Reprinted from Preprint Volume 15th Conference on Severe Local Storms, Feb. 22-26, 1988, Baltimore, Md. Published by the American Meteorological Society, Boston, Mass.

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CHARACTERISTICS OF MICROBURSTS OBSERVED IN THE CONTINENTAL U.S.*

Marilyn M. Wolfson

Massachusetts Institute of Technology
Lincoln Laboratory
Lexington, MA 02173

1. INTRODUCTION

The topic of microbursts is explored in this paper through a historical perspective and review of the studies that have been performed since Fujita (1976) first introduced the concept. Taken as a whole, this body of work actually *defines* microbursts, and begins to take some of the initial steps toward their understanding. However, a number of dynamically distinct phenomena that give rise to strong surface outflows are being referred to as microbursts. The recent emphasis within the scientific and aviation communities on understanding microbursts makes it particularly important to categorize these various phenomena according to their meteorological nature and true aviation hazard potential. This paper takes some of the first steps toward this categorization, and emphasizes some of the differences in storms that can be expected in different climatological regimes.

2. HISTORICAL PERSPECTIVE

The word "downburst" was introduced by Fujita and Byers (1977) to describe the meteorological event which caused the crash of Eastern Flight 66 at JFK airport in New York on 24 June 1975, in which a thunderstorm downdraft became hazardous to the operation of jet aircraft (Fig. 1). If a downdraft has a speed of at least 12 ft/s at an altitude of 300 ft agl (comparable to that 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 on the aircraft (Fujita and Caracena, 1977)), then it qualifies as a downburst. Later the term "microburst" was created to distinguish small downbursts (0.8 – 4.0 km) from larger ones (Fujita, 1978, 1979).

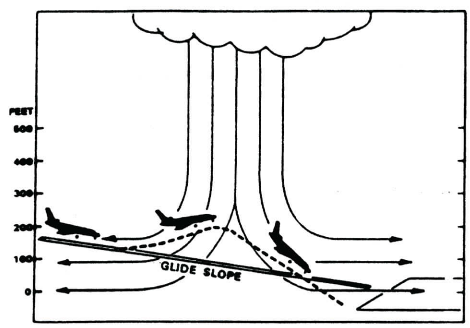

Fig. 1 Schematic drawing of an aircraft encounter with a microburst. Notice that the increased headwind lifts the plane above its intended glideslope while the increased tailwind causes the plane to fall below its intended glideslope.

The introduction to the meteorological community of the concept of the downburst met with some controversy and resistance. As Fujita (1985) notes, most meteorologists believed "that a downdraft, no matter how strong it may be inside or beneath the cloud, should weaken to an insignificant speed long before reaching the surface." Many scientists also wondered what the difference was, if any, between the downburst and the well known thunderstorm downdraft. Fujita (1979) thought they were essentially the same but, following the clear precedent in meteorology for establishing new terminology for extreme meteorological phenomena that are known to be dangerous, chose a term more forceful than even the "downrush" introduced by Fawbush and Miller (1954), and defined it according to its potential hazard to aircraft. Confusion still exists over what exactly the term describes; it will be made clear through the review of observational studies in the next section that several possibly dynamically distinct phenomena can qualify.

Despite rejection of the "downburst", there was great concern in the meteorological community and especially at the National Severe Storms Laboratory (NSSL) with preventing aircraft accidents such as the one mentioned above at JFK airport. However, it appeared to some scientists that the very wind shear related aircraft accidents attributed by Fujita to downbursts were actually caused by aircraft penetration of larger scale gustfronts. Part of this argument was based on detailed dual and triple-Doppler radar analyses of tornadic storms in Oklahoma in which no small scale downdrafts were found (Brandes, 1977; Ray, 1978). The evidence available to these researchers suggested that "straight-line" downburst winds might well be those experienced along the leading edge of advancing gust fronts. An anemometer-based wind shear detection system was designed and installed at airports (the Low Level Wind Shear Alert System (LLWAS); Goff, 1980) based on NSSL recommendations. Fujita (1980, 1981a) went to great lengths in his early papers to explain the differences between downbursts and gustfronts, especially with regard to the wind shear hazard they posed for aviation. A general skepticism that nothing new was being documented remained.

However, Fujita remained convinced that unusually strong, small scale downdrafts not only existed but posed a very real threat to aviation. He obtained scientific support and facilities, including Doppler radars, instrumented aircraft, and mesonet stations, for project NIMROD (Northern Illinois Meteorological Research on Downbursts; with Srivastava) near Chicago in 1978 (Fujita, 1979), project JAWS (Joint Airport Weather Studies; with McCarthy and Wilson) near Denver in 1982 (McCarthy *et al.*, 1982), and most recently, project MIST (Microbursts and Severe Thunderstorms; with Wakimoto) near Huntsville in 1986 (Dodge *et al.*, 1986).

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" (Fujita and Wakimoto, 1981) where "damaging winds" referred to winds of at least 18 m/s; microbursts were simply wind events of this magnitude on a smaller scale. During JAWS, many more microbursts were found and the emphasis was accordingly shifted. 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" (Wilson *et al.*, 1984)**. This definition now encompasses weaker but still highly divergent meteorological phenomena.

A major impetus was added to the meteorological investigation of microbursts when, after the crash of Pan American World Airways Flight 759 in July 1982 shortly after take-off at New Orleans International Airport in which all 149 persons on board and 8 persons on the ground died (Fujita, 1983; Caracena *et al.*, 1983a), 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 Federal Aviation Administration (FAA). The final report of that committee (National Research Council, 1983) states that "Some wind shears have been understood by meteorologists for a number of years. These include those found in gust fronts, warm and cold airmass fronts, [*etc.*]..." and that "most [of these] are predictable, sometimes hours in advance." They go on to note that "Scientists have recently begun to recognize the importance of storm downdrafts that are unusually small in horizontal cross sections and that are of short duration. Such downdrafts have been called microbursts." The meteorological community finally seemed convinced of both the hazard of low-altitude wind shear to aviation and the existence of microbursts (Kessler, 1985).

The National Academy of Sciences Committee made several recommendations, one of which 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

*The work described here was sponsored by the Federal Aviation Administration. The United States Government assumes no liability for its content or use therof.

