Aerial Survey and Photography
of
Tornado and Microburst Damage

Tornado Symposium III

presented at

April 2-5, 1991, Norman, Oklahoma

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WRL (formerly SMRP) Research Paper 235

October 1991

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ABSTRACT

After studying the Yanagawa, Japan tornado of 26 September 1948 on foot and the Fargo, North Dakota tornado of 10 June 1957 by car, Fujita was convinced that the use of low-flying aircraft is the only way to conduct quick-response surveys of extensive damage areas which are often inaccessible on the ground. Immediately after the Palm Sunday Tornadoes of 1965, Fujita organized a survey group to fly over the tornado tracks in five states. Since then, over 300 tornado tracks were flown over, obtaining ground-truth aerial photographs of both tornadic and non-tornadic wind patterns which have never been witnessed by ground-based investigators. Damage patterns of two wind systems, called the suction vortex and downburst (microburst and macroburst), were photographed and confirmed beyond doubt. Along with the improvements of the technique of low-altitude flight and photography, we began identifying interactive winds of tornadoes and nearby microbursts which are often amalgamated into a system of surface-wind complex. Since Doppler-velocity couplets of rotational (tornado) and divergent (microburst) winds are 90-degree off phase, it is likely that the NEXRAD velocity fields of such an interactive storm are complicated and often confusing. Presented in this paper are the overview of the results of the aerial photogrammetric interpretation of tornadic and non-tornadic high winds documented from 1965 to the present.

Introduction

Tornado as defined in the Glossary of Meteorology (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 in 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 term skipping and lifting were used frequently, implying that a tornado funnel intensifies or weakens within a very short distance. During post-tornado interviews we often hear "tornado leveled my neighbor's house but it skipped over my house." In the wake of the Palm Sunday Tornadoes of 11 April 1965, Fujita and his associates conducted their coordinated aerial photography over the vast areas of the northern Midwest, becoming suspicious that a tornado does not skip or lift within short distances, but 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 multi-scale airflows in and around tornado funnels and to identify non-tornadic damaging winds induced by severe thunderstorms. During the 27 years since then, over 300 damage swaths had been flown and mapped photogrammetrically (Fig. 1). A total number of 30,000 aerial photographs were taken from low-flying aircraft, mostly Cessna.

2. Determination of Multi-scale Airflows of Tornadoes

Although the news media took numerous aerial photos of structures, first aerial photos of well-defined circular marks left behind by the North Platte Valley tornado of 27 June 1955 were reported by Van Tassel (1955). He assumed that the grey circles on plowed field (Fig. 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, IA tornado of 5 May 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 AGL and visiting the sites on the paths of the Palm Sunday Tornadoes of 11 April 1965 and the Barrington, IL tornado of 21 April 1967. As evidenced in Fig. 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 tornado (Fig. 4).

The diameter of a suction vortex is at least one 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 cyloidal 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 (Fig. 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 (Fig. 6). As the velocity ratio increases, the size of the loop increases (Fig. 7), reaching a near-circle loop when the ratio approaches 10 (Fig. 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 out of foundations (Fig. 9). On the contrary, several "lucky" houses located between intersecting paths of multiple suctions vortices could be left untouched (Fig. 10). These damage patterns cannot be explained by the so-called skipping phenomenon of a tornado. During 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 survey did alter one of the tornado safety rules.

A large number of aerial photos showed the existence of cycloidal marks in the swaths of many large-core tornadoes. 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 3-4 April 1974. Since then, a large number of multiple (suction) vortex pictures (Fig. 11) became available from various parts of the United States. These pictures, along with cycloidal marks were analyzed by Fujita et al. (1974), Agee et al. (1975), Fujita et al. (1976), Agee et al. (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, turning into darker or lighter colors as an aircraft circles around the target. As has been well-known, tracks of orbiting suction vortices appear as a group of cycloidal curves (Fig. 12). Whereas, a stationary suction vortex leaves behind a pattern of high winds indicating the existence of either a small (Fig. 13) or a large eye (Fig. 14) at the location where the vortex center had existed momentarily.

We also witness the path of an isolated vortex mark suggesting a single-loop motion of the suction vortex (Fig. 15). An interesting vortex signature is the path of twin vortices which traveled side-by-side while rotating slowly around their common center (Fig. 16). Another unbelievable aerial photo shows a curved path with five intensification spots along the centerline (Fig. 17). The picture also shows that the initial vortex disappeared, being taken over by the new vortex which flattened the corn crops 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 crops pushed over by the Hobart, Indiana tornado of 30 June 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 (Fig. 19) in which several corn crops were pulled off the ground. Convergence inside the core of an axisymmetric vortex is approximated by

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

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

One of the best evidence of a small tornado with dominant vertical winds just above the ground is seen in a video sequence of the Minneapolis tornado of 18 July 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, 3 m in diameter on the ground, leaned near the vertical position for about one second before it was blown down when the funnel moved away from the tree (Fig. 20).

A small core tornado less than 10 m in diameter, east of Denver, CO on 30 June 1987 was investigated by Wakimoto and Wilson (1989) based on both aerial and ground photographs combined. In spite of the herringbone-pattern of damage due to the storm motion, their photos evidence the existence of an appreciable inflow into the small core, suggesting a strong rising motion inside the small core.

A library of the tornado data collected by the Fujita group during the past 30 years indicated that tornadoes in general are more complicated than what had been thought to be. It is often very difficult to distinguish a suction vortex from its parent tornado (Fig. 21). Furthermore, their appearance and structure keep changing very rapidly within a matter of seconds (Fig. 22).

There has been a basic disagreement between meteorologists and structural engineers on the mechanism of structural damage of tornado winds. Most engineers, so far, approximate tornado winds as 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 explode vertically under high-speed vertical winds just above the ground (Fig. 23).

4. Microburst, Inducer of Non-tornadic Damaging Winds

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

In investigating the Eastern 66 accident (landing) on 24 June 1975 at John F. Kennedy, New York airport, 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 by Fujita and Byers (1977). Shortly thereafter, Fernando Caracena applied my downburst concept to the probable cause of the Continental 426 accident (takeoff) on 7 August 1975 at the Stapleton, Denver airport. Our joint research on three aircraft accidents resulted in a Fujita and Caracena (1977) paper.

In spite of his confidence in the downburst concept backed by numerous aerial photos of the starburst damage, a large number of non-believers expressed their controversial views which were summarized by West (1979) in Science News, 17 March 1979. Most meteorologists who expressed strong oppositions never had chances to fly over the area of tornado damage. Since then, Fujita trained his group and initiated extensive downburst-hunting flights.

The training was very successful, establishing the multi-scale airflows by Fujita and Wakimoto (1981). By the end of the 1970s, solid evidence of downburst winds and their horizontal scales were established, based on aerial photos and NCAR's Doppler radars operated during the Northern Illinois Meteorological Research on Downburst (NIMROD), a landmark experiment which terminated most controversies that prevailed at that time. At the termination of the experiment, the downburst was subdivided into microburst and macroburst using the 4-km horizontal size as being its dividing dimension.

An aerial photo of a large microburst (Fig. 25) shows an extensive area of diverging winds which blew down numerous corn crops. Frequently, a small microburst touches down with a sharp boundary of the windspeed increase from less than 25 m/s to 40 m/s within a 5- to 10-m distance (Fig. 26). Estimated divergence at the boundary should reach 1.5 to 3.0 $\sec^{-1}$, suggesting that the parent downdraft descended to the tree-top height without weakening significantly. A swath of high winds which slid down on the slope of a farm building in Indiana (Fig. 27) also suggests that a downdraft descended to the roof-top height. An extremely small microburst is only 30 to 50 m wide and 100 to 300 m long, with an appearance of a rush of diverging jet (Fig.28). The parent downward current should have reached very close to the top of the forest before diverging violently.

Microbursts in progress were photographed by many, but the most dramatic sequence of photos were taken by Mike Smith on 1 July 1978 (Fig. 29) and reported by Fujita (1985).

5. Mesocyclone and Twisting Downburst Winds on the Ground

During the overflights of the 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 pre-touchdown or post-liftoff of tornadoes, suggesting that they are probably induced by the parent mesocyclones of tornadoes (Fig. 30).

One of the most significant twisting downbursts was the Coyle, OK twisting downburst of 2 May 1979. Its area was approximately 10 km wide and 30 km long (Fig.31), indicating that the surface winds were induced by a traveling mesocyclone which did not spawn tornado. So far, we have not searched 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 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, IL tornadoes of 23 July 1975, Earlville, IL tornadoes of 30 June 1977, and the Mattoon Lake, IL tornado of 21 August 1977. Thereafter, Forbes and Wakimoto (1983) investigated the Springfield, IL area tornadoes of 6 August 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 3 October 1979 surveyed by Roger Wakimoto, Duane Stiegler, and Pete McGurk of the Fujita group was associated with 8 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 (Fig. 32). The Teton-Yellowstone tornado of 21 July 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, IN tornado of 3 April 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 (Fig. 33). Since then, no action picture of interacting tornado and microburst was obtained until 12 April 1991 when KAKE TV obtained video scenes from Lincoln, KS (Fig. 34). Another interaction was confirmed by the aerial photos by Duane Stiegler. In this case, the Hesston, KS tornado of 13 March 1990 deviated its track, being pushed by a 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 11 December 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 (Fig. 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° when 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.

