SATELLITE & MESOMETEOROLOGY RESEARCH PROJECT

Department of the Geophysical Sciences
The University of Chicago

ANTICYCLONIC TORNADOES

by

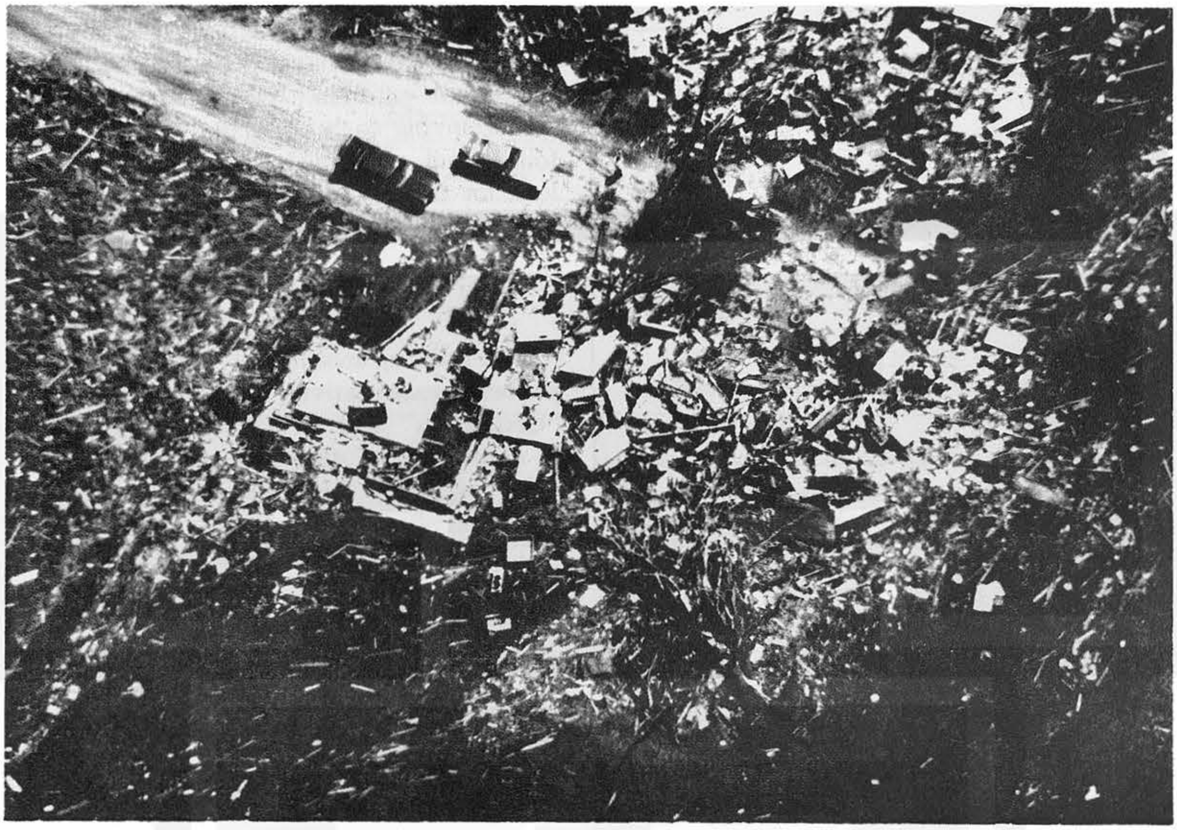
T. Theodore Fujita

reprint of

Weatherwise April 1977
Volume 30, Number 2 pp 51 - 64

SMRP Research Paper No. 146

April 1977



Houses near Lemont IL destroyed by a tornado on 13 June 1976 and rated F4. Photo by Fujita on 14 June 1976.

Anticyclonic Tornadoes

T. THEODORE FUJITA, *Professor of Meteorology, The University of Chicago*

SWIRLING motion of water develops when a bathtub or a kitchen sink is drained from the bottom. One could easily produce, at will, either a clockwise (anticyclonic in Northern Hemisphere) or a counterclockwise (cyclonic) swirl simply by stirring the water in a desired direction.

Dust devils rotate in either direction depending upon the environmental flow in which they develop. Waterspouts, however, tend to rotate cyclonically.

Practically all tornadoes are thought to swirl cyclonically in both hemispheres, counter-clockwise in the Northern Hemisphere and clockwise in the Southern Hemisphere. However, no one knows how many anticyclonic tornadoes occur in the United States each year. In an attempt to improve statistics regarding this matter, Pearson and Fujita came up with a list of 29 anticyclonic tornadoes during a 27-year period, 1950–76 (see Fig. 1).

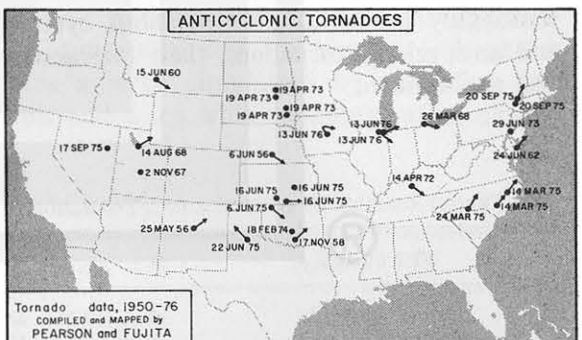


Fig. 1. Distribution of anticyclonic tornadoes during a 27-year period, 1950–76.

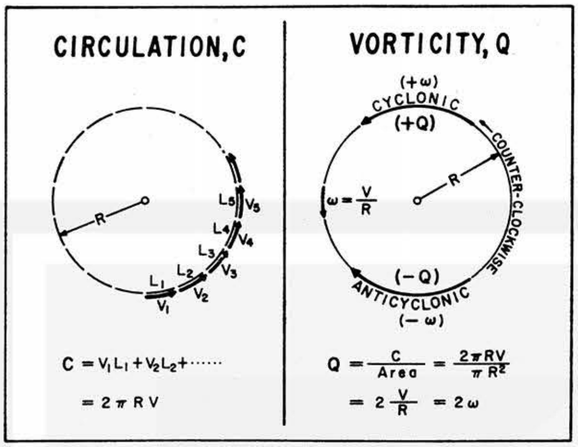


Fig. 2. Circulation is a measure of the size and strength of a vortex. Vorticity denotes the spin rate, positive for cyclonic and negative for anticyclonic swirls.

Anticyclonic tornadoes are usually small, short-lived, and weak. The highest F scale was F4 followed by one F3 and four F2s. The longest path length was 32 km (20 mi), while the widest path was 0.3 mi (see Table 1 for the FPP-scale distributions; FPP refers to the Fujita-Pearson tornado severity scale as described in *Weatherwise*, April 1973, 58).

Only one tornado caused fatalities, killing three persons in Texas. A total of 30 persons were injured by five tornadoes.

Unlike their cyclonic counterparts, most anticyclonic tornadoes in the north-central United States moved from northwest to southeast. Is this evidence accidental? It could be a result of the limited number of storms documented as of this date.

The first step in understanding the structure of an atom is to investigate both positively- and negatively-charged particles, such as electrons and protons. Likewise, violent swirls of the atmosphere can be understood thoroughly by learning more about cyclonic and anticyclonic tornadoes, their interactions and environment.

The purpose of this article is to ask readers to become more sensitive to the direction of tornado rotation. Anticyclonic tornadoes are occurring each year, but they cannot be found and confirmed unless we intensively look for them.

Circulation and Vorticity

The swirling motions of the air can be expressed quantitatively by two quantities: "circulation" and "vorticity." The former is a measure of the "size and strength" of a vortex, while the latter denotes the "rotational rate."

The circulation can be computed as a summation (see Fig. 2):

$$C = V_1L_1 + V_2L_2 + V_3L_3 + \cdots \qquad (1)$$

where V is the wind speed along the arc length, L. V is called the tangential speed or rotational speed. When the tangential speed is the same everywhere along a circle around a vortex center, we write:

$$C = 2\pi RV \qquad (2)$$

where R is the radius and V, the tangential speed.

Table 2 suggests that the circulation of tornadoes varies between about 1000 and 100,000 m^2/s. By virtue of its size, even a weak hurricane is characterized by a circulation in excess of one million m^2/s.

