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Spearhead Echo and Downburst in the Crash of an Airliner

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ABSTRACT

Meteorological conditions leading to the crash of an airliner short of the runway of a New York airport were studied. Thunderstorm downdrafts much stronger than those measured on the 1946–47 Thunderstorm Project were found. These exceptional downdrafts have been designated as "downbursts." The violent cloud systems that produce downburst cells can be identified in the form of forward extensions of radar echoes designated as "spearhead echoes" which move with unusual speed. The development of downburst cells appears to be tied in with overshooting tops of clouds at the anvil level.

1. Introduction

An airliner crashed short of the runway at John F. Kennedy International Airport, New York, on 24 June 1975. The National Transportation Safety Board (1975), in its investigation of the accident, concluded that it was caused by unusually sharp wind changes under a thundershower. Realizing that a similar unexpected sinking of an aircraft at low approach levels might happen again, airline operations personnel asked for an analysis of the meteorological events with a view toward finding a way to give warnings of such conditions without needlessly closing the airport.

The resulting report (Fujita, 1976) used patterns seen by radar plus other meteorological features which would be helpful in pinpointing happenings of this kind. The purpose of this article is to place these findings before the meteorological community.

A striking feature of the airport weather on the afternoon of the accident was a stationary sea-breeze front holding for an hour or more near the touchdown point of the active runway (22 L). Over the airport, south of this shallow front, gentle southerly winds prevailed, while to the north in the near-approach area, hazardous winds and weather were found. As will be noted later, the sea-breeze front had no marked effect on the growth of the thunderstorm, which was already violent before it reached the area. But the front had an indirect effect on events in that the airport wind sensor was located near the seaward end of the runway and thus called for easy 220° landings, while just beyond the other end of the runway unknown wind extremes were occurring. As a matter of fact, while rain poured down at the approach end, most of the runway was dry. Controllers had no basis for changing runways or closing the field to air traffic.

On the day of the accident (24 June 1975), the corrected synoptic analysis showed a weak cold front running northeast to southwest moving slowly into the region, with thunderstorms along and near it. For the mesoscale study, the satellite, ground radar and surface station data through the afternoon hours (1735–2159 GMT) were analyzed on the base map of Fig. 1, which also shows the location of the various reporting stations. The three radar sites (Atlantic City, McGuire Air Force Base and New York City) are marked by right-angle crosses on the map and the three principal airports of the New York area [Newark (EWR), La Guardia (LGA) and John F. Kennedy (JFK)] are shown in bold letters.

2. Satellite data

The life history of the JFK thunderstorm was depicted by the infrared (IR) and visible images of SMS-1, a geostationary satellite positioned above the equator at 75°W. A pair of IR and visible pictures was sent every 30 min. The satellite imagery closest to 2005 (all times GMT), the accident time, was at about 2003. As seen in the hand-drafted representation of Fig. 2, there were two shadows of anvil clouds spreading out from the storm tops. The viewing angle of 50° from nadir makes the 41 000 to 43 000 ft heights of the anvil

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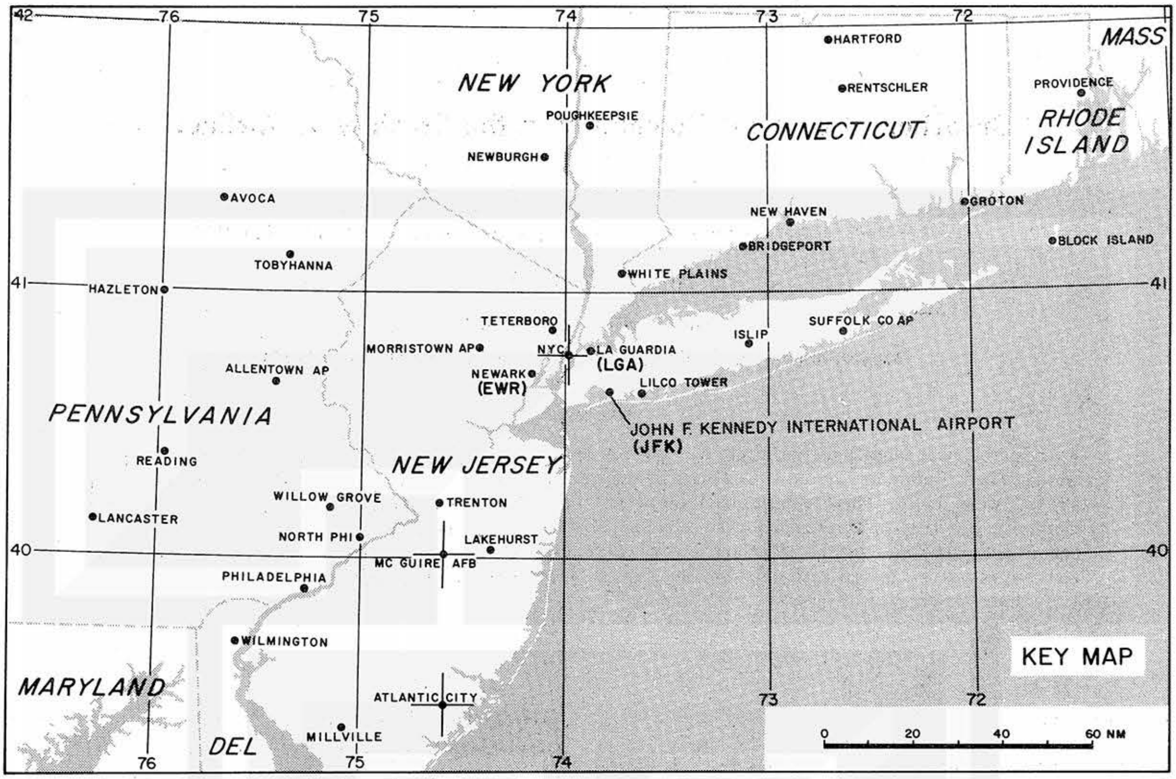

Fig. 1. Key map of analysis area.

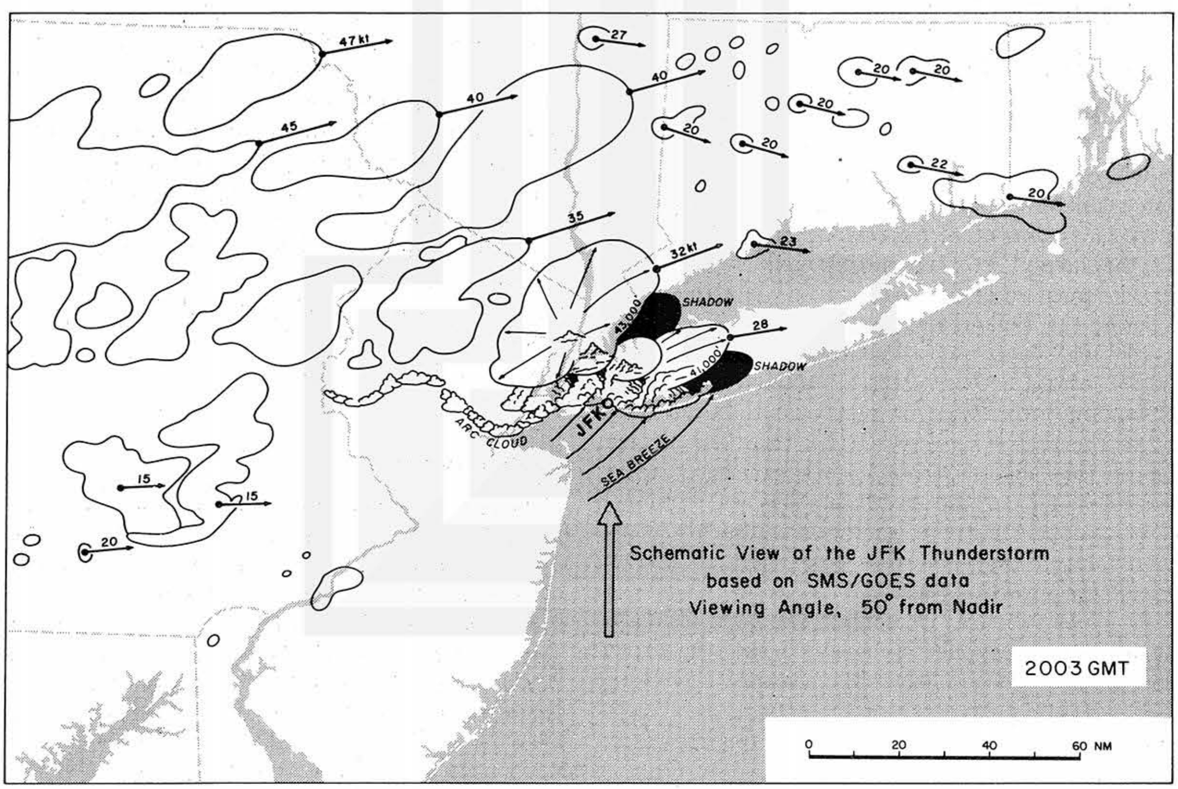

Fig. 2. Schematic view of JFK thunderstorm drawn from geostationary satellite data.

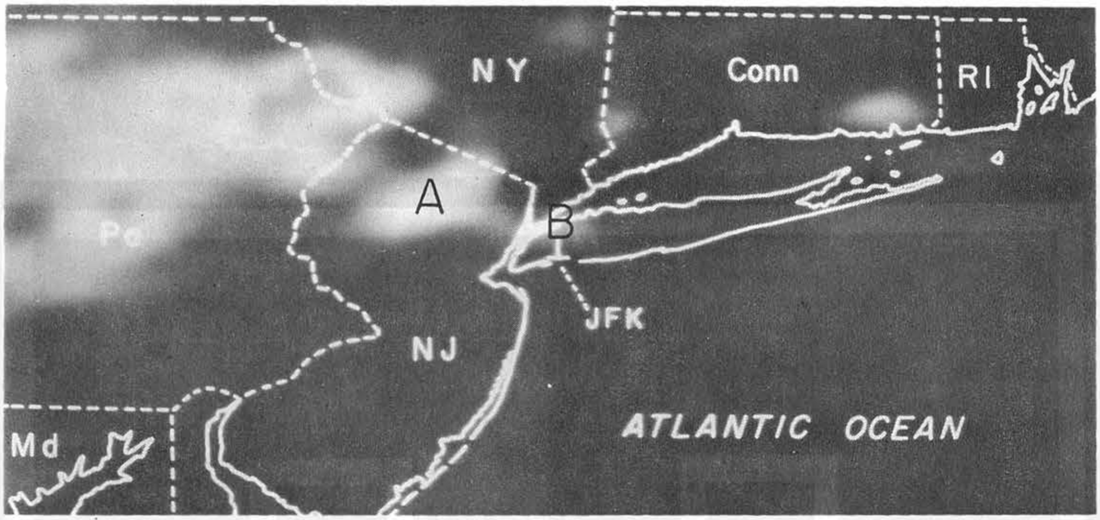

FIG. 3. IR picture at 1903 GMT.

tops look displaced northward from their true geographical positions; hence the shadows may look wrong for the sun angle at this meridian at this time. The anvil heights were computed from the cloud-shadow relationship. As shown by the arrows, the spreading rate of the anvils toward the east-northeast was 30 kt. An arc cloud was seen along the south coast of Long Island passing through the JFK airport. Usually an arc cloud pushes outward rapidly from a thunderstorm area, but the sea breeze kept it from going beyond JFK.

