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Characteristics of Microbursts in the Continental United States

Microbursts — powerful downdrafts generally associated with thunderstorms that occur in hot, humid weather — have caused a number of aircraft crashes. To prevent future accidents, air traffic controllers must be able to detect, and predict, microburst events. All microbursts are not alike, however; several distinct weather patterns can produce microbursts. Thus a categorization of the different types of microbursts is an essential part of understanding these hazardous phenomena. Using this categorization, the relative hazard to aviation of the various types of microbursts can be assessed.

Wind shear is a major cause of air carrier accidents in the United States — seven crashes due to wind shear since 1970 have killed 575 people. Most of these accidents have been caused by a particular form of wind shear, called a microburst. Microbursts are small-scale, low-altitude, intense downdrafts that impact the surface of the earth and cause strong divergent outflows of wind. They arise from thunderstorms and are usually, but not always, associated with heavy rainfall.

A number of meteorologically distinct phenomena, all of which give rise to strong surface outflows, are being called microbursts. The current interest within the scientific and aviation communities in understanding microbursts makes it important to categorize these phenomena according to their meteorological nature and true aviation hazard potential. This categorization is essential to discovering exactly what atmospheric conditions lead to the development of microbursts, and to building a coherent base of knowledge on which automated algorithms for the detection and prediction of microbursts can draw [1].

HISTORY

One of the first illustrations of the hazard posed by thunderstorm downdrafts impacting the surface to planes flying at low altitudes appeared in 1961 [2]. This study was based primarily on the wind pattern encountered by a BOAC Argonaut plane taking off from the Kano, Nigeria, airport in June 1956 [3].

In this type of wind pattern (Fig. 1), the plane experiences a headwind as it approaches the thunderstorm outflow. This headwind causes an increase of lift and an increase in altitude. A pilot who is unaware of what is to follow may try to compensate for the increased lift, especially if it occurs during a landing. (To avoid overshooting the runway, the pilot must maintain a precise glideslope.) But then a downdraft causes the plane to lose altitude, and a tailwind, experienced after the plane flies through the center of the diverging outflow, decreases the lift and causes a further loss of altitude. Although it was not recognized back in 1961, a pilot's reaction to the initial increase in lift can contribute to the overall hazard of the divergent wind pattern.

The term "downburst" was introduced by Fujita and Byers [4] to describe a thunderstorm downdraft, similar to the one shown in Fig. 1, that caused the crash of Eastern Flight 66 at New York's J.F. Kennedy Airport on 24 June 1975. Fujita and Byers chose the term to describe a phenomenon even more forceful than "downrush," introduced in 1954 to describe thunderstorm downdrafts associated with moderate to heavy rain that led to excessively strong local winds and property damage [5].

A downburst is defined in terms of its hazard to aircraft. If a downdraft has a speed of at least 12 ft/s at an altitude of 300 ft agl (above ground level) (comparable to the speed of a jet transport following the usual 3° glideslope on final approach) and a spatial extent of 0.5 mi or larger (large enough to have a noticeable effect

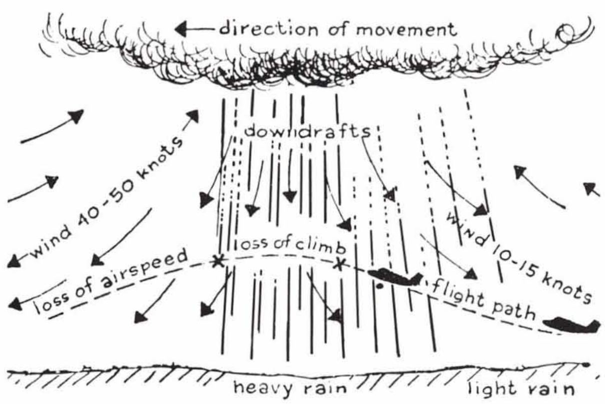


Fig. 1 — Downdrafts from a thunderstorm can be hazardous to an airplane during a takeoff. (Redrawn from Ref 2).

on the aircraft), then it is a downburst [6].

A few years after the downburst was defined, the term "microburst" was created to distinguish small downbursts (0.8 to 4.0 km in horizontal scale) from larger ones [7]. (No reason based on aerodynamic principles or fluid dynamics sets 4 km as the upper limit of a microburst, but the 0.8-km minimum does have a fundamental basis. A downdraft smaller than 0.8 km in horizontal scale is experienced by aircraft as turbulence.) An example of a thunderstorm microburst is shown in Fig. 2.

The introduction to the meteorological community of the downburst concept met with some controversy and resistance. Many scientists wondered if there was a difference between the downburst and the thunderstorm downdraft. Confusion still remains over what exactly the term describes; the observational studies presented here show that several distinct phenomena can qualify.

Despite resistance to a term that was developed specifically to connote a hazard to aviation, the meteorological community and especially researchers at the National Severe Storms Laboratory (NSSL) were concerned with preventing accidents such as the one at J.F Kennedy Airport. However, some scientists believed that the wind shear-related aircraft accidents attributed by Fujita to downbursts were actually caused by aircraft penetration of larger-scale gust fronts — abrupt shifts in wind direction with corresponding increases in wind speed. Rather than encountering downbursts, they believed that the aircraft had encountered the turbulent leading edges of outflows from large-scale storm systems and the strong, but unidirectional, horizontal winds just behind them. Part of this argument was based on detailed analyses of windfields in springtime tornadic storms and of squall lines in Oklahoma, in which no small-scale downdrafts were found [8,9].

In his early papers [10,11], Fujita explained the differences between downbursts and gust fronts, especially with regard to the wind shear hazard they posed for aviation. Nonetheless, skepticism of the microburst as a distinct phenomenon persisted. This skepticism points out the crucial importance of differentiating between storm types that occur in different parts of the country at different times of the year. It also highlights the need for understanding the changes in surface wind shear patterns that occur as these storms evolve.

The Federal Aviation Administration (FAA) developed the anemometer-based Low Level Wind Shear Alert System (LLWAS) [12] in 1976, at the recommendation of NSSL scientists. The first LLWASs were installed at six airports in 1977; by 1982 over 50 more systems were in place, and by 1986 an additional 50 systems had been installed. Before LLWAS, airports typically had only one wind-sensing device, located either at the air traffic control tower or approximately centerfield, which was incapable of detecting winds in the critical approach and departure corridors. NSSL personnel observed that aircraft were sometimes brought in for landing when there were tailwinds on the runways, rather than headwinds. This situation occurred when, for example, gust fronts were moving across an airfield.

With an LLWAS, five additional anemometers are located around an airport periphery. Their data plus the data from the centrally located anemometer are transmitted to a computer, which evaluates wind differences between the outlying and centerfield sensors. Air traffic controllers then warn pilots about detected wind shifts of high strength. The system was designed to detect the wind shear associated with gust fronts, not the newly formed, highly divergent outflows (microbursts) from thunderstorms directly over the airport. Apparently it was felt that if a thunderstorm was present in the middle of the airport it would not be necessary to tell the air traffic controllers, since that is where the control tower is located.

However, Fujita remained convinced that short-lived, highly divergent surface outflows from unusually strong, small-scale downdrafts posed a serious threat to aviation. He directed three research projects, in different parts of the country, using Doppler radars, instrumented aircraft, and a network of automatic weather stations. They were project NIMROD (Northern Illinois Meteorological Research on Downbursts) near Chicago in 1978 [7]; project JAWS (Joint Airport Weather Studies) near Denver in 1982 in cooperation with researchers from the National Center for Atmospheric Research (NCAR) [13]; and, most recently, project MIST (Microbursts and Severe Thunderstorms) near Huntsville, Alabama in 1986 [14].

After both NIMROD and JAWS, the downburst was redefined to encompass newly observed phenomena. After NIMROD the downburst was redefined as "an outburst of damaging winds on or near the ground" [15], where "damaging winds" referred to winds of at least 18 m/s. Microbursts were simply small-scale wind events of this magnitude.

During JAWS, many more microbursts were found, so the emphasis was shifted accordingly. The microburst was redefined as having a "differential Doppler velocity across the divergence center greater than or equal to 10 m/s and the initial distance between maximum approaching and receding centers less than or equal to 4 km" [16]. This definition, now widely accepted, encompasses weaker but still highly

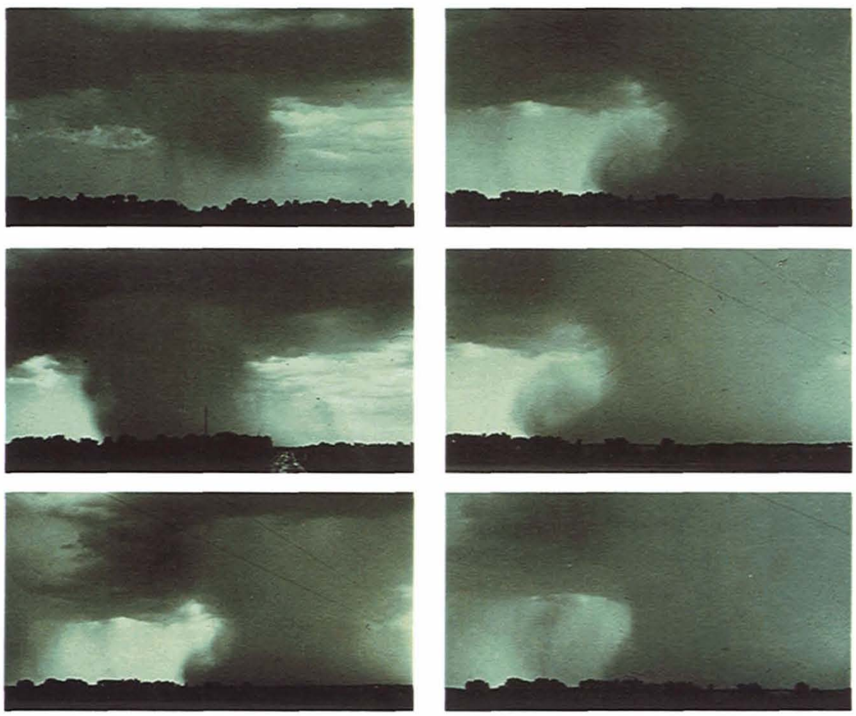


Fig. 2 — Photographs of a wet microburst on 1 July 1978 near Wichita, Kansas, taken at 10- to 60-s intervals, looking south. A curling motion showing a vortex with a horizontal axis is visible near the left edge of the outburst flow. (Copyrighted photos by Mike Smith; reproduced from Ref 25.)

