Geophysical Monograph 79

The Tornado:
Its Structure, Dynamics, Prediction, and Hazards

Aerial Survey and Photography of Tornado and Microburst Damage

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1. INTRODUCTION

The tornado as defined in the *Glossary of Meteorology* [*Huschke*, 1959] is "a violent rotating column of air, pendant from a cumulonimbus cloud, and nearly always observable as a funnel cloud or tuba." In reality, however, no funnel cloud can be confirmed in blinding rain or during a dark night. Furthermore, a well-defined funnel on the ground does not always leave behind a continuous damage swath produced by a single vortex traveling on the ground.

In explaining the break in a vortex swath, the terms skipping and lifting were used frequently, implying that a tornado funnel intensifies or weakens within a very short distance. During posttornado interviews we often hear "the tornado leveled my neighbor's house but it skipped over my house." In the wake of the Palm Sunday tornadoes of April 11, 1965, Fujita and his associates conducted their coordinated aerial photography over the vast areas of the northern U.S. Midwest, becoming suspicious that a tornado does not skip or lift within short distances, but rather its wind structure is very complicated.

The objective of the aerial survey/photography in 1965 by the Fujita group at the University of Chicago was to determine multiscale airflows in and around tornado funnels and to identify nontornadic damaging winds induced by severe thunderstorms. During the 27 years since then, over 300 damage swaths have been flown and mapped photogrammetrically (Figure 1). A total number of 30,000 aerial photographs were taken from low-flying aircraft, mostly Cessna.

2. DETERMINATION OF MULTISCALE AIRFLOWS OF TORNADOES

Although the news media had taken numerous aerial photos of structures, the first aerial photos of well-defined circular marks, left behind by the North Platte Valley tornado of June 27, 1955, were reported by *Van Tassel* [1955]. He assumed that the grey circles on plowed fields (Figure 2) were produced by a single object caught in the tornado funnel, computing 216 m/s rotational speed of the object. Similar ground marks were photographed in the wake of the Shelby, Iowa, tornado of May 5, 1964, and reported by *Prosser* [1964]. These marks gave him an impression that an enormous vacuum cleaner had swept the ground clean of vegetation, loose soil, and other movable objects.

A major advance in the interpretation of the circular/cycloidal marks was made by taking zoom photos from 200 m above ground level (AGL) and visiting the sites on the paths of the Palm Sunday tornadoes of April 11, 1965, and the Barrington, Illinois, tornado of April 21, 1967. As evidenced in Figure 3, a circular mark was neither a scratch mark nor a band of cleaned-up bare ground. Instead, it was a band of debris deposit consisting of short pieces of corn crops, dry leaves, chicken feathers, etc. The maximum height of the deposit was less than 5 to 10 cm. In explaining the mechanism of the debris band, *Fujita* [1971] proposed the concept of a suction vortex in the tornado (Figure 4).

The diameter of a suction vortex is at least 1 order of magnitude smaller than that of the parent tornado. By virtue of its spinning motion and small diameter, the vortex gathers up near-ground debris toward its rotation axis, but it fails to pick up the debris on the ground at the center of rotation, leaving behind a narrow band of debris deposit along the path of the vortex center.

Because the shape of the cycloidal mark is a simple function of the velocity ratio, rotational velocity V divided by the translational velocity U, *Fujita et al.* [1970] generated the shapes of the ground mark by changing the velocity ratio from 1 to 10 (Figure 5). No loop will form when the velocity ratio is 1.00, but a suction vortex stays momentarily at one spot, creating a stepping spot (Figure 6). As the velocity

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Fig. 1. Tracks of tornadoes surveyed by the Fujita group during the 27-year period 1965–1991. The first aerial photography was conducted immediately after the Palm Sunday tornadoes of April 11, 1965.

ratio increases, the size of the loop increases (Figure 7), reaching a near-circular loop when the ratio approaches 10 (Figure 8).

The maximum horizontal wind speed inside an orbiting suction vortex is the sum of U, V, and S, the spinning velocity of the suction vortex. A strong suction vortex in a residential area could induce a one- to two-house-wide swath in which houses could be wiped off their foundations (Figure 9). On the contrary, several "lucky" houses located between intersecting paths of multiple suction vortices could be left untouched (Figure 10). These damage patterns cannot be explained by the so-called skipping phenomenon of a tornado. Threatened by such a tornado, one should not open windows because there is no way of guessing the direction of oncoming suction vortices. At this point, the evidence of aerial surveys did alter one of the traditional tornado safety rules.

A large number of aerial photos showed the existence of cycloidal marks in the swaths of many large-core tornadoes.

Fig. 2. An aerial photo of the circular ground mark assumed to be the scratch mark by a single object caught in the tornado funnel. From *Van Tassel* [1955].

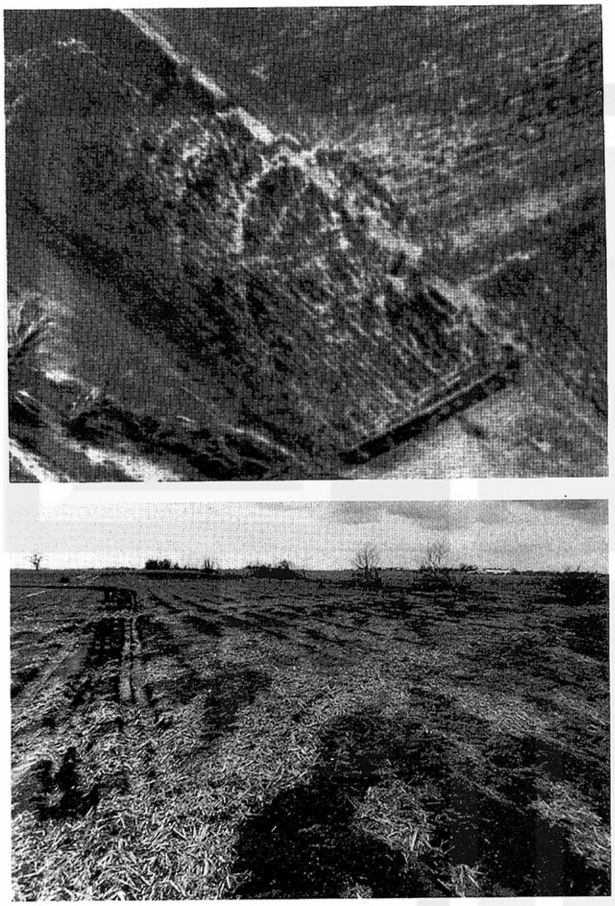

Fig. 3. (Top) Aerial photo of the cycloidal mark of the Barrington, Illinois, tornado of April 21, 1967. (Bottom) The cycloidal mark photographed on the ground. Both photos by Ted Fujita.

Their frequencies far exceeded our initial expectation. Nevertheless, pictures of tornadoes showing suction vortex funnels had been very rare until the Jumbo Tornado Outbreak of April 3–4, 1974. Since then, a large number of multiple-vortex (suction vortex) pictures (Figure 11) have become available from various parts of the United States. These pictures, along with cycloidal marks, were analyzed by *Fujita et al.* [1976], *Agee et al.* [1975, 1977], and many others.

3. Evidence of Suction Vortices

Wind effects of suction vortices on the ground can be photographed from a low-flying aircraft. Their appearances vary with the scattering angle of the sunlight, appearing either relatively darker or lighter as an aircraft circles around the target. As has been well known, tracks of orbiting suction vortices appear as a group of cycloidal curves (Figure 12). On the other hand, a stationary suction vortex leaves behind a pattern of high winds indicating the existence of either a small (Figure 13) or a large (Figure 14) eye at the location where the vortex center had existed momentarily.

