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by Tetsuya Fujita

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ABSTRACT

The original radar film of the Illinois tornadoes was analyzed with the additional use of surface observations from the available stations in the vicinity. This study shows that the tornadoes were associated with a tornado cyclone resembling a miniature hurricane in many respects. The tornado cyclone was only 30 mi in diameter, and it was characterized by an eye at its center, spiral echo bands, *etc.* The echo movement inside the tornado cyclone indicates that air converged at low levels then rose following the boundary of the eye. The location of the Champaign tornado with respect to the tornado cyclone center was carefully examined; it was placed beneath the ring of maximum wind, south of the cyclone center. Such a relative position was maintained at least during the developing stage of the tornado. It was also found that the direction of movement of the tornado cyclone formed a 25 deg angle with that of the echoes in outer fields.

1. Introduction

During the late afternoon of 9 April 1953, a tornado-like echo was observed on the radarscope of the Meteorology Subdivision, Illinois State Water Survey at the University of Illinois Airport, Champaign, Illinois. Radar pictures of this tornado and its associated thunderstorm were taken from an early stage of their development. The radar used, an AN/APS–15A was a three-cm set having a three-degree beamwidth and a pulse length of two microseconds. The PPI was photographed by Navy Type A Scope Camera on 35-mm film. These photographs were taken in steps of reduced gains corresponding to 97, 93, 89, 87, 81, 75, 69 and 63 db below one milliwatt.

Detailed studies were carried out by the staff of the Meteorology Subdivision, the results of which appeared in Report of Investigation No. 22 [3]. They showed that the continuous growth of a parasite echo or appendage with development of a cyclonic curl or eye, such as seen in the Illinois tornado, could be the positive indication of a tornado.

Due to the progress of analysis techniques, it is now possible to re-examine the original film of the Illinois tornado from the viewpoint of mesometeorology.

As a first step in the present analysis, all the 35-mm pictures were copied on tracing paper on which the actual distorted range markers, seen on the microfilm reader, had been mimeographed. The ground clutter was also mimeographed in several reduced gains. The series of reduced-gain pictures was copied on a single sheet in order to show the contour lines of echo intensity. The advantage of using this tracing paper is that we do not have to shift it for adjustment while working on a microfilm reader.

2. Mesoanalysis of surface charts

A method of analyzing surface charts by converting time sections into space sections was developed by the writer [2]. A similar but revised method is presented here. Conventionally, the time section of station weather elements is converted into a space section by assuming that a system carries all these elements in the direction of its own movement, although it is known that a pressure-surge line does not move in the same direction as radar echoes. Our studies showed that the weather at a given station ought to and could be related to several systems, moving with different velocities. Lightning, hail, *etc.*, seen in teletype reports, are supposed to move at the velocity of radar echoes. On the other hand, the velocity of a surface-pressure system related to either a cold front or a mesosystem may differ from the velocity of the echoes by as much as 90 deg.

As shown in fig. 1, vectors indicating the displacement of radar echoes, cold front, mesosystem, and major system in one hour are entered around each station circle. As stated above, the teletype remarks are closely related to the movement of echoes. Therefore, these remarks should be plotted along a vector at point of the vector corresponding to the time of observation.

Hourly mesoanalysis charts.—Two tornadoes occurred on the 9th; one started near Lincoln, and the other, the main one, started its development near Champaign. In order to distinguish them, the terms Lincoln tornado and Champaign tornado are used. The Lincoln tornado struck Logan County Fairground west of

[1] This work was sponsored by the U. S. Weather Bureau, under Contract No. Cwb 8613.

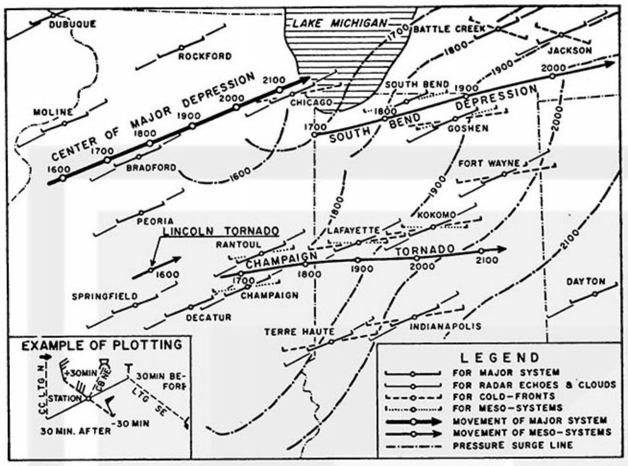

FIG. 1. Space-section chart for meso-analysis. The time-section from each station is converted into space-section by using vectors showing the velocities of different systems.

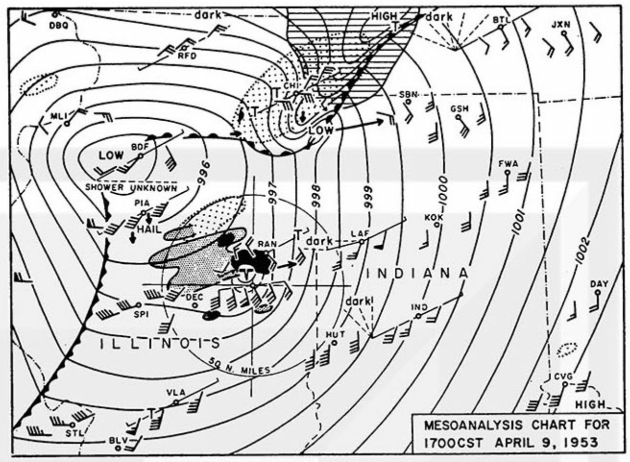

FIG. 3. Mesoanalysis chart for 1700. Meso-depression southeast of Chicago and the Champaign Tornado are noted.

