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COMMON DENOMINATOR OF THREE WEATHER-RELATED AIRCRAFT ACCIDENTS

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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 meteorologists 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 downdraft. Suckstorff (1938) presented a concept of downdraft which spreads out beneath the thunderstorm, resulting in an outflow of cold air.

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 1/2 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.

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. 1. In this example,

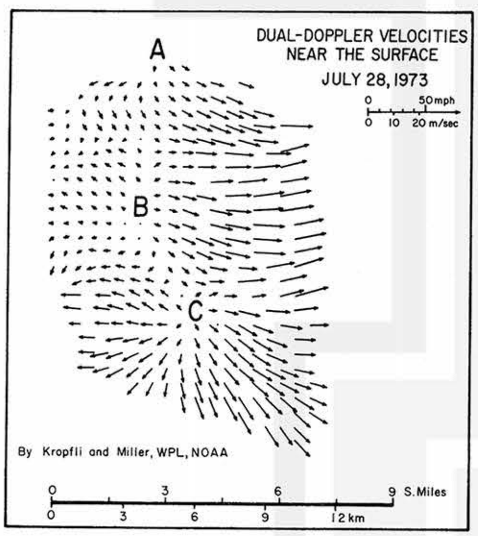

Fig. 1. Dual-Doppler system provides us with a new method of computing divergence values beneath precipitating cells. Cells A, B, and C are downdraft cells, being characterized by up to 17 hr divergence. Courtesy of Kropfli and Miller (1976).

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).

Table 3. 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}

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 runway 22-L at JFK Airport. An estimated 1500 persons in three 747s and other jet aircraft 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. 2. Note that six were international flights, four of which came from European countries. It was the busiest time of the day, and the approach and landing took place as follows. For details refer to NTSB (1975).

FLYING TIGER from Harrisburg, Pa.

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 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. (3:58 PM)

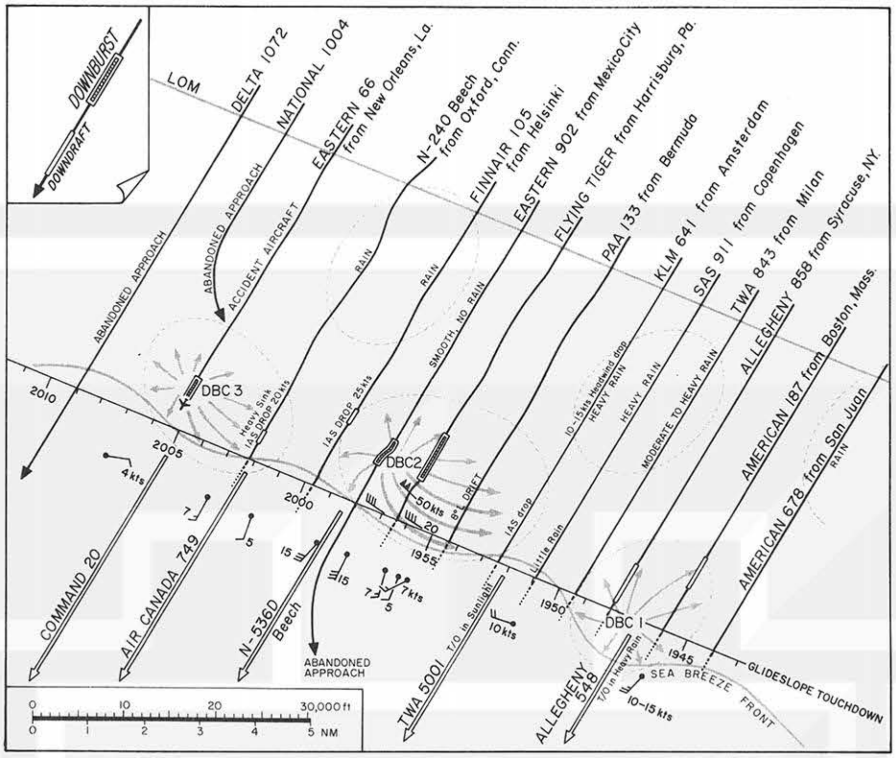

Fig. 2. Paths of 14 aircraft in 25 min at JFK Airport on June 24, 1975. Each path was shifted toward the west-northwest at 30 kt to convert the time into the space relative to the spearhead echo. The echo, as seen by Atlantic City radar, was 20 miles long and 8 miles wide, covering the entire area between LOM (Localizer Outer Marker) and the north end of 22-L. There were downburst cells (DBC) along the south edge of the spearhead echo. Five aircraft took off inside the sea breeze without being affected by downbursts.