The vorticity of a whirlwind is proportional to its rotational or spinning rate. It can be computed as the circulation per unit area (see Fig. 2).

If the tangential speed around a vortex is constant, the vorticity is computed by:

$$Q = \frac{\text{circulation}}{\text{area}} = 2\frac{V}{R}. \qquad (3)$$

Frequencies of 29 Anticyclonic Tornadoes by FPP Scale (for Tornado Locations, See Fig. 1)

FPP SCALE	0	1	2	3	4	5
F-scale intensity	11	12	4	1	1	0
Path length scale	9	11	6	3	0	0
Path width scale	8	12	5	4	0	0

TABLE 2

CIRCULATION OF VARIOUS VORTICES. PEARSON DEFINED MAXI-TORNADOES WITH FPP, 4 4 2 OR LARGER AND MINI-TORNADOES WITH FPP, 0 0 1 OR SMALLER (FOR THE FPP SCALE, REFER TO WEATHERWISE, APRIL 1973, P58)

Vortices	Core radius	Tangential sp.	Circulation
typical Mini-tornado	10 m 33 ft	25 m/sec 56 mph	1,570 m^2/s
typical Maxi-tornado	100 m 328 ft	100 m/sec 224 mph	63,000 m^2/s
weak Hurricane	10,000 m 6 mi	35 m/sec 78 mph	2,200,000 m^2/s

The ratio, V/R, is the angular velocity of the swirling motion seen from the vortex center. In other words, the vorticity is the angular velocity multiplied by two.

Table 3 shows that the range of vorticity of tornadoes is between about 1 and 10 sec^{-1}. Paradoxically, the vorticity of mini-tornadoes is larger than that of maxi-tornadoes. By virtue of its large diameter, a maxi-tornado does not need to have a fast spinning rate in order to generate violent winds. Mini-tornadoes may spin fast, but the tangential speed is small due to their small core radii.

We often observe a small vortex, around a building corner, swirling with flying papers and trash. It could induce a 10 m/s (22 mph) swirl wind around a 2 m (6 ft) core radius. Its vorticity is 10 sec^{-1}, five times that of maxi-tornadoes.

If one looks down on the earth from above the North Pole, he will notice that the earth's surface beneath him rotates counter clockwise. The angular velocity of the rotation is:

$$\frac{360°}{\text{one day}} = \frac{2\pi}{86{,}164 \text{ sec}} = 0.000073 \text{ sec}^{-1}.$$

The earth's vorticity corresponding to this rotation rate is 0.000146 sec^{-1}. Naturally, the vorticity of the rotation around the south pole is -0.000146 sec^{-1}.

It is hard to believe that 1 to 10 sec^{-1} vorticity of tornadoes is affected by the earth's vorticity which is no more than one part in ten thousand. It is so small that a tornado should not know the rotation of the earth's surface on which it swirls. Research during the past few decades has revealed, however, that tornadoes form within the parent swirls embedded inside large cyclonic wind systems, whose rotation is affected by the earth's rotation.

Spin Up by Vertical Stretching

How does a vortex increase its vorticity to swirl fast? The vorticity equation breaks down the sources of vorticity into the following terms, excluding the Rossby parameter:

$$\frac{dQ}{dt} = \text{(Stretching term)} + \text{(Tilting term)} + \text{(Solenoid term)} + \text{(Friction term)}.$$

The stretching term and the tilting term are important for the generation of anticyclonic tornadoes. The friction term acts against the swirling motion. The solenoid term may contribute to the vorticity generation, but it is too slow to be effective in tornado generation.

The stretching term has been utilized, nonmathematically, by ice skaters. A skater gains a large circulation by extending two arms and a leg while spinning rather slowly.

TABLE 3

VORTICITY OF VARIOUS VORTICES

Vortices	Core radius	Tangential sp.	Vorticity
Mini-tornado	10 m	25 m/sec	5 sec^{-1}
Maxi-tornado	100 m	100 m/sec	2 sec^{-1}
Hurricane	10,000 m	35 m/sec	0.07 sec^{-1}

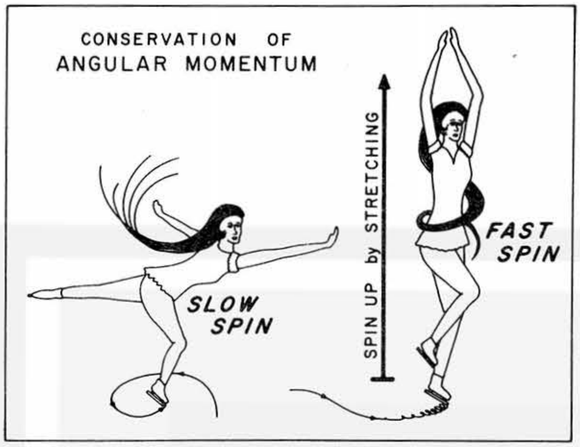


Fig. 3. An ice skater increases the spin rate by stretching her body.

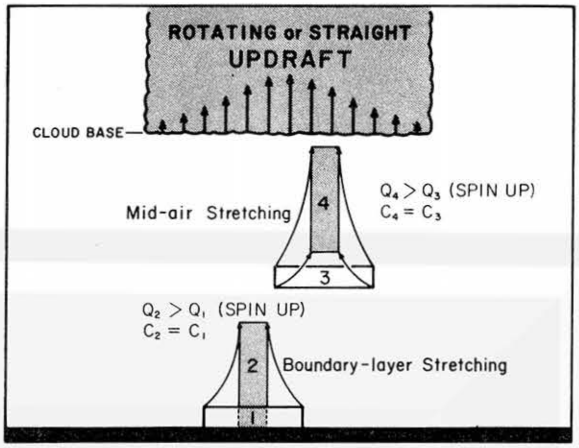


Fig. 4. A growing cloud is an effective agent to initiate stretching processes beneath its base.

If a skater stretches up, the whole body spins several times faster (see Fig. 3).

During the spin-up processes, the angular momentum of the skater is conserved. Likewise, the circulation is conserved when a vortex stretches upward. Since the friction term eventually slows down the spinning motion, the stretching process must be completed as fast as possible: a few seconds for ice skaters and probably a few minutes for tornadoes.

Unlike an ice skater, a parcel of air cannot stretch up by itself. Effective stretching occurs when the environmental air converges toward the parcel forcing it to rise into the overlying cloud base (see Fig. 4).

If a parcel is somehow accompanied by an initial circulation, either positive or negative, the vorticity of the same sign increases during the stretching process. An anticyclonic circulation or a cyclonic circulation at the source is required for the formation of an anticyclonic or cyclonic tornado, respectively.

The stretching can take place anywhere. When stretching occurs near the surface, a tornado develops on the ground. A mid-air stretching may generate a funnel cloud which does not always affect the underlying surface.

Q–C Diagram

When maxi- and mini-tornadoes are compared, the former is characterized by a larger circulation and a smaller vorticity, while the latter by smaller circulation and larger vorticity. It is, therefore, necessary to combine the vorticity with circulation for assessing the kinematic properties of tornadoes.

The Q–C diagram in Fig. 5 is a vorticity-circulation diagram on logarithmic coordinates. Drawn also in the diagram are two groups of isolines; one shows the core radii in meters, and the other, the tangential velocities in m/s.

The domain of tornadoes in a Q–C diagram is an elliptic area with maxi-tornadoes near the lower right and mini-tornadoes near the opposite end. The spin-up lines in the diagram indicate the possibility of producing

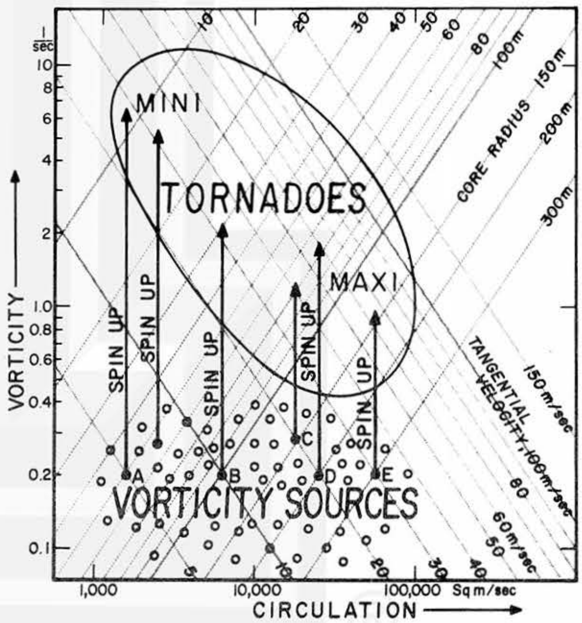


Fig. 5. The Q(vorticity)—C(circulation) diagram in logarithmic coordinates. Isolines of tangential velocities and core radii are straight lines in this figure.

tornadoes by stretching vertically the source disturbances, the vorticity of which is relatively small but covers a large area. Note that the tangential velocity doubles when the core radius shrinks by one-half.