The JFK thunderstorm was first seen at 1703 as a cumulus line in northern New Jersey. Within 30 min the west end of this line grew into a towering cumulus mass. At 1803 the west end became overwhelmingly larger than the east end, and by 1903 a fast-growing anvil formed on the west end, seen in the IR picture of Fig. 3 as A, lightly overlapping the east end, designated as B. Note the inverted T at JFK denoting the projection of an imaginary 45 000 ft tower as seen from the satellite viewing angle. In the IR picture at 1933 (Fig. 4) A and B have come closer together and a light grey area has appeared inside cloud A. The equivalent blackbody temperature at the boundary of this area was -44°C. At 2003 (Fig. 5) clouds A and B had joined into a large thunderstorm complex. This is the IR picture which, combined with the visible, was used to draw Fig. 2. The accident happened 2 min later.

Three pictures taken at half-hour intervals thereafter revealed that the areas of cloud as well as the areas of cold cloud tops kept increasing. However, the rate of spread of the IR cloud was fastest at about 2000. Likewise, the growth rate of the -44°C area was greatest at about the same time. Furthermore, the area covered by radar echo reached its maximum at that time. These

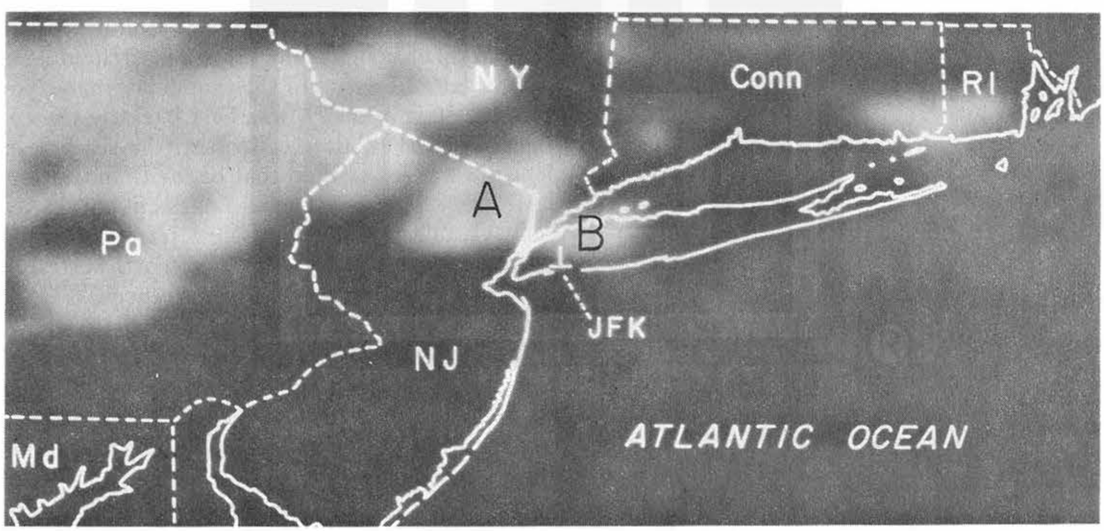

FIG. 4. IR picture at 1933 GMT.

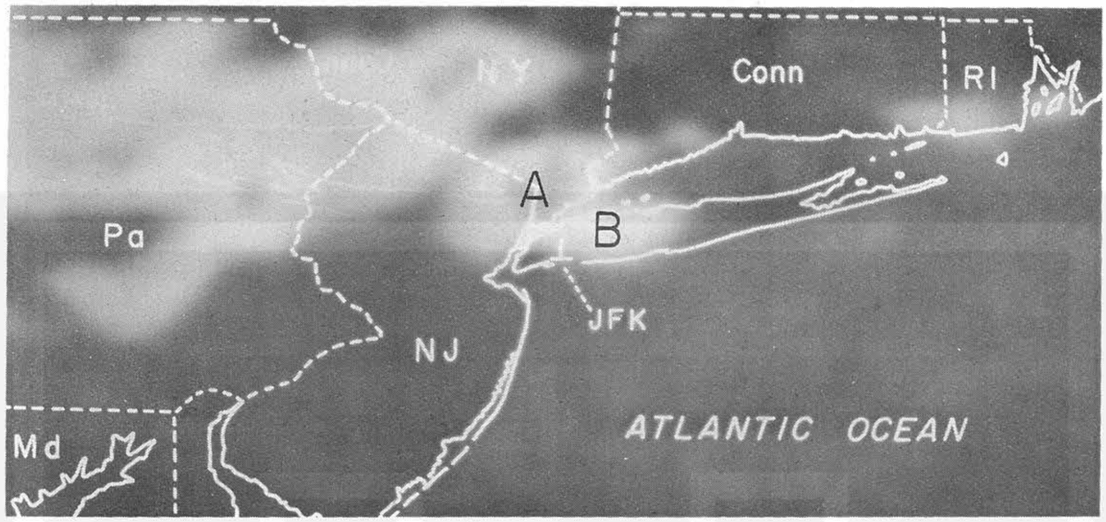

FIG. 5. IR picture at 2003 GMT, 2 min before the aircraft accident at JFK.

developments are shown by the three area-time curves of Fig. 6. They suggest that the accident occurred when the JFK thunderstorm was in its most active stage.

3. Mesoscale weather situation

The mesoscale analysis map for 1753 in Fig. 7 shows the weak front from Pennsylvania to Rhode Island. It was a true cold front at the surface in Pennsylvania and New Jersey, where it was very hot to the south and the temperature contrast was enhanced by the showers just to the north of the front. From southern Connecticut to Rhode Island the temperature contrast across the front was reversed. In the warm land air the absence of clouds suggested heating and drying at the surface by subsidence or downslope winds. However, a line of sea-breeze cumuli was seen in southern Connecticut and Rhode Island. Due to solar heating, the sea breeze was blowing inland across the Atlantic beaches and apparently there was also a weak sea breeze on the north shore of Long Island coming from the Sound, giving rise to the formation of sea-breeze cumuli there. Radar echoes showed an early stage of the JFK thunderstorm (A and B) in northwestern New Jersey on the cold front. The storm was moving toward the east-southeast at 16 kt.

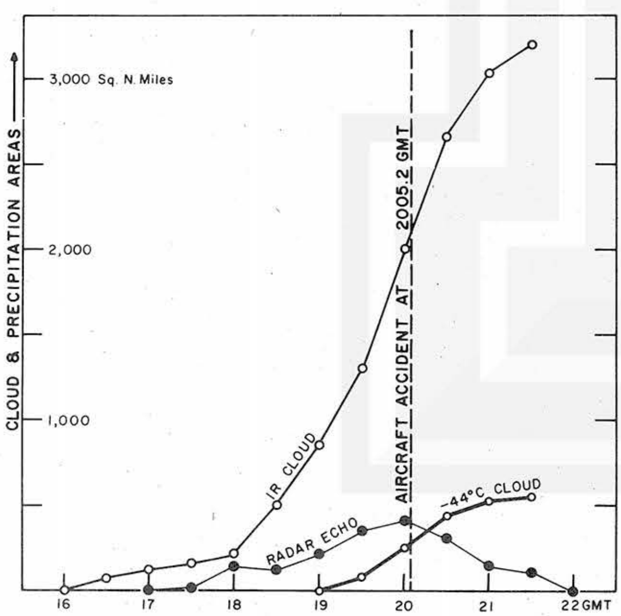

FIG. 6. Variation of areas of cloud imagery and radar echoes during a 6 h period on 24 June 1975.

At 1851 the main storm (A) was still on the front but the forerunner (B) moved away from the front and split into two cells—one located over lower Manhattan and the other northeast of LGA (Fig. 8).

Dramatic changes in the echo patterns took place in the hour from 1900 to 2000, just before the accident. The JFK thunderstorm moved rapidly toward the western tip of Long Island. A line of arc cloud developed along the leading edge of the thunderstorm outflow, the southern part of which was held back by the cold sea breeze from the Atlantic. In fact, the sea-breeze temperature was lower than that of the thunderstorm outflow (Fig. 9). The squall-line activity in eastern Pennsylvania and northern New Jersey was intensifying rapidly. As a result, a surge of northwesterly winds came forth in advance of a line of echoes.

The map at 2053, not reproduced here, showed the JFK thunderstorm to be weakening and accompanied by a radial outflow of cold air which by this time had reached the airport with a light NNE wind. A larger system with an intense squall line was advancing toward central New Jersey.

The JFK thunderstorm was monitored by radar at three stations: 1) WSR-57 radar at the National Weather Service Forecast Office at Rockefeller Center,

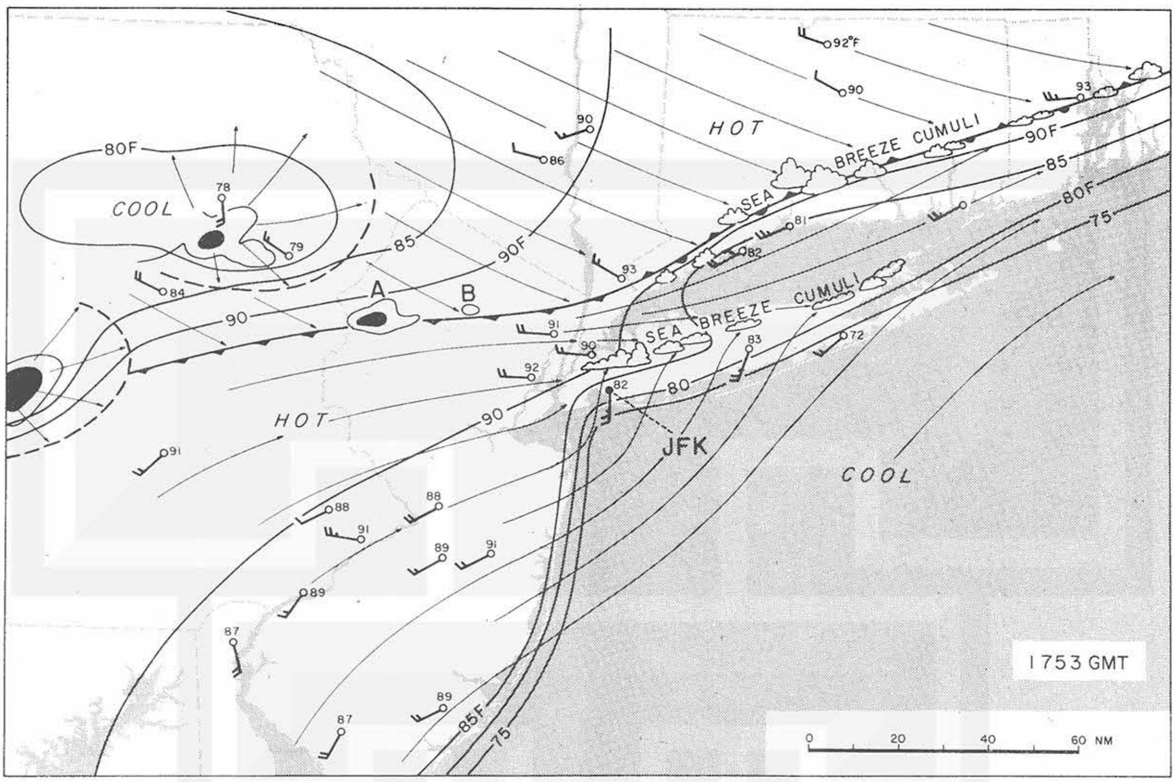

Fig. 7. Mesoscale weather situation at 1753 GMT showing isotherms, streamlines and radar echoes. Numbers at stations are temperatures (°F). Winds are plotted with one full barb denoting 5 kt.