**The significance of the 4 km scale apparently originates from the planetary scale defined by Fujita (1981b). The earth's circumference is 40,000 km and scale divisions are made in steps of two orders of magnitude each, at 400 km, 4 km, and 0.04 km.

automation and to provide information on low-altitude wind shear, turbulence, and rainfall intensity."

The MIT Lincoln Laboratory, under contract to the FAA, began in 1982 the development of an FAA pulse Doppler weather radar testbed to be used for the detection of hazardous aviation weather in enroute and terminal airspace (Evans and Johnson, 1984; Laird and Evans, 1982). The FAA supported the development of the Lincoln testbed (and the meteorological research on low-altitude wind shear in the JAWS project) under its newly commenced Terminal Doppler Weather Radar Program. The transportable radar (called FL-2) was moved to Memphis, TN in mid-1984 and operated during 1985 as part of the multi-year FLOWS (FAA-Lincoln Laboratory Operational Weather Studies) Project. The radar was moved again to Huntsville, AL in 1986 where the FLOWS Project joined with the MIST project in the Cooperative Huntsville Meteorological Experiment (COHMEX). Microbursts were indeed found and datasets with scanning strategies suitable for use in an automatic microburst detection system were collected. Most microbursts in Memphis and Huntsville were caused by the collapsing phase downdrafts of isolated, air-mass thunderstorms, and were accompanied by very heavy rain. These storms appear to be very similar to those that have caused a large number of aircraft accidents (see *e.g.*, Fujita, 1985).

Since the National Academy of Sciences Committee made its recommendations, another aircraft accident occurred that has been attributed to microburst wind shear. This was the crash of Delta 191 at Dallas/Ft.Worth in August 1985 (Fujita, 1986; Caracena *et al.*, 1986). Efforts are now underway within the scientific and engineering communities to refine techniques for automated aviation-hazardous weather detection with the Terminal Doppler Weather Radars (Evans and Turnbull, 1985; Zorpette, 1986). The FL-2 radar has been moved to Denver where, during the 1987 microburst season, many excellent datasets with 1-min. surface update rates and coverage of upper level storm sturcture were gathered. Lincoln Laboratory, NSSL, and NCAR will be demonstrating the feasibility of providing real-time low-altitude wind shear information to air traffic controllers at Denver's Stapleton airport in the summer of 1988. The microburst detections will be generated by automated algorithms developed at MIT Lincoln Laboratory that operate on the FL-2 Doppler weather radar data (Merritt, 1987; Campbell, 1988).

3. OBSERVATIONAL STUDIES OF MICROBURSTS

In this section, a number of studies pertaining to microbursts (those performed before 1987) are reviewed and summarized. The review is divided into categories primarily to differentiate between essentially different phenomena that give rise to microbursts; however, it is shown that some categories are not distinct.

3.1 Spearhead echoes

The parent storm responsible for the outflow in which the Eastern airlines flight crashed at JFK in 1975 was determined to be a type of isolated multicell storm, roughly 35 km long, which occurred on a day with numerous scattered cells of various sizes. The echo took on a "spearhead" shape in the low resolution radar PPI films (Fig. 2).

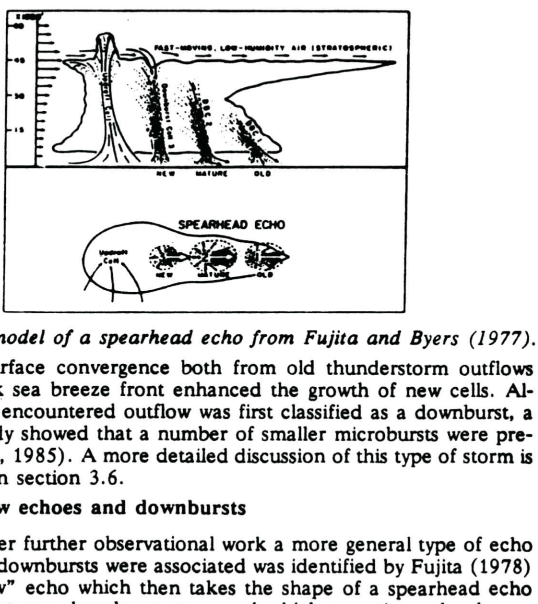

Fig. 2. A model of a spearhead echo from Fujita and Byers (1977).

Unusual surface convergence both from old thunderstorm outflows and a weak sea breeze front enhanced the growth of new cells. Although the encountered outflow was first classified as a downburst, a revised study showed that a number of smaller microbursts were present (Fujita, 1985). A more detailed discussion of this type of storm is presented in section 3.6.

3.2 Bow echoes and downbursts

After further observational work a more general type of echo with which downbursts were associated was identified by Fujita (1978) as the "bow" echo which then takes the shape of a spearhead echo during the strong downburst stage and which sometimes develops a "weak echo channel" at low levels in the area of strongest winds (Fig. 3). Tornadoes sometimes develop on the cyclonic shear side of the area of high winds or in the rotating head (Smith and Partacz, 1985). The maximum echo top becomes displaced ahead of the strong reflectivity gradient along the leading edge of the bow at low levels (Przybylinski and Gery, 1983). Satellite analyses have shown general cloud top warming in advance of the downburst formation, indicating collapse of the cells (*e.g.*, Fujita and Wakimoto, 1981). Fujita (1979) also notes that a hole may appear at the edge of the echo at high levels (5 km); in general this reflectivity notch is observed on the upshear side of the storm system, *i.e.*, the side upon which the environmental winds are impinging at upper levels.

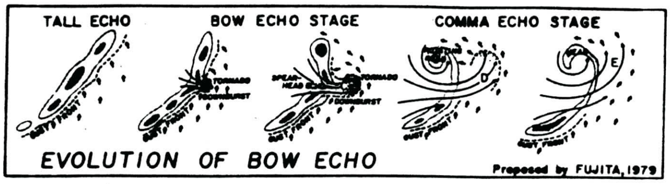

Fig. 3. Evolution of bow echo proposed by Fujita (1981b). In this model a bow echo is produced by a downburst thunderstorm as the downflow cascades down to the ground. Finally the horizontal flow of a weakening downburst induces a mesoscale circulation which distorts the initial line echo into a comma-shaped echo with a rotating head.

