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Department of the Geophysical Sciences
The University of Chicago

AN ANALYSIS OF THREE WEATHER-RELATED AIRCRAFT ACCIDENTS

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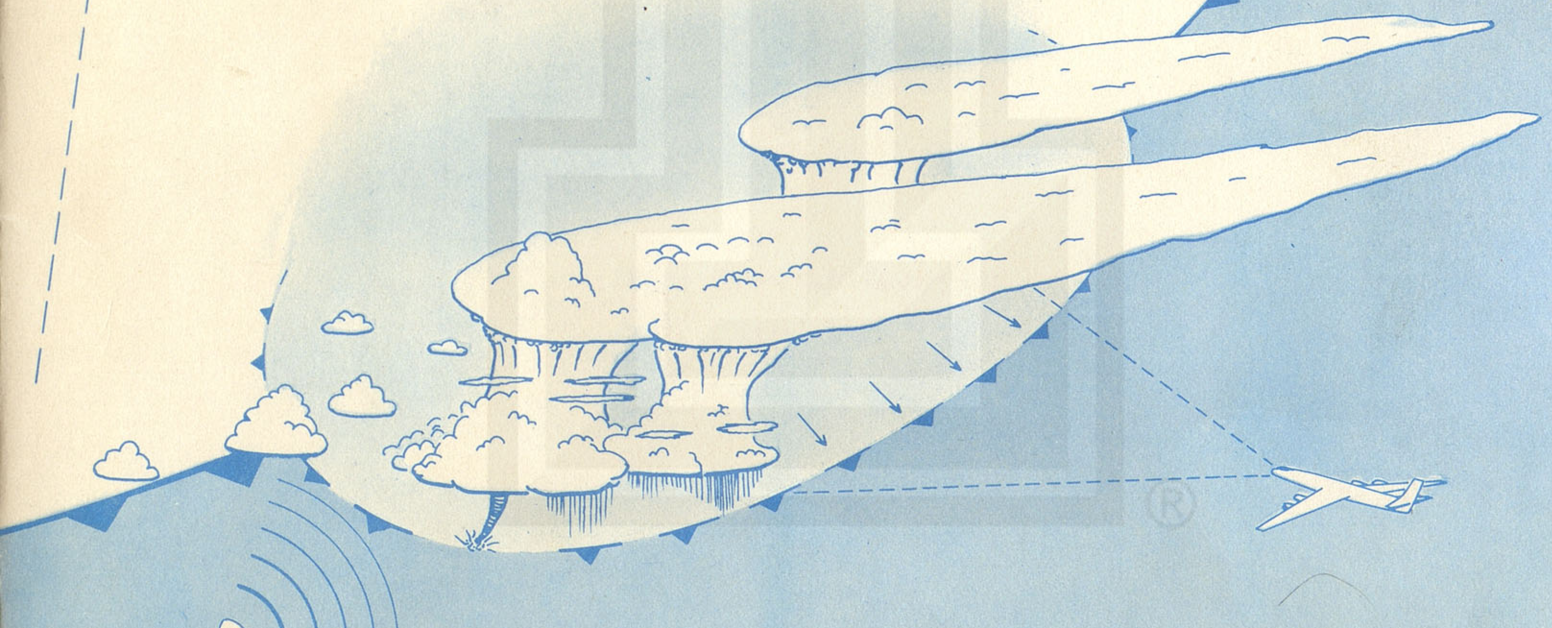
(To be published in Bulletin of American Meteorological Society)



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T. Theodore Fujita[2]

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Abstract: Two aircraft accidents in 1975, one at John F. Kennedy International Airport at New York City on June 24 and the other at Stapleton International Airport at Denver on August 7, were examined in detail. The third accident on June 23, 1976 at Philadelphia International Airport is being investigated. Amazingly, there was a spearhead echo just to the north of each accident site. The echoes formed from 5 to 50 minutes in advance of the accident and moved faster than other echoes in the vicinity. These echoes were photographed by NWS radars, 70 to 110 n. miles away. At closer ranges, however, one or more circular echoes were depicted by airborne and ground radars. These cells were only 2 to 3 miles in diameter, but were accompanied by downdrafts of extreme intensity called downbursts. All accidents occurred as aircraft, either descending or climbing, lost altitude while experiencing strong wind shear inside downburst cells.

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1. Introduction

Tragic airline accidents in recent years have brought out the extreme hazard of intense downdrafts at approach and climb-out levels in thunderstorms at airports.

Eastern Flight 66, inbound from New Orleans on June 24, 1975, was driven down to the ground, 2400 ft short of runway 22-L of John F. Kennedy International Airport, New York City; one hundred and thirteen persons died. About six weeks later, on August 7, Continental Flight 426 suffered a severe and abrupt loss of airspeed after being airborne from runway 35-L of Stapleton International Airport at Denver, Colorado. The aircraft hit the ground, just to the right of the runway, 390 ft (120 m) short of the departure end. Fifteen persons received injuries and 119 others escaped injury. Thunderstorm-induced wind shear gained sudden notoriety in the summer of 1975 as a result of these two accidents, the cause of which can be traced back to the long recognized downdraft currents.

Downdrafts, as descriptive phenomena beneath thunderstorms, have been known to meteorologist long before the aviation age. According to Ludlam's (1963) review of severe local storms, Moller (1884) and Davis (1894) published their models of thunderstorms with downdrafts. Wegener (1911), known as the originator of the Continental Drift theory, speculated on the downdraft in thundershowers. In his article on thunderstorms and aviation, Simpson (1924) described a model storm including both up- and downdrafts. Suckstorff (1938) presented a concept of downdraft which spreads out beneath the thunderstorm, resulting in an outflow of cold air.

These conceptual models of downdrafts presented in early years are informative. From an applications point of view, however, these models were not quantitative enough for assessing both vertical currents and wind shear beneath thunderstorms.

The Thunderstorm Project operated in Florida in 1946 and Ohio in 1947 was the major attempt to measured both horizontal and vertical air currents in and around thunderstorms. Based on the project data, Byers and Braham (1949) established the three stages of the storm cells. They are (1) cumulus stage with updraft throughout the cell, (2) mature stage with coexisting up-and downdrafts, and (3) dissipating stage dominated by the downdraft which eventually weakens and disappears.

A typical downdraft spreads out rapdily as it hits the surface. An example of the fast-spreading downdraft is shown in Fig. 1. As seen in the figure, a new echo formed on the north boundary of an old downdraft. At 3:30 p.m., the downdraft from the new echo reached the surface and started spreading. The old echo weakened and then disappeared.

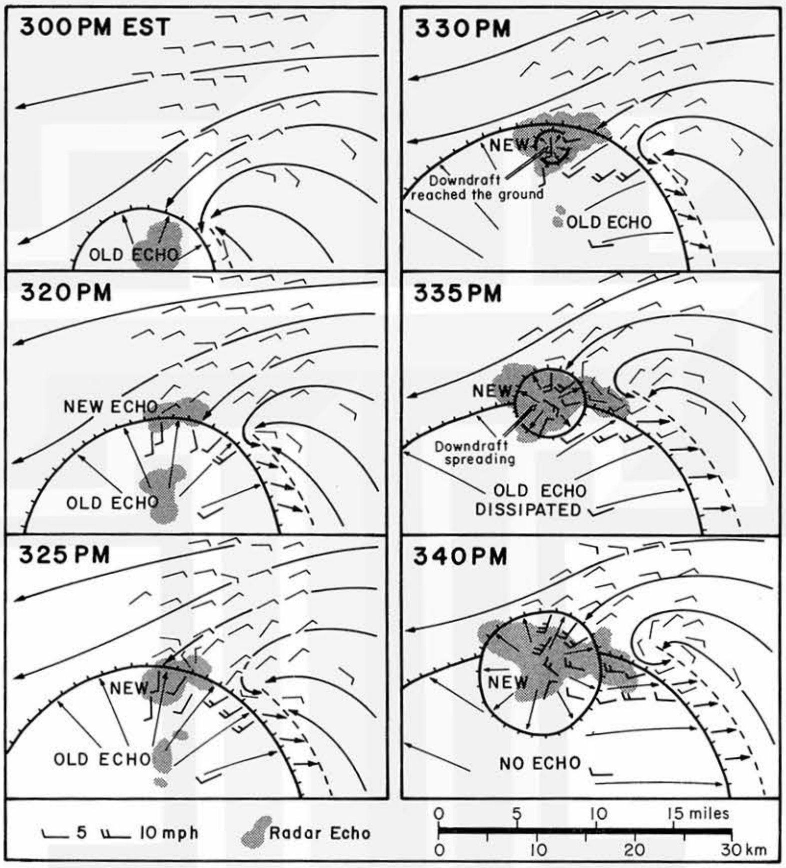

Fig. 1. Formation and development of downdraft cells depicted by mesoanalysis maps drawn at 5-min intervals. Based on the Thunderstorm Project data on August 13, 1947, analyzed by Fujita (1963). Cells were located about 30 miles east of Cincinnati, Ohio.

The growth of the downdraft size can effectively be shown by plotting the diameter of the spreading edge as a function of time (see Fig. 2). The diameter increased, more or less, in proportion to the time after the onset. The fastest outflow and divergence reached their peaks within only 10 to 15 min. The downdraft cell weakened thereafter, indicating the major thrust of a downdraft can be expected to occur shortly after it reaches the surface.

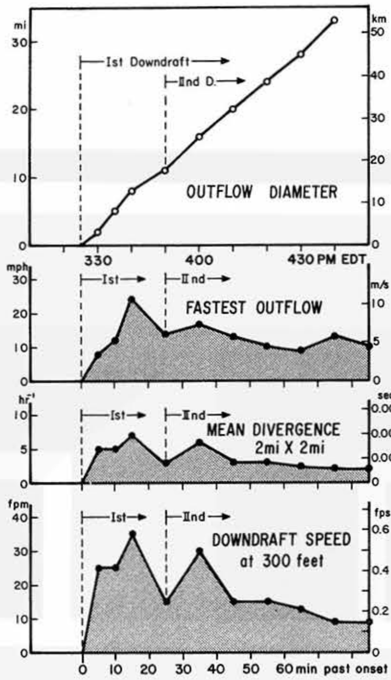

Fig. 2. Time variations in various parameters of the downdraft/outflow cells analyzed in Fig. 1. The new echo generated two downdraft cells at about 325 pm and 350 pm. Note that the effects of these downdrafts reached the peaks only 10 to 15 min after the formation. Downdraft speeds at 300 ft were computed by assuming that the mean divergence at the anemometer level remains constant between the surface and the 300-ft level. Actual draft speeds may reach several times the value shown in the figure.

By virture of their fast spreading rate, downdrafts from several to tens of thunderstorms amalgamate into a large dome of the rain-chilled cold air. The surface pressure inside the dome of cold air is higher than that of its environment, thus forming a mesoscale high-pressure area, called the "mesohigh." Mesoscale in meteorology is the horizontal size of wind systems extending one to several hundred miles. For details, refer to Fujita (1963). Low-flying aircraft often encounter a significant wind shear along the leading edge of an advancing mesohigh, identified as the wind-shift line, the shear line or gust front (see Fig. 3).

To be expected behind the shear line are the cold, plow winds which push the cold dome out into the warm air. Since the spreading of cold air is predominantly a subcloud phenomenon, the speed of the plow winds is insignificant above the convective cloud base.

A barograph often records a sudden rise in pressure as a shear line passes over a recording station. Depending upon the rate of pressure change, a shear line is called the pressure-surge line or pressure-jump line. Quite often, the pressure literally jumps several millibars.