<u>EASTERN 66 from New Orleans, La.</u>

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. 3). (4:05 PM)

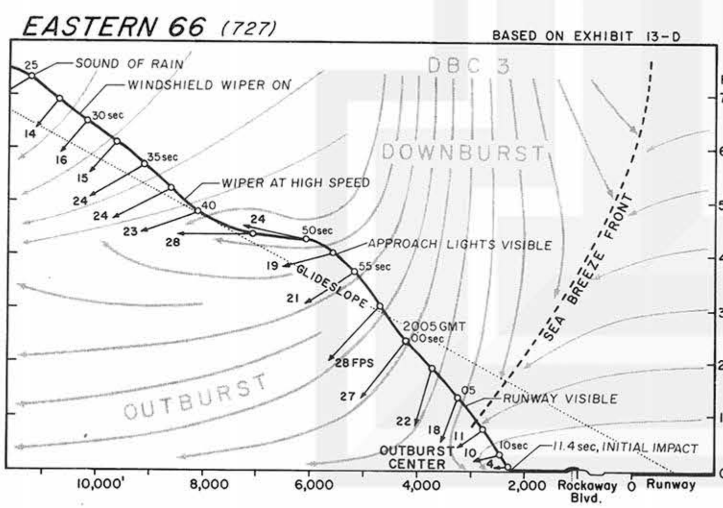

Fig. 3. The path of Eastern 66 on June 24, 1975 in the vertical plane including the glideslope of 22-L at JFK.

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 00 Z August 1 sounding presented in Caracena's (1976) analysis, shows that the lapserate 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 area 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 area were moving at 17 to 18 kt(see Fig. 4)

Echoes over the Denver area moved straight at faster rate 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, travelled 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.

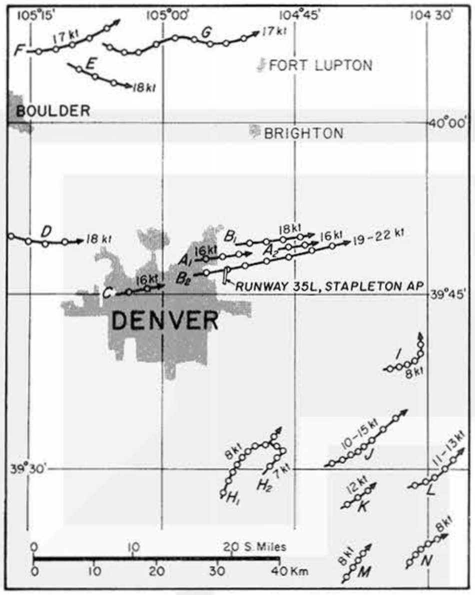

Fig. 4. Movement of scattered storm echoes near Denver on August 7, 1975 between 1518 and 1622 MDT. NWS at Limon, about 70 n. miles SE of Denver, took radar pictures at 5.3-min intervals during this period. Open circles show the echo centroids in each picture.

The authors thus concluded that it was a spearhead echo which moved over 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.

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.

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.

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 ground. Just before the aircraft struck the ground, the stall warning system activated. (See Fig. 5).

