Reprinted from Preprint Volume: Tenth Conference on Severe Local Storms, Oct. 18-21, 1977; Omaha, NE. Published by American Meteorological Society, Boston, Massachusetts.

THUNDERSTORM-SCALE VARIATIONS OF ECHOES ASSOCIATED WITH LEFT-TURN TORNADO FAMILIES

Gregory S. Forbes
The University of Chicago

1. INTRODUCTION

One of the largest tornado outbreaks in history occurred on 3 April 1974. Following the outbreak, an intensive damage survey (Fujita, 1975a) confirmed the existence of 148 tornadoes, whose paths are shown in Figure 1. The outbreak focused attention on the periodic production of tornadoes by a long-lived thunderstorm, creating a tornado family. Of particular interest were several spectacular left-turn tornado families and the preponderance of left-turn tornadoes.

As noted by Darkow and Roos (1970) and others, the periodic formation of tornadoes in a tornado family tantalizingly suggests a concurrent cyclic variation of some thunderstorm feature. This paper shows that such a thunderstorm cycle exists in conjunction with left-turn tornado families. This cycle is revealed in the radar echo by a change of orientation of the hook and successive formations of new hooks.

Other studies have explored possible cyclic thunderstorm features in relation to tornadoes. Foster (1973) studied a tornado family associated with an echo protuberance (rather than a classic hook). He found that the echo grew in bursts with a 46-minute periodicity. Following such a burst, the echo orientation shifted cyclonically and the echo made a right turn in movement. One tornado formed just after the cyclonic shift. The other touchdowns were less precisely known.

Doppler radar observations by Donaldson (1971) and Burgess (1976), for example, indicate that a tornado forms after a mesocyclone signature has descended to the surface.

There has been considerable research on the behavior of the thunderstorm top as a possible indicator of tornado production. In general, these studies have concluded that tornadoes occur as the cloud top descends or is at a minimum height. These studies include Donaldson (1958), Browning and Donaldson (1963), and Fujita (1972), among others.

This paper is a continuation of Forbes (1975). The emphasis in that paper was to establish a statistical estimate of the validity of using echo shape as a tornado indicator. An elaboration on this work is presented in Section 2. Sections 3 and 4 represent the main emphasis of this paper: associating changes in echo features with tornado touchdowns, liftoffs, and turns.

2. DISTINCTIVE ECHO STATISTICS

Two echo configurations that are known to be associated with tornadoes are the hook echo and the line-echo-wave-pattern (LEWP). Nolen (1959) defined a LEWP as "a configuration of radar echoes in which a line of echoes has been subjected to an acceleration along one portion and/or a deceleration along that portion of the line immediately adjacent, with a resulting

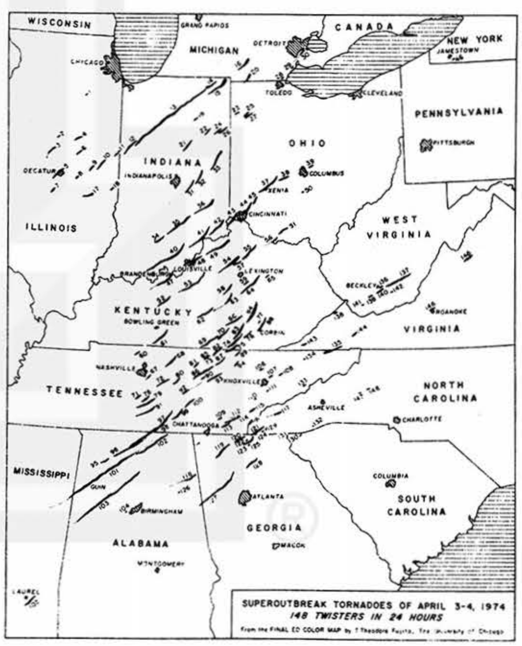


Fig. 1. Tracks of the 148 tornadoes of April 3, 1974. From Fujita (1975a).

sinusoidal mesoscale wave pattern in the line". Hamilton (1970) found that the LEWP was associated with a mesolow and that the acceleration of the south part of the line was accomplished by a spreading out of the mesohigh. Cook (1961) observed that the severe weather occurred with the strongest cell, in the vicinity of the mesolow.

The hook echo has been recognized as a potential tornado indicator since first reported by Stout and Huff (1953). Quantitative evaluations of the reliability of the hook echo as a tornado indicator have been performed only in limited studies, however. Freund (1966) found that 6 of 13 tornadic storms near NSSL in 1964 had hook echoes. Sadowski (1969) studied documented hook echoes from 1953 to 1966. Data tabulated in his appendices indicate that 40 of the 46 hook echoes were tornadic. Using Doppler radar, Burgess (1976) reports that from 1971 to 1975, 23 of 37 mesocyclones detected near NSSL were tornadic.