We also observed the path of an isolated vortex mark suggesting a single-loop motion of the suction vortex (Figure 15). An interesting vortex signature is the path of twin vortices which traveled side by side while rotating slowly around their common center (Figure 16). Another remarkable aerial photo shows a curved path with five intensification spots along the centerline (Figure 17). The picture also shows that the initial vortex disappeared, being taken over by the new vortex which flattened the corn crop along its path. This picture evidences the rapidly changing nature of an orbiting vortex which could cause unexpected damage.

Apparently, the smaller the vortex, the stronger the vertical winds relative to the horizontal winds around a small vortex. Figure 18 shows the corn crop pushed over by the Hobart, Indiana, tornado of June 30, 1977. A telephoto view of the strong shear zone reveals the existence of several tiny vortices, 1 m to 2 m in the core diameter (Figure 19), in which several corn plants were pulled off the ground. Convergence inside the core of an axisymmetric vortex is approximated by

$$\mathrm{Conv} = u/D$$

where u denotes the inflow velocity and D denotes the core diameter. When convergence is 2 s^{-1}, a 2 m/s vertical wind is expected at 1 m AGL, and a 4 m/s vertical wind is expected at 2 m AGL. Vertical winds of these magnitudes would be able to pull loosened young plants out of the ground.

One of the best examples of a small tornado with dominantly vertical winds just above the ground is seen in a video sequence of the Minneapolis tornado of July 18, 1986, which was taken from a low-flying helicopter. *Fujita and Stiegler* [1986] pointed out that a tree in the field caught by a small tornado funnel which was 3 m in diameter on the ground tilted for about 1 s before it was blown down when the funnel moved away from the tree (Figure 20).

A small-core tornado less than 10 m in diameter, east of Denver, Colorado, on June 30, 1987, was investigated by *Wakimoto and Wilson* [1989] using both aerial and ground photographs. In spite of the herringbone pattern of damage due to the storm motion, their photographs suggest the existence of an appreciable inflow into the small core, implying a strong rising motion inside the small core.

The library of the tornado data collected by the Fujita group during the past 30 years indicates that tornadoes in general are more complicated than earlier conceived. It is often very difficult to distinguish a suction vortex from its parent tornado (Figure 21). Furthermore, their appearance and structure keep changing very rapidly within a matter of seconds (Figure 22).

During the 1976 Symposium on Tornadoes at Texas Tech University, it was noticed that there was a basic disagreement between meteorologists and structural engineers on the mechanism of structural damage by tornado winds. Most engineers, at that time, approximated tornado winds as

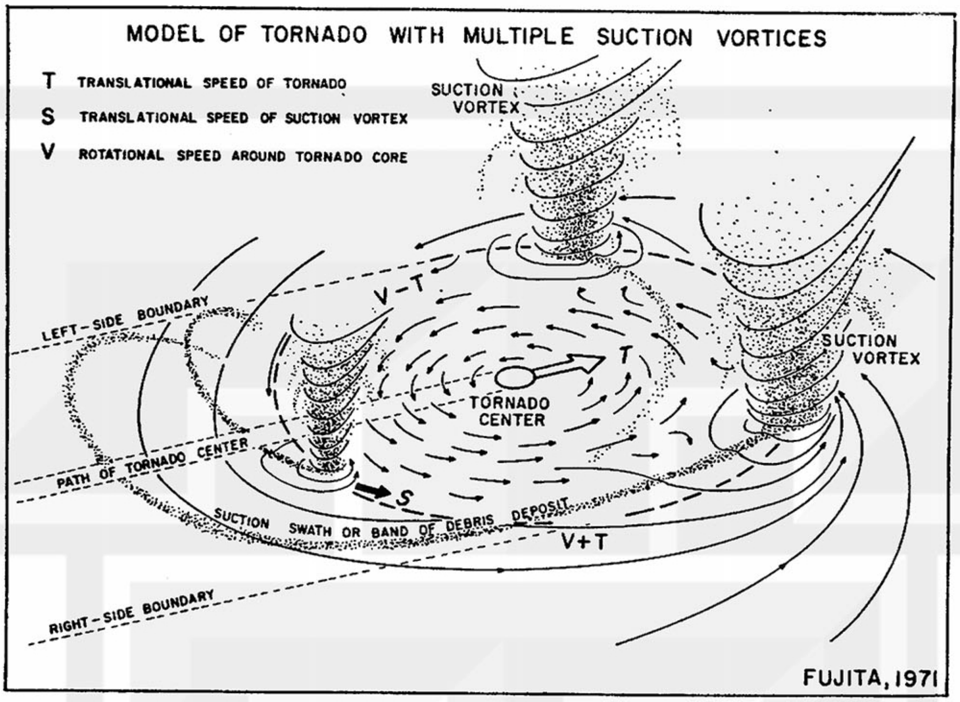

Fig. 4. A model of a tornado with three suction vortices orbiting around the core of the parent tornado. From *Fujita* [1971].

straight-line winds. This assumption is valid when vertical winds are negligibly smaller than horizontal winds, such as in the case of hurricanes and downbursts. Since the near-ground convergence is approximated by the inflow velocity divided by the vortex diameter, the straight-line wind assumption becomes invalid for most small vortices such as small tornado, suction vortex, dust devil, etc. A structure in such a small but intense vortex could be rapidly torn apart vertically under high-speed vertical winds just above the ground (Figure 23).

4. Microburst, Inducer of Nontornadic Damaging Winds

Fujita's aerial survey and photography of the Jumbo Outbreak Tornadoes of April 3–4, 1974, played an important role in developing his concept of the downburst. After the tornadoes, when Fujita was circling over an area of reported tornado damage, he found a diverging pattern of uprooted trees (Figure 24); thereupon he reached the conclusion that the damage was caused by a strong downdraft as it impacted on the tree-covered ground.

While investigating the Eastern Airlines Flight 66 accident (landing) on June 24, 1975, at John F. Kennedy Airport in New York, *Fujita* [1976] attempted to apply his downburst concept in explaining the strong tailwind and downwind shears encountered simultaneously by the accident aircraft. Horace R. Byers, Fujita's mentor professor, was the first person who supported his downburst concept, agreeing to write a joint paper [*Fujita and Byers*, 1977]. Shortly thereafter, Fernando Caracena applied the downburst concept to the probable cause of the Continental Airlines Flight 426 accident (takeoff) on August 7, 1975, at the Stapleton, Denver Airport. The results of the joint research on three aircraft accidents is found in the work of *Fujita and Caracena* [1977].

Fujita had great confidence in the downburst concept, backed by numerous aerial photos of the starburst damage; nevertheless, a large number of nonbelievers expressed their controversial views, summarized by *West* [1979]. Most meteorologists who expressed strong opposition probably did not have the opportunity to fly over areas of tornado damage. Since then, Fujita has trained his group and initiated extensive downburst-hunting flights.

The training and flights have been very successful, establishing the existence of multiscale airflows [*Fujita and Wakimoto*, 1981]. By the end of the 1970s, solid evidence of downburst winds and their horizontal scales was established, on the basis of aerial photos and the National Center for Atmospheric Research's Doppler radars operated during the Northern Illinois Meteorological Research on Downburst (NIMROD), the landmark experiment which ended most controversies that prevailed at that time. At the termination of the experiment, the downburst concept was subdivided into microburst (<4-km horizontal size) and macroburst (>4 km).

