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SATELLITE & MESOMETEOROLOGY RESEARCH PROJECT

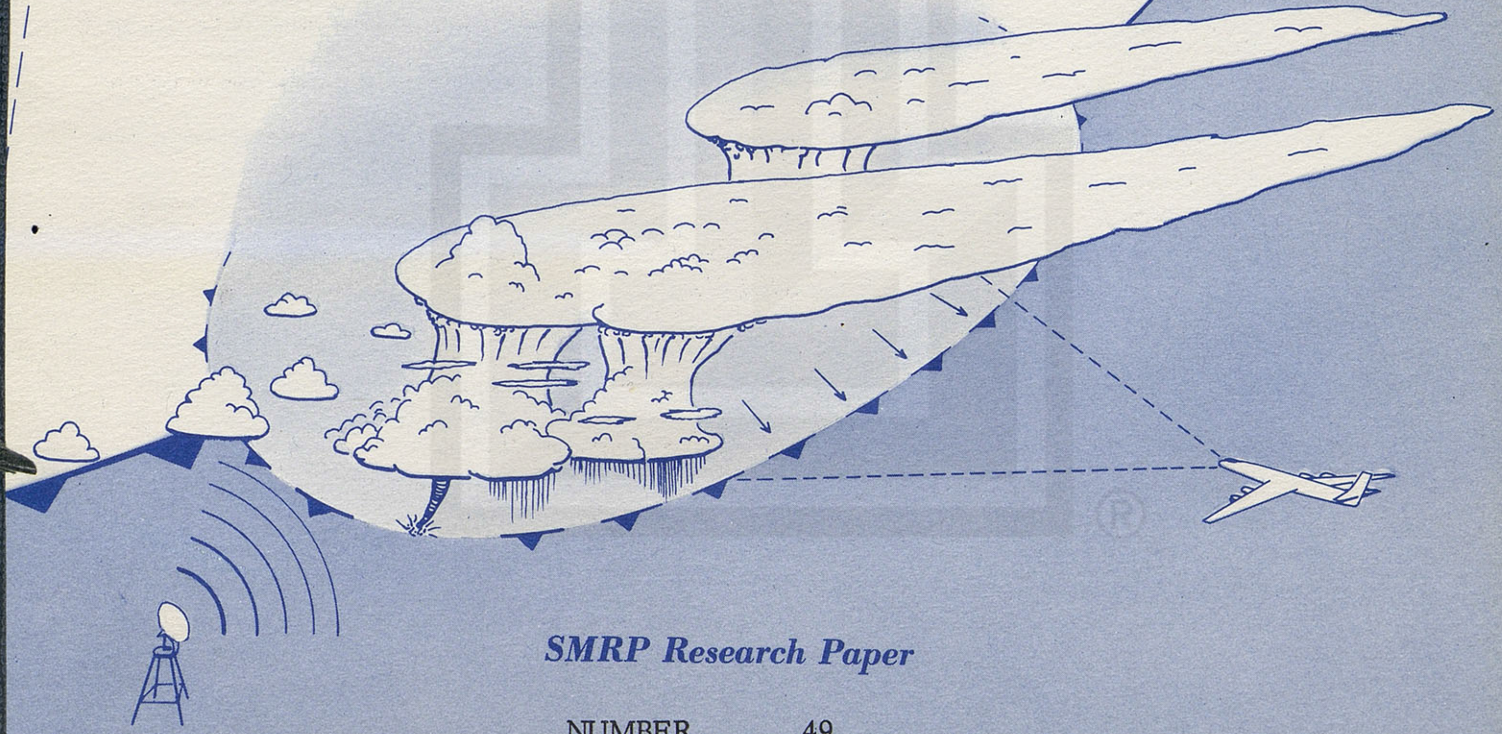
Department of the Geophysical Sciences
The University of Chicago

AERIAL SURVEY OF THE PALM SUNDAY TORNADOES OF APRIL 11, 1965

by

Tetsuya Fujita

(Chapter II of a Comprehensive Study of the Palm Sunday Tornadoes, 1965)



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The research presented in this paper has been sponsored by the U. S. Weather Bureau under grant Cwb WBG-41 (NSSL).

AERIAL SURVEY OF THE PALM SUNDAY TORNADOES OF APRIL 11, 1965[1]

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Chicago, Illinois

ABSTRACT

For the purpose of determining and photographing damage paths of tornadoes which occurred on Palm Sunday, 1965, four separate Cessna-310 flights were made over the five-state areas damaged by the storm. Through visual fixes and aerial photogrammetric analyses, 24 tornado paths were mapped. In addition to the mapping, unusual features left by the tornadoes were thoroughly investigated. These features identified as "marks" are (1) scratch marks probably made by heavy rocks when they were pushed by tornado winds, (2) suction marks produced by the vacuum cleaner effect of a tornado funnel which is not axially symmetric, (3) drift marks representing streak lines of sandy dirt carried by high winds from the loosened soil observed as suction marks, and (4) debris marks which are rather systematic streaks of debris carried away from damaged structures. These marks, examined in detail, led to the estimation of the wind speed of one of the tornadoes as 500 mph.

1. METHOD OF AERIAL SURVEY

Due to the unexpected occurrence of a large number of tornadoes, it was not feasible to make special arrangements with an aerial photogrammetric company for taking large-size aerial photographs while tornado damage was still preserved. Moreover, newspaper and other reports collected by the author within 12 hours after such a large number of tornadoes were so confusing that no systematic aerial survey plans could be laid out. Under the circumstances, a quick decision to undertake an aerial survey by using a small aircraft and hand-held 35-mm cameras was made on Monday morning, April 12.

A Cessna-310 piloted by Mr. Louis Dillon of Great Lakes Aviation, 9801 South Damen Avenue, Chicago, was chartered for this purpose. Four separate

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survey flights were accomplished: 3.5 hr. on April 12 over Illinois, 5.3 hr. on April 13 over Indiana and Michigan, 8.6 hr. on April 16 over Indiana, Ohio, and Michigan, and 6.5 hr. over Wisconsin and Michigan. Presented in figure 1 are the four flight tracks covering the five-state areas. A total of about 7500 mi. was flown by the author, accompanied by either Mr. Bernard Ginsburg, SMRP photographer, or Mr. Ronald Reap, SMRP research meteorologist.

Identifications of tornado damage were made from the air while flying between 1500 and 2000 ft. above the ground. As soon as tornado damage was spotted, it was plotted on a 250,000 U.S. Geological Survey map. Significant damage patterns were then photographed with the use of 25-mm, 50-mm, and 135-mm lenses so that wide-and narrow-angle views could be used later for the purposes of general mapping and detailed examination of significant damage.

While taking damage pictures, it was found that some types of damage are visible only when viewed from particular directions with respect to the sun. The faint marks left on a newly plowed field, especially, appear to be bright when viewed from the directions of large or small backscattering angles. If not so viewed, they cannot be distinguished from the undisturbed surface or may sometimes appear to be dark. When interesting damage patterns were seen from one direction, a series of high-bank circular flights was made to obtain the best possible pictures for further research.

Surveyed tornado paths thus obtained appear in figure 2 which also includes unsurveyed paths reported by Van Thullenar in Chapter I of the Comprehensive Study. These tornado paths were grouped together to identify them as tornado families A through R. The areas of aerial survey were then divided into semi-rectangular, sectional maps, including either 45-min. longitude by 15-min. latitude or 45-min. longitude by 20-min. latitude. Twenty aerial survey maps of damage paths were finally completed. Each map includes major highways, railroads, cities, lakes, photographic locations, and spotted tornado damage.

2. CHARACTERISTICS OF DAMAGE BY EACH SURVEYED TORNADO

A detailed examination of 24 damage paths covered by this aerial survey revealed that some significant features can be used in estimating a storm's characteristics, e.g. the horizontal dimensions and the wind speed required to produce particular damage. Usual damage, such as exploded houses and scattered debris, was used only for confirmation, since this type of damage can be seen after practically all tornadoes.

Included in this section are 20 aerial survey maps showing damage paths and photographs of significant damage patterns, as well as actual tornado pictures taken from the ground.

Aerial Survey Map No. 1. This map includes the damage paths of tornado B-3, the third tornado belonging to family B. The first tornado-like damage was spotted about 1 1/2 mi. north of the intersection of Ill-78 and US-20. Some 15 trees in a small patch of forest were uprooted. There was no confirmed damage to the northeast of these trees until scattered debris was found along the southwest side of the Illinois Central railroad. Thereafter damage gradually became severe and the path widened to the northwest suburb of Monroe, Wisconsin, where extensive damage to buildings and trees was photographed.

Figure 23 shows a view of a damaged motel on Wis-69, one mile north of Monroe. The entire roof of the motel was gone, while the walls were standing practically undamaged. Destruction occurred around 1430 CST. The picture was taken toward the south, the tornado center having passed about one-half block south of the motel from southwest to northeast. The tornado damage continued four miles beyond this motel. The damage path of tornado B-3 was 29 miles.

Aerial Survey Map No. 2. The first damage of tornado B-4 appearing on this map was spotted on Wis-15 about 1/2 mile south of Evansville, Wisconsin. There was no appreciable damage to houses, but debris was scattered over the plowed fields. This tornado left a rather narrow path of moderate destruction before disappearing near US-12 northeast of Ft. Atkinson. The damage path of B-4 was 23 miles long with a maximum width of 0.2 mile. No particular damage features were spotted from the air.

Aerial Survey Map No. 3. After the first damage of tornado B-5 was spotted on US-18, 5 miles west of Jefferson, the damage width increased rapidly to about 3/4 mile as we flew north-eastward. Considerable damage to trees was sighted in forests east of Lake Mills. A one-mile square forest south of Wis-30 was practically leveled: 60% uprooted, 30% torn apart, and the rest badly damaged. After crossing the Chicago and Northwestern Railroad tracks, damage became less severe. The width of the path was maintained at about 3/4 mile until the whole storm weakened after crossing US-16. A search for a possible sixth tornado over the Hartford area turned out to be negative. The length and the maximum width of this B-5 damage path were 24 miles and 3/4 mile, respectively.

Aerial Survey Map No. 4. A weak and short-lived tornado caused some damage in the Lake Geneva, Wisconsin area. This tornado, identified as E-1, formed near the western edge of Williams Bay. Several damaged houses were spotted there but the storm weakened considerably as it moved through Como. Very little tree damage was spotted from the air. Tornado E-1 left a 5-mile path with a width of less than one block.

The Crystal Lake tornado, F-1, left devastating damage to a residential district and a shopping center in this northern Illinois community. Figure 24 shows an aerial view of severe damage to frame houses. The tornado moved from right to upper left in the picture. A detailed survey from the ground appears in the report by Feris, Vermoch, and Yario (1965). The tornado lasted only about 10 min. before disappearing over the forest north of Wauconda. This tornado may be classified as intense but its damage width was less than 1/2 mile, with some local indication of a double damage path which might have been caused by more than one funnel.

The second tornado, F-2, moved over Druce Lake, according to the above-mentioned report. The tornado left moderate damage to suburban houses, resulting in about a 4-mile path. The last damage was confirmed at the Waukegan Memorial Airport where airplanes were turned over and hangars received wind damage. It is debatable whether tornado F-2 was one or two tornadoes. In view of the limited ability to spot all tornado damage from the air, each tornado path was considered as single even though there were small discontinuities such as were observed in this case. It is a well-known fact that a tornado that can be followed visually for some distance does not always produce a long continuous path. This is due to the storm's short-period pulsation, asymmetric structure, slight lifting, etc., combined with the conditions of the buildings and vegetation.

Aerial Survey Map No. 5. Tornado D-1 missed a TV tower west of Rockford. Its first damage was sighted from the air at the midpoint between the tower and Wempletown. After the tornado crossed Ill-70, it left a continuous but very narrow damage path extending to Rockton where several airplanes were blown down and a restaurant was damaged. The storm weakened considerably after moving over Rockton, then it probably disappeared over downtown Beloit, Wisconsin. The total path length was 14 miles, with a maximum width of no more than 1/8 mile.

Aerial Survey Map No. 6. The first damage by tornado H-1 was spotted on Mich-50 near East Allendale. The width of its path and intensity gradually increased until it reached the northern suburb of Comstock Park where the storm's intensity was estimated to be moderate. The maximum width was up to 1/2 mile. The last damage was spotted in the area north of Rockford. The path length measured 24 miles.

Aerial Survey Map No. 7. Only a short damage path in the vicinity of Burnips, Michigan was surveyed from the air. It was 2 miles long and 1/8 mile wide. Ground reports of debris from Saugatuck and damage from Hamilton might have indicated a continuous path if the entire area had been surveyed more completely. This tornado is designated as I-1.

Aerial Survey Map No. 8. This map includes damage paths of four tornadoes belonging to families J and K. Tornado J-1, first reported by the Indiana State Police at 1645 CST, left a rather narrow path across Koontz Lake where severe damage was seen from the air. The damage path widened gradually until the storm crossed US-31 where a remarkable picture of a "white tornado" (figure 26) was taken by Indiana State Trooper Robert Candler near Lapaz. The picture was taken facing eastward less than one min. after the storm crossed the highway about 2 blocks south of where he was standing by his car. The time was 1703 CST. This tornado appeared to be white because it was illuminated by skylight from the west, while the background to the east was very dark. A picture of the same tornado was taken by Mrs. Helen Elliott of South Bend at 1701 CST, facing northwest. This picture shows a dark funnel against a rather bright northwest background. Note that the funnel shows a more or less cylindrical shape almost all the way to the ground (figure 27). Debris and dust clouds are circling around the bottom of the funnel thus taking the shape of a vertical column extending to the ground. Another picture (figure 28) by Mr. Willis Haenes at Bremen was taken at 1703 CST, almost at the same time that the "white tornado" was photographed. The direction of view is toward the west-northwest. The tornado was located at the south end of the low cloud base. A similar relative position of tornado and low cloud base has been studied by Fujita (1960) using pictures of the Fargo tornadoes. After crossing US-31 north of Lapaz, the storm maintained a rather narrow but heavy damage path to Wyatt where it started weakening.

The first damage caused by tornado J-2 was sighted near Wakarusa. The path of this tornado continued to the Midway Trailer Court which appears on the next map.

Tornado K-1 was first reported on Ind-2 near Hebron, but its damage was not seen from the air until south of Wanatah where several farms were damaged along a very narrow path. A tornado picture taken by Mr. Nicolas J. Polite, looking south from Wanatah at 1726 CST, is shown in figure 25. After crossing Ind-421, the storm left a very narrow damage path about 1/2 block in width then continued to South Center where the last damage to buildings was spotted from the air.

The beginning of the damage path by tornado K-2 was spotted one mile west of Ind-331. After crossing the highway, the damage path widened to 1/2 mile. Figure 29 shows a picture of cyclonic tree damage. The picture, taken while looking south, was printed upside down in order to fit the rectified map shown in figure 30. The radius of curvature of the streamlines of the tornado winds when these trees were uprooted was measured to be 300 m. or 0.2 mile, while the width of the damage path was 800 m. or 0.5 mile. From these figures it may be concluded that these trees were uprooted along the fringe of the damaging tornado winds rather than along the circle of maximum winds surrounding the central core of the tornado. When the picture is examined very carefully, it will be found that only a few trees were torn up and that most of them were uprooted before their branches and trunks were finally broken by high winds. Occurrence of such tree damage may be related to the type of trees, not identifiable from the air. On the other hand, the condition of the ground, either dry or soaking wet, could also be the cause. In the latter case, a tree could easily be uprooted by winds of 50-mph mean speed.

Aerial Survey Map No. 9. The damage path of tornado K-2 extends into the area of this map. The damage along this path of 1/2 mile width was extremely severe, especially in the residential area of Dunlap visited by President Johnson a few days after the storm. Here many houses were exploded and completed leveled, with some of the worst damage caused by the Palm Sunday tornadoes. After Dunlap the tornado weakened slightly, leaving a severe to moderate damage path extending to Hunter's Lake where debris from nearby homes was seen along the east shore of the lake. A continuous path was traced from the air across the Indiana Turnpike north of Scott. Newspaper reports show that several cars were blown off the turnpike in the dark between 1830-35 CST. The last damage to trees was spotted north of the turnpike about 3 miles east of the point where the tornado crossed the turnpike.