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 multi-scale surface winds associated with tornadoes. These wind systems are mesocyclone, tornado, and suction vortex which are blended into a complicated system of vortices.

Identified and clarified also are 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 was not 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.

Acknowledgements:

A long-term, continuous support of a specific subject is very difficult to obtain. Fortunately, the aerial survey of tornadoes and microbursts with Fujita as principal investigator, has been supported for 27 years since 1965 without interruption by five agencies as their partial objectives of their grants/contracts to Fujita at the University of Chicago. These objectives are "interpretation of meteorological satellite data," "design of satellite sensors for severe-storms detection," "understanding of tornado winds for nuclear safety," and "ground-truth and detection of microburst for air safety." The principal investigator wishes to express his sincere appreciation to those agencies which rendered their long-term supports in achieving the research presented in this paper.

Specific agencies which contributed in part to the ground-truth aerial surveys are:

- National Science Foundation under grants ATM 78-01074, 79-21260, 81-09828, and 85-16705 (1978-90)
- Nuclear Regulatory Commision under contracts NRC-04-74-239, and 04-82-004 (1974-87)
- Office of Naval Research under Storm Data contract N00014-86-K-0374 (1986-89)
- NOAA/NESDIS under grants 04-4-158-1, NA80-AAD0001, NA85-AADRA064, and NA90-AADRA511 (1973-91)
- National Aeronautics and Space Administration under grant NGR 14-001-008 (1962-90)

Acknowledgement

This paper is funded by Grant No. NA90AADRA511 from the National Oceanic and Atmospheric Administration. The views expressed herein are those of the author and do not necessarily reflect the views of NOAA or any of its sub-agencies.

References:

Agee, E.M., C.R. Church, C.M. Morris, and J.T. Snow, 1975: Some synoptic aspects and dynamic features of vortices associated with the tornado outbreak of 3 April 1974. Mon. Wea. Rev., 103, 318-333.

______, J.T. Snow, F.S. Nickerson, P.R. Clare, C.R. Church, and L.A. Schaal, 1977: An observational study of the West Lafayette, Indiana, tornado of 20 March 1976. Mon. Wea. Rev., 105, 893-907.

Forbes, G.S., and R.M. Wakimoto, 1983: A concentrated outbreak of tornadoes, downbursts, and implications regarding vortex classification. Mon. Wea. Rev., 111, 220-235.

Fujita, T.T., 1970: The Lubbock tornadoes: A study of suction spots. Weatherwise, 23, 160-173.

______, 1971: Proposed mechanism of suction spots accompanied by tornadoes. Preprints. Seventh Conference on Severe Local Storms, Kansas City. Amer. Meteor. Soc., 208-213.

______, 1974: Jumbo tornado outbreak of 3 April 1974. Weatherwise, 27, 116-126.

______, 1976: Spearhead echo and downburst near the approach end of a John F. Kennedy airport runway, New York City. SMRP Res. Paper 137, University of Chicago, Chicago, IL., 51 pp.

______, 1978: Manual of downburst identification for Project NIMROD. SMRP Res. Paper 156, University of Chicago, Chicago, IL., 104 pp. [NTIS PB 286048].

______, 1981: Tornadoes and downbursts in the context of generalized planetary scales. J. Atmos. Sci., 38, 1511-1534.

______, 1985: The downburst-Microburst and macroburst. SMRP Res. Paper 210, University of Chicago, Chicago, IL., 122 pp. [NTIS PB 148880]. Library of Congress Catalog Card 85-50115.

______, 1989: The Teton-Yellowstone tornado of 21 July 1987. Mon. Wea. Rev., 117, 1913-1940.

______, D.L. Bradbury, and C.F. Van Thullenar, 1970: Palm Sunday tornadoes of April 11, 1965. Mon. Wea. Rev., 98, 29-69.

______, and H. R. Byers, 1977: Spearhead echo and downburst in the crash of an airliner. Mon. Wea. Rev., 105, 129-146.

______, and F. Caracena, 1977: An analysis of three weather-related aircraft accidents. Bull. Amer. Meteor. Soc., 58, 1164-1181.

______, G.S. Forbes, and T.A. Umenhofer, 1976: Close-up view of 20 March 1976 tornadoes: Sinking cloud tops to suction vortices. Weatherwise, 29, 116-131.

______, and D.J. Stiegler, 1986: Tornado of Minneapolis, Minnesota on July 18, 1986. NOAA Storm Data, 28, 10-13.

______, and R.M. Wakimoto, 1981: Five scales of airflow associated with a series of downbursts on 16 July 1980. Mon. Wea. Rev., 109, 1438-1456.

Glossary of Meteorology, 1959: Tornado. Amer. Meteor. Soc., 638 pp.

Prosser, N.E., 1964: Aerial photographs of a tornado path in Nebraska, May 5, 1964. Mon Wea. Rev., 92, 593-598.

Van Tassel, E.L., 1955: The North Platte Valley tornado outbreak of June 27, 1955. Mon. Wea. Rev., 83, 255-264.

Wakimoto, R.M., and J.W. Wilson, 1989: Non-supercell tornadoes. Mon. Wea. Rev., 117, 1113-1140.

West, S., 1979: Are downbursts just a lot of hot air? Science News, 115, 170-171.

Figures 1 - 35

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 11 April 1965.

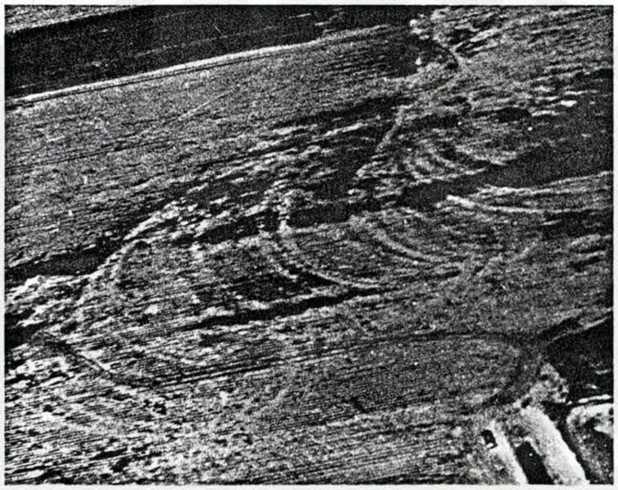

Fig. 2 An aerial photo of the circular ground mark assumed to be the scratch mark by a single object caught in the tornado funnel. From Van Tassel (1955).

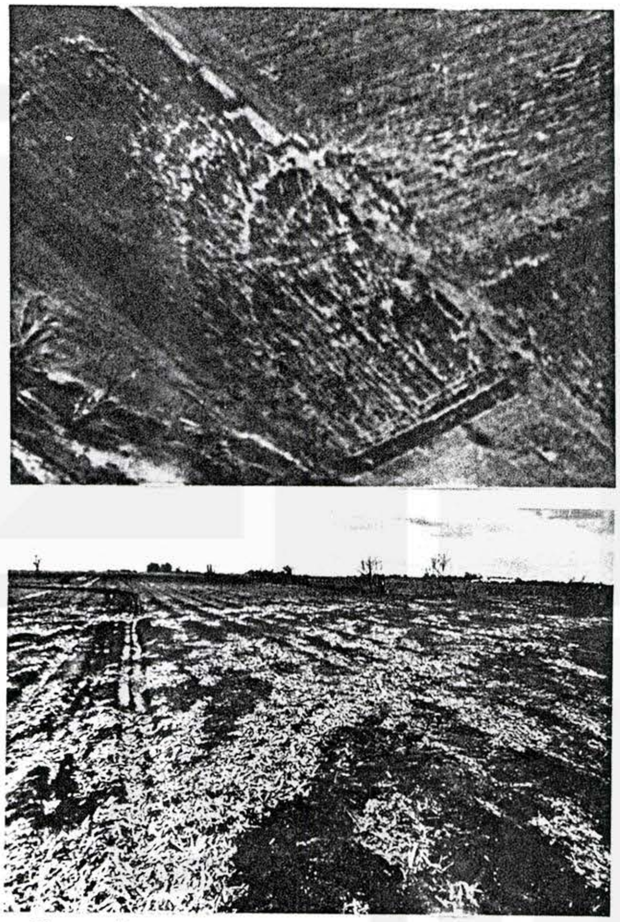

Fig. 3 Upper: Aerial photo of the cycloidal mark of the Barrington, IL tornado of 21 April 1967. Lower: The cycloidal mark photographed on the ground. Both photos by Ted Fujita.

