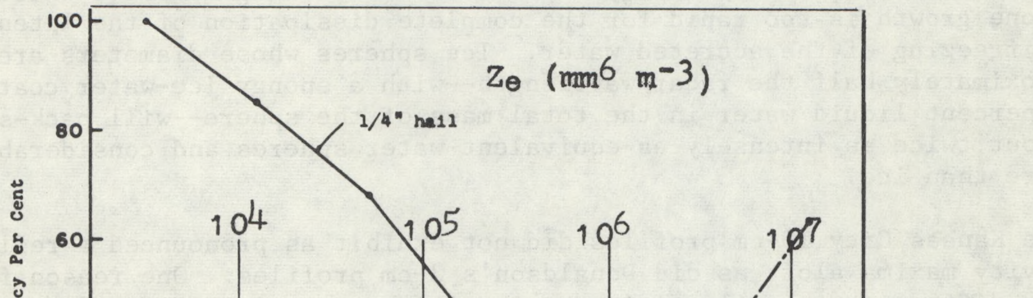


Figure 35. Relative Frequency of Three Size Categories of Oklahoma Hail in Relation to Z_e of Storm Cores.

They point out that almost all of the hail reported when $Z_e \leq 10^4$ is 1/4 inch or smaller in diameter. When $Z_e = 10^7$ nearly 2/3 of the reported hail is 3/4 inch in diameter or larger. This graph gives an idea as to the probability of maximum hail sizes with different Z_e reflectivity values. As the reflectivity increases, the probability of larger size hail increases. NSSL has also found that most hail reports are associated with Z_e values about $10^6 mm^6 m^{-3}$, and most echoes where $Z_e \geq 10^5$ probably contain some significant hail.

The five Kansas City severe weather profiles and reflectivity data collected at St. Louis, Minneapolis and NSSL at Norman indicate a relationship of higher reflectivity values to larger hail sizes. It would be ideal if we could determine the hail size from a measurement of a storm's reflectivity value. However, there is not a unique hail size for a measured Z_e reflectivity value because reflectivity is determined mainly by both hail size and concentration, although size is the dominant factor. Hail concentration and size varies within each storm further reducing the probability of finding a unique relationship between maximum hail size and measured storm reflectivity.

Reflectivity maxima aloft is probably due to a combination of factors. Large raindrops and hailstones accumulate in strong updrafts, resulting in higher reflectivity values aloft. Also, the melting of some hailstones at low altitudes could partially account for this phenomenon. Atlas, Hardy and Joss in 1964 have shown that spongy hailstones have scattering properties that produce unusually high reflectivities. Spongy hail has a coating of porous ice saturated with liquid water. They point out that the occurrence is most likely associated with strong updrafts where hailstone growth is too rapid for the complete dissipation of the latent heat of freezing of the accreted water. Ice spheres whose diameters are approximately half the radar wavelength--with a spongy ice-water coating of 6 percent liquid water in the total mass of the sphere--will back-scatter about twice as intensely as equivalent water spheres and considerably more than ice.

The Kansas City 10-cm profiles did not exhibit as pronounced a reflectivity maxima aloft as did Donaldson's 3-cm profiles. One reason for the difference in reflectivity maxima is that attenuation at 3-cm increases downward due to heavy rain at low altitudes while attenuation at 10-cm from heavy rain is negligible. Large hail that has a coating of water produces significant attenuation on 3-cm energy but has little effect upon 10-cm energy.

Markovich and Muchnik in 1960 suggested that the melting and subsequent fragmentation of 1-cm or smaller hailstones would contribute to weaker reflectivity below the freezing level. Spongy hailstones could also have the sponge coat melt thereby shedding the excess water and leaving a thinly water-coated hailstone and some waterdrops which scatter much less than the original spongy hailstone.

The large severe storms with great vertical updrafts can carry large amounts of super-cooled water aloft above 0°C. Research aircraft flying through these storms have reported super-cooled water at heights considerably above the freezing level. This would also help explain attenuation of 3-cm radars at altitudes above 0°C in severe storms.