Three types of echoes which commonly produced tornadoes were classified as "distinctive" in this study, on the basis of echo shape. These distinctive echoes, shown in Figure 2, are hook echoes, LEWP's, and echoes with appendages on the southwest of the echo and oriented at an angle of at least 40 degrees to the south of the echo movement. The study area was described by Forbes (1975). Briefly, it was composed of all WSR-57 radars operating in the 125 nautical mile range mode.

There were 55 distinctive echoes in the study. This represents a decrease of five from Forbes (1975), due to reanalysis of the echoes which crossed from coverage

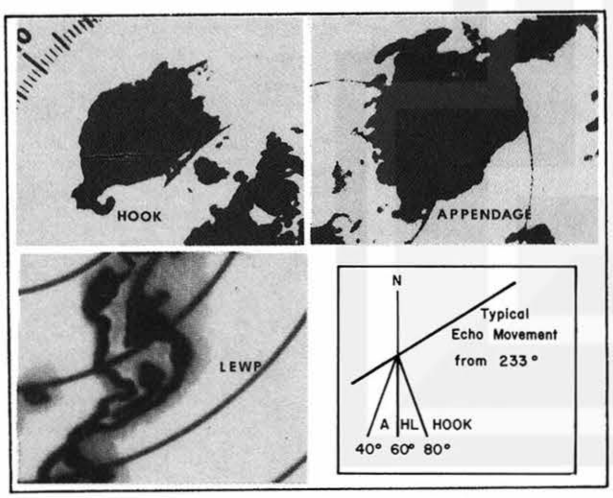


Fig. 2. Types of distinctive echoes. In the diagram, A refers to appendage and HL refers to hooklike--a very pronounced appendage but not of a classic hook shape.

by one radar to another. These were initially counted as new echoes if there was a detectability gap during the crossover; but now each echo is counted only once. The tracks of the distinctive echoes, from echo origin to termination, are shown in Figure 3.

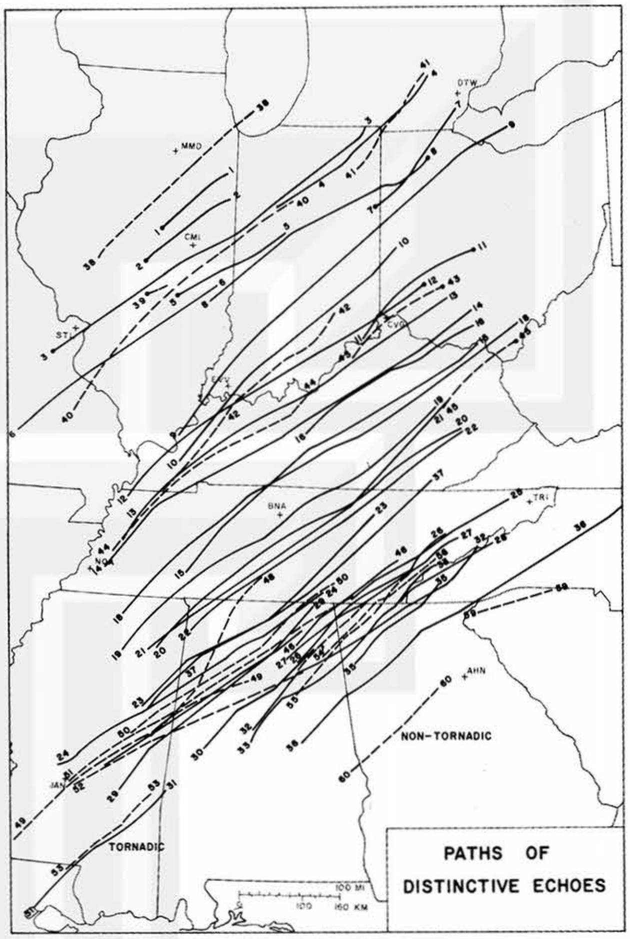


Fig. 3. Paths of distinctive echoes.

Table 1 reveals that 65% of the distinctive echoes produced tornadoes. Also, 65% of the echoes which produced tornadoes were of distinctive shape. (The identical percentages are coincidental.) Distinctive echoes produced 27 of the 28 tornado families in the study. About half of the distinctive echoes produced a tornado family.