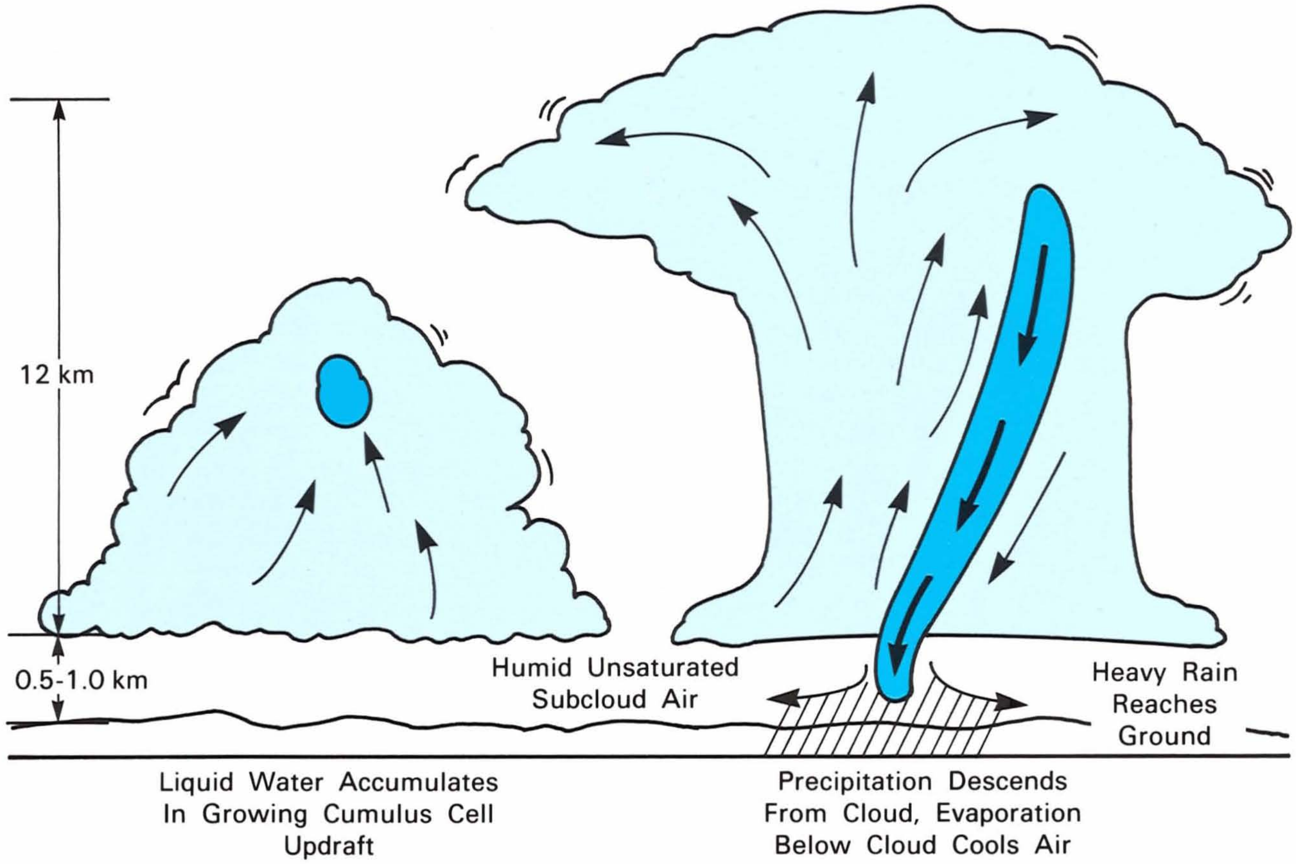


Fig. 3 — Two stages in the lifetime of an air mass thunderstorm cell that produces a microburst. The light blue color represents the visible cloud boundary; the darker blue color represents the radar return from the region of liquid water within the cloud. In the early stage of development (left), the cell is filled throughout with rising air. Notice that the first precipitation radar returns form aloft. About 20 min later (right), updrafts and downdrafts coexist within the cell and rain falls. The microburst outflow is associated with the rain at the surface.

divergent meteorological phenomena. Although the rapidity with which microbursts develop and their short duration were recognized as significant parts of their hazard to aviation, none of these definitions incorporated time constraints.

Shortly after takeoff at New Orleans International Airport, Pan American World Airways Flight 759 crashed in July 1982, and all 149 persons on board and eight persons on the ground died [17,18]. This crash, caused by a microburst, gave a new impetus to the meteorological investigation of microbursts. A National Academy of Sciences Committee for the Study of Low-Altitude Wind Shear and Its Hazard to Aviation was formed under the sponsorship of the FAA.

The final report of that committee [19] stated, "Some wind shears have been understood by meteorologists for a number of years. These include those found in gust fronts, warm and cold air mass fronts, [etc].... Most [of these] are predictable, sometimes hours in advance."

They also noted, "Scientists have recently begun to recognize the importance of storm downdrafts that are unusually small in horizontal cross section and that are of short duration. Such downdrafts have been called microbursts."

The final report of the committee made several recommendations for the detection and prediction of low-altitude wind shear. A key recommendation was that the FAA "take immediate action to develop a pulsed Doppler radar system that can be used to observe weather conditions at and around airport terminals. This terminal radar system should be able to operate with a high degree of automation and to provide information on low-altitude wind shear, turbulence, and rainfall intensity."

The committee also noted the inadequacy of the FAA's LLWAS system for detecting microbursts but, since the LLWAS was the only system available for wind shear detection, the committee made the recommendation that "every effort should be made to assess and improve its performance."

High-Quality Weather Radar Data

In 1982, MIT Lincoln Laboratory began to develop a pulse Doppler weather radar testbed that could be used to detect hazardous weather in en route and terminal airspace [20,21]. Many challenging technical issues have been addressed in the course of developing a radar that can operate as a Terminal Doppler Weather Radar (TDWR).

Since, to detect microburst outflows, the radar has to scan at low elevation angles, ground clutter returns must be filtered [22]. Some clutter will still be present after filtering (residue from very strong returns or moving clutter), so an automated data editing procedure based on site-specific clutter maps is needed [23]. Doppler velocity aliasing and range aliasing of distant echoes can occur with the pulse Doppler system; algorithms for selection of the radar pulse repetition frequency [24] and for cleaning up the recorded data are required. And finally, the system must include algorithms for automatically detecting gust fronts and microburst wind shear hazards based on the Doppler radar measurements.

This last task was especially difficult because microburst parent storm structure varies, both across the country and with the time of year in a given part of the country. Moreover, almost no Doppler radar data (of sufficient quality for use in algorithm development) had been collected. The data sets that had been collected in research experiments like NIMROD and JAWS spanned only one season of the year in one area, and the data collection strategies were inconsistent.

To collect high-quality Doppler weather radar data on thunderstorms, Lincoln Laboratory started the FAA-Lincoln Laboratory Operational Weather Studies (FLOWS) Project in 1984. The FAA-Lincoln Laboratory transportable testbed radar (FL-2) took data in Memphis, Tennessee, from April through November, 1985. The radar moved to Huntsville, Alabama in 1986, where it was operated from April through October of that year.

Memphis and Huntsville were chosen as the first two sites because of the high frequency of thunderstorms there, especially during the summer, and because no Doppler radar data had previously been collected in that part of the country. Microbursts were indeed found and data sets were collected suitable for use in an automatic microburst detection system. Most microbursts in Memphis and Huntsville were caused by collapsing phase downdrafts of iso-

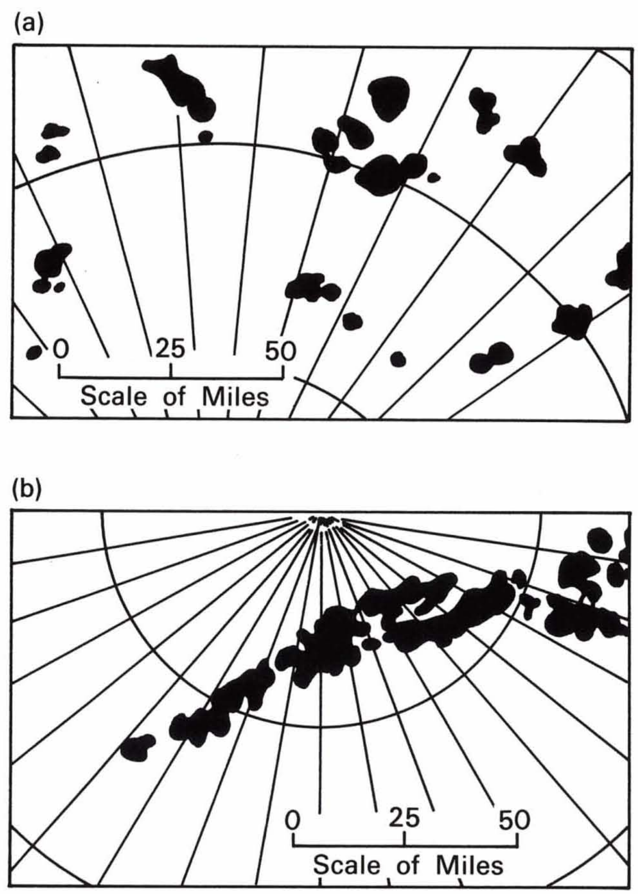


Fig. 4 — a) Radar echoes on a day of random air mass thunderstorms. b) Radar echoes on a day of squall line thunderstorms. The radial lines and arcs indicate the azimuths and ranges from the radar site. (Redrawn from Ref 37.)

lated, air mass thunderstorms, and were accompanied by very heavy rain. As the Table shows, these microburst storms appear to be very similar to the ones that have caused numerous aircraft accidents [25,26].

The FAA commissioned scientists at NCAR in 1984 to investigate how much a change of LLWAS wind-processing algorithms or network geometry could improve the system's ability to detect microburst wind shear. NCAR found that substantial improvements were possible — by increasing the number of anemometers in the array, by distinguishing between microburst and gust front events (which pose very different types of aviation hazards), and by fine-tuning the wind shear thresholds for alarms [28].

Since the National Academy of Sciences Committee made its recommendations, microburst wind shear has caused one more aircraft accident — the crash of Delta 191 at Dallas/Ft. Worth in August 1985 [29,30]. The FAA soon thereafter received funding from Congress to move forward with the operational TDWR program [31,32].