An aerial photo of a large microburst (Figure 25) shows an

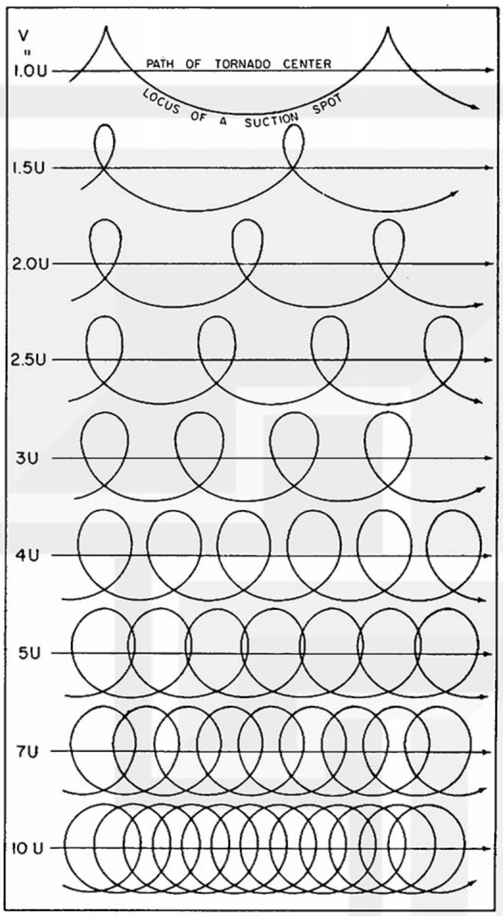

Fig. 5. Geometric path of the center of a suction vortex computed by changing the velocity ratio from 1 to 10. From *Fujita et al.* [1970].

Fig. 7. Cycloidal ground marks left behind by suction vortices with velocity ratio between 2 and 3. Photo by Ted Fujita after the West Lafayette, Indiana, tornado of March 20, 1976.

extensive area of diverging winds which blew down numerous corn plants. Frequently, a small microburst touches down with a sharp boundary of the wind speed increase from less than 25 m/s to 40 m/s within a 5- to 10-m distance (Figure 26). The estimated divergence at the boundary should reach 1.5 to 3.0 s^{-1}, suggesting that the parent downdraft descended to the treetop height without weakening significantly. A swath of high winds which deflected off of the sloping roof of a farm building in Indiana (Figure 27) also suggests that a downdraft descended to the rooftop height. An extremely small microburst may be only 30 to 50 m wide and 100 to 300 m long, with an appearance of a rush of diverging jet (Figure 28). The parent downward current

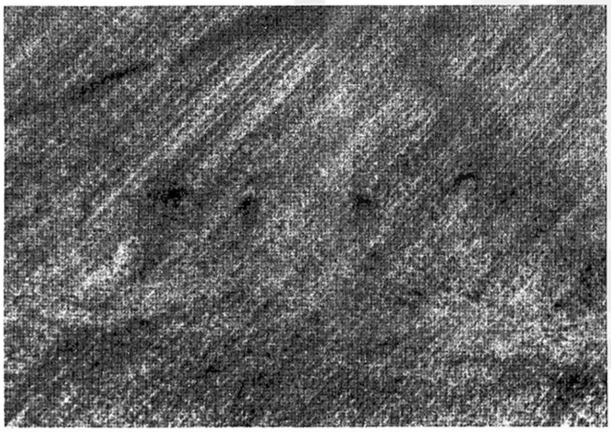

Fig. 6. Stepping spots (West Lafayette, Indiana, tornado of March 20, 1976) where orbiting suction vortices pause momentarily when the velocity ratio is 1.0. Refer to Figure 5. Photo by Ted Fujita.

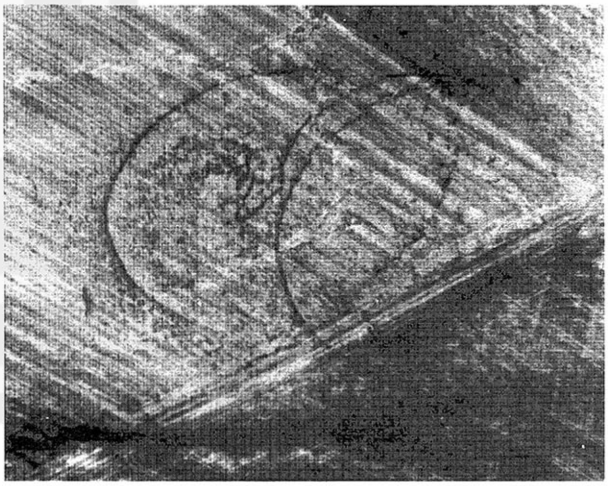

Fig. 8. Near-circular cycloidal marks of the Goessel, Kansas, tornado (F5) of March 13, 1960, as the tornado was traveling at 20 m/s. Aerial photo by Duane Stiegler.

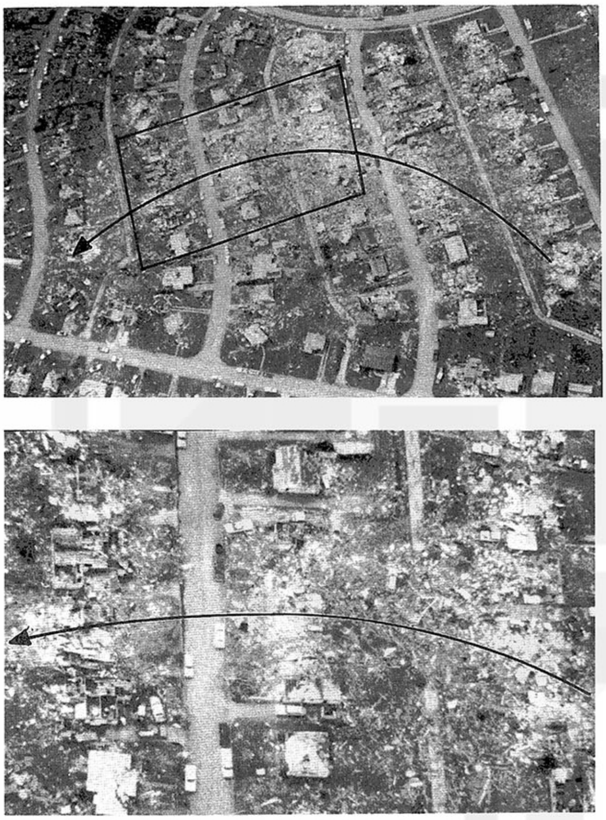

Fig. 9. (Top) An arc of a suction vortex track left in the residential section by the Wichita Falls, Texas, tornado of April 10, 1979. (Bottom) An enlargement of the boxed area. Photo by Ted Fujita. This damage is similar to the Lubbock, Texas, tornado case reported by *Fujita* [1970].

Fig. 10. One-, two-, and three-house groups left untouched by the Wichita Falls, Texas, tornado of April 10, 1979, because they were located between a number of intersecting tracks of suction vortices. Photo by Ted Fujita.

Fig. 11. Six suction vortices inside the Wichita Falls, Texas, tornado of April 10, 1979. Three vortices at the far side are those forming in the inflow region of the tornado airflow. Copyrighted photo by Floyd Styles.