DISTINCTIVE ECHOES	55	
Tornadic	36	(65%)
Non-tornadic	19	(35%)
TORNADIC ECHOES	55	
Distinctive	36	(65%)
Non-distinctive	19	(35%)

Table 1. Distribution of echoes and tornadoes.

Tornadoes produced from distinctive echoes tended to be stronger and lasted longer than those from non-distinctive echoes. Table 2 shows that 85 of the total 105 tornadoes (81%) in the study were produced from distinctive echoes, including all F4 and F5 tornadoes. The mean F-scale of tornadoes from distinctive echoes was 3.26 while those from non-distinctive echoes had mean of 1.88. 35% of the distinctive echoes produced an F4 or F5 tornado. The median duration of tornadoes from distinctive and non-distinctive echoes was 20 and 5 minutes, respectively.

TORNADOES FROM DISTINCTIVE ECHOES			TORNADOES FROM NON-DISTINCTIVE ECHOES		
F 0	5	(6%)	F 0	6	(30%)
F 1	14	(16%)	F 1	6	(30%)
F 2	16	(19%)	F 2	4	(20%)
F 3	24	(28%)	F 3	4	(20%)
F 4	21	(25%)	F 4	0	
F 5	5	(6%)	F 5	0	
Total	85		Total	20	
Mean F = 3.26			Mean F = 1.88		

PERCENT OF TORNADOES PRODUCED FROM DISTINCTIVE ECHOES	
F 0	45%
F 1	70%
F 2	80%
F 3	86%
F 4	100%
F 5	100%
All	81%

Table 2. F-scale distribution of tornadoes produced from distinctive and non-distinctive echoes.

Distinctive echoes produced tornadoes for only 36% of the appendage duration. (The percentage is 28% if never-tornadic distinctive echoes are included.) In addition, otherwise-distinctive echoes were temporarily not distinctive for 12% of the total tornado duration. These temporal considerations combine with the duration and frequency of issuance of tornado warnings to determine the false alarm rate (FAR) and probability of detection (POD). Table 3 revises the definitions of Donaldson et al. (1975a,b) to include these factors.

The definitions of Table 3 represent two extremes. If one is not concerned with false alarms, when the echo first becomes distinctive he might hypothetically issue a warning over an area sufficient to cover the remaining lifetime of the echo. This is defined here as an indefinite warning, and verifies if a tornado occurs for any portion of the warning duration. At the other extreme, one might hypothetically issue warnings of one-minute duration at one-minute intervals, based upon whether the echo was distinctive at that moment. This is defined here as an instantaneous warning. The "real" verification scheme lies between these two schemes, and is determined by the public's concept of how close a tornado must strike in order to justify a warning at their location.

Indefinite Warning

$$\text{P.O.D.} = \frac{\text{Number of tornadoes produced from distinctive echoes}}{\text{Total number of tornadoes}}$$

$$\text{F.A.R.} = \frac{\text{Number of non-tornadic but distinctive echoes}}{\text{Total number of distinctive echoes}}$$

Instantaneous Warning

$$\text{P.O.D.} = \frac{\text{Number of tornadoes produced from distinctive echoes at a particular instant}}{\text{Total number of tornadoes at that instant}}$$

$$\cong \frac{\text{Total time that all tornadoes are accompanied by a distinctive echo}}{\text{Total tornado duration}}$$

$$\text{F.A.R.} = \frac{\text{Total time that distinctive echoes are non-tornadic}}{\text{Total time that distinctive echoes exist}}$$

Table 3. Definitions of "probability of detection (POD)" and "false alarm ratio (FAR)" according to extremes of temporal extent of the warning period.

Figure 4 illustrates the effect of the two verification schemes upon FAR and POD. The FAR is most highly affected. As a more typical scheme, if warnings of one-hour duration are issued at one-hour intervals, beginning when the echo first becomes distinctive, the FAR for the distinctive echoes in the April 3 study is 51%.

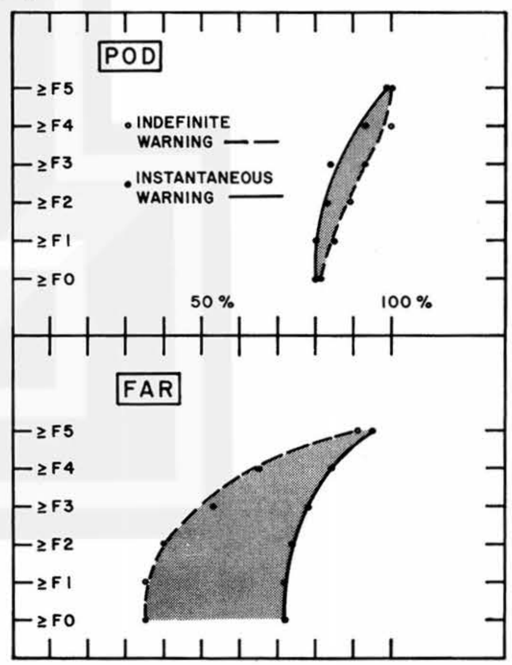


Fig. 4. POD and FAR for indefinite and instantaneous warnings.