A skater can never change spin direction during the stretching act. When one wishes to spin clockwise, the initial spin will have to be clockwise, and vice versa. Likewise, a counter clockwise (cyclonic) tornado is generated by stretching a cyclonic vorticity source. It is, thus, necessary to find anticyclonic vorticity sources in generating anticyclonic tornadoes.

Examples of Anticyclonic Tornadoes

There are fascinating stories and evidence of anticyclonic tornadoes. Seven cases, five in the United States and two in other countries, will be discussed in this paper. They are:

(A) 25 August 1956 GOLITZINO, U.S.S.R.
(B) 28 October 1967 IIOKA, Japan
(C) 26 March 1968 MONROE, Michigan
(D) 6 June 1975 FREEDOM, Oklahoma
(E) 22 June 1975 SILVERTON, Texas
(F) 13 June 1976 THREE-FARM, Iowa
(G) 13 June 1976 LEMONT, Illinois

(A) GOLITZINO Tornado, U.S.S.R. (25 August 1956)

This anticyclonic tornado moved northward in forest areas near Golitzino (55°36′N, 36°59′E) about 40 km (25 mi) west-southwest of Moscow. The time of the tornado was 1830 on 25 August 1956.

The post-storm survey by Kolobkov (1957) revealed that the storm left behind two parallel swaths of tree damage, 100 to 200 m (650 ft) wide and 10 km (6 mi) long. The two swaths were separated by a damage-free zone, about 2 km wide (see Fig. 6).

Detailed analysis of the damage areas and numerous photographs led to the conclusion that there were two tornadoes. The right-hand tornado left behind the cyclonic swaths near the Moscow-Minsk Expressway. The strongest wind effects were found along the east side of the path, where trees were blown down toward the circulation center.

The left-hand tornado rotated anticyclonically, resulting in the heaviest damage near the Golitzino railroad station. Trees of 30 to 60 cm (1 to 2 ft) diameter were snapped 60 to 90 cm (2 to 3 ft) above the ground. It was an anticyclonic tornado which travelled in a northerly direction at 70 kph (44 mph). Numerous trees on the left side of the tornado center were severely damaged.

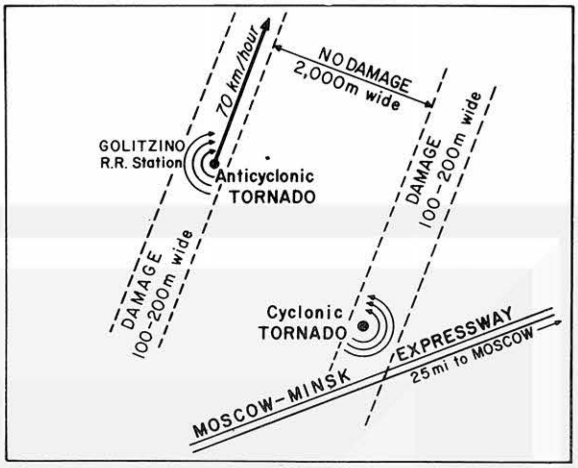


Fig. 6. Schematic paths of anticyclonic and cyclonic tornadoes of 25 August 1956 near Moscow, U.S.S.R. Based on Kolobkov (1957).

(B) IIOKA Tornado, Japan (28 October 1967)

Two anticyclonic tornadoes occurred in Chiba Prefecture, 83 km (52 mi) east of Tokyo on 28 October 1967. A weakening typhoon was about to land on the south coast of Honshu, 480 km (300 mi) to the west-southwest of the tornado sites.

There was a warm front extending from the typhoon eastward across the tornado area into the Pacific. A thunderstorm was in progress between 0100 and 0300. At 0312, a waterspout landed just to the west of Iioka. Refer to Japanese Storm Data (1967).

The waterspout turned into a tornado with an estimated F3 intensity. After removing the main roof of Asama Shrine, the tornado swirled cyclonically over rolling hills. Trees with a 40 to 60 cm (2 ft) diameter were snapped or blown down inside the 80 to 180 m (600 ft) wide swath. It travelled inland as far as 2.3 km (1.4 mi) where it began skipping (see Fig. 7).

A new tornado formed 200 m (650 ft) to the west of the skipping cyclonic tornado. It was a very small anticyclonic tornado with a

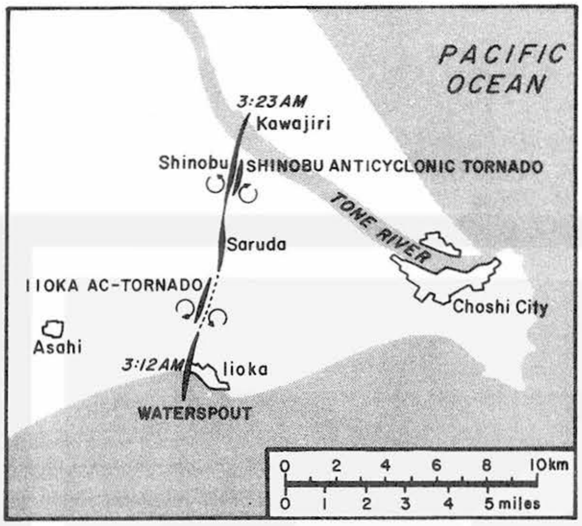


Fig. 7. Paths of one cyclonic and two anticyclonic tornadoes of 28 October 1967 near Tokyo, Japan. Based on Japanese Storm Data (1967).

2 km (1.2 mi) path length and a 12 m (40 ft) path width. The estimated FPP of this tornado, to be called the Iioka anticyclonic tornado, is 1,1,0.

The initial cyclonic tornado regained its intensity while moving across the town of Saruda. From Saruda it headed toward the next town, Shinobu, on the Tone River.

The second tornado, to be called the Shinobu anticyclonic tornado, developed in a rice field 150 m (490 ft) to the east of the cyclonic tornado. Two tornadoes, side-by-side and swirling in opposite directions, smashed into Shinobu, causing heavy damage in the town. The anticyclonic tornado with estimated F P P = 1,0,0 dissipated before reaching the river.

The cyclonic tornado moved across the Tone River as a waterspout and landed on the opposite bank near Kawajiri. The life of the cyclonic tornado, including the skipping path, was 11 min. It travelled through a distance of 11 km at 60 kph (38 mph).

The vortex pair of the Iioka anticyclonic tornado was similar to that of the Golitzino anticyclonic tornado. The left-hand tornado was anticyclonic and the other was cyclonic. The Shinobu anticyclonic tornado formed a different pair. The left-hand tornado was cyclonic, while the other one was anticyclonic. Unfortunately, there was no eyewitness to these tornado pairs which occurred between 0312 and 0323.

(C) MONROE Tornado, Michigan (26 March 1968)

A cyclonic tornado, a precursor of the anticyclonic tornado, touched down at 1745 EST, six miles northwest of Monroe, Michigan. As it was travelling toward the southeast, an anticyclonic tornado formed 500 m to the left of the cyclonic tornado. Both tornadoes travelled side by side toward the southeast for about one mile. At that point the cyclonic storm disappeared.

Thereafter, the anticyclonic tornado intensified, reaching the maximum strength as it crossed US-25 just north of Monroe at about 1755. A thick vertical funnel was observed through heavy rain. Upon interrogation by National Weather Service investigators, an eyewitness repeatedly insisted that the forward edge of the funnel and its associated debris were moving clockwise. Other evidence also supported the eyewitness accounts.

The tornado kept moving toward the southeast until it went into Lake Erie near Woodland Beach. Almost 100 buildings were damaged and one person was injured. Based on Snider (1976).