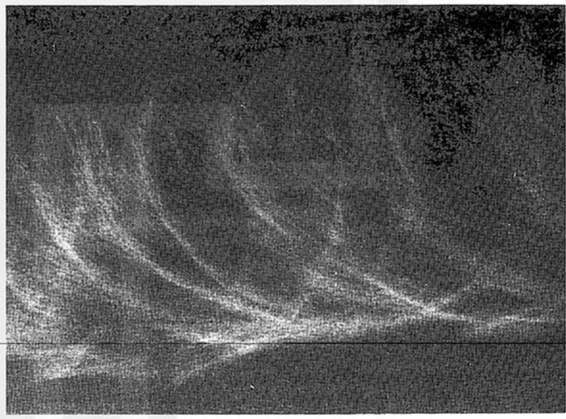

Fig. 12. Typical cycloidal ground marks of the suction vortices orbiting around the core of a traveling tornado. Magnet, Nebraska, tornado of May 6, 1975. From *Fujita* [1981].

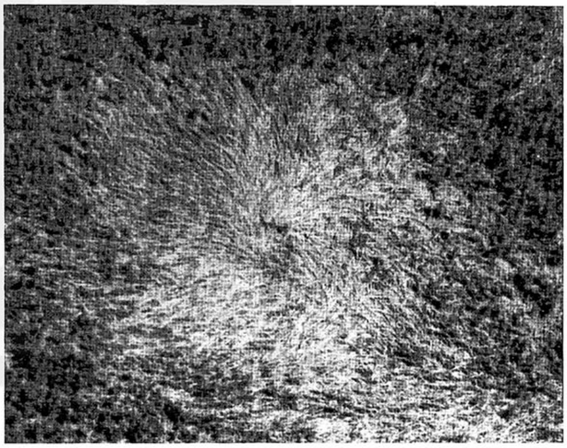

Fig. 13. Small eye of a stationary suction vortex inside the Mattoon Lake, Illinois, tornado of August 21, 1977, made visible by the pattern of blown down corn crops. From *Fujita* [1981].

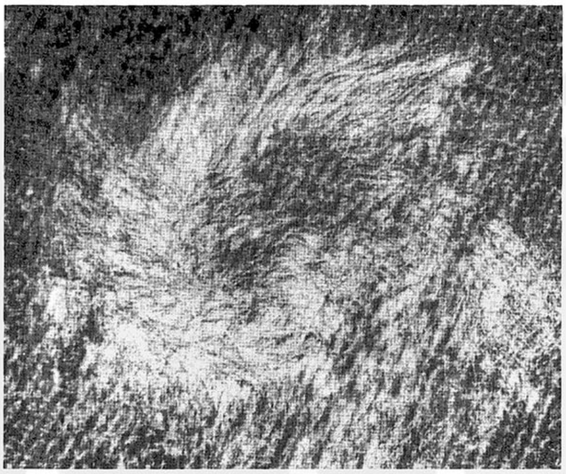

Fig. 14. Large eye of a stationary suction vortex inside the Bloomer, Wisconsin, tornado of July 30, 1977. From *Fujita* [1978].

Fig. 15. A single-loop motion of a suction vortex in the Bloomer, Wisconsin, tornado of July 30, 1977. Photo by Greg Forbes.

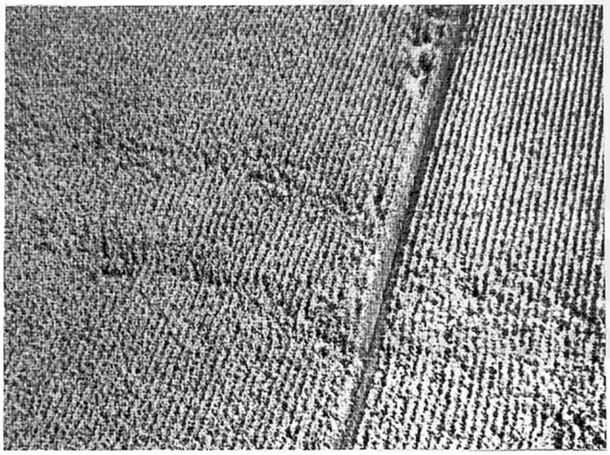

Fig. 16. Two parallel tracks of twin vortices inside the Sandwich, Illinois, tornado of June 30, 1977. Photo by Ted Fujita.

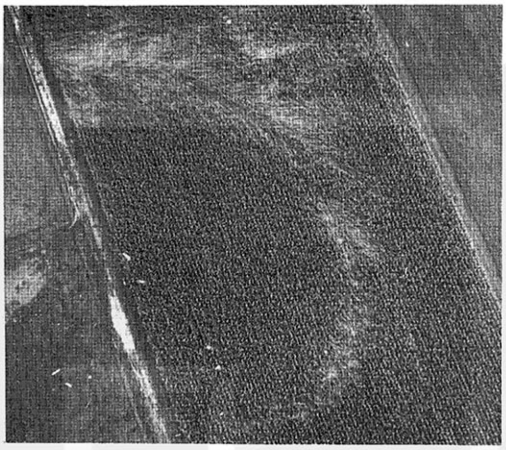

Fig. 17. Paths of two suction vortices which were joined smoothly as the first vortex weakened and was taken over by the second vortex. Bright dots along the centerline of the first vortex denote successive intensifications. Photo by Ted Fujita after the Bloomer, Wisconsin, tornado of July 30, 1977.

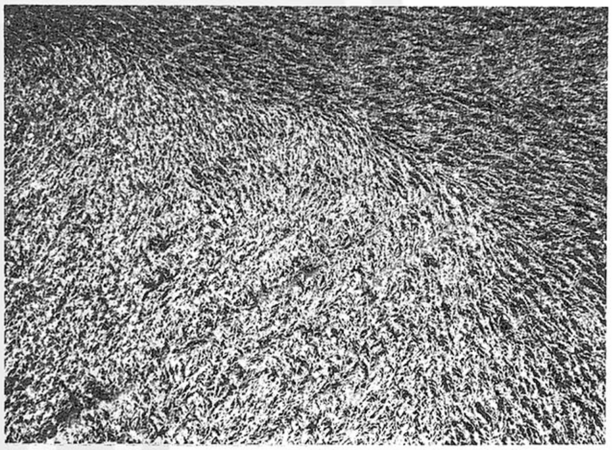

Fig. 18. Corn crops pushed over by the Hobart, Indiana, tornado of June 30, 1977, which moved from right (west) to left (east) across the picture. Photo by Ted Fujita.

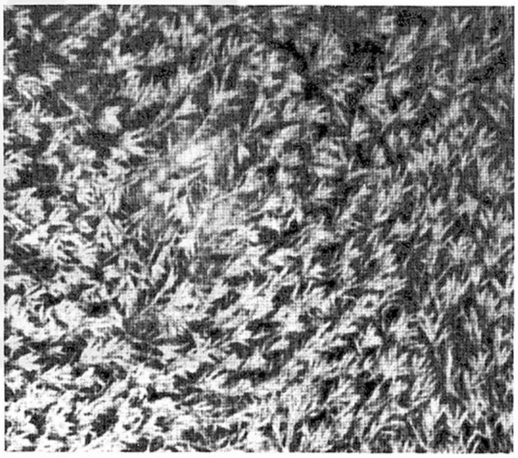

Fig. 19. Telephoto view of the strong shear zone in Figure 18, showing a tiny suction vortex which pulled several corn crops off the ground. Photo by Ted Fujita.