The generality of the FAR and POD for the April 3 study is questionable. Both the data above (65%) and that of Burgess (1976; 62%) indicate that 60 to 65% of detectable mesocyclones produce tornadoes. Thus the above false alarm rates (35% for indefinite warnings and 51% for one-hour warnings) seem reasonable. On the other hand, more research is needed to determine what fraction of all tornadoes are produced from distinctive echoes.

Operational detectability is also a problem, with distinctive echoes going undetected at long ranges. In the April 3 study, the overall detectability was only about 74%, due to gaps in coverage (where the nearest radar was over 100 n.mi./185 km away).

3. ECHO CHANGES AND TORNADO OCCURRENCES

The appendages and hooks of the distinctive echoes were not steady in shape or orientation. Only 45% of the distinctive echoes ever assumed a classic hook shape. Non-tornadic echoes possessed a hook even less frequently. In total, the echo assumed a hook shape for only 20% of the time that it was distinctive. At times, the echo momentarily lost its distinctive shape. Changes in appendage and hook orientation were usually accompanied by tornado turns, as discussed in Section 4.

When studied a posteriori, distinctive echoes which produced tornadoes were distinctive longer than those which were non-tornadic: 145 versus 62 minutes in median duration. Tornadic distinctive echoes also had longer lives: 330 versus 217 minutes in median life. There was a general tendency for distinctive echoes with lives of 300 to 420 minutes to produce the strongest (F5) tornadoes. No echo with life of less than 300 minutes produced an F4 or F5 tornado. On an individual basis, however, it was difficult to distinguish a tornadic from a non-tornadic distinctive echo simply by studying its shape.

After calibrating the echo positions through use of known ground clutter, the tornado was located with respect to the echo. (Figure 7 illustrates the locations of some of the ground clutter used in calibrating the Cincinnati radar.) Table 4 summarizes these observations. The locations are subject to some error, introduced due to some uncertainty in the tornado times, possibly resulting in an overestimate of the percentage of tornadoes occurring within the hook. Of the 53 touchdowns from hook echoes at short ranges, 87% occurred within the hook, rather than to its rear. The 13% occurring to the rear may belong to a separate category of thunderstorm-tornado interaction.

	In Hook	Rear of Hook	LEWP
Formation	46	7	14
Liftoff	42	7	14

Table 4. Location of tornadoes relative to echoes at short ranges.

Table 5 gives a more detailed breakdown of the location of touchdowns and liftoffs. The locations given are with respect to the hook for the categories of hook and rear, and with respect to the echo center for LEWP. 76% of the tornadoes forming in the hook were in the SSE to SSW quadrant of the hook, often within an asc or spiral near the end of the hook. The tornadoes forming in the hook tended to move approximately with the hook, except near liftoff, although the hook often changed orientation. Near liftoff, left-turn tornadoes also changed position within the hook, moving westward or northwestward.

Table 5 also presents a summary of the positions of the 14 LEWP tornadoes. Many occurred near the circulation center, and 85% occurred either near the main echo center or southwest to west of it.

Location of Formation

	Hook	Rear	LEWP
E	-	-	-
ESE	2%	-	-
SE	9	-	-
SSE	17	-	-
S	46	-	-
SSW	13	-	7%
SW	13	43%	14
WSW	-	14	14
W	-	-	36
WNW	-	14	-
NW	-	29	7
Center	-	-	21
Unknown	-	-	-

Location of Liftoff

	Hook	Rear
E	-	-
ESE	-	-
SE	7%	-
SSE	10	-
S	38	-
SSW	2	-
SW	19	-
WSW	7	-
W	17	29%
WNW	-	-
NW	-	71

Table 5. Formation and liftoff of tornadoes relative to the echo, by categories.

There were often specific echo events coincident in time with tornado touchdowns and liftoffs. 46 touchdowns and liftoffs, whose times were well documented, were used in compiling Tables 6 and 7.

Tornado touchdowns were primarily associated with intensification of existing appendages (35% of touchdowns) or mergers on existing appendages (17%). Presumably these cases represent increases in vorticity. About 30% of the touchdowns were not accompanied by a noticeable echo event. See Table 6 for other echo events.

