An Analysis of Three Weather-Related Aircraft Accidents

T. THEODORE FUJITA AND FERNANDO CARACENA

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An Analysis of Three Weather-Related Aircraft Accidents

T. Theodore Fujita [1] and
Fernando Caracena [2]

Abstract

Two aircraft accidents in 1975, one at John F. Kennedy International Airport in New York City on 24 June and the other at Stapleton International Airport in Denver on 7 August, were examined in detail. A third accident on 23 June 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 min in advance of the accident and moved faster than other echoes in the vicinity. These echoes were photographed by National Weather Service radars, 130–205 km away. At closer ranges, however, one or more circular echoes were depicted by airborne and ground radars. These cells were only 3–5 km in diameter, but they 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.

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 24 June 1975, was driven down to the ground, 730 m short of runway 22-L of John F. Kennedy International Airport (JFK), New York City; 113 persons died. About 6 weeks later, on 7 August, Continental Flight 426 suffered a severe and abrupt loss of airspeed after being airborne from runway 35L of Stapleton International Airport at Denver, Colo. The aircraft hit the ground, just to the right of the runway, 120 m short of the departure end; 15 persons received injuries and 119 others escaped unharmed. 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 currents that characterize the base of a downdraft.

Downdrafts, as descriptive phenomena beneath thunderstorms, have been known to meteorologists long before the aviation age. According to Ludlam's (1963) review of severe local storms, Möller (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 updrafts and downdrafts. Suckstorff (1938) presented a concept of downdraft that spreads out beneath the thunderstorm, resulting in an outflow of cold air.

These conceptual models of thunderstorm downdrafts presented in the early years of meteorology are informative, but from an applications point of view, they are 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 a major attempt to measure both horizontal and vertical air currents in and around thunderstorms. Based on 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 updrafts and downdrafts, and 3) dissipating stage dominated by the downdraft, which eventually weakens and disappears.

A typical downdraft spreads out rapidly 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

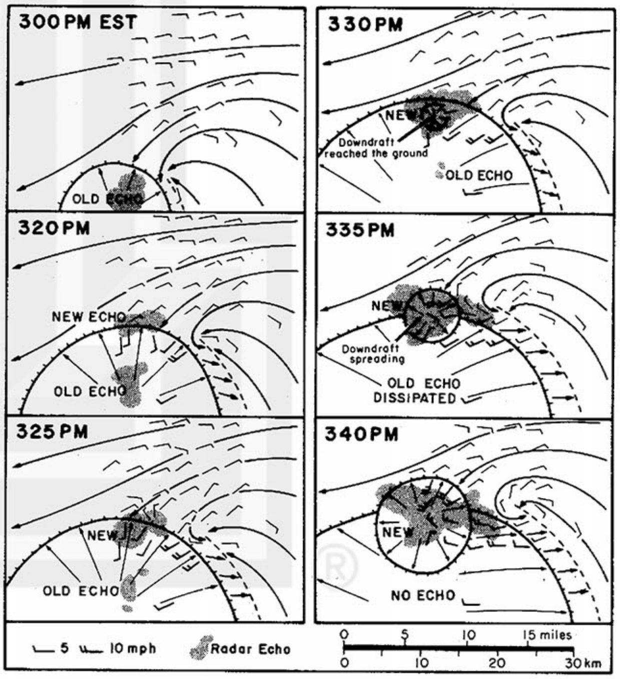

FIG. 1. Formation and development of downdraft cells depicted by mesoanalysis maps drawn at 5 min intervals. Cells were located ~48 km east of Cincinnati, Ohio. (Based on the Thunderstorm Project data on 13 August 1947; analyzed by Fujita (1963).)

[1] Department of the Geophysical Sciences, University of Chicago, Chicago, Ill. 60637.

[2] Atmospheric Physics and Chemistry Laboratory, ERL/NOAA, Boulder, Colo. 80302.

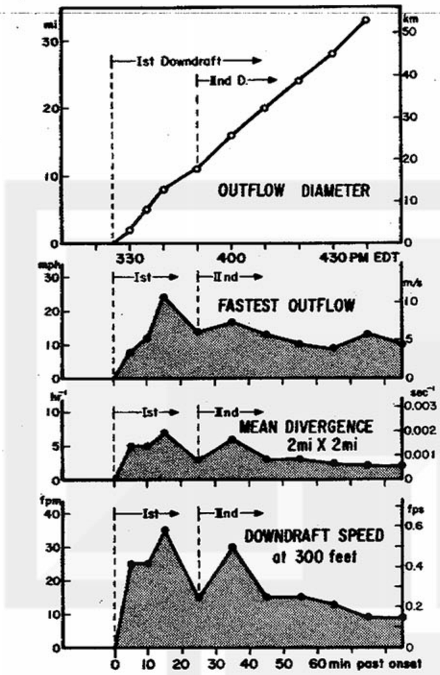

FIG. 2. Time variations in various parameters of the downdraft/outflow cells analyzed in Fig. 1. The new echo generated two downdraft cells at about 3:25 p.m. and 3:50 p.m. Note that the effects of these downdrafts reached a peak only 10–15 min after the formation. Downdraft speeds at 91 m (300 ft) were computed by assuming that the mean divergence at the anemometer level remains constant between the surface and the 91 m (300 ft) level. Actual draft speeds may reach several times the value shown in the figure.

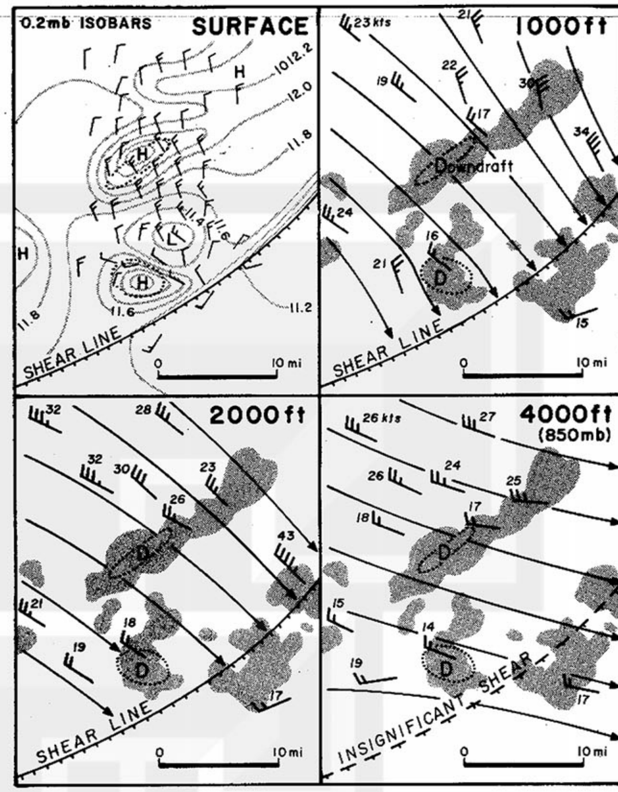

FIG. 3. Mesoanalysis maps showing the pressure noses imbedded inside a large mesoscale dome of outflow. Severe wind shear at low level is expected to occur along the shear line, as well as inside the nose areas, only a few miles across. (Based on the Thunderstorm Project, Ohio, data on 29 June 1947;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

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.

The growth of the downdraft can be shown effectively by plotting the diameter of the spreading edge as a function of time (see Fig. 2). The diameter increased almost linearly with time after onset. The fastest outflow and divergence reached their peaks within 10–15 min. The downdraft cell weakened thereafter; this behavior indicates that the major thrust of a downdraft can be expected to occur shortly after it reaches the surface.

In a squall line, downdrafts from several to tens of thunderstorms, by virtue of their fast spreading rate, amalgamate into a large dome of rain-chilled cold air. The surface pressure inside the dome of cold air is higher than that of its environment, and thus a mesoscale high-pressure area, called the "mesohigh," is formed. Mesoscale in meteorology is the horizontal size of wind systems extending one to several hundred kilometers (for details, refer to Fujita (1963) and Orlanski (1975)). 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 the gust front (see Fig. 3).

Behind the shear line, cold plow winds, which push the cold dome out into the warm air, can be expected. 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 may be called a pressure surge line or a pressure jump line. Quite often, the pressure jumps several millibars.

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, <10–15 min, and covers an area no more than several kilometers 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 regions of strong wind shear. The first region is located along the leading edge of the pressure dome generated by the

TABLE 1. Typical rate of climb of B-727 during the descent and climb at 91 m (300 ft) above the runway.

	ft s^{-1}	ft min^{-1}	m s^{-1}
Climb at Denver	17–28	1000–1700	5–9
Descent at JFK	10–13	600– 800	3–4

TABLE 2. Definition of downdraft and downburst.

	Downdraft	Downburst
Draft velocity at 91 m (300 ft)	<3.6 m s^{-1} (12 ft s^{-2})	≥ 3.6 m s^{-1} (12 ft s^{-1})
Divergence inside 800 m (0.5 mi) diameter	<144 h^{-1}	≥ 144 h^{-1}

combined outflows 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 that fly through the line at low altitudes are affected to a certain degree. An advance, short-time warning of expected wind shear 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 region of strong wind shear, which is likely to be responsible for the three accidents discussed in this paper, is the wind shear within the pressure nose area located at the base of a downdraft. 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 occur all over the world. Wichmann (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 s^{-1} downdraft inside the nose area.

In the early days of aviation history, these two regions of strong wind shear were not distinguished: for example, ". . . some thunderstorms are preceded by a strong squall wind (down draft) . . ." (United Airlines, 1939) and "generally, a locality on the ground is reached first by the heavy downdraft squall which is found on the lee side of the cloud" (Boeing School of Aeronautics, 1940). 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

There is a clear precedent for establishing new terms for extreme meteorological phenomena that are known to be dangerous. Take the term "hurricane" for example. 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 wind speed inside a tropical cyclone exceeds 32.6 m s^{-1}, the storm is called a hurricane. This threshold speed of a hurricane has little physical meaning because the storm structure does not change at this wind speed. 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. For flight safety purposes an analogous alarming term is needed to designate a downdraft that is likely to be hazardous to airport operations.