(D) FREEDOM Tornado, Oklahoma (6 June 1975)

A color picture of this anticyclonic tornado was introduced by Burgess (1976) as the cover picture of the August 1976 issue of *Weatherwise*. It is one of the two color slides taken by Jim Leonard who was working informally with the National Severe Storms Laboratory for the tornado intercept program. His friend, Eddie Sims, also took four color slides. In addition, they took a super-8 movie of the anticyclonic tornado, obtaining the first photographic evidence of an anticyclonic tornado (see Fig. 8).

Leonard and Sims were driving east on US-64 in anticipation of tornadoes. At about six miles northwest of Freeman, they noticed a swirling motion near the cloud base to the northeast of their location. The swirl began moving toward the southeast turning into an anticyclonic tornado. Apparently, the tornado missed all farms and travelled through an estimated distance of three miles.

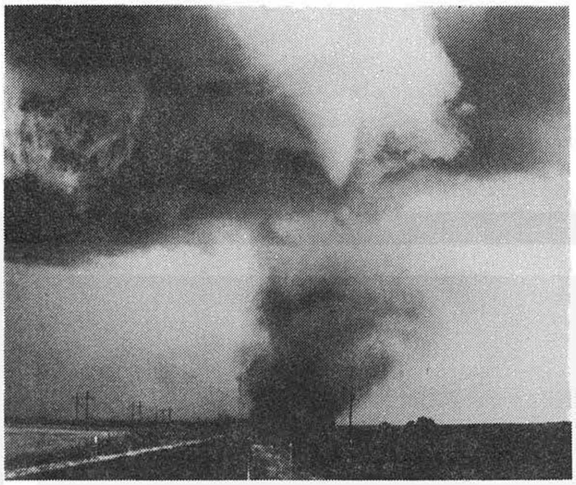


Fig. 8. View of the anticyclonic tornado of 6 June 1975 near Freedom, Oklahoma. Courtesy of Messrs. Jim Leonard and Eddie Sims.

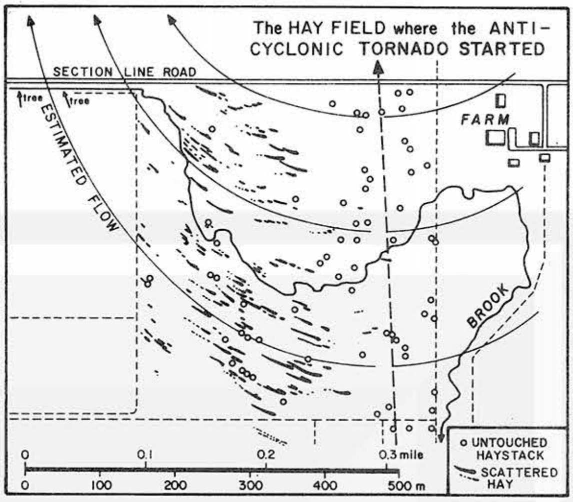


Fig. 9. An anticyclonic flow estimated from the scattered hay. The disturbance occurred at 3:50 PM, 13 June 1976. Based on aerial photos taken on 17 June.

(E) SILVERTON Tornado, Texas (22 June 1975)

A tornado skipped northwestward completely destroying a single story, 27 × 42 ft, farm house, killing a family of three. The foundation was swept clean with the most debris piled 70 ft northwest of the foundation. Some wreckage was located as far away as 400 yd to the northwest. The tornado was apparently anticyclonic. The path length was 10 mi and the width, 240 ft, occurring between 2020 and 2034 CST. Based on Storm Data (1975).

(F) THREE-FARM Tornado, Iowa (13 June 1976)

Three farms in Jackson Township of Boone County, Iowa, were heavily damaged by an anticyclonic tornado of 13 June 1976. The initial damage of this tornado was confirmed in a hay field, 2.0 mi to the northeast of the community of Jordan, which was wiped out by a cyclonic F5 tornado (the Jordan tornado). The Jordan tornado was located 2.5 mi to the northwest of the anticyclonic tornado when it formed in the hay field.

The aerial photography on 17 June and the subsequent mapping by Fujita and Forbes revealed that a large hay field was swept by strong winds of anticyclonic curvature. About 100 haystacks were blown over, leaving long streaks of hay scattered in the direction of the high winds (see Fig. 9).

Evidently, the initial disturbance moved northward across the hay field, causing wind damage over the western half of the field. The estimated radius of anticyclonic curvature was 350 m with a maximum estimated wind of 30 m/s.

About 1.0 km north of the hay field, Mr. William Curvin had finished taking the 15th picture of the Jordan tornado, which was moving away toward the northwest. The time was 1556. It was raining heavily, mixed with small hail, and a brisk wind was blowing from the southeast. "Suddenly," he stated, "the wind changed to the north-northeast with hurricane velocity. A new, unseen tornado forced us to discontinue observation, and we entered the basement."

Later, he found his birdhouse dropped beside the road, 200 m (0.125 mi) northwest of where it had been standing. Roofing materials from the Tripp farm were deposited in his field some 400 m (0.25 mi) away. The estimated radius of the circulation was 250 m with a maximum wind of about 40 m/s from the south (see Fig. 10).

The disturbance intensified into a well-defined tornado as it was moving between the Baker and Congdon farms. A cone-shaped funnel cloud hanging above the Baker farm was observed from the Thomson farm 1.3 km (0.8 mi) to the west. A huge column of dust was swirling beneath the funnel. At this time, strong northerly winds damaged outbuildings on the Congdon farm, and an esti-

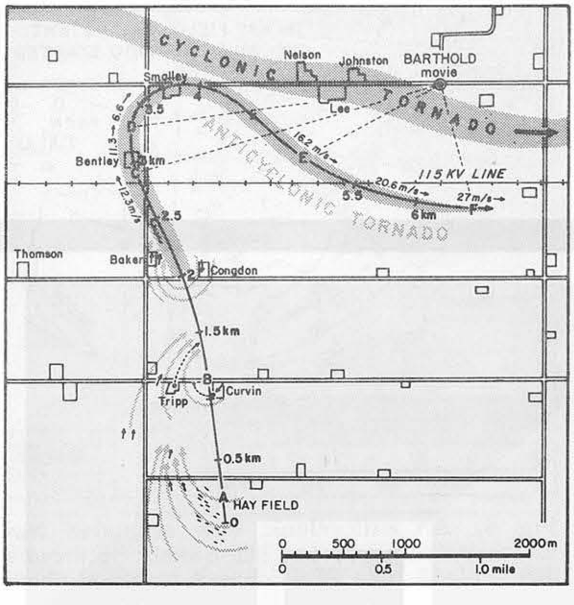


Fig. 10. The path of an anticyclonic tornado of 13 June 1976 in Central Iowa. The storm, called the Three-farm tornado, damaged the Baker, Bentley, and Smalley farms severely.

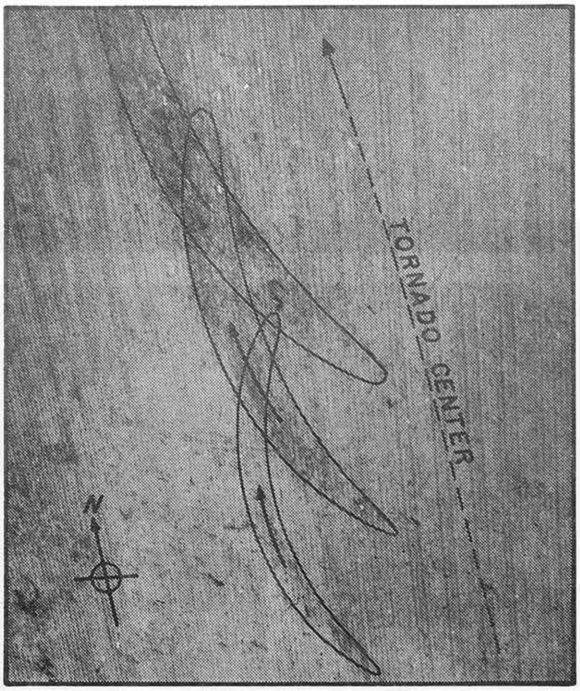


Fig. 12. Three scalloping marks in the field 200 to 300m to the north of the Baker farm.

mated F1 wind from the south battered the Baker farm (see Fig. 11).

Three scalloping marks were found in the plowed field northeast of the Baker farm. As expected, the debris deposit took place to the left of the tornado center, where the maximum winds are expected to occur (see Fig. 12).