There was a definite pattern associated with the liftoff of left-turn tornadoes: the orientation of the appendage shifted toward the southwest or west (48% of the liftoffs). Sometimes a small bump moved up the rear of the appendage or the echo (15% of the liftoffs). See Table 7 for other echo events.

ECHO EVENT	NUMBER	PERCENT
Appendage intensification or formation	16	35%
Intensification southwest, but no appendage present	3	7
Merger of echoes	2	4
Merger on appendage	8	17
Merged echo weakens	1	2
Interaction without merger	3	7
Not noticeable	13	30
Total	46 Touchdowns	

Table 6. Echo events and tornado touchdowns.

ECHO EVENT	NUMBER	PERCENT
Appendage elongation to the southwest or west	22	48%
Bump moves up rear of the echo	7	15
Appendage weakens without elongation	5	11
Merger	9	20
Interacting echo weakens	4	9
Not noticeable	6	13
Total	53 Liftoffs	

Table 7. Echo events and tornado liftoffs.

4. ECHO CHANGES AND TORNADO TURNS

A breakdown of the echo events associated with tornado turns is shown in Table 8. An orientation change, which is referred to as an elongation in the table, was primarily associated with tornadoes making left turns. All of the strong left turns and 80% of all the left turns were accompanied by that event. No-turn and right-turn tornadoes were usually accompanied by echo mergers or weakening appendages.

	Strong Left Turn	Left Turn	No Turn	Right Turn
Elongation and/or bump on echo rear	100%	43%	12%	8%
Appendage weakens	0	7	12	15
Merger	7*	7	18	31
LEWP	0	29	47	31
No event detected	0	14	12	15
Total tornadoes	14	14	17	13

TORNADO BREAKDOWN BY SUB-GROUPS

Elongation and/or bump	
Strong left	14 (61%)
Left	6 (26%)
No turn	2 (9%)
Right	1 (4%)
Total	23

Appendage weakens	
Strong left	0 (0%)
Left	1 (20%)
No turn	2 (40%)
Right	2 (40%)
Total	5

Merger	
Strong left	1 (11%)
Left	1 (11%)
No turn	3 (33%)
Right	4 (44%)
Total	9

Line Echo Wave Pattern	
Strong left	0 (0%)
Left	4 (25%)
No turn	8 (50%)
Right	4 (25%)
Total	16

No Event	
Strong left	0 (0%)
Left	2 (33%)
No turn	2 (33%)
Right	2 (33%)
Total	6

* One liftoff involved both events.

Table 8. Tornado turns and echo events.

The Hamburg echo underwent probably the most spectacular orientation change, as the Hamburg tornado was occurring. Figure 5 shows that the orientation of the hook changed from about 200 degrees to about 245 degrees in a 30-minute period. This orientation change was accompanied by an increase in the length of the neck portion of the hook, as graphed in Figure 6. The orientation gradually changed, and then accelerated in bursts after 1515 CDT, with the bursts occurring during the left-turn portion of the tornado. Figure 7 relates the location of the tornado along its path with the tornado position in the echo, shown in Fig. 5.

The left turn of the Hamburg tornado was only partially caused by the orientation change of the hook. It can be seen in Fig. 5 that the tornado also changed position within the hook. Until 1535, the tornado was located in the oval-shaped echo forming the southeast portion of the hook. After 1539, the tornado moved northwestward toward the neck of the hook. This movement is diagrammed in Figure 8. Similar movement of the tornado relative to the hook has been cited by Fujita (1975b) by the Xenia, Brandenburg, and Sayler Park tornadoes of April 3, 1974.