Tornado J-2, reported near Wakarusa at 1718 CST, moved into the area of this map leaving a rather narrow path. While approaching Midway, northwest of Goshen, the storm intensified considerably and destroyed a large number of trailers, as shown in figure 32. The picture was taken toward the southeast, and the tornado moved from right to upper left in the picture. A twin-funnel picture of this tornado shown in figure 31 was taken by Mr. Paul Huffman of the Elkhart Truth, looking northeast from the shoulder of US-33, 0.7 mile southeast of this trailer court while devastation by the left funnel was taking place. He took a total of six pictures in succession to show how a single funnel split into two and then reorganized into one after about a minute or so. A photogrammetric analysis of these pictures will be presented later. A continuous narrow but severe damage path was spotted from Midway to the west of Middlesbury where it was lost completely. A local witness reported that a car traveling west on the rural highway north of Goshen was pushed backward toward the east, then was blown off the highway into a field.

Tornado J-3 was first reported as a waterspout crossing a small lake south of Goshen. Tornado damage was not clearly visible until about one mile east of Ind-13 where demolished farms were spotted. Near the Rainbow Lake area, damage appeared to be very heavy and devastating. The storm then gradually weakened until its path was lost at a spot about 3 miles east of Brighton.

Aerial Survey Map No. 10. Damage caused by tornado J-4 was spotted about 2 miles west-southwest of Lake Pleasant. Destruction along the eastern shore of this lake was almost complete (figure 33), probably because of the additional effect of water sucked up and carried by the tornado. Most of the trees along the shore were stripped and torn, thus giving the impression that water spray and droplets caught in the tornado wind acted like flying bullets. Upon approaching Coldwater Lake, the damage path widened to about one mile, covering almost half of the western shore. There was floating debris, as shown in figure 34 in many parts of the lake. This picture also shows exploded houses along the lake front. The damage path to the east of the lake was extremely wide, reaching over two miles in the area north of Algansee. Detailed examination of the damage, which was relatively heavy and scattered in nature, revealed that it was caused by two tornadoes, J-4 and K-3. Cyclonic tree damage left by K-3 is shown in figure 35, together with the mapped damage in figure 36. The radius of curvature of the streamlines determined from the directions of uprooted trees was very large - 600 m. - suggesting that the diameter was about 0.7 mile. There were some areas of little or no damage to the north of this area of uprooted trees, thus suggesting the presence of two separate damage paths caused by J-4 and K-3. Witnesses from the Coldwater Lake area stated that two tornadoes moved over the area about 30 min. apart.

The damage width which was one mile or so near Long Lake widened to 2 miles , then narrowed to one mile over Baw Beese Lake. The damage inside the path was moderate except in local areas near the lake where many houses were completely demolished. Two separate tornadoes, 30 to 45 min. apart, were also reported from this area.

Aerial Survey Map No. 11. The combined tornado path of J-4 and K-3 on this map is between 2 and 3 miles wide, characterized by scattered light to moderate damage to buildings and trees. Some houses between Devils Lake and Round Lake were badly damaged. A wind tower operated by the Tecumseh Health Study Project north of Tecumseh survived, recording a 150-mph wind from the west at 1907 CST and a 74-mph wind from the south at 2004 CST. These two maxima were evidently caused by two separate tornadoes, J-4 and K-3, moving east-northeastward along almost identical paths. Since such records of tornado winds are very rare, their meteorological analyses will be presented later in the chapter dealing with the computation of tornado winds.

Another tornado left a damage path which started in northwestern Toledo. The width and the destruction increased toward the Fuller's Creekside Addition where the storm moved out from land. Because of darkness, no reports on tornadic storms over Lake Erie were received. The time of destruction was about 2035 CST.

Aerial Survey Map No. 12. The first damage, to a barn, was spotted southeast of Lafayette, Indiana. This tornado, identified as L-1, is the first of six tornadoes which covered a total distance of 274 miles in 4 hr. and 23 min., maintaining an amazingly constant speed of 62.5 mph. There were definite indications of weakening and redevelopment of the storm so that the damage path east of US-29 may be identified as that of L-2. Tornado L-2 developed very rapidly and when it moved directly over Russiaville, the whole town was badly damaged. The damage width there was about 3/4 mile.

Aerial Survey Map No. 13. Aerial photographs indicated that the entire community of Alto was demolished by tornado L-2 which then moved to the south of Kokomo, Indiana. Figure 37 shows eight brick apartments that suffered various degrees of destruction. The picture was taken facing south, and the tornado center moved from right to left near the top of the photograph. It is seen that the south-west corner apartment was completely destroyed, probably down to the basement of this two-storey building. The roofs of the northern buildings were lifted and probably smashed to pieces when they were blown against the others to the left. After completing destruction in southern Kokomo, the storm moved eastward leaving a 1/2 mile damage path as far as the southern suburb of Marion, Indiana. In Greentown, it was reported that this tornado dug the lawn out from many backyards. A scratch mark probably made by a heavy object was photographed in a plowed field 2 miles west of Greentown (figure 38). This picture was taken toward the south, and the tornado center moved from right to left through the picture center. It is of interest to see the difference between the trajectories of relatively light debris and of the heavy object which left a curved scratch mark extending from lower right to upper left. Seen at the end of this scratch mark is a small gray object which finally rested there.

In contrast with the above-mentioned black scratch mark, a group of white cycloidal marks, as shown in figure 39, was photographed east of Greentown. In this picture, tornado L-2 moved from lower left to upper right. Similar marks have been reported only twice in the past. The first ones near Scottsbluff, Nebraska were reported by Van Tassel (1955) who assumed that they were produced by an object which was trapped inside a tornado vortex, thus scratching the newly plowed surface as it circled around the vortex center. The second ones were reported by Prosser (1964) who gave no explanation regarding the cause of the marks. In taking aerial pictures of these marks made by tornado L-2, the author used a 135-mm telephoto lens, and Cessna-310 was brought down to about 1000 ft. above the ground. Detailed examination of the marks indicated that they represent sandy soil loosened probably by the pressure effect of a tornado funnel which dug out the lawns in Greentown a few minutes earlier. The marks in the picture very likely represent a high reflectivity of sandy soil that was loosened by the tornado funnel at its periphery. The fact that there were 4 to 5 cycloidal marks during one rotation of the funnel suggests the probable existence of the same number of suction heads attached to the periphery of the funnel. In the chapter dealing with the wind speed of tornadoes, the marks and their use in the wind computation resulting in a 500-mph wind will be discussed in detail. To distinguish these marks from the scratch marks presented earlier, they are called suction marks.

Aerial Survey Map No. 14. The damage path of tornado L-3 was no more than 1/2 mile wide and was characterized by moderate damage to farms and trees in rural areas. A number of exploded farm houses were spotted from the air, though no particular damage was found or photographed.

Aerial Survey Map No. 15. The damage path of tornado L-3 extending into the left half of this map was very narrow. Before its dissipation southwest of

Delphos, well-defined suction marks as shown in figure 40 were photographed. The wind speed of the tornado computed from these marks was about 300 mph, indicating that it was still very high even at a spot only two miles from the last damage visible from the air. These particular marks and the wind-speed computation will be discussed separately.

The damage by the fourth tornado L-4 was first spotted to the east of US-30S northwest of Lima, Ohio. It then continued beyond Cairo, Ohio into the area of the next map. The damage was moderate to light.

Aerial Survey Map No. 16. This map includes the rest of the damage path of tornado L-4. The width varied between 1/4 and 1/2 mile with typical explosive damage to structures and wind-blown debris. No funnel was sighted by local residents because of darkness. The last damage was spotted northeast of Houcktown, Ohio.

Aerial Survey Map No. 17. A 17-mile damage path with a width of less than 1/2 mile is shown on this map. The first damage spotted was along Ohio-100 where considerable damage to barns was visible but no farm residences next to the barns were destroyed. The heaviest damage to buildings was spotted at Rockaway near the intersections of Ohio-18, US-224, and the Pennsylvania Railroad tracks. Damage east of Rockaway gradually became spotty then was lost near Ohio-162, 2 miles east of Omar, Ohio.

Aerial Survey Map No. 18. Damage by the last tornado belonging to the L-family, L-6, was spotted west-southwest of Pittsfield. A continuous damage path 1/2 mile wide runs through Grafton and the northern part of Strongsville. The damage to buildings in these two towns was moderate to severe. The path was visible almost to the Ohio Turnpike. An attempt to spot any tornadic damage beyond the turnpike failed after circling the suspected areas for almost 10 min.

Aerial Survey Map No. 19. The damage path due to M-1, the first tornado of the M-family, started near Crawfordsville, Indiana. It then gradually widened to one mile near US-52. During an investigation of the damage path east of this highway, northwest of Lebanon, Indiana, a group of seven scratch marks was photographed. Figure 41 shows overall views of these marks with the exception of the seventh one, and figure 42 shows enlarged views of marks 2, 4, 5, and 6. Of these, mark 4 is of extreme interest since it hit objects 5 and 6 while it was traveling at an estimated speed of between 60 and 70 mph. As in the case of nuclear physics experiments using cloud chambers, a high-speed object accelerated and pushed by tornado winds left a non-ionized scratch mark of its own as well as others which moved after having been hit by the first one. The picture in figure 41 was taken looking southwest, and the tornado center moved diagonally in the picture from the upper right to the lower left corner at the rate of about 50 mph. More detailed analysis of these scratch marks will be presented in the chapter on tornado wind computation.

Aerial Survey Map No. 20. This map includes the last 12-mile section of tornado M-1. No particular features of damage were spotted from the air. The path became narrower after crossing the C.I. & L. Railroad tracks and it was finally lost near Ind-19.

3. DAMAGE PATHS ASSOCIATED WITH TWIN FUNNELS

When an aerial photogrammetric survey of damage by tornado J-2 which smashed the Midway Trailer Court (Aerial Survey Map No. 9 and figure 32) was taken, it was found that extremely severe damage could be traced along two paths which seemed to represent those of the twin funnels photographed by Huffman (figure 31). As a matter of fact, Huffman took a series of six pictures standing at the same spot between US-33 and the New York Central Railroad tracks about 0.7 mile from the Midway Trailer Court. These six pictures, gridded with azimuths and elevation angles for every 10^{o}, are shown in figures 43 through 48. These grid lines were computed by the author after visiting the photographed site.

Huffman's photographed site and the damage path are shown in a topographic map at the top of figure 49. His first picture was taken looking almost due west and his second picture revealed that the funnel was still single. The third picture, when examined carefully, shows some evidence of a splitting funnel. The fourth one, which appeared in newspapers and magazines after the storm, shows twin funnels on both sides of the highway, thus giving an impression that US-33 runs through a tunnel between the funnels. The fifth picture very clearly indicates the patterns of stratified low clouds wrapping around the twin funnels, permitting us to determine the direction of both funnels to be identical and cyclonic. The patterns also give dimensions of circulation which are closely related to the tilt of the tornado axis. The best estimate of the tilt is 29^{o} toward the north-northeast.

Returning to figure 49, the middle chart represents photogrammetric positions of the funnels appearing in Huffman's six pictures. Black circles designate the initial funnel touching the ground and the small circles, the complemental funnel which appears in the third picture. The picture sequence reveals that the funnel near the ground increased rapidly in diameter between the first and second pictures, then began splitting in two. After the split, the two funnels rotated about each other around their common center. The bottom drawing in figure 49 represents such rotation and the photographic directions.

Based on his analysis, the author would like to offer the following explanation of the cause of the split in the funnel. This split was due to the rapid increase in the funnel diameter while the tilt of the funnel axis was in excess of 30°. From the translational speed of this tornado, about 50 mph, the estimated time intervals between successive pictures in seconds are: No. 1 (17 sec.), No. 2 (27 sec.), No. 3 (13 sec.), No. 4 (8 sec.), No. 5 (31 sec.) No. 6. This result reveals that the increase in funnel diameter between the first and second pictures took place within no more than 17 sec. When a tilted column of rotating air increases its diameter very rapidly, the air parcels near the ground cannot move around the center. The motion beneath the tilted axis, especially, is restricted because of limited flow space and surface friction. Thus the funnel may quickly take a shape as of short-cut circulation while the rest of the vortex starts forming another funnel. The split starting to take place at position 3 can be explained in this manner. When position 4 is reached, the initial vortex will die out rapidly while the complemental vortex intensifies. About 50 sec. after the funnel started splitting at position 3, the twin funnels changed again into an almost single one at position 6. It should be noted that the entire process took only less than one minute. If one had not been watching and photographing with extreme care, such a phenomenon would not have been revealed.

Eyewitness accounts of double or even multiple funnels near Kokomo, Indiana were gathered through local newspapers. The Kokomo Morning Times of April 13, 1965 indicated that at least three swiftly moving funnel-shaped tornadoes swooped down across Altc (Aerial Survey Map No. 13). Some said that they saw even more funnels touch the ground in a bouncing motion. One witness said that the tornado had an unusually broad base which appeared as if it had three or four spouts in it. When the storm was moving over southern Kokomo, a local resident spotted four funnels, moving in approximately the same plane and direction. All funnels moved toward Greentown. He saw two directly over his house with several hundred yards between them and two others perhaps 1/4 mile from the twin funnels. These twin funnels were seen by several other witnesses. One of them stated that they came together and just hovered over Greentown. The author's picture showing suction marks was taken over the plowed field 10 miles east of Greentown. The marks showed the existence of only one funnel.

It is extremely difficult to draw reasonable scientific conclusions based upon eyewitness accounts unless they are supported by some photographic evidence such as that presented by Huffman. Nevertheless, the structure of tornadoes is so complicated and different in each storm that we should be all means gather all necessary evidence of any kind in order to construct reasonable tornado models.

4. CONCLUSIONS

Aerial photographic survey of damage paths by a large number of tornadoes such as those of Palm Sunday, 1965 was found to be extremely valuable. It is important, however, to look for and photograph particular patterns from a low-flying airplane so that they can be utilized in determining quantitatively the dynamical characteristics of tornadoes. Those patterns which were found to be significant through photographic survey are 1. scratch marks, 2. suction marks, 3. drift marks, 4 debris marks, and 5. patterns of uprooted trees. Typical damage, such as exploded houses, torn trees, etc., is, of course, important for the determination of relative intensity and extent of damage paths but its potential value in determining dynamical storm structure is limited. Such damage could be photographed from the ground for computation purposes.

Another advantage in making an aerial survey of tornado paths is the exact determination of the positions of tornadoes in relation to radar echoes and other observations. A large area can be covered by an airplane much quicker than by several automobiles so that a desired survey can be accomplished before debris and important marks left on the ground disappear.

Acknowledgments: The author is very grateful to Messrs. Ginsburg and Reap for their assistance in taking aerial pictures and keeping important records while flying with the author. Sincere appreciation should be expressed to Mr. Louis Dillon, the Cessna-310 pilot who maneuvered the plane under difficult requirements at various flight altitudes for the purpose of damage spotting and aerial photography.

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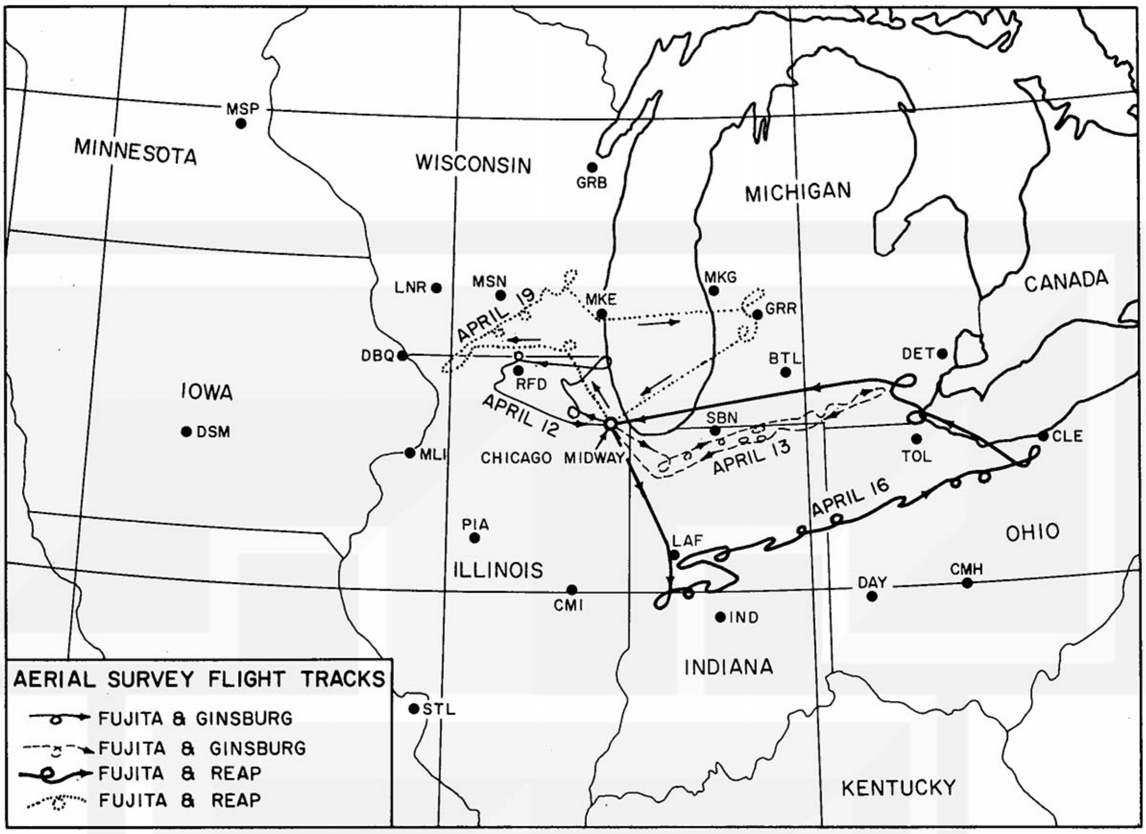


FIGURE 1. Flight tracks of a Cessna-310 aircraft chartered for damage survey of the Palm Sunday tornadoes of April 11, 1965. A total of about 7500 miles was flown over the five-state areas of tornado damage.