Mr. Charles Barthold of WHO-TV, Des Moines, saw this tornado from the roadside, about 2.4 km (1.5 mi) away. The first scene of his 16-mm movie, taken with a 50-mm lens, shows a swirling dust cloud, 130 to 150 m in diameter at the surface. The second, a wide-angle scene, reveals the existence of a cone-shaped funnel cloud with its tip at 400 m above the ground (see Fig. 13).

The tornado attained its maximum strength, F3, shortly before reaching the Bentley farm. As it swirled across the farm, just about every structure on the farm was damaged (see Fig. 14). Results of photogrammetric analyses of the Barthold movie revealed that the maximum speed of the dust cloud, 70 m

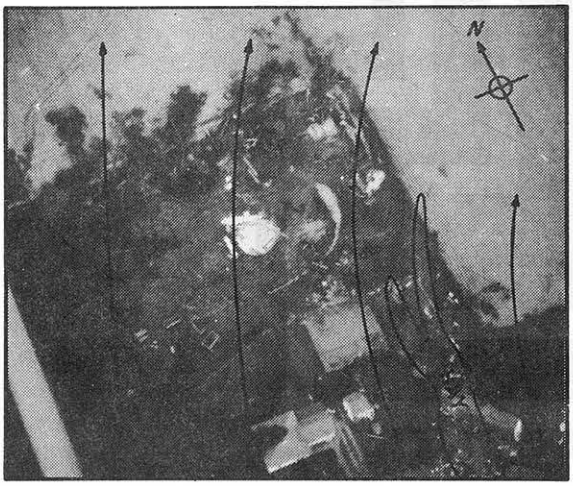


Fig. 11. The Baker farm damaged by southerly winds when the anticyclonic tornado passed 200m east of the farm. Photo on 17 June.

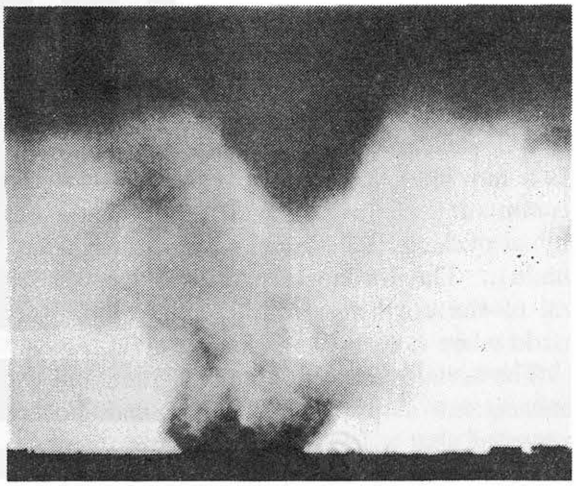


Fig. 13. A view of the Three-farm tornado at 3:45 PM CDT shortly before it moved across the Bentley farm. Photo, courtesy of Mr. Charles Barthold.

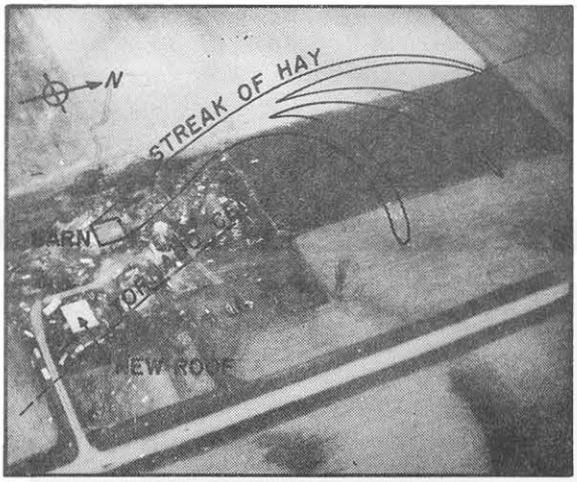


Fig. 14. The Bentley farm smashed by the Three-farm tornado. The new roof of the residence was put up on 14 June. Photo on 17 June.

above the surface, was 75 m/s (168 mph), while the storm was travelling at 12.3 m/s (28 mph).

The travelling velocity of the tornado slowed down to 6.6 m/sec (15 mph) as it made a right turn toward the Smalley farm. It passed directly over the farm, unroofing a hay barn. The hay picked up by the wind was deposited in a band showing a definite anticyclonic curvature. A large tree at the southeast corner of the farm snapped at the ground and flew as a missile, hitting the south wall of the Smalley residence, which was twisted anticyclonically six feet off the foundation (see Fig. 15).

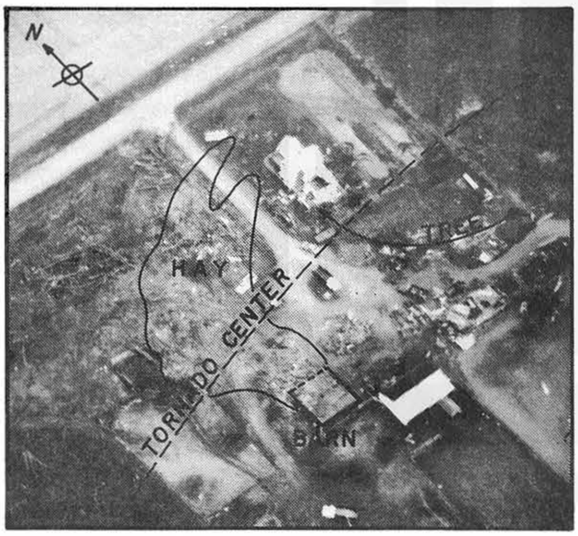


Fig. 15. The Smalley farm after the tornado. The residence was twisted 6ft off the foundation. Photo on 17 June.

Fig. 16. A view of the Three-farm tornado at 3:58 PM CDT. The tornado weakened and the funnel touched the ground. Photo, courtesy of Mr. Charles Barthold.

After re-loading the film, Barthold took the 8th scene of this anticyclonic tornado. By then, the tornado had completed a right turn which was 20° short of a "U" turn. The travelling velocity increased to 16.2 m/s (36 mph), while the tangential velocity was 42 m/s (94 mph). The pressure deficit of the tornado, computed from the combined Rankine vortex, was only 18 mb. In spite of its weakening stage with a small pressure deficit, the funnel cloud was on the ground (see Fig. 16).

Funnel Cloud Touched Ground When Tornado Weakened

Against the expectation that the stronger the tornado vortex, the lower the funnel tip, the condensation funnel of this tornado kept descending as the tangential speed was decreasing. The estimated tangential speed at touch down was less than 50 m/s or about 100 mph (see Fig. 17).

Apparently, the height of the funnel cloud above the ground was not uniquely related to the maximum wind speed of this tornado. The increase in the moisture inside the north-

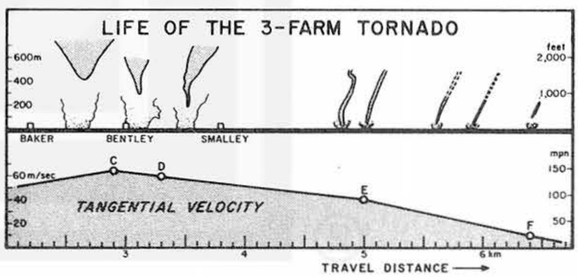


Fig. 17. The funnel cloud of the Three-farm tornado descended to the ground when the tangential velocity was decreasing. For locations, see Fig. 10.