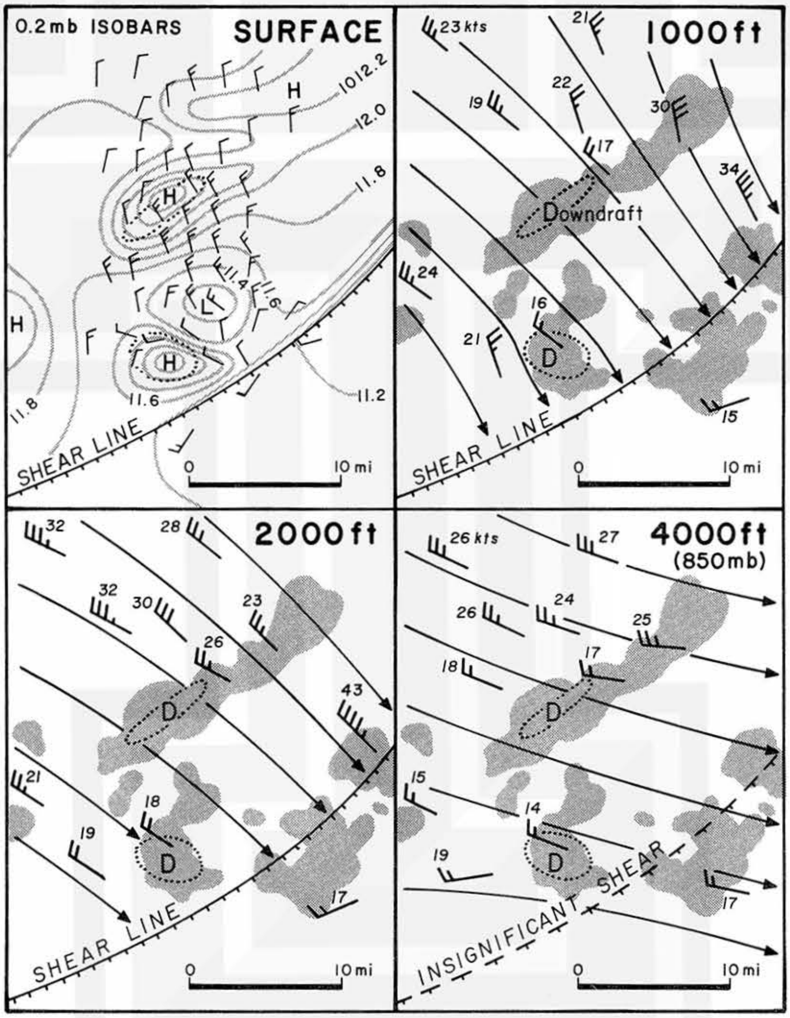

Fig. 3. Mesoanalysis maps showing the pressure noses imbedded inside a large, mesoscale dome of outflow. Severe wind shear at low level is expected to occur along the shear line, as well as inside the nose areas, only a few miles across. Based on the Thunderstorm Project, Ohio data on June 29, 1947. From Fujita (1963).

The pressure distribution inside a mesohigh with active thunderstorms is by no means smooth. Imbedded inside the overall high pressure area are peaks of pressure called pressure noses. A pressure nose is found where a strong downdraft hits the surface and spreads out. The active stage of the pressure nose is short, less than 10 to 15 minutes, covering an areas no more than several miles in diameter. No matter how prominent a pressure nose is, it will eventually be flattened to become an integral part of the pressure dome. The dynamic pressure directly beneath the downdraft and the weight of the descending cold air are the major causes of the pressure nose.

The foregoing characteristics of the winds beneath thunderstorms suggest the existence of two types of wind shear. The first type is located along the leading edge of the pressure dome generated by a joint effort of many thunderstorms in various stages. The shear line is usually long, extending along the entire length of an advancing squall line. Practically all aircraft which fly through the line at low altitudes are affected to a certain degree. An advanced, short-time warning on expected windshear can be transmitted to the penetrating aircraft. If necessary, an airport can be closed during the short time of the shear-line passage.

The second type, which is likely to be responsible for the three accidents discussed in this paper, is the wind shear within the pressure nose area. It is very difficult to warn of this type of shear, because of its short life and small area. One aircraft could experience serious difficulties while others are able to perform near-normal landings or takeoffs.

Evidently, concentrated downdrafts have been reported from all over the world. Wichman (1951), for instance, constructed a model of an asymmetric thunderstorm, in which an intense downdraft from near the cloud top descends straight down to the ground. In studying Japanese thunderstorms, Fujita (1951) estimated a 7 m/sec downdraft inside the nose area.

In the early days of aviation history, these two types were put into one basket. For example: "... that some thunderstorms are preceded by a strong squall wind (down draft)..." from "Thunderstorms," a section of Meteorology Circular No. 6, United Airlines, June 15, 1939. Another example, "Generally, a locality on the ground is reached first by the heavy downdraft squall which is found on the lee side of the cloud," from the 1940 edition of "Basic Aeronautical Meteorology" by the Boeing School of Aeronautics. There has been no confusion regarding the two types of wind systems since they were clarified by the Thunderstorm Project in 1946 and 1947.

2. Downdraft and Downburst

A larger number of tropical cyclones develop in the tropics each year but only a few of them grow to extreme intensity. When the maximum windspeed inside a tropical cyclone exceeds 64 knots (73 mph) or 32.6 m/sec, the storm is called a hurricane. The 73-mph threshold speed of a hurricane has little physical meaning, because the storm structure does not change at this windspeed. A hurricane is a tropical storm of an extreme intensity. Although the introduction of the term "hurricane" has no technical connotation, it serves the purpose of alerting people more explicitly than the modified terms such as "strong tropical storm," "damaging tropical storm," "intense tropical storm," etc.

In the "Glossary of Selected Terms", Miller (1972) introduced the term "downrush" as being the downward-flowing air currents associated with thunderstorms. This term gives one the impression that the downrush is stronger than "downdraft", defined by Byers and Braham (1949).

Fujita (1976), and Fujita and Byers (1977) proposed using the term "downburst" when the downdraft speed becomes comparable to or greater than the approximate rate of climb or descent of a jet aircraft on the final approach or takeoff. A downburst, therefore, is a downdraft in the uppermost intensity category, endangering aircraft operation near the ground.

Table 1. Typical rate of climb of B-727 during the descent and climb below 300 ft above runway

Rate	fps	fpm	m/sec
Climb at Denver	17 to 28	1000 to 1700	5 to 9
Descent at JFK	10 to 13	600 to 800	3 to 4

This table shows that 10 to 13 fps (3 to 4 m/sec) is comparable to the descent rate, although it is much smaller than the climb rate. In view of the necessity that an alarming term should be adopted based on conservatism, 12 fps (3.6 m/sec) at 300 ft was selected as the threshold speed of the downburst.

The aerial extent of the downburst was chosen to be ½ miles or larger, mainly because an aircraft is able to fly through a mini-draft area in a few seconds with a short jolt. If we assume a linear change of draft speed along the vertical, the mean divergence in the downburst area should be larger than

$$12 \text{ fps} / 300 \text{ ft} = 0.04 \text{ sec}^{-1}$$

or

$$0.04 \text{ sec}^{-1} = 144 \text{ hr}^{-1}$$

Table 2. Definition of downburst

	Downdraft	Downburst
Draft velocity at 300 ft	less than 12 fps	12 fps or larger
Divergence inside 0.5-mile diameter	less than 144 hr^{-1}	144^{-1} or larger

DOWNBURST - A localized, intense downdraft with vertical currents exceeding the downward speed of 12 fps (3.6 m/sec) at 300 ft (91 m) above the surface. The aerial extent of a downburst is 0.5 mile (800 m) or larger in diameter, characterized by a 144 hr^{-1} (0.04 sec^{-1}) or larger divergence.

The largest divergence published in "The Thunderstorm" was about 20 hr^{-1} which is only a fraction of the 144 hr^{-1}, the threshold of the downburst. This is because the smaller the area of measurement, the larger the computed divergence. Another reason might be the lack of downburst cells during the periods and the areas of the Thunderstorm Project in 1946 and 47.

Shown in Fig. 4 are the divergence values computed beneath 32 downdraft cells analyzed and published in "The Thunderstorm". To determine the influence of horizontal dimensions, the computation areas were selected as 6, 5, 4, 3 and 2 miles in diameter. As expected, the maximum divergence increases as diameter decreases. Due to the network resolutions, one mile in Florida and two miles in Ohio network, areas of

2-mile diameter were chosen as the smallest areas for which a reasonable divergence can be computed. To estimate the values for 0.5-mile diameter, the curve will have to be extrapolated like A (25 hr^{-1}), B (35 hr^{-1}), or C (50 hr^{-1}). Extreme values, which are most unlikely to occur, can be computed by concentrating the downdraft into smaller areas such as 1.8, 1.6, 1.4, 1.2-mile diameters.

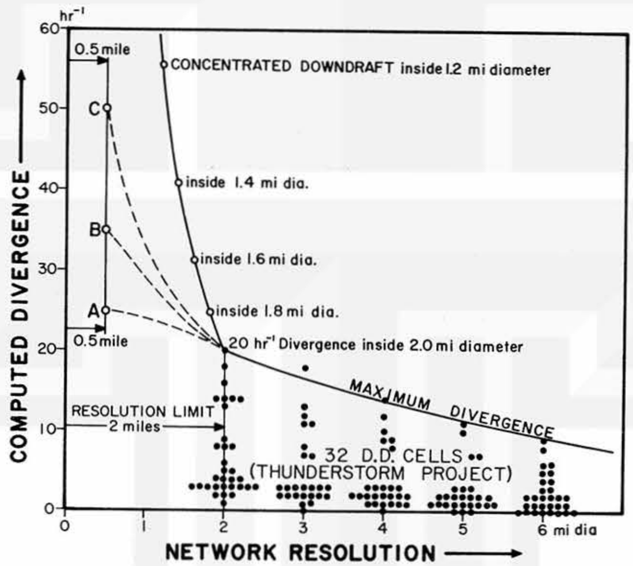

Fig. 4. Divergence values computed as a function of the area within the downdraft/outflow cells over the Thunderstorm Project network in Florida and ohio. Divergence inside the areas of 0.5-mile diameter can't be estimated accurately without knowing the distribution of the draft speeds within the reso lution limit, one to two miles in this case.

Recent development of Dual-Doppler systems will permit us to estimate the divergence with much better resolution than that of surface networks. Doppler investigation of a July 28, 1973 thunderstorm in northeast Colorado by Kropfli and Miller (1976) is presented in Fig. 5. In this example, Doppler velocities of precipitation near the surface were computed for every 0.5 mile (800 m) grid spacing. These velocity fields clearly show interaction of multiple outflow systems and their asymmetry. In terms of divergence, cells B and C are rather weak (see Table 3).

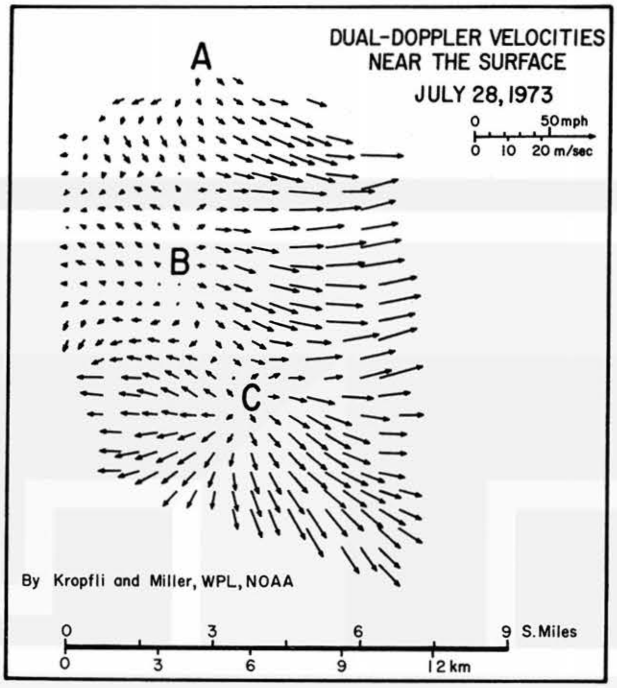

Fig. 5. Dual-Doppler system provides us with a new method of computing divergence values beneath precipitating cells. Cells A, B, C are downdraft cell, being characterized by up to 17 hr divergence. Courtesy of Kropfli and Miller (1976).

Table III. Spatial variation of divergence of the July 28, 1973, storm by Kropfli and Miller (1976).

Computation Diameter	1.0	2.0	3.0	4.0 miles
Cell B	12.0	11.2	9.5	7.4 hr^{-1}
Cell C	16.0	16.1	15.8	11.2 hr^{-1}

This table reveals that both cells are characterized by 11 to 16 hr^{-1} divergence inside the 2-mile diameter. The values are no more than those measured in the Thunderstorm Project. Even by reducing the computation diameter to 1.0 mile, the divergence remains almost unchanged. These cells are, thus, by no means the downburst category. In future years, some downburst cells with divergence in excess of 144 hr^{-1} will be measured by Dual-Dopplers, the most effective tool for investigating the velocity field of thunderstorms.