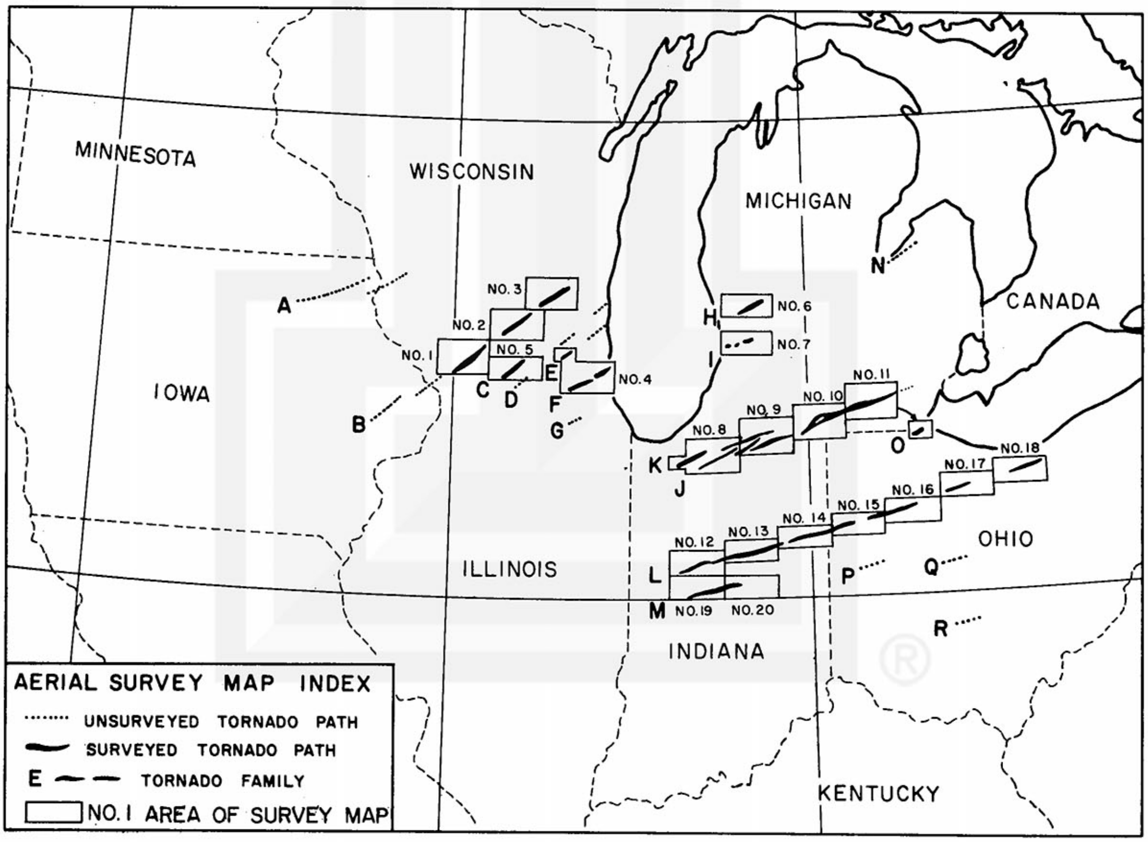


FIGURE 2. An index map showing 20 aerial survey maps which include damage paths and positions of aerial photographs. Tornadoes formed out of each parent echo were grouped together as a family identified by letters A, B, ...R.

AERIAL SURVEY MAP NO. 1

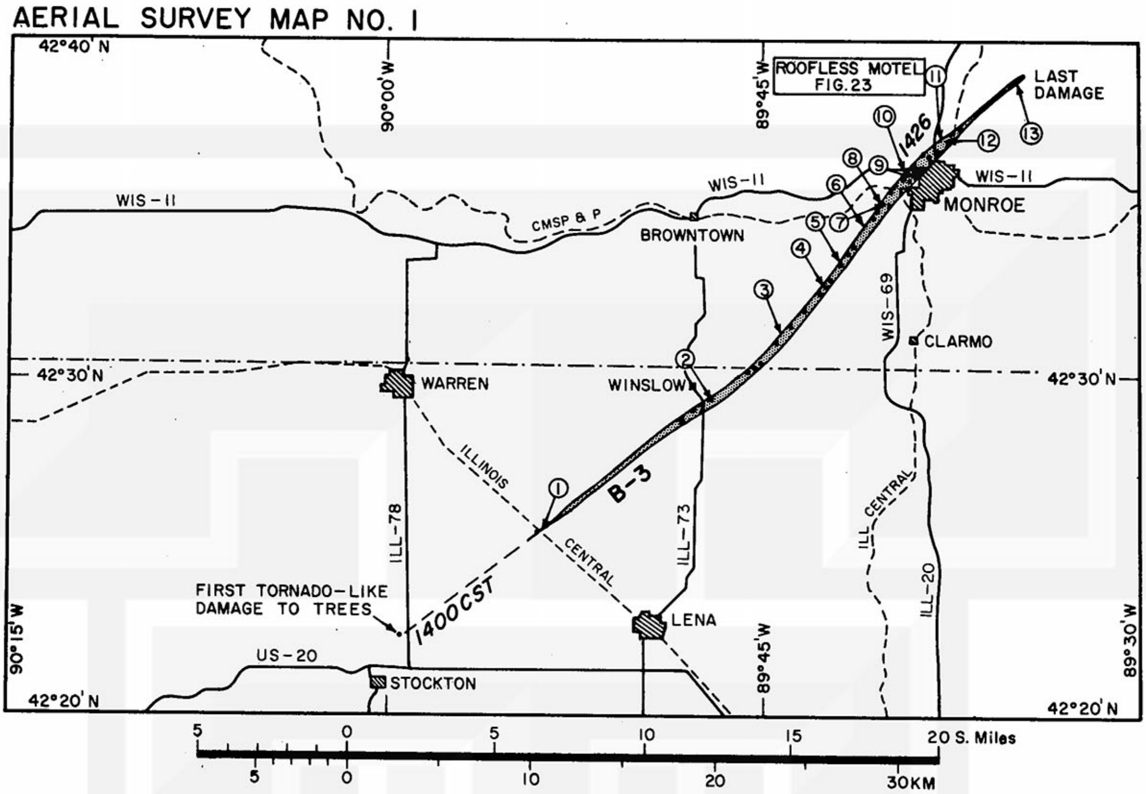


FIGURE 3. Aerial survey map No. 1, covering an area of Wisconsin and Illinois.

AERIAL SURVEY MAP NO. 2

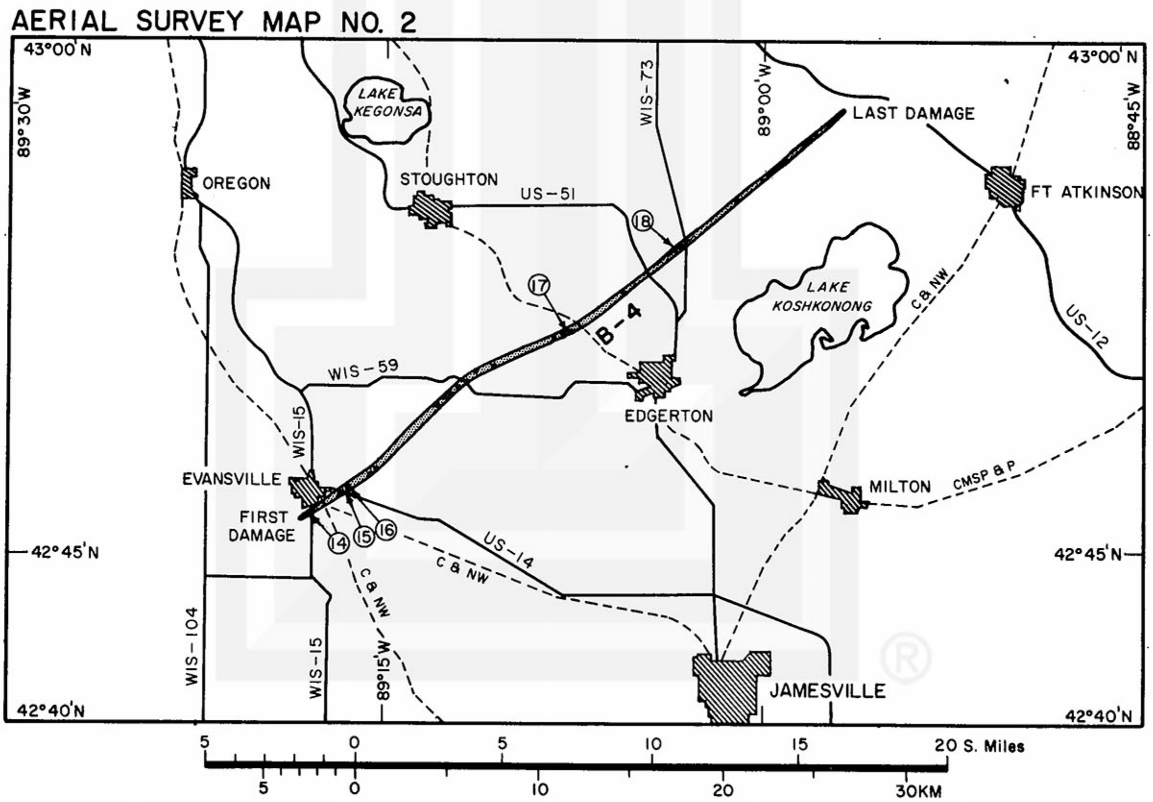


FIGURE 4. Aerial survey map No. 2, covering an area of Wisconsin.

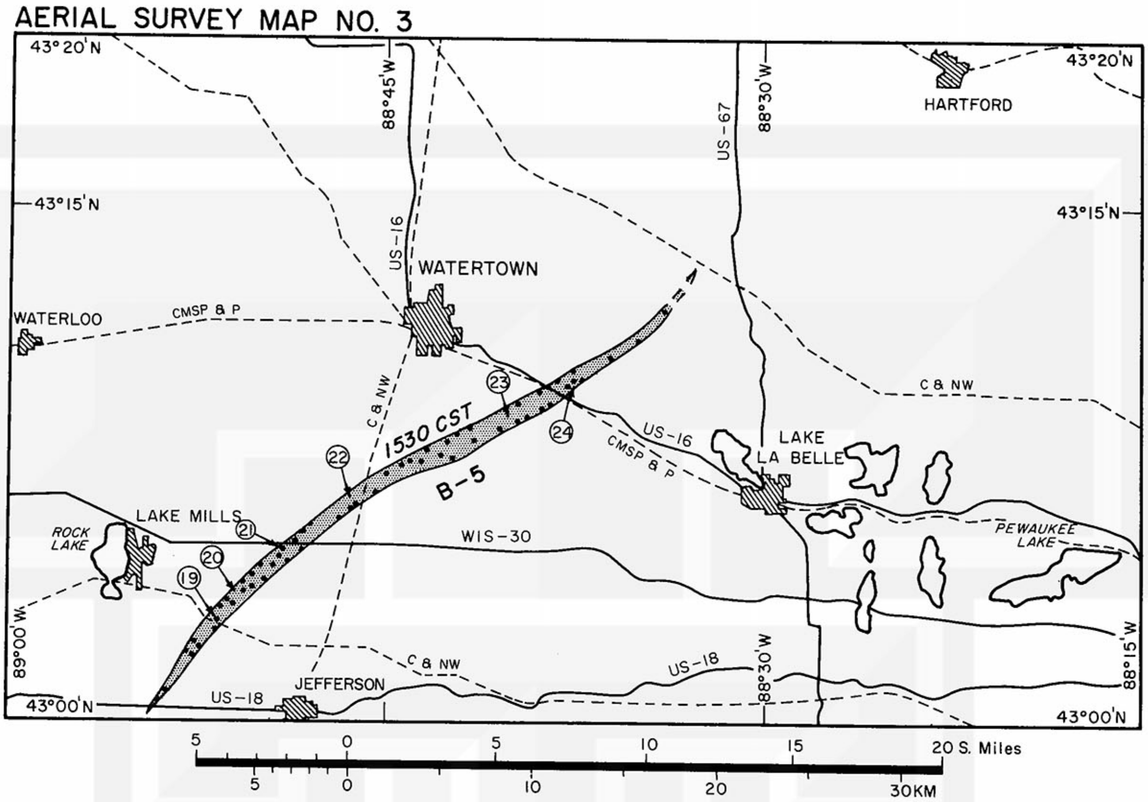


FIGURE 5. Aerial survey map No. 3, covering an area of Wisconsin.

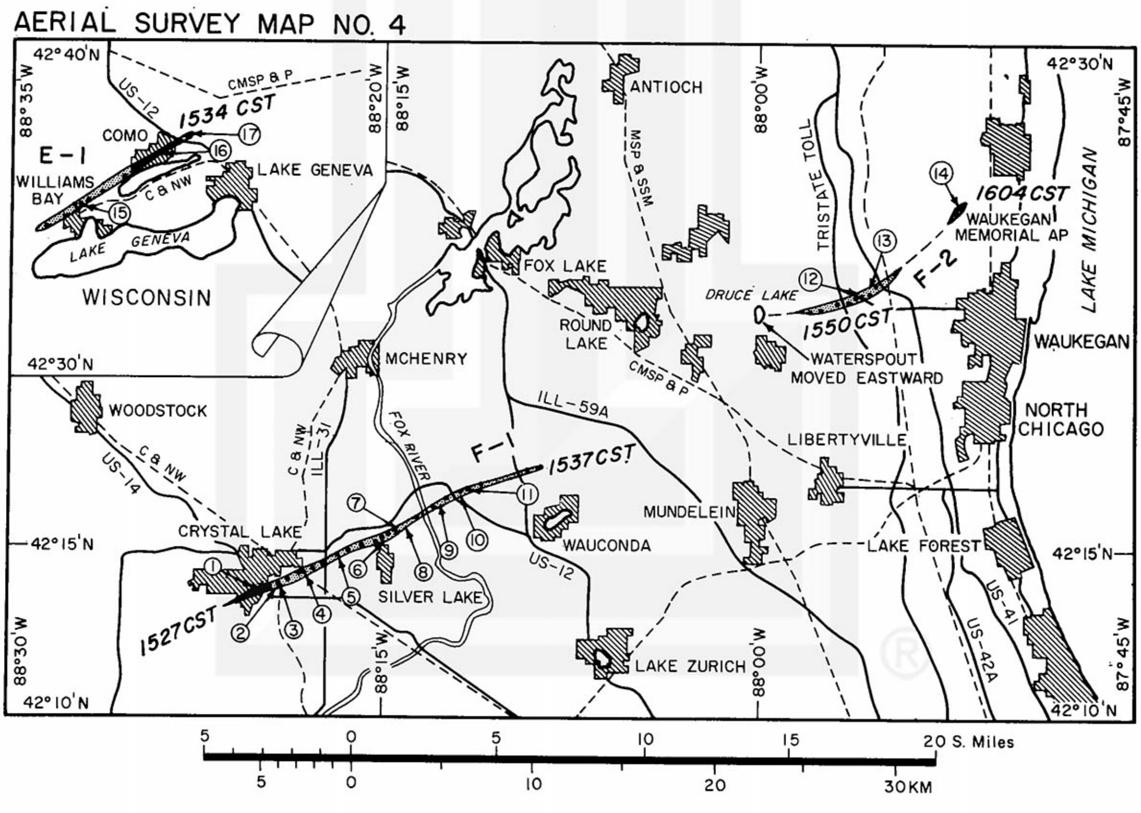


FIGURE 6. Aerial survey map No. 4, covering an area of Wisconsin and Illinois.