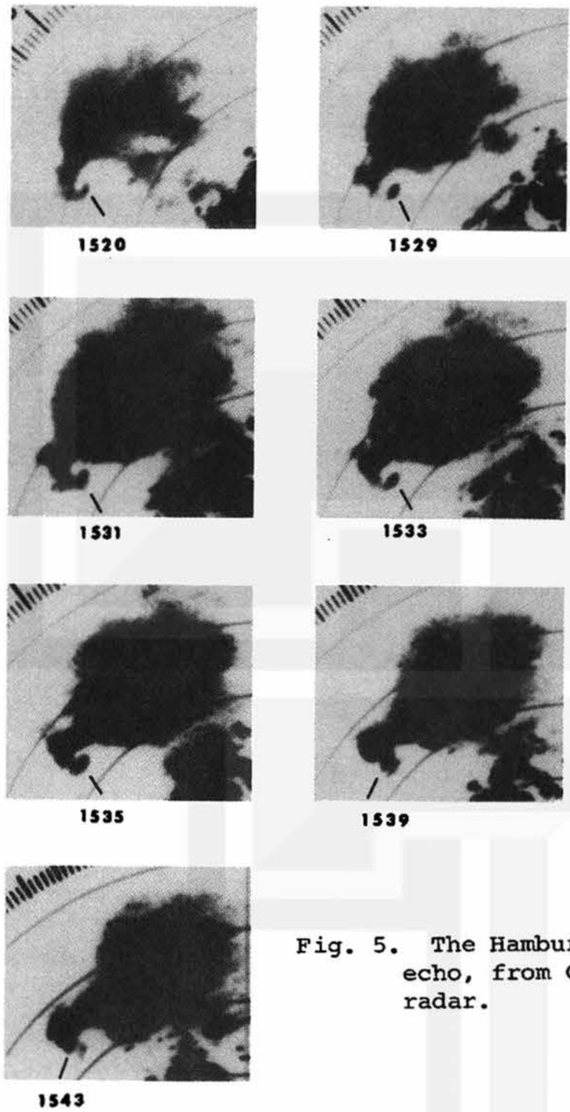


Fig. 5. The Hamburg echo, from CVG radar.

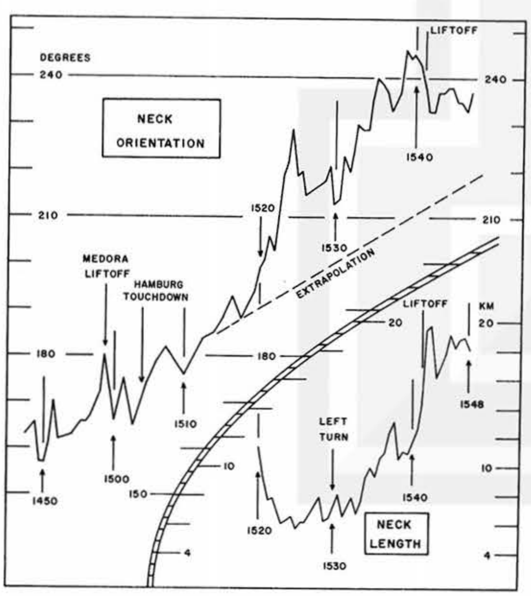


Fig. 6. Orientation and neck length of the Hamburg echo.

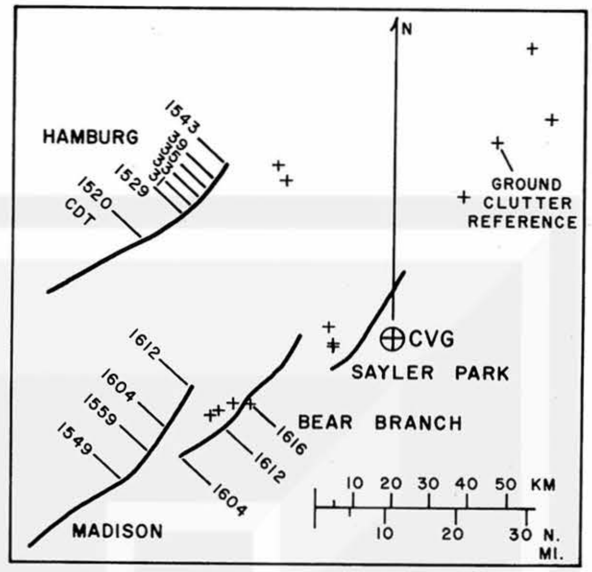


Fig. 7. Tracks of the Hamburg tornado and the Depauw family.

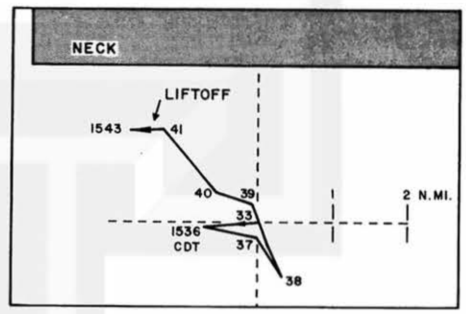
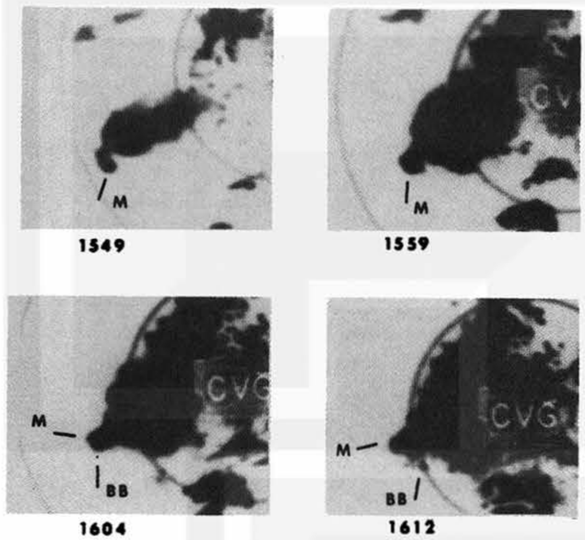


Fig. 8. Movement of the Hamburg tornado relative to the hook.