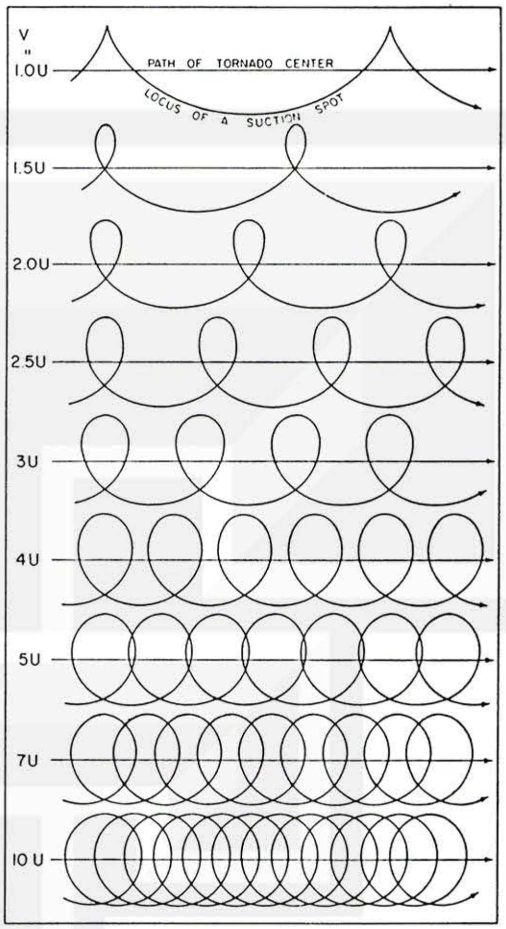

Fig. 5 Geometric path of the center of a suction vortex computed by changing the velocity ratio from 1 to 10. From Fujita, Bradbury, and Van Thullener (1970).

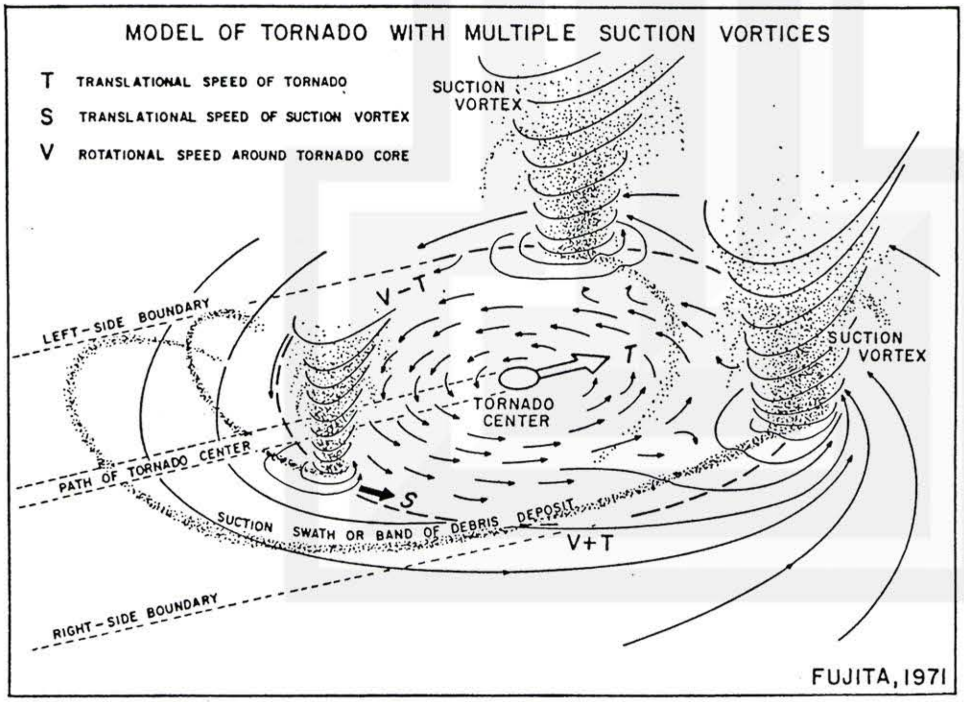

Fig. 4 A model of tornado with three suction vortices orbiting around the core of the parent tornado. From Fujita (1971).

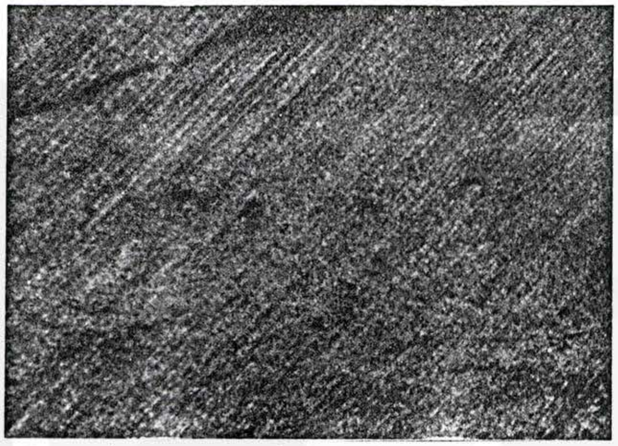

Fig. 6 Stepping spots (West Lafayette, IN tornado of 20 March 1976) where orbiting suction vortices pause momentarily when the velocity ratio is 1.0. Refer to Fig. 5. Photo by Ted Fujita.

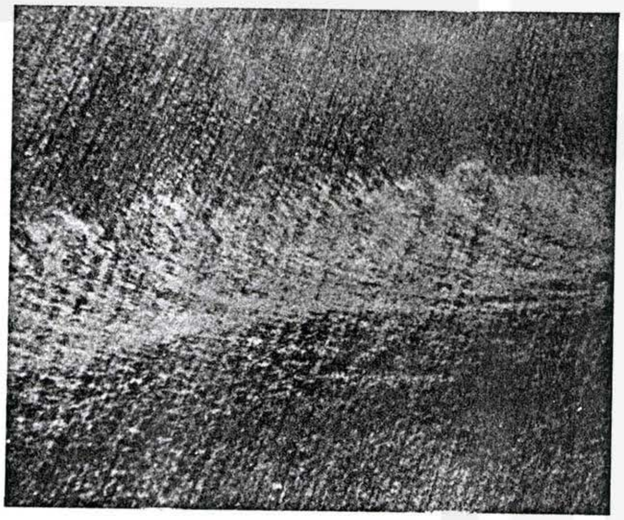

Fig. 7 Cycloidal ground marks left behind by suction vortices with velocity ratio between 2 and 3. Photo by Ted Fujita after the West Lafayette, IN tornado of 20 March 1976.

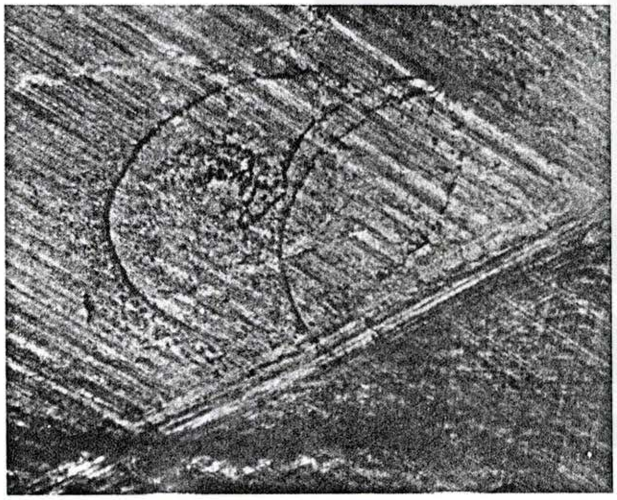

Fig. 8 Near circular cycloidal marks of the Goessel, KS tornado (F5) of 13 March 1960 as the tornado was traveling at 20 m/s. Aerial photo by Duane Stiegler.

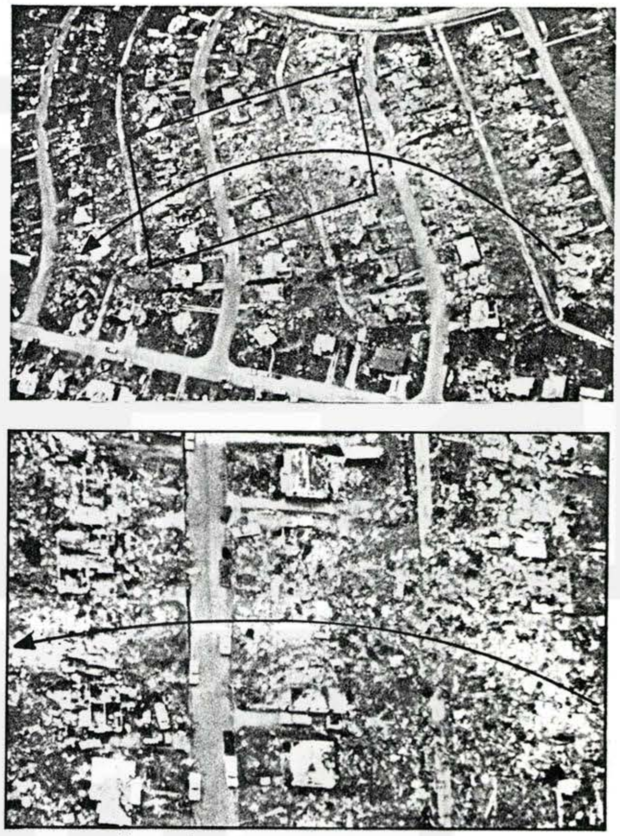

Fig. 9 Upper: An arc of a suction-vortex track left in the residential section by the Wichita Falls, TX tornado of 10 April 1979. Lower: An enlargement of the boxed area. Photo by Ted Fujita. This damage is similar to the Lubbock, TX tornado case reported by Fujita (1970).