Lincoln at 1615 CST, then moved northeastward through rural areas. Buildings were damaged on six farms before the tornado lifted. Later on a funnel aloft was observed in McLean County. The mesoscale chart for 1600 CST, with radar echoes, is shown in fig. 2. Using a technique similar to that of Stout and Hiser [5] in their study of wind, hail and heavy rain storm, a composite of full-gain echoes was obtained. In this case, however, the map was constructed by superimposing the five-minute interval photographs taken during the hour preceding the map time. The stippled areas extending southwest of the echoes at 1600 CST shown in black are the composite of echoes from 1500 to 1600 CST, namely, the areas swept by the echoes during that period. The first echo of the mother cloud of the Lincoln tornado appeared in the full-gain picture at 1537 CST, then its rapid growth was observed until 1557 CST when the range was reduced to 30 mi. The tornado appears to have developed south of the mother echo.

The weather reports from Springfield, Illinois, 20-mi south southwest of Lincoln, indicate a towering cumulus to the north of the station. At 1530 and again at 1630 CST they note a cumulonimbus to the north, which could be the mother cloud of the Lincoln tornado. No appreciable change was seen in the pressure and wind traces. It can be said that the tornado was initiated before the pressure-surge line was organized.

At 1700 CST, a tornado, the detailed pictures of which were taken at the Champaign Radar Station, was visible to the south of the mother cloud and was accompanied by hail. This tornado passing north of the radar station seen in fig. 3 is the well-known Champaign tornado. It will be seen in the figure that this tornado is not related to a line system but to an isolated system. Detailed analysis of the surface chart for that time is shown in fig. 25.

A mesodepression had started to develop southeast of Chicago. This depression could be related to a thunderstorm high over the Chicago area. As shown in fig. 4 for 1800 CST, the Champaign Tornado moved eastward, accompanied by a converging echo to the

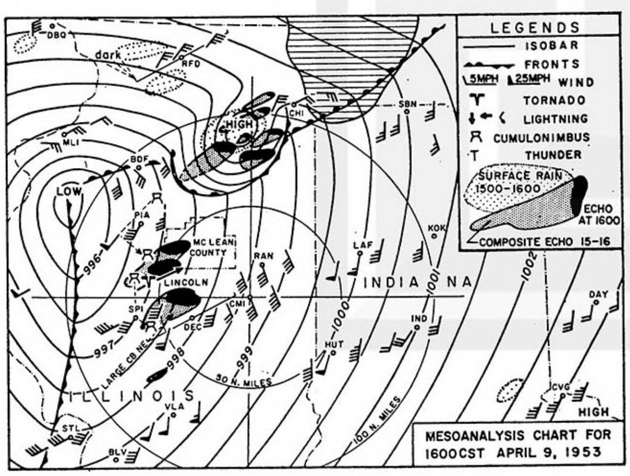

FIG. 2. Mesoanalysis chart for 1600. Lincoln tornado is seen to the southwest of the mother cloud.

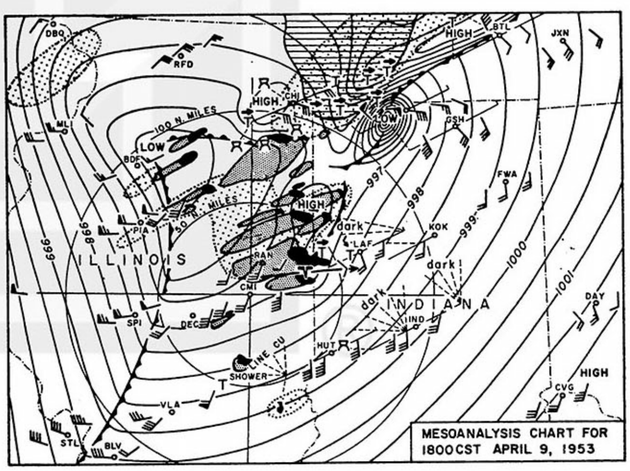

FIG. 4. Mesoanalysis chart for 1800. South Bend depression is in mature stage.

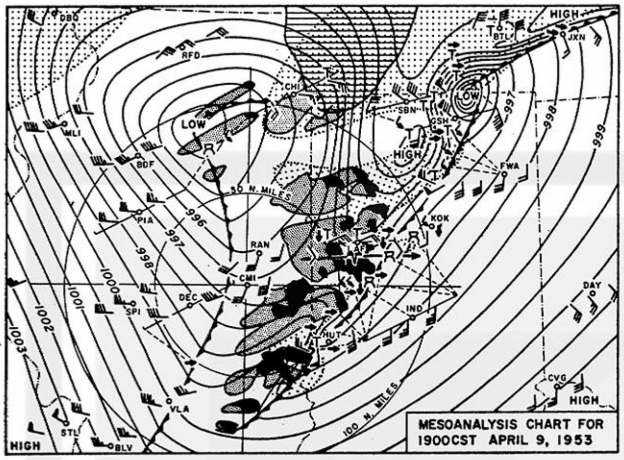

FIG. 5. Mesoanalysis chart for 1900. Prefrontal squall line is now organized.