The Depauw tornado family was a family of six left-turn tornadoes. Figure 9 illustrates the thunderstorm cycle associated with the left-turn tornado family. The locations of the tornadoes along their paths are shown in Fig. 7. At 1549, the Madison tornado was within the hook echo. At 1554 the hook appeared to wrap up, and it began to shift northwestward, as evident by 1559. After 1602, the appendage no longer had a hook shape. The old appendage continued to move northwestward until about 1614, when it began to dissipate. The Madison tornado moved basically with the appendage, and slightly northwestward relative to it.

Meanwhile, the Bear Branch tornado touched down in an ehco-free region south of the Madison appendage at 1604. A hook began forming around the Bear Branch tornado at 1609 and was distinct after 1614. It appears that this left-turn tornado family was associated with an unsteady thunderstorm. Each tornado was associated with its own hook, which changed orientation and was succeeded by a new hook to the south. The Xenia and Acworth echoes, among others, behaved similarly. There was no evidence that the tornado families were produced by several tornado cyclones revolving about a common center, as proposed by Agee et al. (1976).

by eyewitnesses that there is often clear sky immediately west of the tornado. This may represent a different category of tornado origin from the unsteady-hook mode described above in conjunction with the Depauw family.



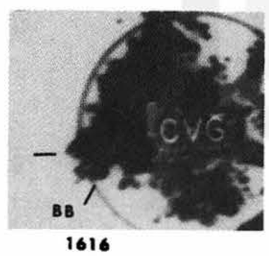


Fig. 9. The Depauw-family echo, from CVG radar.

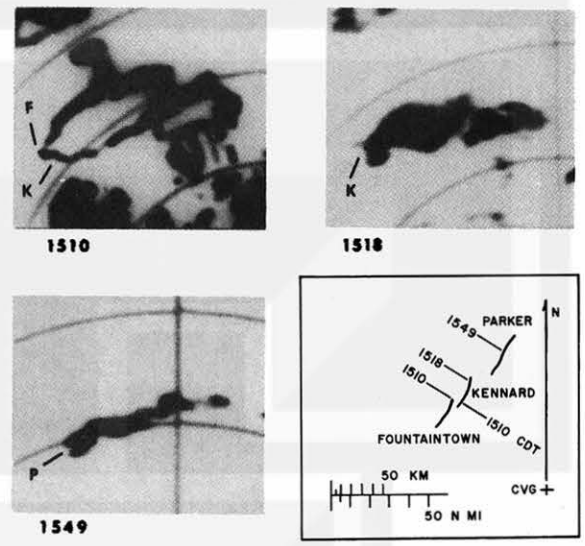


Fig. 10. The Parker-family echo, from CVG radar.

By contrast with the Depauw echo, the Parker echo was quite dissimilar in terms of tornado locations relative to the echo. This difference might be related to the difference in orientations of the families, which can be seen in Figure 1. The Parker family was oriented along a more northerly track.

Figure 10 shows that the Parker-family tornadoes occurred primarily on the rear of the echo. In particular, the Kennard tornado at 1518 and the Parker tornado at 1549 appeared to be associated with protuberances on the rear of the echo. Such an occurrence was also suspected by Garrett and Rockney (1962). The locations of the Parker-family tornadoes along their paths is also shown in Fig. 10.

It became apparent in relating radar echoes and tornado times that some other tornadoes were not occurring inside a classic hook, but rather on the rear edge of the echo. (This type of occurrence has been tabulated in Tables 4 and 5.) This observation is consistent with observations

5. DISCUSSION

Based upon the study of echo shape and its changes, and tornado location relative to the echo, it appears that there may be at least three classes of tornado origin associated with hook echoes:

1. A "steady" hook mode, producing no-turn or perhaps right-turn tornadoes, where the hook does not change shape or orientation;
2. An "unsteady" hook mode, producing left-turn tornado families, where the hook changes orientation and a new hook forms in association with each successive tornado;
3. A "rear-subcell" mode, producing left-turn tornado families, where tornadoes move along the rear of a hook which does not undergo an orientation change.