Since the vertical current of the downburst spreads out in the form of an *outburst*, a landing aircraft will first encounter a headwind, then downburst, and finally a tailwind (see Fig. 6). A similar sequence of headwind, downburst, and tailwind will be experienced by a climbing aircraft immediately after the liftoff. In either case, the aircraft could most likely fly out of the danger, provided that the intensity of a draft cell is that of a downdraft. When a downburst is encountered, especially at a crucial moment, the chance of fly-out depends upon various factors, such as the extent and intensity of downburst, the altitude and airspeed, the pilot response, etc.

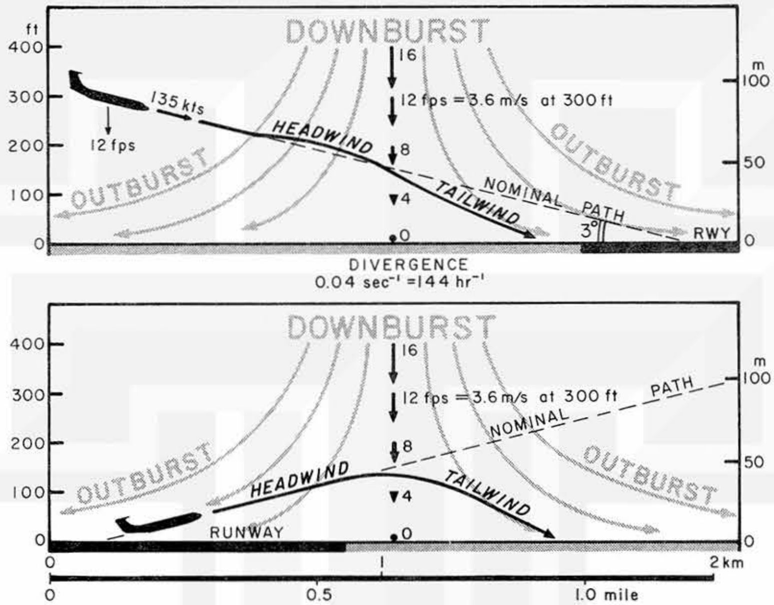

Fig. 6. Schematical diagrams of flight paths under the influence of a downburst cell.

3. June 24, 1975 Accident at JFK, New York City

It was a very hot, smoggy day in New Jersey where 90 to 93°F temperatures were reported early in the afternoon. At 1900 GMT (3:00 PM local time) several weak thunderstorms formed in northern New Jersey and headed toward Long Island. John F. Kennedy International Airport (JFK) was enjoying 77°F under the influence of the sea breeze.

It was approximately 1915 GMT (3:15 PM) when a small, pendant echo formed on the east edge of a large echo north of Morristown Airport, New Jersey. While other echoes were moving at 16 kt, the pendant echo extended toward JFK at 30 kt. As the pendant was moving across Manhattan, it became so large that its tail end began swallowing the parent echo into its pendant body. By 1945 GMT (3:45 PM) the parent echo lost its identity, having been absorbed entirely into the pendant which had grown into a spearhead echo both in shape and fast speed. For details, refer to Fujita (1976) and Fujita and Byers (1977).

During the 25-minute period between 1945 and 2010 GMT (3:45 - 4:10 PM) fourteen aircraft either landed or attempted to land on raunway 22-L at JFK Airport. An estimate 1500 persons in three 747s, and other jet landed at JFK. Each of the 14 aircraft flew through a portion of the spearhead echo, experiencing situations ranging from no problems to serious difficulties.

The flight paths in relation to the spearhead echo, moving ESE at 30 kt, are presented in Fig. 7. Note that six were international flights, four of which came from European countries. It was the businest time of the day, and the approach and landing took place as follows. For details refer to NTSB (1975).

<u>AMERICAN 678 from San Juan</u>. Encountered some wind shear on final approach but it was not significant enough to mention to the tower. (3:44 PM)

<u>AMERICAN 187 from Boston, Mass</u>. Sighted a thunderstorm about one mile to the right of the approach path, just short of runway 22-L. (3:46 PM)

<u>ALLEGHENY 858 from Syracuse, NY</u>. Experienced downdraft one mile from the end of runway 22-L. Landed in light rain. (3:48 PM)

<u>TWA 843 from Milan, Italy</u>. The approach and landing were normal. Landed on dry runway. (3:49 PM)

<u>SAS 911 from Copenhagen, Denmark</u>. There was little rain on touchdown. (3.51 PM)

<u>KLM 641 from Amsterdam, Holland</u>. Rain stopped at touchdown. First half of the runway was wet but the other half was dry. (3:52 PM)

<u>PAA 133 from Bermuda</u>. 18 kt crosswind from right at 200 ft in extremely heavy rain. After rolling for 1000 ft, broke out on dry runway in sunlight. While on the taxiway, the pilot saw the next aircraft, Flying Tiger, in difficult landing maneuver. (3:54 PM)

<u>FLYING TIGER from Harrisburg, Pa</u>. Encountered strong, sustained downdraft (downburst) from 700 to 200 ft altitude. From 200 ft to touchdown the downdraft was moderate, but the crosswind from the right

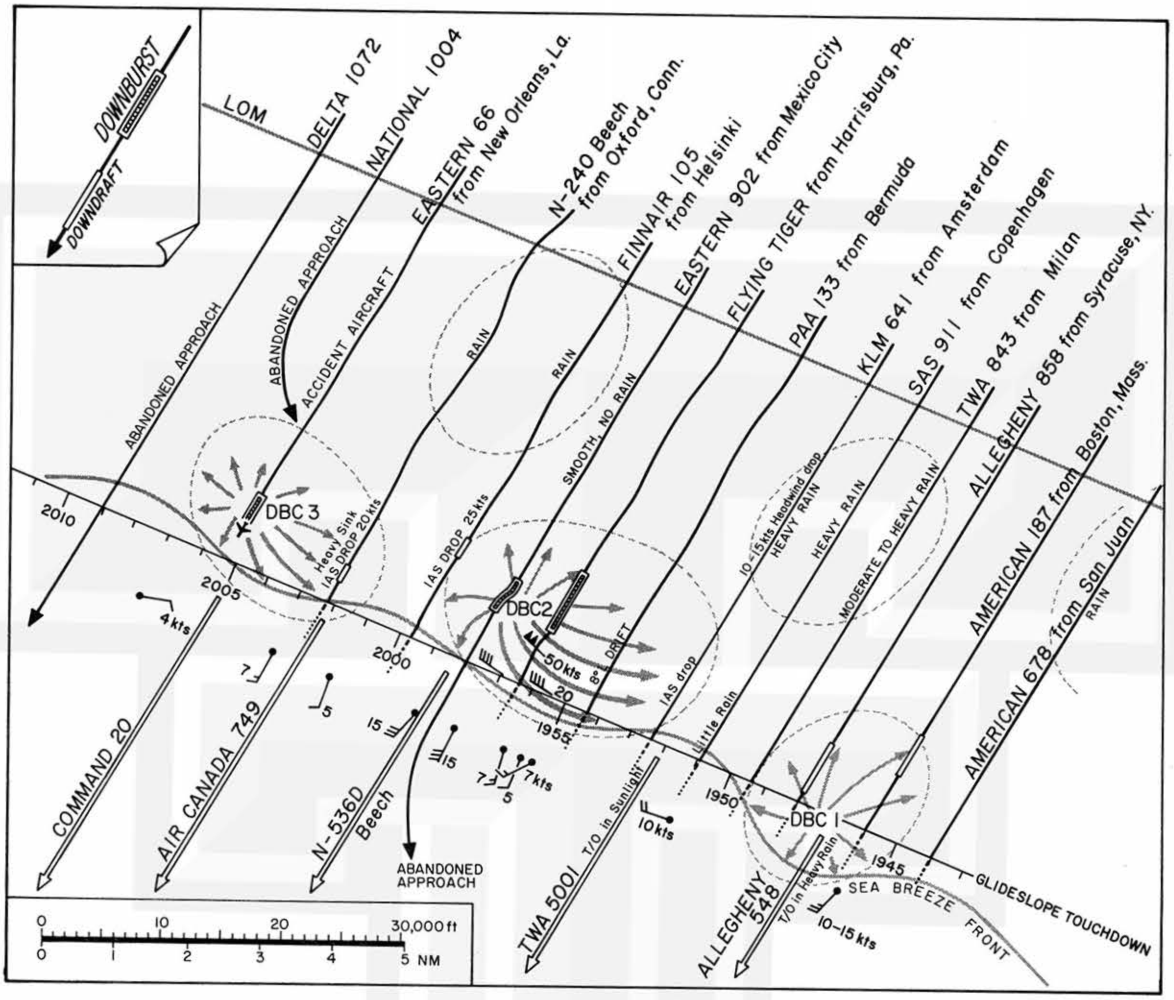

Fig. 7. Paths of 14 aircraft in 25 min at JFK Airport on June 24, 1975. Each path was shifted toward the west-northwest at 30 kt to convert the time into the space relative to the spearhead echo. The echo, as seen by Atlantic City radar, was 20 miles long and 8 miles wide, covering the entire area between LOM (Localizer Outer Marker) and the north end of 22-L. There were down burst cells (DBC) along the south edge of the spearhead echo. Five aircraft took off inside the sea breeze with out being affected by downbursts.

was very strong. It was blowing 50 to 55 kt just off the ground, and, all of a sudden, there was no wind on the ground. (3:56 PM)

EASTERN 902 from Mexico City. Air was smooth and normal down to 400 ft. They flew into extremely heavy rain with zero visibility. Aircraft sank and drifted to the right. Airspeed dropped from 144 to 121 kt. Applied power for abandoned approach. L-1011 kept sinking down to 60 ft (18 m) above the ground before the pilot was able to gain altitude (see Fig. 8). (3:58 PM)

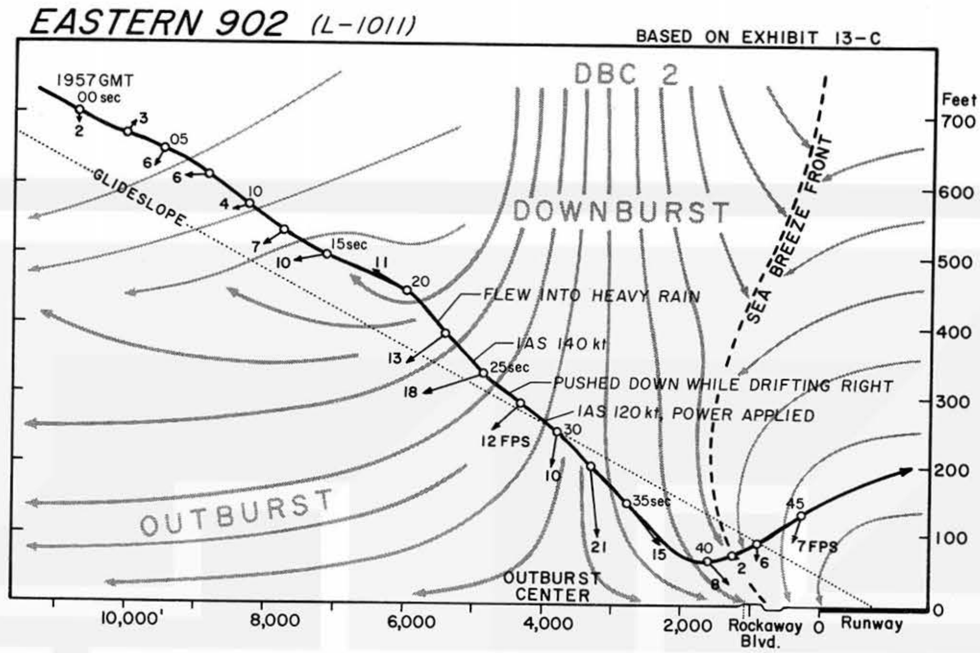

Fig. 8. The path of Eastern 902 on June 24, 1975 in the vertical plane including the glideslope of 22-L at JFK.