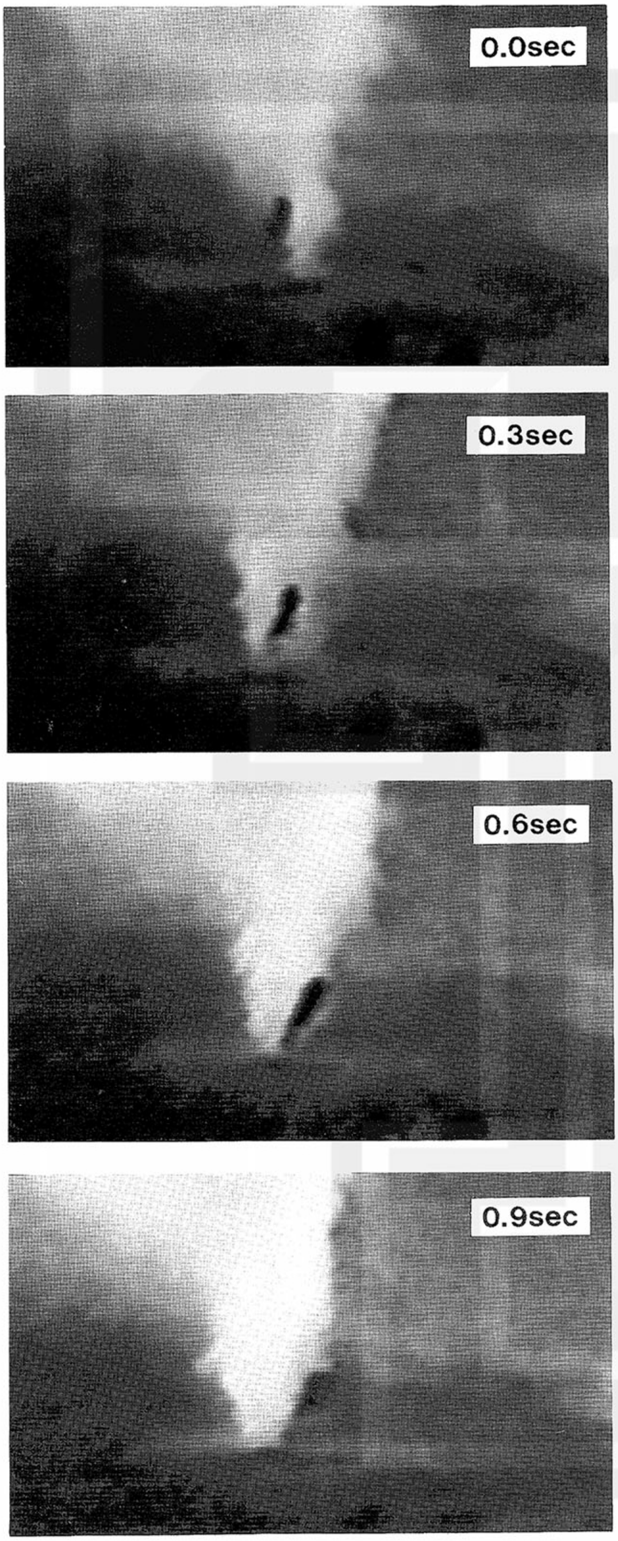

Fig. 20. A tree trying to stand up in the small funnel of the Minneapolis, Minnesota, tornado of July 18, 1986. Four selected frames of the video taken from the helicopter of KARE TV. Courtesy of Paul Douglas, Chief Meteorologist, News 11.

Fig. 21. Suction vortices and their parent tornado amalgamated into a complex system of vortices.

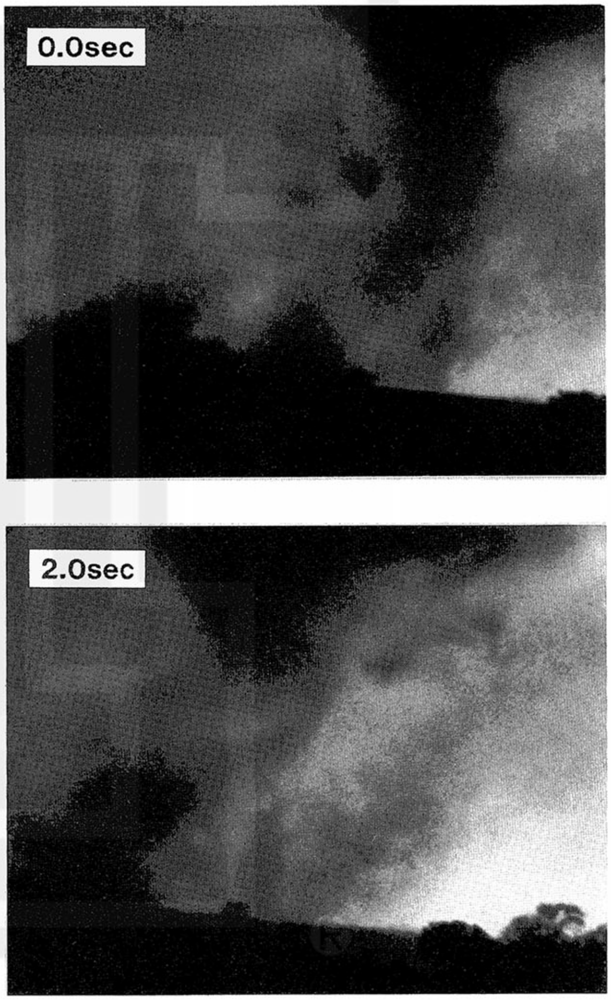

Fig. 22. Two frames of the movie in Figure 21. These frames are 2 s apart, showing the rapid change of the vortex system. Figures 21 and 22 were enlarged from the movie of the first Lomira, Wisconsin, tornado of April 21, 1974. Courtesy of Larry Floeter.