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 the "downdraft," defined by Byers and Braham (1949).

Fujita (1976a) and Fujita and Byers (1977) proposed using the term "downburst" when the downdraft speed becomes comparable to or greater than the approximate rate of descent or climb of a jet aircraft on the final approach or takeoff at 91 m (300 ft) above the surface. A downburst, therefore, is a downdraft in the uppermost intensity category, endangering aircraft operation near the ground.

Table 1 shows that 3–4 m s^{-1} (10–13 ft s^{-1}) is comparable to the descent rate, although it is much smaller than the climb rate. Because the alarming term that is adopted should be based on a conservative figure, 3.6 m s^{-1} (12 ft s^{-1}) at 91 m (300 ft) was selected as the threshold speed of the downburst.

Here, we further restrict the aerial extent of the downburst to be 800 m or larger, mainly because an aircraft is able to fly through a minidraft 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

$$3.6 \text{ m s}^{-1}/91 \text{ m} = 0.04 \text{ s}^{-1}$$

or

$$0.04 \text{ s}^{-1} = 144 \text{ h}^{-1}.$$

A downburst is therefore defined as a localized, intense downdraft with vertical currents exceeding a downward speed of 3.6 m s^{-1} (12 ft s^{-1}) at 91 m (300 ft) above the surface. The aerial extent of a downburst is 800 m (0.5 mi) or larger in diameter, characterized by a 144 h^{-1} (0.04 s^{-1}) or larger divergence (see Table 2).

The largest divergence published by Byers and Braham (1949) was ~20 h^{-1}, which is only a fraction of the 144 h^{-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 in the areas of the Thunderstorm Project in 1946–47.

Shown in Fig. 4 are the divergence values computed beneath 32 downdraft cells analyzed by Byers and Braham (1949). To determine the influence of horizontal dimensions, the computation areas were selected as 9.7,

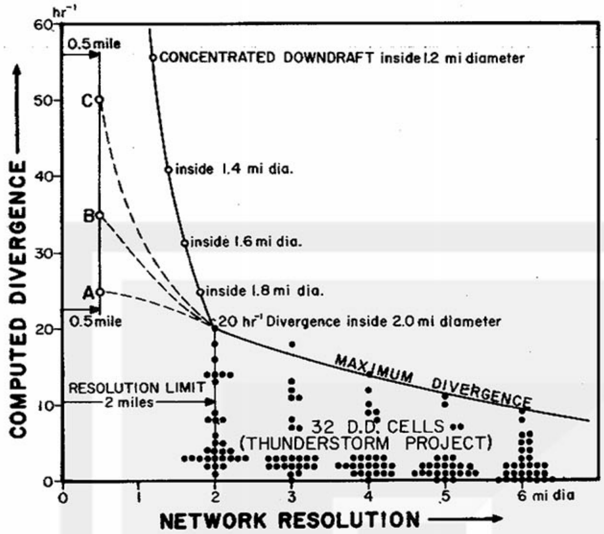

FIG. 4. Divergence values computed as a function of the area within the downdraft/outflow cells over the Thunderstorm Project network in Florida and Ohio. Divergence inside the areas of 800 m (0.5 mi) diameter cannot be estimated accurately without knowing the distribution of the draft speeds within the resolution limit, 1.5–3 km (1–2 mi) in this case.

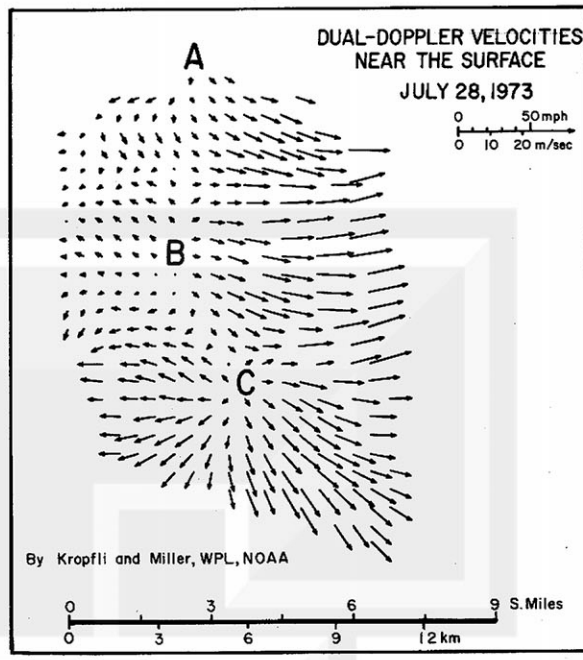

FIG. 5. Dual-Doppler system provides a new method of computing divergence values beneath precipitating cells. Cells A, B, and C are downdraft cells, being characterized by up to 17 h⁻¹ divergence. (Courtesy of Kropfli and Miller, 1976.)

8.0, 6.4, 4.8, and 3.2 km (6, 5, 4, 3, and 2 mi) in diameter. As was expected, the maximum divergence increased as the diameter decreased. Due to the network resolutions, 1.6 km (1 mi) in Florida and 3.2 km (2 mi) in Ohio, areas of 3.2 km (2 mi) diameter were chosen as the smallest areas for which a reasonable divergence could be computed. To estimate the values for 800 m (0.5 mi) diameter, the curve in Fig. 4 would have to be extrapolated like curves A (25 h^{-1}), B (35 h^{-1}), or C (50 h^{-1}). Extreme values, which are most unlikely to occur, can be computed by concentrating the downdraft into smaller areas with diameters such as 290, 260, 230, and 200 m (1.8, 1.6, 1.4, and 1.2 mi).

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 28 July 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 800 m (0.5 mi) 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).

This table reveals that both cells are characterized by 11–16 h^{-1} (0.003–0.004 s^{-1}) divergence inside the 3.2 km (2 mi) diameter. The values are no more than those measured in the Thunderstorm Project. Even by reducing the computation diameter to 1.6 km (1.0 mi), the divergence remains almost unchanged. These cells are, thus, by no means the downburst category. In future years, some downburst cells with divergence >144 h^{-1} will be measured by dual Dopplers, the most effective tool for investigating the velocity field of thunderstorms.

Although neither Doppler radar nor meteorological networks have reported measuring three-dimensional air motions inside downbursts, there is nevertheless direct evidence, in addition to the data related to aircraft accidents discussed in this paper, that they do exist.

Fujita (1976a) and Piaget (1976) have sighted and photographed numerous patches of trees blown down in diverging patterns; these observations suggest effects of downdraft of extreme intensity (see Fig. 6). Very recently Fujita confirmed, through an extensive aerial mapping, that 25 downbursts caused $50 million damage to trees in northern Wisconsin on 4 July 1977. The damage swath was 267 km long and 27 km wide and did not show any sign of a tornado in it.

Even a closer encounter of a downburst with a meteorological tower is likely to remain undetected. For example, Hall *et al.* (1976) reported that an intense outflow from a thunderstorm with tops above 17 km located 5

TABLE 3. Spatial variation of divergence (h^{-1}) of the 28 July 1973 storm (Kropfli and Miller, 1976).

	Computation Diameter,* km			
	1.6 (1.0)	3.2 (2.0)	4.8 (3.0)	6.4 (4.0)
Cell B	12.0	11.2	9.5	7.4
Cell C	16.0	16.1	15.8	11.2

* Diameter in miles is given in parentheses.

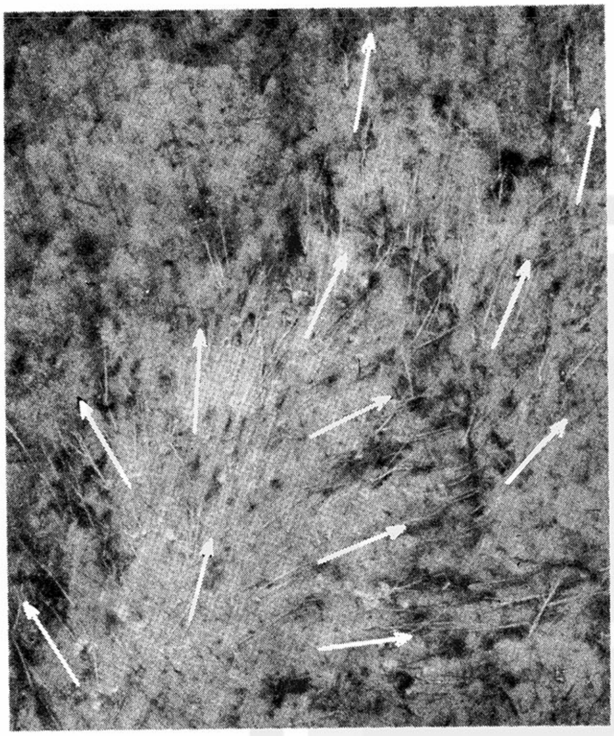

FIG. 6. A diverging pattern of tree damage near Beckley, N.C. Damage was probably caused by an intense downburst descending on the forest on 3 April 1974. (Photo by Fujita; taken from Cessna 172.)

km from a meteorological tower at Haswell, Colo., stripped the tower of its bivane anemometers. Thus it appears that a downburst moving over a meteorological tower may very well destroy anemometers before these currents become significant.

Since the vertical current of the downburst spreads out in the form of an outburst, a landing aircraft will first encounter a headwind, then a downburst, and finally a tailwind (see Fig. 7). 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 the 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.

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

It was a very hot, smoggy day in New Jersey with 32°–34°C temperatures reported early in the afternoon. At 1900 GMT (3:00 p.m. local time), several weak thunderstorms formed in northern New Jersey and headed toward Long Island. The temperature at JFK Airport was 25°C under the influence of the sea breeze.