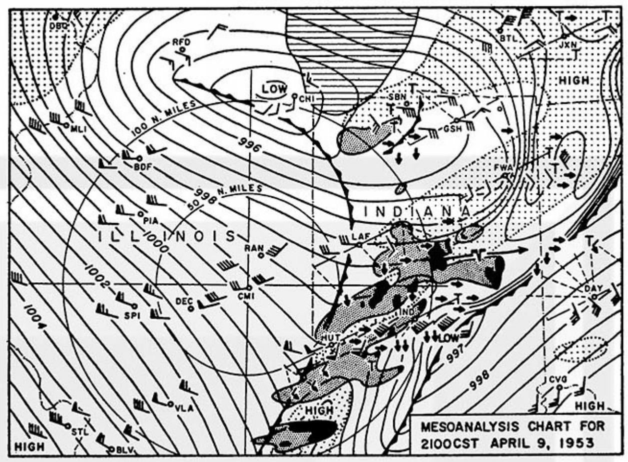

FIG. 7. Mesoanalysis chart for 2100. The Champaign tornado is dissipating, surrounded by underlying cold air.

south. Scattered echoes appeared to the north, producing rain over a large area. Echoes and rain field, stippled and outlined by dotted lines, can easily be compared with the composite radar areas, since both represent integrated activity during the same period. At the same hour, Lafayette reported a dark cloud and lightning approaching from the west. A fine-weather cold front, bringing in pressure rises and an increase in wind speed, was sweeping Illinois from the west. An interesting feature of the chart under consideration is the rapid development of what we may call the "South Bend depression," west of that city in Indiana. When this depression passed over South Bend, pressure dropped 5 mb in 15 min, then it recovered in another 15 min. At the time of minimum pressure, thunder was heard and cloud-to-cloud lightning was seen to the northwest, but no rain was reported. Hail began six minutes after the pressure recovery and lasted for 25 min. A small thunderstorm high, located behind the depression and east northeast of the rain area, was slowly pushing southward.

The chart for 1900 CST, fig. 5, shows the South Bend depression fully developed and accompanied by heavy thunder and rain to the rear. The Champaign tornado which has now entered the state of Indiana is located south of Lafayette. A long pressure-surge line is organized at the eastern edge of the echo group, and it shows features of a so-called prefrontal squall line in its mature stage.

At 2000 CST, as seen in fig. 6, the Champaign tornado has reached the pressure-surge line. An aerial survey in Indiana reported that damage was traceable from just south of Attica, 15-mi east of the Illinois border, to about 10-mi northeast of Muncie, west of the Ohio border. It is evident from this report that the tornado was still intense when crossing Indiana. Although observers described hail stones as large as walnuts or small lemons, no precise chronological relationship could be established between this phenomenon and the tornado; however, a hail cloud reported by Lafayette was located 10-mi northwest of the tornado.

As the thunderstorm high to the rear of the pressure-

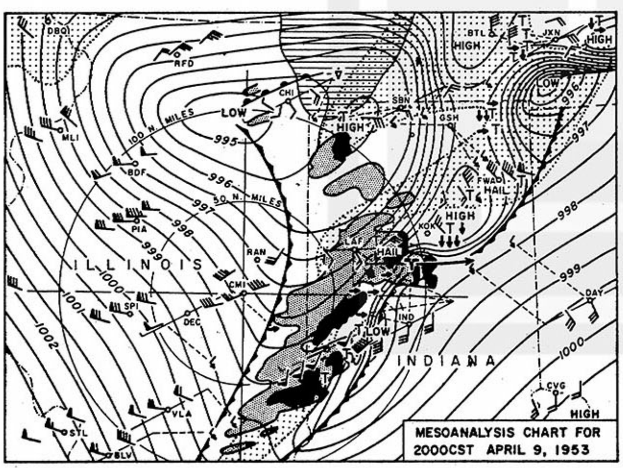

FIG. 6. Mesoanalysis chart for 2000. The Champaign Tornado has reached the pressure-surge line.

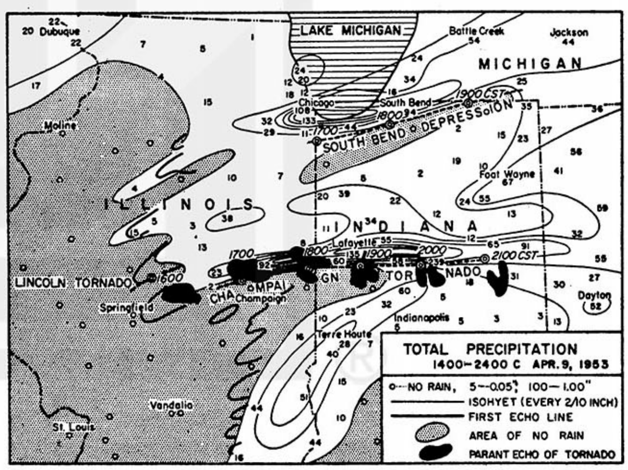

FIG. 8. Total precipitation chart for the period 1400–2400 CST 9 April 1953. No rain areas are seen to the south of the paths of mesosystems.

surge line moved eastward (fig. 7 for 2100 CST), a wake depression appeared in the vicinity of Fort Wayne, Indiana. Radar echoes were weakening in the Indianapolis area; this fact is corroborated by the pattern of rain distribution. The tornado could potentially produce some intense echoes, but it was out of the range of the Champaign radar. Toward the end of our map time span or shortly after, the Champaign tornado was surrounded by the underlying cold-air aloft, and it finally dissipated around 2115 CST while approaching the Ohio border.

A total precipitation chart in fig. 8 made for the period 1400–2400 CST, 9 April 1953 shows a very interesting distribution of surface rain. The first echo line on the chart indicates where the echoes first appeared. Surface rain is seen to the east of the line. This fact supports the results of the Thunderstorm Project [6] which reported that convective clouds develop through three stages and that rain reaches the ground sometime after the appearance of the first echo.

Looking at the precipitation chart, we see areas of heavy rain to the north of both the tornado and the depression paths, while the south remains practically dry. This important fact indicates that mesosystems may develop in the southern sector of a heavy rain shower. A similar relationship was shown by Penn, Pierce, and McGuire [4], and by Stout and Hiser [5]. Accumulation of these analyzed results will lead us to a clearer understanding of the mechanism of tornado and tornado cyclone initiation.

3. Technique of radar echo analysis

Horizontal time-section of PPI echoes.—A time-section chart for each weather station inside the mesoscale area is essential to the analysis. In addition to the conventional plotting of pressure, temperature, rain intensities, winds and clouds, the writer made a horizontal time-section chart of PPI echoes.