The FL-2 radar has been moved to Denver where, during the 1987 microburst season, many excellent data sets with 1-min surface update rates and coverage of upper level storm structure were gathered. These data are being used to test and refine the TDWR microburst

Table — Aircraft Accidents Attributable Specifically to Microburst Wind Shear[a]

Location	*Date*	*Wind Speed (knots)*	*Diameter (km)*	*Rain*	*Surface Weather*	*F/I/U[b]*
Kano, Nigeria	24 Jun 1956	>20	3	Heavy	Small-scale outflow cell	32/11/2
Pago Pago, Samoa	30 Jan 1974	22-35	3	Heavy nearby	Heavy rain showers near airport	96/5/0
New York	24 Jun 1975	22-35	5-10	Heavy	Hot smoggy day, sea breeze, light, moderate, & heavy rain numerous small cells, "spearhead" echo 8 × 32 km	112/12/0
Denver	7 Aug 1975	>25	2	Light	Numerous scattered showers small and weak, cell broke into 2, thunder heard, "spearhead" echo 8 × 16 km	0/15/119
Doha, Qatar	14 May 1976	28	6	Yes	Thunderstorms of unknown strength	45/15/4
Philadelphia	23 Jun 1976	39	4	Yes	Headwind increase in front of shower; scattered showers & thunderstorms in cold sector near warm front, growing "spearhead" echo	0/86/20
Tuscon	3 Jun 1977	28	2	None	Numerous cumulonimbi around airport; gust front passed earlier with 49 knots surface wind speed	0/0/All
New Orleans	9 Jul 1982	>30	2	Heavy	Scattered showers, 7 gust fronts nearby, recent growth of convective cloud tops	152/9/0
Dallas	2 Aug 1985	45-70	4	Very heavy	Scattered small cells initiated on gust front out of larger cell to northwest, very hot day, cloud top of microburst cell 23 Kft (questionable: National Transportation Safety Board reported 40 to 50 Kft [27])	130/31/0

[a]All accidents with fatalities occurred in or near thunderstorms with heavy rain. Modified from Ref. 25.
[b]F = fatalities, I = injuries, U = uninjured.

recognition algorithm, developed at MIT Lincoln Laboratory [33,34], and the TDWR gust front recognition algorithm, developed at NSSL [35], for the types of storms found in the Denver area.

Lincoln Laboratory, NSSL, and NCAR will be cooperating this summer in a real-time demonstration of the TDWR system at Denver's Stapleton International Airport with FL-2 as the primary sensor. The demonstration will involve providing low-altitude wind shear information to air traffic controllers on detected microbursts and gust fronts that threaten to impact airport operations. A new enhanced LLWAS system, which has greatly improved performance over the original system, will also be operating during the TDWR demonstration.

STRENGTH OF THE THUNDERSTORM OUTFLOW

Before reviewing meteorological studies on microbursts produced by thunderstorms, it is instructive to examine the factors that affect the speed of thunderstorm outflows. The material in this section provides a simple mathematical framework that is helpful in understanding the emprical evidence presented in the remainder of this article.

Two factors primarily determine the speed of thunderstorm outflows: the speed of the downdraft that impacts the surface and spreads horizontally (with roughly the same speed as the downdraft), and the temperature of the outflow air. Even if the downdraft air reaches the surface with essentially zero velocity it will spread horizontally, as a gravity current, if it is colder than the environment. Other factors that also influence the strength of the thunderstorm outflow include the outflow depth, which is influenced in part by storm geometry (*eg*, linear vs circular), and the horizontal momentum of the air that originally feeds the downdraft.

The first factor, the speed of the downdraft, depends on the forces that accelerate the downdraft air vertically. The approximate vertical acceleration equation is:

$$\frac{dW}{dt} = g\,\frac{\Delta T}{T} - g\,(l + i) - \frac{\partial}{\partial z}\,\frac{P'}{\rho_0} \qquad (1)$$

(Vertical acceleration equals thermal buoyancy minus precipitation loading minus nonhydrostatic pressure gradient.) W is the vertical velocity of an air parcel; t is time; g is the gravitational acceleration; T is the temperature of the environment; ΔT is the temperature difference between the air parcel and the environment; l and i are the mass mixing ratios (kilograms of water per kilogram of air) of liquid water and ice, respectively, in the air parcel; z is the vertical coordinate; P' is the pressure perturbation from a hydrostatic basic state; and ρ_0 is the basic state density.

The first term on the right side of Eq. 1 shows that, if a thunderstorm air parcel is colder than the ambient air, the thermal buoyancy is negative and the acceleration is downward. The second term shows that any amount of precipitation acts to accelerate the thunderstorm air parcel downward. The third term shows that, when the perturbation pressure increases with height, the force on the thunderstorm air parcels is directed downward. This term becomes large only in very unusual situations — such as occur near a tornado.

These forces contribute to the vertical acceleration that, over time, builds the speed of the downdraft. The horizontal outflow of the microburst forms when the downdraft impacts the surface.

Because water phase changes occur, the first two terms on the right side of Eq. 1 are not independent. Ice may melt, with an associated cooling due to the latent heat of fusion, as the air parcel moves vertically through the freezing level. Liquid water may evaporate, with an even greater associated cooling due to the latent heat of vaporization, when it comes into contact with unsaturated air. Evaporation occurs, for example, when dry midlevel air is entrained into a thunderstorm or when rain falls into the unsaturated air below cloud base. The connection between thermal buoyancy and precipitation loading provides a way to evaluate their relative effects on the downdraft [36].

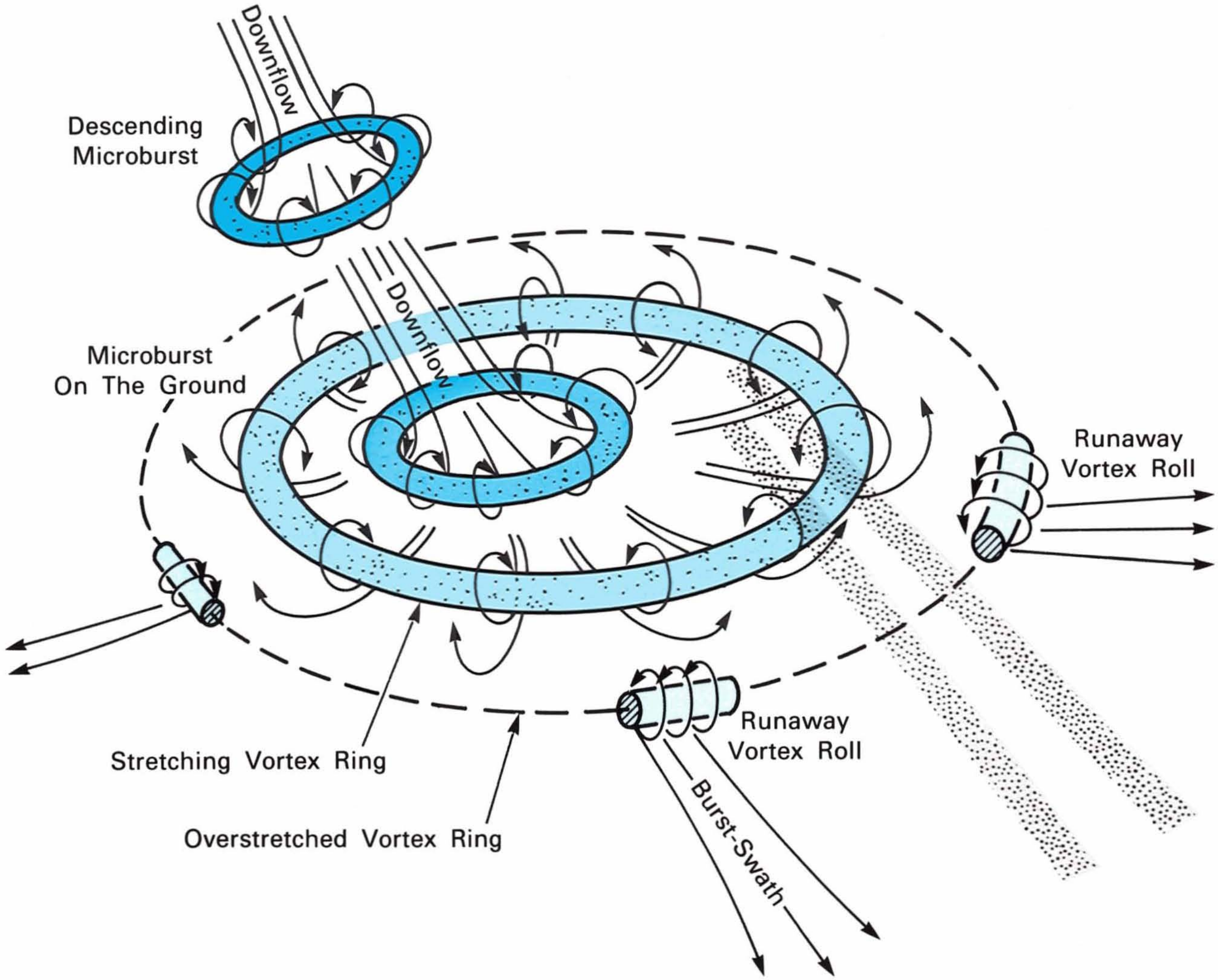


Fig. 5 — Four stages of microburst at Andrews Air Force Base. Stage 1 (descending): midair microburst descends. Stage 2 (contact): microburst hits the ground. Stage 3 (mature): stretching of the ring vortex intensifies the surface wind speeds. Stage 4 (breakup): runaway vortex rolls induce burst swaths. (Redrawn from Ref 41.)

If a liquid water mixing ratio l is evaporated, the temperature deficit is

$$\Delta T = \frac{L_v l}{C_p}$$

where L_v is the latent heat of vaporization of water and C_p is the specific heat of air at constant pressure. The negative buoyancy, $\Delta T/T$, is roughly equal to 10 l. Therefore, when evaporation occurs, the downward acceleration due to the weight of the water is replaced by a downward acceleration due to the colder air that is ten times larger!

This result shows that evaporating rain is a very efficient way to create strong downdrafts. A similar forcing occurs when ice melts, but this effect is proportionately smaller because of the smaller associated latent heat.