Donaldson in 1961 suggested the storage of precipitation in the strong convective storms could cause a 3-cm reflectivity maxima aloft. The absence of a pronounced 10-cm reflectivity maximum aloft in the Kansas City and Geotis profiles leads one to believe that this is not a significant cause of reflectivity maxima aloft for the 3-cm radars.

The 2° beam of the WSR-57 presents a much larger search volume than the 1° beam of most 3-cm radars; therefore, more storms will fill the 1° beam than the 2° beam. For example, the WSR-57 2° beam is approximately 15,000 feet across at 70 n.mi. compared with 8,000 feet for the 1° beam. Storms that do not fill the 2° beam result in an underestimate of the reflectivity maximum. It appears that the Z_e maxima noted by WSR-57 radars must be mainly due to larger particle concentration and wet hailstones aloft.

Closely associated with severe storms is the problem of extreme turbulence. J. Lee of NSSL in 1965 found that for storms having maximum Z_e values less than $10^4 mm^6 m^{-3}$ the chance of encountering severe or extreme turbulence was small. Above this value, the probability of severe or extreme turbulence increased rapidly. Contradictory to previous concepts the maximum radar reflectivity of a given storm was found more indicative of turbulence than the gradient of intensity. However, the correlation improved when both echo intensity and echo gradients were used simultaneously. Mr. Lee also stated, "The maximum turbulence encountered is not necessarily in the area of maximum radar reflectivity". Any part of a storm that has a $Z_e \geq 10^5$, especially with strong intensity gradients, should be suspect for severe or extreme turbulence.

Since the discussion of reflectivity has been rather lengthy, a summary of the more important findings is provided.

Rainstorms generally display the greatest reflectivity near the ground. Storms containing large hail frequently show a reflectivity maximum aloft especially with 3-cm radars. The most frequent height of the maximum is about 20,000 feet for the 10-cm radar, but it may vary with radar location and season. The reflectivity maximum aloft can occur with both 3-cm and 10-cm radars in association with surface hail. The 10-cm radar generally does not have as sharply defined a maximum aloft as does the 3-cm type.

The lack of a reflectivity maximum aloft does not mean that no hail exists. For a 10-cm radar, the most important criteria for indicating hail is a Z_e reflectivity value of $10^5 mm^6 m^{-3}$ or greater whether aloft or near the surface. When the Z_e value reaches $10^7 mm^6 m^{-3}$ the storm has a high probability of 3/4 inch hail or larger. Although you cannot determine a unique hial size for a specific reflectivity value, studies suggest that the reflectivity increases with the probability of hail and hail size. There is some indication that higher reflectivities are observed with the 10-cm WSR-57 radar than with the 3-cm (CPS-9) radar.

Tornadoes generally have higher reflectivity values than hailstorms, but not always as illustrated by the Kansas City profile.

RUSSIAN RESEARCH

In Russia a study entitled "Radar Characteristics of Hail Clouds" by Borovikov and others, developed a procedure by which convective clouds and their probability of hail can be classified on the basis of radar parameters. The radar parameters used to classify the storms were:

1. Maximum height of radio echo above sea level - H_m
2. Temperature at level H_m-T HM
3. Thickness of reflection zone - ΔH
4. Maximum radar reflectivity - Z_m
5. Height of Z_m above sea level - H_{Zm}
6. Temperature at level H_{Zm} - T_{HZm}
7. Thickness of zone of high reflectivity - $\Delta H_{\Delta Z}$
8. Temperature at the top of the zone of high reflectivity - $t_T \Delta H_{\Delta Z}$
9. Ratio of the thickness of the freezing part of the zone to the warm part - $\frac{h-}{h+}$

Frequency graphs based on radar observations were developed using data from 108 hail-bearing storms. The probability of hail precipitation was determined by intervals, as the ratio of the number of cases of hail to the total number of zones observed in a particular interval. For temperature the interval was 3°, for H_m, H_{Zm}, ΔH and $\Delta H_{\Delta Z}$ 0.5km, for $\frac{h-}{h+}$ 0.2, and for $\lg Z_m$ 0.25. They found each parameter useful, but a reliable assessment of hail-bearing characteristics of the thunderstorms could not be made on the basis of a single radar parameter alone. By combining the radar parameters, a much more reliable technique was available. By taking a mean value of the percentages of all the radar parameters, the following rough classification of convective clouds was developed.