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

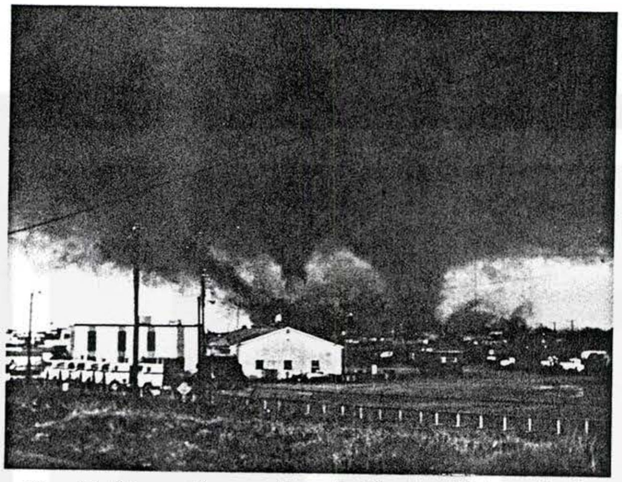

Fig. 11 Six suction vortices inside the Wichita Falls, TX tornado of 10 April 1979. Three vortices at the far side are those forming in the inflow region of the tornado airflow. Copyrighted photo by Mr. Floyd Styles.

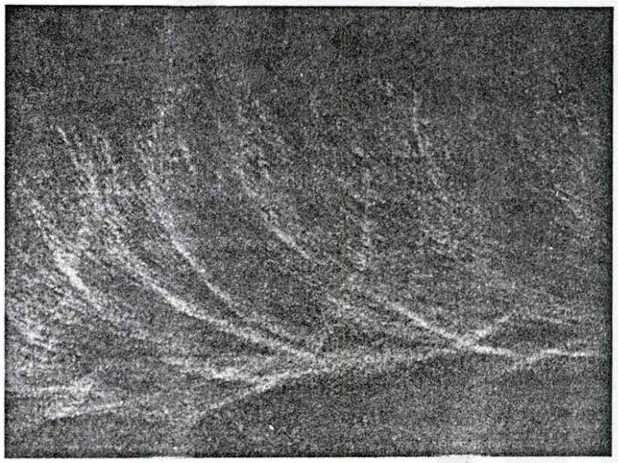

Fig. 12 Typical cycloidal ground marks of the suction vortices orbiting around the core of traveling tornado. Magnet, NE tornado of 6 May 1975. From Fujita (1981).

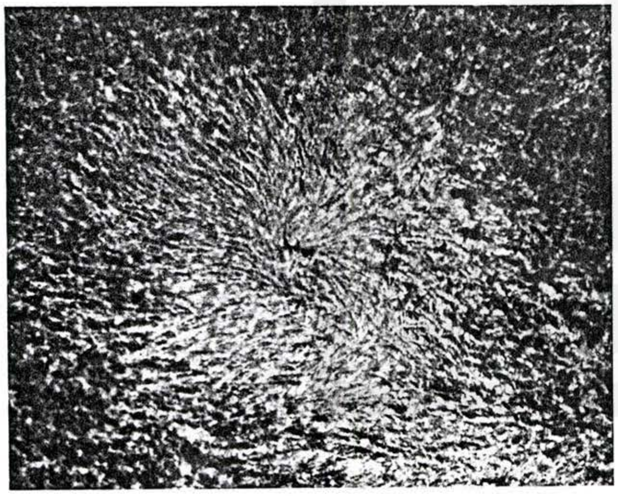

Fig. 13 Small eye of a stationary suction vortex inside the Mattoon Lake, IL tornado of 21 August 1977 made visible by the pattern of blown down corn crops. From Fujita (1981).

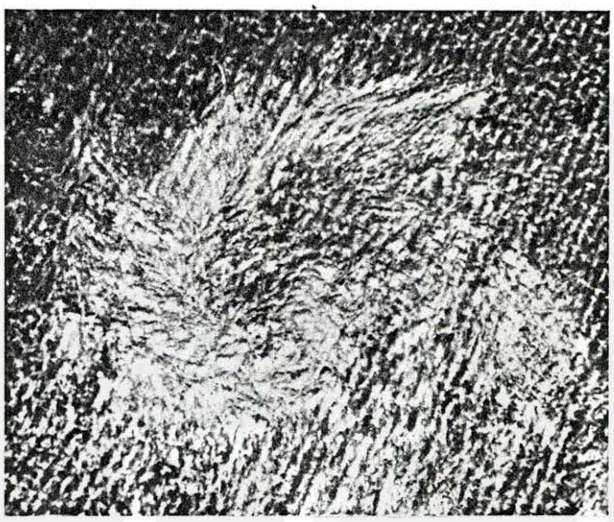

Fig. 14 Large eye of a stationary suction vortex inside the Bloomer, WI tornado of 30 July 1977. From Fujita (1978).

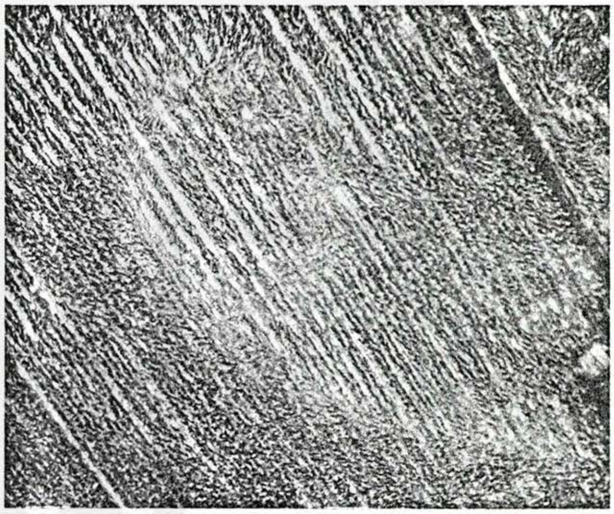

Fig. 15 A single-loop motion of a suction vortex in the Bloomer, WI tornado of 30 July 1977. Photo by Greg Forbes.

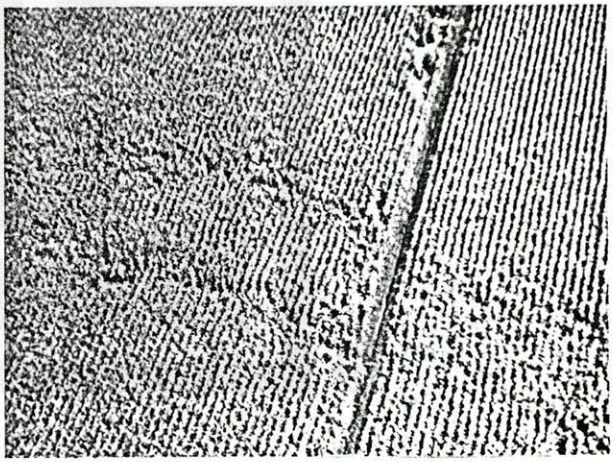

Fig. 16 Two parallel tracks of twin vortices inside the Sandwich, IL tornado of 30 June 1977. Photo by Ted Fujita.

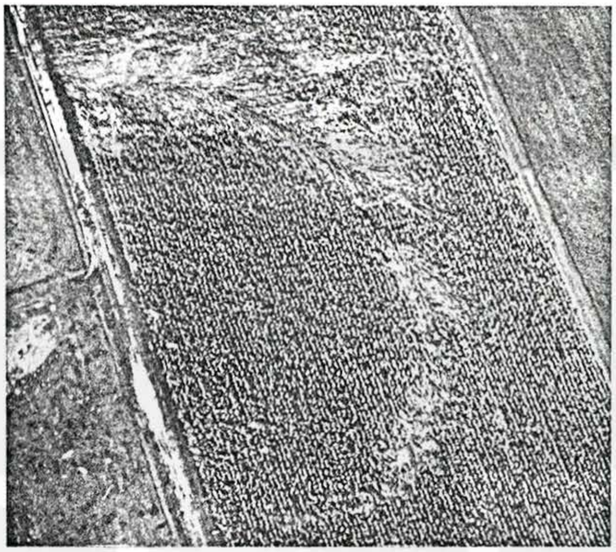

Fig. 17 Paths of two suction vortices which were joined smoothly as the first vortex weakened and was taken over by the second vortex. Bright dots along the centerline of the first vortex denote successive intensifications. Photo by Ted Fujita after the Bloomer, WI tornado of 30 July 1977.

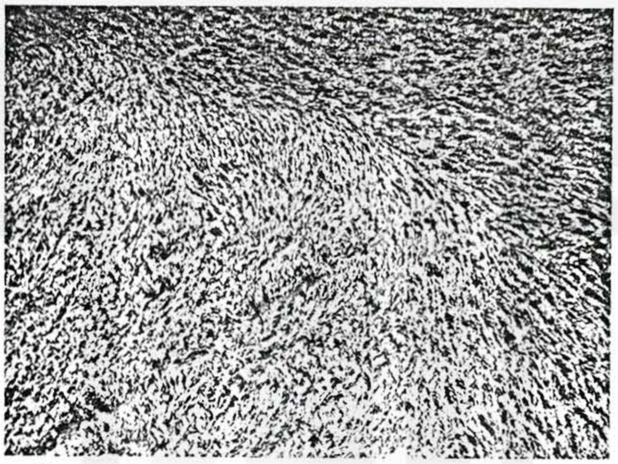

Fig. 18 Corn crops pushed over by the Hobart, IN tornado of 30 June 1977 which moved from right (west) to left (east) across the picture. Photo by Ted Fujita.