The bow shaped echo is generally part of a synoptic scale squall line (Wolfson, 1983; DiStefano, 1983), part of a mesoscale linear echo configuration or cluster (Fujita and Wakimoto, 1981; Forbes and Wakimoto, 1983; Knupp and Jorgensen, 1985; Cooley, 1986), or a combination of supercell and weaker storms (Caracena, 1978; Schmidt and Cotton, 1985). Similar storm reflectivity patterns have been called "line echo wave patterns" or LEWPs by Nolen (1959) and Hamilton (1970). A resurrected term "derecho*" (Hinrichs, 1888) has been used by those with operational experience to describe some four different types of severe weather producing mesoscale convective systems exhibiting bow echo characteristics (Johns and Hirt, 1983; Przybylinski and DeCaire, 1985); these storms all have either one large or numerous smaller channels of weak echo behind the main cells. Eilts and Doviak (1987) note that Oklahoma downbursts often have asymmetric surface wind shear patterns which make their strength difficult to estimate with single Doppler radars.

Knupp and Jorgensen (1985) studied a downburst-producing bow echo storm that developed in southeastern Kansas in an environment characterized by "moderately low" wind shear, abundant moisture up to 850 mb, and a nearly dry adiabatic lapse rate up to 600 mb. The authors analyzed P-3 aircraft data, including airborne Doppler radar data taken near the weak echo region of the bow just after damaging surface winds had occurred. They concluded that negative buoyancy created by melting and evaporation in the lowest 2-3 km of the storm caused pressure reductions of up to 1.6 mb over the large stratiform rain region behind the bow, as air parcels were accelerated downward. Schmidt and Cotton (1985) show, for a similar storm, 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. This large scale downdraft generated a strong low-level outflow which reached damaging speeds when convective scale downdrafts of only moderate intensity were superimposed.

A study of synoptic and mesoscale factors associated with downburst producing thunderstorms by Forbes *et al.* (1980) showed that a marked low-level (850 mb) jet was always present as was a jet streak at the 300 mb level, implying the possible importance of a coupling of the two and the possibility that the flux of momentum from these levels to the surface could at least partially account for the high speed outflow winds. They also found that stability indices were generally indicative of considerable thunderstorm potential, that the precipitable water content of the atmosphere was high, and that the 1000-500 mb mean relative humidity was typically moderate. The downbursts studied were often accompanied by tornadoes but it was not determined if the environmental conditions which tend to promote the two types of storms differ.

Damage surveys by, *e.g.*, Forbes and Wakimoto (1983), Fujita (1978), and Fujita and Wakimoto (1981) revealed that small microbursts and tornadoes, twisting downbursts, and other rotational and divergent wind patterns coincidently occurred. This led Wolfson (1983) to hypothesize that a small scale occlusion downdraft, dynamically induced by low pressure associated with the strong rotation at low levels, was forcing a smaller scale microburst within a larger scale thunderstorm outflow, and that *this* superposition caused the damaging surface winds. The small scale downdraft was thought to be essen-

*"Derecho" is Spanish for "straight" and is used to describe straight line winds just as "tornado" is used to describe rotational winds.

tially the same as the occlusion downdraft found by Klemp and Rotunno (1983) in a high resolution numerical model of the tornadic region in a supercell storm.

In summary, these organized downburst storms occur throughout the Continental US at times of the year when synoptic scale instabilities dominate the weather patterns (typically through the central part of the country during spring and fall; farther north during early and late summer). They 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 present at midlevels. These bow echo storms generally are part of a larger mesoscale or synoptic scale storm complex or frontal line storm, have high radar reflectivity levels (at least 50 dBZ), produce downbursts that are quite large (typically 20 km or more across), and often contain embedded microbursts and tornadoes. With some confidence it can be stated that the large scale downdraft is driven by the cooling due to evaporation and melting as dry environmental air enters the storm from behind in a region of stratiform rain with small, readily evaporated precipitation particles, and that 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 the high surface wind speeds in some cases. The smaller embedded microbursts may be produced in a variety of ways. In general, these storms are long lived with fairly predictable paths, and apparently threatening enough that aircraft rarely if ever try to fly through them. Thus while these storms are inherently very hazardous to aviation, the hazardous regions are predictable and avoidable using the currently available meteorological information.

3.3 Bow echoes and microbursts

Care must be taken when categorizing storms according to their radar echo appearance. Elmore (1986) discusses the evolution of a microburst associated with a bow-shaped, low reflectivity echo (34 dBZ maximum) that occurred near Denver, in which the reflectivity notch was observed to develop on the *downshear* side of the storm coincident with anticyclonic rotation. This storm, roughly 8 km in horizontal extent, was very different from those described in the previous section. Elmore notes that this storm was tilted significantly downwind (and downshear) throughout its lifetime, and suggests that the observed anticyclonic circulation might have been part of a von Karmann vortex pair in which the cyclonic half was somehow attenuated in the environment characterized by anticyclonic shear.

Knupp and Cotton (1985a), through analysis of a numerically simulated convective cloud (15 km diameter), have come up with a more convincing explanation. They show that weak, tilted updrafts allow precipitation to descend to lower levels where downdrafts are produced, and that the flow around the updraft at midlevels systematically transports precipitation to this downshear region (Fig. 4; see also

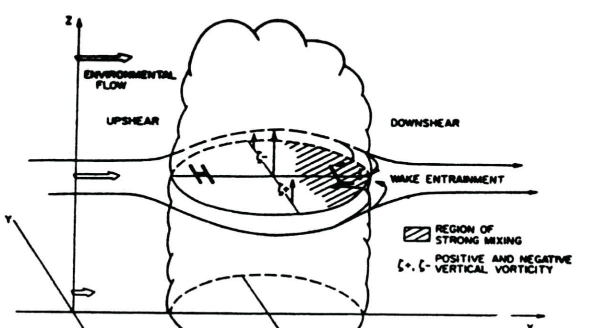

Fig.4. Schematic diagram illustrating wake entrainment within the downshear flank of a convective cloud. The symbols H *and* L *represent high- and low-pressure perturbations. These perturbations, along with the vertical vorticity patterns, are produced by cloud vertical motion interacting with environmental flow increasing with height in this case. From Knupp and Cotton (1985b).*

Heymsfield, *et al.*, 1978). They also note that the equivalent potential temperature values in the downshear region were quickly reduced as the downdraft matured, and that "this process provides a method by which surface precipitation may nearly coincide with developing downdrafts and low-valued equivalent potential temperature air...". Although no dramatic vorticity developed in the wake region of the model cloud, it is quite plausible that vertical stretching in a similarly created downdraft concentrated the ambient anticyclonic vorticity in Elmore's observed bow echo and microburst. This type of "bow echo", then, actually belongs in the following category (section 3.4).