FINNAIR 105 from Helsinki, Finland. About 2 miles before touchdown, airspeed dropped 25 kt. The subsequent approach and landing were normal. (4:00 PM)

N-240V, Beech. A heavy sinking was experienced at 200 to 300 ft altitude. Airspeed dropped 20 kt. Applied power. Remainder was normal. (4:02 PM)

EASTERN 66 from New Orleans, La. Encountered heavy rain at 500 ft altitude and wiper was operated at high speed. Approach lights were visible at 400 ft, then airspeed dropped from 138 to 122 kt in 7 seconds. Sank in 22 fps downburst at 200 ft altitude. Hit approach lights at 2005 GMT (4:05 PM), about 2,400 ft short of runway (see Fig. 9). (4:05 PM)

NATIONAL 1004. While approaching, 6 to 8 miles to runway, saw a circular echo, 2 to 3 miles in diameter, moving eastward very rapidly. The echo reached over threshold of 22-L at 2006 GMT (4:06 PM). Airport was closed due to the accident. Made an immediate left turn in front of the echo and climbed for landing at La Guardia. (4:07 PM)

DELTA 1072. At about 1,500 ft altitude it was told by the tower to go-around. Climbed back to 2000 ft and flew to runway 22-L. While over the threshold, saw a circular echo moving away toward the east. Diverted to Newark. (4:09 PM)

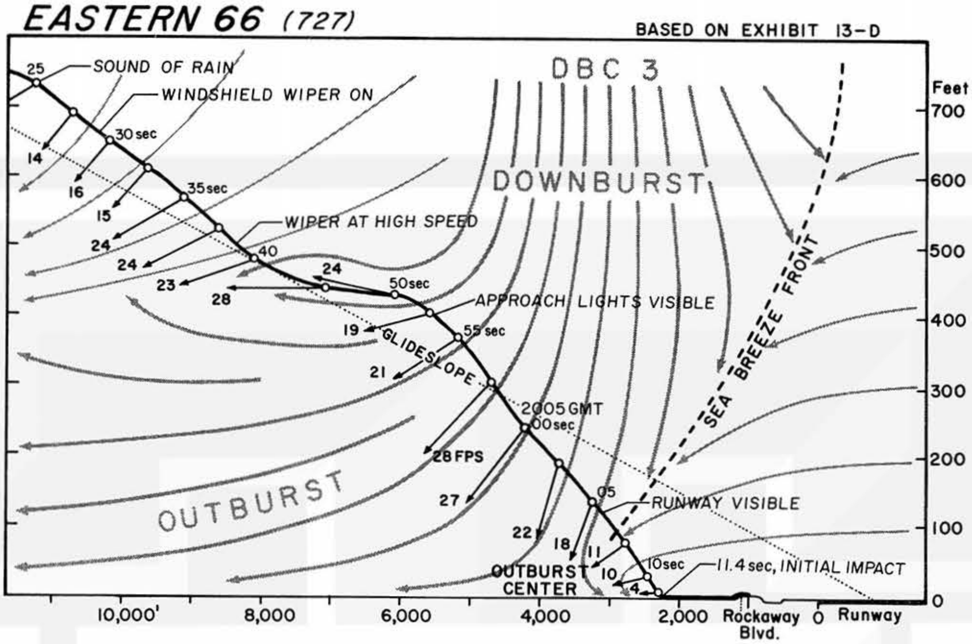

Fig. 9. The path of Eastern 66 on June 24, 1975 in the vertical plane including the glideslope of 22-L at JFK.

Of the 14 aircraft which flew through the spearhead echo, only three encountered serious difficulties. The WIND SHEAR--the time variation of vector winds along the flight path--was determined to be the cause. What the Flying Tiger had encountered was crosswind shear (time variation of crosswind). The aircraft flew into the outburst which was distorted by the sea-breeze front. The front held back the advancement of the outburst air into the runway area. The aircraft did not lose airspeed (see Fig. 10).

Eastern 902 lost airspeed when a 10 kt headwind changed into a vertical wind as it flew into a downburst cell. The airspeed gradually increased after power was applied at 270 ft. But the aircraft kept descending for about 10 seconds, suffering from tailwind and a downburst of 21 fps (6.4 m/sec) at 200 ft (see Figs. 8 and 10).

Eastern 66 lost airspeed suddenly at 300 ft when a 16 kt headwind changed into a 22 fps (6.4 m/sec) downburst. Evidently the aircraft flew straight into the downburst center. The loss of airspeed and the intense downburst at 200 ft were so severe that the aircraft had no chance to go around. The aircraft did not deviate much from the approach center line because it flew through the dead center of the downburst cell. About 2,400 ft (730 m) short of runway, the left wing clipped

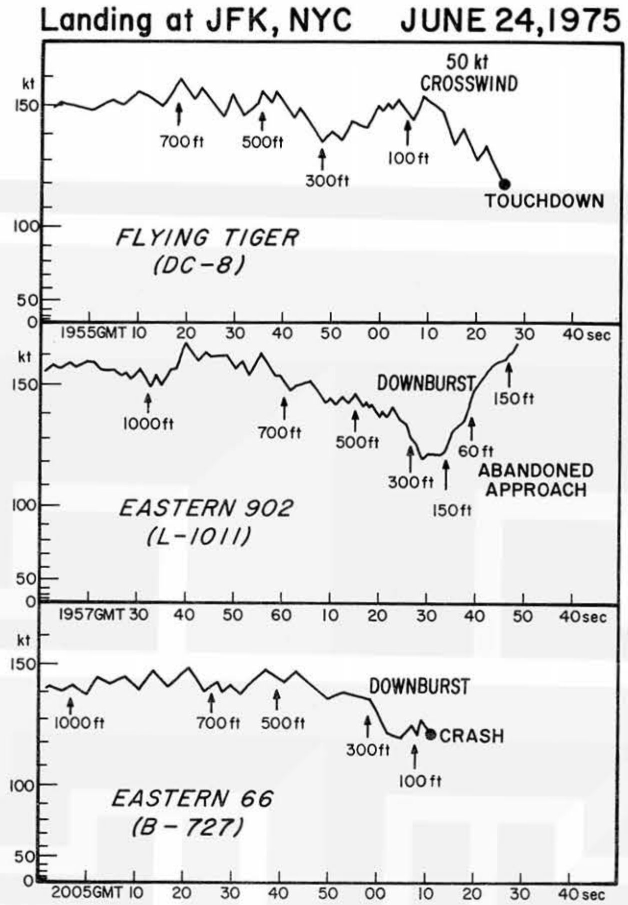

Fig. 10. Indicated airspeed of three aircraft on June 24, 1975 at JFK. The vertical scale is proportional to the square of the indicated airspeed.

some approach lights and skidded 1,000 ft (300 m) while breaking up. (see Figs. 9 and 10).

The SPEARHEAD ECHO, 20 miles long and 5 miles wide, produced at least four downburst cells. Although we do not know how many cells co-existed simultaneously, cells marched across just north of the JFK Airport one after another. The paths of five aircraft relative to the spearhead echo at 2002.4 GMT (4:02. 4 PM) are shown in Fig. 11.

La Guardia Airport, only 10 miles away, was not affected by any of these downburst cells. Even the airport area of JFK was not affected. A sustained sea-breeze front prevented the outburst air from pushing southward. The JFK wind tower near the south end of runway 22-L reported southerly winds up to only 15 kt. This is why 22-L was used for landing.

Apparently the downburst cells passed across a meteorological tower with an anemometer at 205 ft, instrumented and operated by the Long Island Lighting Company (LILCO). The tower is located about 7 miles

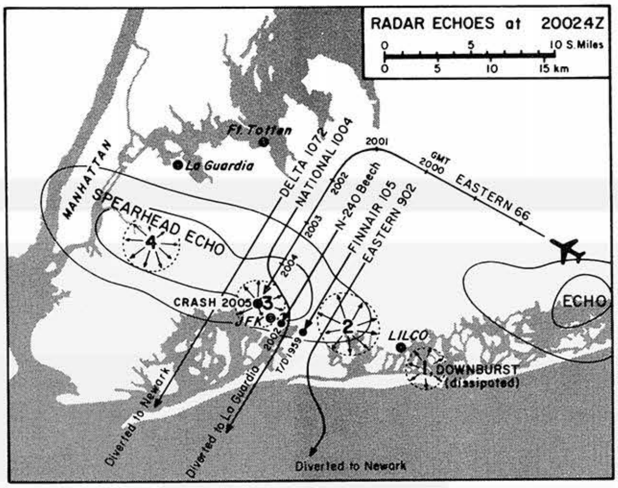

Fig. 11. The paths of 5 aircraft on June 24, 1975, drawn relative to the spearhead echo at 2002.4 GMT. Although the NWS Atlantic City radar showed a large spearhead echo, the airborne radar of approaching aircraft painted a circular, small echo near the approach end of 22-L. The radar-beam altitude of the echo from Atlantic City, 0.2° elevation at 80 n. miles, was about 7,000 ft (2100 m).

east-southeast of the accident site. The time-space conversion of winds reveals the passage of three downburst cells (DBCs) which had weakened considerably (see Figs. 11 and 12).

Mesometeorological analyses of downburst cells near the approach end of 22-L at JFK revealed that a fast-moving spearhead echo produced several downburst cells. These cells in the active stage were only 2 to 3 miles (3 to 5 km) in diameter, but they were accompanied by intense

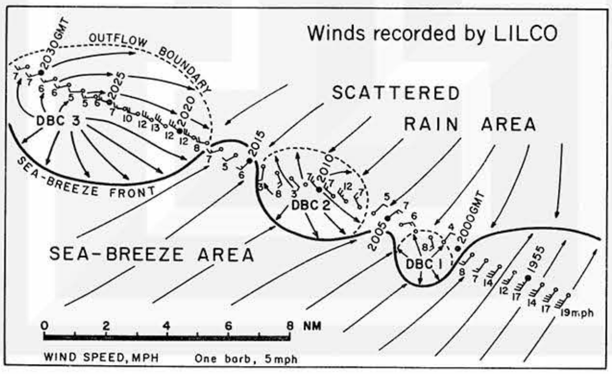

Fig. 12. 205-ft winds recorded by the Long Island Light Company (LILCO) on June 24, 1975. Time-space conversion of the winds reveals the passage of downburst cells in weakening stages across the wind tower.

downward currents near the center and surrounded by strong outflows about the center. Due to a 2 to 3 mile (3 to 5 km) space between the cells, some aircraft landed without problems while others encountered serious difficulties.

4. August 7, 1975, Accident at Stapleton Airport, Denver

The Denver area in the early afternoon hours on August 7, 1975, was in the lower 90s with scattered thundershowers. Thunder began at the Stapleton Airport at 1429 MDT, with storms scattered around the area. The last reported thunder was at 1550 MDT. The 00Z August 1 sounding presented in Caracena's (1976) analysis, shows that the lapse rate was almost dry adiabatic up to about 500 mb with surface winds from the south-southeast. The situation was favorable for scattered showers and thunderstorms in eastern Colorado.

Not all thunderstorms in the Denver are were alike, however. The echoes to the southeast of the city acted like slow-moving bubbles. Most of them travelled toward the northeast at 7 to 15 kt. In contrast, the echoes over the Boulder-Fort Lupton area were moving at 17 to 18 kt along wavy paths (see Fig. 13).

Echoes over the Denver area moved straight, at faster rates than those expected from the motion of neighboring echoes. Echo B, between 1518 and 1544 MDT, sped toward the ENE at 19 to 22 kt. Echo A, between 1606 and 1622 MDT, which moved over the accident area, traveled at 16 kt along a straight path. Furthermore, the shape of Echo A at its mature stage was somewhat like a spearhead, 5 miles wide and 10 miles long. Later, it changed into two circular cells; one located behind its tip and the other near the rear end.

The authors thus concluded that it was a spearhead echo which moved over the Stapleton runway 35-L at the time of the accident at 1611 MDT. The spearhead echo in the Stapleton area was just about half the size of the JFK thunderstorm, which was 5 miles wide and 20 miles long.