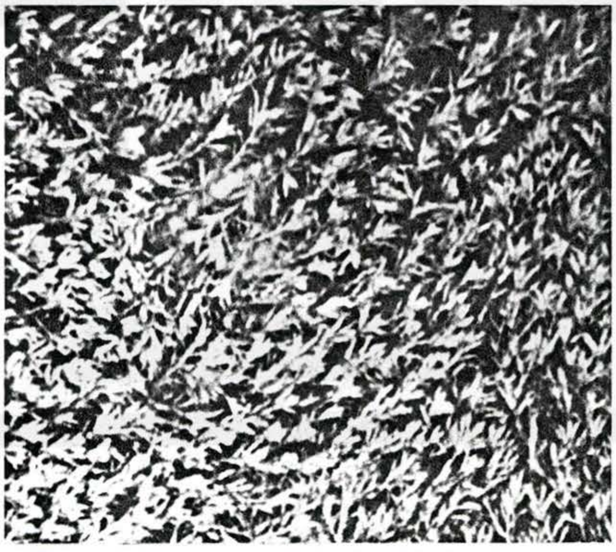

Fig. 19 Telephoto view of the strong shear zone in Fig. 18, showing a tiny suction vortex which pulled several corn crops off the ground. Photo by Ted Fujita.

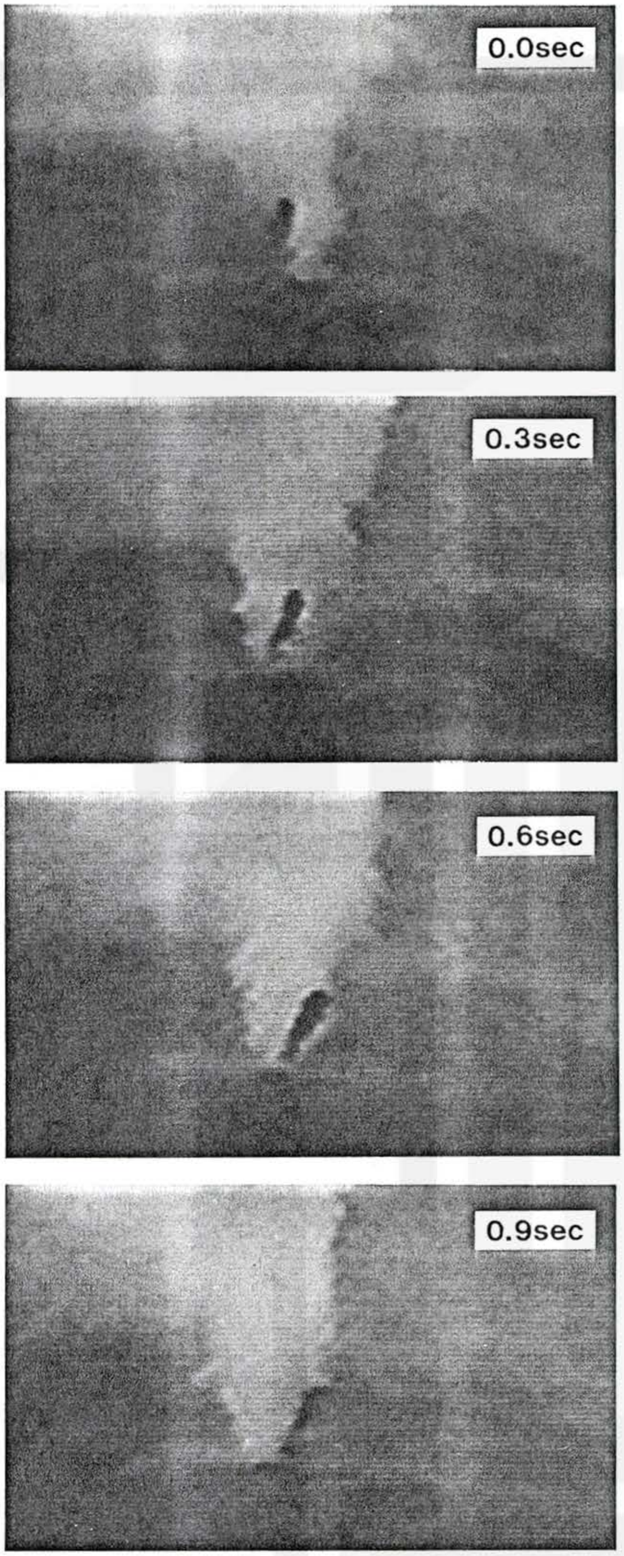

Fig. 20 A tree trying to stand up in the small funnel of the Minneapolis, MN tornado of 18 July 1986. Four selected frames of the video taken from the helicopter of KARE TV. Courtesy of Mr. Paul Douglas, Chief Meteorologist, News 11.

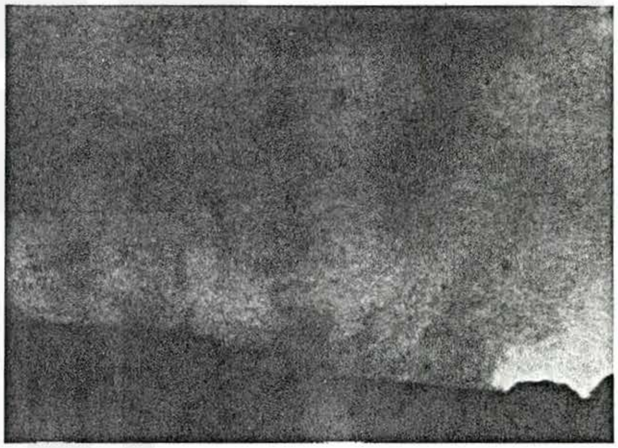

Fig. 21 Suction vortices and their parent tornado amalgamated into a complex system of vortices.

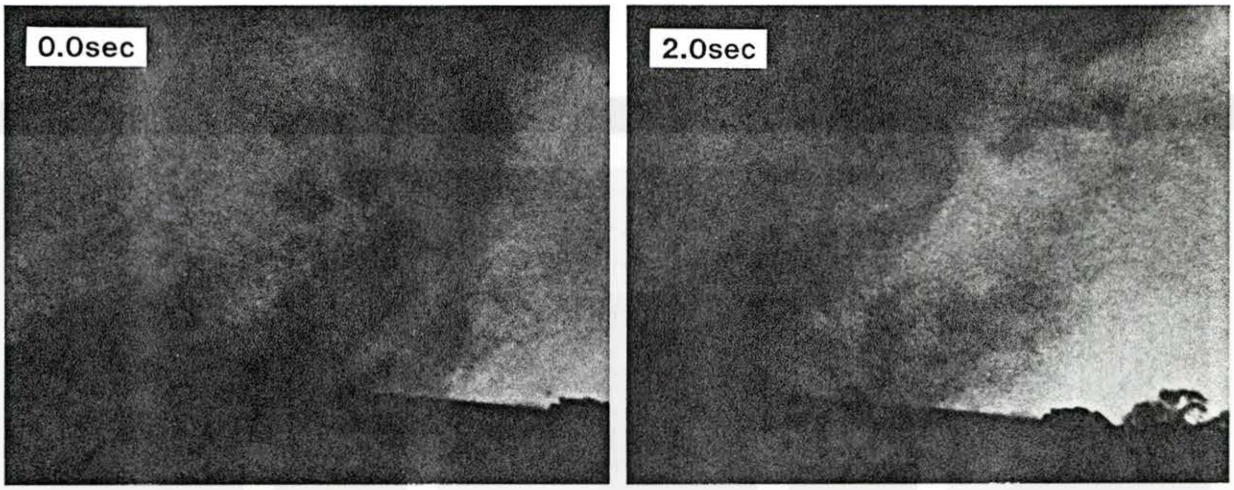

Fig. 22 Two frames of the movie in Fig. 21. These frames are 2-seconds apart, showing the rapid change of the vortex system. Figures 21 and 22 were enlarged from the movie of the 1st Lomira, WI tornado of 21 April 1974. Courtesy of Mr. Larry Floeter.