A method of constructing a horizontal time-section chart of PPI echoes will now be discussed. Fig. 9a shows schematical radar echoes photographed at time $T = t_1$. The open circle indicated by P is the weather station for which the horizontal time-section chart is to be made. A–B is parallel to the direction of V, the average velocity of the echoes. As will be seen in fig. 9b, the horizontal time-section chart has its ordinate scaled by the distance of the PPI range marker, and its abscissa by $\bar{V}t$. We slice the time-section chart by vertical lines separated by the length of $\bar{V}\Delta t$, where Δt is the interval of the PPI pictures. Taking P' on $A' - B'$, the abscissa, at the half-point of the slice $T = t_1$, we put the time-section chart over the radar picture as an overlay. Putting P' exactly over P, we turn the overlay so that $A' - B'$ comes on $A - B$, the direction of the echo movement. Finally, we trace the echoes appearing under the slice for t_1.

Echoes are traced in other slices with the use of successive radar pictures. Finally, we must smooth the echo contours because echoes deform or develop during a short time span.

When the echoes move approximately from west to east, we may conveniently use $\bar{V}x$, x-component of echo velocity, instead of $\bar{V}$. In this case $A' - B'$ will be parallel to a west-east line.

A horizontal time-section of the tornado-related cloud at Rantoul is shown in fig. 10. Its shape, as expected, is similar to what we see on the PPI picture around 1710 CST. From observations taken under the radar echo, we know that light rain occurred from the eastern part of the cloud and heavy rain and hail from its western half. As will be seen later, the cloud showed a similar characteristic when it passed over the Goose Creek Rain Gauge Network. A schematical vertical time-section of the cloud is illustrated in the lower chart. It seems that cold air converged in the eastern part of the cloud while there was a pronounced downdraft in its western segment. The writer believes that, in the early stages of tornado development, the tornado-related thundercloud may be divided into two parts by a line running northeastward from the tornado center. We may assume the structure of the

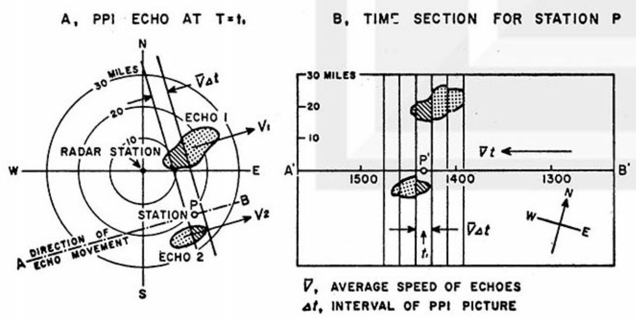

FIG. 9. A method of converting a radar picture into time-section chart for a particular station.

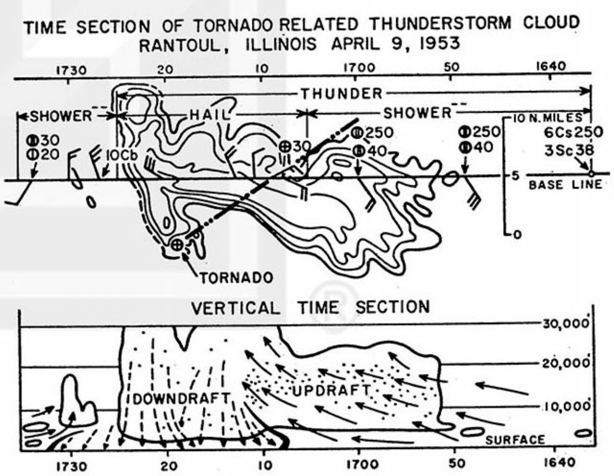

FIG. 10. Time-section chart for Rantoul, Illinois.

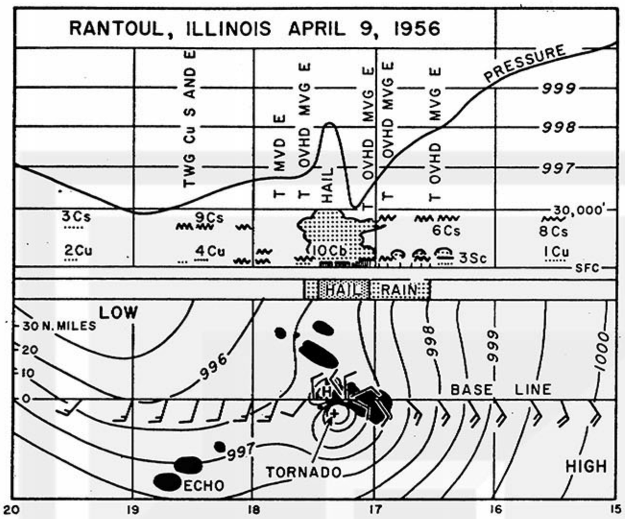

FIG. 11. Radar time-section for Rantoul, Illinois.

mother cloud to be closely related to the initiation of the tornado.

Time-sections of radar echoes from Rantoul, Illinois, and Lafayette, Indiana are shown in figs. 11 and 12, respectively. These time-sections include the surface weather elements and show hail related to the pressure nose. A time-section of isobars, obtained by dropping perpendiculars from the intersections of barograph traces and pressure lines of 1000, 999 mb, *etc.*, is very helpful in analyzing mesoscale charts. The time-sections of isobars are drawn with reference to both pressure values and wind directions. Weather remarks can be fully utilized when related to radar echoes on the time-section chart. In a favorable case, it is possible to identify the echoes with the activity reported by teletype.

Technique of determining echo movement.—Inspection of radar films is a convenient way to obtain the movement of an echo. However, accuracy is impaired by the distortion of the pictures and by the short life span of an individual echo. Tracing the echoes at different times also proved unsatisfactory because successive echoes separated by a short time interval tend to superimpose upon each other. A time gap of 15 to 20 min would prevent superimposition. But since, according to the Thunderstorm Project [6], the average life of echoes is very short, and since their shape changes rapidly during their stages of formation, maturity and dissipation, such a time interval is too long for identification of successive cells.