The second factor influencing the strength of the thunderstorm outflow is the difference in temperature between the outflow air and the ambient surface air. This can be expressed by the equation for the propagation speed of shallow density currents:

$$V = k\left(g\,h\,\frac{\Delta T}{T}\right)^{1/2} \qquad (2)$$

where V is the speed of the leading edge of the density current, ΔT is now the temperature difference between the environment and the density current, h is the outflow depth, and k is the internal Froude number (ratio of the inertial force to the force of gravity). The Froude number is greater than 1 initially, depending mainly on the downdraft speed, but with time tends toward a value somewhat less than 1 (~ 0.77).

Aside from any horizontal momentum derived from the vertical velocity, Eq. 2 shows that the deeper and colder the outflow, the higher the speed at which it will spread. The cooling of thunderstorm air is basically due to water phase changes. Thus if evaporation begins in a rainshaft as it falls below cloud base, it will cool the already downward moving air. But the resulting negative buoyancy force may not act long enough to increase the vertical velocity substantially (cloud base is often only 1 km agl). Nonetheless, as shown by Eq. 2, the outflow strength can still be augmented by the cooling.

OBSERVATIONAL STUDIES OF MICROBURSTS

A rapidly growing number of meteorological studies on downbursts and microbursts have been performed since Fujita developed this term in 1976. In studies both before and after 1976, authors occasionally described damaging wind phenomena without specifically discussing the hazard to aviation. This section categorizes those studies, as well as studies specifically of downbursts and microbursts, into four meteorologically distinct types: air mass thunderstorms; bow echo downbursts; shallow, high-based cumulonimbus clouds; and microburst lines.

This categorization is a prerequisite to achieving two goals: the discovery of exactly what conditions or dynamical interactions lead to the development of unusually strong downdrafts and/or the development of unusually small-scale, high speed outflows; and the development of automated algorithms (*eg,* for use in the TDWR) that use this base of knowledge for accurate early detections, and perhaps eventually predictions, of microburst wind shear.

Air Mass Thunderstorms

One of the first parent cell types to be associated with microbursts was the isolated cumulonimbus cloud. Although called simply "air mass thunderstorms" at the time (1949), Byers and Braham [37] measured very strong, small-scale divergent surface outflows that would today be classified as microbursts (*eg,* "When the cold downdraft of a cell reaches the surface layers of the atmosphere, it spreads out in a

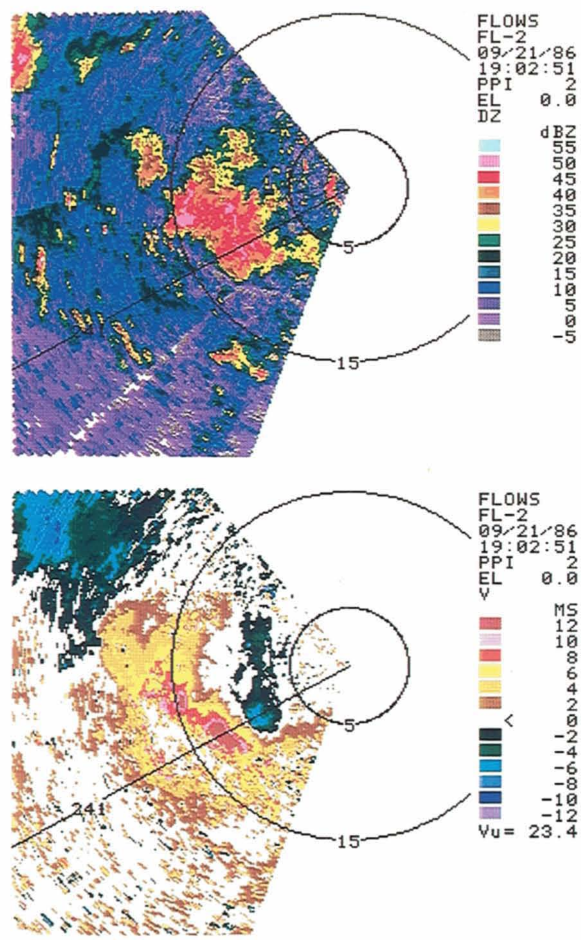


Fig. 6 — FL-2 PPI scan (at 0.0° elevation) of a microburst storm in Huntsville, Alabama on 21 September 1986 at 19:02:51 GMT (Greenwich mean time). Top: Radar reflectivity field, which measures the amount of precipitation. Bottom: Doppler velocity field. The Doppler velocity is negative toward the radar and positive away from the radar in the radial direction. The labelled azimuth line, at 241°, passes directly through the center of the microburst. A "classical" microburst divergent outflow signature (dipole pattern of 12 m/s flow away from the radar and 8 to 10 m/s flow toward the radar) is visible between the 5-km and 15-km range rings.

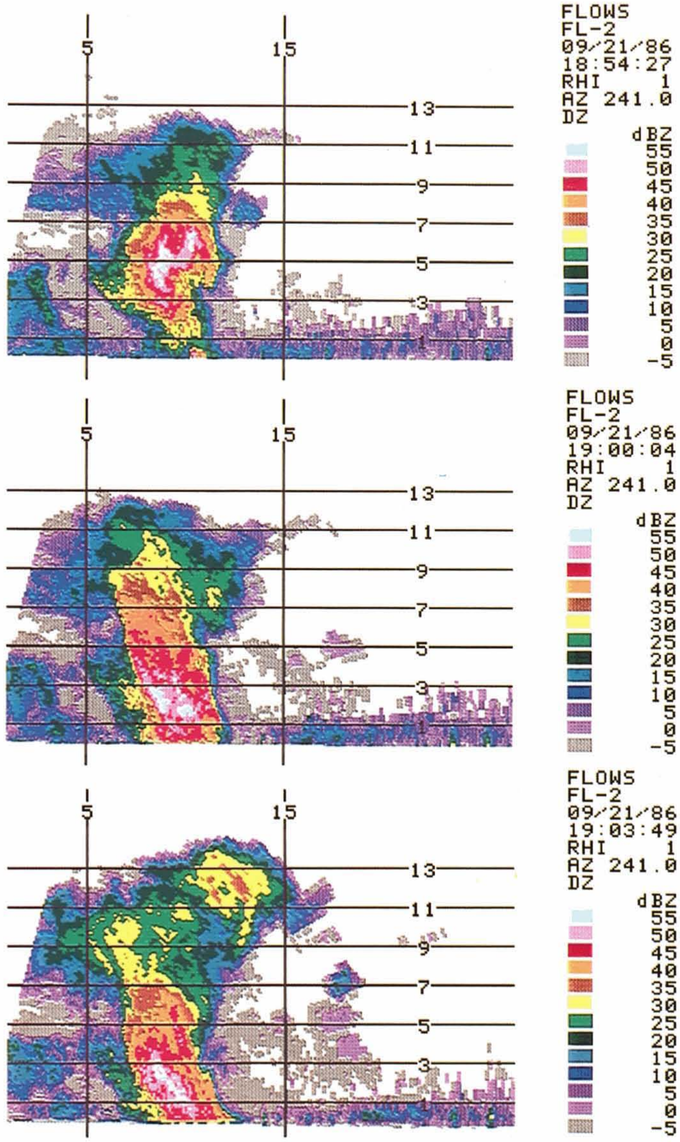
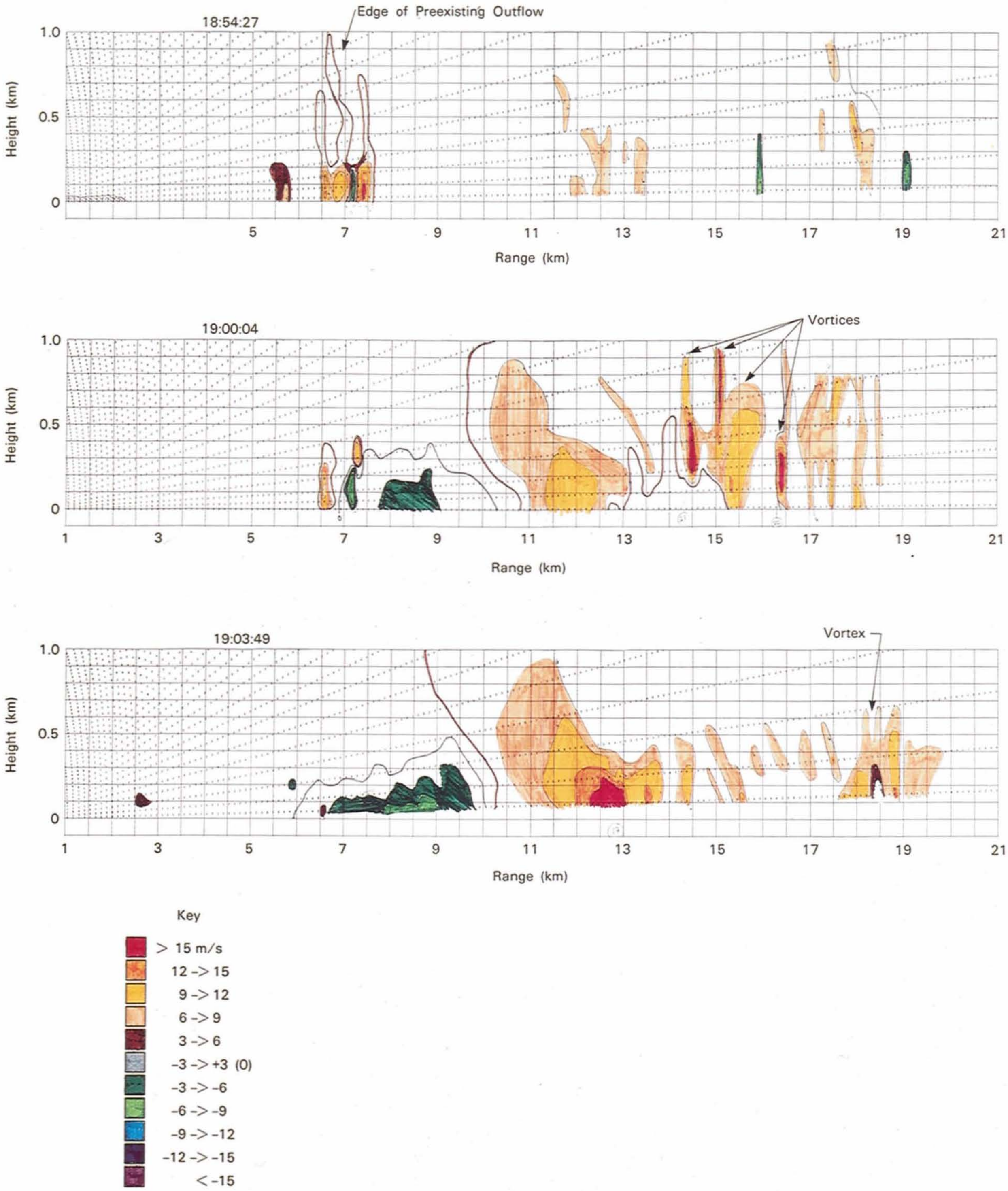


Fig. 7 — Time sequence of FL-2 RHI scans (at 241° azimuth) through a microburst storm in Huntsville, Alabama on 21 September 1986.