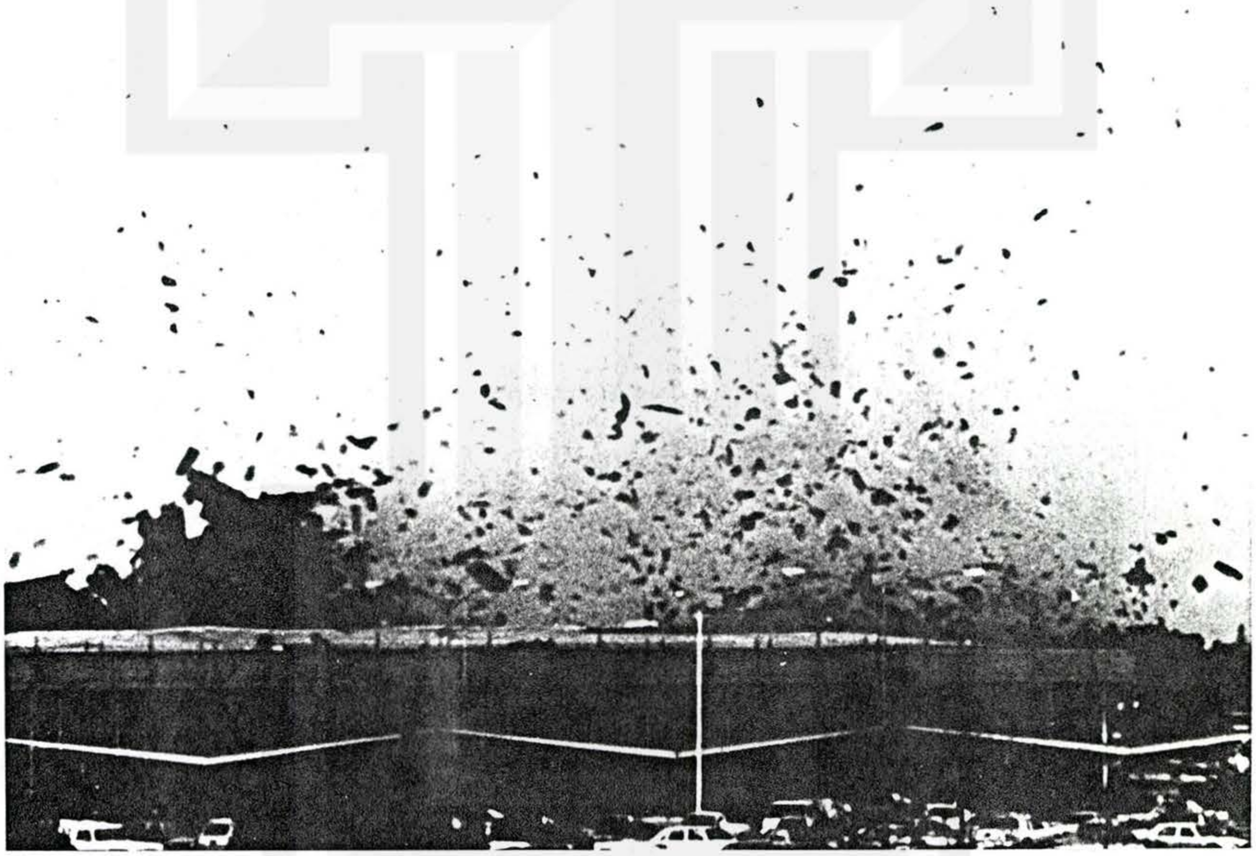

Fig. 23 At 2:05 p.m. PST on 19 February 1980, a small funnel cloud moved over the Fresno, CA airport. Although the funnel was not on the ground, the roof of an airport building was blown upward and broken into pieces, suggesting the existence of strong vertical winds beneath the funnel cloud. The damage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

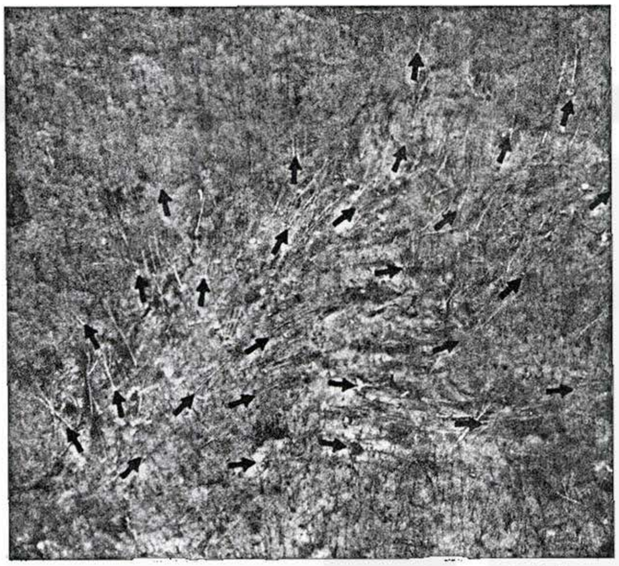

Fig. 24 The diverging pattern of uprooted trees photographed near Beckley, WV where a tornado damage by one of the Jumbo Outbreak Tornadoes of 3 April 1974 had been reported. We believe that this starburst damage was located at the root of the downdraft which induced a microburst. Photo by Ted Fujita.

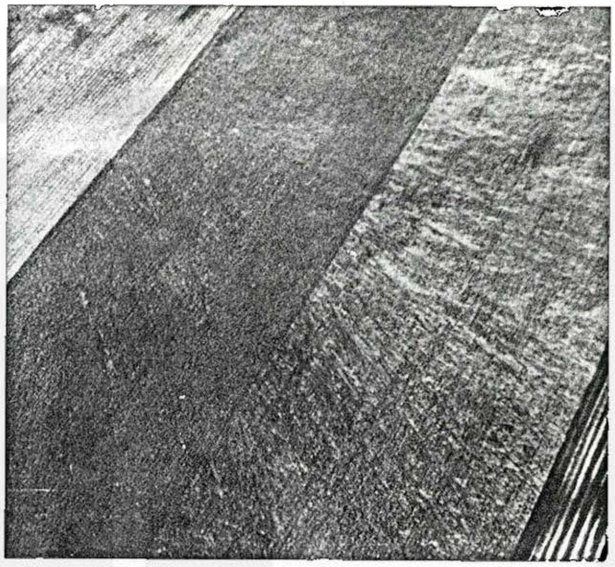

Fig. 25 The Danville, IL microburst of 30 September 1977 which blew down pre-harvested corn crops in a large area. From Fujita (1978).

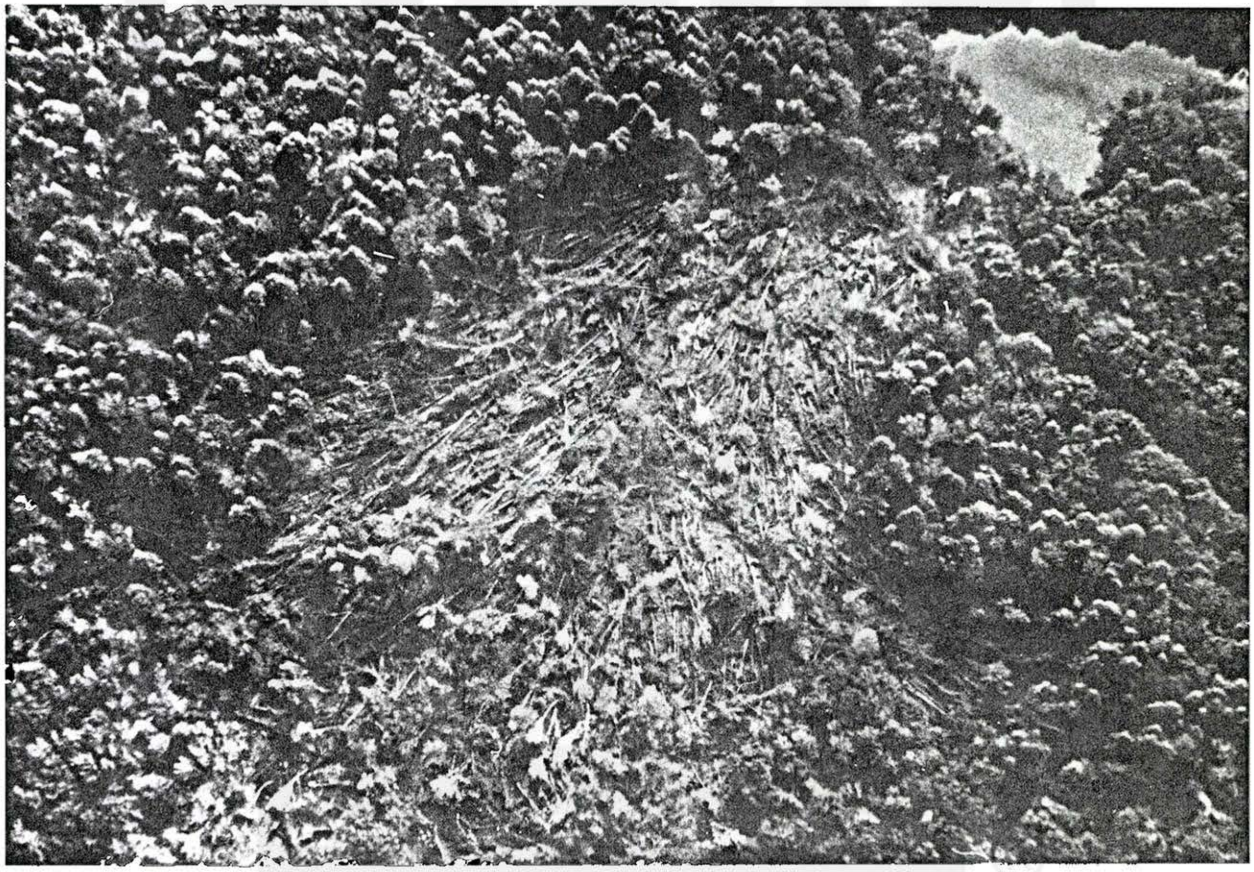

Fig. 26 A small but intense microburst found near the Cornell, WI tornado of 30 July 1977. The 100-m wide and 130-m long damage area was located on Brunet Island in the Chippewa River. Photo by Ted Fujita.