3.4 Shallow, high-based cumulonimbus clouds

Since the JAWS project in 1982, a great deal of attention has been given to microbursts which originate from benign-looking, high-based (-4 km agl), shallow (-2 km deep) stratocumulus or cumulus congestus clouds. These clouds often have glaciated tops and lack the rapidly rising convective towers, thunder, and lightning of typical lower-based cumulonimbus clouds (Wakimoto, 1985), although some small convective turrets can occasionally be seen (Hjelmfelt *et al.*, 1986). Virga is commonly visible below cloud base (giving rise to the term *virga microbursts*) but often little or no rain reaches the ground (Fujita and Wakimoto, 1983b). Braham (1952) briefly mentioned this phenomenon, and Krumm (1954) characterized the "dry thunderstorm over the plateau area of the United States" with, in retrospect, amazing accuracy. Brown *et al.* (1982) also documented this type of storm, and noted that its damaging outflow could qualify as a downburst. They also predicted what the JAWS investigators were soon to discover, that this type of storm is much more common than was generally recognized at the time.

Attempts to generalize the characteristics of the environment in which this type of microburst forms, primarily for forecasting purposes, have been quite successful. Caracena, *et al.* (1983b) and Wakimoto (1985) found that a deep, dry subcloud layer (dew point depression greater than 30°C) with a nearly dry adiabatic lapse rate was common, and that a moist layer around the 500 mb level nearly always occurred. Winds typically had a strong westerly component, and increased with height. Using a simple rule that the dew point depression at 700 mb be greater than 8°C and that it be less that 8°C at 500 mb, Caracena, *et al.* (1983b) were able to correctly classify 26 of 30 days on which dry microbursts occurred.

Radar and flow characteristics of this type of storm have been documented by Wilson, *et al.* (1984), Fujita and Wakimoto (1983a), Roberts and Wilson (1984), Hjelmfelt (1984), Mueller and Hildebrand (1985), Fujita (1985), Elmore (1986), and summarized by Kessinger, *et al.* (1986). Statistical results of surface mesonet measurements of JAWS microbursts have been summarized by Bedard and LeFebvre (1986). These microbursts all formed between 1300 and 1900 MDT with 75% occurring between 1400 and 1700 MDT. Reflectivity values were always less that 30 dBZ at 500 m agl. The evolution of the surface flow field typical of nearly all microbursts observed during JAWS is schematically illustrated in Figure 5. The

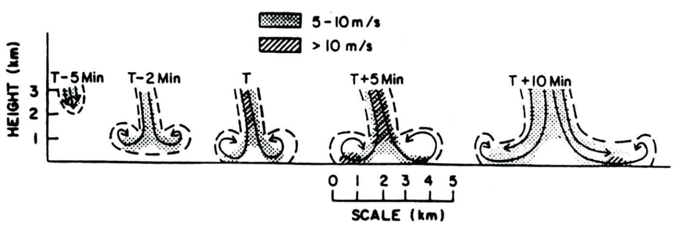

Fig. 5. Vertical cross section of the evolution of the microburst wind field based on JAWS data. T is the time of initial divergence at the surface. The shading refers to the vector wind speeds. From Wilson et al. (1984).

horizontal vortex roll at the periphery of the downdraft (T-2 Min in Fig. 5) led Fujita and Wakimoto (1983a) to define the "mid-air" microburst; Roberts and Wilson (1984) showed that this divergence aloft primarily occurred for the low reflectivity virga microbursts.

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 (McCarthy, *et al.*, 1983; Fujita and Wakimoto, 1983b). Rainfall rates never exceeded 3 inches per hour, and only on 6 days was the rainfall rate associated with microbursts above 1 inch per hour. The strong surface outflow typically lasted from 2-5 minutes with outflow speeds between 10 and 20 m/s. Fujita (1985) also found that the surface temperature was just as likely to rise as to fall, by as much as 3°C; Kessinger, *et al.* (1986) found a 1-2°C surface temperature drop and no rain for the one case they discuss.

Brown, *et al.* (1982) hypothesize that the combination of the deep dry subcloud layer allowing negatively buoyant air near cloud base to descend to the surface without losing all of its negative buoyancy (and to accelerate over a great distance), and the weak updrafts producing small precipitation particles which evaporate and melt more rapidly than the larger particles formed in more vigorous convection, allows the very strong downdrafts to form.

Srivastava (1985), using a simple one-dimensional time-dependent model of an evaporatively driven downdraft, systematically considered the various factors that could influence the ultimate strength of the downdraft. He found that intense downdrafts were favored when the lapse rate was close to dry adiabatic, when the rainwater mixing ratio near cloud base (origin of the downdraft) was high, and when the downdraft radius was at least 1 km. Srivastava also confirmed that "a given rainwater content distributed in smaller drops is generally a more efficient producer of cooling and intense downdrafts", but did find that under some circumstances larger drops, with their greater terminal fall velocities, were able to produce a deeper, stronger downdraft by spreading the cooling over a greater depth. He also noted that the relative humidity of the environment, in the idealized but not too far from realistic case of no mixing, affects the downdraft only indirectly by affecting its buoyancy. Thus a virtually warmer (more humid) atmosphere would actually be *more* conducive to strong downdrafts.

Krueger and Wakimoto (1985) used a two dimensional axisymmetric numerical cloud model to simulate the dry microburst life cycle. Their results basically agreed with those of Srivastava (1985) but since they included a lower boundary, the attained downward velocities were lower, as expected. They found that the vertical velocity decreased appreciably as the radius of the initial rainwater region was increased but that the subsequent surface outflow velocity increased only slightly. This result is more generally 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 a linear function of the initial radius of the rainwater region (U/W - R/2). Although it was not discussed, the numerical model output data presented by the authors did fall along a straight line (U/W - R/3 + 0.75, where R is in km).

Krueger, *et al.* (1986) used this same model to study the role of ice-phase microphysics in determining the downdraft and outflow strength of dry microbursts. They performed experiments in which the precipitation dropped at the top of the model consisted of either rain, graupel, or snow at each of three cloud base precipitation rates with identical radial distributions. They found that the more precipitation, the stronger the downdrafts and surface outflows, and that these variations were much larger than those attributable to the different forms of precipitation with the same concentration. However, for a given precipitation rate, rain generally produced the strongest downdraft and graupel produced the coldest, strongest surface outflow. The ratio of the outflow to the downflow speed was always smallest for rain and largest for graupel. This emphasizes the importance of the vertical distribution of negative buoyancy on the ratio of maximum outflow speed to maximum downflow speed for storms of equal horizontal scales.