It was ~1915 GMT (3:15 p.m.) when a small pendant echo formed on the east edge of a large echo north of the Morristown Airport in New Jersey. While other echoes were moving at 8 m s^{-1} (16 kt), the pendant echo extended toward JFK at 15 m s^{-1} (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 p.m.) the parent echo lost its identity, having been absorbed entirely into the pendant, which had grown into a spearhead echo both in shape and in speed. (For details, refer to Fujita (1976a) and Fujita and Byers (1977).)

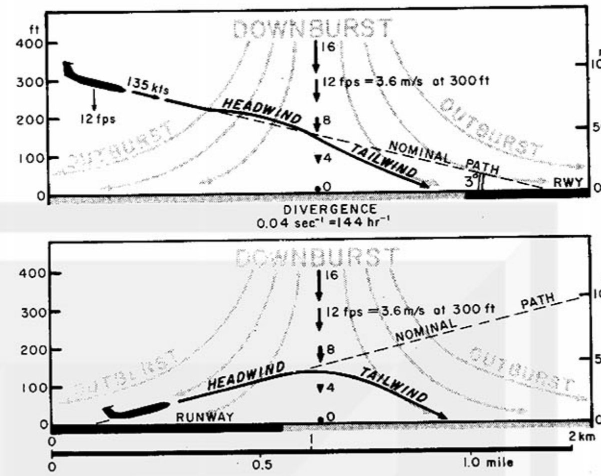

FIG. 7. Schematic diagrams of flight paths under the influence of a downburst cell.

During the 25 min period between 1945 and 2010 GMT (3:45–4:10 p.m.), 14 aircraft either landed or attempted to land on runway 22-L at JFK Airport. An estimated 1500 persons in three 747s and other jets 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 15 m s^{-1} (30 kt), are presented in Fig. 8. Note that 6 were international flights, 4 of which came from European countries. It was the busiest time of the day, and the approaches and landings took place as follows (for details, refer to National Transportation Safety Board (1975) and Fujita and Byers (1977)):

1) *American 678 from San Juan (3:44 p.m.).* Some wind shear was encountered on the final approach but it was not significant enough to mention to the tower.
2) *American 187 from Boston (3:46 p.m.).* A thunderstorm was sighted ~1.6 km (1 mi) to the right of the approach path, just short of runway 22-L.
3) *Allegheny 858 from Syracuse (3:48 p.m.).* A downdraft was experienced 1.6 km (1 mi) from the end of runway 22-L, and the plane landed in light rain.
4) *TWA 843 from Milan (3:49 p.m.).* The approach and landing were normal, and the plane landed on a dry runway.
5) *SAS 911 from Copenhagen (3:51 p.m.).* There was a little rain on touchdown.

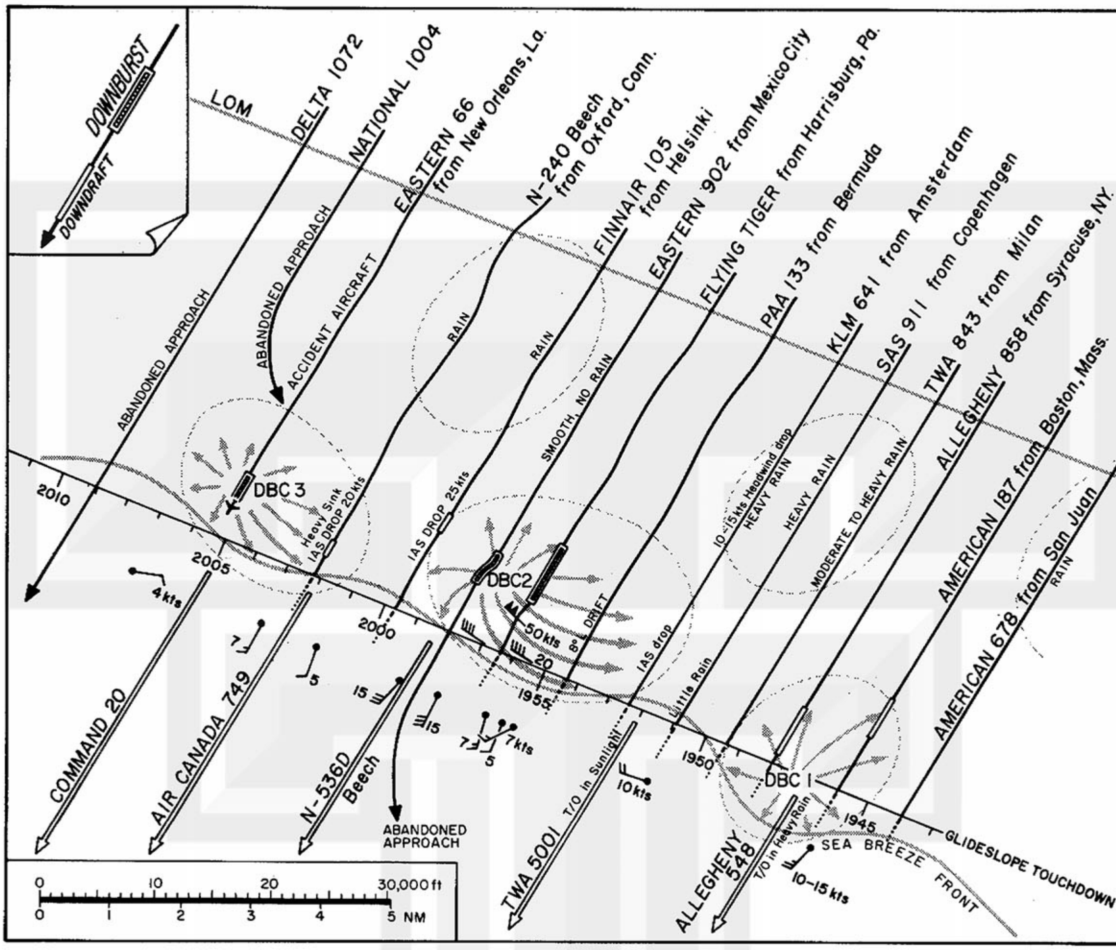

Fig. 8. Paths of 14 aircraft in 25 min at JFK Airport on 24 June 1975. Each path was shifted toward the WNW at 15 m s^{-1} (30 kt) to convert the time into the space relative to the spearhead echo. The echo, as seen by the Atlantic City radar, was 32 km (20 mi) long and 13 km (8 mi) wide, covering the entire area between LOM (Localizer Outer Marker) and the north end of runway 22-L. There were downburst cells (DBCs) along the south edge of the spearhead echo. Five aircraft took off inside the sea breeze without being affected by downbursts.

6) *KLM 641 from Amsterdam (3:52 p.m.).* The rain stopped at touchdown. The first half of the runway was wet, but the other half was dry.

7) *PAA 133 from Bermuda (3:54 p.m.).* There was a crosswind of 9 m s^{-1} (18 kt) from the right at 60 m (200 ft) in extremely heavy rain. After rolling for 305 m (100 ft), the plane broke out on a dry runway in sunlight. While on the taxiway, the pilot saw the next aircraft, Flying Tiger, in a difficult landing maneuver.

8) *Flying Tiger 161 from Harrisburg, Pa. (3:56 p.m.).* It encountered a strong, sustained downdraft (downburst) from 215 to 60 m (700–200 ft) altitude. From 60 m (200 ft) to touchdown the downdraft was moderate, but the crosswind from the right was very strong. It was blowing 25–28 m s^{-1} (50–55 kt) just off the ground, and all of a sudden there was no wind on the ground.

9) *Eastern 902 from Mexico City (3:58 p.m.).* The air was smooth and normal down to 122 m (400 ft). They flew into extremely heavy rain with zero visibility. The aircraft sank and drifted to the right, and the airspeed dropped from 74 to 62 m s^{-1} (144–121 kt). Power was applied to abandon the approach. It kept sinking down to 18 m above the ground before the pilot was able to gain altitude (see Fig. 9).

10) *Finnair 105 from Helsinki (4:00 p.m.).* About 3 km (2 mi) before touchdown, the airspeed dropped 13 m s^{-1} (25 kt). The subsequent approach and landing were normal.

11) *N-240 Beech from Oxford, Conn. (4:02 p.m.).* A heavy sinking was experienced at 60–90 m (200–300 ft) altitude. The airspeed dropped 10 m s^{-1} (20 kt), power was applied, and the remainder was normal.

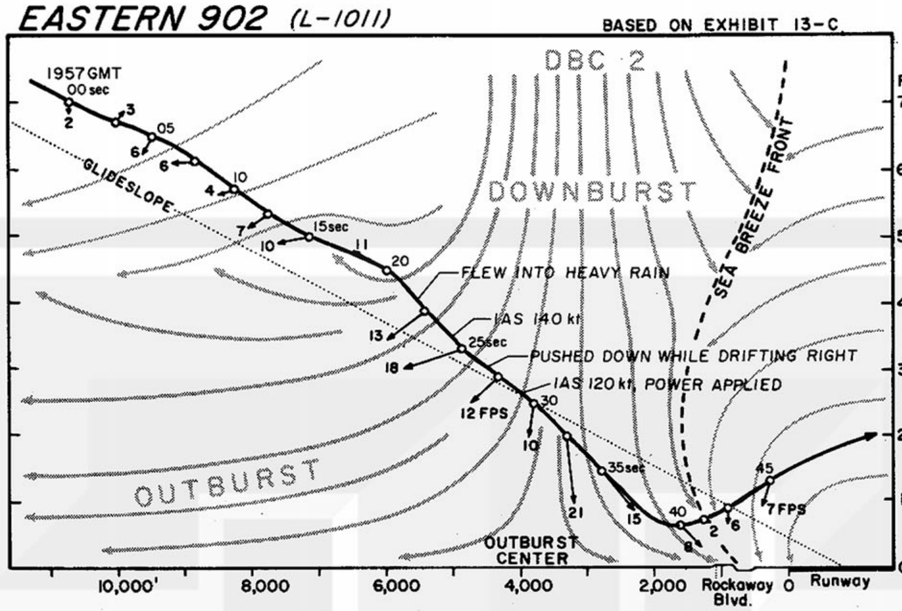

FIG. 9. The path of Eastern 902 on 24 June 1975 in the vertical plane including the glide slope of runway 22-L at JFK.