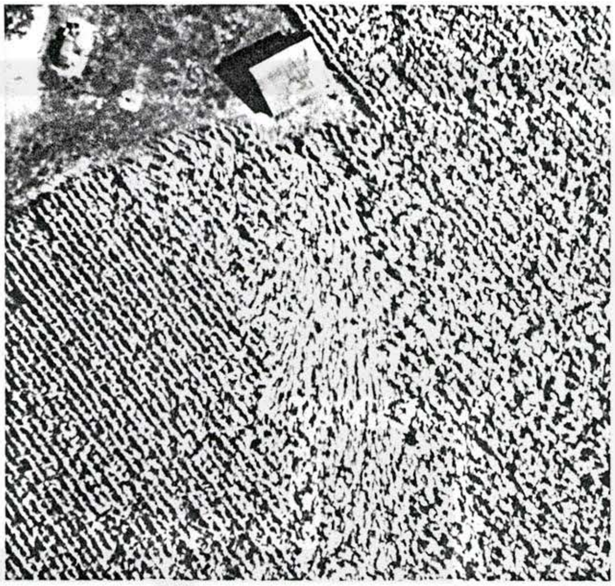

Fig. 27 A microburst airflow deflected by a tin roof during the downburst storm of 30 September 1977. Photo by Ted Fujita at Kingman, IN. From Fujita (1978).

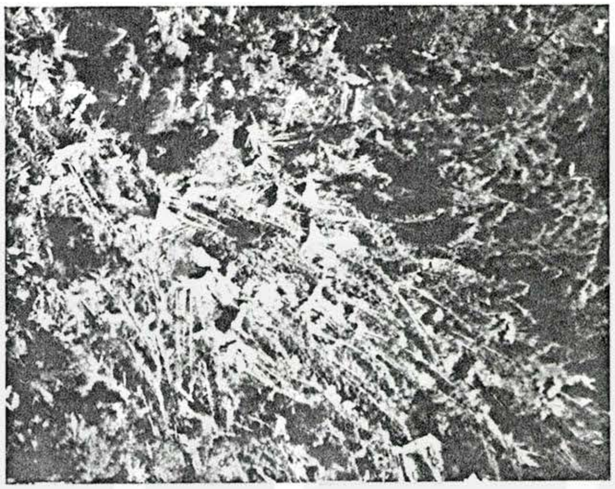

Fig. 28 A forest in northern Wisconsin blown down by a rush of diverging winds embedded inside the large downburst of 4 July 1977. Photo by Ted Fujita.

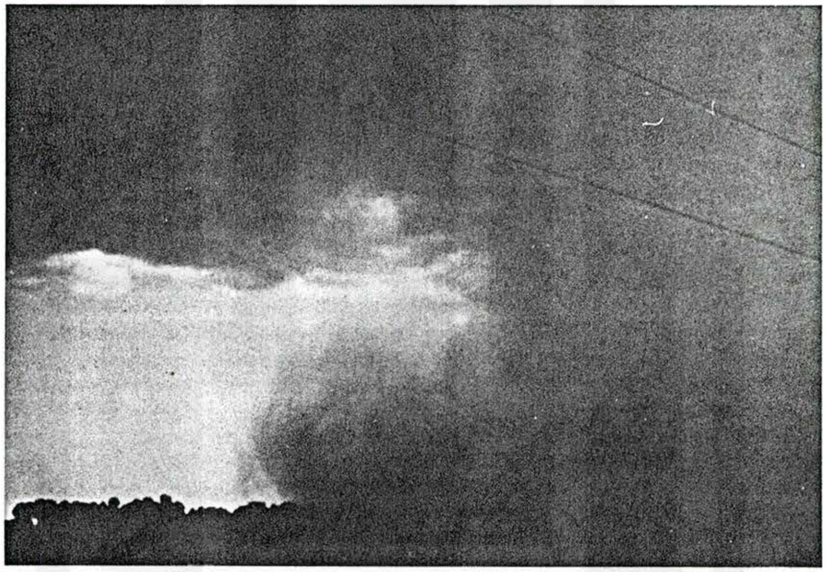

Fig. 29 A rare photograph of a microburst outflow with a ring vortex along the spreading edge. Photo taken on 1 July 1978 from near Wichita, KS. Courtesy of Mr. Mike Smith of Weather Data Inc.

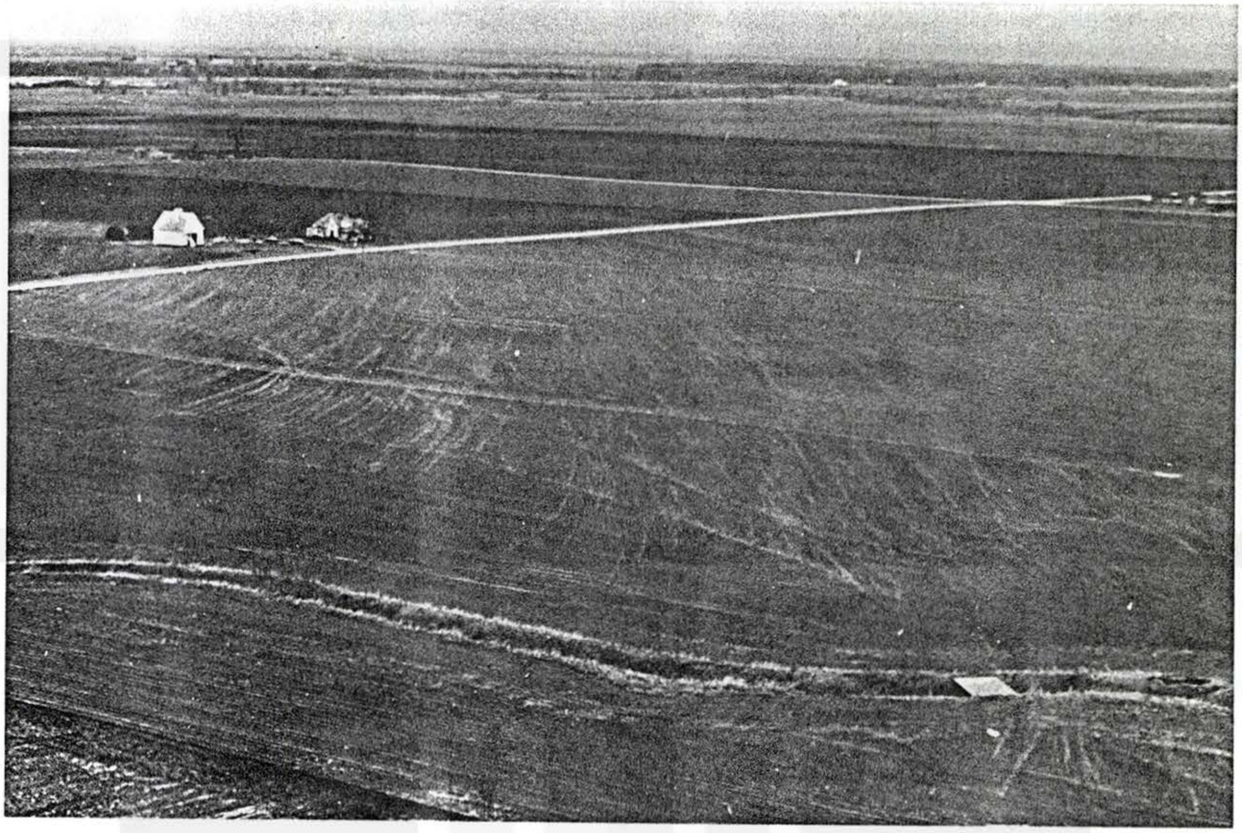

Fig. 30 A trace of mesocyclone winds with large radii of curvature photographed near the touchdown location of the Sadorus, IL tornado of 20 March 1976 investigated by Fujita, et al. (1976). Are such winds the precursor of a tornado touchdown? Photo by Ted Fujita.

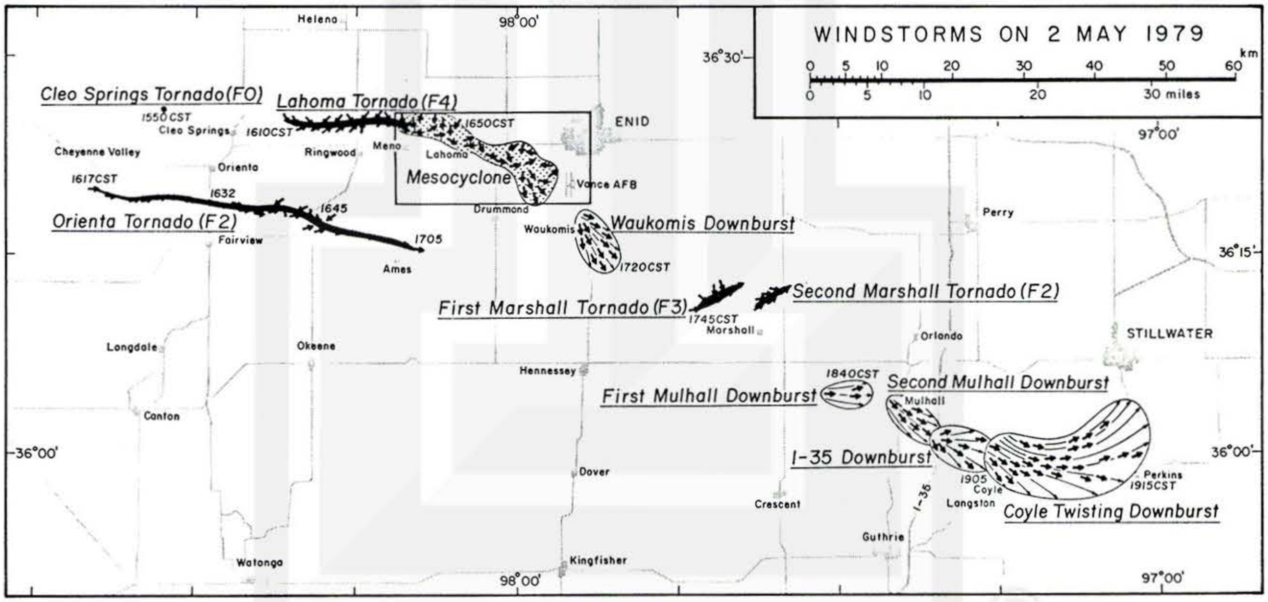

Fig. 31 The Coyle, OK twisting downburst of 2 May 1979, extending from Mullhall to Coyle to the south of Stillwater, OK. The center of a mesocyclone moved along the north edge of the twisting downburst which did not spawn a tornado.