Mahoney (1983) developed an evaporation model to estimate the subcloud cooling rates in JAWS microbursts using aircraft-measured hydrometeor spectra (Rodi, *et al.*, 1983) and ambient relative humidity values. He found a maximum in the cooling rate just below cloud base where high concentrations of small ice particles were present. Using equivalent potential temperature as a tracer, he found that the air in the downdraft was originating at the base of the cumulus cloud, and not from within or from the top of the cloud. He, too, concluded that strong downdrafts occurred with a deep, dry adiabatic subcloud layer and a large concentration of small particles, but for *low* relative humidity values. It may be that with higher atmospheric relative humidity values, different forms of convection arise. Rodi, *et al.* (1986) used a similar model to compute the maximum cooling rates resulting from initial graupel particle densities of 0.1 and 0.9 g/cm^3, with a typically observed size spectrum, and found them to be very different. Although the vertical equation of motion was not solved, they too concluded that knowledge of the precipitation rate or particle density is crucial to the understanding of downdraft magnitudes.

Compensating convergence must develop at or above the downdraft initiation level to replace the descending air in the microburst. This downward motion and convergence will increase the vertical vorticity in the same region. Significant convergence, including sinking of the visible cloud into the downdraft region has been observed (Fujita, 1985), as has increased rotation coincident with the downdraft and reflectivity core (Fujita and Wakimoto, 1983a; Roberts and Wilson, 1984).

In summary, all observations and simulations indicate that downward acceleration from negative buoyancy, generated as precipitation with the typically observed distribution of small drops falls from cloud base into the deep, dry adiabatic subcloud layer and evaporates (and melts), can lead 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 Mtns. during the summer months, although they can certainly occur elsewhere*. It is probable that the downdrafts are originally initiated by precipitation loading within the elevated clouds. The small horizontal scale of the phenomenon has not been adequately explained, but it cannot be decoupled from the scale of the original updrafts, that is, the preferred scale of the instability that created the cumulus clouds in the first place.

Model results show that the narrowest downdrafts will be the most hazardous to aviation; not only will the vertical velocities be the strongest, but the outflow winds will be nearly as strong as those from larger storms while the horizontal scale is smaller. The actual hazard to aviation of this type of microburst has been assessed through observations of air traffic response by Stevenson (1984, 1985). He found that aircraft do fly through microbursts at Stapleton International Airport in Denver, and that 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. The surface reflectivity values of these microbursts are low and, because they occur in an urban (high clutter level) environment, a Doppler radar with sophisticated ground clutter supression capability is required for their effective detection.

3.5 Microburst lines

The observation that microbursts occurred in "families" was first made by Fujita (1978) based on damage surveys. During JAWS, it was found that two or more microbursts could occur simultaneously, forming a line (Kessinger *et al.*, 1983). Hjelmfelt and Roberts (1985) define the microburst line as consisting of "two or more microbursts, at least twice as long as it is 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." A preliminary schematic of the basic microburst line structure is shown in Fig. 6.

Hjelmfelt and Roberts (1985) have found that microburst lines are produced from high-based shallow cloud lines. These original cloud lines may be initiated by surface convergence lines that develop daily over the Rocky mountains (Wilson and Schreiber, 1986), or perhaps in response to orographically forced Von Karman-like vortex streets that are set up parallel to the prevailing winds (Fujita, 1985; Peterson, 1985). The lines generally have embedded centers of divergence at the surface, coincident with local maxima in the radar reflectivity field. Whereas a single microburst might have a lifetime on the order of 15 minutes, the microburst line typically lasts for about an hour.

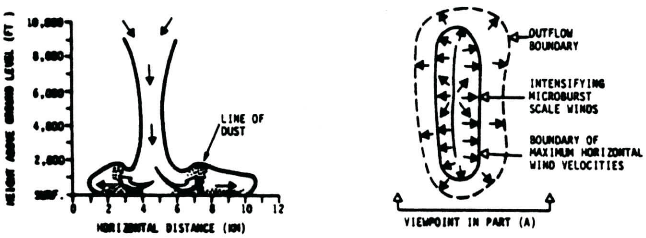

Fig.6. Basic microburst line structure by Stevenson (1985).

Stevenson (1985) has shown that microburst lines have a severe impact on airport operations primarily because they are long-lived and propagate slowly (mean speed 1.3 m/s (Hjelmfelt and Roberts, 1985)); however, this also implies that they can be more easily predicted. Using a quasi-compressible three-dimensional numerical model, Anderson *et al.*, (1985) showed that merging microburst outflows may pose an even greater 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 the microburst line outflow and the corresponding hazard to aviation can vary tremendously. Al-

*Wieler (personal communication) has observed microburst wind shear associated with a very low reflectivity storm near Boston, MA with the Raytheon Co. prototype NEXRAD Doppler weather radar.

though microbursts have been observed to form in groups or "families" in other parts of the country, the identification of the microburst line as a new storm type arose from observations of weather phenomena near the Rocky Mtns, 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.

3.6 Airmass thunderstorms

One of the first parent cell types to be associated with microbursts was the isolated cumulonimbus cloud (Fig. 7) . Although

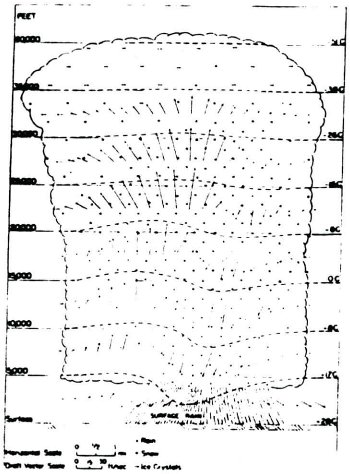

Fig. 7. Conditions that might be expected in a thunderstorm cell in the mature stage. From Byers and Braham (1949).

called simply "thunderstorms" at the time, Byers and Braham (1949) measured very strong, small scale divergent surface outflows that would today be classified as microbursts (*e.g.*, "When the cold downdraft of a cell reaches the surface layers of the atmosphere, it spreads out in a fashion similar to that of a fluid jet striking a flat plate"). Based on the number of fatalities that have occurred in wind shear related accidents, these are the storms that produce the most hazardous forms of low-altitude wind shear. The research question then becomes how to distinguish in advance the thunderstorms that will produce violent outflows from those that will produce outflows of ordinary strength.