AERIAL SURVEY MAP NO. 5

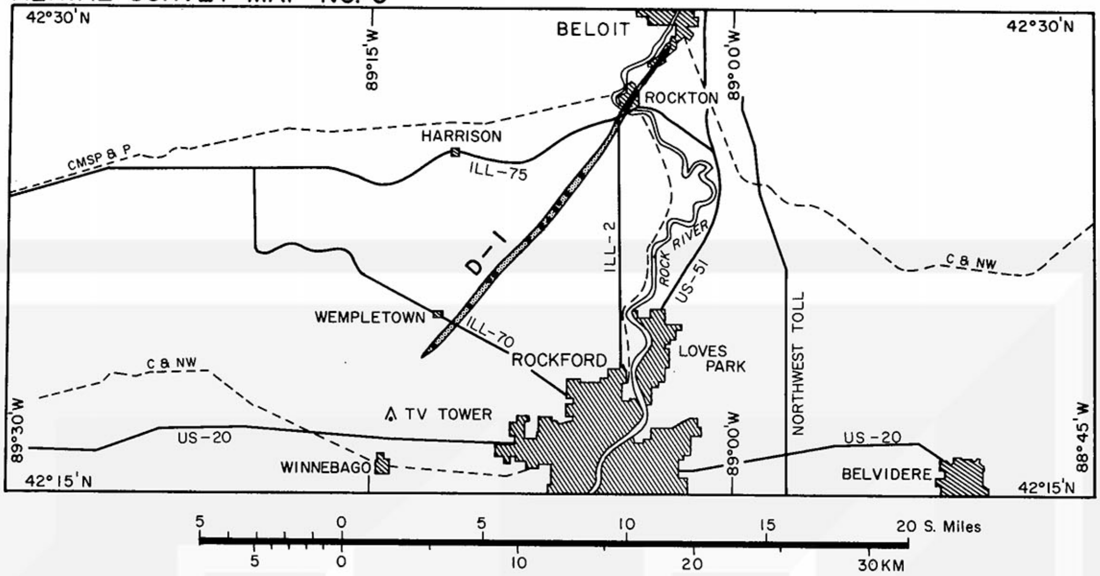


FIGURE 7. Aerial survey map No. 5, covering an area of Illinois.

AERIAL SURVEY MAP NO. 6

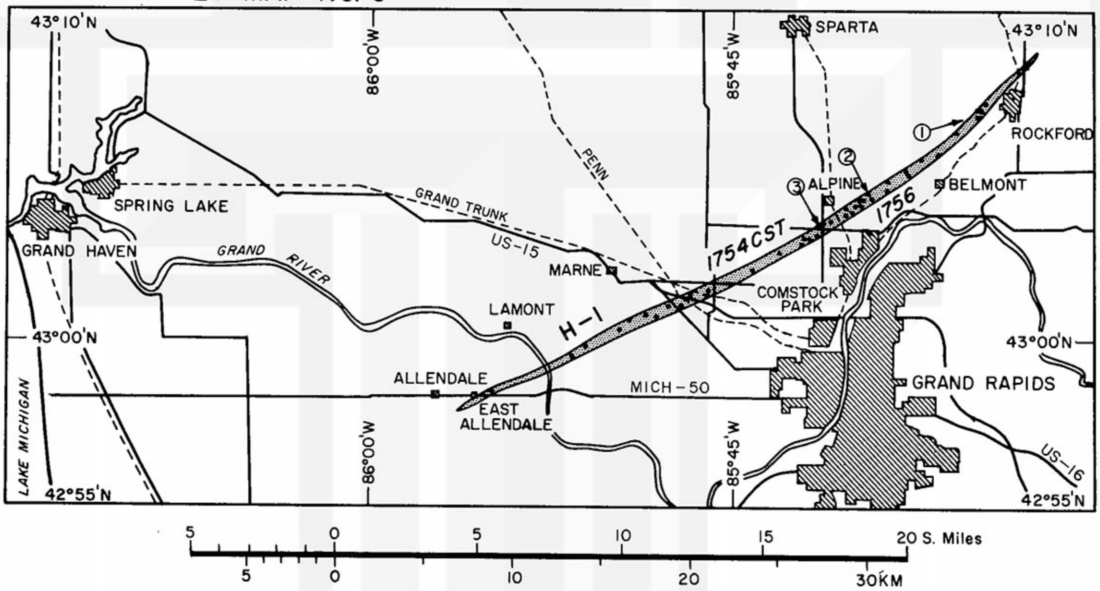


FIGURE 8. Aerial survey map No. 6, covering an area of Michigan.

AERIAL SURVEY MAP NO. 7

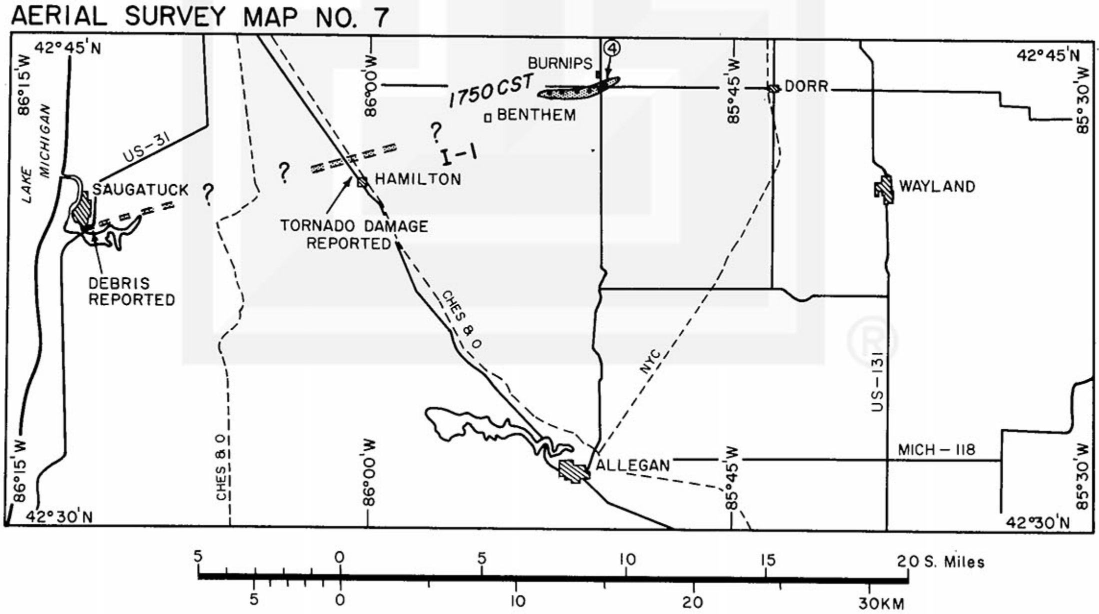


FIGURE 9. Aerial survey map No. 7, covering an area of Michigan.

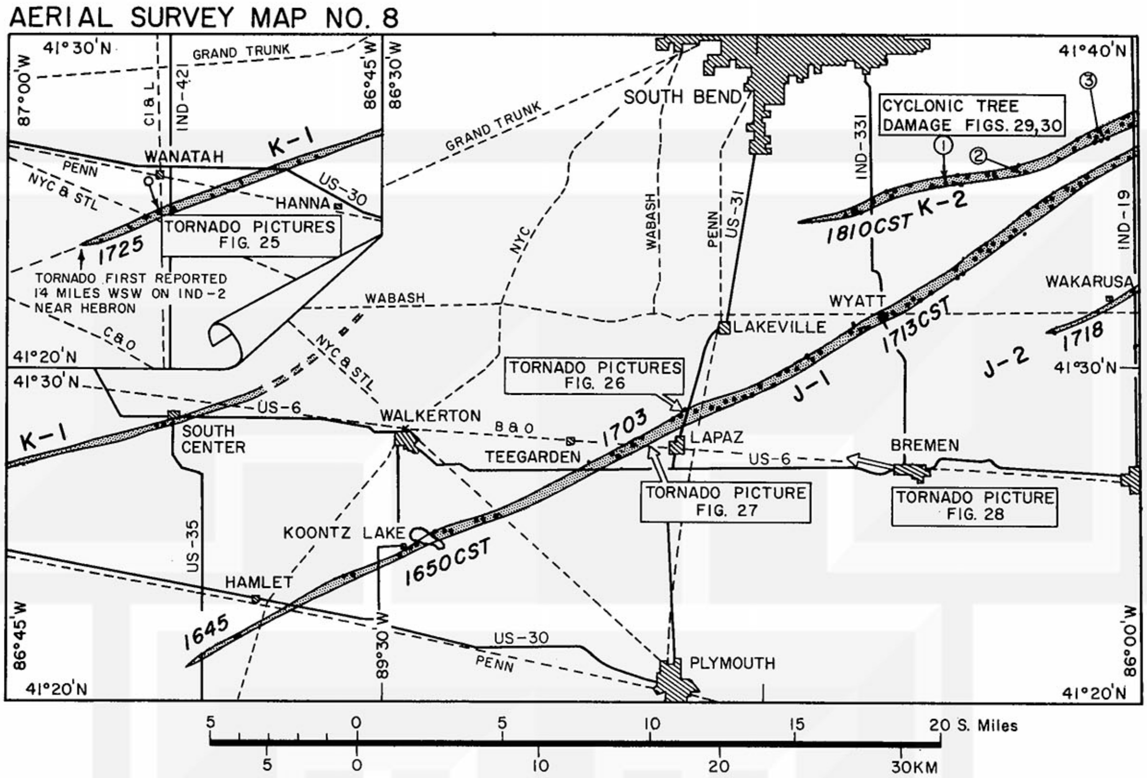


FIGURE 10. Aerial survey map No. 8, covering an area of Indiana.

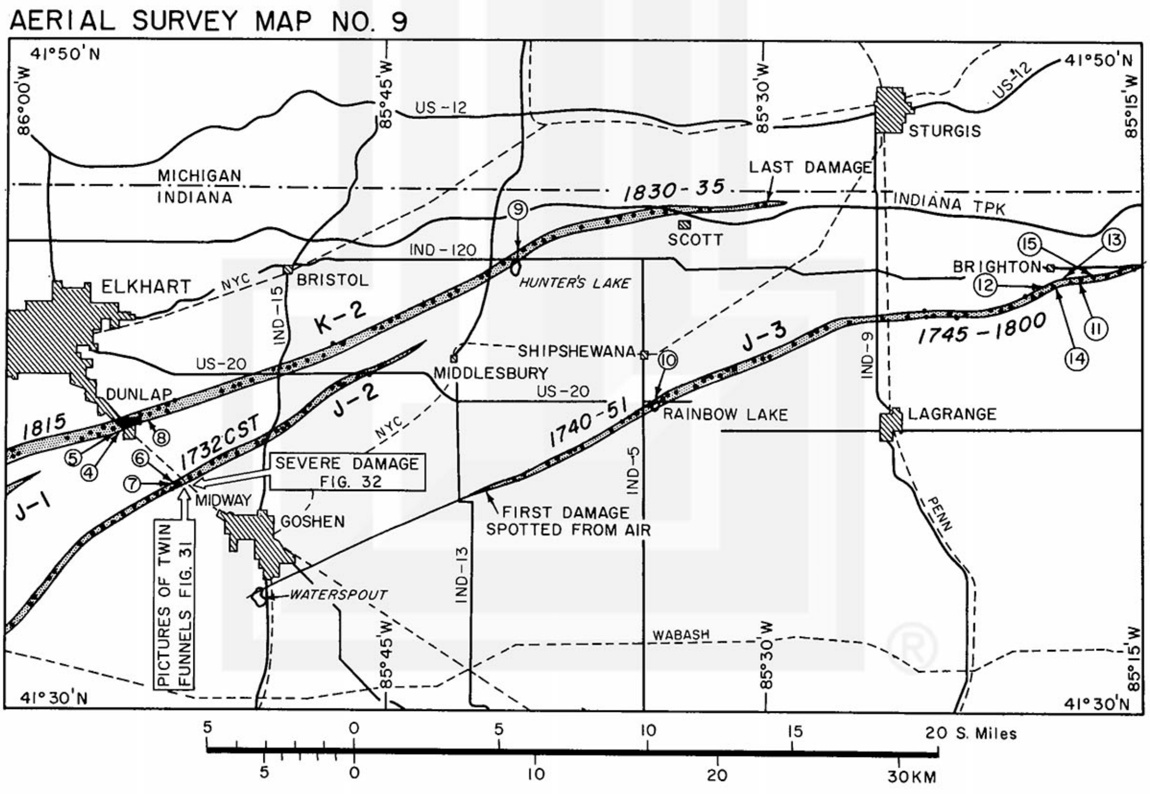


FIGURE 11. Aerial survey map No. 9, covering an area of Michigan and Indiana.

AERIAL SURVEY MAP NO. 10

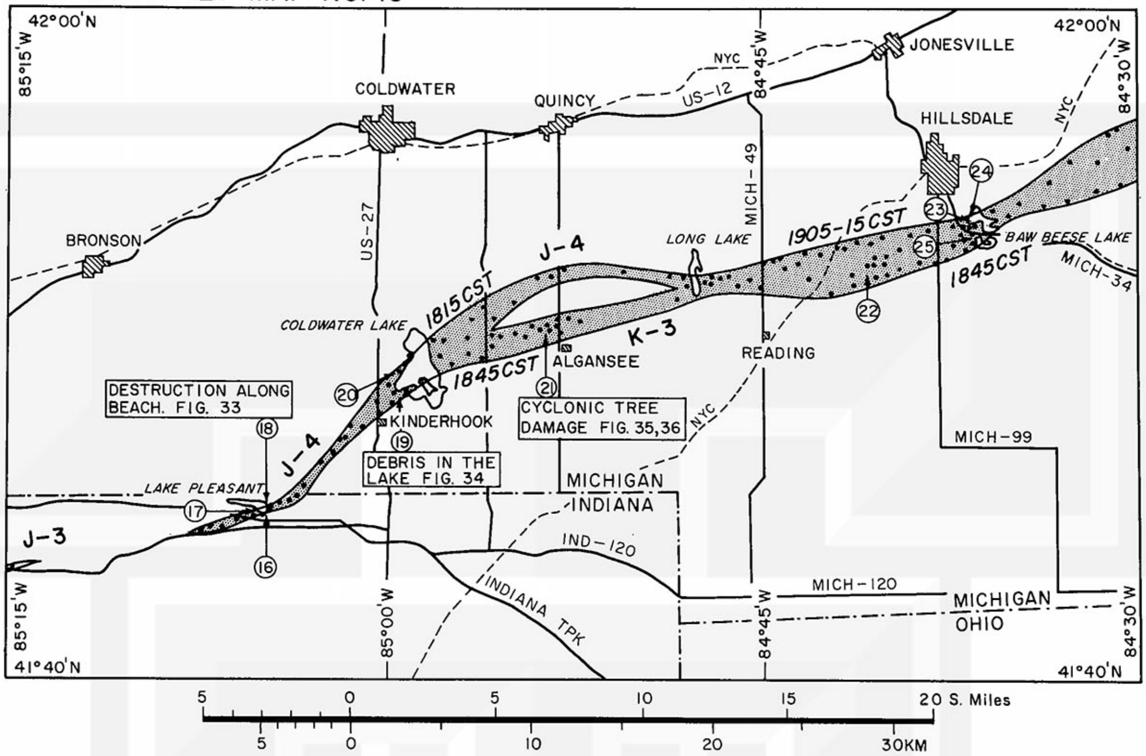


FIGURE 12. Aerial survey map No. 10, covering an area of Michigan, Indiana, and Ohio.