Above: Radar reflectivity fields. The background grid is labelled in kilometers. The core of high reflectivity (light blue) drops in altitude from the first to the second panel; in the third panel, it has dropped still farther (the microburst outflow is strongest here). The upper level reflectivity has also decreased markedly in the third panel.

Right: Doppler velocity fields, contoured at 3 m/s intervals, in the lowest 1 km. The background grid spaces are 0.1 km in the vertical by 0.5 km in the horizontal. Negative velocities represent flow towards the radar and positive velocities, away. The outflow is stronger away from the radar than toward it because the microburst fell into a preexisting outflow that was moving away from the radar. In the second panel, vortices are set up in advance of, and at the leading edge of, the outflow. In the third panel, the outflow has become thinner (200 m deep), broader, and has increased in speed; the highest speed winds were at the lowest sampled altitude. The transient vortices have dissipated, leaving the microburst outflow and one vortex at the leading (outbound) edge of the outflow pool.



Edge of Preexisting Outflow
18:54:27
1.0
0.5
0
Height (km)
5
7
9
11
13
15
17
19
21
Range (km)
19:00:04
Vortices
1
3
Range (km)
19:03:49
Vortex
Range (km)
Key
> 15 m/s
12 -> 15
9 -> 12
6 -> 9
3 -> 6
-3 -> +3 (0)
-3 -> -6
-6 -> -9
-9 -> -12
-12 -> -15
< -15

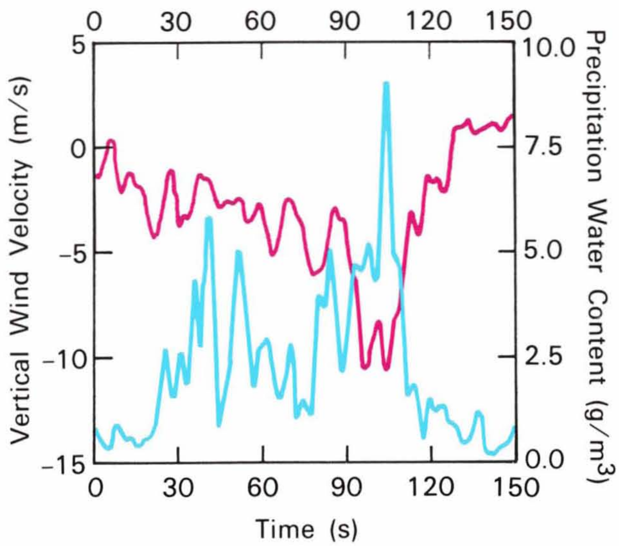


Fig. 8 — Aircraft-measured vertical velocity of the air (red) and precipitation water content (blue) are plotted for one pass through a microburst storm on 10 August 1985 in Memphis, Tennessee. Aircraft altitude was 0.66 km. (Redrawn from Ref 45.)

fashion similar to that of a fluid jet striking a flat plate").

Figure 2 shows an air mass thunderstorm that is just reaching the mature stage — rain is beginning to fall from the base. Figure 3 schematically illustrates this stage, as well as an earlier stage in the development of such a cell. Air mass thunderstorms usually form in the afternoon, in calm, hot, humid air masses; there is little or no vertical shear of the horizontal wind. These thunderstorms can occur in most parts of the country during the "heat waves" of the summer months.

Air mass storms, which form as randomly scattered thundershowers, are distinct from "squall lines" or "frontal" thunderstorms (discussed later), which appear in organized linear patterns (Fig. 4). Considering the number of fatalities that have occurred in accidents related to microburst wind shear, air mass storms are the most hazardous form of low-altitude wind shear. Therefore, the primary research question is how to distinguish, *in advance*, air mass thunderstorms that will produce violent outflows from those that will produce outflows of ordinary strength.

The Air Force Geophysics Laboratory in Sudbury, Massachusetts, collected Doppler radar data of a windstorm in which a "brief phenomenon" associated with heavy rain caused straight-line wind damage "confined to a region less than 1.5 square miles in area" [37]. Radar operators failed to recognize the damage potential since no characteristic severe storm radar signature was present, such as the famous "hook" echo (created as raindrops are drawn into a tornadic thunderstorm circulation). A subsequent examination of the data showed a disorganized multicell air mass storm with one large, tall cell and a weak echo region at the surface in the area of highest winds.

An analysis of a dual microburst event that occurred in the Florida Area Cumulus Experiment (FACE) weather station network revealed that the cell that produced the microbursts was, again, one of the tallest within a disorganized multicell storm complex [38]; it was forced more vigorously at the surface in the convergence zone of two colliding outflow boundaries. The "spearhead" shape of the radar echo was attributed to rapid growth of new cells on the advancing edge of a storm. (The microburst that caused the crash of Eastern 66 at J.F. Kennedy Airport in 1975 also came from a spearhead-shaped echo.) The microbursts, lasting less than 5 min, were associated with heavy rain and embedded in a storm-scale downdraft that continued for over 30 min. Careful analysis of the synoptic-scale (a horizontal size of roughly 500 to 2,500 km) situation revealed conditions favorable for thunderstorm development, as well as very dry air at midlevels in the atmosphere.

Although these storms had 30 m/s surface outflow speeds, a downdraft speed estimation technique [40] predicted gusts of less than 19 m/s. Additional sources of negative buoyancy were proposed [39]: the melting of large quantities of ice; efficient entrainment of dry midlevel air into the downdraft without mixing with updraft air; and precipitation loading, although the observed precipitation rates were too low to account for the discrepancy.

None of these factors completely explained the large difference between probable downdraft speeds and observed outflow speeds.

Through analysis of a microburst that caused damage at Andrews Air Force Base, through visual and multiple Doppler observations of JAWS microbursts, and through laboratory simulations with cold descending air currents, Fujita showed that a well-defined rotor existed at the leading edge of microburst outflows, which could explain the measured wind speeds [41].

The sequence of photographs in Fig. 2 shows the development of a horizontal vortex at the outflow edge. Fujita hypothesized that, through vortex-tube stretching and the resultant "spin-up" at the leading edge of an expanding outflow, a weak or moderate downdraft could produce strong surface winds, which would appear in small patches along the outflow boundary as the vortex tube separated (Fig. 5). He suggested that embedded vortices in an outflow pose an additional wind shear threat to aviation, and that the microburst-related crash of Delta 191 at Dallas/Ft. Worth may have been caused by the downward motion on the backside of one of these vortices [29].

The conditions that encourage the development of high-speed horizontal vortex rolls and how often these conditions occur are unknown. In an air mass thunderstorm microburst observed during the FLOWS Project with the FL-2 radar (Huntsville, Alabama, 21 September 1986), horizontal vortices were excited in a preexisting outflow pool when fresh outflow from a newly forming microburst impacted the surface.

Figure 6 shows a plan-position indicator (PPI) Doppler-radar scan taken during the maximum outflow of the Huntsville event. In a PPI radar scan, the antenna elevation angle is fixed and the azimuth angle is varied. Figure 7 shows a time sequence of range-height indicator (RHI) scans through this event. In an RHI scan, the antenna azimuth angle is fixed and the elevation angle is varied.

The time of the last RHI in Fig. 7 corresponds as closely as possible to that of the PPI shown in Fig. 6. The small vortices that developed when the microburst formed dissipated rapidly, leaving the largest, fastest wave traveling outward at the head of the outflow current. The presence of a well-developed leading outflow wave was the rule, rather than the exception, for microbursts observed in Memphis and Huntsville.

A key radar-detectable precursor of a microburst outflow is a descending reflectivity core in a collapsing thunderstorm cell [42,43]. This effect can be seen in the sequence of RHIs shown in Fig. 7. The descending reflectivity core, together with the very high rainfall rates and radar reflectivity levels observed in these storms, suggests that precipitation loading plays a central role in forcing the intense downward vertical acceleration.

Analyses of surface weather station data [44] collected during the FLOWS project in Memphis show a significant correlation between surface rainfall rate, which was extremely heavy at times, and the strength of the peak

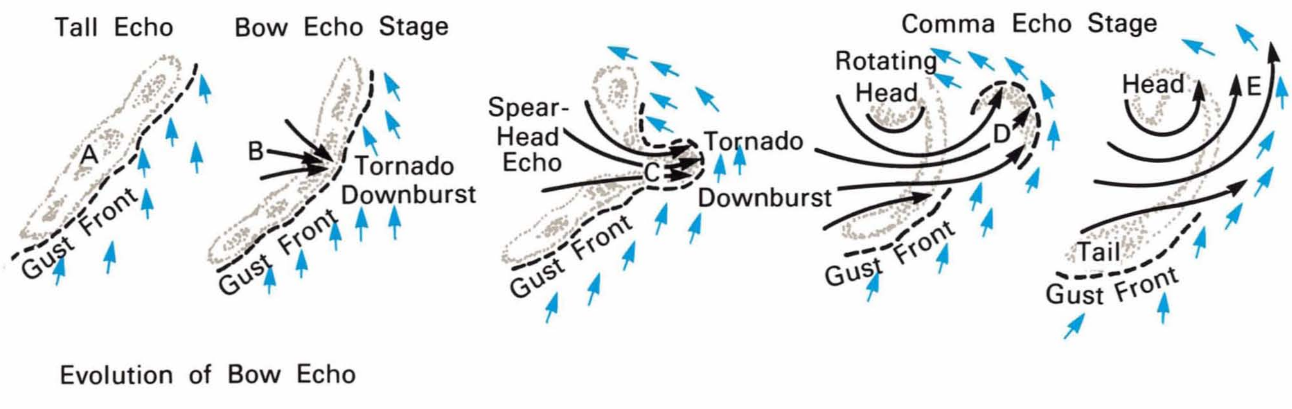


Fig. 9 — Evolution of bow echo proposed by Fujita. In this model a downburst thunderstorm produces a bow echo as the downflow cascades to the ground. The horizontal flow of a weakening downburst induces a mesoscale circulation, which distorts the initial line echo into a comma-shaped echo with a rotating head. (Redrawn from Ref 53.)