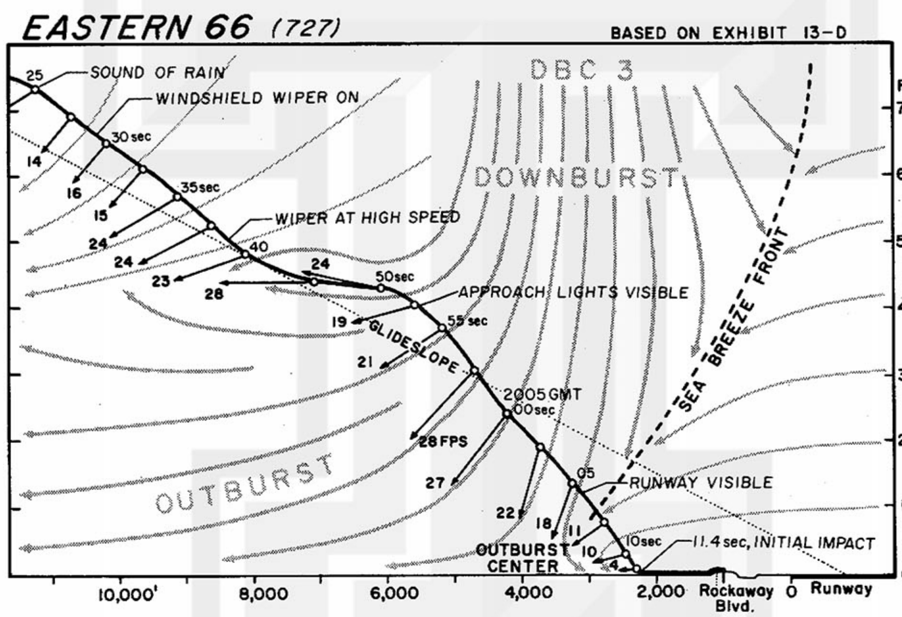

FIG. 10. The path of Eastern 66 on 24 June 1975 in the vertical plane including the glide slope of runway 22-L at JFK.

12) *Eastern 66 from New Orleans (4:05 p.m.).* It encountered heavy rain at 150 m (500 ft) altitude, and the wiper was operated at high speed. The approach lights were visible at 120 m, and then the airspeed dropped from 71 to 63 m s^{-1} (138–122 kt) in 7 s. The plane sank in a 6.7 m s^{-1} (22 ft s^{-1}) downburst at 60 m (200 ft) altitude and hit the approach lights at 2005 GMT (4:05 p.m.), about 730 m (2400 ft) short of the runway (see Fig. 10).

13) *National 1004 (4:07 p.m.).* While approaching, 10–13 km (6–8 mi) from the runway, a circular echo was observed, 3–5 km (2–3 mi) in diameter, moving eastward very rapidly. The echo reached over threshold on runway 22-L at 2006 GMT (4:06 p.m.). The airport was closed due to the accident of Eastern 66. The plane made an immediate left turn in front of the echo and climbed for landing at La Guardia.

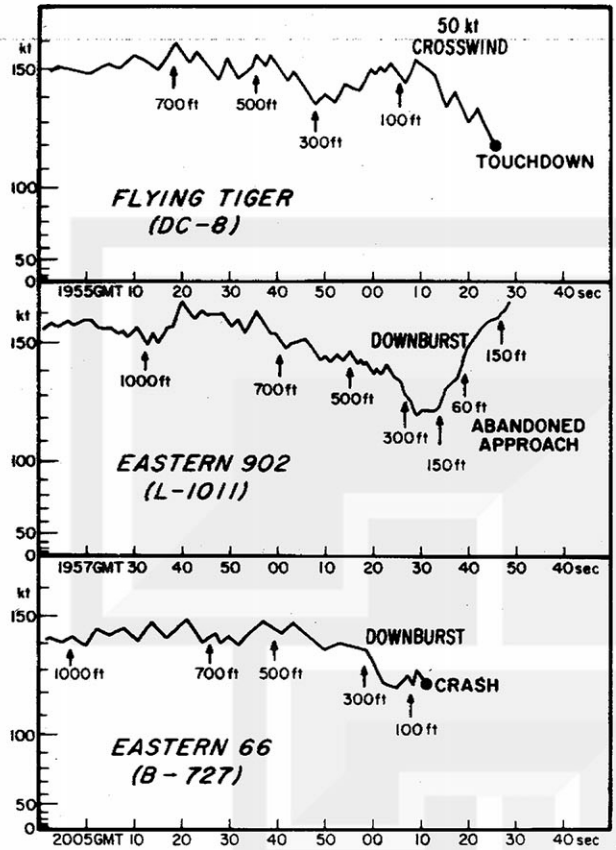

FIG. 11. Indicated airspeed of three aircraft landing at JFK on 24 June 1975. The vertical scale is proportional to the square of the indicated airspeed.

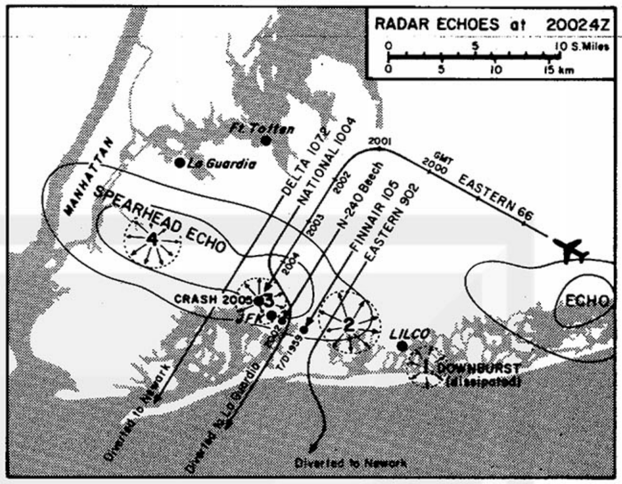

FIG. 12. The paths of five aircraft on 24 June 1975, drawn relative to the spearhead echo at 2002.4 GMT. Although the NWS Altantic City radar showed a large spearhead echo, the airborne radar of approaching aircraft painted a circular, small echo near the approach end of runway 22-L. The radar beam altitude of the echo from Atlantic City, 0.2° elevation at 148 km (80 n mi), was ~2100 m (7000 ft).

14) *Delta 1072 (4:09 p.m.)*. At ~60 m (1500 ft) altitude the pilot was told by the tower to go around. The plane climbed back to 610 m (2000 ft) and flew to runway 22-L. While over the threshold, a circular echo was seen that was moving away toward the east. The plane was diverted to Newark.

Of the 14 aircraft that flew through the spearhead echo, only 3 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 that 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. 11).

Eastern 902 lost airspeed when a 5 m s^{-1} (10 kt) headwind changed into a vertical wind as the plane flew into a downburst cell. The airspeed gradually increased after power was applied at 82 m (270 ft). But the aircraft kept descending for ~10 s, suffering from a tailwind and a downburst of 6.4 m s^{-1} (21 ft s^{-1}) at 60 m (200 ft) (see Figs. 9 and 11).

Eastern 66 lost airspeed suddenly at 91 m (300 ft) when an 8 m s^{-1} (16 kt) headwind changed into a 6.4 m s^{-1} (22 ft s^{-1}) downburst. Evidently the aircraft flew straight into the downburst center. The loss of airspeed and the intense downburst at 60 m (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 730 m (2400 ft) short of the runway, the left wing clipped some approach lights and the plane skidded 300 m (1000 ft) while breaking up (see Figs. 10 and 11).

The spearhead echo, 32 km (20 mi) long and 8 km (5 mi) wide, produced at least four downburst cells. Although we do not know how many cells coexisted simultaneously, cells marched across just north of the JFK Airport one after another. The paths of 5 aircraft relative to the spearhead echo at 2002.4 GMT (4:02.4 p.m.) are shown in Fig. 12.

La Guardia Airport, only 16 km (10 mi) 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 8 m s^{-1} (15 kt). This is why 22-L was used for landing.

Apparently the downburst cells passed across a meteorological tower with an anemometer at 62.5 m (205 ft), instrumented and operated by the Long Island Lighting Co. The tower is located about ~11 km (7 mi) ESE of the accident site. The time-space conversion of winds reveals the passage of three downburst cells, which had weakened considerably (see Figs. 12 and 13).

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 3–5 km (2–3 mi) in diameter, but they were accompanied by intense downward currents near the center and surrounded by

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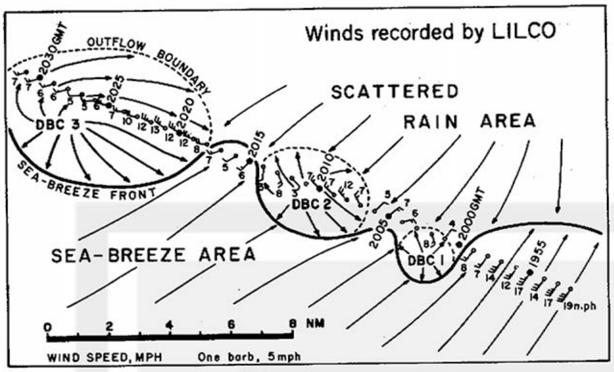

FIG. 13. Winds at 62.5 m (205 ft) recorded by the Long Island Light Co. (LILCO) on 24 June 1975. Time-space conversion of the winds reveals the passage of downburst cells (DBCs) in weakening stages across the wind tower.

strong outflows about the center. Due to a 3–5 km (2–3 mi) space between the cells, some aircraft landed without problems, while others encountered serious difficulties.

4. 7 August 1975 accident at Stapleton Airport, Denver

The Denver area in the early afternoon hours on 7 August 1975 was having temperatures in the low 30s (°C) with scattered thundershowers. Thunder began at Stapleton Airport at 1429 MDT, with storms scattered around the area. The last reported thunder was at 1550 MDT. The sounding at 0000 GMT on 1 August presented in Caracena's (1976) analysis shows that the lapse rate was almost dry adiabatic up to ~500 mb with surface winds from the SSE. The situation was favorable for scattered showers and thunderstorms in eastern Colorado.