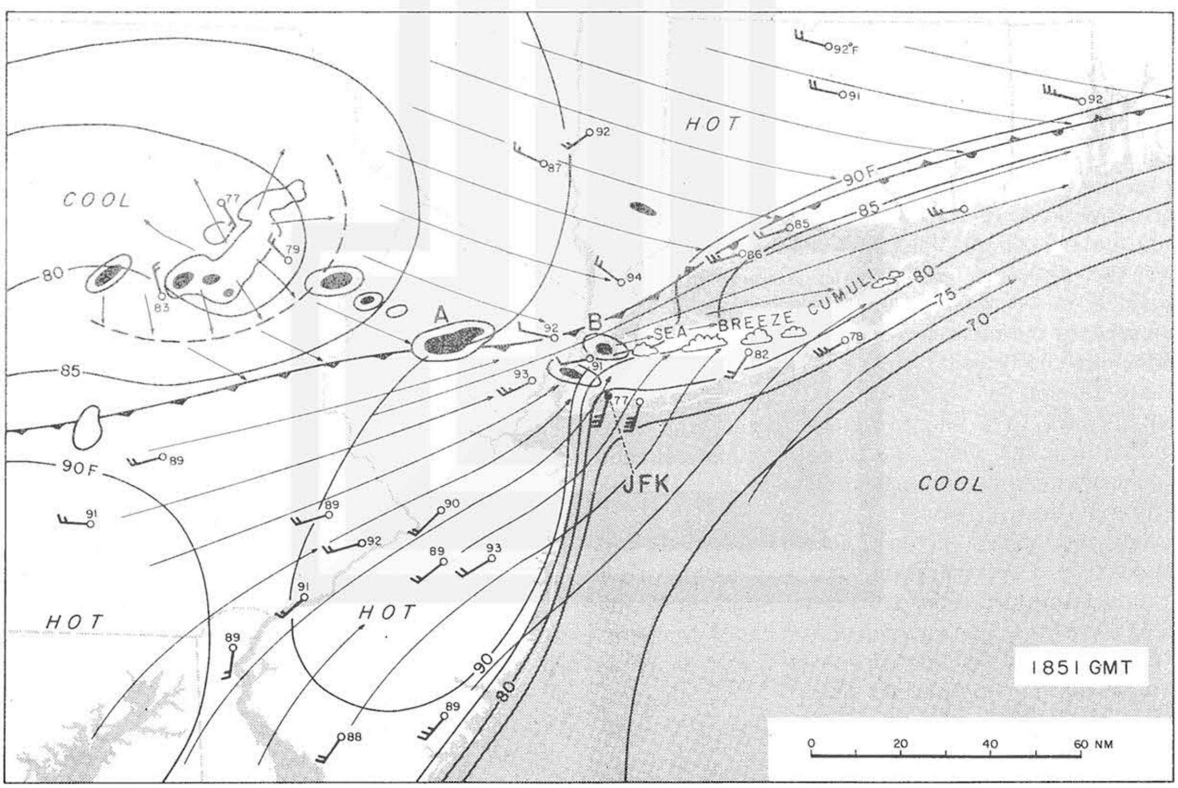

Fig. 8. As in Fig. 7 except at 1851 GMT.

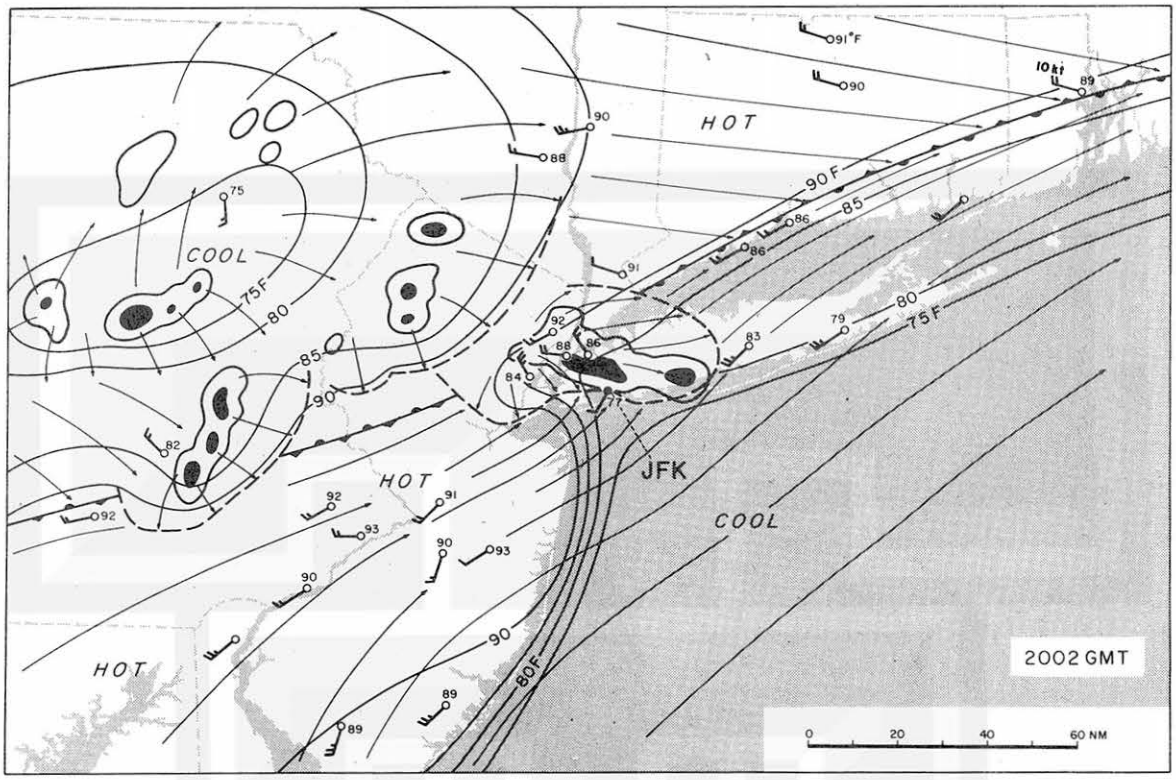

FIG. 9. As in Fig. 7 except at 2002 GMT. Aircraft accident occurred at 2005 GMT and the airport was closed.

New York City (NYC); 2) AN/FPS-77 radar at McGuire Air Force Base, N. J. (MCG); and 3) WSR-57 radar at Atlantic City, N. J. (ACY). A total of seven measurements of the echo tops of the thunderstorm were made by these three stations. The results are given in Fig. 10, where the lines from the radars are drawn to maximum altitude points (heights given in feet). Arrows show direction and speed (kt) of echo motion. After corrections, the echo-top height ranged between 35 000 and 49 000 ft. The NYC radar was checked under the direction of Gibson (1975) who found everything to be within required tolerance. Corrections made to the radar took account of the following: 1) McGuire AFB radar has a tendency to underestimate the range by 10–15%; 2) the further the cloud distance from the radar, the higher the echo top; 3) it is unlikely that the top of an identical echo was measured simultaneously, and the echo top varied rapidly with time.

Taking the satellite pictures, nearby radiosonde and radar data into consideration, one may assume that the thunderstorm was topped by anvil clouds at 40 000 to 43 000 ft. Since the equivalent blackbody temperature of the anvil was colder than −44°C (air temperature at 36 000 ft) but warmer than −58°C (air temperature at 41 000 ft), its emissivity must have been <1.00. The anvil must have been relatively thin.

The detailed mesoscale weather analyses presented in this section provide a better understanding of the local weather of 24 June 1975. Yet they do not tell why the JFK thunderstorm was more dangerous than numerous other storms that have been studied in detail.

4. Spearhead echo

In a manuscript report prepared after the accident, Gibson (1975) emphasized a very important characteristic of the JFK thunderstorm. Echo A moved to the east-southeast at a speed of 30–35 kt, while the forerunner echoes were moving in the same direction at 20–25 kt. The greater speed of echo A resulted in an overtaking and subsequent merger of echoes. All of this was taking place in the immediate vicinity of JFK at the approximate time of the accident.

Expanding on Gibson's findings, Fujita (1976) made a time-sequence analysis of the JFK thunderstorm (Fig. 11), displaying the appearance of the echoes at 11 min intervals. It is evident that two forerunner echoes existed to the north and northwest of JFK at 1905 and moved slowly toward the east-southeast. The echo that was moving behind the JFK thunderstorm also traveled slowly. The motion of these echoes was only 15–17 kt. At 1916 the JFK thunderstorm had shown a sudden acceleration toward JFK. One should find a reason for this fast movement of the echo.

Within the 11 min between 1905 and 1916, an appendage formed near the east end of the major echo. The first appendage, seen in the 1910.7 picture, was

3 mi long with a sharp point. The point, acting like a spearhead, extended very rapidly. By 1940 the spearhead became so large that the parent echo began losing its identity, so that by 1951 the parent echo was not only drawn entirely into the appendage but the combined echo was moving rapidly toward JFK airport. The appendage had now lost its identity, redeveloping into a fast-moving spearhead echo which merged with a small echo located to the north of JFK.

The spearhead echo at 2002 was about 15 mi long and 5 mi wide and located just north of the airport. The radar picture was taken from the Atlantic City radar, 80 mi away, with a 0.2° antenna tilt angle. The height of the radar beam above JFK was computed to be about 7000 ft. Due to the beam width the image of a point target elongates in the direction perpendicular to the beam. The elongation for a 1° beam width is 1.3 mi at 80 mi. The radar images are evaluated taking these values into consideration.

We now define a spearhead echo. It is a radar echo with a pointed appendage extending toward the direction of the echo motion. The appendage moves faster than the parent echo which is being drawn into the appendage. During the mature stage, the appendage turns into a major echo and the parent echo loses its identity. Ground-based weather radar will be able to detect such a spearhead echo.[2]

In an attempt to determine the frequency of spearhead echoes on 24 June 1975, the Atlantic City radar film was examined in detail, leading to the finding of another spearhead echo. The second one formed just to the north of Allentown, Pa. At 2015 the echo was about 90 mi from the Atlantic City radar. Its development and movement are shown in Fig. 12. The life of a spearhead echo seems to be relatively short. The appendage of the JFK echo started forming at 1910, reaching its mature stage in about 50 min. The Allentown echo repeated a similar cycle between 2015 and 2111. The map of Fig. 13 shows these two developments. It was fortunate that Allentown airport was not affected by the spearhead echo.

The question naturally arises: What is the probability of occurrence of a spearhead echo? For 24 June this question was examined from the Atlantic City radar data. The hourly counts of echoes over the Middle Atlantic States are summarized in Table 1. Only two out of 109 echoes are classified as spearhead echoes. All others were, more or less, summertime echoes which probably do not present serious problems to aviation. The chance that a spearhead echo would develop at such a crucial point at a given airport must be very small indeed.

Gibson (1975) found that the only report on this

[2] An anonymous editorial reviewer of this manuscript suggested that the spearhead echo is what airline meteorologists designate as "fingers" seen on airborne radar displays (see, e.g., Harrison, 1956; Hoffman and Peckham, 1968). It is not clear to the present authors that the two features are the same except in special cases.