A revised method is demonstrated in fig. 13. In this technique, echoes are plotted by shifting the location of the radar station about half an inch for every one or two minutes. For example, the echoes for 1800 CST are plotted in reference to the radar station as indicated at that time, and the echoes for 1802 are plotted after shifting the station toward either the south or the east. The direction of the shift does not fundamentally affect the results. But to render analyses easier, we recommend an eastward shift for echoes oriented north-south. After plotting the echoes on such a shifted coordinate, we connect their centers by a line which is straight as long as the echo velocity remains constant. Irregular movement, deformation and attenuation of echoes cause a slight deviation from the straight line.

As will be seen in the figure, a straight line parallel to the time axis is drawn through the center of the first echo, then it is scaled by the same interval as the time axis. The vectors labeled 14 min, 16 min, *etc.*, represent the displacements of the echoes in 14, 16 min, *etc.*, respectively. We might consider that echoes No. 2 and No. 3 in fig. 13b are the same, but the analysis made after a southward shift shows a new development east of the old echo.

4. Echoes inside the tornado cyclone

In order to show the intensity of the tornado-related echoes, their brightness was contoured (fig. 14).

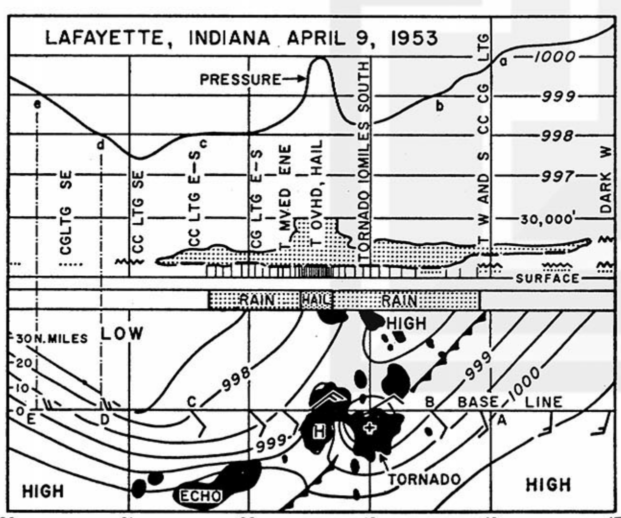

FIG. 12. Radar time-section for Lafayette, Indiana.

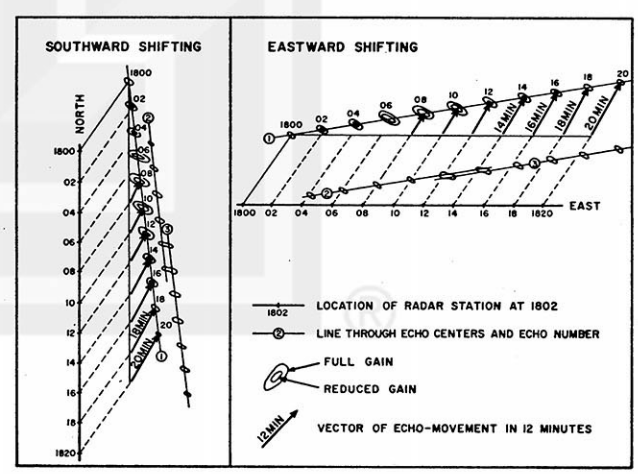

FIG. 13. Technique used in obtaining the velocity of radar echoes.

The echoes were located roughly 20-n mi from the PPI radar, which had a beam width of three degrees and an elevation angle of zero degrees. Therefore, the echoes resulted from integrated returns coming mostly from the levels between the ground and 5000 ft., possibly 10,000 ft. Thus the echoes analyzed here represent obstacles at low levels.

The heavy lines indicate the echo axes or the ridge lines of echo intensity. When we look at the echo axes more closely, we see that new developments are occurring in line formation. The echoes numbered 30, 27 and 25, which finally formed axis III, initiated a narrow spiral band. Axes I and II formed other spiral bands. The shape of these bands appears similar to that of rain bands inside a hurricane. We can easily imagine the existence of a cyclonic wind field 30 mi in diameter.

In his study of barograms and winds associated with tornadoes, Brooks [1] stated that there exists a cyclone, intermediate in size between a regular cyclone and a tornado funnel itself, in which tornadoes exist. The dimension of the cyclonic circulation seen here is identical with that of Brooks' tornado cyclone.

It is true that the dimensions of a hurricane are much larger than those of a tornado cyclone and that its rain bands have an angle of inflow smaller than the

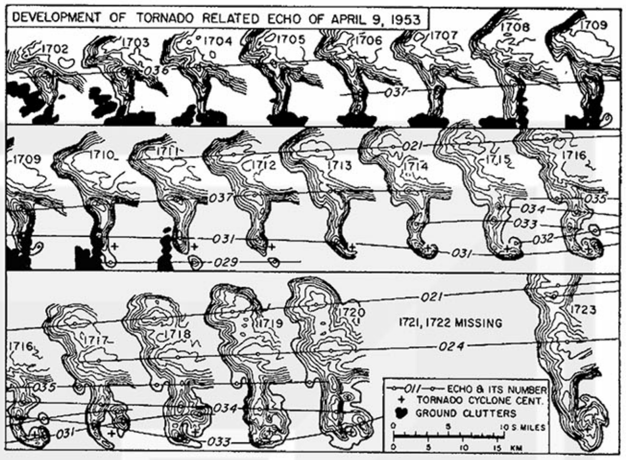

FIG. 15. Development of pendant echo of the Champaign tornado from 1702–1723 CST.