The time-space coordinates of the three aircraft in Fig. 14 were constructed by moving runway 35-L relative to the spearhead echo. The winds from the Stapleton windtower, 0.3 miles (500 m) east of the runway threshold, and from windtower No. 7, located 0.5 mile (800 m) northwest of the north end of the runway, were added in the figure. Following are

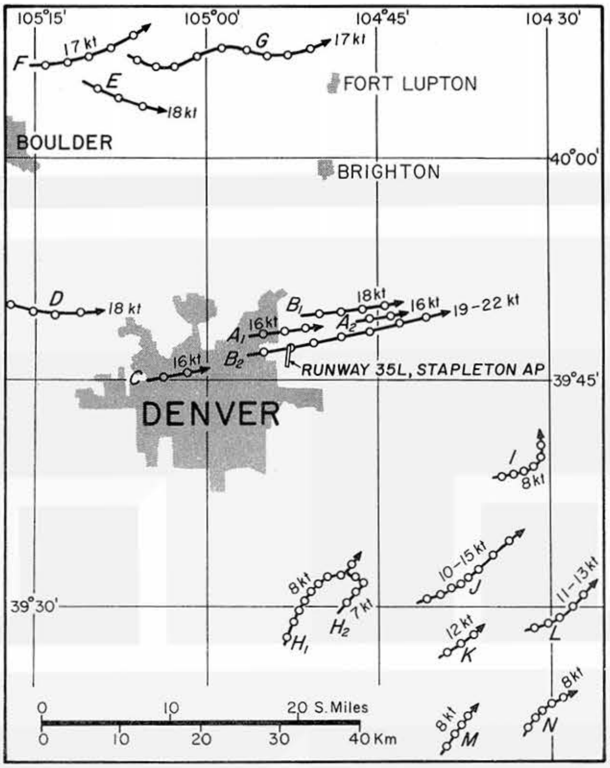

Fig. 13. Movement of scattered storm echoes near Denver on August 7, 1975 between 1518 and 1622 MDT. NWS at Limon, about 70 n. miles SE of Denver, took radar pictures at 5.3-min intervals during this period. Open circles show the echo centroids in each picture.

the conditions encountered by the three aircraft during their takeoff and climb-out period. For details, refer to NTSB (1976), Kadlec et al. (1975) and Pittman's letter to NTSB (1975).

BRANIFF 67. While taxiing, saw a dust cloud moving westward near 35-L, possible 3/4 of the way down the runway. After delaying for dust cloud to clear runway, took off at 1605 MDT with normal acceleration. Then suddenly the aircraft did not respond to inputs for 2 to 3 seconds. This happened approximately when the aircraft was crossing a weak shear line. The pilot stated, "In 30 years of airline flying, I have never felt anything quite like it". The aircraft might have been in a vortex which could form on a shear line. All became normal again and it rotated and lifted off. At 100 to 300 ft altitude, a downdraft and tailwind were encountered, resulting in a 10 to 15 kt loss of the indicated airspeed (see Figs. 14 and 15).

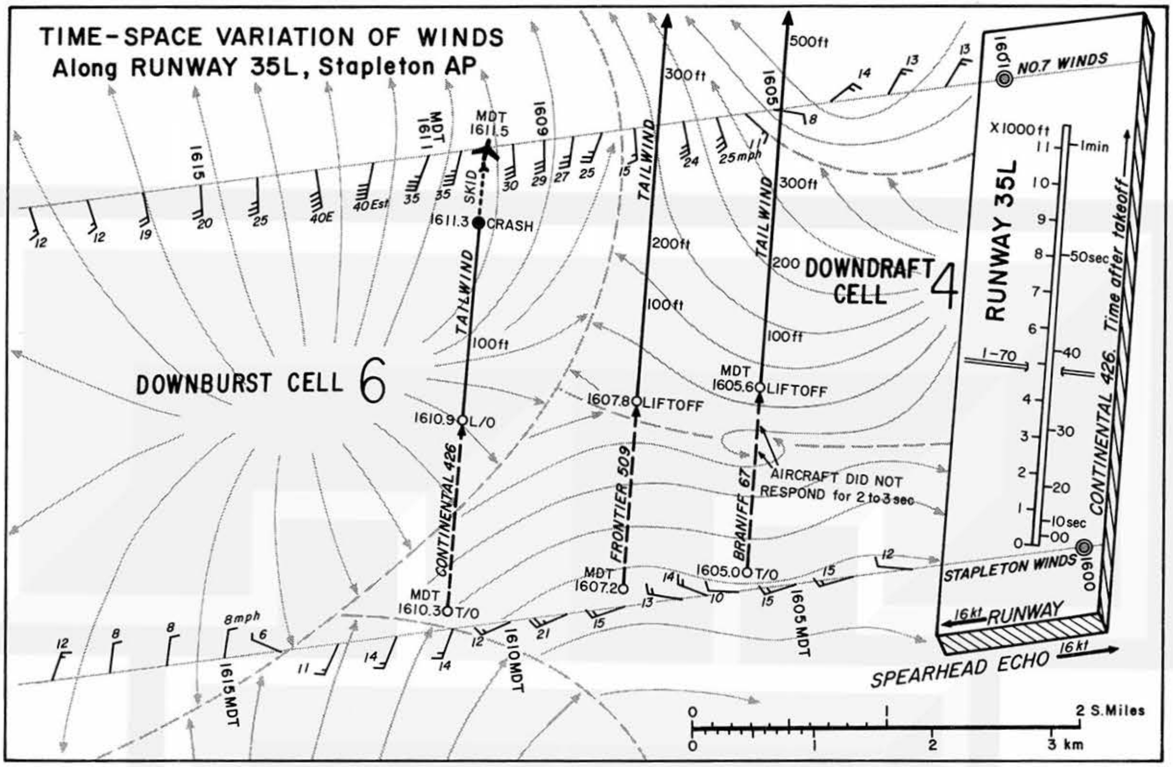

Fig. 14. Three aircraft which took off from runway 35-L of Stapleton Airport between 1605 and 1610 MDT on August 7, 1975. In constructing these time-space coordinates, the runway and two wind towers were moved, at 16 kt, in the opposite direction of the spearhead echo. One minute was added to the time of Wind Tower No. 7, taking into account the travel time of the aircraft from takeoff to the end of the runway.

FRONTIER 509. Experienced downdraft and tailwind shear just as the previous aircraft had. The airspeed dropped from 155 to 120 kt in 10 seconds, at the rate of 3.5 kt/sec. The aircraft rotated nose down to gain airspeed while flying horizontally for about 20 sec (see Fig. 14 and 15).

CONTINENTAL 426. Aircraft took off at 1610 MDT, using maximum takeoff thrust. All instrument readings were normal at 80 kt indicated airspeed. Entered rain shortly before the liftoff, which required the use of windshield wipers. After a normal liftoff, it climbed with a 14° body angle. While climbing at approximately 100 ft above the runway, the airspeed decreased from 158 kt to 116 kt in about 5 seconds. The rate of air speed loss was an amazing 8 kt/sec. The captain lowered the nose to about 10° pitch, but the aircraft continued to descend to the

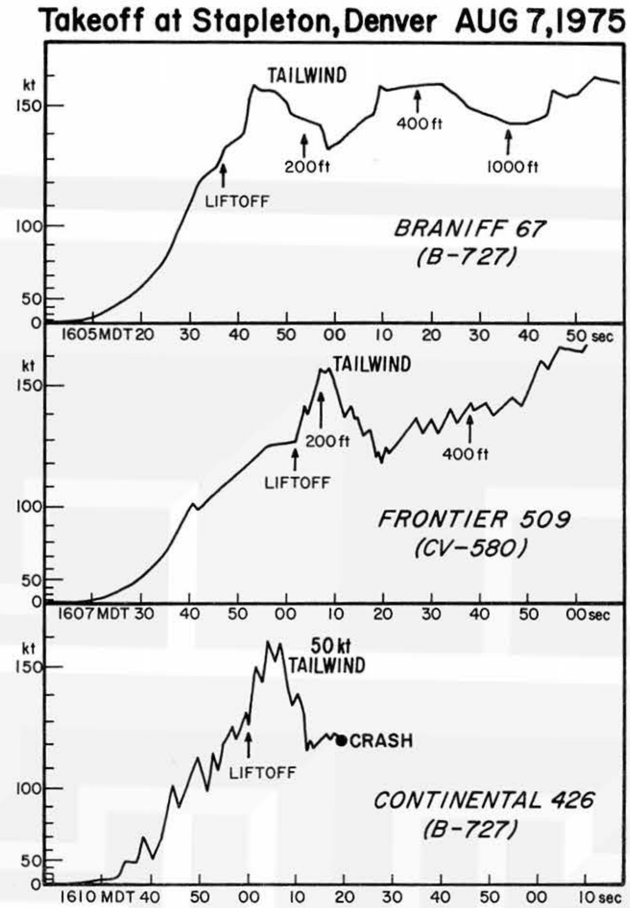

Fig. 15. Variation of indicated airspeed of three aircraft which took off from runway 35-L of Stapleton Airport on August 7, 1975. The airspeed scale was plotted in proportion to the square of the speed.

ground. Just before the aircraft struck the ground, the stall warning system activated (see Fig. 14, 15, and 16).

After hitting the ground, just to the right of the runway, 390 ft (120 m) short of the departure end, the aircraft skidded about 2000 ft (600 m) until it came to a stop at East 56th Avenue. All 134 persons aboard the aircraft survived the crash, however 15 persons received various degrees of injuries.

The maximum divergence at the surface, as estimated by the authors, was 150 to 250 hr^{-1}. The downdraft encountered by Continental 426 was undoubtedly a "strong downburst". The outburst was strong enough to cause an uncontrollable rate of airspeed loss, 8 kt/sec. It should be noted also that the outburst was not symmetric with respect to the outburst center. The outburst was strong toward the north but weak toward the south, the direction of pre-existing downdraft air.

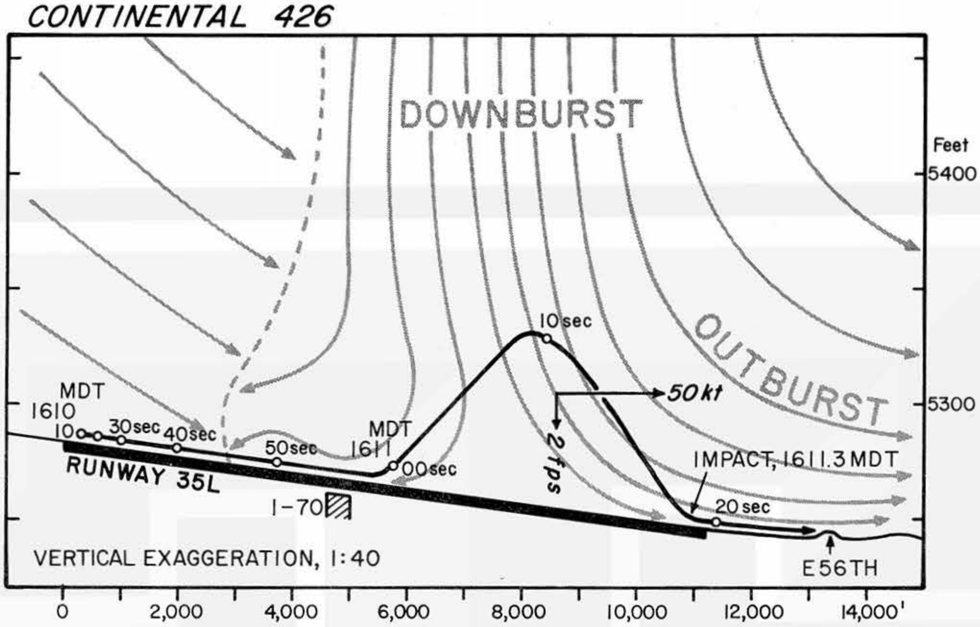

Fig. 16. A schematic figure showing the path of Continental 426 in relation to the downburst cell on August 7, 1975. The maximum height of the aircraft is approximate because the alti meter was affected by the aerodynamic characteristics of the Pitot tube during the climb. The height scale is in feet, MSL.

It is unusual to have an anemometer network near an accident site. Fortunately, the Rocky Mountain Arsenal to the north of Stapleton International Airport operated nine wind towers around its 21-mile boundary. As shown in Fig. 17, the towers are numbered 1 through 9. In addition, there are five more anemometers listed below.

Station S , at Stapleton Airport - Operated by NWS

Station B , at Buckley Air National Guard - maintained by the U.S. Air Force

Station D , Colorado Department of Public Health

Station L , at Lowry Air Force Base - Operated by Dr. Raymond Jordan

Station U , at Dr. Jordan's house

The following mesoanalysis is based on data furnished by this network and, on echoes recorded by Limon radar.