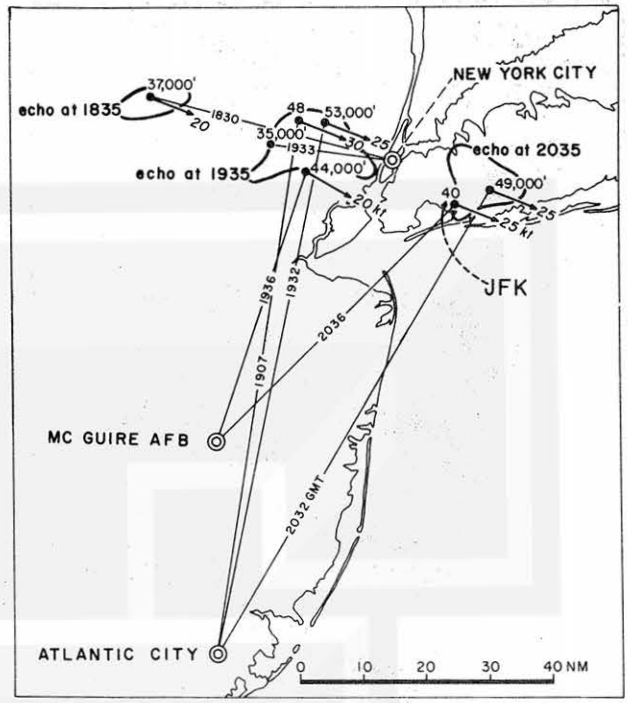

FIG. 10. Height of echo tops of the JFK thunderstorm measured by three radars: Atlantic City, McGuire Air Force Base and Rockefeller Center, New York City.

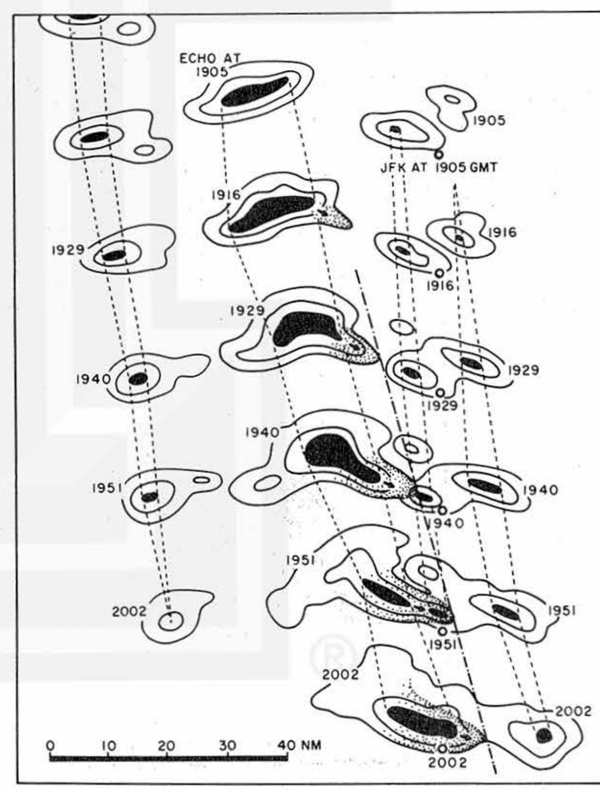

FIG. 11. Formation and advance of spearhead echo. Small circles show relative positions of JFK airport at the various times. Heavy dashed line marks the tip of the spearhead.

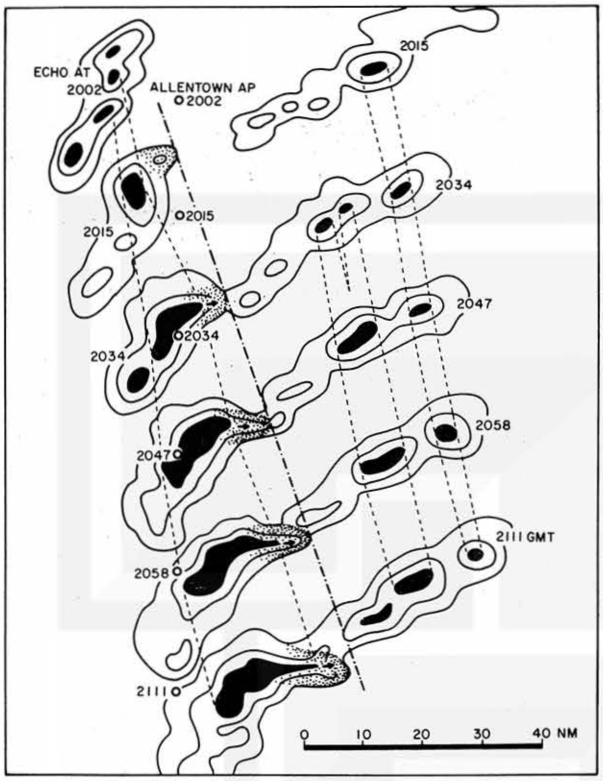

FIG. 12. Another spearhead echo of 24 June 1975, which developed north of Allentown Airport, Pa.

TABLE 1. Frequency of spearhead echoes on 24 June 1975.

Time (GMT)	Number of ordinary echoes	Spearhead echoes
1652	1	0
1753	3	0
1850	13	0
1950	14	1
2052	18	1
2152	19	0
2247	24	0
2354	15	0
Total	107	2

date of a wind gust ⩾ 35 kt came from Morristown, N. J. Municipal Airport, which reported 55 kt occurring at 1915. Although he does not preclude the possibility of an unreported occurrence, this record was the only such report from northern New Jersey, New York City and Long Island. A spearhead echo was forming just to the north of the Morristown airport when the 55 kt wind was reported (Fig. 13). It is interesting to note that the spearhead echo passed between the four stations in the New York area—Central Park, Newark, La Guardia and JFK; thus the maximum recorded wind speed in the area (32 kt at EWR, 1937 GMT), was simply a reflection of the mean motion of echo A.

5. Time-space analysis of approach area

During the critical period of 22 min prior to the accident at 2005.2 GMT, 12 airplanes made approaches along the localizer course of the instrument landing system (ILS) of runway 22-L. However, not all aircraft encountered difficulties serious enough to cause the pilots to report them to the tower. The chronological events experienced by the landing aircraft are given in Table 2. The detailed testimony of the pilots is summarized at greater length by Fujita (1976).

It is important, first of all, to recognize that the landing difficulties occurred during three distinct periods separated by normal landings. The three

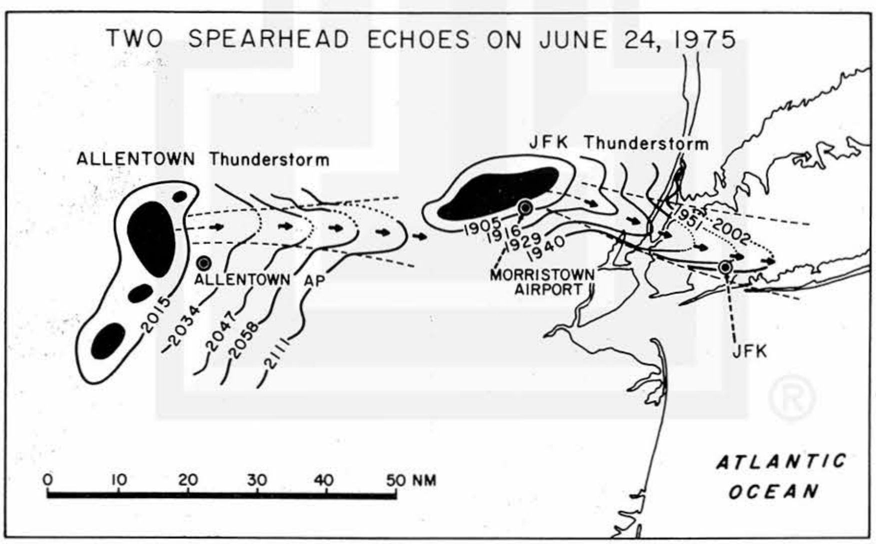

FIG. 13. Isochrones of the boundaries of two spearhead echoes showing their development in approximately 1 h.

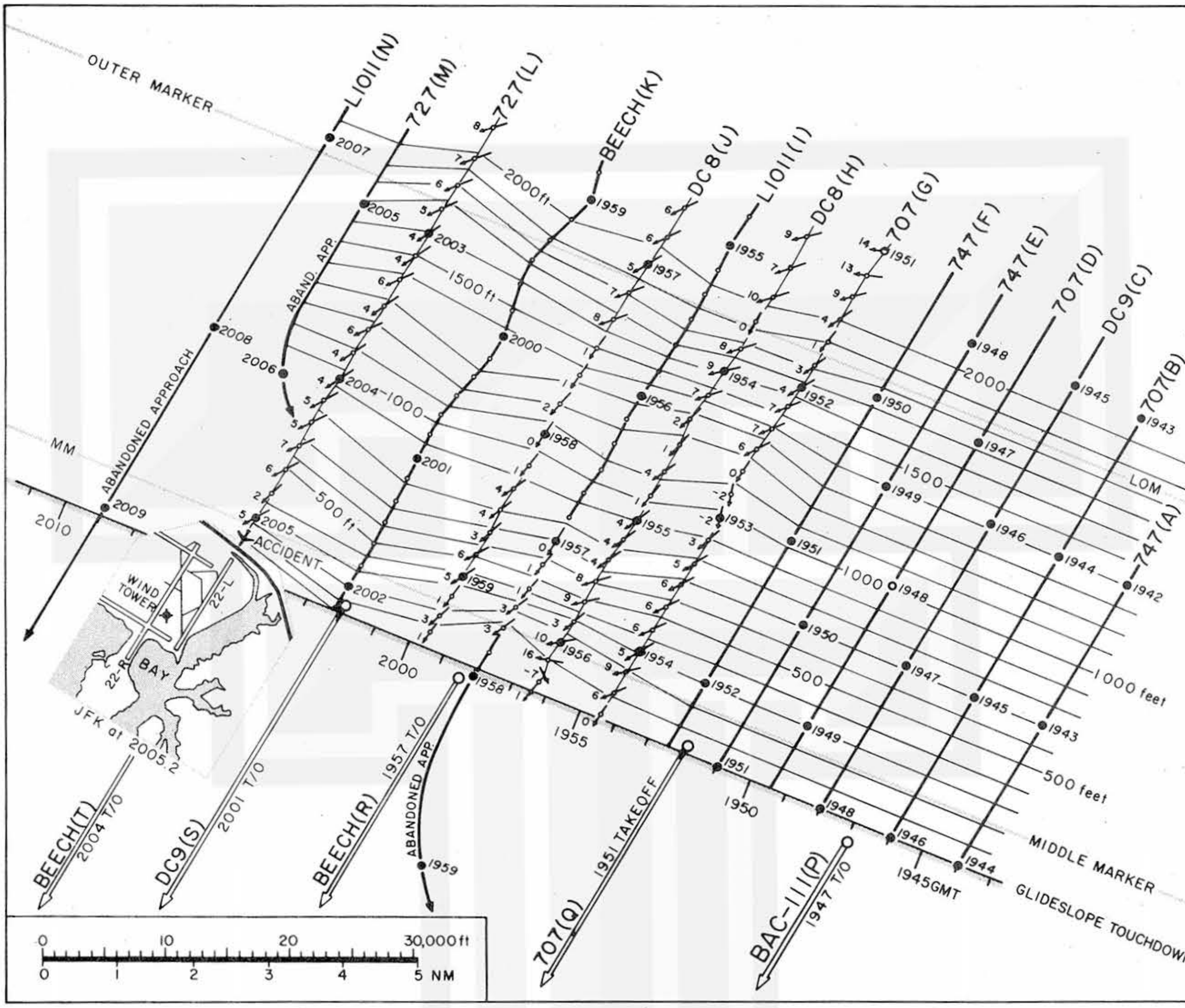

FIG. 14. Time-space coordinates of the 22-L approach path relative to the moving weather systems. The glide slope, the outer marker (LOM) and middle marker (MM), and runways were shifted toward 292° true at 30 kt. Aircraft headings at 10 s intervals are plotted after subtracting the magnetic heading of the runway. The directions of small arrows are exaggerated five times. Inset at left shows portion of airport containing runways 22-L and 22-R.

periods were 1945 to 1952, 1952 to 1959 and 2002–2005+. If we assume the motion of the spearhead echo to be at 30 kt, the horizontal dimension of the hazardous areas would be only 3–5 mi. A pilot could complete a normal approach and landing during the calmer interludes without being able to see or be aware of the danger areas on either side of his approach path.