45 deg observed in the Champaign tornado cyclone; however, the mechanism for producing such convergence bands could be essentially the same in both phenomena. Another similarity between these cyclonic systems is observed in the inner portion of the vortices. At the center of the tornado cyclone, we see a miniature eye which appears as a hole in the reduced-gain pictures. However, it is not unusual to see weak spots or openings in the ring surrounding the eye.

A magnified contour representation of echoes in the vicinity of the tornado cyclone center is given in figs. 15, 16. The contours were drawn by tracing the echo boundaries seen in eight steps of reduced-gain pictures. Actually, 280 pictures were used. Echo centers shown by small circles are joined by lines on which the echo numbers appear.

With use of these contour representation charts, the axes of hook echoes were analyzed (fig. 17). More than one hook-shaped axis existed around the center of the tornado cyclone, and the radius of curvature of each axis increased with time. These axes are designated as $A, B, C \cdots$. Their radii of curvature shown in paren-

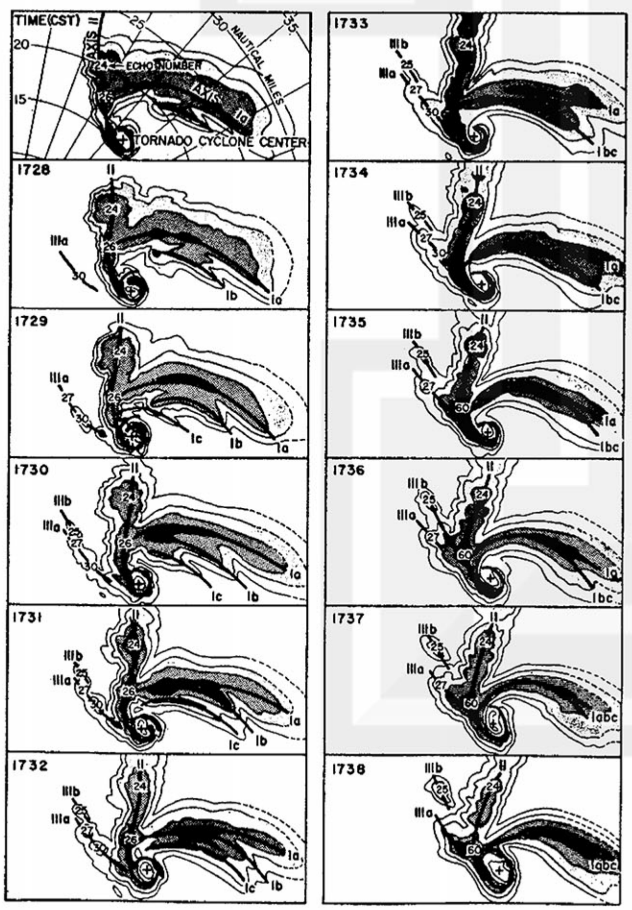

FIG. 14. Contour representation of tornado-related echo.

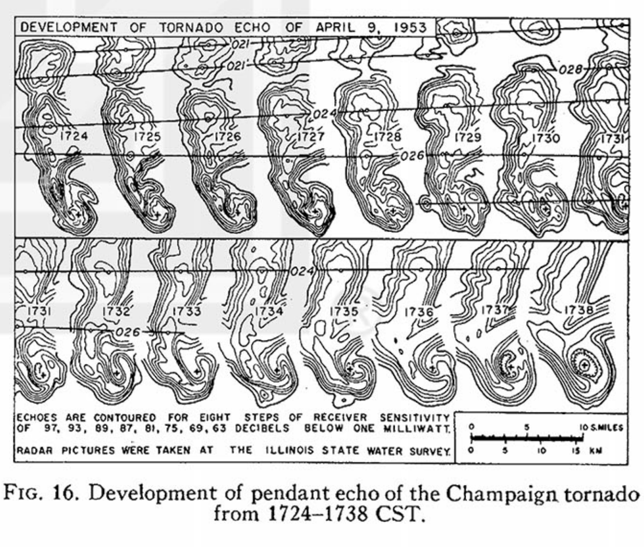

FIG. 16. Development of pendant echo of the Champaign tornado from 1724–1738 CST.

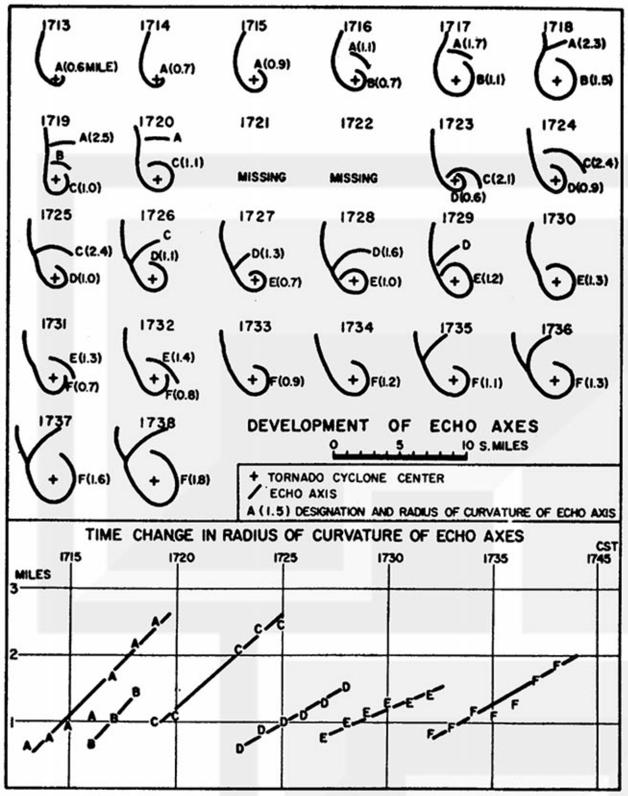

FIG. 17. Showing successive increases in radius of curvature of hook echo axis and new formation of hook.