1. No danger of hail - mean value less than 20%.

2. Hail possible - mean value between 20% and 40%.

3. Hail highly probable - mean value between 40% and 70%.

4. Hail present - mean value is equal to greater than 70%.

It was interesting to note that one parameter we in the United States find very useful--lgZm--was not used since all probabilities were below 50% in their data.

A new parameter, $\frac{h-}{h+}$, was one of the main criteria for determining hail-bearing characteristics. Their observations indicated that hail could only be produced by a convective cloud if the thickness of the radio echo from the freezing part of the cloud is greater than that of the warm part. Other interesting results were:

(1) When the temperature at the top of the zone of high reflectivity was lower than -36°, hail was precipitated from the convective cloud.

(2) Hail did not occur when the thickness of the reflection zone was less than 6.2 km, while values of 10.5 and greater for ΔH always produced hail.

The above findings have provided some additional parameters for determining hail storms. The use of these parameters together with all the other parameters can improve upon the determination of hail-bearing storms.

CONCLUSIONS

Research on severe storms using radar has revealed many echo characteristics of these storms. At this time a highly trained radar operator together with a specialized weather radar are the most important items needed to detect severe storms. The operator must rely upon a severe weather spotter network to correlate the type and intensity of severe phenomena produced by the echo. It doesn't appear that with the present radar equipment a unique and completely reliable indicator of severe weather will be discovered soon. Present-day radars are designed to detect all rain so that detailed information on rainfall for flood forecasting and aviation users and for many other users can be provided. This increased detection capability of all forms of precipitation actually makes it more difficult to discern severe storms until the radar operator skillfully manipulates the many sophisticated controls. The capable radar operator now has a number of radar indicators of severe storms. The most reliable radar criteria are:

1. Hook echo on PPI scope.

2. Persistent vault on RHI scope.

3. Echo tops exceed 45,000 feet or a critical value determined for each area.

4. Echo tops penetrate the tropopause.

5. Equivalent reflectivity factor of $10^5 mm^6 m^{-3}$ or greater for 10-cm radar.

6. Echoes in a LEWP.

7. Echo convergence.

8. Echo line intersection.

9. Strong echoes with fingers, scalloped-shaped edges and "V" notches.

10. Echo motion which is significantly different from mid-tropospheric wind.

11. Rapidly pivoting echo lines.

Special Parameters for Tornadoes

1. Hook echo.

2. Persistent vault.

3. Echo tops penetrate the tropopause by 10,000 feet.

Even though the many radar techniques do not provide positive identification of severe storms, they can serve as an alerting mechanism to the radar operator. The reliability of many of the techniques is very high and, in most cases, the forecaster can issue warnings based entirely on radar indications. In many cases, the radar indications can be verified by severe spotter reports to the radar operator. The combined use of the radar and public reports has worked remarkably well in the midwest, saving thousands of lives and property over the past 10 years. Even though some form of severe weather is likely with one or more of the discussed echo features, severe storms may occur when none of these echo features are observed. Radar can still play an important role in providing warnings for storms without characterisitc features. If a severe report is received shortly after it occurred, the radar operator can determine which echo is responsible, then maintain continuous surveillance and issue warnings to localities in its path.

Hopefully, additional research will discover more reliable techniques. Doppler radar which has offered great promise for a number of years has not proven it can do the job operationally, but still may be the best radar for severe storm identification if a number of limitations can be overcome.

REFERENCES

Atlas, D., 1963: Radar analysis of severe storms, Severe Local Storms, Meteor. Monogr., 5, No. 27, Amer. Meteor. Soc., Boston, Mass., pp 177-220.

Atlas, D., W.G. Harper, F.H. Ludlam and W.C. Macklin, 1960: Radar Scatter by Large Hail, Quart. J. F. Meteor. Soc., 86, pp. 468-482.