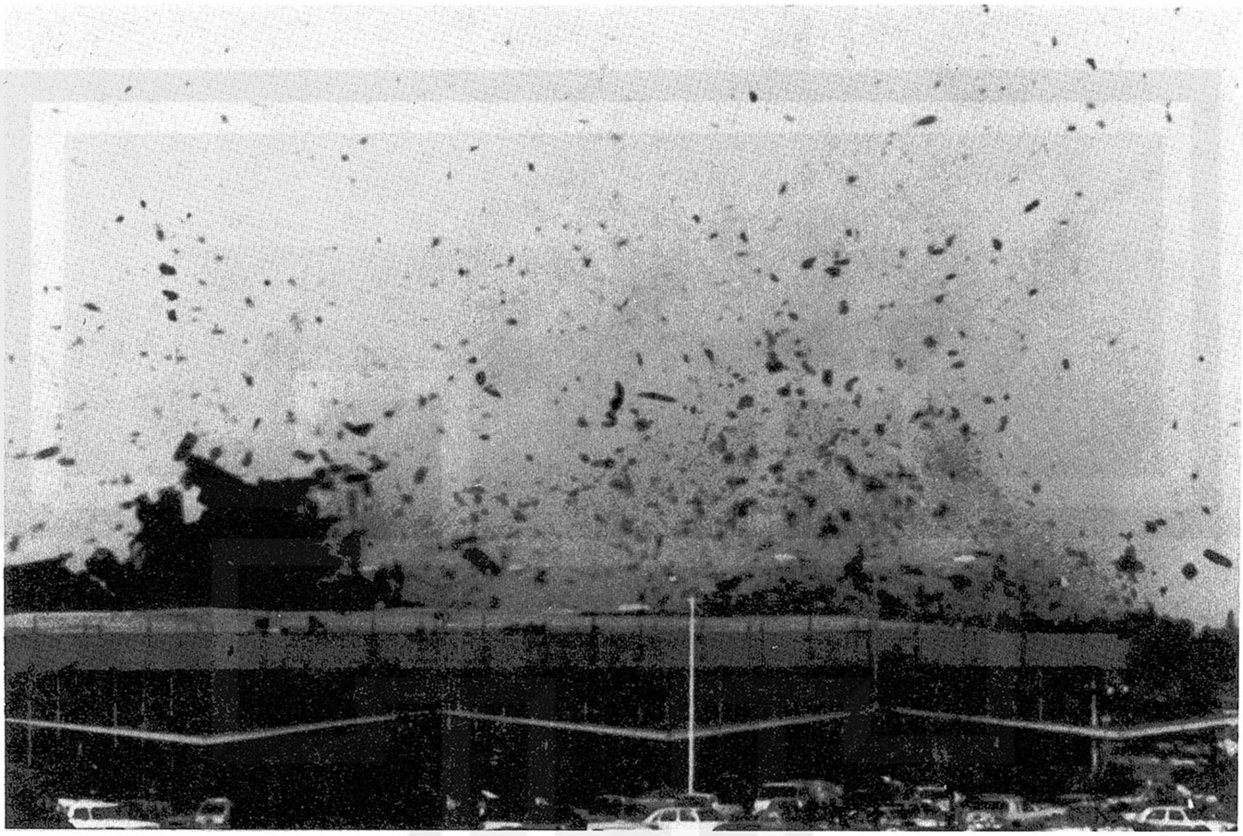

Fig. 23. At 2:05 P.M. PST on February 19, 1980, a small funnel cloud moved over the Fresno, California, Airport. Although the funnel was not on the ground, the roof of an airport building was blown upward and broken into pieces, suggesting the existence of strong vertical winds beneath the funnel cloud. The damage path extended from the airport into the residential areas of Fresno, California. Courtesy of Peter Stommel.

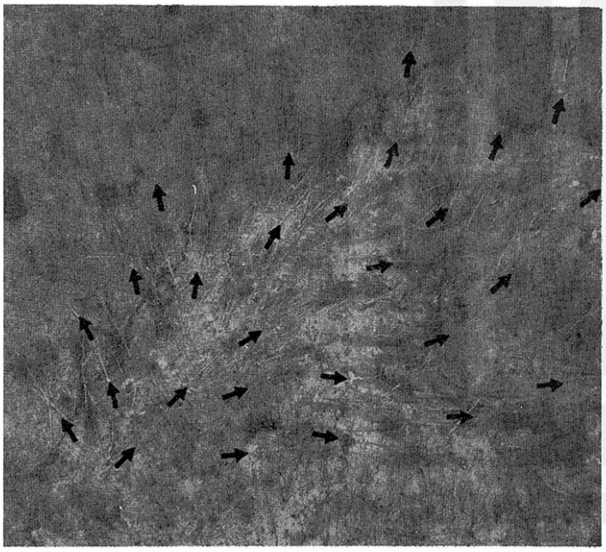

Fig. 24. The diverging pattern of uprooted trees photographed near Beckley, West Virginia, where tornado damage by one of the Jumbo Outbreak Tornadoes of April 3, 1974, had been reported. We believe that this starburst damage was located at the root of the downdraft which induced a microburst. Photo by Ted Fujita.

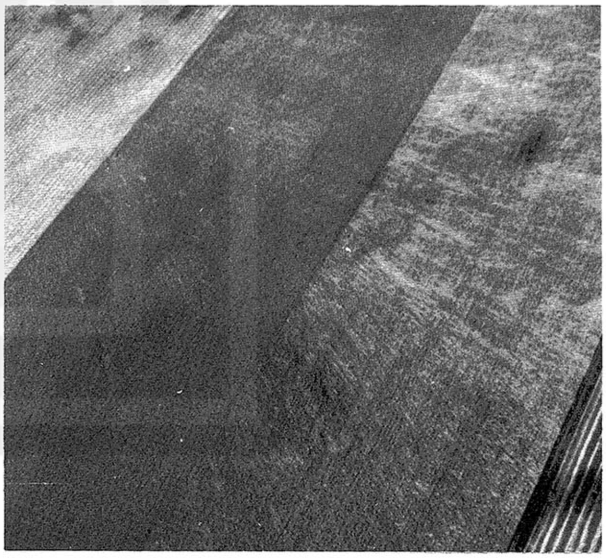

Fig. 25. The Danville, Illinois, microburst of September 30, 1977, which blew down corn plants in a large area. From *Fujita* [1978].

Fig. 26. A small but intense microburst found near the Cornell, Wisconsin, tornado of July 30, 1977. The 100-m-wide and 130-m-long damage area was located on Brunet Island in the Chippewa River. Photo by Ted Fujita.

Fig. 27. A microburst airflow deflected by a tin roof during the downburst storm of September 30, 1977. Photo by Ted Fujita in Kingman, Indiana. From *Fujita* [1978].

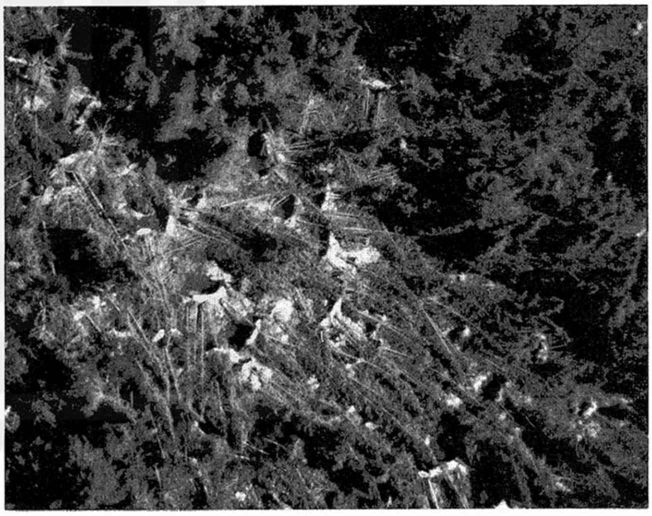

Fig. 28. A forest in northern Wisconsin blown down by a rush of diverging winds embedded inside the large downburst of July 4, 1977. Photo by Ted Fujita.

Fig. 29. A photograph of a microburst outflow with a ring vortex along the spreading edge. Photo taken on July 1, 1978, from near Wichita, Kansas. Courtesy of Mike Smith of Weather Data, Inc.

Fig. 30. A trace of mesocyclone winds with large radii of curvature photographed near the touchdown location of the Sadorus, Illinois, tornado of March 20, 1976, investigated by *Fujita et al.* [1976]. Are such winds the precursor of a tornado touchdown? Photo by Ted Fujita.