AERIAL SURVEY MAP NO. 11

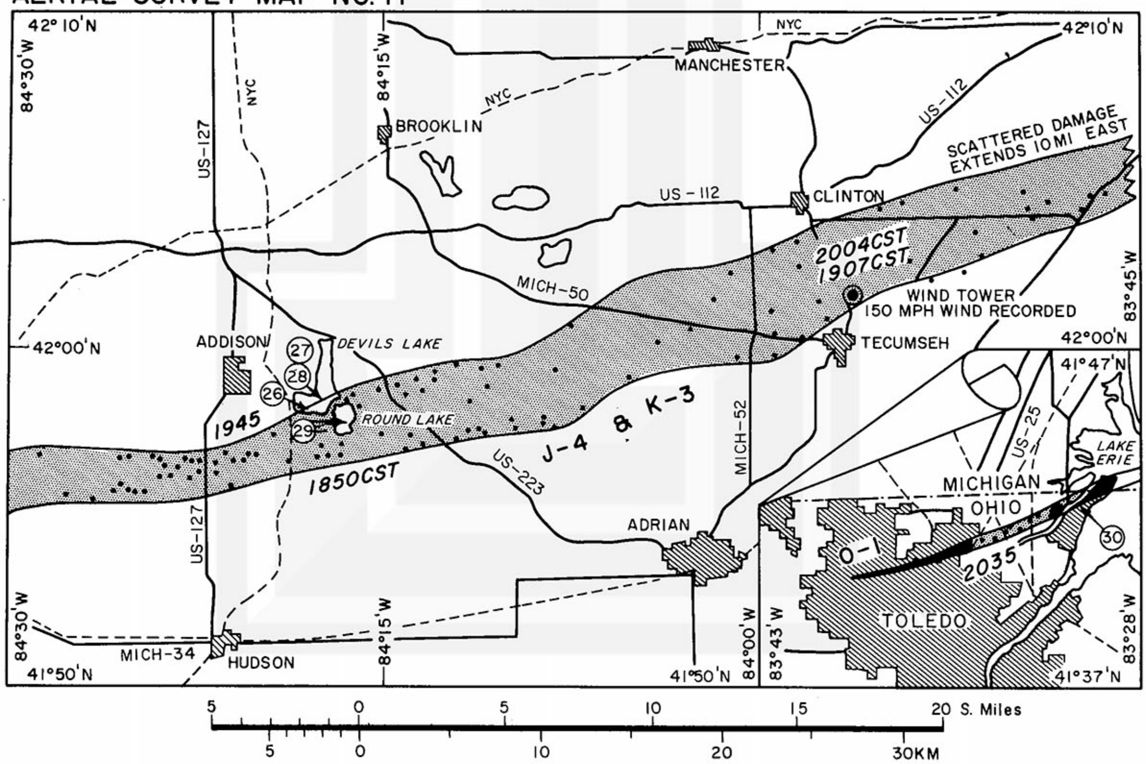


FIGURE 13. Aerial survey map No. 11, covering an area of Michigan and Ohio.

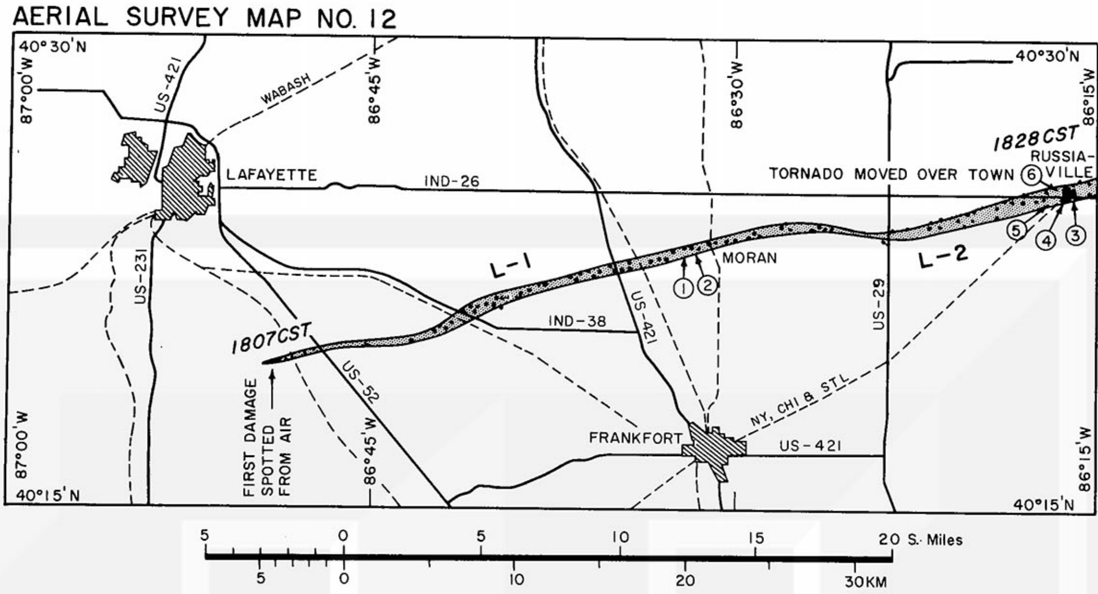


FIGURE 14. Aerial survey map No. 12, covering an area of Indiana.

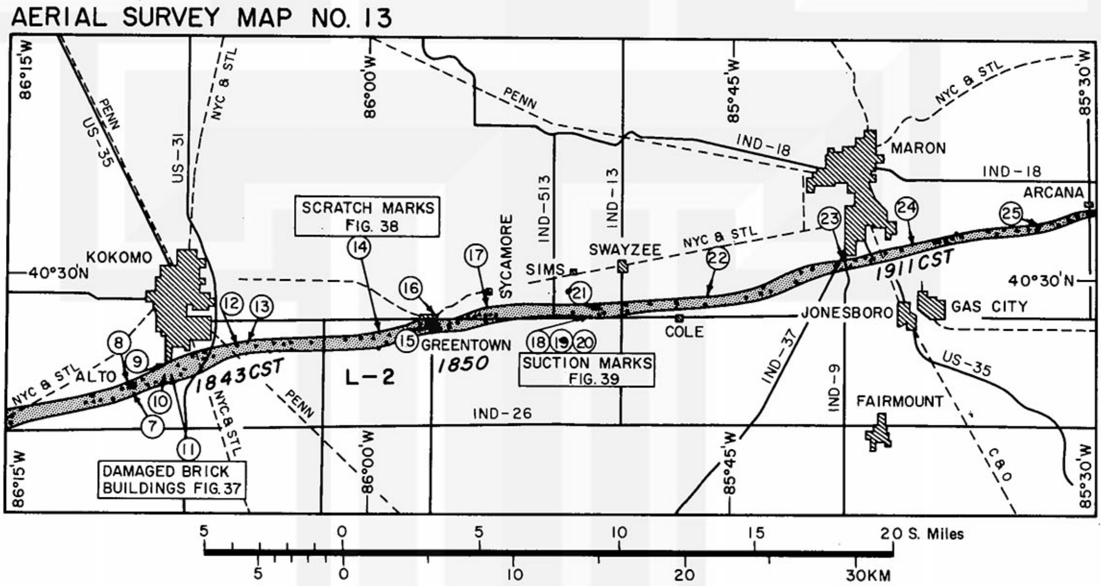


FIGURE 15. Aerial survey map No. 13, covering an area of Indiana.

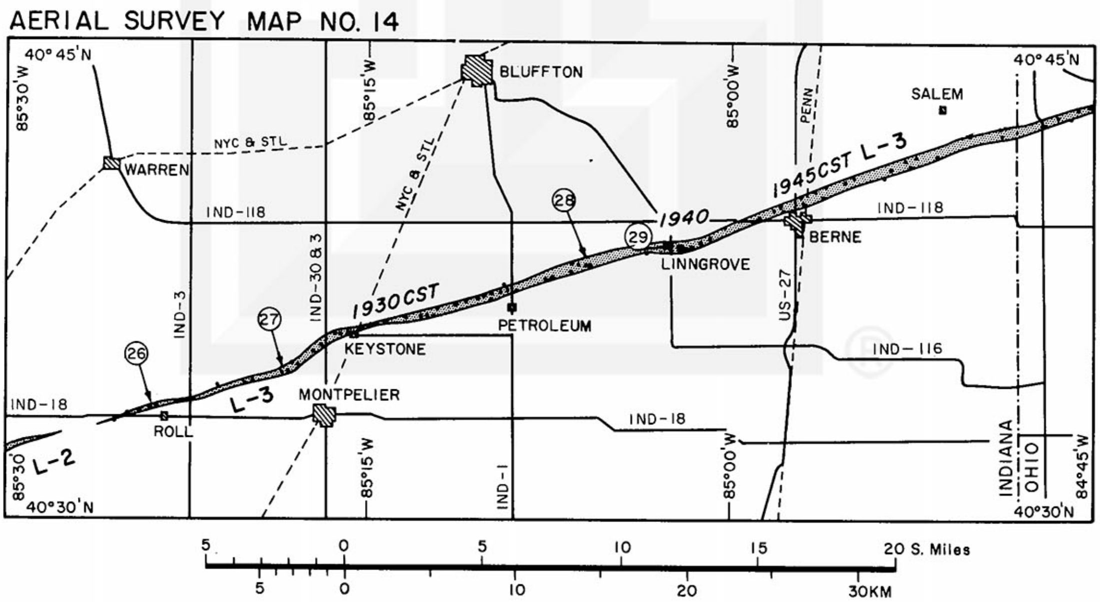


FIGURE 16. Aerial survey map No. 14, covering an area of Indiana and Ohio.

AERIAL SURVEY MAP NO. 15

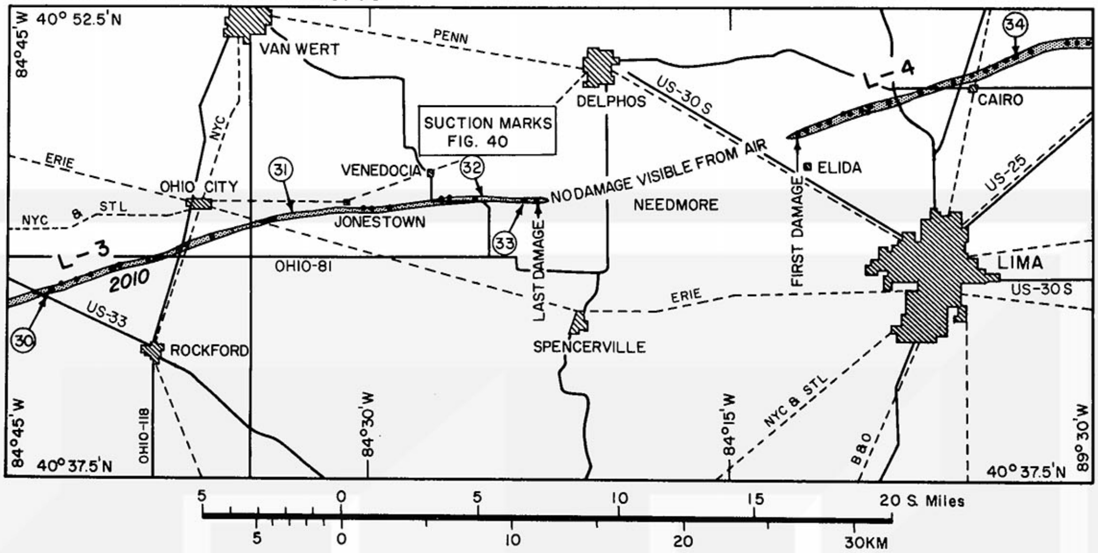


FIGURE 17. Aerial survey map No. 15, covering an area of Ohio.

AERIAL SURVEY MAP NO. 17

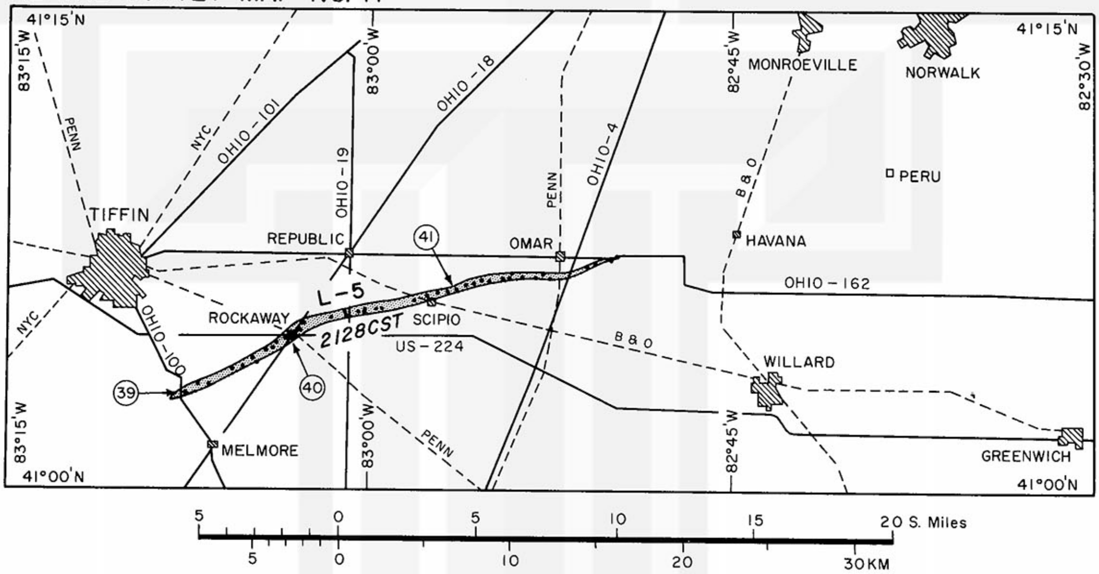


FIGURE 18. Aerial survey map No. 16, covering an area of Ohio.

AERIAL SURVEY MAP NO. 16

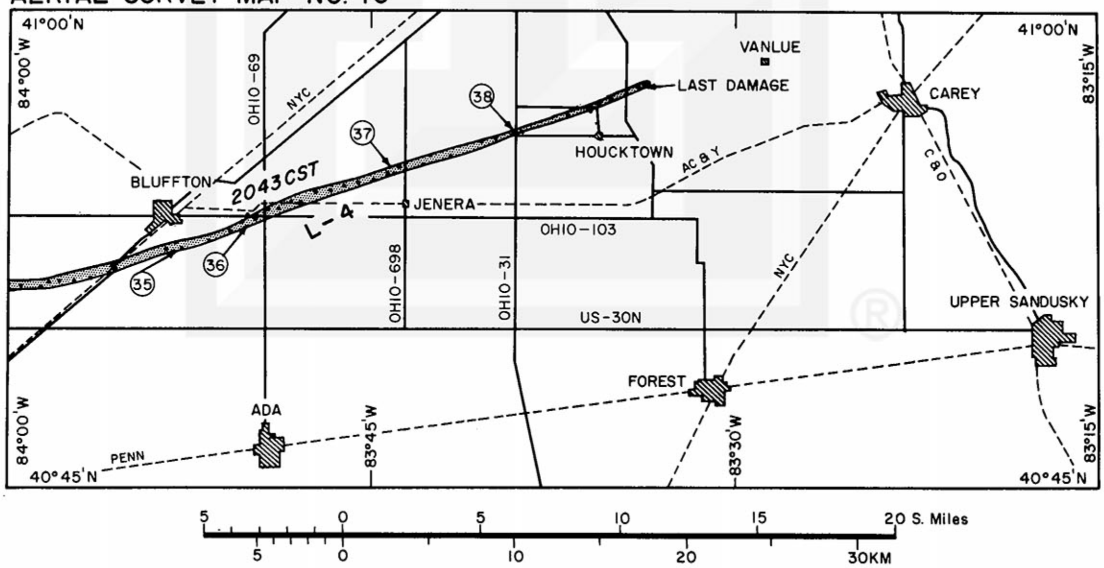


FIGURE 19. Aerial survey map No. 17, covering an area of Ohio.