The airflow patterns near the approach end of runway 22-L can be depicted by plotting the events experienced by each aircraft as revealed in flight recorders and pilots' remarks in exhibits of the investigation by the National Transportation Safety Board (1975). To overcome analytical difficulties, the concept of time-space coordinates was developed. For the original ideas one may refer to Fujita (1963). The coordinates consist of the paths of the aircraft shifted successively in a direction opposite to that of the movement of the spearhead echo. In constructing the time-space coordinates for this study, the approach path of runway 22-L was shifted toward 292° true (304° magnetic) at 30 kt (Fig. 14).

The coordinates were designed to include the touchdown times between 1943 and 2021. A map of the JFK area corresponding to the localizer approach of the accident aircraft L was placed in the coordinates. The black circles with the time in GMT denote the 1 min positions of the landing aircraft. The take-off positions of the departing aircraft are shown by larger open circles, and their paths are given by the light, double-lined arrows. The heights along the glide slope are shown at 100 ft intervals. Actual heights are indicated for those aircraft for which radar and altimeter altitudes were available. As a measure of the crosswind component, the aircraft headings at 10 s intervals were plotted

TABLE 2. Wind shear experienced by the landing aircraft.

Aircraft	Type	Landing time (GMT)	Approach and landing conditions
A	747	1944*	Some wind shear; not enough to report
B	707	1946*	Add power, 500 ft down: normal landing
C	DC-9	1948*	Downdraft before touchdown in rain
D	707	1949	Approach and landing normal
E	747	1951	Slight rain at touchdown
F	747	1952*	Some wind shear; not enough to report
G	707	1954*	At 200 ft, 8° drift to left
H	DC-8	1956**	Strong sink, strong crosswind
I	L-1011	1958**	Plane sank, drifted right; abandoned approach
J	DC-8	1959	Landed normally without difficulties
K	Beech	2002*	Add power in sink; landing normal
L	747	2005**	Strong downburst, 400 ft down. Accident.

* Slight difficulty.
** Experienced major difficulty.

after subtracting the magnetic heading of the runway. Since the crosswind component was mostly from the right, most aircraft kept correcting a 1–8° drift during the approaches. The experience of aircraft H was extreme in this respect.

The events experienced by aircraft A through N were replotted on the time-space coordinates in order to correlate them with the meteorological conditions (Fig. 15). The result revealed the existence of three major areas of localized outflow. There must have been a concentrated downward motion above each of these outflow areas, for without a massive supply of descending air, the intense outflow could not have originated nor have been maintained.

The concept of a downdraft in a thunderstorm has appeared in the literature for many years, such as in an article by Brooks (1922). Quantitative measurements were provided by Byers and Braham in *The Thunderstorm*. They tabulated as a downdraft any sustained, non-horizontal current of air descending in a thunder-

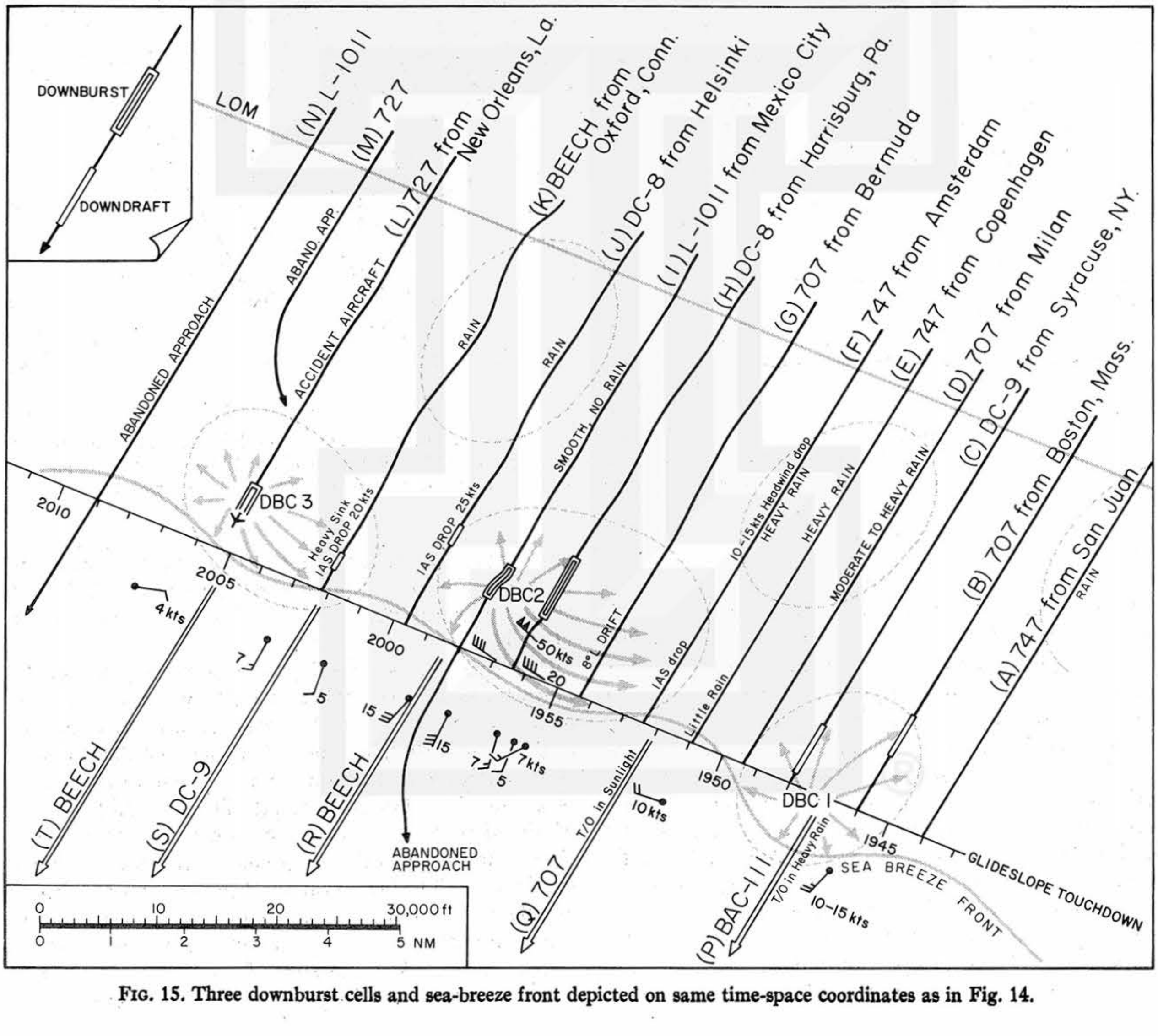

FIG. 15. Three downburst cells and sea-breeze front depicted on same time-space coordinates as in Fig. 14.

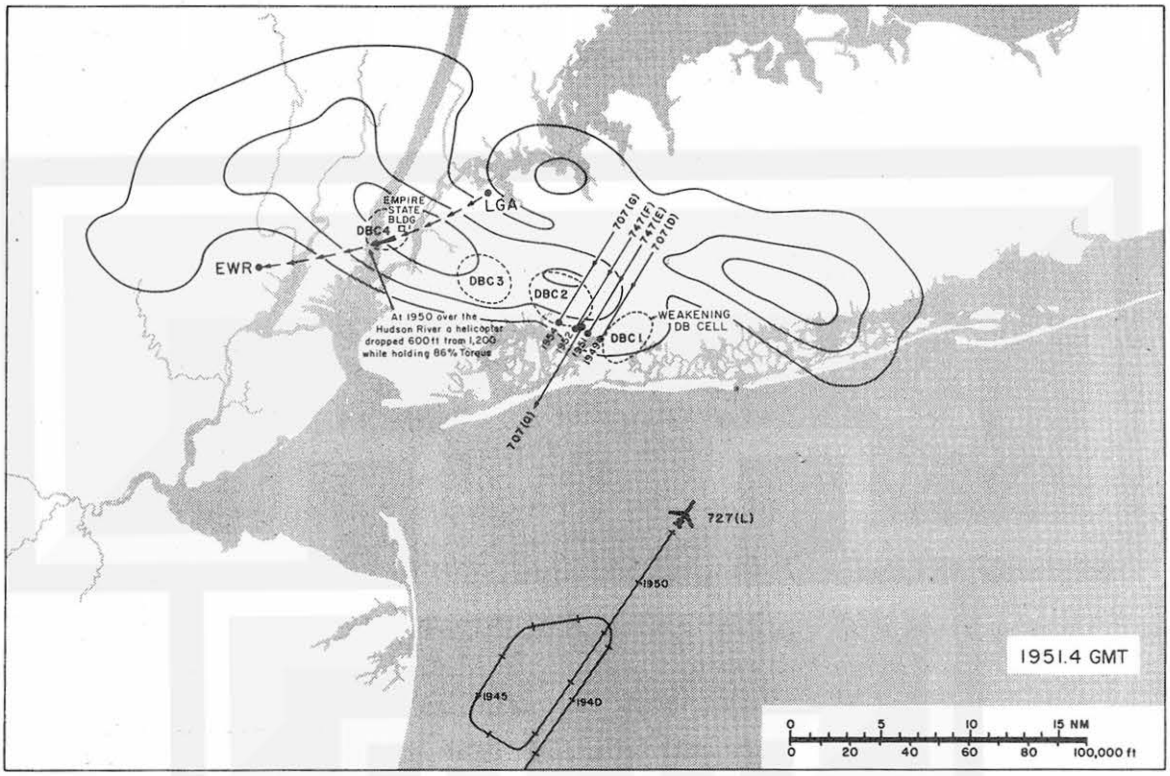

FIG. 16. Four downburst cells in relation to spearhead echo and flight operations at 1951.4 GMT.

storm at a speed exceeding 3 ft s^{-1}. To distinguish an extremely intense downdraft from an ordinary one, a new term, "downburst" is introduced. A downburst is a localized, intense downdraft with vertical currents exceeding a downward speed of 12 ft s^{-1} at 300 ft above the surface. This value corresponds to a point divergence of 4×10^{-2} s^{-1}. The downward speed is about equal to that of a jet transport coming down the usual 3° glide slope below 500 ft. Therefore, a downburst of this threshold value tends to double the sinking speed of this type of aircraft trimmed for normal approach near touchdown unless corrective action is effective. Since an aircraft may fly into a downburst cell abruptly and unexpectedly, immediate recognition and quick action by the pilot is necessary to overcome its effects. If the aircraft's position along the approach path does not provide sufficient time for pilot recognition and action, and aircraft response, the flight might not be able to execute a missed approach before contacting the ground.