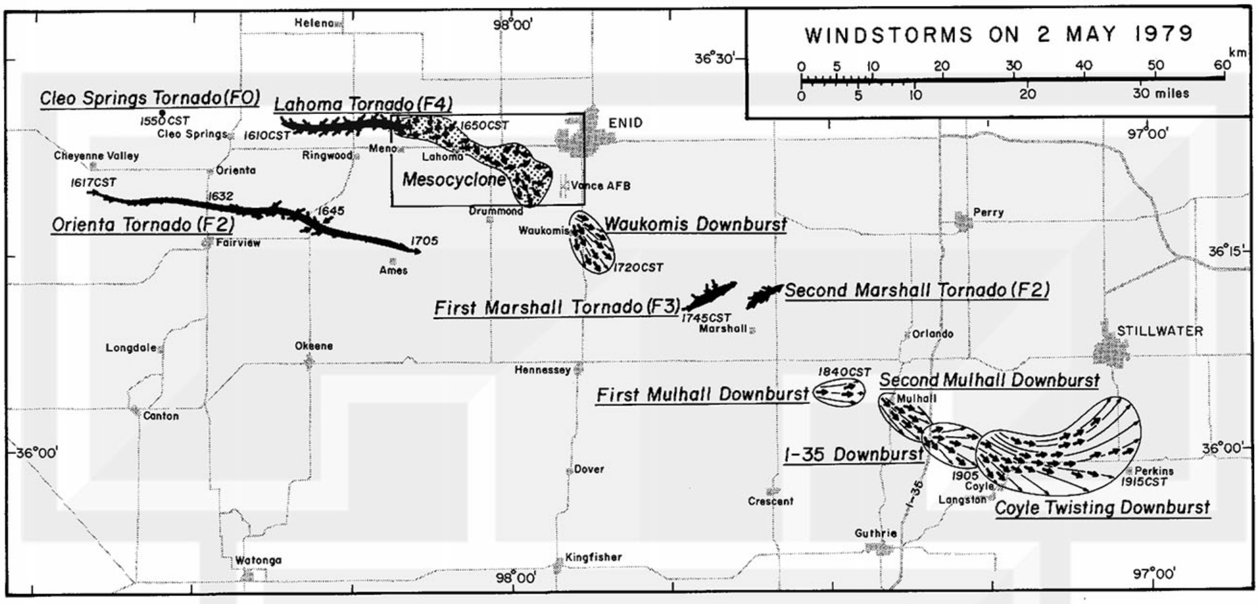

Fig. 31. The Coyle, Oklahoma, twisting downburst of May 2, 1979, extending from Mullhall to Coyle to the south of Stillwater, Oklahoma. The center of the mesocyclone, which did not spawn a tornado, moved along the north edge of the twisting downburst.

should have reached very close to the top of the forest before diverging violently.

Microbursts in progress have been photographed by many, but the most dramatic sequence of photographs was taken by Mike Smith on July 1, 1978 (Figure 29), and reported by *Fujita* [1985].

5. Mesocyclone and Twisting Downburst Winds on the Ground

During the overflights of an area of wind damage, we often found traces of twisting downburst winds with large radii of curvature. These winds are often located in the areas of either pretouchdown or postliftoff of tornadoes, suggesting that they are probably induced by the parent mesocyclones of tornadoes (Figure 30).

One of the most significant twisting downbursts was the Coyle, Oklahoma, twisting downburst of May 2, 1979. Its area was approximately 10 km wide and 30 km long (Figure 31), indicating that the surface winds were induced by a traveling mesocyclone which did not spawn a tornado. So far, we have not researched the mesocyclone winds on the ground. However, an intensive effort in search of large radius of curvature winds on the ground will be important for a better understanding of the velocity data from the future NEXRAD covering the United States.

6. Tornado-Microburst Interaction

Prior to the NIMROD experiment in 1978, *Fujita* [1978] documented a number of microbursts in the proximity of tornado tracks flown over for the purpose of aerial survey, photography, and mapping. Documented tornadoes with nearby microbursts were the Canton, Illinois, tornadoes of July 23, 1975; the Earlville, Illinois, tornadoes of June 30, 1977; and the Mattoon Lake, Illinois, tornado of August 21, 1977. Thereafter, *Forbes and Wakimoto* [1983] investigated the Springfield, Illinois, area tornadoes of August 6, 1977, revealing that 7 out of 18 tornadoes mapped from the air were located on the left (cyclonic shear) side of microbursts.

The Windsor Locks tornado of October 3, 1979, surveyed by Roger Wakimoto, Duane Stiegler, and Pete McGurk of the Fujita group was associated with eight microbursts, all located on the right-hand side of the 30-km-long, F4 tornado which moved from south to north across the Massachusetts-Connecticut state line (Figure 32). The Teton-Yellowstone tornado of July 21, 1987, surveyed by Brian Smith, Jim Partacz, and Bradley Churchill was analyzed in detail by *Fujita* [1989], revealing that there were 72 microbursts located mostly on the right-hand side of the 40-km-long path of the F4 tornado.

The interaction between a tornado and a nearby microburst was first evidenced while taking aerial photos of the path of the Rainsville, Indiana, tornado of April 3, 1974. Figure 33 shows that the course of the tornado deviated by 30° toward the east as microburst winds from the northwest blew toward the tornado (Figure 33). Since then, no action pictures of a tornado interacting with a microburst were obtained until April 12, 1991, when KAKE TV obtained video scenes from Lincoln, Kansas (Figure 34). Another interaction was confirmed by the aerial photos by Duane Stiegler. In this case, the Hesston, Kansas, tornado of March 13, 1990, deviated its track, being pushed by a

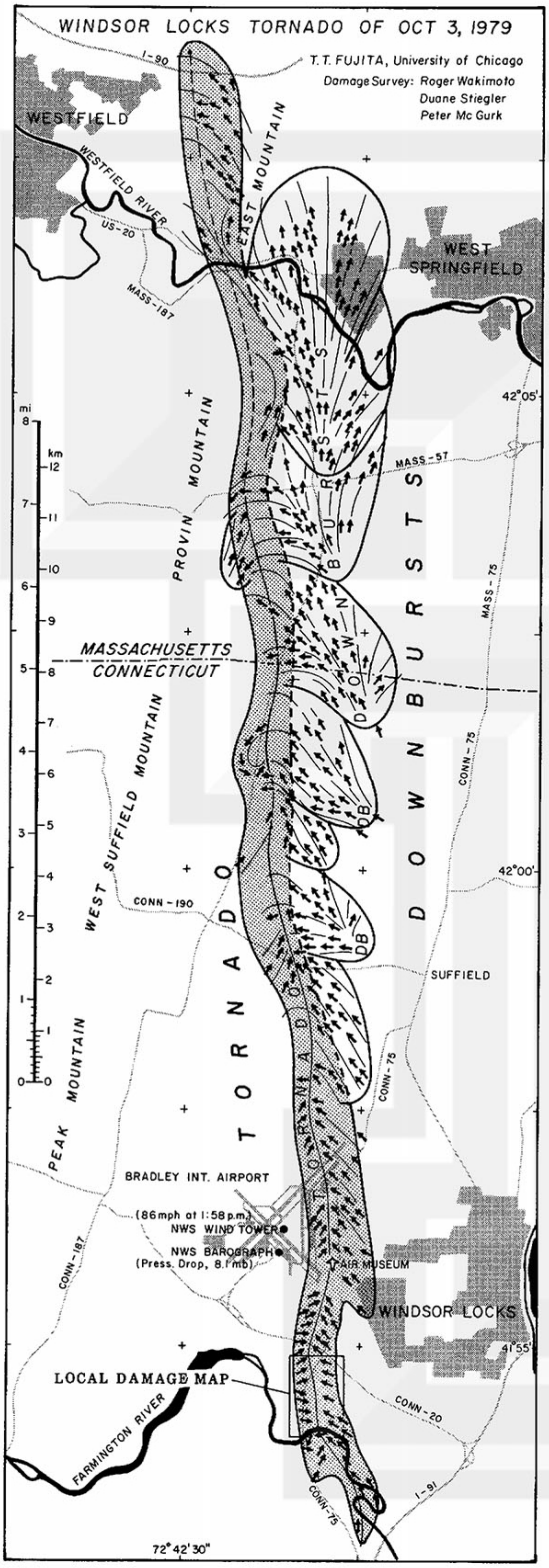

Fig. 32. The Windsor Locks tornado of October 3, 1979, which traveled from south to north. Seven microbursts were mapped on the right-hand side of the tornado track.