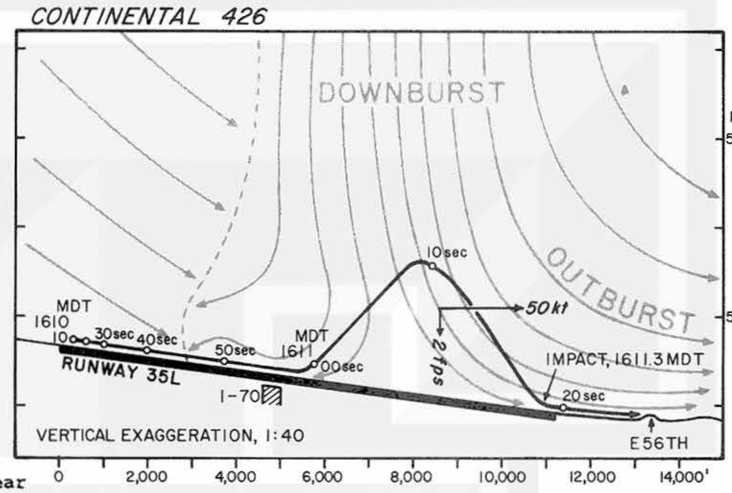

Fig. 5. A schematic figure showing the path of Continental 426 in relation to the downburst cell on August 7, 1975. The maximum height of the aircraft is approximate because the altimeter was affected by the aerodynamic characteristics of the Pitot tube during the climb. The height scale is in feet, MSL.

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.

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. 6, the towers are numbered 1 through 9. In addition, there are five more anemometers listed below.

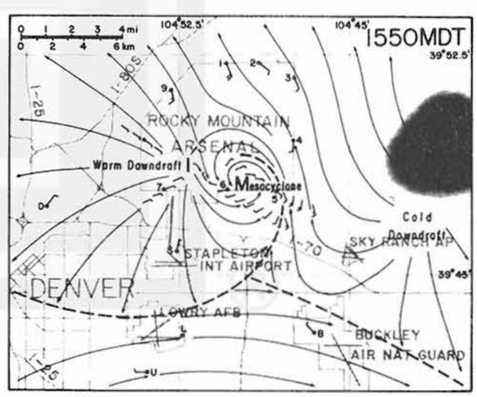

Fig. 6. Mesoanalysis map for 1550 MDT, August 7, 1975. A small mesocyclone is seen on the south boundary of Rocky Mountain Arsenal.

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 eachoes 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. 6).

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. 7).

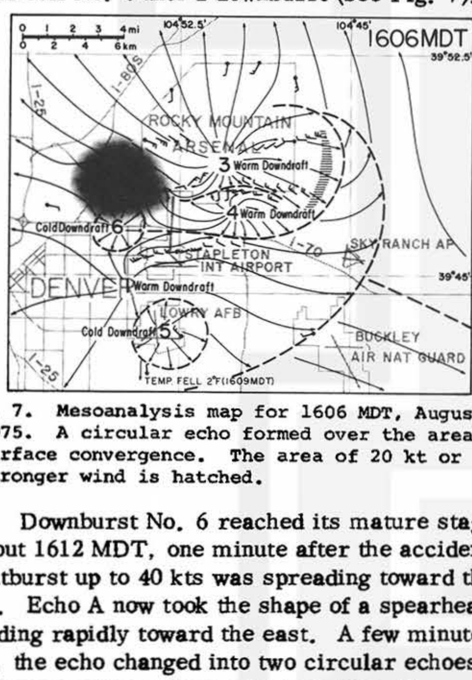

Fig. 7. Mesoanalysis map for 1606 MDT, August 7, 1975. A circular echo formed over the area of surface convergence. The area of 20 kt or stronger wind is hatched.

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. 8).

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.

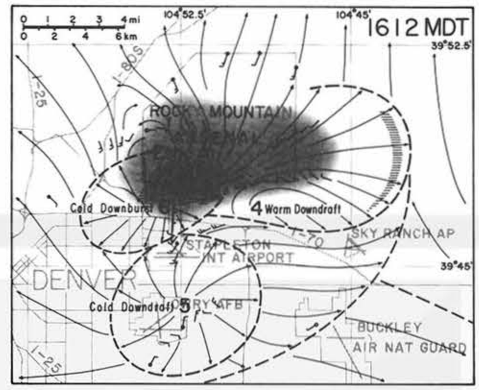

Fig. 8. Mesoanalysis map for 1612 MDT, August 7, 1975. The circular echo changed into a spearhead echo which extended rapidly toward the east. Areas of 20 kt or stronger winds are hatched.