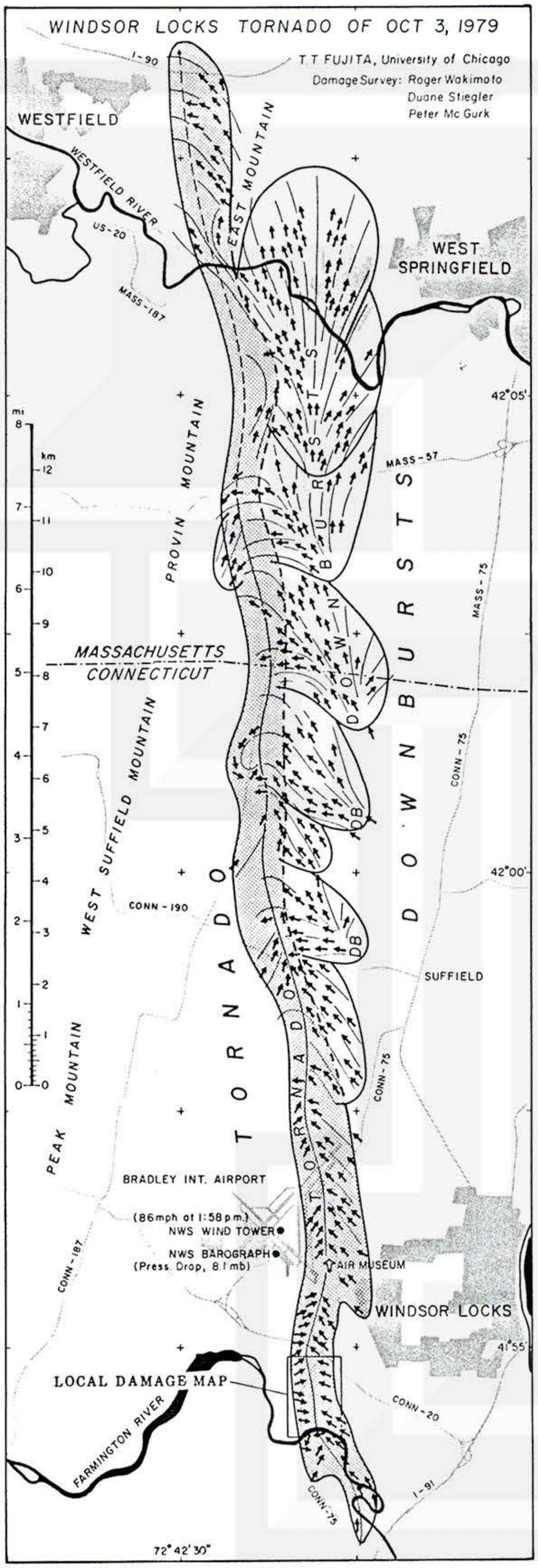

Fig. 32 The Windson Locks tornado of 3 October 1979 which traveled from south to north. Seven microbursts were mapped on the right-hand side of the tornado track.

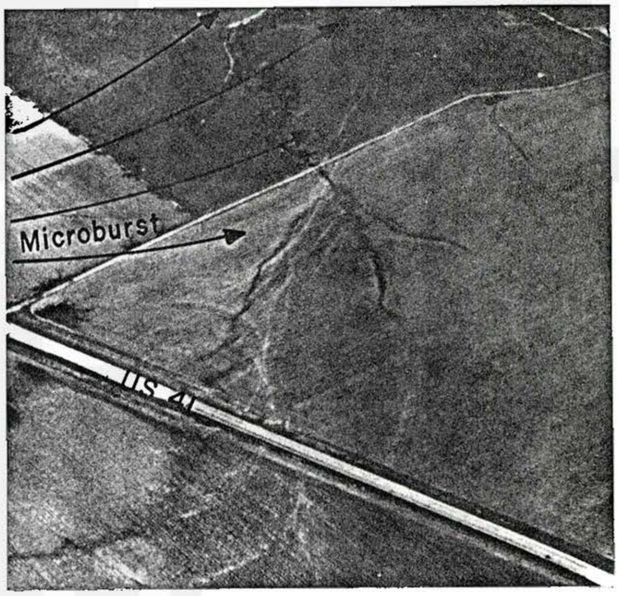

Fig. 33 Swirl marks of the Rainsville, IN tornado of 3 April 1974. Undisturbed ground marks extend until crossing U.S. Highway 41. Thereafter, a microburst airflow from the left (northwest) of the picture pushed the track toward the right. From Fujita (1978).

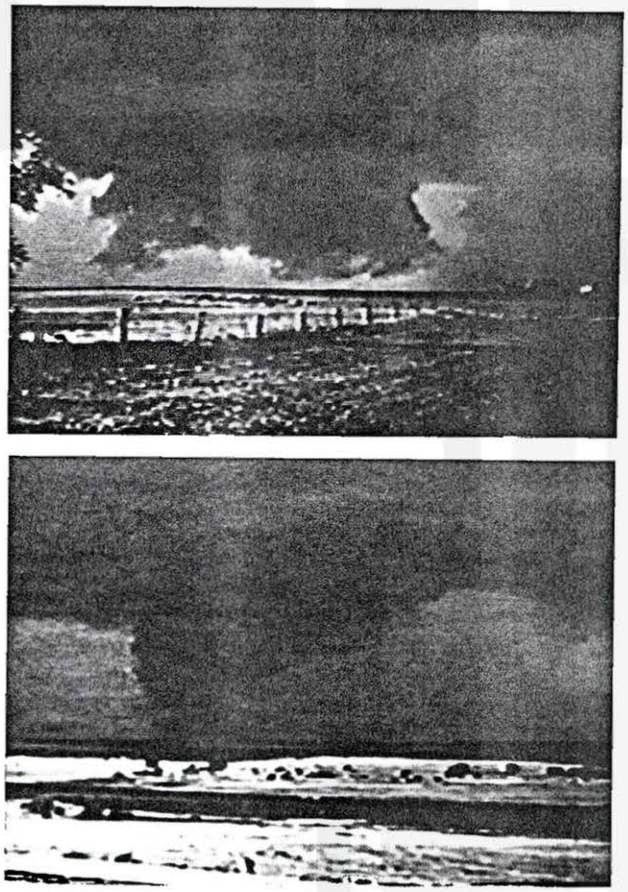

Fig. 34 Two video scenes of the 12 April 1991 tornado and a nearby microburst near Linclon, NE. Courtesy of Mr. Mike Phelps. Upper: Formative stage of a tornado and a microburst on the right side. Lower: The tornado after touchdown was pushed toward the left by microburst winds.

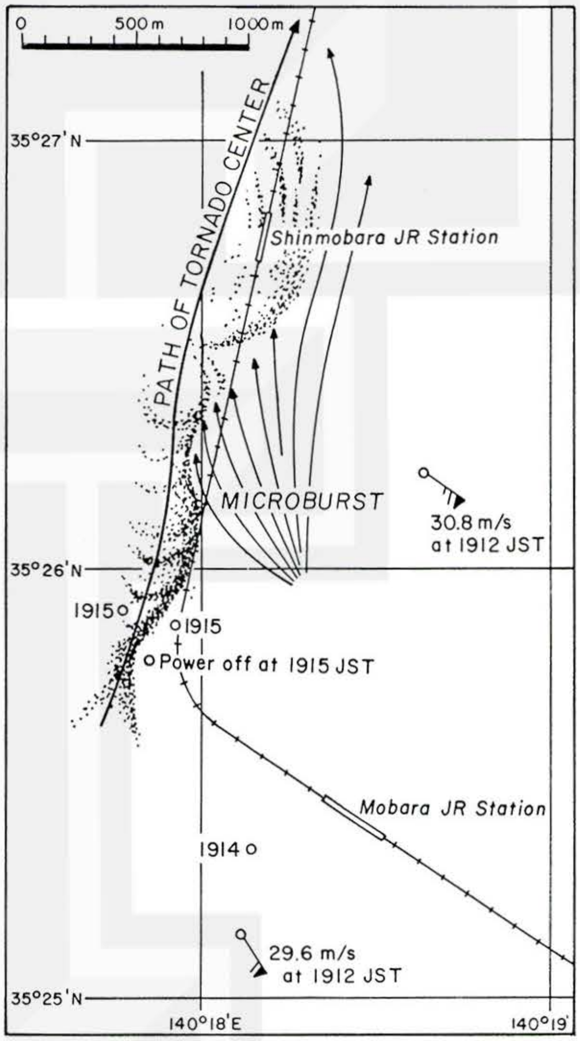

Fig. 35 The Mobara, Japan tornado of 11 December 1990. The tornado was pushed toward the left by a microburst which touched down on the right-hand side of the tornado track. The interactive process is similar to that shown in Fig. 34.