TABLE 4

Variation of Parameters during the Life of the Three-Farm Tornado of 13 June 1976 in Central Iowa. Time in PM, CDT

Location of Tornado (Fig. 10) Time in hr and min	A 3:50.0 PM	B 3:51.7	C 3:54.5	D 3:55.1	E 3:58.0	F 3:58.9 PM
Travel distance (km)	0.0	1.0	2.9	3.3	5.0	6.5
(miles)	0.0	0.6	1.8	2.1	3.1	4.1
Dust swirl diameter (m)	700	400	200	130	160	45
Translational speed (m/sec)	10	10	12	8	18	27
Tangential speed (m/sec)	20	30	63	59	42	11
Total speed (m/sec)	30	40	75	67	60	38
(mph)	67	90	168	150	134	85
F scale	F 0	F 1	F 3	F 2	F 2	F 1
Vorticity (sec^{-1})	-0.1	-0.3	-1.3	-1.8	-1.1	-1.0
Circulation (m^2/sec)	$-44,000$	$-38,000$	$-40,000$	$-24,000$	$-21,000$	$-1,500$

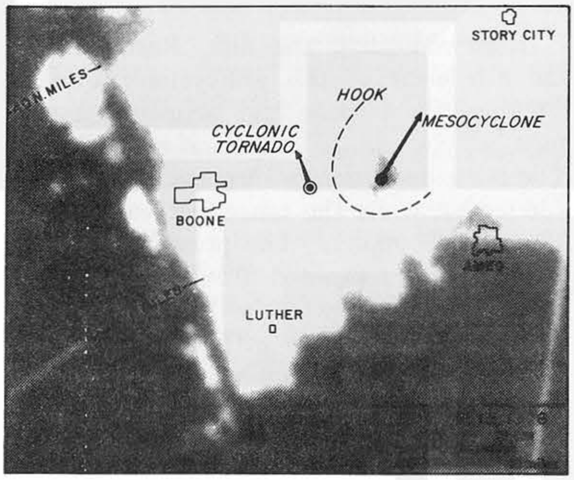


Fig. 18. The location of the hook, cyclonic tornado, and mesocyclone superimposed upon the Des Moines radar picture at 3:48 PM. Beam height, 2.0° which intersects the storm cloud at 2.2km (7,200ft) above the ground.

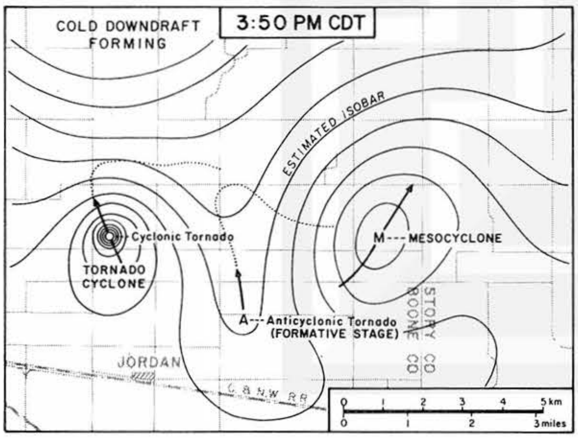


Fig. 19. An anticyclonic ridge at 3:50 PM located between the parent mesocyclone and the tornado cyclone encircling the Jordon tornado.

westerly flow pushed into the tornado area counteracted the pressure field of the weakening tornado, resulting in the condensation under a small deficit pressure. The variations of parameters shown in Table 4 reveal the life history of this tornado.

Formation of Three-Farm Anticyclonic Tornado

Under what circumstances was this anticyclonic tornado born? As the first step in solving this mystery, the location of the Jordan cyclonic tornado was placed on the Des Moines radar picture taken at 1548. The mesocyclone which spawned the cyclonic tornado some 20 min earlier was located 8 km (5 mi) northwest of Ames, Iowa, moving toward Story City (see Fig. 18).

The cyclonic tornado was moving toward the north-northwest outside the estimated hook encircling the mesocyclone center. Fujita (1975) reported that the Xenia, Louisville, and Brandenburg tornadoes formed inside their parent hooks. Toward the end of their lives, each tornado at the ground moved out of the hook.

At 1550 an anticyclonic tornado, in the formative stage, moved northward across the hay field. The location of the hay field was in an expected ridge between the mesocyclone and the cyclonic tornado surrounded by its tornado cyclone. The pattern of the scattered hay revealed the existence of an anticyclonic source vorticity of -0.2 sec^{-1} (see Fig. 19).

Right-Angle Turn of Two Tornadoes

Both the Jordan and the Three-farm tornadoes moved toward the north-northwest at about 8 m/s (13 mph), keeping their separation of about 3 km (2 mi). Both tornadoes started slowing down simultaneously at 1555 while making sharp right turns. When the turns were completed in one to two minutes, their travelling speeds increased to about 27 m/s (60 mph) toward the east-southeast. Evidently, both tornadoes were caught by a strong outflow from the northwest (see Fig. 20).

The strength of the violent outflow was witnessed by the residents of the farms located between the two tornado paths. When both tornadoes had moved northward across the east-west roads by the farms, residents thought that the tornadoes were gone. Several minutes later, residents saw the roofs of the buildings and silos on their farms start flying in violent winds from the northwest. The air temperature dropped while a severe thunderstorm was in progress to the north.

When the outflow wind blew toward the south of the mesocyclone center, both tornadoes were blown in toward the mesocyclone. The anticyclone tornado weakened and disappeared. But the cyclonic tornado made its way into the mesocyclone, becoming an integral part of a wide path of the damaging wind extending to Story City.

(G) LEMONT Tornado, Illinois (13 June 1976)

At 1718 CDT a powerful tornado touched down in Lemont, Illinois, some 24 mi west-southwest of Downtown Chicago. As it travelled southeast, the tornado center moved along a looping path. Characterized by a huge column of swirling dust, about 500 m (0.3 mi) in diameter, the cyclonic tornado reached F4 intensity.

A few minutes later at 1730 the tornado began making a sharp left turn toward the north. Suddenly two anticyclonic tornadoes, A1 and A2, formed one after another to the west and southwest of the parent tornado. Those who were near the tornadoes were confused. Some thought that it was one tornado which was moving back and forth, while others believed that tornadoes were popping up everywhere.

A severe thunderstorm was in progress to the northeast of the tornado area. Aerial survey showed that there was severe tree damage especially to the northwest of the tornado center. It is very likely that a super-

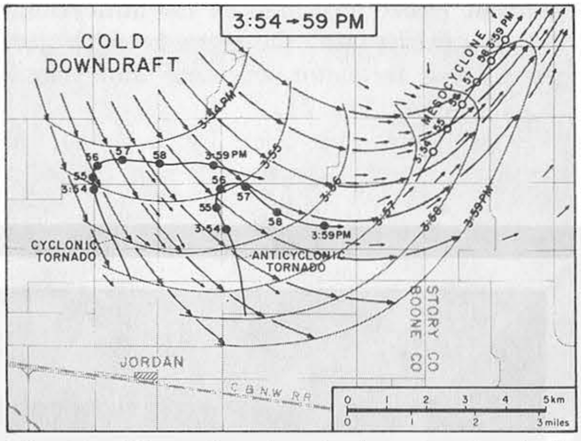


Fig. 20. The paths of cyclonic and anticyclonic tornadoes which were blown back toward the parent mesocyclone. Between 3:54 and 3:49 PM CDT 13 June 1976.

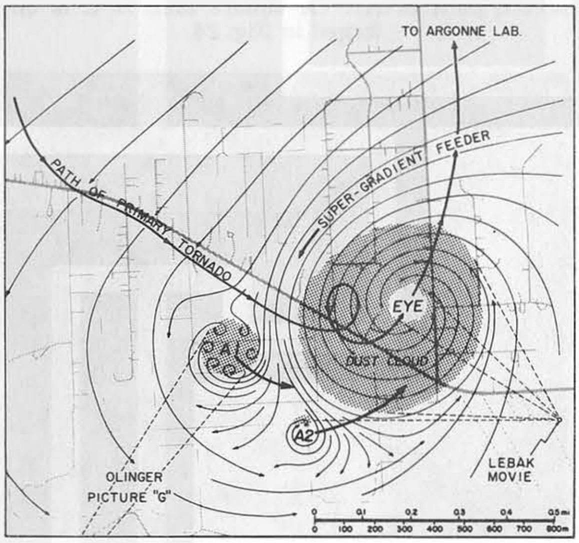


Fig. 21. Location of two anticyclonic tornadoes in relation to a violent tornado near Lemont, 24 miles southwest of Chicago.