Three downburst cells (DBC) near the approach end of runway 22-L were identified—DBC1, DBC2 and DBC3. Their widths were less than 3 mi and were separated by relatively calm spaces as seen in Fig. 15.

Apparently the outflow from downburst areas did not move into the runway area. None of the five aircrafts P through T encountered problems during their takeoff from runway 22-R. The wind tower, located about $1\frac{1}{4}$ mi southwest of the approach end of 22-L, was not affected by the outflow wind. The sea-breeze front lay between the wind sensor and the approach path to runway 22-L.

The ground-level wind near the north boundary of the airport was entirely different from the reported winds. The captain of departing aircraft S, while taxiing on runway 31-L, observed small trees bending over from an estimated 20–30 kt wind blowing almost parallel to runway 13–31 i.e., from the northwest. Then he looked toward the approach end of 22-L to find aircraft H getting into a nose-high attitude with its left wing down. However, the pilot of aircraft H was able to recover to a more normal position before landing on 22-L.

The crosswind shear experienced by aircraft H was spectacular. The 228° heading at 1955:58 was changed to 237° at 1956:04. It is likely that the pilot responded to the sudden increase of crosswind from his right. The drift determined by the inertial navigation system was 25°–30° when the indicated air speed was 150 kt. A 60–70 kt crosswind would be required to produce such an extreme drift.

6. Flight paths and radar echoes

Excellent scope pictures at the WSR-57 radar of the National Weather Service at Atlantic City were taken every 5 to 6 min. The times of pictures taken shortly before the accident are 1945.7, 1951.4, 1956.7 and 2002.4. Echoes in these pictures were contoured by

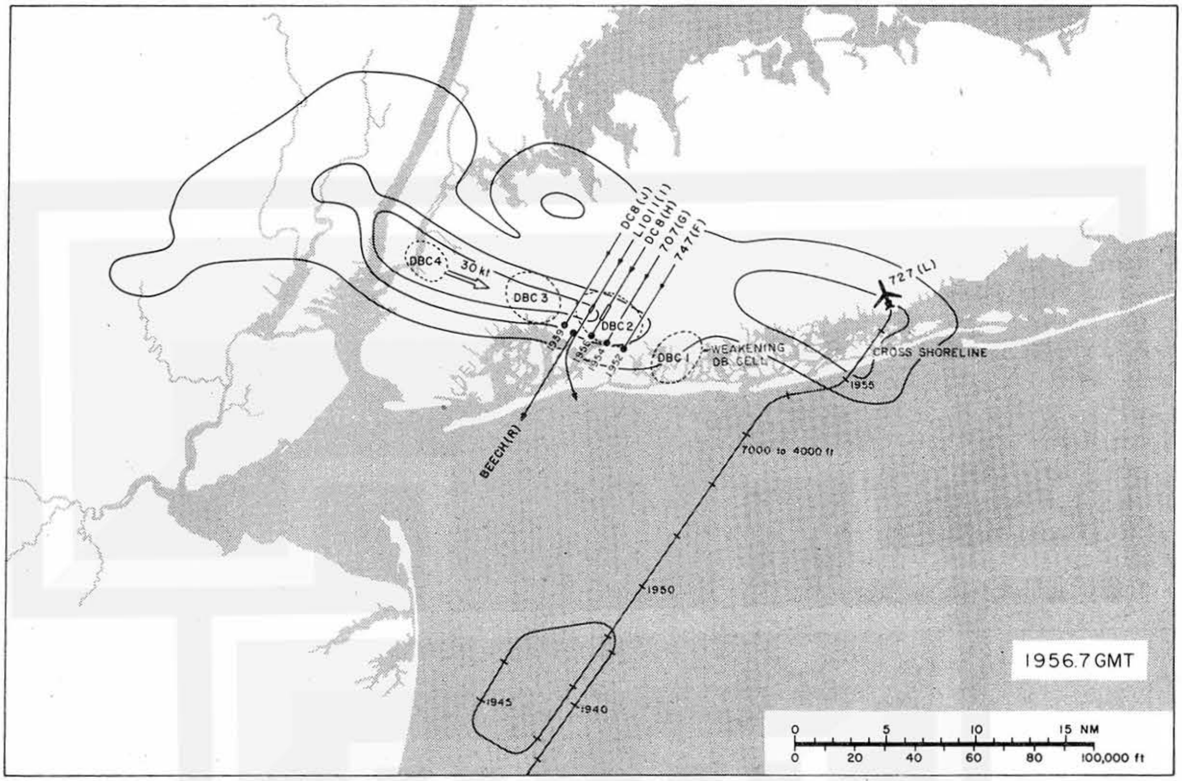

FIG. 17. As in Fig. 16 except for 1956.7 GMT.

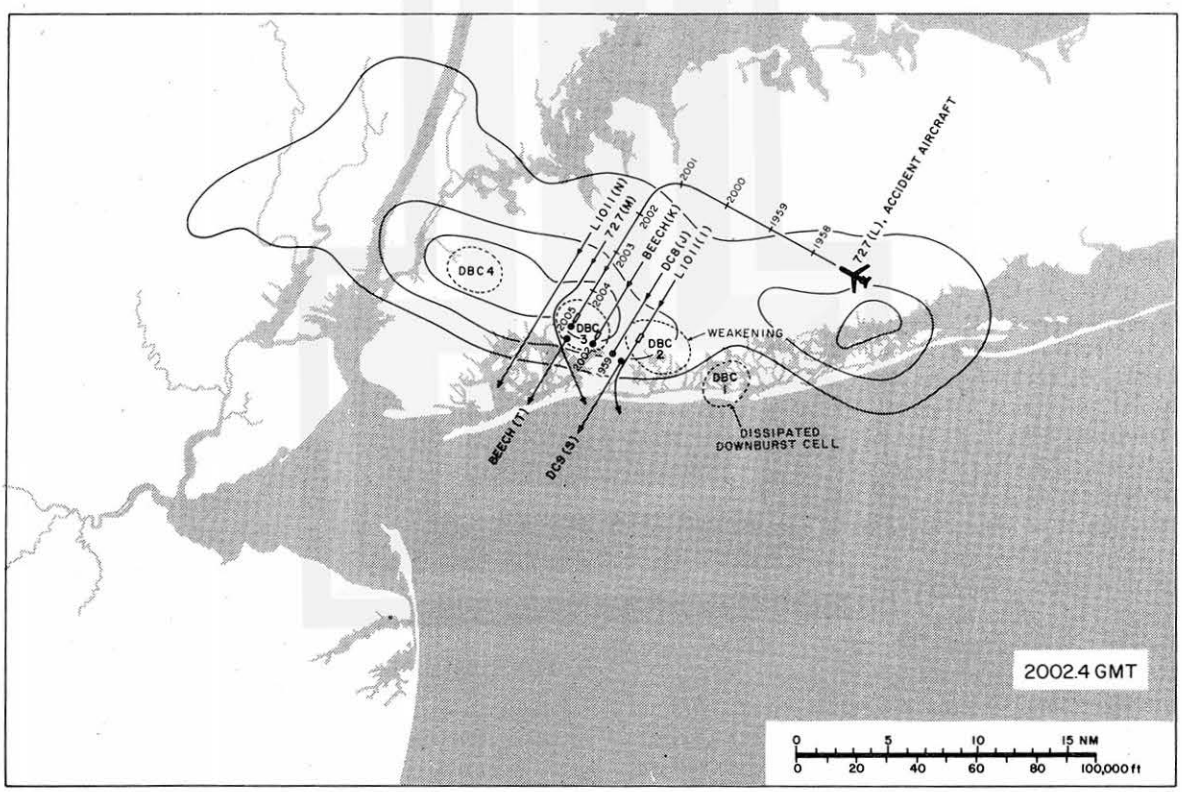

FIG. 18. Downburst cells and approach paths at 2002.4 GMT, about 3 min before the accident.

their intensity. According to Gibson's (1975) interpretation, the three-level contours represent the theoretical rainfall rates of 0.1, 0.5 and 1.0 inches h^{-1}. Since height of the radar beam above JFK was about 7000 ft, these rainfall rates could be less than those along the lower glide slope.

The three iso-echo contours from the pictures were placed on a local map covering the area around JFK. The 1945.7 map is not reproduced here, but from Fig. 15 it is seen that DBC1 was passing over the approach end of 22-L. Aircraft P took off from 22-R in heavy rain with windshield wipers at full speed. The rain ended as the aircraft was lifting off the runway. Aircraft B and C were affected by DBC1, which was already beginning to weaken.

DBC2 was moving toward JFK followed by DBC3, which had crossed the East River into northern Brooklyn. As mentioned before, all three DBC's missed the four wind recorders in the New York area. An irony of fate had permitted four, or possibly five, DBC's to sneak through between the wind recorders. Had they approached from due west, the first one certainly would have been caught by EWR. An approach from the northwest would have provided detection by both Central Park and LGA.

At 1951.4, Fig. 16 shows that the spearhead echo extends from lower Manhattan to the north of JFK. Three aircraft (D, E, F) landed without trouble between DBC1 and DBC2. Accident aircraft L was headed toward the south coast of Long Island.

A helicopter en route from LGA to EWR encountered DBC4. A thunderstorm with heavy rain was moving over the south half of Manhattan and the upper New York Bay area. At 1950 the helicopter, flying at 1200 ft over the Hudson River, came upon heavy rain with

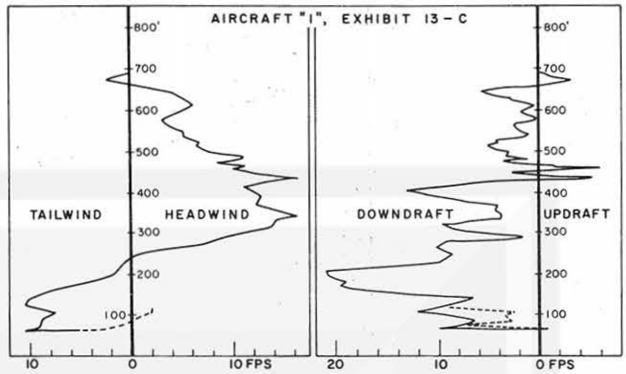

FIG. 19. Winds and drafts (ft s^{-1}) experienced by aircraft I, from Lockheed Exhibit 13-C. Curves are plotted as a function of height (ft) above runway.

drastically reduced visibility. On the west side of the river the helicopter dropped to 600 ft while holding 86% torque, which is the maximum continuous power. The path of the helicopter is included in Fig. 16.

The map at 1956.7 (Fig. 17) shows the accident aircraft L about 15 mi east of JFK flying around a rain cell and turning toward the approach zone. At this time aircraft H was just landing after suffering from a severe crosswind shear in DBC2, and aircraft I was approaching the center of DBC2. At 2002.4, the next radar time (Fig. 18), aircraft L was approaching the outer marker with the landing gear down, while DBC3 was rapidly moving into the glide path ahead. A few minutes later at 2006, aircraft M, after being told to abandon approach, observed on airborne radar a circular cell about 3 mi in diameter located over the threshold of runway 22-L. Aircraft L had hit the ground short of the runway.