During the afternoon the National Weather Service (NWS) 10 cm radar located at Limon, Colo., observed a number of echoes moving eastward off the Front Range. These echoes did not move uniformly. The echoes to the southeast of the city acted like slow-moving bubbles. Most of them traveled toward the northeast at 3.5–7.5 m s^{-1} (7–15 kt). In contrast, the echoes over the Boulder–Ft. Lupton area were moving at 8.5–9 m s^{-1} (17–18 kt) along wavy paths (see Fig. 14).

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 9.5–11 m s^{-1} (19–22 kt). Echo A, between 1606 and 1622 MDT, which moved over the accident area, traveled at 8 m s^{-1} (16 kt) along a straight path. Furthermore, the shape of echo A at its mature stage was somewhat like a spearhead, 8 km (5 mi) wide and 16 km (10 mi) 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 that moved over Stapleton runway 35L at the time of the accident at 1611 MDT. The spearhead echo in the Stapleton area was just about half the size of the

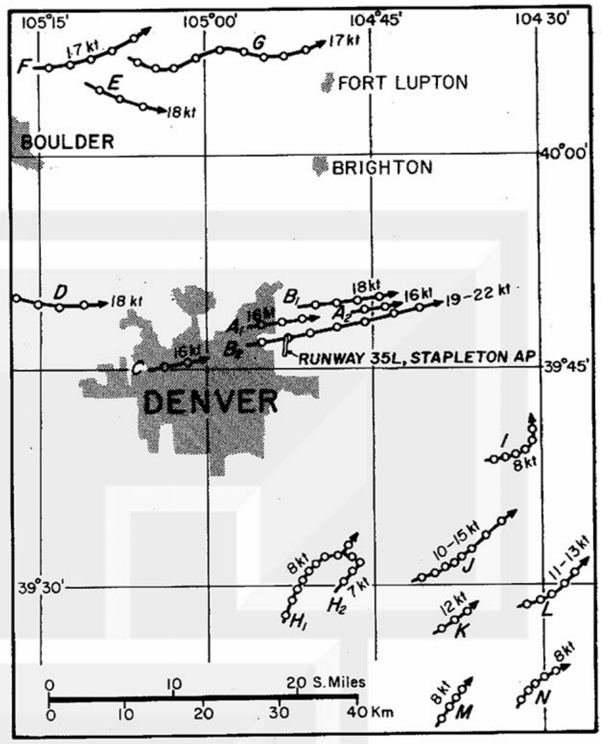

FIG. 14. Movement of scattered storm echoes near Denver on 7 August 1975 between 1518 and 1622 MDT. NWS radar at Limon, Colo., ~130 km (70 n mi) southeast of Denver, took pictures at 5.3 min intervals during this period. Open circles show the echo centroids in each picture.

JFK thunderstorm, which was 8 km (5 mi) wide and 32 km (20 mi) long.

The time-space coordinates of the three aircraft in Fig. 15 were constructed by moving runway 35L relative to the spearhead echo. The pattern shows clear evidence for the impact of a strong downdrift just west of the center of runway 35L. The winds from the Stapleton wind tower, 500 m (0.3 mi) east of the runway threshold, and from wind tower No. 7, located 800 m (0.5 mi) northwest of the north end of the runway, were added in the figure. Following are the conditions encountered by the three aircraft during their takeoff and climb-out period (for details, refer to National Transportation Safety Board (1976), Kadlec *et al.* (1975), and J. B. Pittman (personal communication to NTSB, 1975)):

1) *Braniff 67.* While the plane was taxiing, a dust cloud was seen moving westward near 35L, possibly three-fourths of the way down the runway. After waiting for the dust cloud to clear the runway, the plane took off at 1605 MDT with normal acceleration. Then suddenly the aircraft did not respond to inputs for 2–3 s. 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

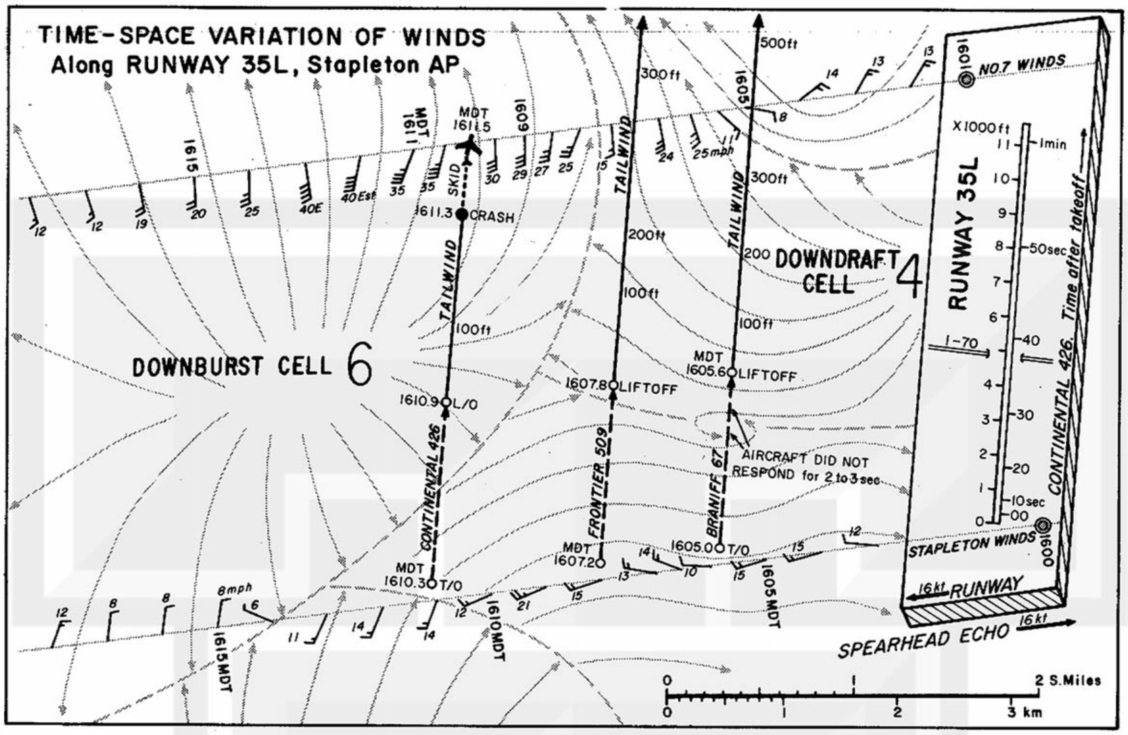

Fig. 15. Three aircraft that took off from runway 35L of Stapleton Airport between 1605 and 1610 MDT on 7 August 1975. In constructing these time-space coordinates, the runway and two wind towers were moved, at 8 m s⁻¹ (16 kt), in the opposite direction of the spearhead echo. One minute was added to the time of wind tower No. 7 to take into account the travel time of the aircraft from takeoff to the end of the runway.

and lifted off. At 30–90 m (100–300 ft) altitude, a downdraft and tailwind were encountered, resulting in a 5–7.5 m s^{-1} (10–15 kt) loss of the indicated airspeed (see Figs. 15 and 16).

2) *Frontier 509*. It experienced a downdraft and tailwind shear just as the previous aircraft had. The airspeed dropped from 80 to 62 m s^{-1} (155 to 120 kt) in 10 s, at the rate of 1.8 m s^{-2} (3.5 kt/s). The aircraft rotated nose down to gain airspeed while flying horizontally for ~20 s (see Figs. 15 and 16).
3) *Continental 426*. The aircraft took off at 1610 MDT, using maximum takeoff thrust. All instrument readings were normal at 40 m s^{-1} (80 kt) indicated airspeed. It 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 ~30 m (100 ft) above the runway, the airspeed decreased from 81 to 60 m s^{-1} (158 to 116 kt) in ~5 s. The rate of airspeed loss was an amazing 4 m s^{-2} (8 kt/s). The captain lowered the nose to ~10° pitch, but the aircraft continued to descend to the ground. Just before the aircraft struck the ground, the stall warning system activated (see Figs. 15, 16, and 17).

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

The maximum divergence at the surface, as estimated by the authors, was 150–250 h^{-1} (0.04–0.07 s^{-1}). This implies that Continental 426 flew through the base of what was undoubtedly a strong downburst. The outburst was strong enough to cause an uncontrollable rate of airspeed loss, 4 m s^{-2} (8 kt/s). 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 preexisting downdraft air.

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 34 km (21 mi) boundary. As shown in Fig. 18, the towers are numbered 1–9. In addition, there were five more anemometers in the area:

1) Station S, at Stapleton Airport, operated by NWS;
2) Station B, at Buckley Air National Guard, maintained by the U.S. Air Force;
3) Station D, Colorado Department of Public Health;
4) Station L, at Lowry Air Force Base, operated by Dr. Raymond Jordan;
5) Station U, at Dr. Jordan's house, where he also operated a recording thermograph.