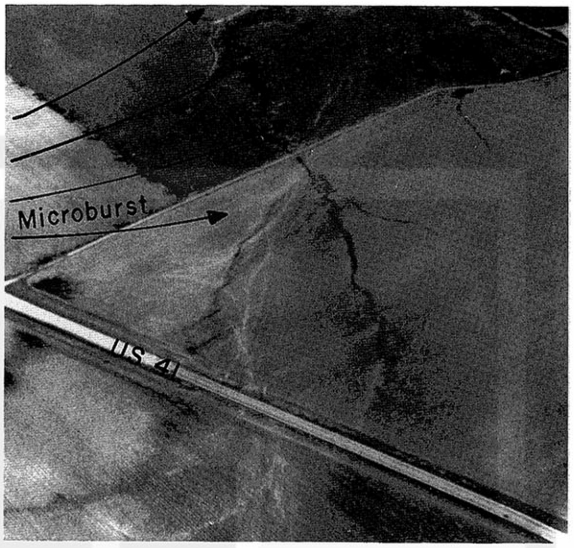

Fig. 33. Swirl marks of the Rainsville, Indiana, tornado of April 3, 1974. Undisturbed ground marks extend until crossing U.S. Highway 41. Thereafter, a microburst airflow from the left (northwest) of the picture pushed the track toward the right. From *Fujita* [1978].

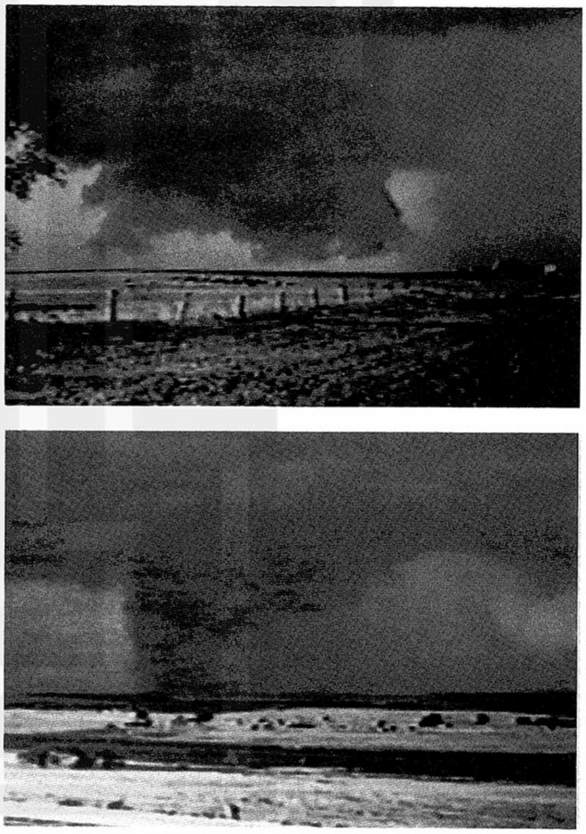

Fig. 34. Two video scenes of the April 12, 1991, tornado and a nearby microburst near Lincoln, Nebraska. Courtesy of Mike Phelps. (Top) Formative stage of a tornado and a microburst on the right side. (Bottom) The tornado after touchdown was pushed toward the left by microburst winds.

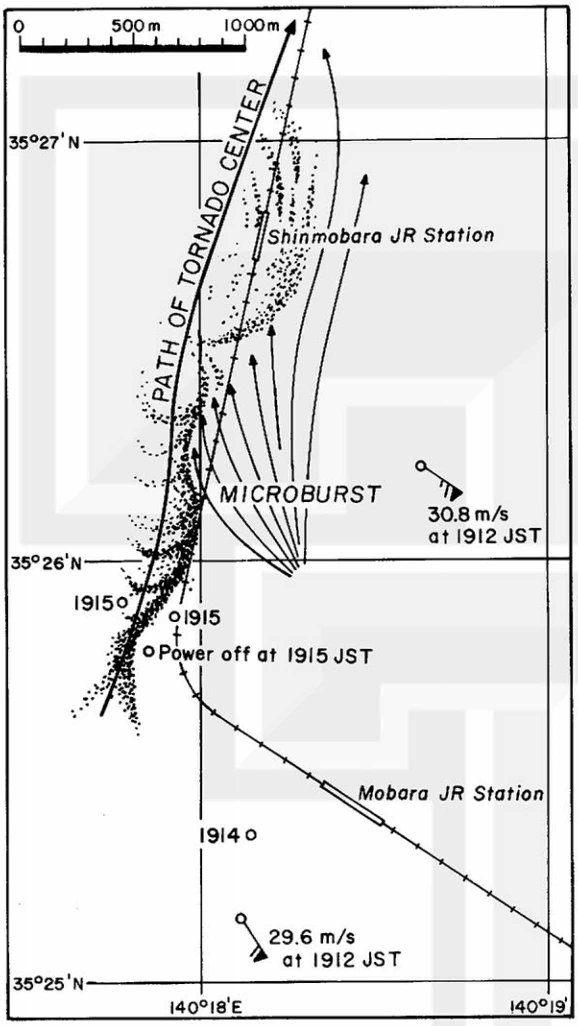

Fig. 35. The Mobara, Japan, tornado of December 11, 1990. The tornado was pushed toward the left by a microburst which touched down on the right-hand side of the tornado track. The interactive process is similar to that shown in Figure 34.

microburst located on the right side of the tornado track. Such interactions will alter or contaminate the velocity pattern of tornadoes.

In analyzing the Mobara, Japan, tornado of December 11, 1990, it was found that the tornado was pushed off the straight-line track by an F1 microburst on the right-hand side of the tornado (Figure 35). This tornado was rated by the Japan Meteorological Agency as the worst tornado in 50 years. A research Doppler radar of the Meteorological Research Institute of Japan indicated that the direction of the positive-negative velocity couplet rotated 45° while the large tornado was being pushed off the track by a microburst. It is obvious that the existence of a nearby microburst does alter the Doppler-velocity field, making the NEXRAD data interpretation difficult for tornado warnings.

7. Conclusions

An organized effort of fact-finding aerial survey, photography, and mapping of selected U.S. tornadoes by the Fujita group gave rise to the identification of the multiscale surface winds associated with tornadoes. These wind systems are the mesocyclone, tornado, and suction vortex which are blended into a complicated system of vortices.

Also identified and clarified were downbursts which are subclassified into microbursts and macrobursts based on their horizontal dimensions. It has been recognized that the microburst is the inducer of the intense wind shear which endangers aircraft during takeoff and landing operations. It is likely that the microburst would not have been identified and confirmed in the 1970s had there been no aerial photos of strange starburst damage found in the vicinity of tornado tracks.

The renewed aerial survey and photography of the damage in storm-affected areas in future years will be important in evaluating the NEXRAD data, velocity in particular, in relation to the estimated surface winds in different scales.

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