Fig. 10 — A large thunderstorm, which is producing an outflow. The base of the cloud shows some structure that indicates storm rotation, such as occurs before a tornado forms. (Copyrighted photo by A. & J. Verkaik.)

microburst outflow winds. In nearly every case, however, the outflow current was significantly colder than the surface air that it was displacing. The cold temperature of the outflow current indicates that evaporation, and to some degree melting, must contribute to the negative buoyancy and the resulting outflow speeds. The analyses show that the peak microburst outflow speeds are also correlated with the temperature deficit of the outflow.

The role of precipitation loading in forcing a microburst was investigated during a Memphis storm. In this experiment, an airplane measured cloud liquid water content and vertical velocity. In every pass through the storm "the strong downdrafts were found in close association with the areas of heavy precipitation loading" [45], but the correlation between vertical velocity and liquid water content was by no means perfect (Fig. 8). At the flight altitude within the storm (660 m agl), the negative buoyancy contribution from a mean liquid water content of 6 g/m^3 was slightly less than the contribution from the observed temperature deficit of 2.3°C (42% due to water loading and 58% to temperature deficit).

Even if dry air is entrained into the precipitation core at high levels, little evaporative cooling can occur because the air is too cold. In fact, the temperature deviation in the downdraft may actually be positive above the freezing level [46], because the cooling from the sublimation of hail is too small to compensate for the effects of compressional heating. As the core descends, the effects of evaporative cooling become much more important.

At upper levels in the region of liquid (frozen) water accumulation, precipitation loading is the dominant forcing mechanism that initiates the the collapse of the cell. However, cooling due to water phase changes during the descent of the core also plays a significant role in providing the forcing that produces the extraordinary outflow speeds of the few cells that produce microbursts. Examples have been published [47] of visually impressive, high-reflectivity (> 60 dBz) thunderstorm rainshafts that produced only weak outflows.

Significant evaporation can take place without altering the general appearance of a radar echo, which makes it difficult to use radar data to determine whether negative thermal buoyancy is forcing a downdraft. The smallest drops evaporate first and most efficiently, but they contribute relatively little to the reflectivity, which is proportional to the sixth power of the raindrop diameter. Also, because reflectivity measurements are displayed on a log scale, the reduction in liquid water content (*ie*, the reduction in downward forcing from precipitation loading) associated with a reduction in radar reflectivity of 55 to 50 dBz is almost six times as great as the reduction in liquid water content associated with the change from 40 to 35 dBz.

In summary, air mass thunderstorms with very strong collapsing phase downdrafts and subsequent outflows are microbursts. Conditions conducive to the development of air mass thunderstorms occur in most parts of the country during the summer months. But not every air mass thunderstorm cell produces an outflow that is strong enough to be a microburst.

In essentially every case, these storms are characterized by very heavy rainfall concentrated in an area of small horizontal extent and by large decreases in temperature at the surface. It is possible that the presence of dry air at midlevels in the atmosphere is required to permit enough evaporation to occur to sufficiently cool the downdraft and outflow air.

The convection that creates the microbursts is often initiated by convergence at the edge of older outflows, so microburst surface flow patterns are often embedded in larger storm outflows. Thus the microburst-inducing convection often appears in the form of multicell storms.

Storms with overshooting tops have greater energy levels than other storms. Furthermore, their cores contain more ice, which adds to the negative buoyancy as the downdrafts pass through the freezing melting level. Vortices at the leading edge and within the microburst outflow occur commonly and are associated with very strong surface winds.

Among the aircraft accidents attributed to microburst wind shear, the greatest number of fatalities have occurred during those in which heavy rain was present. In some cases, the rain was so heavy that it may have caused the aerodynamic performance of the aircraft to deteriorate, which would have compounded the problem caused by the wind shear [48-50].

An investigation of the microburst that caused the crash of Eastern 66 at J.F. Kennedy Airport showed that the wind shear spectrum contained high energy at the aircraft's resonant frequency [51]. By producing sudden os-

Fig. 11 — Damage pattern left in a pine forest after a tornado moved through the area. Tornado damage is shown by the swath of missing trees in the upper portion of the picture; a microburst knocked down the trees in the lower part of the picture. (Photo courtesy of T.T. Fujita, The University of Chicago.)

Fig. 12 — Virga descending from the base of benign-looking cumulus cloud. This virga shaft indicates a small-scale downdraft that could produce a microburst if it impacts the surface. (Copyrighted photo by A. & J. Verkaik.)

cillations in airspeed and height about the glideslope, this resonance may have seriously deteriorated the aircraft's performance, additionally compounding the problem caused by the wind shear.

Air mass thunderstorms produce the most dangerous type of microbursts. These storms combine a deadly set of factors: frequent occurrence; highly divergent outflows with embedded vortices; small, insignificant-looking cells that produce microbursts; and very heavy rain.

Bow Echoes and Downbursts

Another type of echo with which downbursts are associated was identified by Fujita [52] in 1978 as the "bow" echo. This type of storm takes the shape of a "spearhead echo" during its strong downburst stage and sometimes develops a "weak echo channel" at low levels in the area of strongest winds (Fig. 9). Tornadoes sometimes develop on the cyclonic-shear (counterclockwise flow) side of the area of high winds or in the "rotating head" [54]. Figure 10 shows a photograph of a downburst-producing cell.

The bow-shaped echo is generally part of a synoptic-scale squall line [55,56], a mesoscale (horizontal size of roughly 25 to 500 km) linear echo configuration or cluster [57-59], or a combination of supercell and weaker storms [60,61].

Satellite analyses have shown general cloud top warming before a downburst forms, indicating collapse of the cell [15]. A hole may appear at the edge of the echo at midlevels around 5 km [7]. In general, this reflectivity "notch" appears on the upwind (at midlevels) side of the storm system.

A downburst-producing bow echo storm that developed in southeastern Kansas was studied [59] with airborne Doppler radar data, taken near the weak echo region of the bow — just after damaging surface winds had occurred. Negative buoyancy created by melting and evaporation in the lowest 2 to 3 km of the storm caused strong downward acceleration in the large stratiform rain region behind the bow. A study of a similar storm [61] showed a strong inflow from the rear of the storm directly into the vertex of the "bow" at 5 km, apparently in response to this type of large-scale downdraft. The downdraft generated a strong low-level outflow, which reached damaging speeds when smaller-scale embedded downdrafts of only moderate intensity were superimposed.

Damage surveys [15,52,58] revealed that small microbursts and tornadoes, twisting downbursts, and other rotational and divergent wind patterns coincidentally occurred. This led to the hypothesis that the vertical pressure gradient set up by strong rotation at low levels can dynamically force a small-scale downdraft or microburst [56].

Figure 11 shows the damage caused to a forest of pine trees when a tornado moved through the area. Notice the small burst pattern of flattened trees close to, but distinct from, the tornado damage path (where the trees are actually missing). This pattern was caused by a small-scale downdraft, which is thought to be essentially the same as the "occlusion" downdraft found in a high-resolution numerical model of the tornadic region in a supercell storm [62].

Organized downburst storms occur throughout the continental United States at times of the year when synoptic-scale instabilities and frontal storms dominate the weather patterns. In the central part of the country, these storms typically occur in the spring and fall; farther north, they appear in the early and late summer.

In summary, bow echo storms develop in environments characterized by moderate vertical shear of the horizontal wind, instability or conditional instability, and abundant moisture. In the cases analyzed, a layer of dry air was found at midlevels. A bow echo storm is generally part of a larger mesoscale or synoptic-scale

Fig. 13 — A ring of dust generated by the outburst winds of a microburst 27 km east of Stapleton International Airport on 14 July 1982. (Reproduced from Ref 25.)

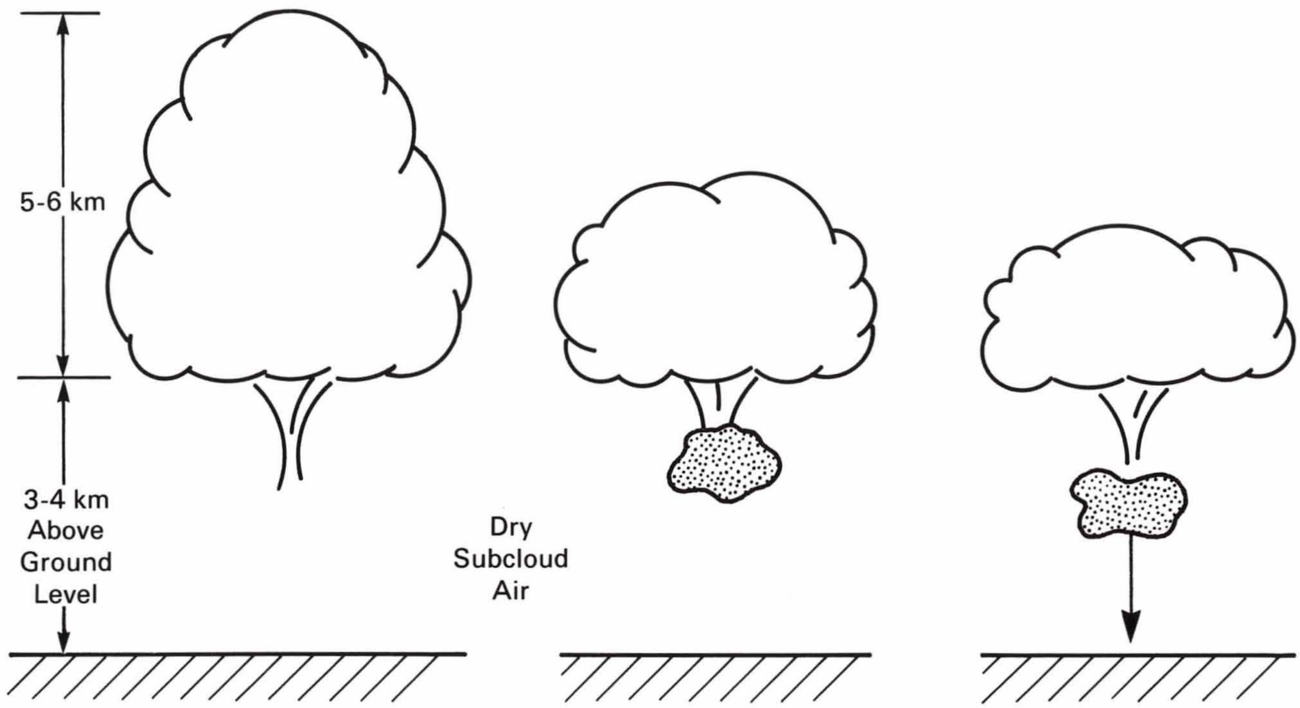


Fig. 14 — Various stages in the development of a microburst from a shallow, high-based cumulus cloud. Little or no rain is reaching the ground. This type of parent cloud and the microbursts it produces are common in the Denver area during the summer.

storm complex or frontal line storm, has high radar reflectivity levels (at least 50 dBz), produces downbursts that are quite large (typically 20 km or more across), and often contains embedded microbursts and tornadoes.