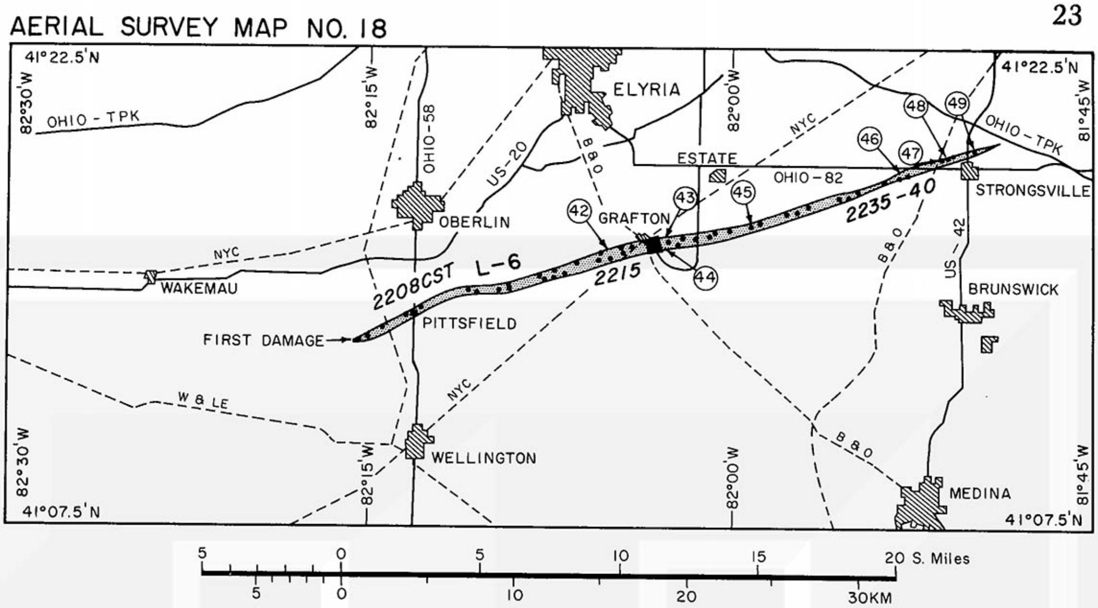


FIGURE 20. Aerial survey map No. 18, covering an area of Ohio.

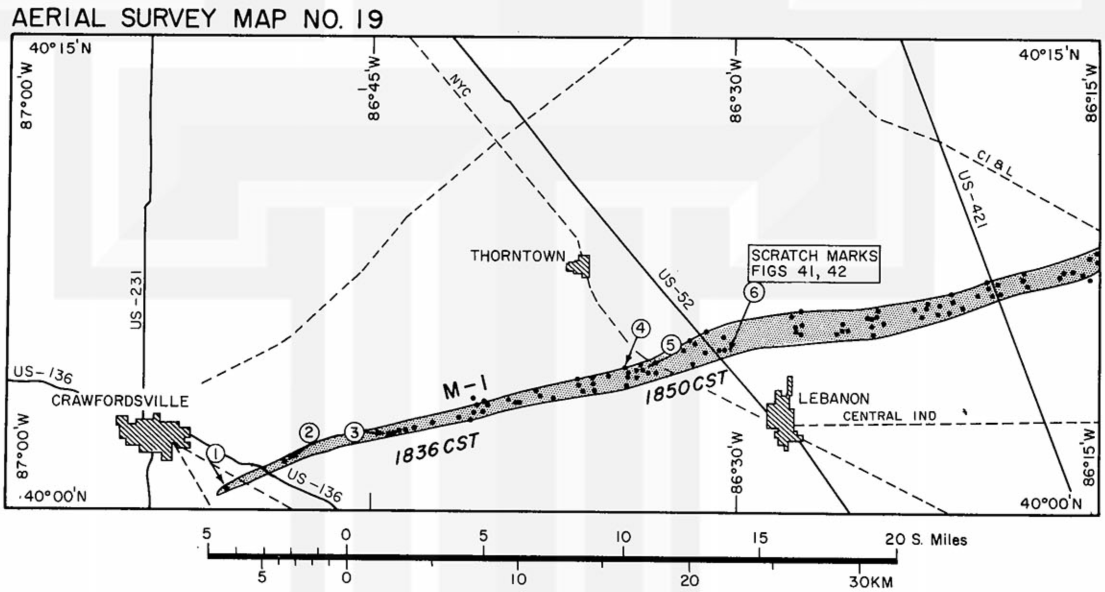


FIGURE 21. Aerial survey map No. 19, covering an area of Indiana.

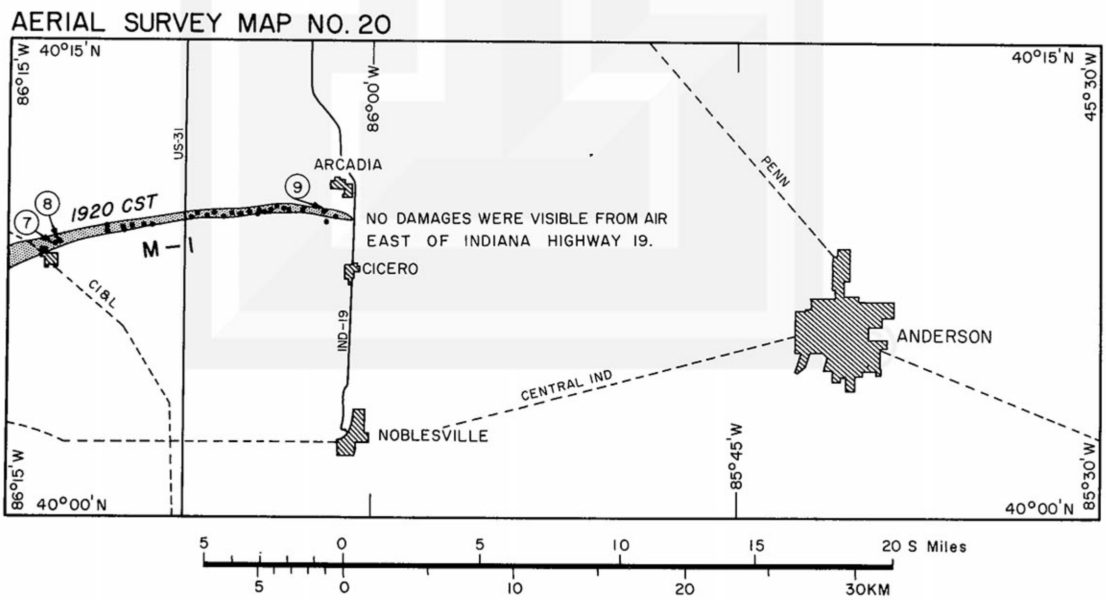


FIGURE 22. Aerial survey map No. 20, covering an area of Indiana.

FIGURE 23. Aerial view of a roofless motel on Wis-29, north of Monroe, Wisconsin. Time of destruction estimated to be 2:30 p.m. CST on April 11; picture was taken on April 19. (For exact location, refer to Aerial Survey Map No. 1)

FIGURE 24. Severe damage in the residential section of Crystal Lake, Illinois that occurred at 3:27 p.m. CST on April 11; picture was taken on April 12. (For exact location, refer to Aerial Survey Map No. 4)

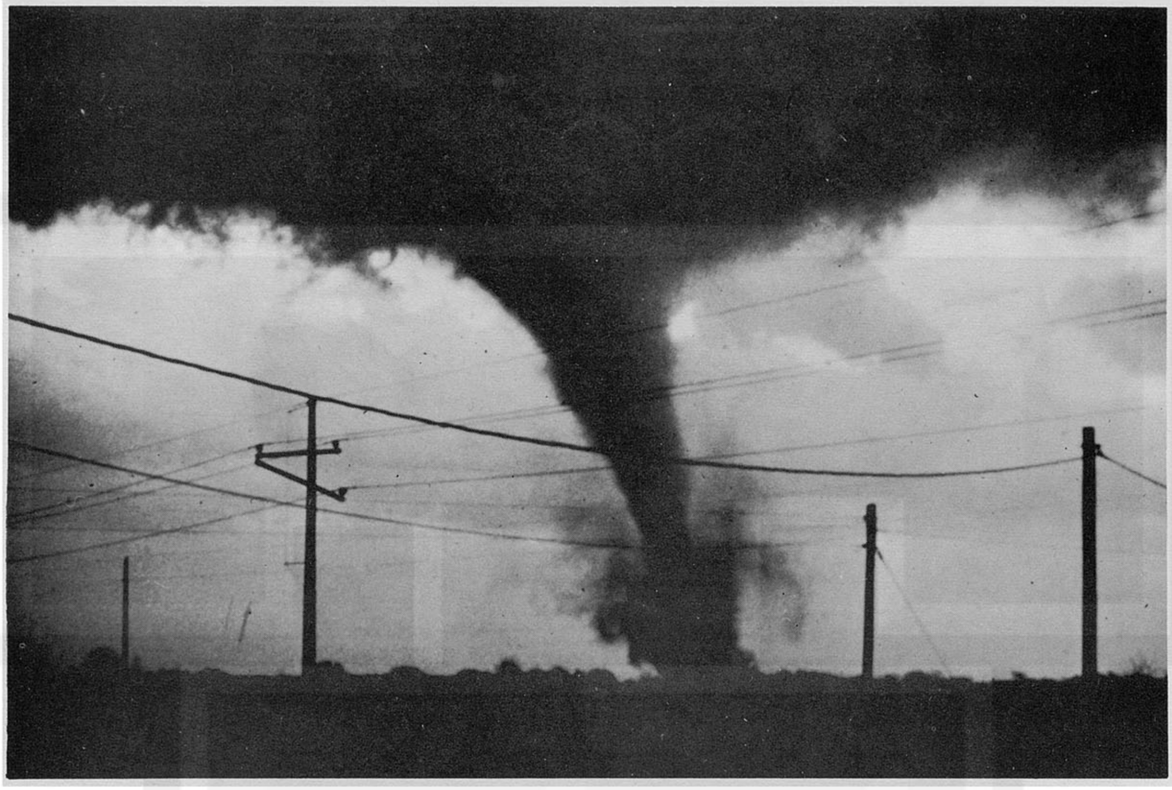


FIGURE 25. Tornado K-1 seen from Wanatah, Indiana looking south-southeast, at 5:26 p.m. CST. The damage path left by this tornado was only about 1/2 block wide. (For exact location, refer to Aerial Survey Map No. 8) Courtesy of Mr. Nicolas J. Polite.

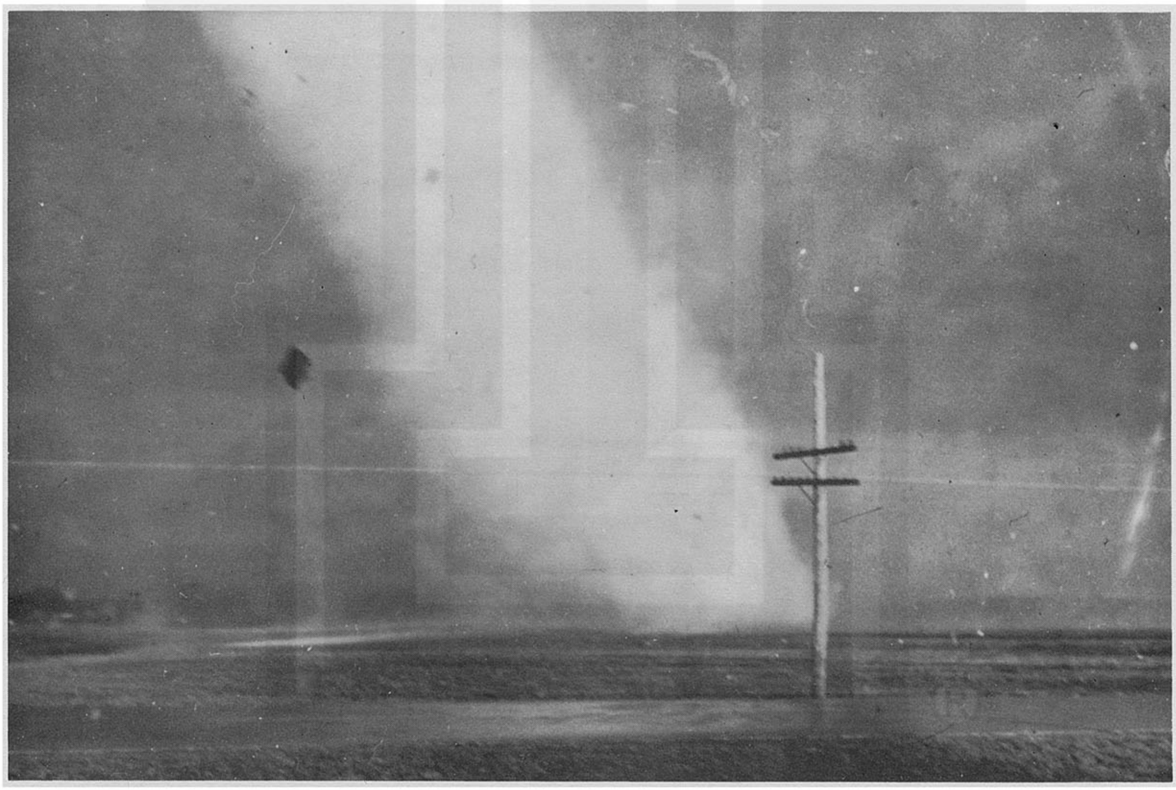


FIGURE 26. A "white tornado", identified as J-1, photographed by Indiana State Trooper Robert Candler on US-31 north of Lapaz, Indiana. Its white appearance is due to the skylight from the west, while the eastern background was extremely dark. The tornado funnel consisted mainly of water vapor that condensed into droplets due to the low pressure inside the tornado vortex. (For exact location, refer to Aerial Survey Map No. 8) Courtesy of Mr. Robert Candler.

FIGURE 27. Another view of tornado J-1 taken at 5:01 p.m., 2 min. before that of the "white tornado" of figure 26. From this direction, the tornado appeared against a brighter background. (For exact location, refer to Aerial Survey Map No. 8) Courtesy of Mrs. Helen Elliott.

FIGURE 28. Tornado J-1 as photographed by Mr. Willis Haenes at Bremen showing a simultaneous view of the "white tornado" taken from the direction opposite to that in figure 26. Note the bright background to the west. (For exact location, refer to Aerial Survey Map No.8) Courtesy of Mr. Willis Haenes.

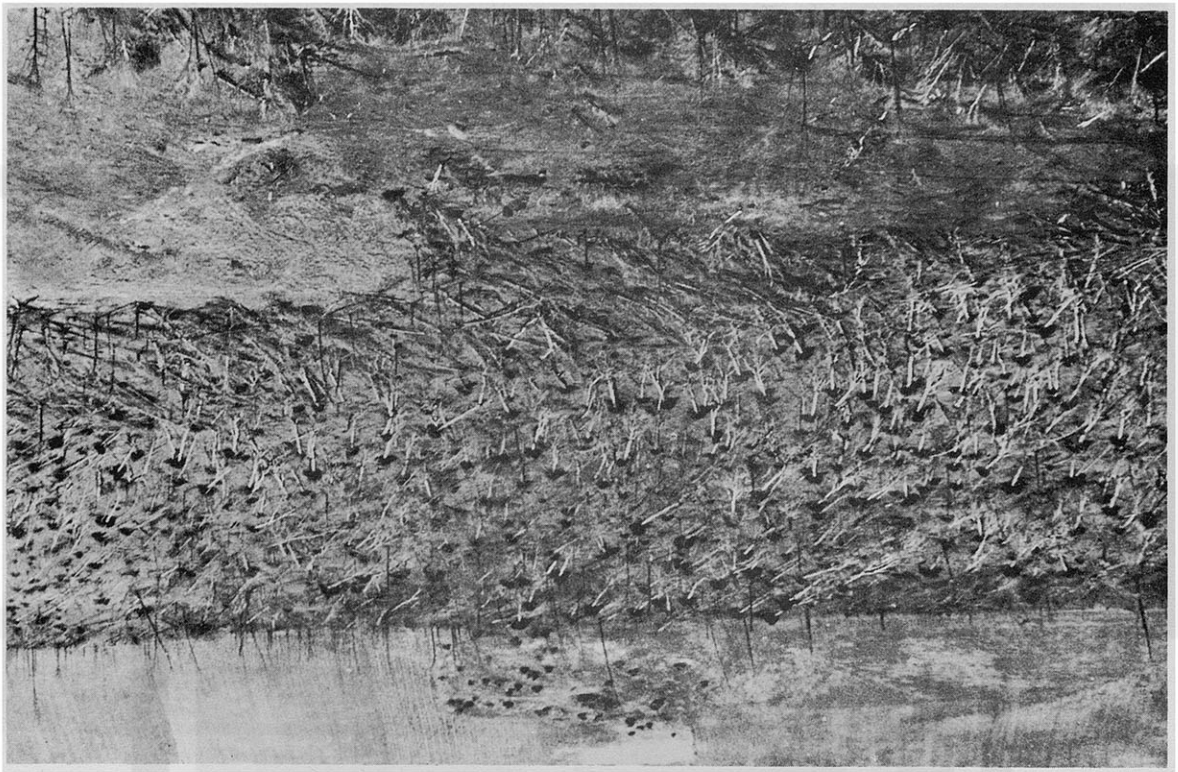


FIGURE 29. Aerial view of uprooted trees oriented along the streamlines of cyclonic winds. The damage occurred at about 6:15 p.m. CST, April 11; picture was taken April 13. Its position here is intentionally upside down in order to orient it with north at the top. (For exact location, refer to Aerial Survey Map No. 8)