Atlas, D., K.R.Hendy and J. Juss, 1964: Radar Reflectivity of Storms Containing Spongy Hail, J. Geophys. Res., 69, pp 1955-1961.

Bailey, R.W., 1955: On the Motion of Precipitation Echoes in a Cyclone., Proc. Fifth Weather Radar Conf., Amer. Meteor. Soc., Boston, Mass. pp 121-129.

Battan, L.J., 1959: Radar Meteorology, The University of Chicago Press, Chapters 4-6, 10-12 and 15.

Bigler, S.G., 1955: An Analysis of Tornado and Severe Weather Echoes, Proc. Fifth Weather Radar Conf., American Meteor. Soc., Boston, Mass., pp 167-175.

Bigler, S.G., 1958: Observations of a Tornado using the AN/CPS-9 Radar, Proc. Seventh Weather Radar Conf., Amer. Meteor. Soc., Boston, Mass.

Borovikov, A.M. et al, 1969: Radar Characteristics of Hail Clouds, Translation from Russian Publication (unknown), 25 pp.

Boucher, R.S. and Wexler, R., 1961: The Motion and Predictability of Precipitation Lines, J. Meteor., 18, pp 160-171.

Brooks, E.M. 1949: The Tornado Cyclone, Weatherwise, 2, pp 32-33.

Browning, K.A., 1964: Interaction of Two Severe Local Storms, Proc. World Conf. on Radio Meteor. and Eleventh Weather Radar Conf., Amer. Meteor. Soc., Boston, Mass., pp 366-371.

Browning, K.A., and R.J. Donaldson, Jr., 1963: Airflow and Structure of a Tornadic Storm, J. Atmos. Soc., 20, pp 533-545.

Browning, K.A., and F.H.Ludlam, 1962: Airflow in Convective Storms, Quart. J.R. Meteor. Soc., 88, pp 117-135.

Browning, K.A., R.J. Donaldson and W.E. Lamkin, 1963: Severe Local Storms near Oklahoma City, 26 May 1963., Third Conference on Severe Local Storms, Amer. Meteor. Soc., Urbana, Ill., 21 pp.

REFERENCES (contd)

Byers, H.R., and R.R. Braham, 1949: The Thunderstorm, U.S. Gov't. Printing Office, Washington, D.C., 287 pp.

Cook, B.J., 1961: Some Radar LEWP Observations and Associated Severe Weather, Proc. Ninth Weather Radar Conf., Amer. Meteor. Soc., Boston, Mass., pp 181-185.

Conte, J.J. and Radar Staff, 1964: Radar Determination of Hail Occurrence, Progress Report No. 14, WSR-57 Radar Program, U.S. Weather Bureau

Copeland, R.C., 1958: A Relationship between Echo Intensity and the Observation of Hail in New England., Proc. Seventh Weather Radar Conf., Amer. Meteor. Soc., Boston, Mass., pp 122-230.

Donaldson, R.J., Jr., 1961: Radar Reflectivity Profiles in Thunderstorms, J. Meteor., 18, pp 292-305.

Donaldson, R.J., Jr., 1958: Analysis of Severe Convective Storms by Radar, J. Meteor., 15, pp 44-50.

Donaldson, R.J., A.C. Chmela, and C.R. Shackford, 1960: Some Behavior Patterns of New England Hailstorms, Physics of Precipitation, Geophys. Monogr. No. 5, Amer. Geophys Union, Washington, D.C., pp 354-368.

Donaldson, R.J., Jr., 1965: Methods for Identifying Severe Thunderstorms by Radar, Bull. Amer. Meteor. Soc., 46, pp 174-193.

Douglas, R.H., 1960: Size Distributions, Ice Contents, and Radar Reflectivities of Hail in Alberta, Nubila, 3, No. 1, 5-11.

Douglas, R.H., 1961: Radar Observations of Alberta Hailstorms, Nubila, 4, No. 2, pp 52-58.

Douglas, R.H., 1964: Hail Size Distributions. Proc. World Conf. on Radio Meteor. and Eleventh Weather Radar Conf., Amer. Meteor. Soc., Boston, Mass., pp 146-149.