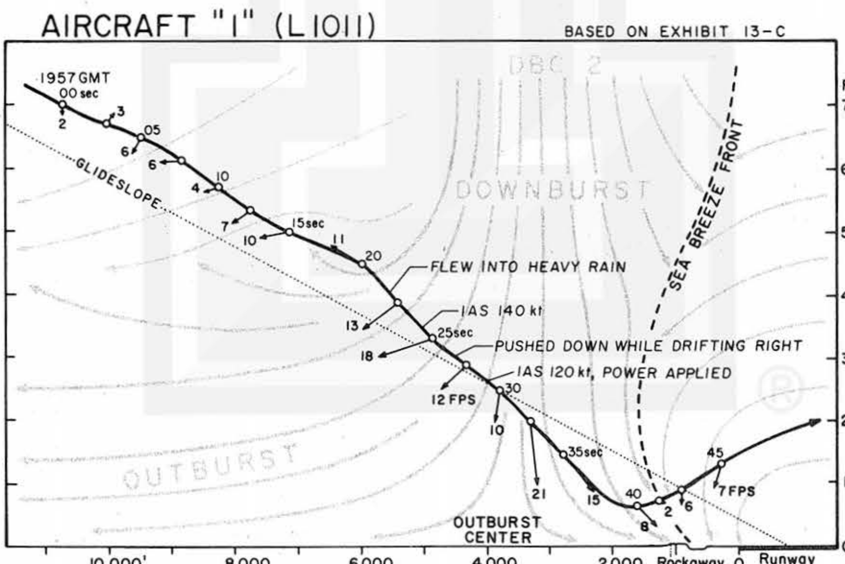

FIG. 20. Path of aircraft I through downburst cell No. 2.

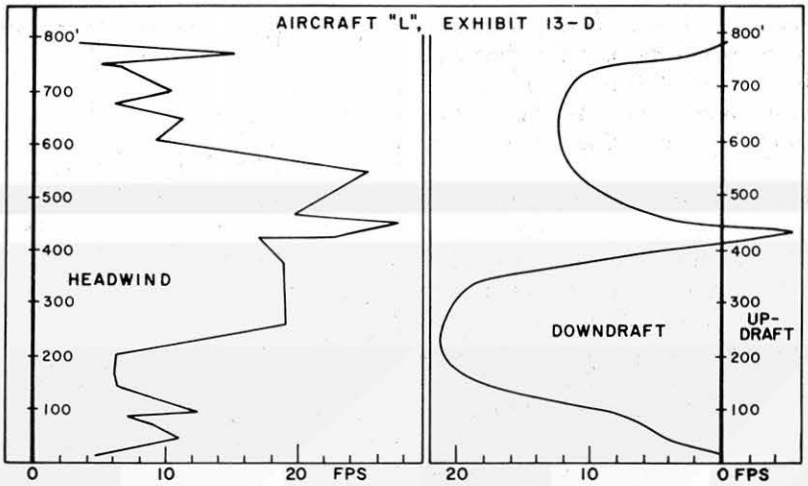

FIG. 21. Winds and drafts (ft s^{-1}) experienced by aircraft L, from Boeing Exhibit 13-D. Curves are plotted as a function of height (ft) above the runway.

7. Effects of downburst and wind shear

Aircraft I, an L-1011, had initiated the missed approach through DBC2 after experiencing a heavy sink and right drift. The plane was obviously under the influence of a strong descending current and a crosswind from the left. The loss of indicated air speed suggests a significant decrease in the headwind component.

In an attempt to reconstruct the pattern of airflow in the vertical plane, solutions of environmental winds by Lockheed engineers given in their Exhibit 13-C and its supplement (National Transportation Safety Board, 1975) were examined. When the flow fields were delineated from these two solutions, the one in the main exhibit rather than the supplement appeared to be more realistic from a meteorological point of view.

Fig. 19 shows that aircraft I was experiencing about 15 ft s^{-1} headwind when it flew into heavy rain at about 400 ft. At 250 ft the headwind changed into a tailwind. The downward current then intensified to 21 ft s^{-1} at 210 ft.

Words cannot describe the effects of DBC2 on aircraft I as dramatically as can a careful look at Fig. 20. At 250 ft, after the indicated air speed dropped from 140 to 120 kt, coupled with a drift to the right, power was applied but faster sinking was still experienced, so a missed approach was executed as thrust was pushed to approximately takeoff range. The pilot was able to keep the wings level while the aircraft continued sinking until it started recovering altitude at 60 ft above the ground. A few minutes later, the JFK airport was

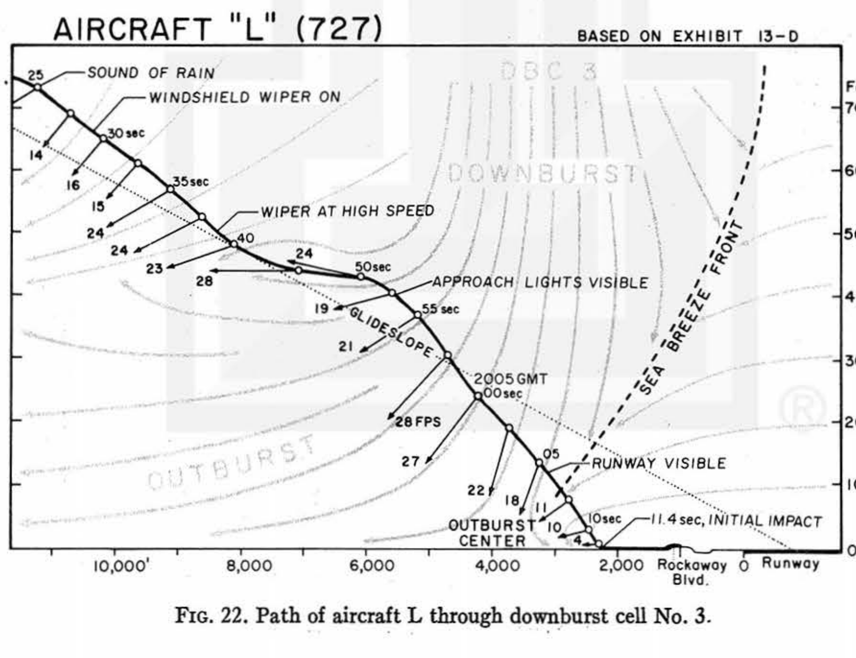

FIG. 22. Path of aircraft L through downburst cell No. 3.

closed due to the accident of aircraft L, and the L-1011 was diverted to EWR.

Three wind profiles from the flight recorders of aircraft L, prepared under different assumptions by Boeing engineers and included in their Exhibit 13-D (NTSB, 197S), were examined. Of these, the profile that was the most reasonable from a meteorological point of view was the one computed by assuming that the approach power was a fuel flow of 4596 lb h^{-1} per engine, a constant until descending to 140 ft. Thereafter, the power setting was 58%. The profile in Fig. 21 shows two maxima in downdraft speed, at about 600 and 200 ft. The one at 220 ft reached 21 ft s^{-1} which would induce a point divergence of 9.5×10^{-1} s^{-1} below the flight altitude.

As shown in Fig. 22 aircraft L descended slightly above the glide slope in smooth air from the outer marker to 730 ft, where light rain was encountered. As it approached 500 ft the windshield wipers were set at high speed and the glide slope was intercepted. Fig. 21 indicates two strong headwind gusts at 25 and 28 ft s^{-1} as it entered the downburst shown in Fig. 22. The headwind decreased from 28 to 7 ft s^{-1}, while a 5 ft s^{-1} updraft changed to a 21 ft s^{-1} downburst. The loss of headwind and the downburst encountered accentuated the descent to place the aircraft below the glide slope at 300 ft near the core of the downburst. The runway became visible at 2005:06 at 130 ft. About 5 s later the initial impact took place. It is difficult to determine the crosswind component during the final descent below 200 ft. The data of the flight recorder show that the headings were 227° at 200 ft, 226° at 150 ft, 225° at 100 ft, 227° at 50 ft and 224° at initial impact.

At the time of impact, the aircraft was very slightly to the right of the approach center line with the left wing down. The left wing clipped three approach-light standards, swinging the aircraft around the next three, through the next four, to scatter its pieces and debris on the left side of the next five across Rockaway Blvd.

One is struck by the similarity between the experiences of aircraft I in DBC2 and aircraft L in DBC3, and might ask why L could not recover at 60 ft as I did. The changes in headwind component were about the same below 400 ft in both cases, and the peak downdrafts were roughly the same. However, I experienced downdrafts of downburst magnitude (>12 ft s^{-1}) for 3 s, barely reaching 20 ft s^{-1} momentarily, while L was in downburst values for 11 s, with speeds greater than 20 ft s^{-1} during this time. Due to increased headwind components at 450 ft which were corrected for by increasing the glide angle, aircraft L apparently did not experience the drop in air speed at 300 ft which caused the pilot of I to apply power. In the 8 s remaining before impact, L was subjected to the most intense downdrafts. Other factors might be differences in the manner in which power can be applied in the two different types of aircraft and in their equipment for automation.

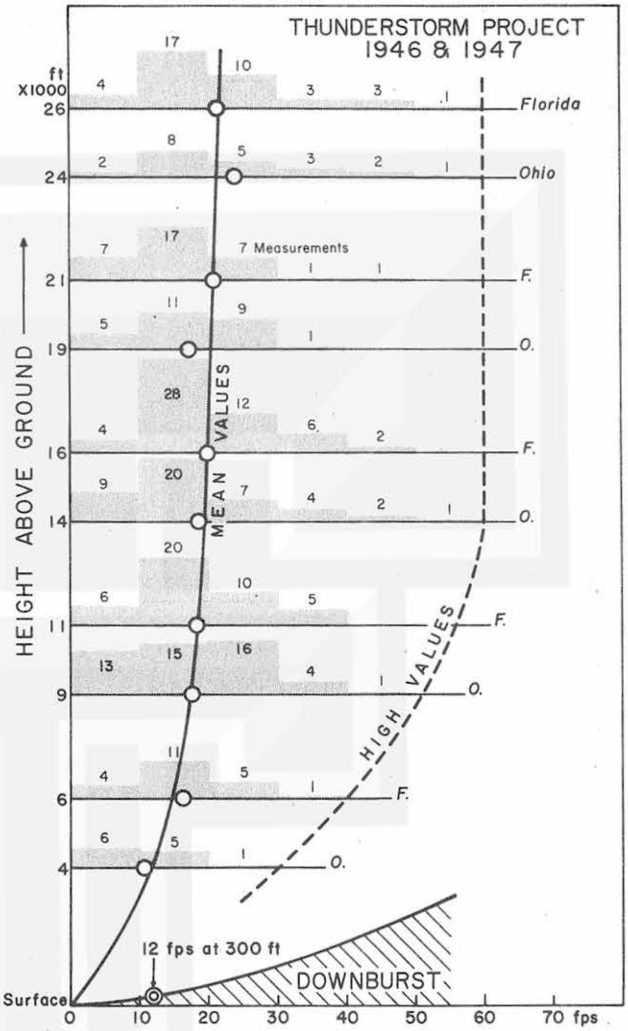

FIG. 23. Frequencies of downdraft speeds measured by the Thunderstorm Project, compared with downburst speeds at low levels.