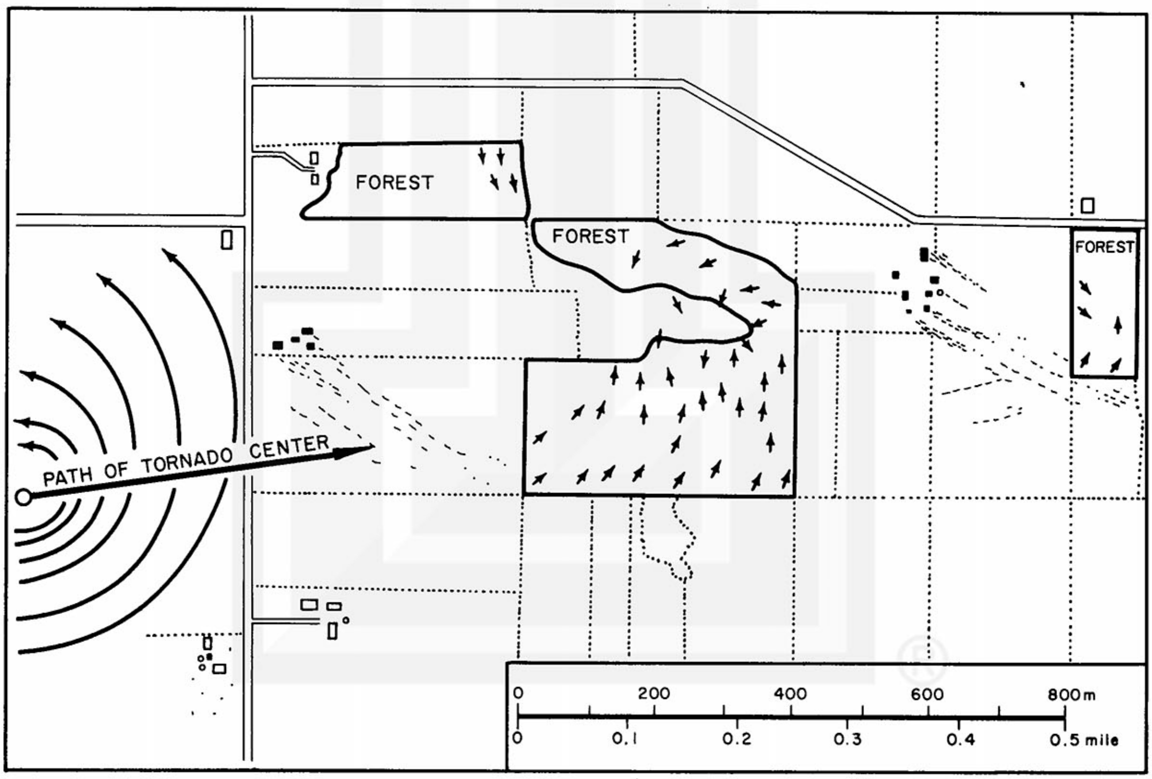


FIGURE 30. Rectified patterns showing the orientation of uprooted trees and debris marks in the vicinity of the area seen in figure 29. About 10 aerial photographs were used for this mapping. (For the exact location, refer to Aerial Survey Map No. 8.)

FIGURE 31. An unusually spectacular photograph of the twin-funnel tornado J-2, taken by Mr. Paul Huffman, staff photographer of the Elkhart Truth, at 5:32 p.m. CST, April 11, one of a series of six pictures appearing in figures 43-48. (For exact location, refer to Aerial Survey Map No. 9) Courtesy of Mr. Huffman.

FIGURE 32. Aerial photograph of severe damage to the Midway Trailer Court northwest of Goshen, Indiana. The devastation seen near the center of the picture was caused by the left funnel of the tornado shown in figure 31, while the right funnel moved over the plowed field from right to left, cutting across the upper corner of the court. For more detail, refer to figure 49. Damage occurred at 5:32 p.m. CST, April 11; picture was taken April 13. (For exact location, refer to Aerial Survey Map No. 9)

FIGURE 33. Destruction along the eastern shore of Lake Pleasant, Indiana. Tornado J-4 moved from right to left in the picture, sucking up water from the lake. The time of the tornado was about 6:00 p.m. CST, April 11; picture was taken April 13. (For exact location, refer to Aerial Survey Map No. 10)

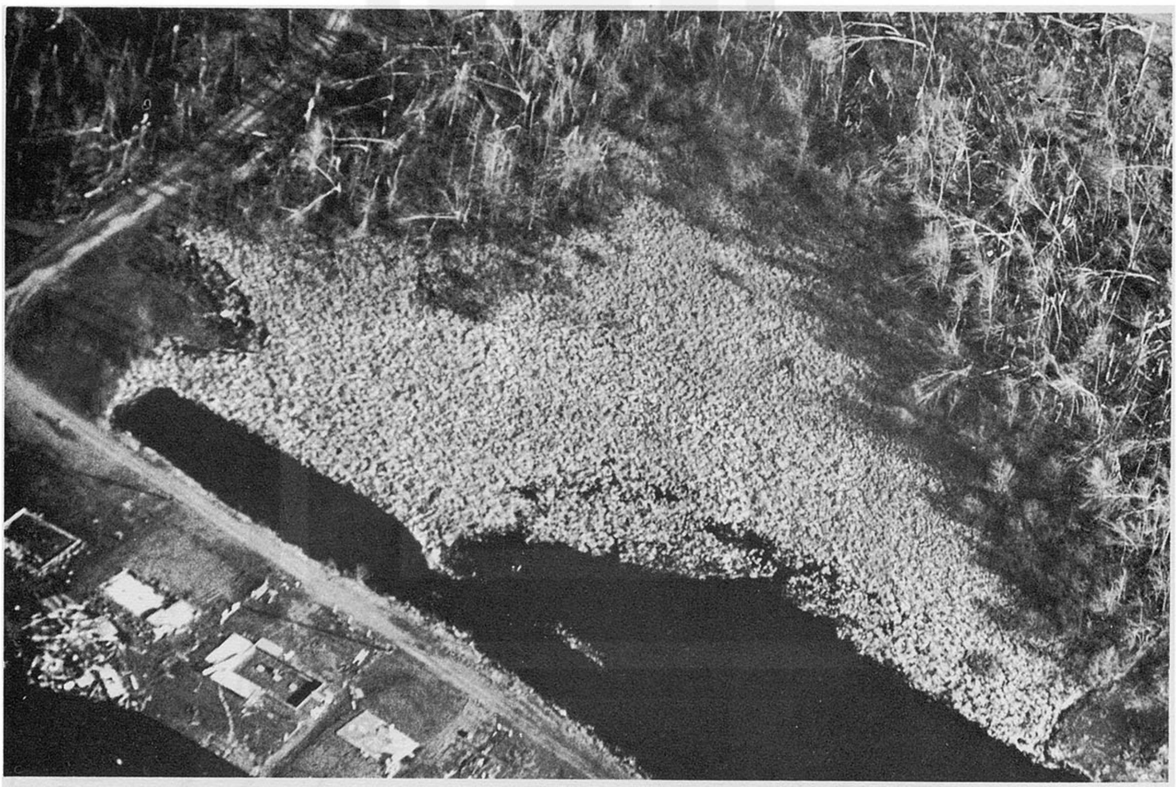


FIGURE 34. Concentration of debris in a small cove of Coldwater Lake, Michigan. Two tornadoes, J-4 and K-3, moved over the lake at about 6:15 p.m. and 6:45 p.m. CST, April 11; picture was taken April 13. (For exact location, refer to Aerial Survey Map No. 10)

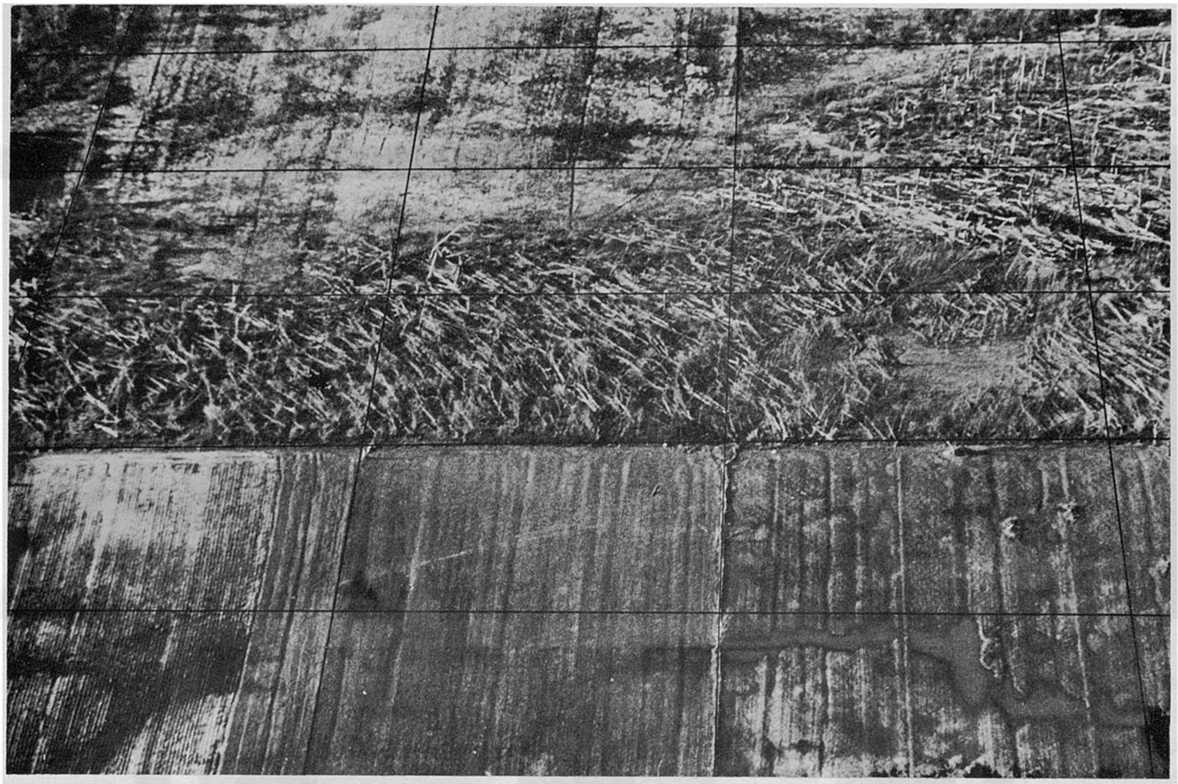


FIGURE 35. Cyclonic tree damage spotted near Algansee, Michigan. Damage was caused by tornado K-3 as it moved over this area about 6:45 p.m. CST, April 11; picture was taken April 13. (For exact location, refer to Aerial Survey Map No. 10)

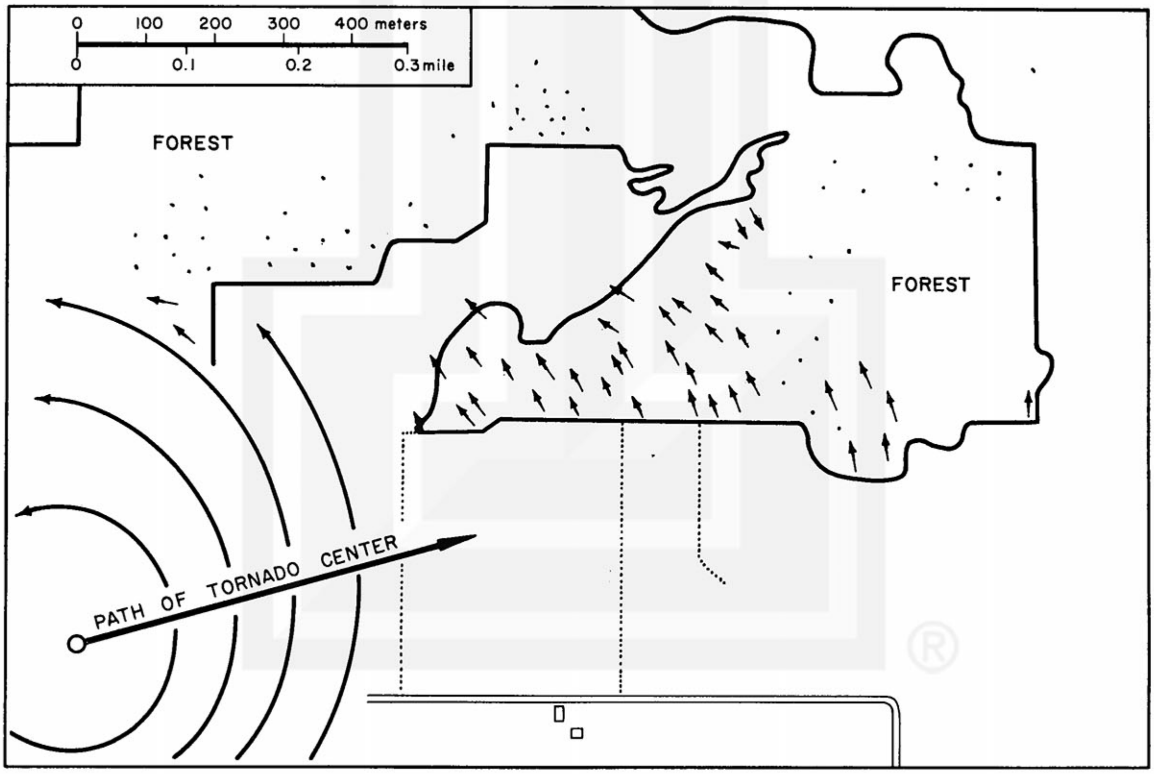


FIGURE 36. Rectified pattern of uprooted trees seen in figure 35. Note that the radius of curvature of streamlines is much larger than that appearing in figure 30. (For exact location, refer to Aerial Survey Map No. 10)

FIGURE 37. Eight brick apartment buildings south of Kokomo, Indiana in various states of destruction ranging from loss of roofs to collapse of walls. Destruction occurred at 6:43 p.m. CST, April 11; picture was taken April 16. (For exact location, refer to Aerial Survey Map No. 13)

FIGURE 38. A locus of a heavy object, the dark curved scratch mark extending from the lower right to the upper center of the picture photographed over a plowed field west of Greentown, Indiana. Tornado L-2 moved over the field shortly before 6:50 p.m. CST, April 11; picture was taken April 16. Note the difference in the direction of the scratch mark which forms an angle of about 20° from that of the debris. (For exact location, refer to Aerial Survey Map No. 13)

FIGURE 39. Aerial view of suction marks assumed to have been produced at several points around the periphery of the funnel of tornado L-2 where localized suction was particularly intense. The marks actually represent sandy soil loosened by this suction. The tornado moved over this area at about 6:00 p.m. CST, April 11; picture was taken April 16. (For exact location, refer to Aerial Survey Map No. 13)

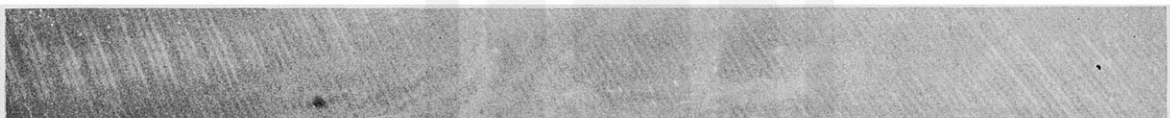


FIGURE 40. Suction marks appearing 2 miles to the west of the last damage visible from the air. The tornado wind speed computed from these marks was 300 mph. The tornado time was about 8:20 p.m. CST, April 11; picture was taken April 16. (For exact location, refer to Aerial Survey Map No. 15)