At 1550 MDT, echo B is going to leave the mesoanalysis area. There was a center of warm downdraft near the southwest corner of the Arsenal. A mesocyclone was swirling slowly where the flow from two downdrafts met (see Fig. 17).

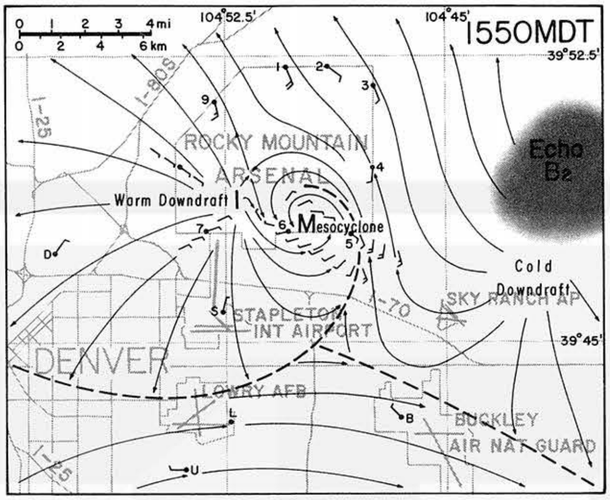

Fig. 17. Mesoanalysis map for 1550 MDT, August 7, 1975. A small mesocyclone is seen on the south boundary of Rocky Mountain Arsenal.

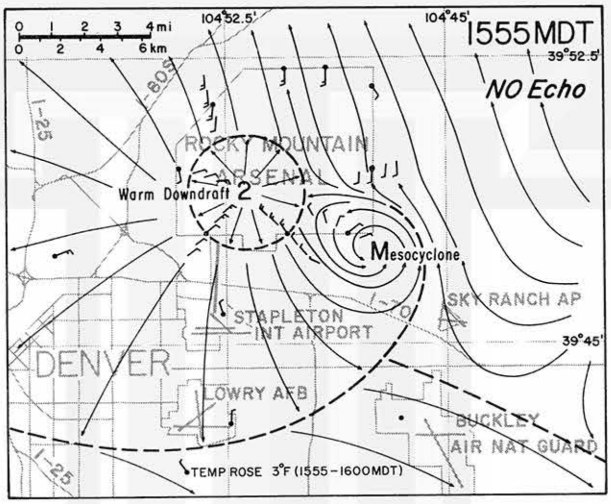

Fig. 18. Mesoanalysis map for 1555 MDT, August 7, 1975. A warm downdraft formed while the mesocyclone weakened.

Between 1555 and 1600 MDT, air temperature at Station U rose 3°F, indicating that the flow from downdraft No. 1 was warm. Meanwhile, a warm downdraft, No. 2, began spreading out in all directions (see Fig. 18).

Then a much stronger downdraft, No. 3, overtook the old one. At 1601 MDT, it was characterized by a first gust line located only along the eastern boundary. There was no radar echo associated with downdrafts No. 1, 2, and 3 which, apparently, had descended at the same spot, one after another. A small echo was approaching Dr. Jordan's stations, U and L (see Fig. 19).

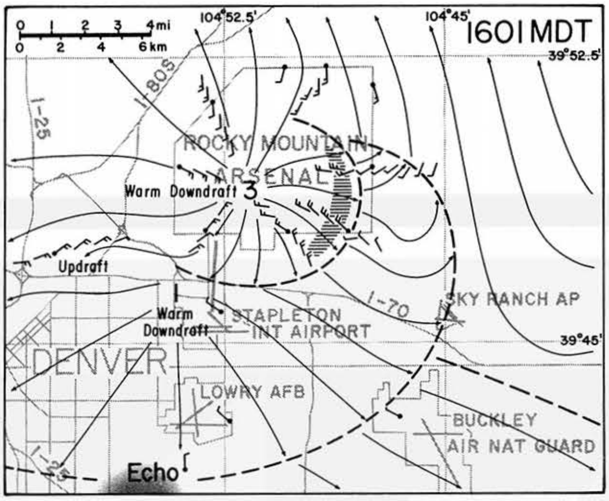

Fig. 19. Mesoanalysis map for 1601 MDT, August 7, 1975. The warm downdraft spread out, especially toward the east. The area of 20 kt or stronger wind is hatched.

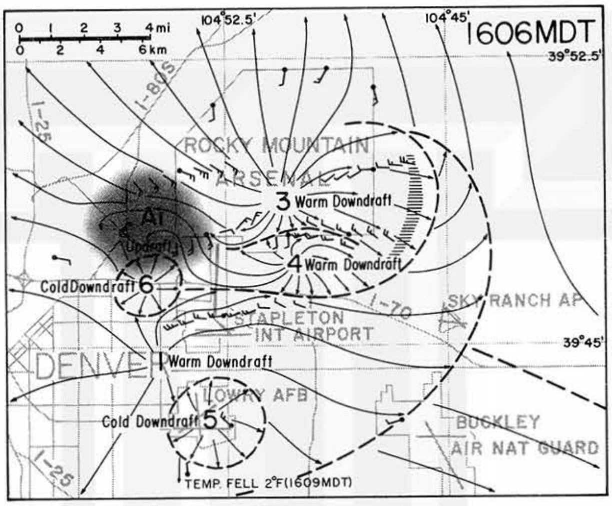

Fig. 20. Mesoanalysis map for 1606 MDT, August 7, 1975. A circular echo formed over the area of surface con vergence. The area of 20 kt or stronger wind is hatched.

By 1606 MDT, a new downdraft, No. 4, descended to the south of No. 3, resulting in a distinct convergence line along the outflow boundary. The echo to the south of Station U disappeared, leaving a cold downdraft, No. 5, centered over Lowry Air Force Base. A circular echo, about 3 miles in diameter, formed where the downdraft air was converging. We may suspect that the echo was producing a cold downdraft, No. 6, near its southern edge. Braniff 67 took off one minute before this map time while Frontier 509 lifted off two minutes later. Both aircraft were probably unaware of the development of cell No. 6 into a downburst (see Fig. 20).

Downburst No. 6 reached its mature stage at about 1612 MDT, one minute after the accident. An outburst up to 40 kts was spreading toward the north. Echo A now took the shape of a spearhead, extending rapidly toward the east. A few minutes later, the echo changed into two circular echoes interconnected by a weak echo (see Fig. 21).

Meteorological analysis of the data on August 7, 1975, revealed that the accident of Continental 426 occurred shortly after it climbed into a strong downburst cell. The downburst cell formed near the south boundary of a spearhead echo, only about 5 minutes before the accident. The cell developed very rapidly.

Warm downdrafts, such as those reported by Fujita (1976), were also found in the analyses area. At the leading edge of the outflow from Downdraft No. 1, the temperature rose as much as 3°F. The second and the third impulses of warm downdraft took place inside the Arsenal, resulting each time in a surge of outflow air. Although no radar echoes existed within these downdraft areas, we may assume that the in-cloud precipitation turned into virga before reaching the radar-beam altitude. By the time the cold downdraft hits the surface, the draft temperature may be higher than the pre-existing downdraft air.

It was the warm downdraft air from cells 1, 3, and 4 which converged into echo A in its updraft stage at 1606 MDT. We are unable to prove, based on actual data, whether the warm downdraft air is more favorable than the cold downdraft air for the development of a spearhead echo.

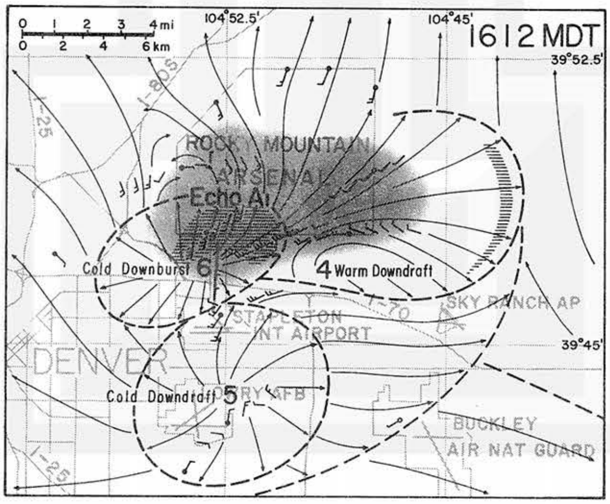

Fig. 21. Mesoanalysis map for 1612 MDT, August 7, 1975. The circular echo changed into a spearhead echo which extended rapidly toward the east. Areas of 20 kt or stronger winds are hatched.

5. June 23, 1976 Accident at Philadelphia International Airport

During the afternoon, a weak warm front moved slowly northward across the east coast, reaching Baltimore, Md., at 1700 EDT. The temperature contrast across the front was about 10°F. At 1712 EDT when Allegheny 121 crashed on the runway, there were scattered showers and thunderstorms in the cold sector. NWS radars at Atlantic City and Patuxent River depicted a few isolated cells over the area but none of which appears to be of an alarming level of intensity and echo size.

The aircraft approached from the east attempting to land on 27-R. Suddenly it ran into a strong headwind shear while approaching the runway threshold. Headwinds increased to an estimated 50 to 60 kt. Power was cut down to reduce airspeed, and the INS ground speed dropped to less than 100 kt. About 60 ft above the runway near its threshold the aircraft started climbing, in an attempt to go around. When it reached 260 ft above the runway, the headwind was gone. The aircraft sank onto the runway.

Evidently the aircraft flew straight through the center of a downburst cell with a very intense core of blinding rain. An eyewitness saw the aircraft crash on the runway after emerging out of a wall of water.

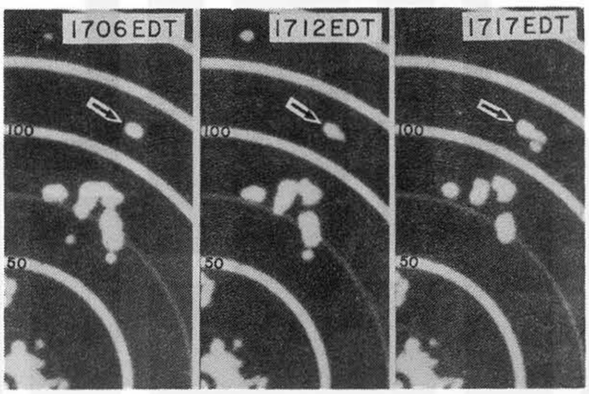

Fig. 22. Rapid development of a small spearhead echo over Philadelphia airport. Three pictures were taken by NWS Patuxent River, Md. radar at 1706 (left), 1712, and 1717 EDT on June 23, 1976. Heavy range marks are 50, 100, 125, and 150 n. miles. Time of accident was 1712 EDT.

Radar pictures from Patuxent River, about 110 n. miles south-southwest, showed a small, circular echo at 1706 EDT. At 1712 EDT, when the accident occurred, it grew into a spearhead echo with a point on its east-southeast end. Five minutes later, the echo grew in size to 8 miles wide and 17 miles long (see Fig. 22).

6. Composite Analysis of Three Accident Cases

Meteorological analyses of the three accident cases presented herein suggest the existence of two important weather systems. They are

(1) DOWNBURST, a downdraft of extreme intensity which induces dangerous wind shear of both vertical and horizontal winds, and

(2) SPEARHEAD ECHO, a fast-moving echo which spawns downburst cells.

Shown in Fig. 23 are the composite paths of four aircraft which penetrated the downburst cells near JFK and Stapleton. The outcome of the penetration is obvious: the two aircraft closest to the downburst center could not make it. Allegheny 121 at Philadelphia also crashed shortly after it flew through the center.

Two others, the paths of which were off the center, barely made it. Eastern 902 was pushed down while drifting to the right. A go around was executed, and the aircraft began climbing from a minimum altitude of only 60 ft (18 m) above the ground.

Flying Tiger 161 first encountered a sustained downburst, requiring the use of near maximum power just to maintain a position near glideslope. The crosswind shear, which followed the vertical wind shear, was very severe, resulting in a dangerous drift shortly before the touchdown. Captain Bliss who piloted the aircraft said, "I did not want anyone else to have to go through the same." Captain Drummey who watched the Flying Tiger's landing commented, "The pilot must have been like a cat on a hot tin roof trying to save that airplane."