The unsteady-hook mode confirms suspicions that periodic tornado production is related to a thunderstorm-scale cycle. The mechanism of this cycle is not understood. Closing of the hook seems to play a key role in the process, however. As the hook becomes overdeveloped, the hook wraps up into a spiral, closing off a segment of the WER. When this occurs, the closed-off spiral appears to drift northwestward. Garrett and Rockney (1962) also observed this phenomenon. Presumably the closing of the hook disrupts the mesocyclone and the inflow/updraft of the thunderstorm. This mode may be associated with a vigorous flanking cell. This type of thunderstorm may be of the severely-sheared or multicell type, defined by Marwitz (1971).

The rear-subcell mode probably represents tornado formation in a cell of a multicell or severely-sheared thunderstorm. The tornado is probably associated with the updraft of an individual cell, moving along the rear of the thunderstorm, and moving to the left of the overall storm propagation.

Acknowledgement:- Research sponsored by NASA under Grant NGR 14-001-008, NOAA under Grant 04-4-158-1 and by NRC under Contract No. AT(49-24)-0239. The author is grateful to Professor T. T. Fujita for his support.

REFERENCES

Agee, E.M., J.T. Snow, and P.R. Clare, 1976: Multiple vortex features in the tornado cyclone and the occurrence of tornado families. Mon. Wea. Rev., 104, 552-563.

Browning, K.A. and R.J. Donaldson, 1963: Airflow and structure of a tornadic storm. J.Atmos.Sci., 20, 533-545.

Burgess, D.W., 1976: Single Doppler vortex recognition: part I - mesocyclone signatures. Preprints, 17th Conf. Radar Meteor., AMS, 97-103.

Cook, B.J., 1961: Some radar LEWP observations and associated severe weather. Proceedings, 9th Weather Radar Conf., AMS, 181-185.

Darkow, G.L. and J.C. Roos, 1970: Multiple tornado-producing thunderstorms and their apparent cyclic variations in intensity. Preprints, 14th Conf. Radar Meteor., AMS, 305-308.

Donaldson, R.J., 1958: Analysis of severe convective storms observed by radar. J.Meteor., 15, 44-50.

Donaldson, R.J., 1971: Doppler radar identification of damaging convective storms by plan shear indicator. Preprints, Seventh Conf. Severe Local Storms, AMS, 71-74.

Donaldson, R.J., R.M. Dyer, and M.J. Kraus, 1975a: Operational benefits of meteorological Doppler radar. AFCRL-TR-75-0103, Air Force Cambridge Research Lab., 26pp.

Donaldson, R.J., R.M. Dyer, and M.J. Kraus, 1975b: An objective evaluator of techniques for predicting severe weather events. Preprints, Ninth Conf. Severe Local Storms, AMS, 321-326.

Forbes, G.S., 1975: Relationship between tornadoes and hook echoes on April 3, 1974. Preprints, Ninth Conf. Severe Local Storms, AMS, 280-285.

Foster, H., 1973: Tornado echo study with VIP. Preprints, Eighth Conf. Severe Local Storms, AMS, 161-164.

Freund, R.F., 1966: Radar echo signature of tornadoes. Proceedings, 12th Conf. Radar Meteor., AMS, 362-365.

Fujita, T.T., 1972: Tornado occurrences related to overshooting cloud-top heights as determined from ATS pictures. SMRP Res. Paper. No. 97, Univ. of Chicago, 32pp.

Fujita, T.T., 1975a: Superoutbreak tornadoes of April 3-4, 1974. Final edition map, The Univ. of Chicago.

Fujita, T.T., 1975b: New evidence from April 3-4, 1974 tornadoes. Preprints, Ninth Conf. Severe Local Storms, AMS, 248-255.

Garrett, R.A. and V.D. Rockney, 1962: Tornadoes in northeastern Kansas, May 19, 1960. Mon. Wea. Rev., 90, 231-240.

Hamilton, R.E., 1970: Use of detailed intensity radar data in mesoscale surface analysis of the July 4, 1969 storm in Ohio. Preprints, 14th Conf. Radar Meteor., AMS, 339-342.

Marwitz, J.D., 1971: Severe storm types in relation to wind shear. Preprints, Seventh Conf. Severe Local Storms, AMS, 240-243.

Nolen, R.H., 1959: A radar pattern associated with tornadoes. Bull. Amer. Meteor. Soc., 40, 277-279.

Sadowski, A., 1969: Size of tornado warning area when issued on basis of radar hook echo. ESSA Tech. Mem. WBTM FCST- 10, 26pp.