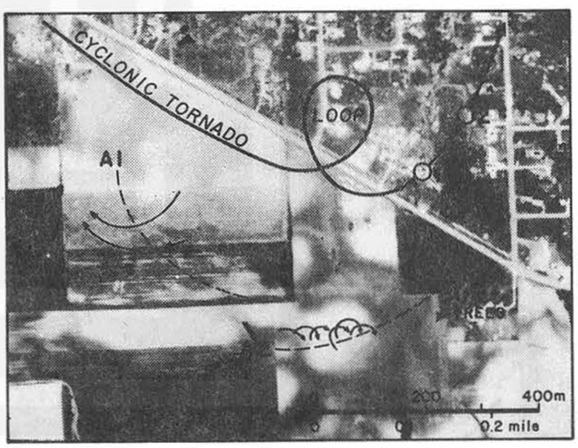


Fig. 22. The paths of cyclonic and anticyclonic tornadoes superimposed upon an aerial photograph. Anticyclonic tornadoes, A1 and A2 formed when parent tornado was at 1 and 2, respectively.

gradient feeder flow induced the anticyclonic source vorticity near the ground, which gave rise to the formation of these anticyclonic tornadoes (see Fig. 21).

Aerial photographs taken by the author the

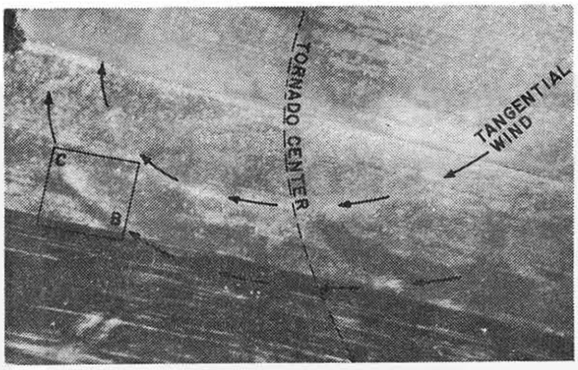


Fig. 23. An enlarged view of the wheat field in the path of A1. A square area B C is enlarged in Fig. 24.

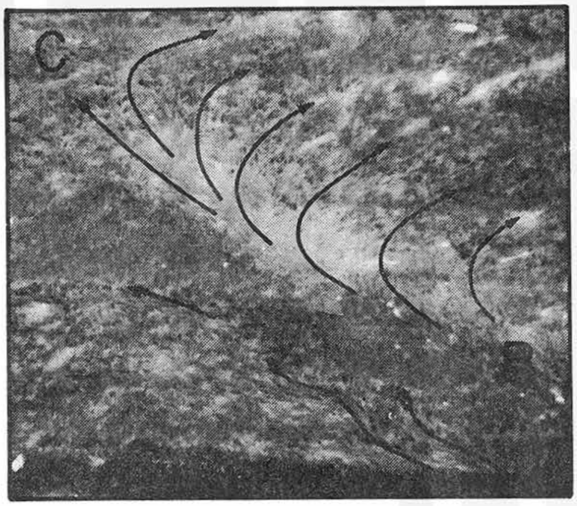


Fig. 24. Close-up view of the area B C from 30m (100ft) above the field.

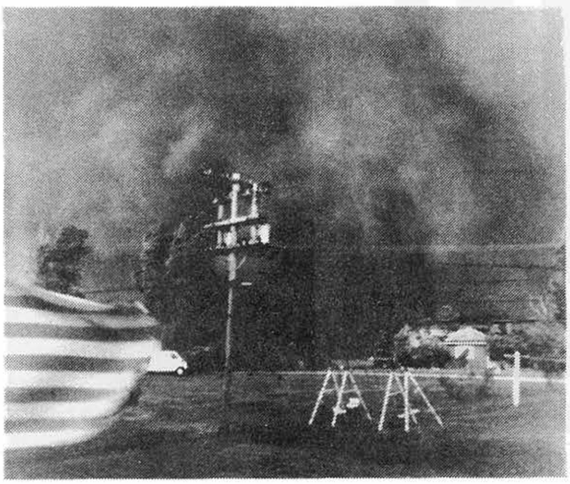


Fig. 25. Anticyclonic tornado, A1 in action viewed from the southwest. Courtesy of Mrs. David Olinger.

next morning revealed the existence of anticyclonic disturbances, A1 and A2 in Fig. 22. A wheat field was blown down, leaving behind two distinct patterns of tangential winds that had swept the field anticyclonically (see Fig. 23). A close-up view of the wheat field in Fig. 24 was taken from a helicopter 30 m (100 ft) above the field. This picture shows fossilized stream lines evidenced by the blown-down wheat.

This anticyclonic tornado in action was photographed by Mrs. Olinger from her house, 1,100 m (0.7 mi) to the southwest (see Fig. 25 and Fig. 26).

Anticyclonic tornado, A2, left behind remarkable cycloidal marks on a plowed field. They are similar to those reported by Fujita, Forbes, and Umenhofer (1976). Due to clockwise swirl and its movement toward the east-northeast, scalloping marks are seen predominantly along the north edge of the path (see Fig. 27).

Analyses of Mr. Edward Lebak's movie, looking west from 800 m (0.5 mi) away, revealed that there were fast-rising columns of dust directly over these cycloidal marks (see Fig. 28).

A sequence of four pictures in Fig. 28 was made by enlarging every 4th frame of his super-8 movie. The picture interval is 0.22 second. The dust column, 6 to 7 m (20 ft) in diameter rose from 14 m (left frame) to 25 m (right frame) in 0.66 sec. During this period the vertical velocity of the top increased from 15 to 18 m/s. The vertical acceleration at the 25 m height was 0.7 g, and that at the 14 m height was 0.8 g, the gravitational acceleration. Estimated vertical acceleration of the swirling air just above the ground is far in excess of 1 g; possibly over 2 g.

The term "suction spot" was first introduced by Fujita (1967) about 10 years ago, based on cycloidal marks left by the Palm Sunday tornadoes of 11 April 1965, which consisted of debris accumulation rather than evacuation.

Now, the Lebak movie reveals that suction spots/vortices existed inside an anticyclonic tornado, and that the vertical acceleration of the air rushing into the vortices was in excess of the gravitational acceleration. A suction vortex, by virtue of its small diameter and fast spin rate, generates a "swirling upburst" around its center near the ground.

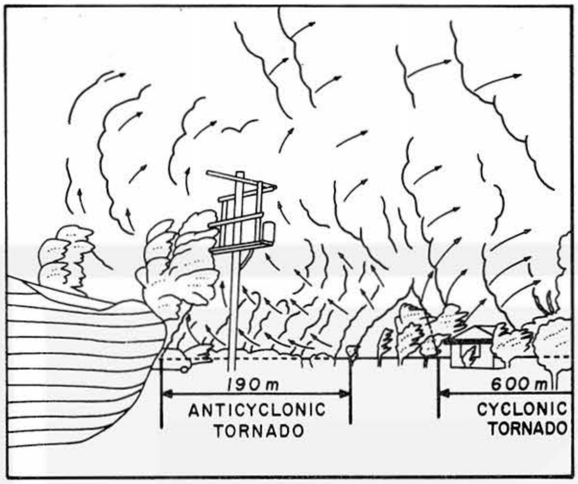


Fig. 26. Schematic flow patterns of swirling dust clouds in Fig. 25. Note that the axes of dust columns above the ground tilt backward as they swirl around the parent anticyclonic tornado center.

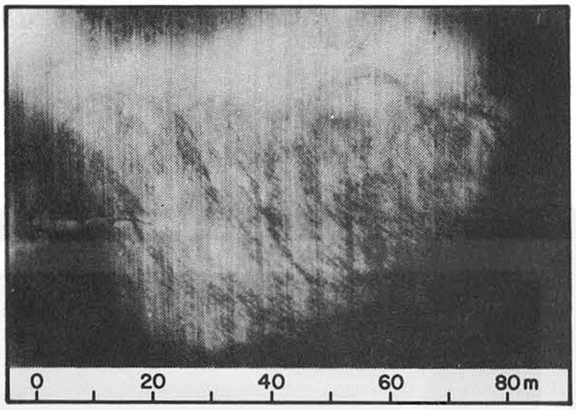


Fig. 27. Cycloidal marks, such as reported by Fujita et al (1976), left behind by anticyclonic tornado A2. The tornado center moved from left to right across the picture.