Douglas, R.H., and W. Hitschfield, 1959: Patterns of Hailstorms in Alberta, Quart. J.R. Meteor. Soc., 85, pp 105-119.

Douglas, R.H., 1962: Recent Hail Research: A Review., Severe Local Storms, Meteor. Monogr., 5, No. 27, Amer. Meteor. Soc., Boston, Mass., pp 157-167

Fujita, T., 1958: Mesoanalysis of the Illinois Tornadoes of 9 April 1953, J. Meteor., 15, pp 288-296.

REFERENCES (contd)

Fujita, T., and D.C. Bradbury, 1966: Features and Motions of Radar Echoes on Palm Sunday, Twelfth Conference on Radar Meteorology, Amer. Meteor. Soc., Boston, Mass., pp 319-324.

Fujita, T., 1965: Formation and Steering Mechanisms of Tornado Cyclones and Associated Hook echoes. Monthly Weather Review, 93, pp 67-78.

Garrett, R.A., and V.D. Rockney, 1962: Tornadoes in Northeastern Kansas, May 19, 1960, Monthly Weather Review, 90, pp 231-240.

Garrett, R.A., and R.T.Tice, 1957: Some Radar Aspects of the May 20, 1957 Kansas-Missouri Tornado, Monthly Weather Review, 85, pp 206-207.

Geotis, S.G., 1963: Some Radar Measurements of Hailstorms, J. Appl. Meteor., 2, pp 270-275.

Hamilton, R.E., 1963: Thunderstorm Reflectivity Profiles, Progress Report No. 13, WSR-57 Radar Program, U.S. Weather Bureau.

Hamilton, R.E., 1966: Use of Reflectivity Measurements and Reflectivity Profiles for Determining Severe Storms, Technical Memorandum WBTM-ER-17, U.S. Weather Bureau

Harrison, H.T., and E.A. Post, 1954: Evaluation of C Band (5.5 cm) Airborne Weather Radar, Denver, Colorado, United Air Lines, Inc., 108 pp.

Hq., AWS, 1956: Severe Weather Forecasting, AWSM 105-37, 147 pp.

Hiser, H.W., 1958: Radar Analysis of Two Severe Storms in South Florida, Bull. Amer. Meteor. Soc., 39, pp 353-359.

Inman, R.L., and J.G. Bigler, 1958: A Preliminary Classification of Radar Precipitation Echo Patterns Associated with Midwestern Tornadoes. Proc. Seventh Weather Radar Conf., Amer. Meteor. Soc., Boston, Mass., pp 281-285.

Inman, R.L., and J.E. Arnold, 1961: Thunderstorm characteristics Chapter II of Utilization of AN/CPS-9 Radar in Weather Analysis and Forecasting, Final Report, Contract AF 19(604)-6136, A&M College of Texas, pp 8-73.

Jones, D.M.A., 1956: 3-cm and 10-cm Wavelength Radiation Backscatter from Rain, Proc. 5th Weather Radar Conf., Amer. Meteor. Soc., Boston, Mass., pp 281-285.

Kulshvestha, S.M. and K.E. Wilk, 1965: Wave Length Dependence of the Radar Reflectivity of Water and Ice Spheres, Technical Note 3 - NSSL-24, pp 33-38.

REFERENCES (contd)

Lee, J.T., 1965: Thunderstorm Turbulence and Radar Echoes 1964 Data Studies, Technical Note 3 - NSSL-24, pp 9-28.

Marshall, J.S., R.C. Langille and W. McK. Palmer, 1947: Measurements of Rainfall by Radar, Journal of Meteorology, Vol. 4, No.6, pp 186-192.

Markowish, M.L., and V.M. Muchvik, 1960: Structure of Thunderstorm Showers, According to Data on the Intensity Distribution of Radar Echoes with Height, Ukrains Ki Fizycnyi Zhurnal, 5 pp 259-269.

Newton, C.W., 1963: Movements and Patterns of Development of Thunderstorms, Severe Storm Detection and Circumnavigation, U.S. Dept. of Commerce, Weather Bureau, NSSP, Final Report on FAA Contract, ARDS-A-176.