Airmass storms are common in areas of convective instability, high surface relative humidity, and little or no vertical wind shear, implying that they could occur in most any part of the country during the summer months. Dyer *et al.* (1976) present Doppler observations of a windstorm near Boston 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". They also note that none of the characteristic severe storm radar signatures were present so radar operators failed to recognize the damage potential. A subsequent reexamination of the same case showed a disorganized multicell airmass storm with one large, tall cell and a weak echo region at the surface in the area of highest winds.

Caracena and Maier (1979) present an analysis of a dual microburst event that occurred in the FACE (Florida Area Cumulus Experiment) mesonet. The cell which produced the microbursts was, again, one of the tallest within a disorganized multicell line of storms, having been forced more vigorously at the surface in the convergence zone of two colliding outflow boundaries. The authors conclude, as have others since, that the spearhead shape taken on by the radar echo was attributable to the rapid growth of new cells on the advancing edge of the storm. The microbursts, lasting less than 5 minutes, were associated with heavy rain and embedded in a storm scale downdraft that continued for over 30 minutes. Careful analysis of the synoptic scale situation revealed 1) a broad area of enhanced positive vertical velocity ahead of a 500 mb meso-low, 2) the intrusion of air with low equivalent potential temperature between 400 and 500 mb, and 3) intensifying vertical wind shear, as north-northwesterly winds of 5-7.5 m/s at 500 mb overlaid boundary layer easterly winds of 5 m/s. Hourly photographs taken before the microbursts occurred showed that the towering cumuli tilted significantly downshear.

In trying to account for the observed 30 m/s surface outflow speeds, the authors found that a technique by Foster (1958), based on moist adiabatic descent of downdraft air consisting of a mixture of midlevel air and updraft air (equal proportions), predicted gusts of less than 19 m/s. They suggested that the additional source of negative buoyancy could come from: 1) the melting of large quantities of ice; an unusually large quantity may have formed since, with the extraordinary boundary layer forcing of the microburst cell, the precipitation core remained aloft with overshooting tops of 17 km for 45 minutes, 2) efficient entrainment of midlevel air of low equivalent potential temperature into the downdraft without mixing with updraft air, and/or 3) precipitation loading; however the observed precipitation rates were too low to completely account for the discrepancy.

The striking difference between probable downdraft speeds and observed outflow speeds has also been observed by Fujita (1984, 1986). Through analysis of a microburst that caused damage at Andrews AFB, through visual and multiple Doppler observations of JAWS microbursts, and through laboratory simulations with cold descending air currents, the presence of a well defined rotor at the leading edge of the microburst outflow was demonstrated. Wakimoto (1982) has also shown Doppler observations of a vortex roll at the leading edge of a downburst outflow. Waranauskas (1985) notes that "the lower pressure at the rotor core acts to accelerate the surface winds, thereby making the axial center and the microburst coincident on spatial and temporal scales". It is hypothesized by Fujita that in this way, through vortex tube stretching at the leading edge of an expanding outflow, a weak or moderate downdraft could produce strong surface winds that would appear in small patches along the outflow boundary as the vortex tube separated (Fig. 8).

Linden and Simpson (1985) used a laboratory model with aqueous salt solutions of two different densities to show the existence and increasing vorticity of both the primary vortex roll at the leading edge of the expanding outflow, and a secondary vortex (Figure 8). They suggest that the vortices are manifestations of Kelvin-Helmholtz instability; in two dimensional flows the K-H billows are restricted to the upper half of the current but in this three dimensional case "the billows temporarily occupy the full depth of the outflow". They also note that an already existing circulation in the descending air would further increase the intensity of the primary vortex.

Both Fujita (1986) and Linden and Simpson (1985) suggest that the embedded vortices in the outflow pose an additional wind shear threat to aviation, and that the recent 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. One unknown

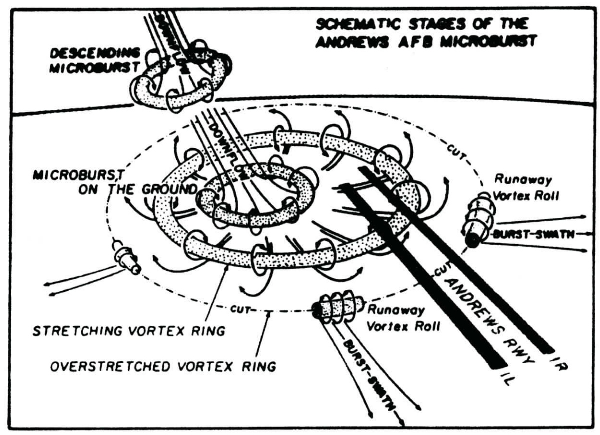

Fig. 8. Four stages of Andrews AFB microburst. They are: 1st Stage (DESCENDING) Midair microburst descends. 2nd Stage (CONTACT) Microburst hits the ground. 3rd Stage (MATURE) Stretching of the ring vortex intensifies the surface wind speeds. 4th Stage (BREAKUP) Runaway vortex rolls induce burst swaths. From Fujita (1984).

is how often and under what conditions these high speed horizontal vortex rolls will develop. In one microburst observed with RHIs taken with the FL-2 radar in Huntsville, AL (9/21/86), horizontal vortices were excited in a pre-existing outflow pool when the fresher outflow from a newly forming microburst impacted the surface (Fig. 9a). These smaller vortices rapidly dissipated (Fig. 9b) leaving the largest, fastest wave travelling outward at the head of the outflow current. The presence of this type of well developed leading outflow wave is the rule rather than the exception in microbursts observed in Memphis, TN and Huntsville, AL.