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.

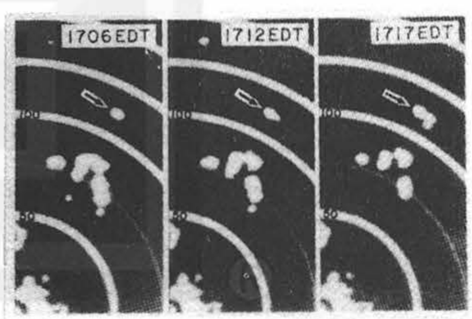

Fig. 9. Rapid development of a small spearhead echo over Philadelphia airport. Three pictures were taken by NWS Patuxent River, Md. radar at 1706 (left), 1712, and 1717 EDT on June 23, 1976. Heavy range marks are 50, 100, 125, and 150 n. miles. Time of accident was 1712 EDT.

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. 9).

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 windshear of both vertical and horizontal winds, and

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

Shown in Fig. 10 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.

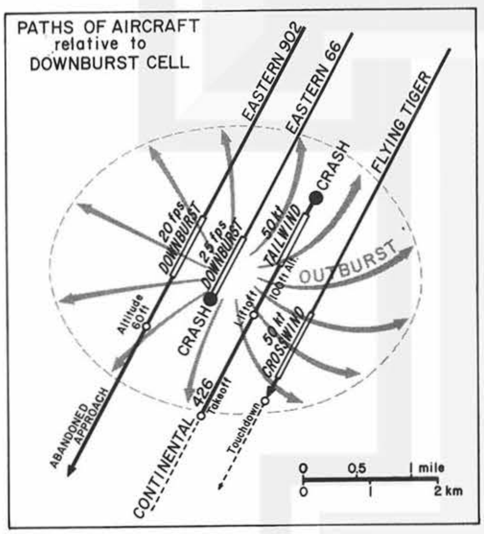

Fig. 10. Composite paths of Flying Tiger, Eastern 66, and Eastern 902 at JFK on June 24, 1975, and Continental 426 at Stapleton on August 7, 1975. Allegheny 121 at Philadelphia on June 23, 1976, flew through the downburst center from right to left, experiencing a 50 to 60 kt headwind, calm, and 6 kt tailwind before it crashed on the runway.

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, 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.

Table 4. Characteristics of spearhead 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

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. 11).

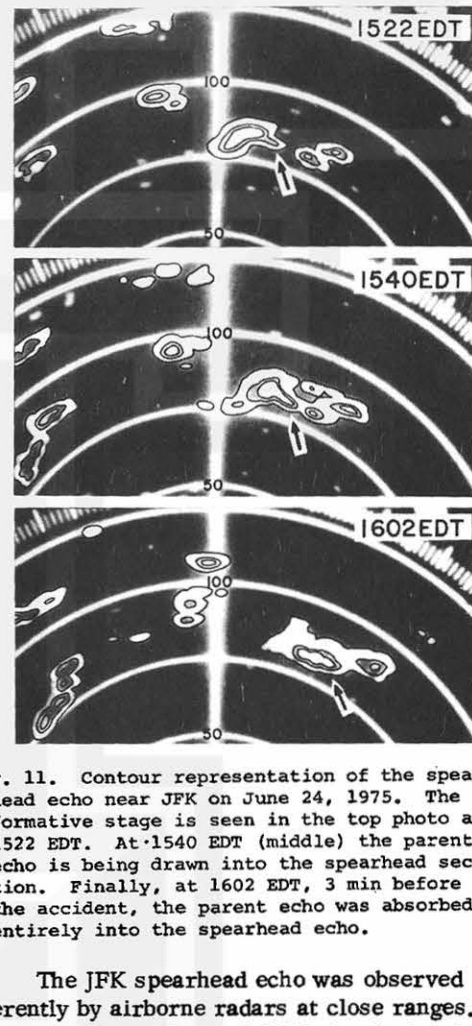

Fig. 11. Contour representation of the spearhead echo near JFK on June 24, 1975. The formative stage is seen in the top photo at 1522 EDT. At 1540 EDT (middle) the parent echo is being drawn into the spearhead section. Finally, at 1602 EDT, 3 min before the accident, the parent echo was absorbed entirely into the spearhead echo.