The large-scale downdraft is driven by the cooling due to evaporation and melting as dry environmental air enters a storm. This process leads to the formation of the weak echo regions behind the bow. The downward flux of horizontal momentum from midlevels is also important in accounting for high surface wind speeds in some cases. Smaller embedded microbursts can be produced in a variety of ways.

In general, these storms are long-lived and have fairly predictable paths. Moreover, their appearance is sufficiently threatening that aircraft rarely, if ever, try to fly through them. Thus even though these storms are hazardous to aviation, the hazardous regions are predictable and avoidable with currently available meteorological information.

Shallow, High-based Cumulonimbus Clouds

A great deal of attention has been given to microbursts that originate from benign-looking, high-based (3 to 4 km agl), shallow (2 to 3 km deep) cumulus congestus or stratocumulus clouds. One of these clouds is shown in Fig. 12.

These clouds often have glaciated tops and lack the rapidly rising convective towers, thunder, and lightning of typical lower-based cumulonimbus clouds [63], although some small convective turrets occasionally appear [64].

Virga (wisps of precipitation that evaporate before reaching the ground) is commonly visible below cloud base but little or no rain reaches the ground [65]. Therefore, these microbursts are called "dry" or "virga" microbursts.

Figure 13 shows a ring of dust "kicked up" by a microburst outflow with no visible rainshaft feeding it. A schematic illustration of this type of dry microburst-producing cloud is given in Fig. 14.

A 1952 paper briefly mentioned the "dry thunderstorm over the plateau area of the United States" [66]. This type of storm was characterized in a 1954 paper with, in retrospect, amazing accuracy [67]. The dry microburst was also documented [68], where it was noted that the storm's damaging outflow qualified as a downburst. The 1982 paper correctly predicted (as the JAWS investigators quickly confirmed) that this type of storm is much more common than was generally recognized at the time.

The characteristics of the environment in which this type of microburst forms have been successfully described. Studies [63,69] show that a deep, dry subcloud layer (dew point depression greater than 30°C) with a nearly dry adiabatic (neutrally stable) lapse rate is common. A moist layer around the 500-mbar level (5.6 km msl [mean sea level]) nearly always occurs. Winds typically have a strong westerly component and increase with height.

A simple rule was discovered that predicted the days on which dry microbursts would occur [69]. On 26 of the 30 days that had dry microbursts, the dew point depression (the difference between the temperature and the dew point temperature) was greater than 8°C at 700 mbar (3.0 km msl) and less than 8°C at 500 mbar.

Radar and flow characteristics of this type of storm have been documented [16,25,70-73] and summarized [74]. These microbursts all formed between 1300 and 1900 MDT (mountain daylight time) with 75% occurring between 1400 and 1700 MDT. Reflectivity values were always less that 30 dBz at 500 m agl, in stark contrast to the high reflectivity values (50 to 60 dBz) found at the surface in air mass thunderstorm microbursts.

An example of FL-2 radar data collected during one of these dry microbursts is shown in Fig. 15. The maximum reflectivity in the cell is only 20 dBz, yet the differential velocity in the outflow (20 m/s over 3 km) is quite strong. The evolution of the surface-flow field typical of nearly all microbursts observed during JAWS is schematically illustrated in Fig. 16.

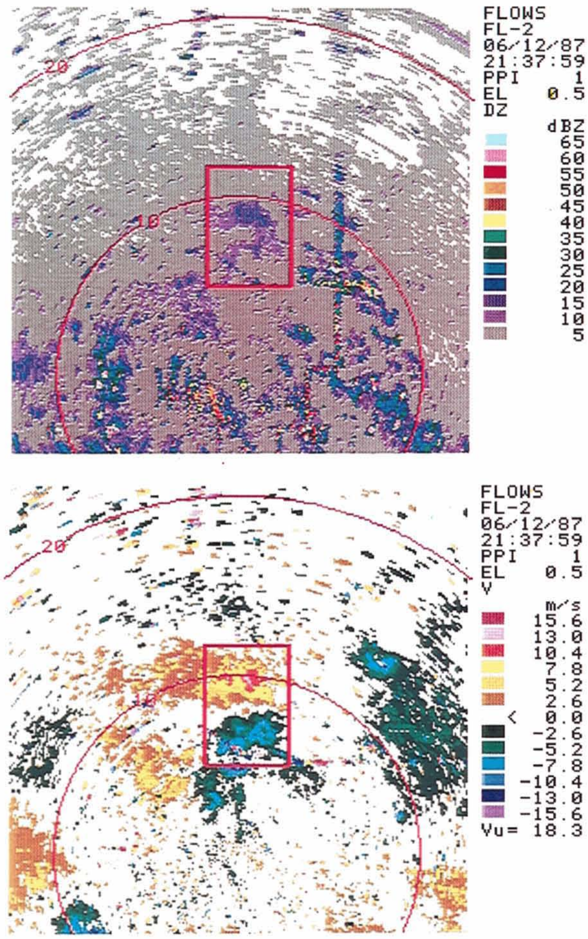


Fig. 15 — Reflectivity and Doppler velocity PPI data of a "dry" microburst collected with the FL-2 radar in Denver, Colorado on 12 June 1987 at 21:37:59 GMT. The high reflectivity regions associated with regions of 0 m/s Doppler velocity are ground-clutter targets that remained in the data after filtering. The microburst, enclosed by the red rectangle, has a maximum reflectivity of 20 dBz. The Doppler velocity field shows flow of roughly 10 m/s toward the radar, and 10 m/s away from the radar, giving a differential velocity of 20 m/s over a distance of about 3 km in the microburst.

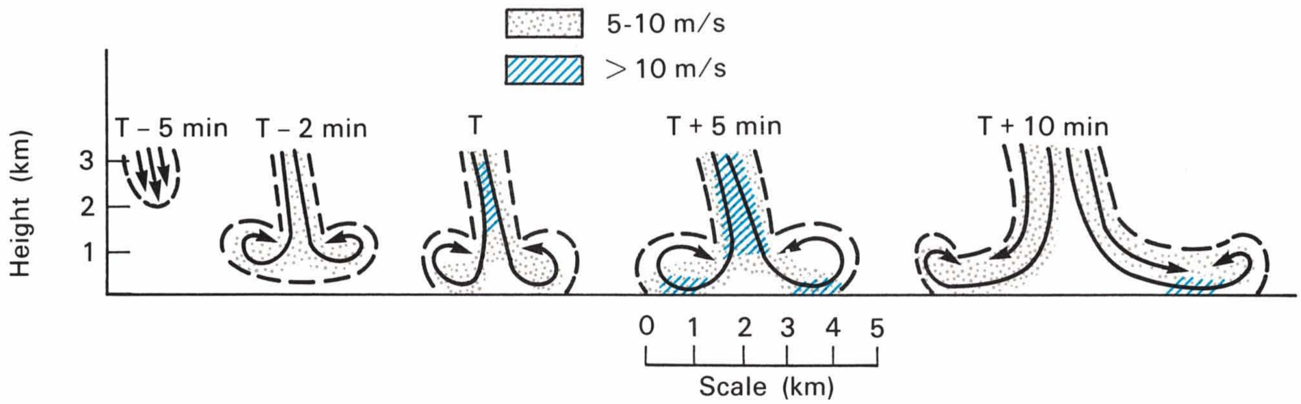


Fig. 16 — Vertical cross section of the evolution of a microburst wind field, based on Denver area data. T is the time of initial divergence at the surface. The shading refers to the vector wind speeds. (Taken from Ref 16.)

Observations based on all microbursts in JAWS (approximately half were associated with virga or light rain) show that there is no correlation between radar reflectivity or surface rainfall rate and the subsequent strength of the outflow [75]. Rainfall rates never exceeded 3 in/h, and on only 6 days was the rainfall rate associated with microbursts above 1 in/h. The strong surface outflow winds typically lasted from 2 to 5 min, with speeds between 10 m/s and 20 m/s. The surface temperature was just as likely to rise as to fall [25], and by as much as 3°C.

It has been hypothesized that the combination of the deep, dry, neutrally stable subcloud layer, which permits cold air near cloud base to continue to accelerate all the way to the surface, and the weak updrafts, which produce small precipitation particles that evaporate and melt efficiently, allows the very strong downdrafts to form [68]. Simple one-dimensional [36] and two-dimensional [76] numerical models have confirmed this hypothesis.

The two-dimensional (axisymmetric) model results revealed that the vertical velocity decreases appreciably as the width of the rainshaft increases (which is to be expected since the hydrostatic pressure balance in the atmosphere inhibits broad-scale vertical motion), but that the resulting surface outflow speeds increase only slightly. This result is applicable to any isolated downdraft; the cylindrical geometry and mass continuity alone determine that the ratio of the outflow speed to the downflow speed is linearly proportional to the initial radius of the rainwater region.

This same model was used to study the role of ice-phase microphysics in determining the downdraft and outflow strength of dry microbursts [77]. Experiments were performed in which the precipitation dropped at the top of the model consisted of either rain, graupel (granular snow pellets or soft, spongy hail), or snow at each of three cloud base precipitation rates.

Greater amounts of precipitation were found to be linked to stronger downdrafts and surface outflows. These variations were much larger than those attributable to the different forms of precipitation with the same water content. However, for a given precipitation rate, rain generally produced the strongest downdraft and graupel produced the coldest, strongest surface outflow.