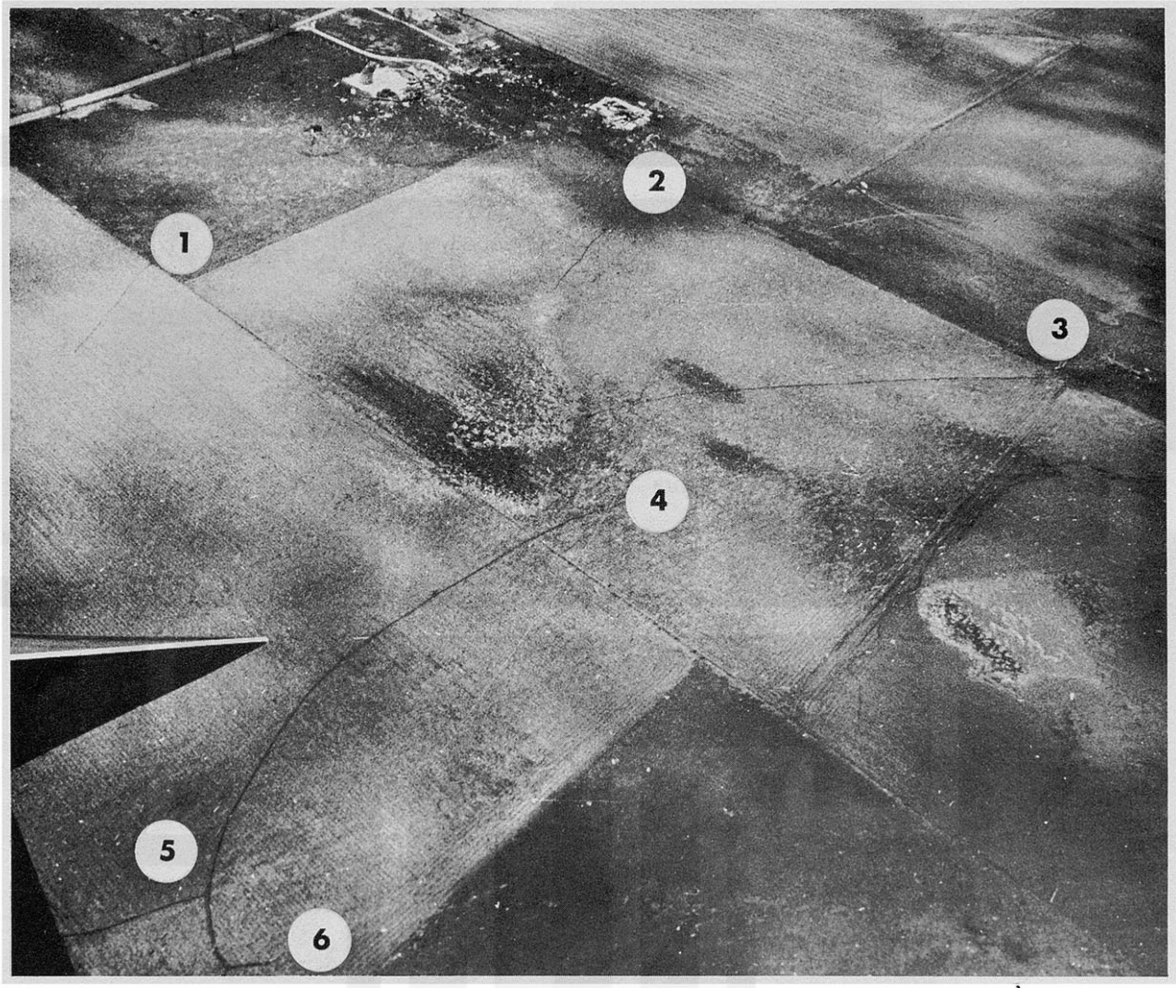
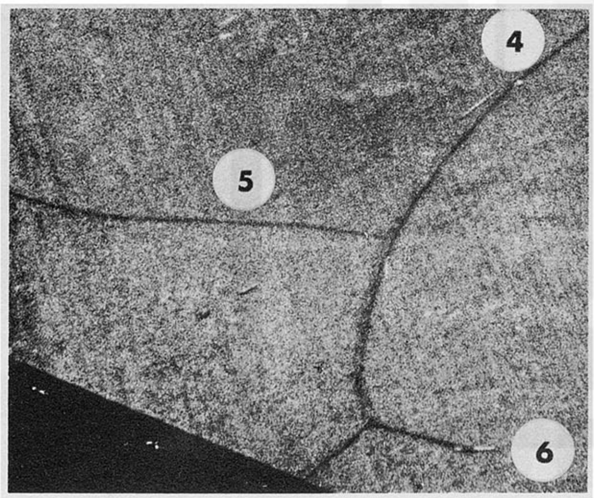


FIGURE 41. Six scratch marks left on a plowed field after tornado M-1 moved over the area northwest of Lebanon, Indiana. The time of the tornado was about 6:50 p.m. CST, April 11; picture was taken April 16. (For exact location, refer to Aerial Survey Map No. 19)



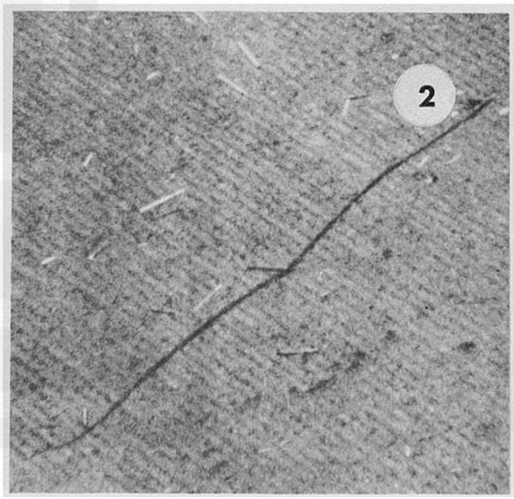


FIGURE 42. Enlarged views of scratch marks 2, 4, 5, 6. The dark triangular section in the lower left corner represents an area outside of the film. At the end of scratch mark 6, note particularly a lumber-like object to which something that probably produced the mark is attached.

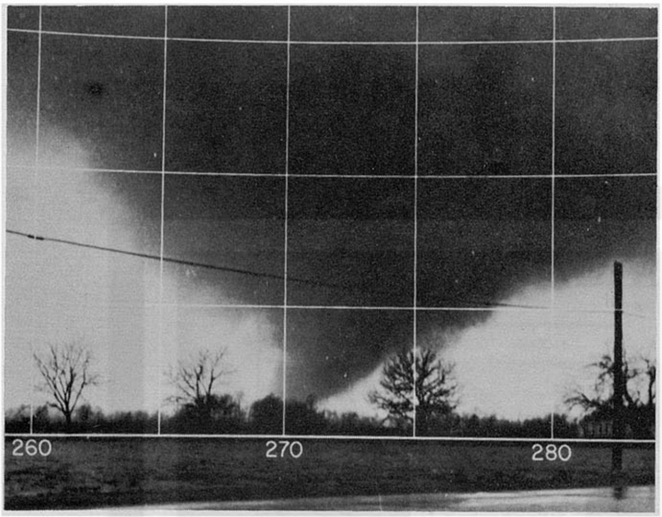


FIGURE 43. First picture in the series.

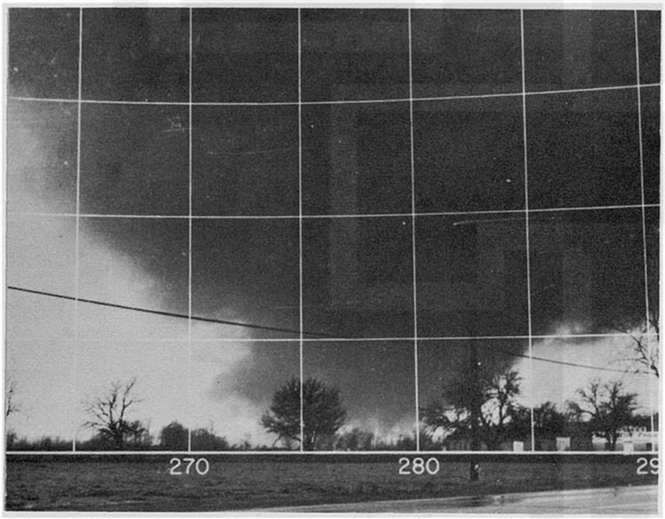


FIGURE 44. Second picture taken 17 sec. later.

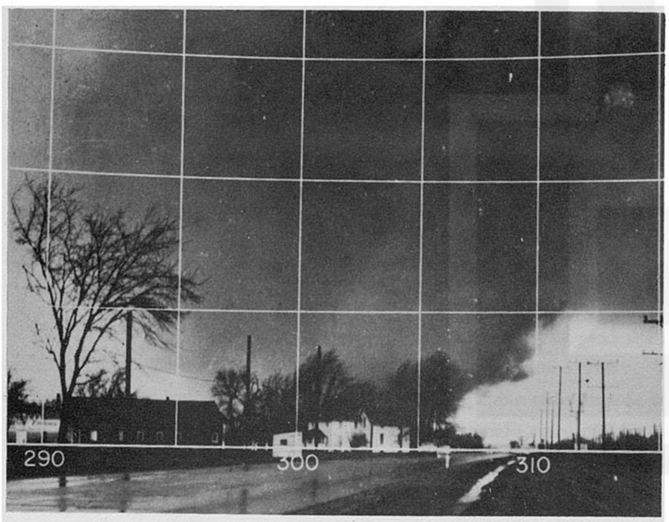


FIGURE 45. Third picture taken 27 sec. later.

FIGURE 46. Fourth picture taken 13 sec. later.

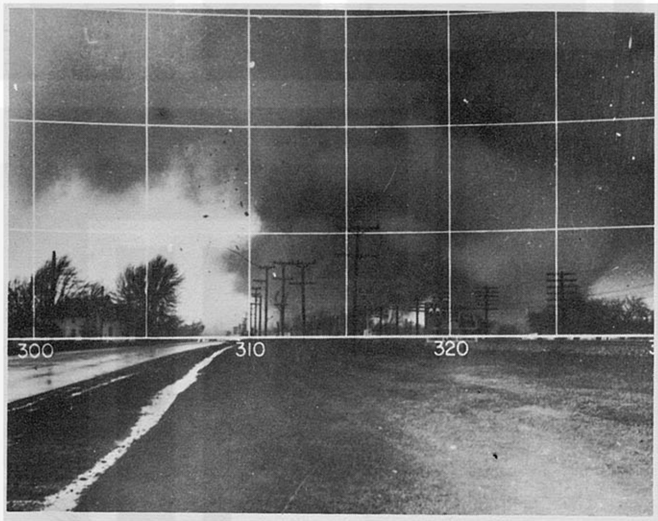


FIGURE 47. Fifth picture taken 8 sec. later.

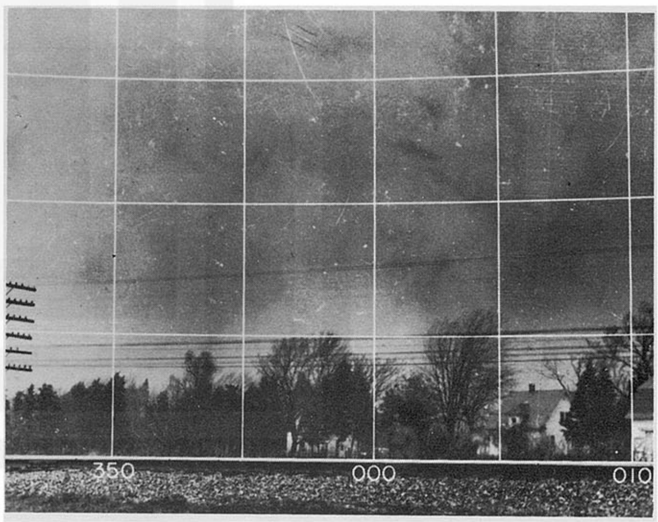


FIGURE 48. Sixth picture taken 31 sec. later.

FIGURES 43-48. A series of six pictures taken by Mr. Paul Huffman, staff photographer of the Elkhart Truth, at about 5:32 p.m. CST, April 11. (For exact location, refer to Aerial Survey Map No. 9) Courtesy of Mr. Huffman.

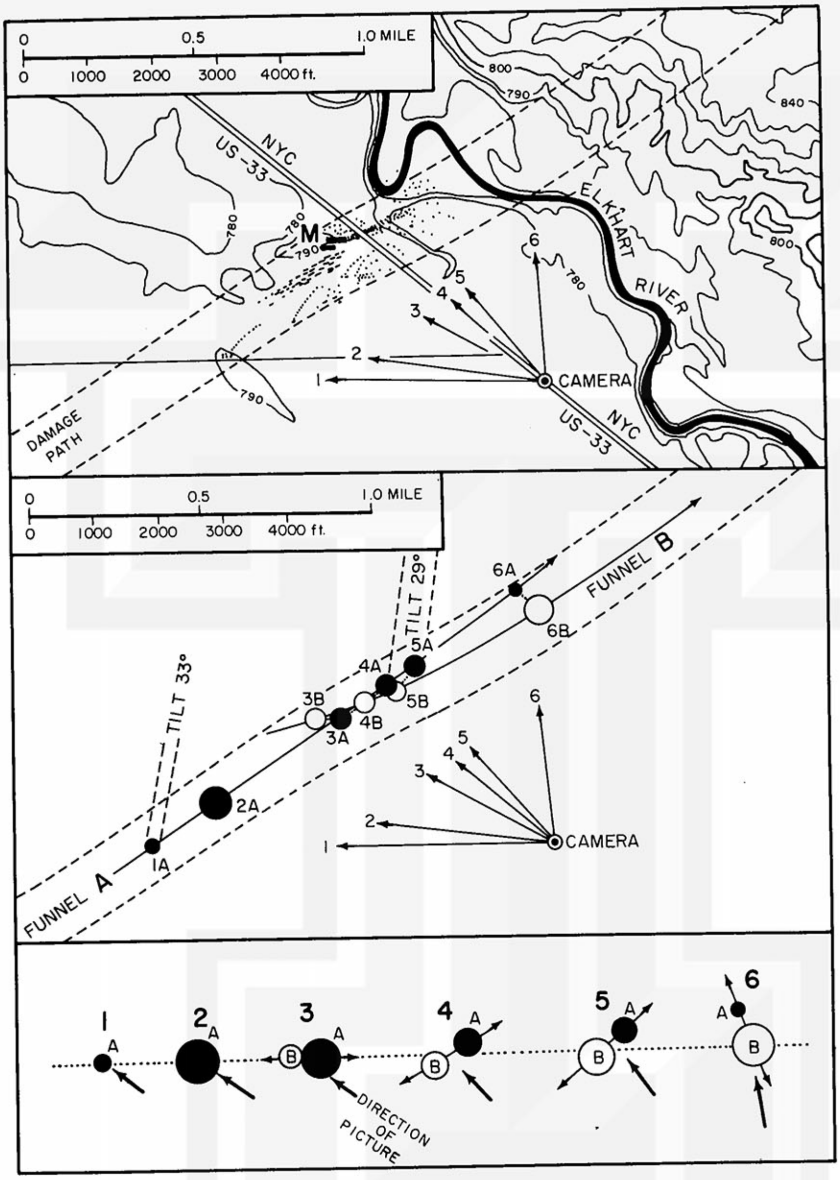


FIGURE 49. Damage path and debris marks near the Midway Trailer Court indicated by letter "M" (upper). Huffman took six pictures in the directions of the arrows. The initial funnel shown by black circle A was overtaken by the complemental funnel B. Remarkable twin funnels were photographed from a direction perpendicular to the line connecting A with B when the funnels were moving over the trailer court.

MESOMETEOROLOGY PROJECT - - - RESEARCH PAPERS

(Continued from front cover)

42. A Study of Factors Contributing to Dissipation of Energy in a Developing Cumulonimbus - Rodger A. Brown and Tetsuya Fujita

43. A Program for Computer Gridding of Satellite Photographs for Mesoscale Research - William D. Bonner

44. Comparison of Grassland Surface Temperatures Measured by TIROS VII and Airborne Radiometers under Clear Sky and Cirriform Cloud Conditions - Ronald M. Reap

45. Death Valley Temperature Analysis Utilizing Nimbus I Infrared Data and Ground-Based Measurements - Ronald M. Reap and Tetsuya Fujita

46. On the "Thunderstorm - High Controversy" - Rodger A. Brown

47. Application of Precise Fujita Method on Nimbus I Photo Gridding - Lt. Cmd. Ruben Nasta

48. A Proposed Method of Estimating Cloud-top Temperature, Cloud Cover, and Emissivity and Whiteness of Clouds from Short- and Long-wave Radiation Data Obtained by TIROS Scanning Radiometers - T. Fujita and H. Grandoso