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.

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.

Fujita's (1976) and Fujita and Byers' (1977) model of the spearhead echo was produced based on the JFK thunderstorm. Shown in Fig. 12 are the downburst cells embedded inside a spearhead echo. In actual cases, downburst cells were located near or on the south edge of the spearhead echoes.

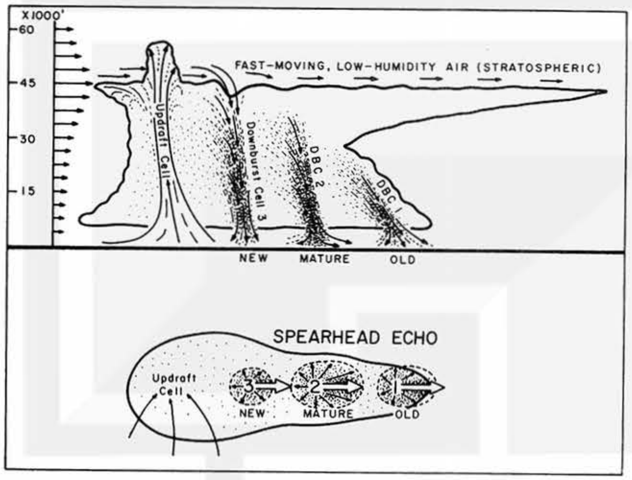

Fig. 12. The Fujita-Byers model of spearhead echo. They assumed that the fast-moving air is brought into the source region of the downburst, when an overshooting top collapses into the anvil cloud. When observed by distant radar, a spearhead echo will appear. At close range, especially below the cloud base, the radar paints small circular echoes. From Fujita (1976) and Fujita and Byers (1977).

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. 13. If a rapid collapse, such as this, induces an intense downburst on the ground, some trees and vegetation could receive downburst damage.

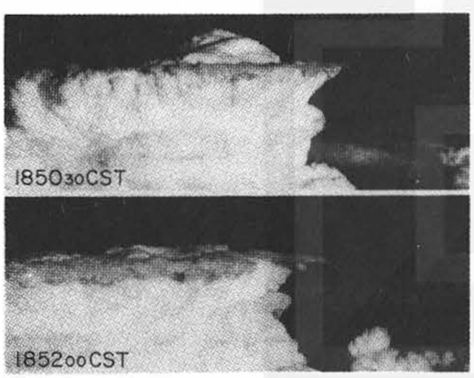

Fig. 13. Collapse of an overshooting dome within 1.5 minutes. Sometimes a large, tall dome collapses so fast, as in this case, that the skin of the anvil is pushed outward. The collapsed dome descends into the anvil and the hole is filled gradually. Pictures taken near San Antonio, Texas, on May 6, 1973. From Fujita (1974).

It should be pointed out 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. 14). 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.

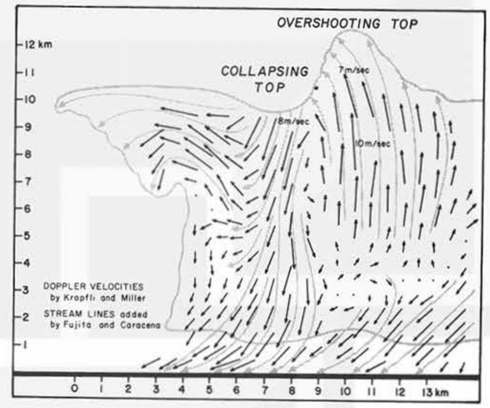

Fig. 14. A vertical cross section of Doppler velocities inside a 28 July 1973 thunderstorm in Colorado. Dual-Doppler velocities were obtained by Kropfli and Miller (1976). Both cloud boundary and streamlines were added by the authors.

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. 15).

Fig. 15. 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 from Cessna 172.

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.

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