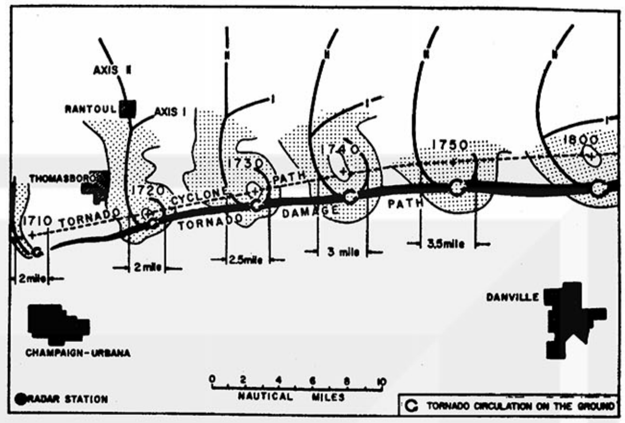

FIG. 19. Tornado cyclone path fixed by Champaign radar and the tornado damage path surveyed by the Illinois State Water Survey.

theses are plotted in the bottom chart which indicates that the radii increased two to three times in five minutes.

It is natural to imagine that an echo sucked into the tornado cyclone elongates in the direction of its motion, then tends to rotate on the circle of strongest wind surrounding the center of a tornado cyclone. This circle may be termed the "ring of maximum wind." Its diameter will increase with height, thus forming the surface of a reversed cone of maximum wind. The expansion phenomenon of a hook echo as mentioned in the previous paragraph can be explained by assuming that an echo approaches the cone of maximum wind at a low level and upon reaching it is lifted in a helical motion. An echo undergoing such a motion will appear as an expanding hook on the PPI scope until it moves above the effective intensity of the radar beam.

5. Tornado and tornado cyclone

After a careful examination of the tornado traces, Brooks [1] pointed out the fact that three tornadoes in St. Louis County, Missouri on 19 March 1948, were located inside a tornado cyclone 10 mi in diameter. In the case of the Massachusetts tornadoes of 19 June 1953, studied by Penn, Pierce and McGuire [4], a second tornado appeared 15 min before the first one dissipated. After comparing the radar pictures with results of the damage survey, these authors placed the first tornado on the well-developed hook echo. The second tornado was also placed very close to the hook. Similar twin tornadoes were reported by W. F. Staats and C. M. Turrentine [5] in their study of the Blackwell and Udall tornadoes of 25 May 1955. From these reports it is evident that several tornadoes

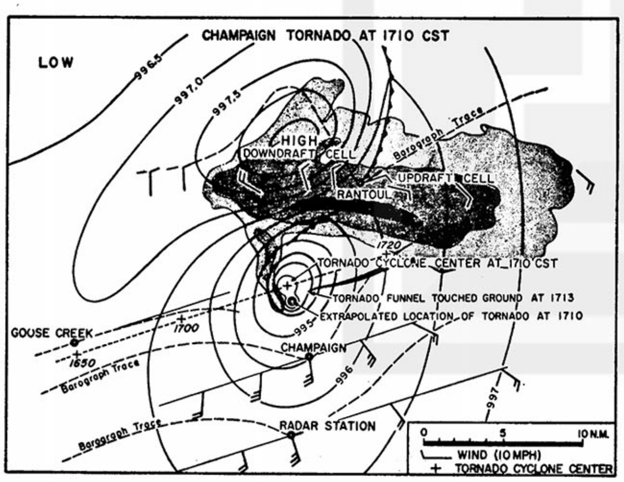

FIG. 18. Surface chart of Champaign tornado cyclone at 1710 CST.

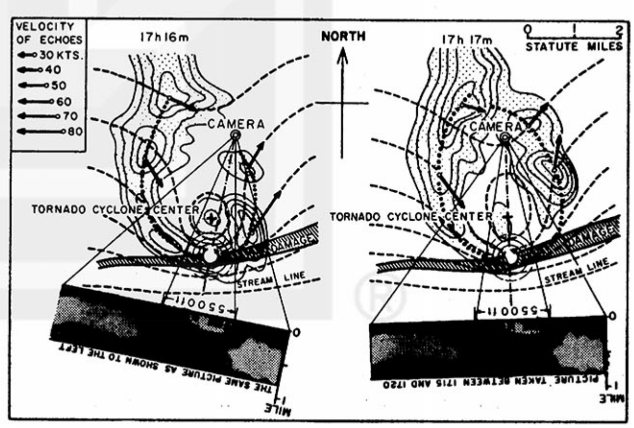

FIG. 20. Location and size of the surface tornado based upon the picture taken by Capt. J. H. Yancy.

may exist in one tornado cyclone. That is to say, a tornado can be a secondary circulation imbedded in a much larger mother circulation.

The analysis of echoes associated with the Champaign tornado revealed the presence of a "Brooks' type" tornado cyclone. The tornado itself, however, was not picked up by radar. Where was the tornado? This is our next question.

The Champaign tornado had not yet appeared by 1710 CST (fig. 18) but the existence of a tornado cyclone is confirmed by radar and by pressure dips lasting 30 min. Four barographs were in operation within 10 mi of the storm. The pressure dipped 2.7 mb at Goose Creek, 1.7 mb at Champaign, and 1.0 mb at the radar station. At Goose Creek, the pressure dip occurred at 1650. Later, at 1713 CST, the tornado touched ground at a point one-mile south of the tornado cyclone center. Photographs taken by ground observers reveal that the Champaign tornado was a huge trunk-type cloud with a vertical axis extending up into the cloud base. The tornado in the chart is therefore separated from the circulation of the tornado cyclone.

As will be seen in fig. 19, the damage path of the Champaign tornado was located one- to two-miles south of the tornado cyclone center fixed by the PPI whose effective beam was below 9000 ft. The surface tornado appeared directly under the ring of maximum wind.