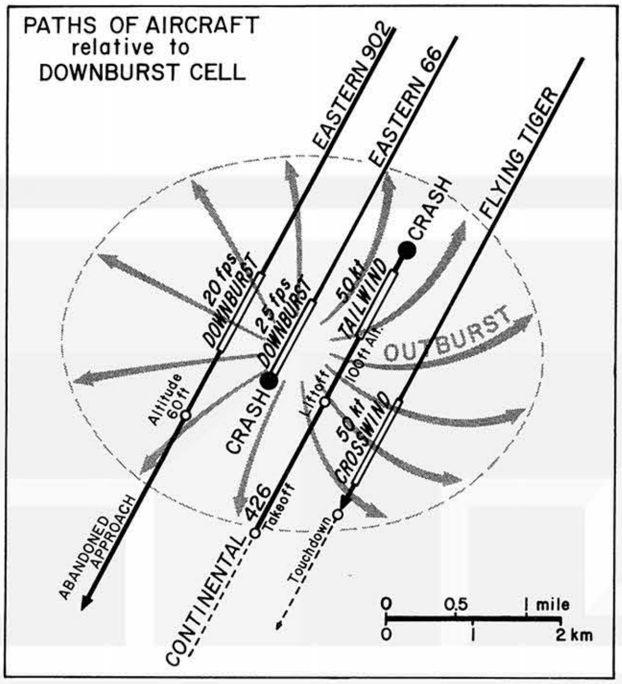

Fig. 23. Composite paths of Flying Tiger, Eastern 66, and Eastern 902 at JFK on June 24, 1975, and Continental 426 at Stapleton on August 7, 1975. Allegheny 121 at Phila delphia on June 23, 1976, flew through the downburst center from right to left, experiencing a 50 to 60 kt headwind, calm, and 6 kt tailwind before it crashed on the runway.

In effect a downburst cell induces four types of wind shear to be encountered by a penetrating aircraft. They are

HEADWIND SHEAR - Indicated airspeed increases and aircraft gains altitude.

TAILWIND SHEAR - Indicated airspeed drops and aircraft sinks.

CROSSWIND SHEAR- Aircraft drifts to the right or left.

DOWNBURST SHEAR- Aircraft drops abruptly due to the shear of vertical wind.

In most cases, a mixture of above shear occurs simultaneously, although one type often dominates the others.

It is very likely that the spearhead echoes played an important role in the development of the downburst cells related to the three accidents (see Table IV).

Table 4. Characteristics of spearhed echoes.

	Accident	Echo began	Lead time	Echo Dimensions
JFK Thunderstorm	1605 EDT	1515 EDT	50 min	5 x 20 miles
Stapleton Storm	1611 MDT	1606	5 min	5 x 10 miles
Philadelphia Storm	1712 EDT	1706 EDT	5 min	8 x 17 miles

In all cases, the spearhead echo moved straight, faster than other echoes in the vicinity. Gibson (1975) should be credited for first pointing out the existence of a fast-moving echo just to the north of JFK at the time of the Eastern 66 accident.

Earlier a number of radar meteorologists examined echo shapes in relation to specific weather. Hoffman and Peckham (1968) discussed the fingers, hooked fingers, and scalloped edge of echoes in relation to hail tornadoes, severe turublence, and violent surface winds. These features which, since then, have been recognized and used by pilots are different from spearhead echoes.

A spearhead echo, in its mature stage, is not a pendant to a larger parent echo. Instead, the whole echo takes the shape of a spearhead when observed by radar from a long distance, such as 80 n.m. (JFK thunderstorm), 70 n.m. (Stapleton thunderstorm), and 110 n.m. (Philadelphia thunderstorm). They are relatively small echoes with an appearance of harmless air-mass showers (see Fig. 24).

The JFK spearhead echo was observed differently by airborne radars at close ranges. Captain Walker of National 1004 sketched a circular echo over the threshold of 22-L based on his airborne radar. The echo, 2 to 3 miles in diameter, was just about 6 miles in front of him.

The same echo was sketched also by Captain Baggett of Delta 1072 which was following National 1004. The onboard radar was painting a small storm, no more than 3 to 4 miles in diameter. Although the appear--ance of the echo gave him a false sense of security perhaps, it was, in fact, the rain-loaded downburst cell inside of which Eastern 66 had crashed a few minutes earlier.

Although the echo over Stapleton Airport was observed by Limon radar as a spearhead echo, pilots of aircraft flying near the airport at low levels saw the different echoes on their airborne radar scopes. There were three circular echoes, the one located in the vicinity of 35-L and two others, to the east of the airport.

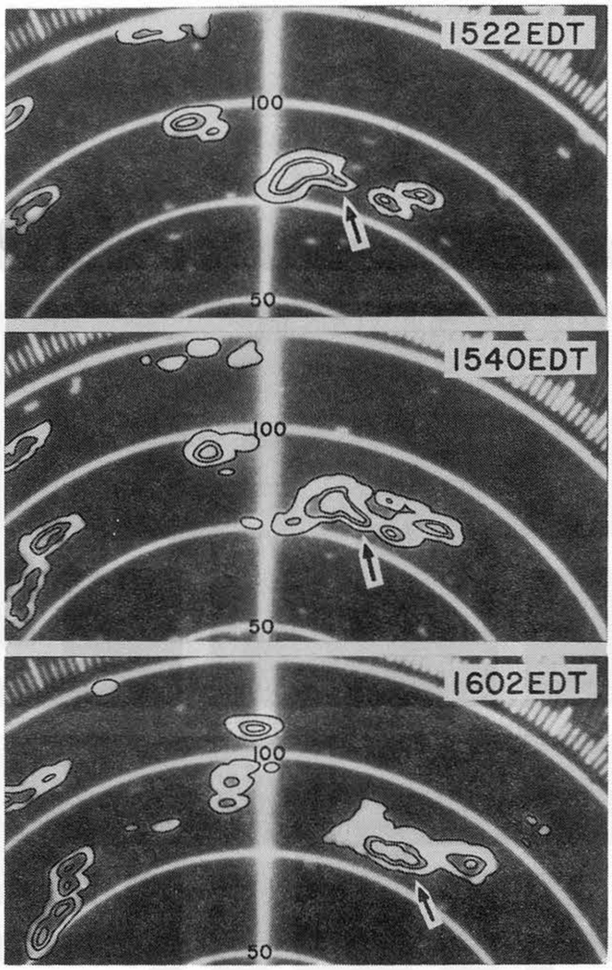

Fig. 24. Contour representation of the spearhead echo near JFK on June 24, 1975. The formative stage is seen in the top photo at 1522 EDT. At 1540 EDT (middle) the parent echo is being drawn into the spearhead section. Finally, at 1602 EDT, 3 min before the accident, the parent echo was absorbed entirely into the spearhead echo.

Since the airborne radar scans a beam of less than 4° in elevation, during a final approach it would normally be looking at approximately the lower 4,000 ft of any thunderstorm. This would probably be of little use in differentiating the downburst cells of the intensity associated with known spearhead echoes, from the normal, small cell.

At a 30 m. mile range from Atlantic City radar, the echo at Philadelphia on June 23, 1976, was observed as circular cluster of echoes, about 12 miles in diameter. The height of the radar beam at this range was about 400 ft above the airport.

Fujita's (1976) and Fujita and Byers' (1977) model of the spearhead echo was produced based on the JFK thunderstorm. Shown in Fig. 25 are the downburst cells imbedded inside a spearhead echo. In actual cases, downburst cells were located near or on the south edge of the spearhead echoes.

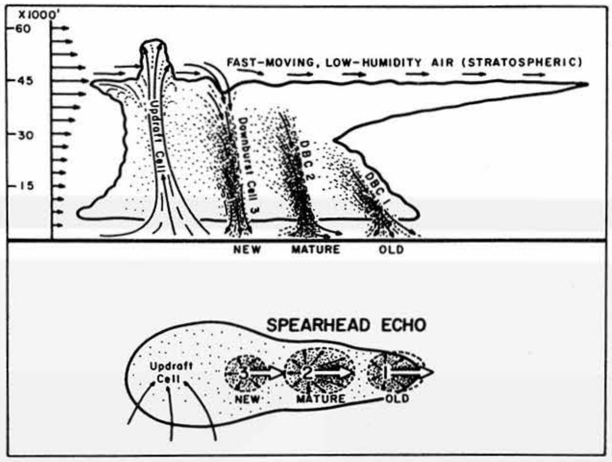

Fig. 25. The Fujita-Byers model of spearhead echo. They assumed that the fast-moving air is brought into the source region of the downburst, when an overshooting top collapses into the anvil cloud. When observed by distant radar, a spearhead echo will appear. At close range, especially below the cloud base, the radar paints small circular echoes. From Fujita (1976) and Fujita and Byers (1977).

A majority of thunderstorms, in their mature to dissipating stage, entrain mid-tropospheric air into the downdraft. For each of the three spearhead echoes discussed in this paper, the mid-tropospheric flow was not fast enough to generate the horizontal momentum to drive the spearhead echo and the outburst air (see Table 5).

Table 5. The direction and speed of outburst in relation to the winds aloft

	Strongest Outburst	Estimated Speed	500 mb Wind	150 mb Wind
JFK Thunderstorm	from WNW	50 to 60 kt	West 22 kt	West 38 kt
Stapleton Storm	from SSW	40 to 50 kt	WNW 10 kt	SW 26 kt
Philadelphia Storm	from West	50 to 60 kt	SW 15 kt	West 10 kt

Adiabatic charts from Ft. Totten and Denver in Figs. 26 and 27 reveal the existence of fast-moving currents at the altitude where overshooting is likely to occur. How does a spearhead echo tap the horizontal momentum existing near the cloud top? One explanation is the action of the overshooting-collapsing cloud top.

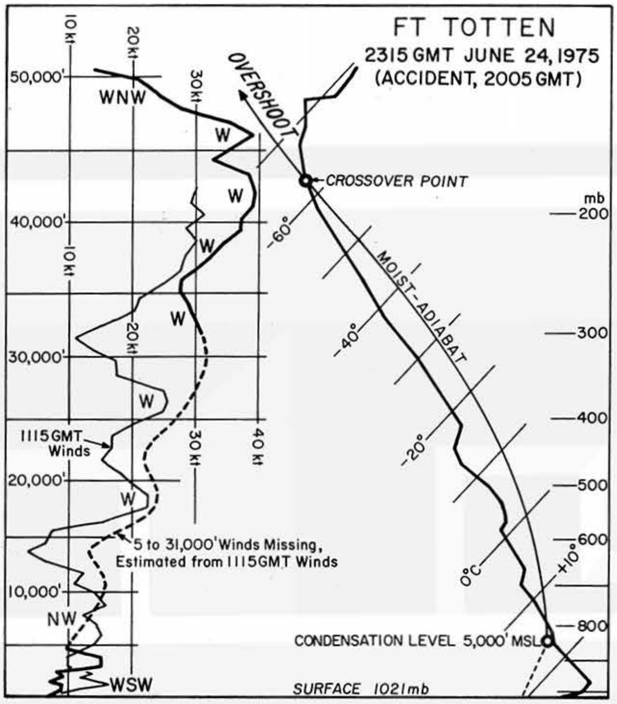

Fig. 26. Sounding at Ft. Totten, 10 miles north of JFK, released at 2315 GMT (1915 EDT) on June 24, 1975.

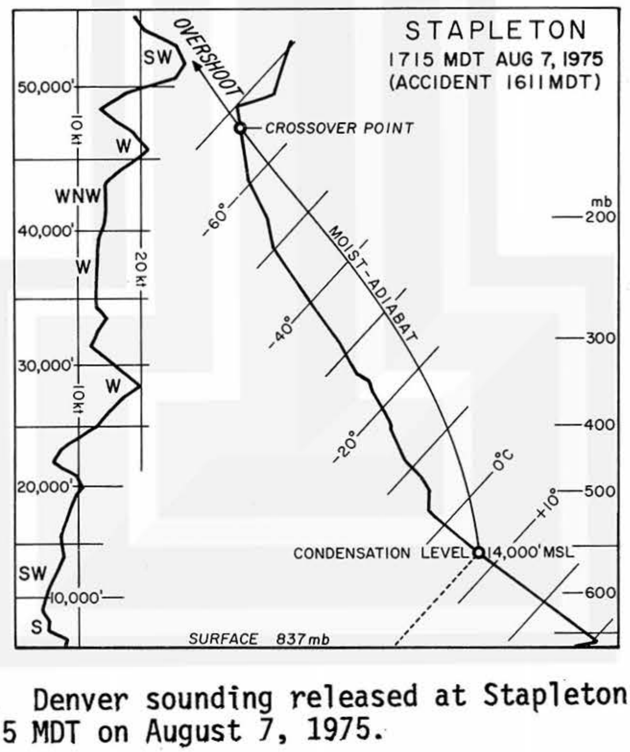

Fig. 27. Denver sounding released at Stapleton Airport at 1715 MDT on August 7, 1975.