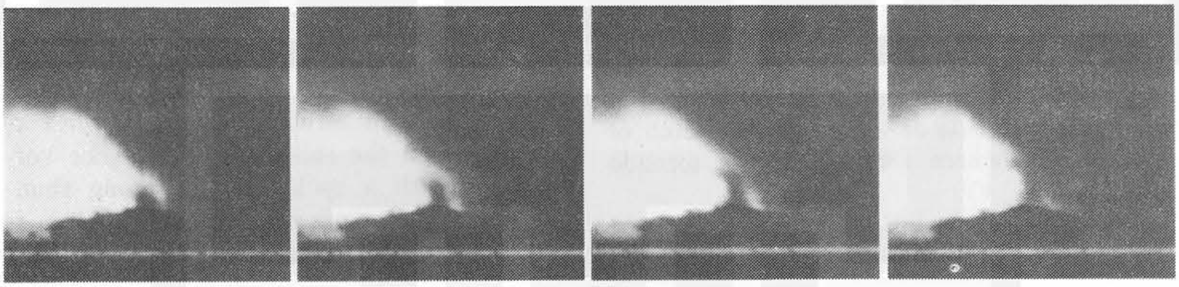


Fig. 28. Vertical growth of a dust column swirling inside a suction vortex around anticyclonic tornado A2. The vertical acceleration near the ground is estimated to be 1 to 2 g, the gravitational acceleration. One of the cycloidal marks in Fig. 27. was produced by this suction vortex. Courtesy of Edward Lebak.

Laboratory Model Experiment

There is much evidence that most maxi-tornadoes form beneath rotating-thunderstorms which are detected by Doppler radars. These thunderstorms may appear as hooks on PPI radar scopes, sometimes visible to the naked eye as giant rotating clouds.

A conceptual model of a rotating cloud at the University of Chicago generates a tornado-like vortex made visible by dry-ice "smoke." The rotating cloud is simulated by mechanical chopper-cups designed to turn cyclonically.

A "cyclonic" tornado forms when cups rotate cyclonically while the air is being drawn upward through holes at the cloud-top level (see Fig. 29).

An "anticyclonic" tornado can be created, at will, beneath the identical cloud rotating cyclonically. To do this, however, we have to introduce an anticyclonic vorticity near the surface where the dry-ice "smoke" is released through tiny holes (see Fig. 30).

This experiment reveals clearly that either a cyclonic or an anticyclonic tornado can be created beneath a "cyclonically rotating cloud." Apparently, it is the vorticity source near the

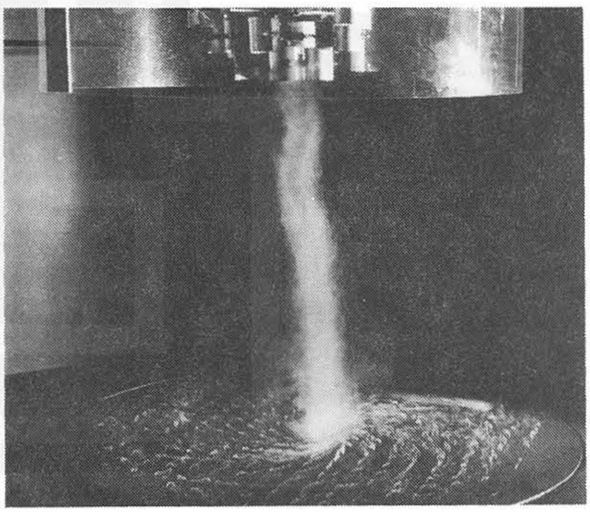


Fig. 29. A cyclonic tornado beneath a cyclonically-rotating cloud simulated by turning chopper-cups. The motion of the cups is frozen due to the use of an electronic flash.

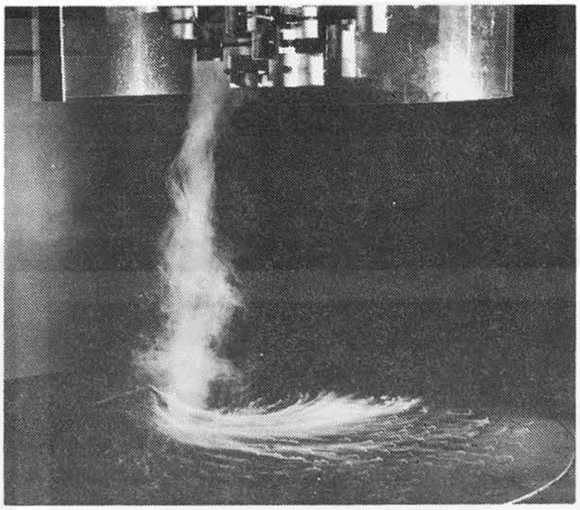


Fig. 30. An anticyclonic tornado beneath a cyclonically-rotating cloud. In this case an anticyclonic shear vorticity was added near the surface.

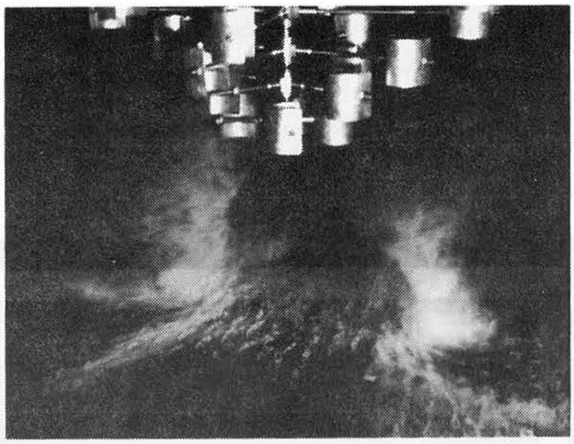


Fig. 31. A pair of anticyclonic and cyclonic tornadoes developed beneath a cyclonically-rotating cloud. In this experiment a low-level jet, blowing from lower-left to upper-right was added. Courtesy of Gregory Forbes.

surface (refer to Fig. 5) which determines the tornado's sign of rotation, no matter which direction the cloud aloft rotates. The rotating cloud acts as an agent to stretch or spin up the source vorticity into a tornado (refer to Fig. 4).

Even a pair of anticyclonic and cyclonic tornadoes can be generated beneath a rotating cloud. A vortex pair of Fig. 31 was created by adding a horizontal jet just above the surface beneath the cyclonically-rotating model cloud.

The Golitzino, Iioka, and Monroe tornadoes might have been caused by the mechanism shown in Fig. 31.

The Three-farm and possibly the Freedom tornado formed when an anticyclonic source vorticity was stretched (see Fig. 30) by a rotating thunderstorm which also spawned a cyclonic tornado nearby.

Two Lemont tornadoes developed on the fringe of a giant cyclonic tornado. It is very likely that the anticyclonic source vorticity induced by the super-gradient inflow was stretched by the vertical-motion field around the parent tornado (see Fig. 30).

Conclusions

Anticyclonic tornadoes have been thought to be extremely rare. This study revealed, on the contrary, that these storms could be found more often. Furthermore, anticyclonic tornadoes may frequently develop in the vicinity of a cyclonic tornado. Their separation may vary from several miles to a fraction of a mile, sometimes standing side by side.

Evidence of actual phenomena along with laboratory experiments, suggests that a rotating thunderstorm stretches vertically the vorticity field in the subcloud layer. The vorticity beneath a cyclonically rotating thunderstorm is predominantly cyclonic. This is why cyclonic tornadoes are prevalent. But if a significant anticyclonic vorticity field forms beneath the cloud, an anticyclonic tornado may develop. The importance of the vorticity field of the planetary boundary layer in relation to tornado formation should be re-emphasized.

As a matter of both scientific interest and public safety, it should be recognized that anticyclonic tornadoes may develop in the vicinity of a cyclonic tornado.

References

Burgess, Don W. (1976): *Weatherwise,* **29**, Front Cover.

Fujita, T. Theodore (1967): Estimated Wind Speeds of the Palm Sunday Tornadoes. SMRP Res. Paper No. 49, Univ. of Chicago, 25 pp.

Fujita, T. Theodore (1975): New Evidence from April 3–4, 1974 Tornadoes. Preprint, 9th Conf. on Severe Local Storms, AMS, 248-255.

Fujita, T. T., 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.

Japanese Storm Data (1967): *Kisho Yoran,* October 1967. Japan Meteorological Agency, Tokyo (in Japanese).

Kolobkov, H. B. (1957): Smirch near Moscow. *Meteorology and Hydrology, Leningrad* **6**, 32–33 (in Russian).

Snider, C. R. (1976): An Anticyclonic Tornado. *Mon. Wea. Review,* **104**, 1186–87.

Storm Data (1975): Texas, June 1975, p. 27.