Fig. 20 was prepared to show the relative size of the tornado and of the tornado cyclone. The photograph taken by Capt. J. H. Yancy, between 1715 and 1720, looking south, is combined with the radar picture. It is evident that Capt. Yancy was inside the ring of maximum wind indicated by the dotted line. He reported tremendous turbulence and boiling motion in the cloud overhead. The visual angle of the tornado itself permits us to compute the diameter of smoke and flying debris: 5500 ft. The upper portion of the funnel in the photograph, which extended into the cloud base, gives the impression that this tornado increased in diameter upward. This is true to a certain extent, but the diameter of the funnel has nothing to do with that of the tornado; a funnel merely indicates the level of condensation.

The reason why the Champaign tornado was located under the ring of maximum wind is still unknown; however, the Worcester tornado, one of the Massachusetts tornadoes, was also found to be on the ring echo.

6. Movement of the tornado cyclone

Using one-minute interval radar pictures analyzed with the aid of the technique presented in section 3, the velocities of minor echoes near the center of the tornado were obtained (fig. 21). The echoes located far from the cyclone center moved east northeast at 55 kn, while the tornado cyclone moved at the lower speed of 35 kn. The velocity profile along $A - B$, perpendicular to the general echo velocity, revealed a marked drop as we approach the tornado center from the north. An increase in velocity is noticed as we move south from the center. This echo movement reveals the possible radius of the tornado cyclone to be 15 mi.

The echo movement within the effective range of the Champaign Radar is summarized in fig. 22. These echoes were followed as long as they appeared in radar pictures. An important finding is that echoes approaching the effective range of the tornado cyclone tend to move with the cyclone after entering its range. This may be called a "capture phenomenon." The solid circles in the figure show the position of the echoes

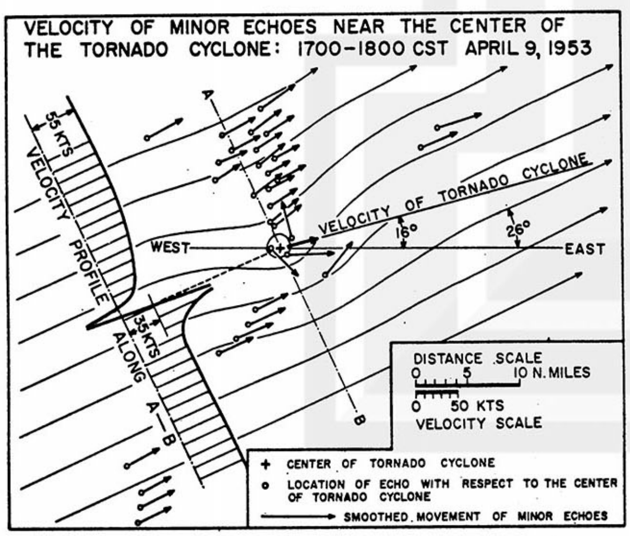

Fig. 21. Velocity of minor echoes near the tornado cyclone center. Echoes between 1700 and 1800 CST were used, and they were placed in their relative position with respect to the tornado cyclone center.

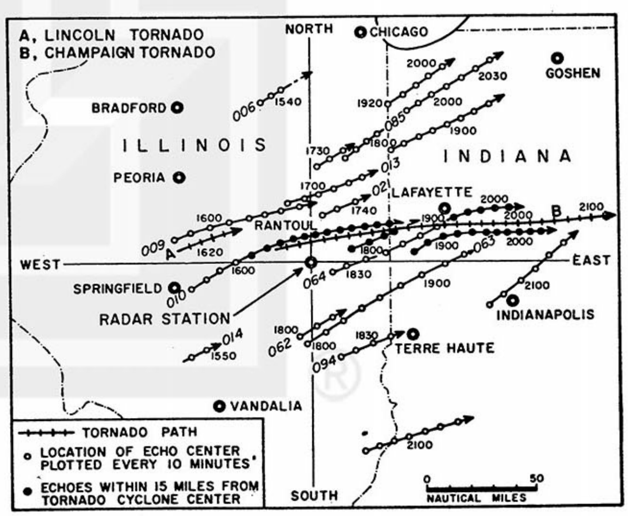

Fig. 22. Unusual movement of echoes associated with the Lincoln and Champaign tornadoes.

after their capture. A similar peculiar movement of tornado cyclones was reported in the case of the Blackwell and Udall tornadoes, as well as in the case of the Massachusetts tornadoes. The direction of movement of the tornado cyclone (θt) and that of the minor echoes (θe), far from the cyclone, is summarized in table 1.

TABLE 1. Summary of the direction of movement of the tornado cyclone (θt) and that of the minor echoes (θe), far from the cyclone.

	θt	θe	$\theta t - \theta e$
Champaign tornado Cyclone	70°–90°	50°–60°	+25°
Blackwell and Udall T. C.	10°	20°–50°	−25°
Massachusetts T. C.	290°–300°	270°	+25°

So far, no successful explanation of such movement has been given; however, the circulation of the tornado cyclone and the height difference of steering levels between echoes and tornado cyclone will play an important role in solving this problem.

7. Conclusions

This study shows that the mesoanalysis of a tornado-related system is feasible when radar pictures and synoptic data from regular Weather Bureau stations are carefully used. The present study threw some light upon the relative location of the tornado and of the tornado cyclone axes. These axes did not coincide throughout the period of observation. The position of the surface tornado was found to be directly under the ring of maximum wind surrounding the eye of a tornado cyclone. The wind system of a tornado cyclone was clarified—it very much resembles that of a miniature hurricane. The direction of motion of the tornado cyclone was found to form an angle of about 25 deg with that of the echoes far from the cyclone. When echoes approach the effective range of the tornado cyclone a "capture phenomenon" occurs, and after their capture they move with the cyclone.

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