The following mesoanalysis is based on data furnished

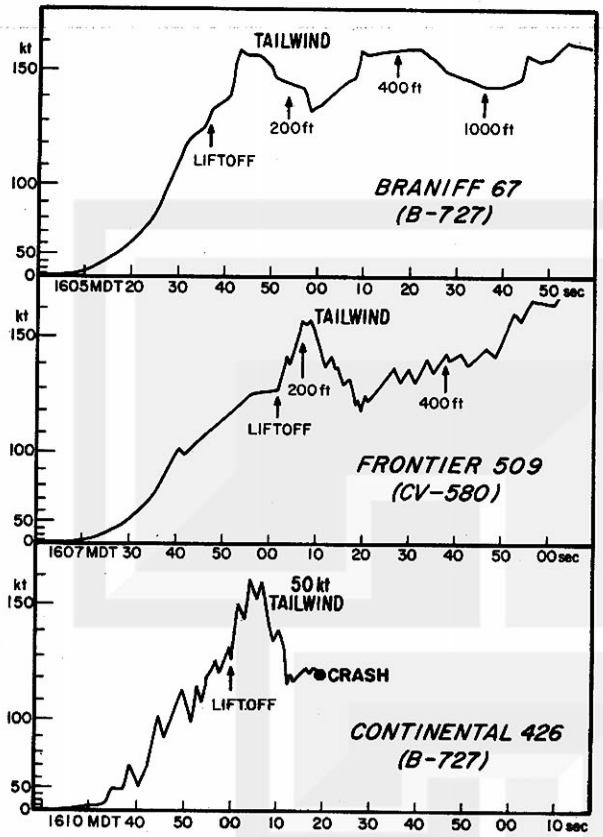

FIG. 16. Variation of indicated airspeed of three aircraft that took off from runway 35L of Stapleton Airport on 7 August 1975. The airspeed scale was plotted in proportion to the square of the speed.

by this network and on echoes recorded by Limon radar.

At 1550 MDT, echo B was leaving 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. 18).

Between 1555 and 1600 MDT, air temperature at Station U rose 1.7°C, indicating that the flow from downdraft 1 was warm. Meanwhile, a warm downdraft, No. 2, began spreading out in all directions (see Fig. 19).

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 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. 20).

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, ~5 km (3 mi) 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 1 min before this map time, whereas Frontier 509 lifted off 2 min later. Both aircraft were probably unaware of the development of cell No. 6 into a downburst (see Fig. 21).

Downburst 6 reached its mature stage at ~1612 MDT, 1 min after the accident. An outburst up to 20 m s^{-1} (40 kt) was spreading toward the north. Echo A

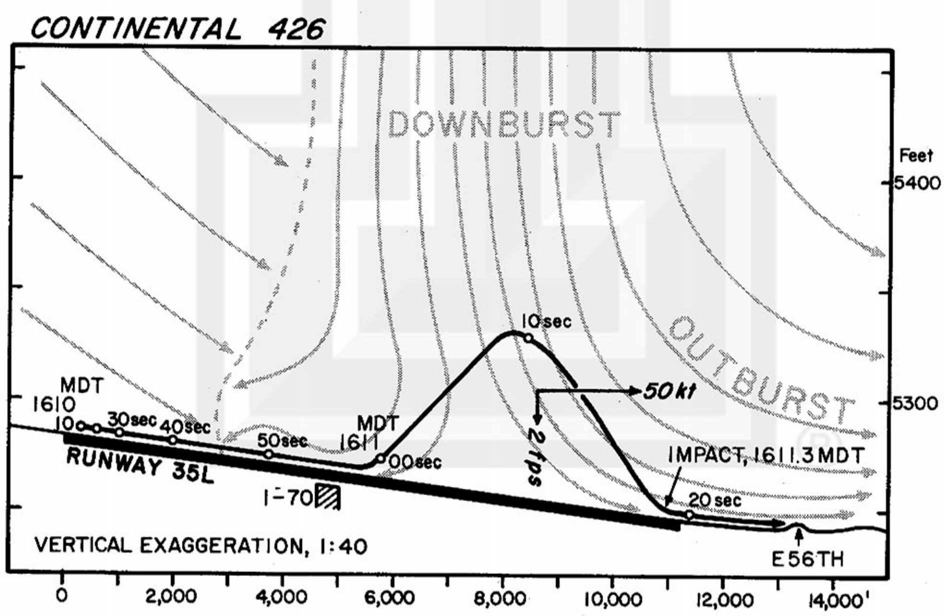

FIG. 17. A schematic figure showing the path of Continental 426 in relation to the downburst cell on 7 August 1975. The maximum height of the aircraft is approximate because the altimeter was affected by the aerodynamic characteristics of the pitot tube during the climb. The height scale is in feet at MSL.

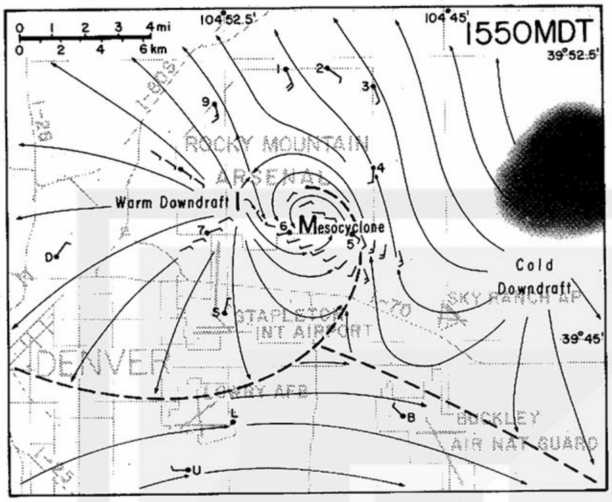

FIG. 18. Mesoanalysis map for 1550 MDT, 7 August 1975. A small mesocyclone is seen on the south boundary of Rocky Mountain Arsenal.

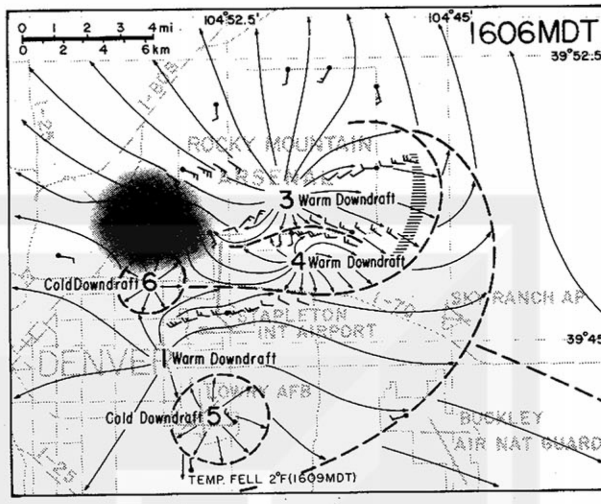

FIG. 21. Mesonalysis map for 1606 MDT, 7 August 1975. A circular echo formed over the area of surface convergence. The area of 10 m s⁻¹ (20 kt) or stronger wind is hatched.

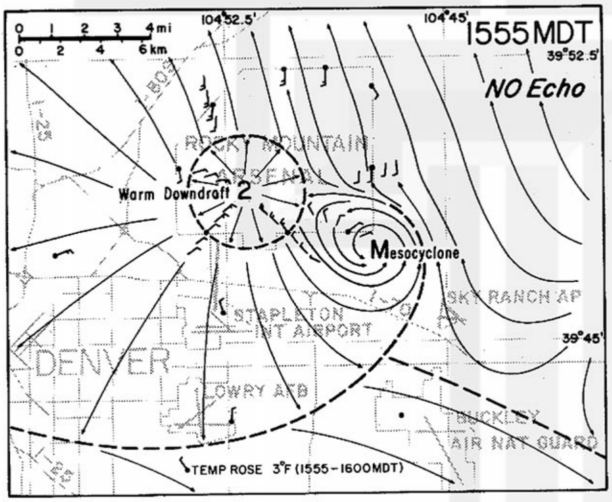

FIG. 19. Mesoanalysis map for 1555 MDT, 7 August 1975. A warm downdraft formed while the mesocyclone weakened.

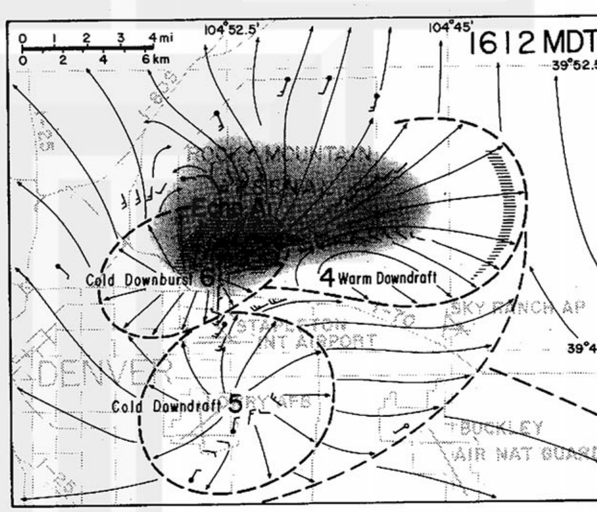

FIG. 22. Mesoanalysis map for 1612 MDT, 7 August 1975. The circular echo changed into a spearhead echo that extended rapidly toward the east. Areas of 10 m s⁻¹ (20 kt) or stronger winds are hatched.

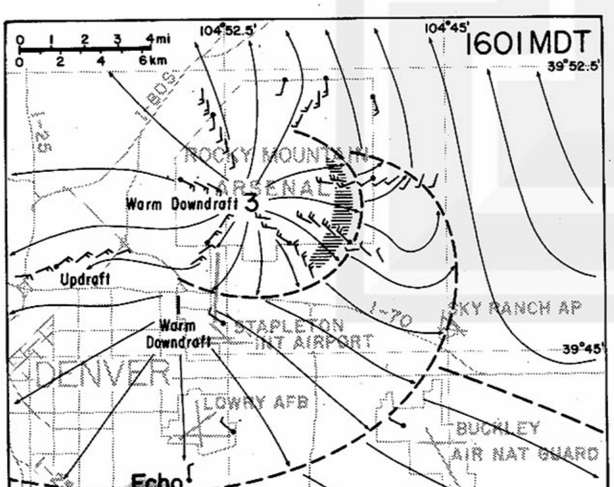

FIG. 20. Mesoanalysis map for 1601 MDT, 7 August 1975. The warm downdraft spread out, especially toward the east. The area of 10 m s⁻¹ (20 kt) or stronger wind is hatched.

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. 22).

Meteorological analysis of the data on 7 August 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 ~5 min before the accident. The cell developed very rapidly.