Some of the JAWS microbursts were associated with isolated, unsteady multicell airmass thunderstorms that produced very heavy rain, although commonly the cloud bases were quite high and the storms were fairly long-lived. One impressive storm that occurred on 30 June 1982 has received considerable attention (*e.g.*, Kessinger, *et al.*, 1983; Smith and Waranauskas, 1983; Weisman, *et al.*, 1983;

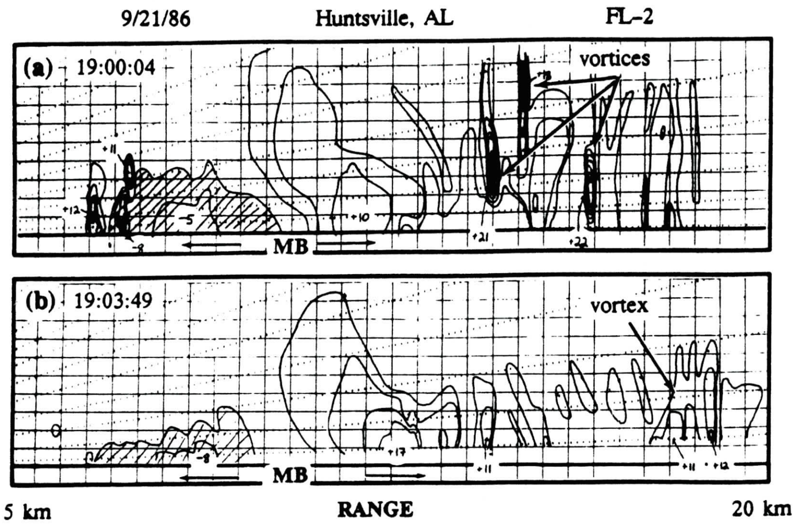

Fig. 9. RHI cross section through a microburst storm on 9/21/86. The background grid spaces are 0.1 km in the vertical and 0.5 km in the horizontal. The region shown is thus 1 km high by 15 km across, at a range of 5–20 km from FL-2 (the radar is at the left). Contours of Doppler velocity at 3 m/s intervals are shown. Numbers are Doppler velocities in m/s; negative velocities (hatched) represent flow toward the radar. The outflow is stronger away from the radar than toward because the microburst fell into a pre-existing outflow that was moving away from the radar.

a.) *Contoured Doppler velocity from an RHI scan taken one minute after the microburst impacted the ground, at 19:00:04 GMT. Note the vortices set up in advance of, and at the leading edge of, the outflow.*

b.) *Contoured Doppler velocity from an RHI scan taken at 19:03:49. Notice that 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 itself and one vortex at the leading (outbound) edge of the outflow pool.*

Kessinger, *et al.*, 1984; Parsons, *et al.*, 1985). It evolved in an environment characterized by low vertical wind shear and moderate instability, had a lifetime of about 80 minutes, produced 1 cm sized hail, and maintained a reflectivity core in excess of 50 dBZ at the surface. A number of microbursts occurred within the larger scale storm outflow.

One of the key radar-detectable precursors of the occurrence of the microburst outflow is the descending reflectivity core of a collapsing thunderstorm cell (Roberts and Wilson, 1984 and 1986). This evidence, together with the very high rainfall rates and radar reflectivity levels observed in these storms, has led many investigators to conclude that liquid water loading must play a primary role in forcing the intense downward vertical acceleration. Analyses by Wolfson *et al.* (1985) of mesonet data collected during the 1984 FLOWS project in Memphis, TN show significant correlation between surface rainfall, which was at times extremely heavy, and the strength of the peak microburst outflow winds (Fig. 10a).

In nearly every case, however, the outflow current was significantly colder, and had lower equivalent potential temperature (EPT) than the surface air it was displacing. This implies that evaporation, and to some degree melting, must have contributed to the negative buoyancy. The peak microburst outflow speeds are also significantly correlated with the temperature deficit and the EPT deficit of the outflow (Figs. 10b and 10c).

Burrows and Osborne (1986) investigated the role of precipitation loading in forcing a microburst that occurred during FLOWS 1985 in Memphis, TN using aircraft measured hydrometeor spectra, cloud liquid water content, and vertical velocity. They showed that in every pass through the storm "the strong downdrafts were found in close association with the areas of heavy precipitation loading", but the correlation between vertical velocity and liquid water content was by no means perfect (Fig. 11). At that altitude in the storm (660 m agl), the negative buoyancy contribution from a mean liquid water content of 6 g/m^3 was slightly less than that from the observed temperature deficit of 2.3°C (42% water loading and 58% temperature deficit).

Leech (1985) makes the point that even if dry air is entrained into the precipitation core at high levels, little evaporative cooling can occur since the air is so cold. In fact, as Proctor (1985) showed with results from a two-dimensional (axisymmetric) numerical model of a thunderstorm, the temperature deviation in the downdraft may actually be positive above the freezing level, since the cooling from the evaporation 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; these effects will be most important near the level of the minimum in equivalent potential temperature. As Srivastava (1985) has noted, when a given water mixing ratio l is completely evaporated, it will contribute roughly $10l$ to the negative buoyancy through the resulting temperature deficit.

At upper levels in the region of liquid and/or frozen water accumulation, precipitation loading is the dominant forcing mechanism in initiating the the collapse of the cell. However, cooling due to water phase changes during the descent of the core must play a significant role in the additional forcing that gives rise to the extraordinary outflow speeds of the few cells that produce microbursts (see Smith and Waranauskas (1985) for examples of visually impressive microbursts, with reflectivity levels over 60 dBZ, that produced only weak outflows). Thus the nature of the entrainment process of dry air into the downdraft is of great interest. It should be noted that significant evaporation may take place without altering the general appearance of the radar echo. The smallest drops will evaporate first and most efficiently, but they contribute relatively little to the reflectivity, which is proportional to the sixth power of the rain drop diameter. Also, the reduction in liquid water content associated with a reduction in radar reflectivity of 5 dBZ from 55 to 50 dBZ is almost 6 times as great as the reduction in liquid water content associated with a 5 dBZ reduction from 40 to 35 dBZ.

In summary, the air mass thunderstorms with the strongest collapsing phase downdrafts and subsequent outflows qualify as microbursts. In essentially every case, very heavy rainfall concentrated in an area of small horizontal extent, and large decreases in both temperature and equivalent potential temperature at the surface are observed. Often the convection from which microbursts arise is itself initiated by the convergence at the edge of older outflows, so the microburst surface flow pattern is often embedded in a larger scale

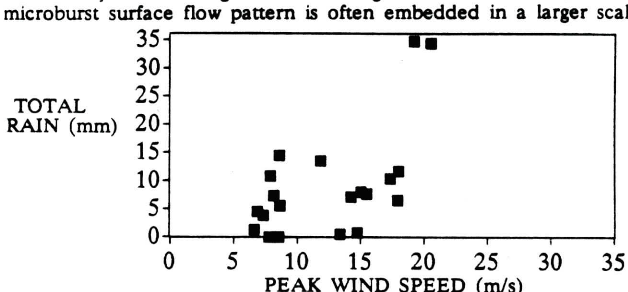

Fig. 10a. Total rain vs. peak wind speed in Memphis microbursts.