To compensate for the descending air in a microburst, convergence must develop at or above the downdraft initiation level. The downward motion and convergence increase the vertical vorticity in the same region. A schematic model of this overall microburst flow pattern is shown in Fig. 17.

Significant convergence, including sinking of the visible cloud into the downdraft region has been observed, as has increased rotation coincident with the downdraft and reflectivity core. These upper-level velocity features, detectable with Doppler radars, can give an early indication of microburst formation and can increase confidence in a surface microburst detection.

In summary, all observations and simulations indicate that downward acceleration from negative buoyancy, generated as precipitation falls from cloud base and evaporates (or melts), leads to the observed downdraft speeds in the microbursts originating from shallow, high-based cumulonimbus clouds. The conditions suitable for the formation of this type of microburst have mainly been observed in the high plains east of the Rocky Mountains during the summer months. However, they can certainly occur elsewhere.

The downdrafts are probably initiated by precipitation loading within the elevated clouds. Model results show that the narrowest downdrafts (excepting downdrafts less than 1 km in horizontal scale) produce the most divergent and thus the most hazardous outflows. Not only are the vertical velocities strongest, but the outflow winds are nearly as strong as those from larger storms, even though the horizontal scale is smaller.

The actual hazard to aviation of this type of microburst has been assessed through observations of air traffic response at Stapleton International Airport in Denver [78,79]. Aircraft do fly through microbursts at Stapleton, and pilot reports of encountered wind shear are used to warn subsequent flights. Because these microbursts occur only in the afternoon (daylight hours), and because they are often marked by virga below cloud base, pilots can sometimes avoid flying through them.

Microburst Lines

During the JAWS project, it was found that two or more microbursts could occur simultaneously, forming a line [80]. This led to the definition of the "microburst line" [81] as consisting of two or more microbursts, being at least twice as long as wide (between velocity maxima on either side of the line), and having a velocity differential in the cross-line direction meeting microburst criteria. A microburst line may be nearly homogeneous along its length or may be made up of distinct, discrete microbursts. The basic microburst line structure is shown in Fig. 18.

Microburst lines originate from high-based shallow cloud lines. These cloud lines are often initiated by the surface convergence lines that develop daily over the Rocky Mountains [82]. It has also been suggested that the cloud lines may form in response to eddy flow patterns forced by the mountains, similar to Von Karman vortex streets, that are set up parallel to the prevailing winds [25,83]. (Von Karman vortex streets are long staggered rows of vortices, where each vortex of one row has equal but opposite circulation to each vortex of the other row, created in the wake of a long cylinder as fluid flows past.) The lines generally have embedded centers of divergence at the surface, coincident with local maxima in the radar reflectivity field. A single microburst may have a lifetime of about 15 min, but a microburst line typically lasts for about an hour.

Microburst lines have a severe impact on airport operations primarily because they are long-lived and propagate slowly (mean speed 1.3 m/s). However, this also implies that they can be more easily predicted. Through the use of a three-dimensional numerical flow simulation [84], it has been shown that merging microburst outflows, such as would be present in a microburst line, may pose an even greater

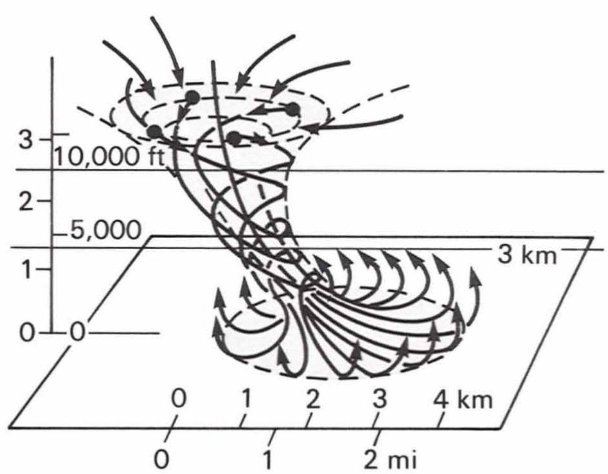


Fig. 17 — Overall microburst flow pattern in Denver. (Redrawn from Ref 70.)

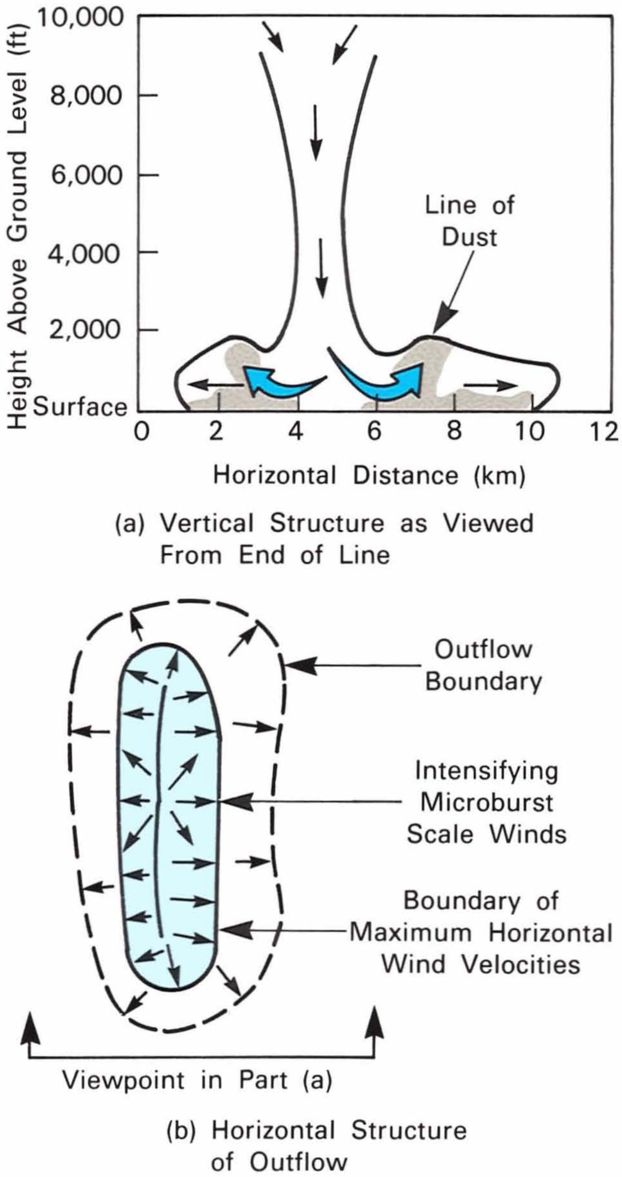


Fig. 18 — Basic microburst line structure. (Redrawn from Ref 79.)

danger to aviation than solitary outflows for two reasons: the effective divergent outflow depth increases and thus so does the total amount of hazardous airspace; and the increased horizontal pressure gradients can lead to even stronger, more divergent outflows.

In summary, the strength of a microburst line outflow and the corresponding hazard to aviation vary tremendously. Although microbursts have been observed to form in groups or "families" in other parts of the country [52], the identification of the microburst line as a new storm type arose from observations of weather phenomena near the Rocky Mountains, suggesting orographic influences in the organization of this storm type. The primary concern for aviation appears to be the severe impact that a slow-moving large-scale storm with embedded divergent outflows has on airport operations.

SUMMARY

Several distinct phenomena can cause strong surface outflows that qualify as microbursts. At the largest scales, organized downburst storms occur in association with mesoscale or synoptic-scale linear radar echo configurations, in environments characterized by moderate vertical wind shear and strong thunderstorm potential. The strength of the observed outflow is determined by the strength of the vertical velocity and the downward flux of horizontal momentum, and may be influenced by the nearly two-dimensional, linear storm geometry. Because the storms are large-scale, long-lived, infrequent, and severe, aircraft are generally able to avoid them.

When there is little vertical shear of the horizontal wind, but similar conditional instability, isolated air mass thunderstorms form. In hot and humid conditions, the strength of the outflow from these storms is determined by evaporative cooling both in cloud and below cloud base, as well as by precipitation loading, especially at upper levels. As the outflow pool expands rapidly, strong straight-line winds form in association with the leading edge vortex roll. For a number of reasons, these microburst-producing air mass storms pose the greatest hazard to aviation: relatively high frequency; rapid development; small-scale, very strong outflows; and lack of translational motion. Moreover, storms that are identical in appearance, at least visually and on conventional aircraft radar, are successfully flown through on a regular basis.

Between the isolated thunderstorm and the large, organized storm are the other forms of loosely organized multicell storms. These storms, with closely spaced echoes that merge to form a "spearhead" appearance on low-resolution radar scopes, may be similar to the microburst lines found near Denver; however, they form without any orographic organization. Strong forcing of updrafts can occur as the outflow from a nearby decaying cell triggers the enhanced growth of new cells. Cells that form later in the "chain" appear to grow faster and taller, perhaps because more humid air is entrained into their updrafts. The downdrafts and outflows are correspondingly stronger, increasing the forcing for the next cell, and so on. To the extent that these multicell storms are larger and longer-lived than isolated storms, they are easier for air traffic to avoid. But because of their explosive growth, they are unpredictable, so air space that was a safe distance away from such a storm complex one minute could be inundated with microburst wind shear the next minute.

The microbursts that arise from shallow, high-based cumulonimbus clouds can only occur in an environment with a deep, dry adiabatic mixed layer. Sufficient moisture must be available aloft to sustain a downdraft all the way to the surface, even in the face of strong evaporation. These microbursts occur as isolated cells, or in clusters of two or more as microburst lines. Suitable conditions for their development have mainly been observed in the high plains east of the Rocky Mountains during the summer. The surface reflectivity values of these microbursts are low, but the outflows are often just as strong as those arising from high-reflectivity air mass thunderstorms.

The development at Lincoln Laboratory of FL-2 — a sophisticated, highly capable Doppler weather radar — and the collection of data with that radar for the FLOWS project in Memphis, Huntsville, and Denver have dramatically increased our understanding of the characteristics of microbursts in the continental United States. Using this increased understanding of microbursts, the varied phenomena that have been called microbursts can now be divided into distinct categories.

This review has presented a first attempt at categorizing storms along lines that are meteorologically meaningful and that consider their relative hazard to aviation. This categorization is an essential first step towards discovering exactly which atmospheric conditions and dynamic interactions lead to the development of microbursts — so meteorologists can predict their occurrence. The categorization of microbursts will also aid the development of automated algorithms for the TDWRs that utilize this knowledge to make accurate early detections and predictions of microbursts.

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