Warm downdrafts, such as those reported by Fujita (1976b), were also found in the analyses area. At the leading edge of the outflow from downdraft 1, the temperature rose as much as 1.7°C. 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

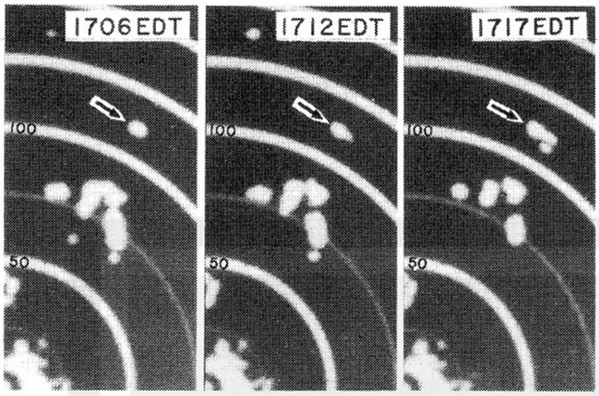

FIG. 23. Rapid development of a small spearhead echo over Philadelphia Airport. Three pictures were taken by NWS Patuxent River, Md., radar at 1706, 1712, and 1717 EDT on 23 June 1976. Heavy range marks are 50, 100, 125, and 150 n mi. Time of accident was 1712 EDT.

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 preexisting downdraft air.

It was the warm downdraft air from cells 1, 3, and 4 that 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.

5. 23 June 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 ~5.5°C. At 1712 EDT, when Allegheny 121 crashed on the runway, there were scattered showers and thunderstorms in the cold sector. The Atlantic City, N.J., and the Patuxent River, Md., NWS radars depicted a few isolated cells over the area, but none appeared to be of an alarming level of intensity and echo size.

The aircraft approached from the east attempting to land on runway 27-R. Suddenly it ran into a strong headwind shear while approaching the runway threshold. Headwinds increased to an estimated 25–30 m s^{-1} (50–60 kt). Power was cut down to reduce airspeed, and the inertial navigation system ground speed dropped to <50 m s^{-1} (100 kt). About 18 m (60 ft) above the runway near its threshold the aircraft started climbing, in an attempt to go around. When it reached 79 m (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.

Pictures from the Patuxent River radar, ~204 km (110 n mi) SSW, showed a small, circular echo at 1706

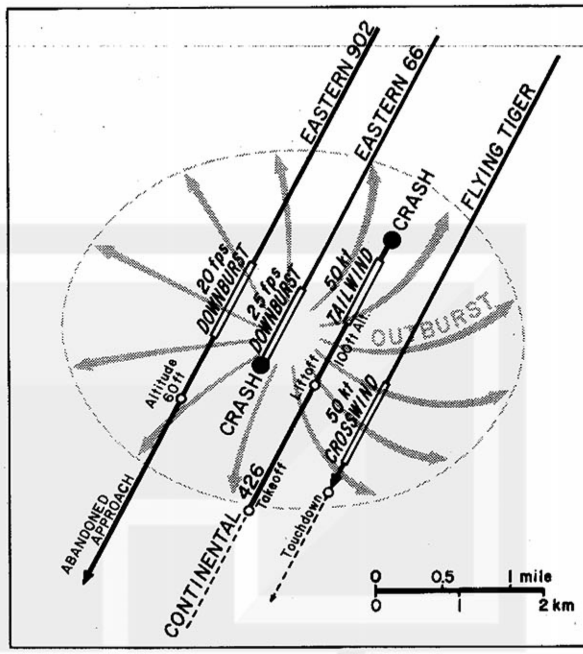

FIG. 24. Composite paths of aircraft relative to downburst cell for Flying Tiger, Eastern 66, and Eastern 902 at JFK on 24 June 1975, and Continental 426 at Stapleton on 7 August 1975. Allegheny 121 at Philadelphia on 23 June 1976 flew through the downburst center from right to left, experiencing a 25–30 m s^{-1} (50–60 kt) headwind, calm, and 3 m s^{-1} (6 kt) tailwind before it crashed on the runway.

EDT. At 1712 EDT, when the accident occurred, it grew into a spearhead echo with a point on its ESE end. Five minutes later, the echo grew in size to 13 km (8 mi) wide and 27 km (17 mi) long (see Fig. 23).

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 that induces dangerous wind shear of both vertical and horizontal winds;
2) *spearhead echo*—a fast-moving echo that spawns downburst cells.

Shown in Fig. 24 are the composite paths of four aircraft that 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 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 glide slope. The crosswind

TABLE 4. Characteristics of spearhead echoes.

Location of Thunderstorm	Time of Accident	Time Echo Began	Lead Time, min	Echo Dimensions,* km
JFK	1605 EDT	1515 EDT	50	8 × 32 (5 × 20)
Stapleton	1611 MDT	1606 MDT	5	8 × 16 (5 × 10)
Philadelphia	1712 EDT	1706 EDT	5	13 × 27 (8 × 17)

* Echo dimensions in miles are given in parentheses.

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."

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

1) *headwind shear*—indicated airspeed increases and aircraft gains altitude;
2) *tailwind shear*—indicated airspeed drops and aircraft sinks;
3) *crosswind shear*—aircraft drifts to the right or left;
4) *downburst shear*—aircraft drops abruptly due to the shear of vertical wind.

In most cases, a mixture of the above types of 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 4).

In all cases, the spearhead echo moved straight and 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 turbulence, 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 148 km (80 n mi) (JFK thunderstorm), 130 km (70 n mi) (Stapleton thunderstorm), and 204 km (110 n mi) (Philadelphia thunderstorm). They are relatively small echoes with an appearance of harmless air-mass showers (see Fig. 25).

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 runway 22-L based on his airborne radar. The echo, 3–5 km (2–3 m) in diameter, was just ~10 km (6 mi) in front of him.

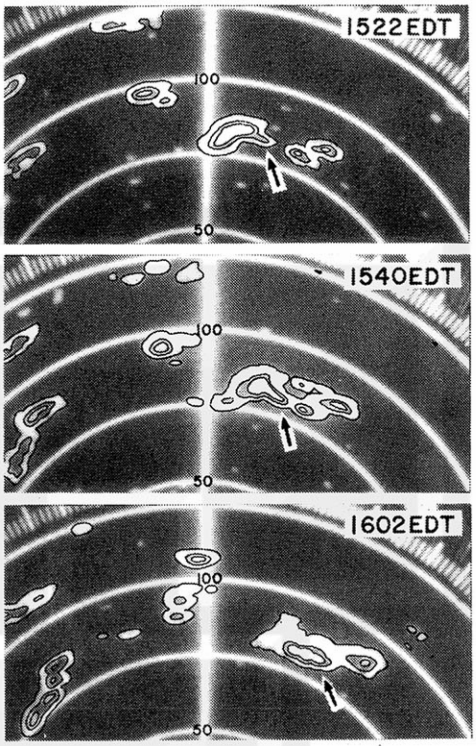

FIG. 25. Contour representation of the spearhead echo near JFK on 24 June 1975. The formative stage is seen in the picture at 1522 EDT. At 1540 EDT, the parent echo is being drawn into the spearhead section. Finally, at 1602 EDT, 3 min before the accident, the parent echo was absorbed entirely into the spearhead echo.

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 5–6 km (3–4 mi) in diameter. Although the appearance 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 three circular echoes on their airborne radar scopes. One of these was the downburst cell located in the vicinity of runway 35L. The two others were to the east of the airport.

Since the airborne radar scans a beam of <4° in elevation, during a final approach it would normally be looking at approximately the low 1200 m (4000 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 55 km (30 n mi) range from the Atlantic City

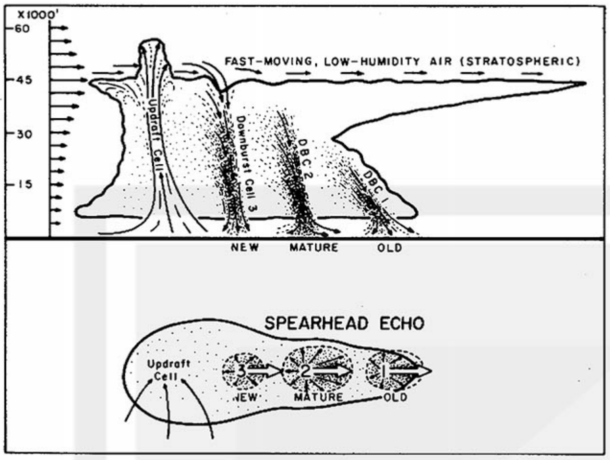

FIG. 26. The Fujita-Byers model of a spearhead echo. They assumed that the fast-moving air is brought into the source region of the downburst when an overshooting top collapses into the anvil cloud. By virtue of large horizontal momentum drawn into a downburst cell, the cell moves faster than other portions of the echo. In effect, downburst cells run away from the parent echo and weaken, resulting in a pointed shape on the advancing end of the echo. At close range, especially below the cloud base, the radar paints small circular echoes. (From Fujita (1976a) and Fujita and Byers (1977).)

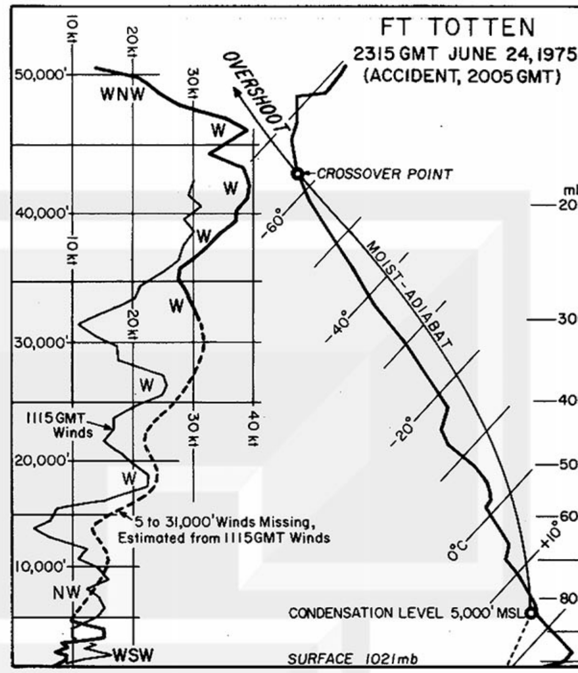

FIG. 27. Sounding at Ft. Totten, 16 km (10 mi) north of JFK, released at 2315 GMT (1915 EDT) on 24 June 1975.

radar, the echo at Philadelphia on 23 June 1976 was observed as a circular cluster of echoes, ~120 m (400 ft) above the airport.