8. Spearhead echoes and downburst cells

The downburst cells inside the spearhead echo of the JFK thunderstorm were different from most downdraft cells found inside the ordinary thunderstorm. The downburst cells moved faster than normal while maintaining a very strong downdraft current near the ground. To show the difference in downward speeds, the downburst cells are compared in Fig. 23 with downdrafts in the majority of thunderstorms as reported by Byers and Braham (1949) from the Thunderstorm Project measurements of 1946–47. According to the statistics, the mean downdraft values increase from theoretical zero at the surface to about 10 ft s^{-1} at the 4000 ft level in the Florida and Ohio measurements. The high values are approximately three times the mean values at various altitudes (Fig. 23). It is evident

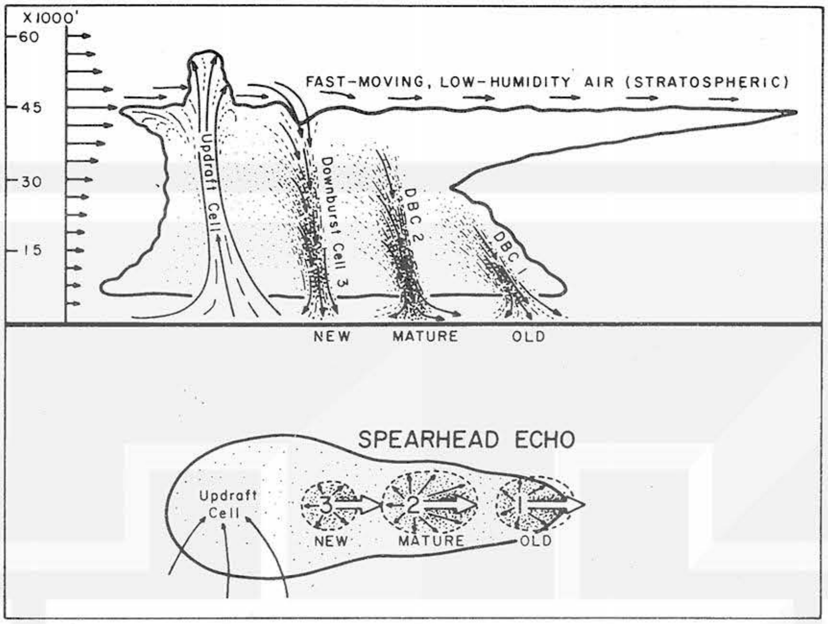

FIG. 24. A model of a spearhead echo.

that the vertical speed of the downburst, 12 ft s^{-1} or larger at 300 ft above the ground, is about 10 times the mean downdraft speed estimated from Thunderstorm Project data.

The downburst cell has about the same horizontal dimension as the usual thunderstorm downdraft; therefore, it represents a much greater concentration of released energy. On the Thunderstorm Project no measurements were made above 26 000 ft, hence the level of origin of downdrafts detected at that height is unknown. The cell model was constructed with a cloud top at 43 000 ft and a downdraft starting down

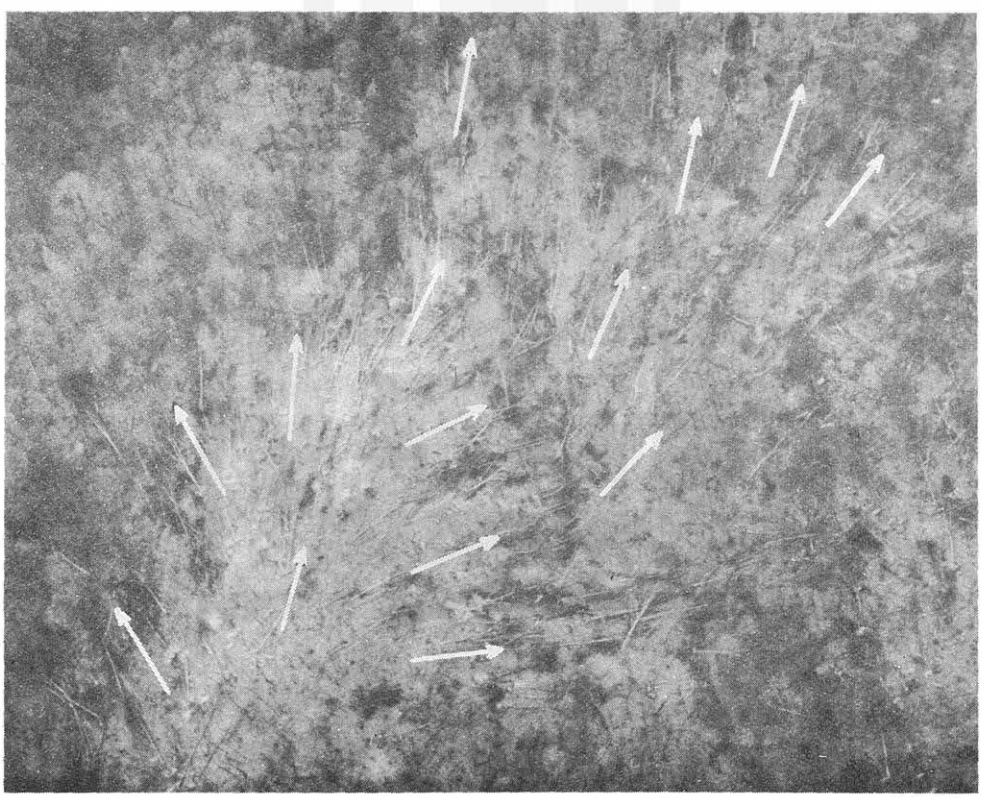

FIG. 25. More than 300 trees blown over by an intense outburst near Beckley, W. Va.

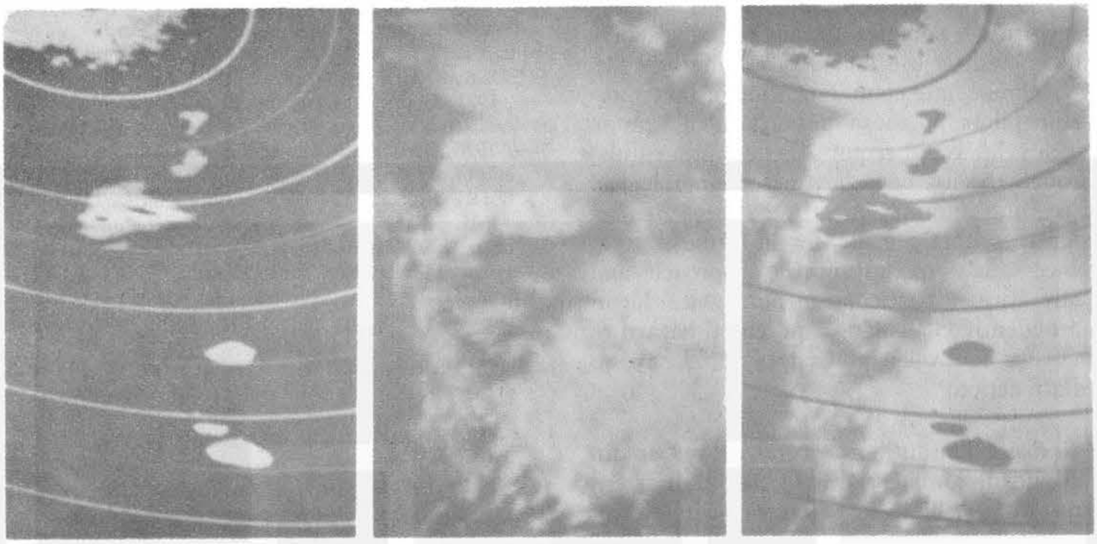

FIG. 26. Features of a spearhead echo 100 n mi south of Kansas City on 6 May 1975. Radar echoes at 2222 GMT (left), SMS picture at 2222 GMT (center), and their superposition (right).

from about 28 000 or 30 000 ft. Entrainment of environmental air was considered to be from across the cloud's lateral boundary. From stratospheric flights above thunderstorms, Fujita (1974) has found fast descending motion in thunderstorm turrets reaching above 50 000 ft. The model involves tops overshooting the anvil then collapsing into a strong downdraft and trail of precipitation. Entrainment at the top transports dry air and large horizontal momentum downward. One of the greatest sinking speeds of the collapsing tops measured from a Learjet airplane by Fujita was 41 m s^{-1} (135 ft s^{-1}). Sauvageot (1975) has shown by millimeter wavelength radar data in France that trails of precipitation fall from protuberances on top of convective systems.

In the subsaturated mixture of cloud air with dry, entrained air from stratospheric levels, ice crystals sublime rapidly, taking up heat from the air to make the downdraft cold and negatively buoyant. The collapsing top and entrained air accelerate the train of precipitation and impart fast horizontal momentum from the stratosphere. A successive rise and fall of the top will create a family of downburst cells that moves away from the parent thunderstorm, as shown in Fig. 24.

On a PPI scope, the family of downburst cells might appear as a spearhead echo pointing downwind. From a close range, less than 30 mi for instance, an airborne radar may be able to identify a downburst cell as being a circular area of rain. The pilot of aircraft M observed a circular cell 2–3 mi in diameter located over the approach end of runway 22 L. The time of observation was 2006 when aircraft M was following the accident aircraft L.

As another example of a downburst and its radial outburst, Fujita witnessed from a low-flying Cessna airplane various patterns of tree damage accompanying the 3 April 1974 tornado super-outbreak. At some distance away from the tornado paths, trees in the forests were blown over in radial directions, as if they had been blown outward from a downburst. A photograph of this phenomenon is shown in Fig. 25.

Another example of a spearhead echo was found on 6 May 1975, the day of the Omaha tornado, when the WSR-57 radar of the National Weather Service at Kansas City depicted the echo shown in Fig. 26. The echo, located ~100 n mi south of the radar, showed a feature of a spearhead pointing toward the east-southeast. A geostationary satellite picture taken at 2222, the time of the radar picture, shows an overshooting top. When the radar and satellite pictures were combined into a single image, it was evident that the overshooting top and the spearhead echo coincided in their locations.

9. Conclusions

The research results presented in this paper suggest the existence of downburst cells in specific thunderstorms. These cells seem to arise in spearhead echoes, as newly introduced in this paper. About 2% of the echoes in the New York area and Middle Atlantic States were spearhead echoes.

Some obvious recommendations for avoiding the repetition of similar hazardous aircraft operations can be made, such as 1) operating additional wind sensors in the near-approach zone and climb-out end of the active runway, 2) monitoring wind speed and direction continuously during a thunderstorm, especially when a sea breeze or lake breeze exists, 3) monitoring continuously the shape and motion of radar echoes using newly developed monitoring techniques and display equipment, and 4) monitoring continuously cloud-top activities, especially by satellite techniques.

The detection and identification of any downburst cells that constitute a potential hazard to approaching aircraft will be of little use unless procedures are developed for the immediate communication of this information to the pilots of those aircraft. The rate of change of such cells would require their uninterrupted analysis through the use of radar, mesometeorological maps, surface wind information in the approach zone, etc., in order to properly evaluate the thunderstorm without unnecessarily disrupting the approach and landing of aircraft at a particular airport. Once downburst cells are identified as being a potential hazard to aircraft, air traffic controllers and pilots would have to take immediate action.

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2-U. Statements of witness crewmembers, aircraft G through M.

2-V. Statements of crew members of flights that preceded or followed aircraft L.

3-C. FAA transcripts, JFK tower and NYCIFRR.

6-A. Human factors group chairman's factual report of investigation.

7-A. Structures group chairman's factual report of investigation.

12-A. Supplement to specialist factual report of investigation. Cockpit voice recorder, aircraft L.

12-B. Cockpit voice recorder group chairman's factual report of investigation, aircraft H.

13-B. Position and altitude data relating to the final approaches of aircraft inbound to JFK between 1950 and 2005.

13-C and Supplement. Data submitted by Lockheed California Co. regarding analysis of DFDR information from L-1011 aircraft I.

13-D. Data submitted by Boeing Co. regarding analysis of FDR information from 727 aircraft L.

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