The updraft air acquires horizontal momentum as it rises and overshoots. As the overshooting height increases, the kinetic energy of the updraft is converted into the potential energy of the cold top, and stored. Then the heavy cloud top descends rapidly as the potential energy is reconverted into kinetic energy of the downward currents.

The fast-moving, low-humidity air entrained from above the anvil top stimulates the evaporation inside the downdraft while maintaining the rapid advancement of the cell. The downdraft, thus created, is likely to become a downburst on the ground. The fastest sinking motion measured by Fujita (1974) on May 6, 1973 over Texas was 41 m/sec (92 mph) at 48,000 ft. An example of a collapsing top is shown in Fig. 28. If a rapid collapse, such as this, induces an intense downburst on the ground, some trees and vegetation could receive downburst damage.

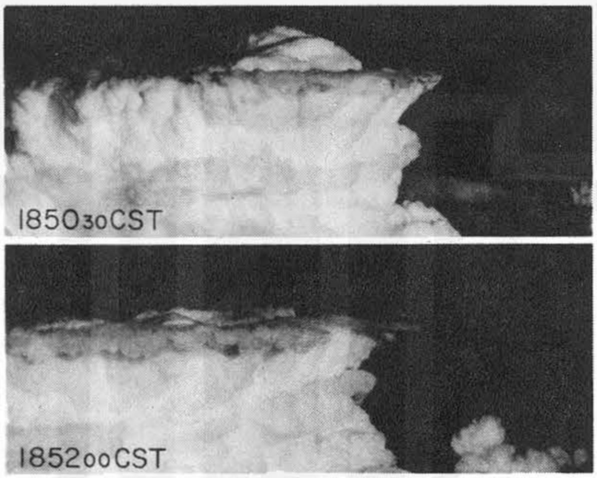

Fig. 28. Collapse of an overshooting dome within 1.5 minutes. Sometimes a large, tall dome collapses so fast, as in this case, that the skin of the anvil is pushed outward. The collapsed dome descends into the anvil and the hole is filled gradually. Pictures taken near San Antonio, Texas, on May 6, 1973. From Fujita (1974).

Although a number of fast-collapsing tops such as Fig. 28 have been documented during the past few years, some meteorologists are skeptical as to the mechanism of an air current descending from anvil-top level all-the-way to the ground;--because, it has been postulated that most downdrafts originate inside storm clouds.

It should be pointed out, however, that Doppler velocities obtained by Wave Propagation Laboratory, NOAA, at Boulder, Colorado, depicted cases of strong downdrafts originating at the cloud-top level (see an example in Fig. 29). This cross section strongly suggests a possibility of experiencing a downburst beneath a fast-collapsing cloud top. In other words, the occurrence of downbursts might not be as rare as had been thought to be. Their short lives coupled with small areas would have escaped detection and subsequent reporting for awareness and preparedness.

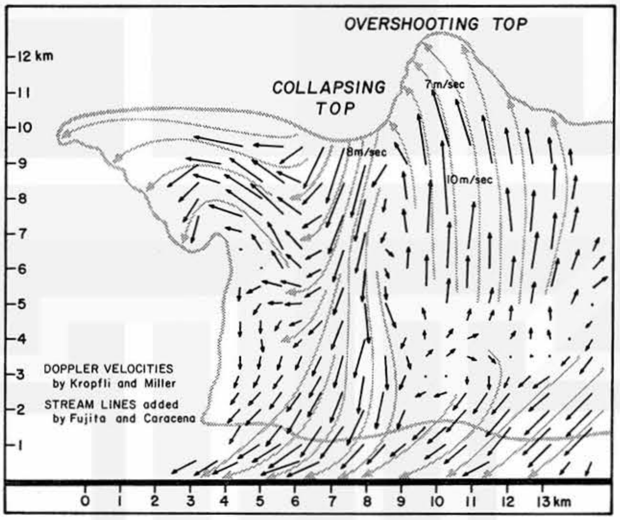

Fig. 29. A vertical cross section of Doppler velocities inside a 28 July 1973 thunderstorm in Colorado. Dual-Doppler velocities were obtained by Kropfli and Miller (1976). Both cloud boundary and stream lines were added by the authors.

During the damage survey of the 148 tornadoes on April 3, 1974, Fujita found diverging patterns of blown-down trees located a considerable distance away from tornado paths (see Fig. 30). In Switzerland, Piaget (1976) mapped 25 isolated spots of tree damage outside the path of the August 26, 1971, tornado.

On May 6, 1975, NWS Kansas City radar depicted a spearhead echo located approximately 100 n. miles away. Meanwhile, the SMS/GOES satellite took pictures, looking down from the geostationary altitude 25,300 miles above the equator (see Fig. 31). One of the Learjets on the University of Chicago/ NASA research mission took cloud top pictures of this spearhead echo while flying at 45,000 ft. The picture sequence revealed that the overshooting in the echo area was very significant.

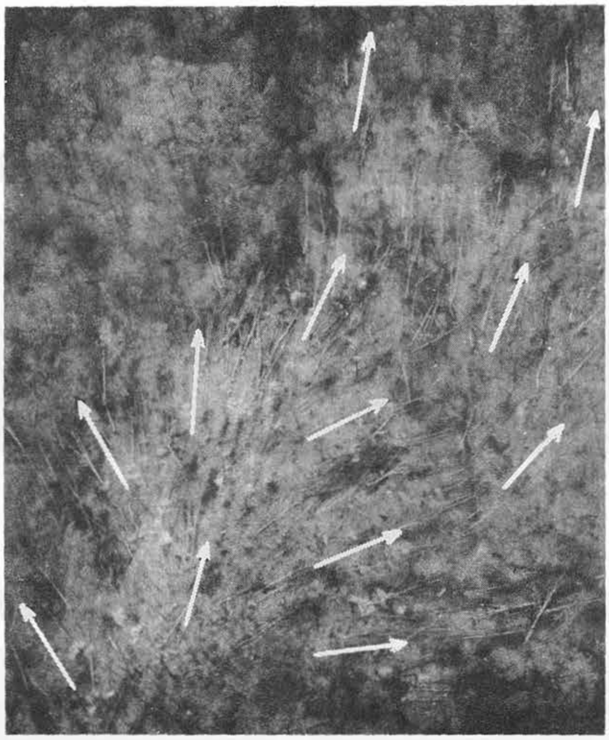

Fig. 30. A diverging pattern of tree damage near Beckley, North Carolina. Damage was probably caused by an intense downburst descending on the forest on April 3, 1974. Photo by Fujita, taken form Cessna 172.

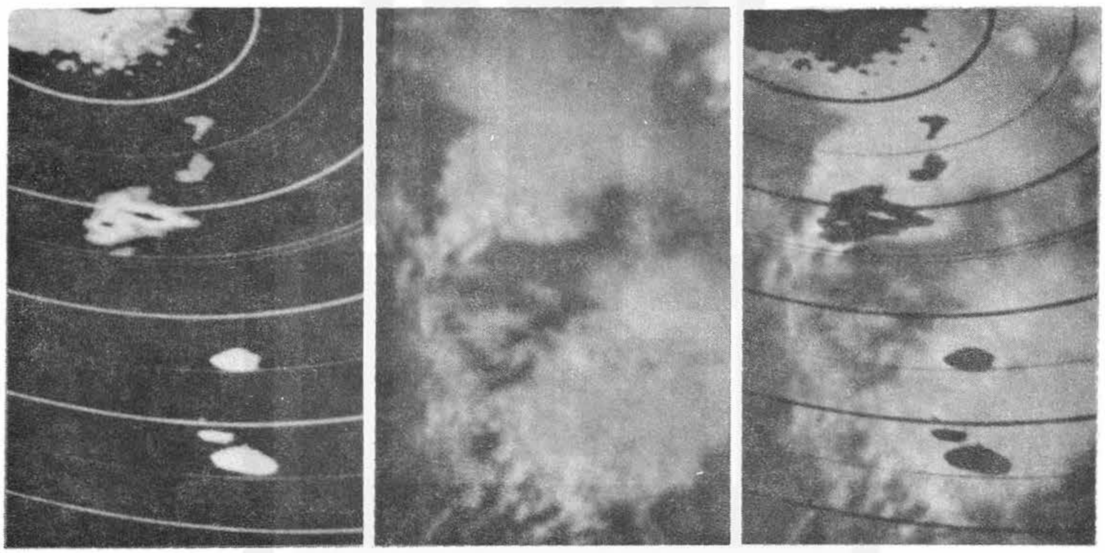

Fig. 31. A spearhead echo of May 6, 1975. Radar echo at 1722 CDT (left), SMS/GOES picture at 1722 CDT (center), and their combination.

A composite analysis of the three accident cases revealed that the downburst winds, accompanied by spearhead echoes, are localized but very strong. It is unlikely that a jet aircraft is able to fly through the center of a downburst cell below 300 ft. Coleman (1976) in her article in "Airline Pilot" introduced the importantce of identifying downbursts to assist safe landing and take-off of jet aircraft.

The descending currents of downburst intensity have not been emphasized until recently. Some accidents in the past could have been related to the wind shear in downbursts. Furthermore, the evidence of the tree damage with diverging patterns suggests the existence of strong downbursts more often than had been reported and confirmed.

7. Conclusions

Meteorological analyses of the accidents at JFK, Stapleton, and Philadelphia uncovered the following evidence.

(1) Only a small fraction of the strongest downdrafts reaches the intensity of a downburst.

(2) The mature stage of a downburst is reached only 5 to 10 minutes after its formation.

(3) Downburst cells are very small, reaching only 3 to 4 miles in diameter during the mature stage.

(4) A downburst cell creates four types of strong wind shear, which are headwind shear, tailwind shear, crosswind shear, and downburst shear.

(5) There was a spearhead echo, just to the north of each accident site.

(6) A spearhead echo tends to move straight and fast. It is likely that the high-level momentum is transported down to the ground, being driven by the overshooting-collapsing cycle of the cloud tops.

The most important lesson learned in this study is that "No one should attempt to fly through the center of a downburst cell." Even a one-minute delay could reduce the wind shear from a dangerous to a safe level. Since a spearhead echo is likely to spawn downburst cells, its characteristics must be investigated in detail.

After investigating the three weather-related accidents, the authors wish to recommend the following:

1. Instrument airports with arrays of detectors such as pressure sensors, wind speed detectors, some anemometers and possible temperature sensors. These arrays should have at least a resolution of 0.5 miles. The output from these instruments should be reduced by means of microprocessors into forms which are displayed visually to tower personnel. These displays will depict positions of shear lines, pressure noses, identify downburst and regions of dangerous shear, and have an alarm device such as a blinking red light to call attention to potential windshear threats.
2. Most NWS radar sites are remote from the airports from which they serve. These sites, the small storm echoes which may harbor downbursts, do not appear very impressive. For this reason it would be appropriate to process radar signals with a computer and display computer enhanced (and corrected) images of echoes over airport area space. At CRT terminals located at the airport itself, this high resolution display would be focused on the airport and its immediate vicinity. The display should be available to both pilots and tower personnel.
3. Tighten up communications so that reports of turbulence, shear lines, wet runways, strong up- and downdrafts, etc., are relayed promptly to pilot. Communication lags of a few minutes are inadmissible in view of the rapid development of downburst cells.
4. It is also recommended that researches be conducted around the major airports for obtaining Doppler velocities and for monitoring cloud-top activities. These data should be analyzed and evaluated along with ground and airborne observations.

8. Acknowledgements

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