Fujita's (1976a) and Fujita and Byers's (1977) model of the spearhead echo was based on the JFK thunderstorm. Shown in Fig. 26 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.

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).

Adiabatic charts from Ft. Totten and Stapleton in Figs. 27 and 28 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.

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

Location of Thunderstorm	Strongest Outburst	Estimated Speed,* m s^{-1}	500 mb Wind,* m s^{-1}	150 mb Wind,* m s^{-1}
JFK	from WNW	25–30 (50–60)	West at 11 (22)	West at 19 (38)
Stapleton	from SSW	20–25 (40–50)	WNW at 5 (10)	SW at 13 (26)
Philadelphia	from West	25–30 (50–60)	SW at 8 (15)	West†

* Speed in knots is given in parentheses.
† Speed unknown.

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 is 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 6 May 1973 over Texas was 41 m s^{-1} at 14.6 km (48 000 ft). An example of a collapsing top is shown in Fig. 29. If a rapid collapse, such as this, induces an intense downburst on the ground, some trees and vegetation could receive downburst damage.

Although a number of fast-collapsing tops, such as those in Fig. 29, 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 the Wave Propagation Laboratory, NOAA, at Boulder, Colo., depicted cases of strong downdrafts originating at the cloud-top level (see an example

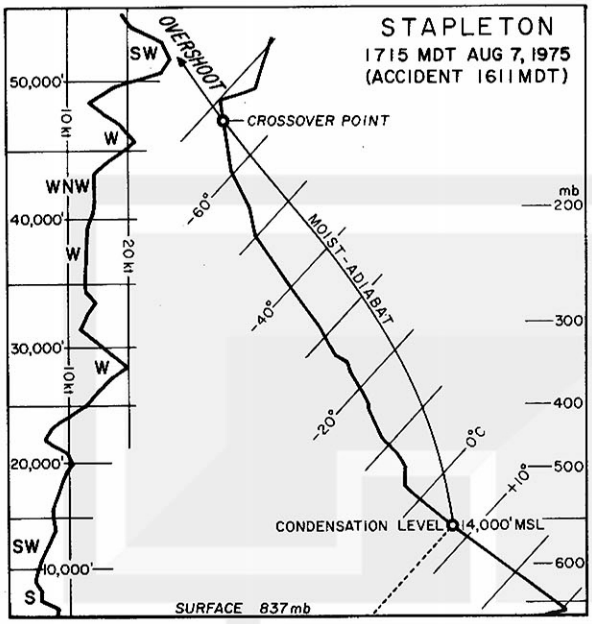

FIG. 28. Denver sounding released at Stapleton Airport at 1715 MDT on 7 August 1975.

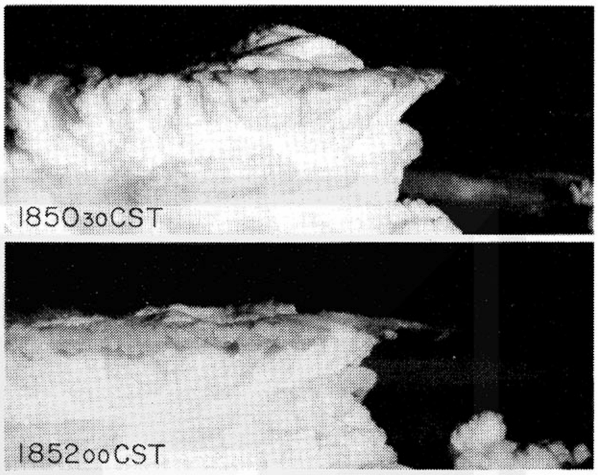

FIG. 29. Collapse of an overshooting dome within 1.5 min. Sometimes a large, tall dome collapses so fast, as in this case, that the skin of the anvil is pushed outward. The collapsed dome descends into the anvil and the hole is filled gradually. (Pictures taken near San Antonio, Tex., on 6 May 1973; from Fujita (1974).)

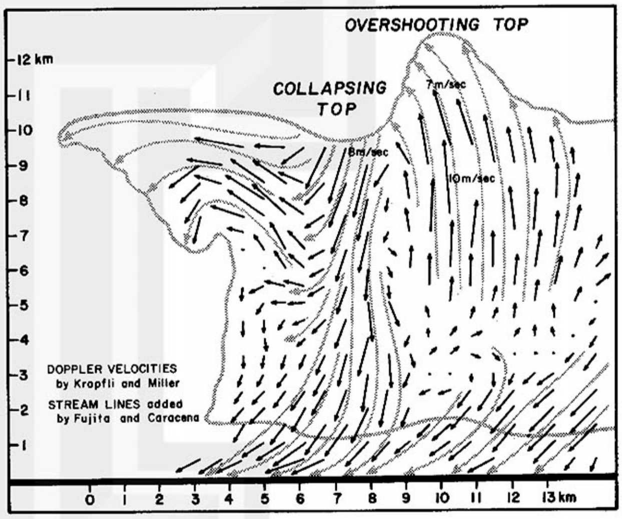

FIG. 30. A vertical cross section of Doppler velocities inside a 28 July 1973 thunderstorm in Colorado. Dual-Doppler velocities were obtained by Kropfli and Miller (1976). (Original data obtained through personal communication.) Both cloud boundary and streamlines were added by the authors.

in Fig. 30). 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. Their short lives, coupled with small areas, would have escaped detection and subsequent reporting for awareness and preparedness.

During the damage survey of the 148 tornadoes on 3 April 1974, Fujita found diverging patterns of blown-down trees located a considerable distance away from tornado paths (see Fig. 7). In Switzerland, Piaget (1976) mapped 25 isolated spots of tree damage outside the path of the 26 August 1971 tornado.

On 6 May 1975, NWS Kansas City radar depicted a spearhead echo located ~185 km (100 n mi) away. Meanwhile, the SMS/GOES satellite took pictures, looking down from a geostationary altitude 40 700 km (25 300 mi) 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 13.7 km (45 000 ft). The picture sequence revealed that the overshooting in the echo area was very significant.

A composite analysis of the three accident cases revealed that the downburst winds, accompanied by spearhead echoes, were localized but very strong. It is unlikely that a jet aircraft would be able to fly through the center of a downburst cell below 91 m (300 ft). Coleman (1976) introduced the importance of identifying downbursts to assist safe landing and takeoff 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 reach the intensity of a downburst.

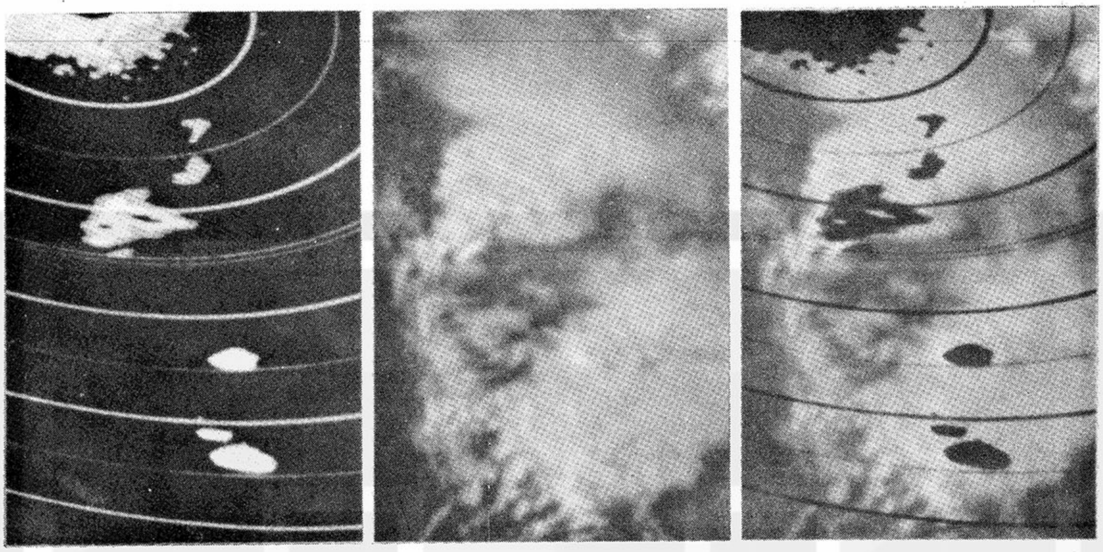

FIG. 31. A spearhead echo of 6 May 1975. Radar echo at 1722 CDT (left), SMS/GOES picture at 1722 CDT (center), and their combination (right).

2) The mature stage of a downburst is reached only 5–10 min after its formation.
3) Downburst cells are very small, reaching only 5–6 km (3–4 mi) 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 1 min 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) Airports should be instrumented with arrays of detectors such as pressure sensors, wind speed detectors, some anemometers, and possibly temperature sensors. These arrays should have at least a resolution of 800 m (0.5 mi). The output from these instruments should be reduced by means of microprocessors into forms that are displayed visually to tower personnel. These displays would depict positions of shear lines and pressure noses, identify downbursts and regions of dangerous shear, and have an alarm device such as a blinking red light to call attention to potential wind shear threats.
2) Most NWS radar sites are remote from the airports they serve. From 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) Rapid communication to pilots of information on known weather hazards is a problem urgently needing a solution. In the case of thunderstorm wind shear, communication lags of a few minutes are inadmissible in view of the rapid development of downburst cells.
4) It is also recommended that research be conducted around the major airports to obtain Doppler velocities and to monitor cloud-top activities. These data should be analyzed and evaluated along with ground and airborne observations.

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