Newton, C. W., and S. Katz, 1958: Movement of Large Convective Rainstorms in Relation to Winds Aloft, Bull. Amer. Meteor. Soc., 39, pp 129-143.

Nolen, R. H., 1959: A Radar Pattern Associated with Tornadoes, Bull. Amer. Meteor. Soc., 40, pp 277-279.

Parrish, S.K., 1962: Spire-like Protrusions Observed on the RHI Scope, Progress Report No. 10, WSR-57 Radar Program, U.S. Weather Bureau, pp 31-32.

Pautz, M., and F. Doloresco, 1963: On the Relation Between Radar Echo Tops, the Tropopause and Severe Weather Occurrences. Proc. Tenth Weather Radar Conf., Amer. Meteor. Soc., Boston, Mass., pp 51-56.

Probert-Jones, J.R., 1962: The Radar Equation in Meteorology, Quart. J.R. Meteor. Soc., 88, pp 485-495.

Prosser, N.E., 1967: Radar Depiction of the Topeka Tornado, Proc. Fifth Conference on Severe Local Storms, Amer. Meteor. Soc., Boston, pp 258-259.

Ryde, J.W., 1945: The Attenuation and Radar Echoes Produced at Centimetre Wavelength by Various Meteorological Phenomena, Meteorological Factors in Radio Wave Propogation, Phys. Soc.

Schaefer, V.J., 1960: Hailstorms and Hailstones of the Western Great Plains, Nubila, 3, No. 1, pp 18-29.

Schlousener, R.A., and J.D. Maruitz, 1963: Characteristics of Hailstorms in the High Plains as Deduced from 3-cm Radar Observations, Proc. Tenth Weather Radar Conf., Amer. Meteor. Soc., Boston, Mass., pp 157-167.

REFERENCES (contd)

Smith, R.L., 1962: Vertical Echo Protrusions Observed by WSR-57 Radar, Progress Report No. 10, WSR-57 Radar Program, U.S. Weather Bureau, pp 20-30.

Stoats, W.F. and C.M. Turrentine, 1956: Some Observations and Radar Pictures of the Blackwell and Udall Tornadoes of May 25, 1955, Bull. Amer. Meteor. Soc., 37, pp 495-505.

Stout, G.E., and H.W. Hiser, 1955: Radar Scope Interpretations of Wind, Hail, and Heavy Rain Storms between May 27 and June 8, 1954, Bull. Amer. Meteor. Soc., 36, pp 519-527.

Stout, G.E., B.H. Blackmer and K.E. Wilk, 1960: Hail Studies in Illinois Relating to Cloud Physics, Physics of Precipitation Geophysics, Monogr., No. 5, Amer. Geophys. Union, Washington, pp 369-381.

Tepper, M., 1950: Radar and Synoptic Analysis of a Tornado Situation, Monthly Weather Review, 78, pp 170-176.

U.S. Weather Bureau, 1968: Weather Surveillance Radar Manual.

Ward, N., R. Wilk and W. Herrmann, 1965: WSR-57 Reflectivity Measurements and Hail Observations, Technical Note 3 - NSSL-24, pp 1-8.

Whalen, R.J., 1963: The Height of Maximum Reflectivity of Radar Echoes, Progress Report No. 13, WSR-57 Radar Program, U.S. Weather Bureau, pp 28-29.

Whalen, R.J., 1963: A Hail Study Utilizing WSR-57 Data, Progress Report No. 13, WSR-57 Radar Program, U.S. Weather Bureau, pp 30-31.

Williams, W.E., and Radar Staff, 1965: Radar Detection of Hail Occurrence, Progress Report No. 15, WSR-57 Radar Program, U.S. Weather Bureau, pp 12-17.

Yates, J.M., 1963: The Association of Vertical Radar Echo Protrusions with Hail, Progress Report No. 12, WSR-57 Radar Program, U.S. Weather Bureau, pp 47-51.

List of Eastern Region Technical Memoranda
(continued from inside front cover)