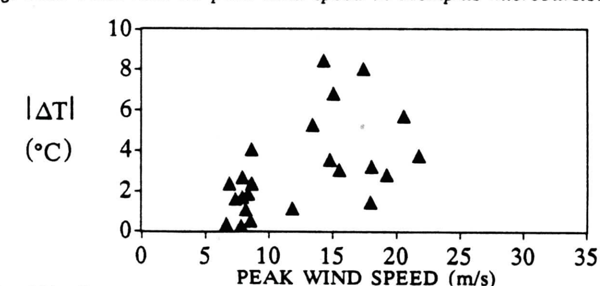

Fig. 10b. Temp. drop vs. peak wind speed in Memphis microbursts.

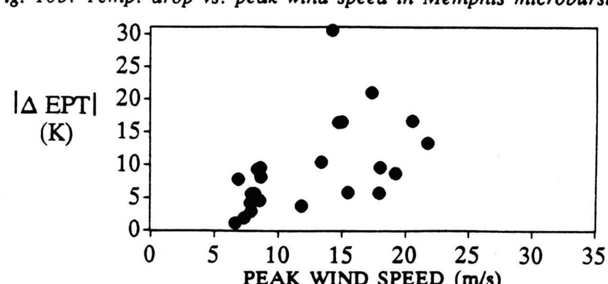

Fig. 10c. EPT drop vs. peak wind speed in Memphis microbursts.

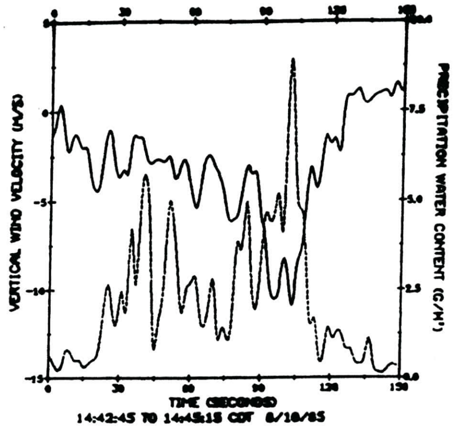

Fig. 11. Vertical velocity (solid line) and precipitation water content (dashed line) are plotted for one pass through the microburst storm on 10 August 1985 in Memphis, TN. Aircraft altitude was 0.66 km agl. From Burrows and Osborne (1986).

storm outflow. Thus, the convection is often but not always in the form of multicell storms, both "secondary" or discretely propagating as described above, or loosely organized with closer cell spacing in a line. Storms with overshooting tops have greater energy levels than other storms, and their cores contain more ice which can lead to greater generation of negative buoyancy as the downdrafts pass through the freezing level. Vortices at the leading edge and within the microburst outflow commonly occur and are associated with very strong surface winds.

Aircraft accidents attributed to microburst wind shear and accompanied by very heavy rain have lead to the greatest number of fatalities. The rain in some cases has been so heavy that it has been suggested that the aerodynamic performance of the aircraft deteriorates because of it, resulting in an overall loss of lift (Luers and Haines, 1981; Dunham *et al.*, 1985; Hansman and Craig, 1987). McCarthy *et al.* (1979) investigated the aircraft response to the Eastern 66 microburst at JFK, and found that the wind shear spectrum contained high energy at the aircraft's "phugoid" or resonant frequency. They believe that this resonance seriously deteriorated aircraft performance by giving rise to sudden oscillations in airspeed and height about the glideslope. Obviously, the high rate of occurrence of airmass storms, their highly divergent outflows, and the small, insignificant-looking size of the cells from which the microbursts form all add to the aviation hazard.

4. SUMMARY

Through the preceding review, it has been implied but not proven that a number of dynamically distinct phenomena give rise to strong surface outflows. At the largest scales, the 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 the result of both the strength of the vertical velocity and the downward flux of horizontal momentum, and may also be influenced by the nearly two-dimensional, linear storm geometry. Because these storms are large scale, long-lived, infrequent, and severe, aircraft have largely been vectored away from them successfully.

In environments with little wind shear, and similar conditional instability, isolated air mass thunderstorms form. In warm, humid conditions the strength of the outflow from these storms is determined by evaporative cooling, both in cloud and below cloud base, and by precipitation loading, especially at upper levels. As the outflow pool rapidly expands, strong straight-line microburst winds form in association with the leading edge vortex roll. This type of microburst-producing storm has proven to be the most hazardous for aviation for a number of reasons: the frequency with which they occur, the rapidity with which they develop, their small scale, the very strong outflows that they produce, their lack of translational motion, and also the fact that storms identical in appearance, at least visually and on conventional aircraft radar, are successfully flown through on a regular basis.

In between, to varying degrees, other forms of loosely organized multicell storms form. It is possible that these storms, with closely spaced echoes that merge to form a spearhead appearance on low resolution radar scopes, are similar to the microburst lines found near Denver; however, they form without any orographic organization. Strong forcing of the updraft 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 allowing for less diluted cores. These downdrafts and outflows will be correspondingly stronger, providing more 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; however their explosive growth makes them very unpredictable and airspace that was a safe distance away from such a storm complex one minute could be inundated with microburst wind shear the next.

The microbursts that arise from shallow, high-based cumulonimbus clouds can only occur in an environment with a deep, dry adiabatic mixed layer, with sufficient moisture aloft to sustain a downdraft all the way to the surface in the face of strong evaporation. Suitable conditions have mainly been observed in the high plains east of the Rocky Mtns. during the summer months. The surface reflectivity values of these microbursts are low and, because they occur in an urban (high clutter level) environment, a Doppler radar with sophisticated ground clutter supression capability is required for their effective detection.

ACKNOWLEDGEMENTS

The author wishes to thank Dr. T.T. Fujita for numerous enlightening discussions about microbursts, Dr. K.A. Emanuel and Dr. J.E. Evans for their constructive comments, and J. Cullen for his help compiling the Memphis microburst surface characteristics.

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