CHARACTERISTICS OF THUNDERSTORM-GENERATED LOW ALTITUDE WIND SHEAR: A SURVEY BASED ON NATIONWIDE TERMINAL DOPPLER WEATHER RADAR TESTBED MEASUREMENTS*

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The characteristics of microbursts and gust fronts, two forms of aviation-hazardous low altitude wind shear, are presented. Data were collected with a prototype Terminal Doppler Weather Radar and a network of surface weather stations in Memphis, Huntsville, Denver, Kansas City, and Orlando. Regional differences and features that could be exploited in detection systems such as the associated reflectivity, surface wind shear, and temperature change are emphasized.

1. INTRODUCTION

Low altitude wind shear is a major cause of air carrier accidents in the United States. Most of these accidents have been caused by either microbursts (small scale, low altitude, intense thunderstorm downdrafts which impact the surface and cause strong divergent outflows of wind) or by the gust front at the leading edge of expanding thunderstorm outflows. The destructive nature of microbursts and gust fronts, and the high risk they pose to the safe low altitude operation of aircraft in the vicinity of thunderstorms, makes their accurate detection a very desirable goal. The development of detection systems and pilot/ATC personnel training systems must rely on accurate information about the phenomena to be detected. In this paper we discuss in detail the characteristics of thunderstorm-generated low altitude wind shear, focussing in particular on features that could be exploited in these systems, such as the associated radar reflectivity, surface wind shear, temperature relative to the ambient air, and the three dimensional wind shear pattern as a function of time.

2. LOW ALTITUDE WIND SHEAR HAZARD TO AVIATION

Three major aircraft accidents account for all of the aviation fatalities attributed specifically to microbursts in the United States (see Table 1). These are the crash of Eastern 66 at J.F. Kennedy airport in New York on 24 June 1975 (112 fatali-

Table 1. Aircraft accidents in the United States attributable to microbursts or low altitude wind shear associated with thunderstorms. Wind speed is given in meters per second, and cell diameters are given in kilometers. F/I/U indicates number of fatalities, injured, and uninjured. Information adapted from [1],[2],[3], and [4]. MB indicates microburst.

Location	Date	Winds	Diameter	Rain	Weather	F / I / U
Bowling Green	28 Jul 43	strong	10–15	yes	strong squall wind from violent downdraft fanning out at surface; unusually severe turbulence	?/ ?/ 2
Mason City, IA	22 Aug 54	strong	5	heavy	plane entered thunderstorm at 400–500 ft; sank in downdraft	12/ 7/ 0
Rochester NY	2 Jul 63	shifting	?	heavy	thunderstorm approaching runway from west, plane took off into heavy rain and shifting winds	7/ ?/ ?
Falls City, NE	6 Aug 66	gusty	n/a	light	roll cloud preceding thunderstorm; severe turbulence	42/ 0/ 0
St. Louis	23 Jul 73	strong	?	heavy	severe thunderstorm with roll clouds, heavy rain, strong winds	38/ 6/ 0
Chattanooga	27 Nov 73	?	?	heavy	low altitude wind shear existed in heavy rain on approach	0/42/37
New York	24 Jun 75	10–17	5–10	heavy	hot smoggy day, seabreeze; light, moderate, & heavy rain; numerous small cells, spearhead echo 8 x 32 km; MB	112/12/ 0
Denver	7 Aug 75	>12	2	light	numerous scattered showers-small and weak; cell broke into two, thunder heard, spearhead echo 8 x 16 km; MB	0/15/119
Raleigh-Durham	12 Nov 75	?	?	heavy	unexpected heavy rain, windshear and downdraft at 100 ft agl	0/ 1/138
Philadelphia	23 Jun 76	20	4	yes	headwind increase in front of shower; scattered showers and thunderstorms near warm front, growing spearhead echo 13 x 27 km; MB	0/86/20
Tucson	3 Jun 77	14	2	none	numerous CB around airport; gust front passed with 25 m/s surface winds; MB	0/ 0/ALL
New Orleans	9 Jul 82	>15	2	heavy	scattered showers, 7 gust fronts nearby, recent growth of convective cloud tops; MB	152/ 9/ 0
Detroit	13 Jun 84	10–16	?	heavy + hail	thunderstorm with heavy rain; 3/4 inch hail at 100–200 ft agl; turbulence, severe wind shear	0/ 0/ALL
Dallas	2 Aug 85	22–35	4	very heavy	scattered small cells initiated on gust front out of large cell to NW, very hot day, cloud top of MB cell 23 Kft (questionable – NTSB reported 40–50 Kft.); MB	130/31/ 0

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ties, 12 injuries), of Pan Am 759 at New Orleans International airport on 9 July 1982 (152 fatalities, 9 injuries), and of Delta 191 at Dallas/Ft. Worth International airport on 2 August 1985 (130 fatalities, 31 injuries). No one escaped injury in any of these accidents. In all three of these cases, the thunderstorm downdraft implicated in the accident descended into a pre-existing outflow that was produced from a nearby thunderstorm. Recent work suggests that the wind shear and turbulence associated with the leading edge of the pre-existing outflow may have added a crucial ingredient to the overall hazard [5]. The presence of the gust front from another storm was not taken into consideration in assessments of the wind shear hazard in these cases.

In two of the four additional fatal accidents attributed to thunderstorm low altitude wind shear (Table 1), roll clouds were noted by eyewitnesses. These were the crash of a Braniff Airways plane at Falls City, NE on 6 August 1966 and the crash of an Ozark Air Lines plane at St. Louis, MO on 23 July 1973. No one escaped injury in these two accidents, either. In the Falls City crash, "ground witnesses observed the aircraft to fly into or over a roll cloud preceding a thunderstorm and shortly thereafter saw an explosion in the sky followed by a fireball falling out of the cloud. Two pieces, later identified as major portions of the right wing and empennage, were seen falling separately from the main part of the aircraft. Shortly thereafter the witnesses noted high gusty surface winds and light to moderate rain which accompanied the passage of a squall line through the area. The cause of the accident was determined to be inflight structural failure caused by extreme turbulence" [3]. Roll clouds mark the ascending branch of a horizontal vortex, usually either the gust front itself, a solitary wave, or part of an undular bore [6].

What role did the low altitude downdrafts and turbulence associated with older, pre-existing gust fronts play in the three microburst related fatal aircraft accidents? Certainly the divergent headwind-tailwind shear of the thunderstorm downdraft air spreading horizontally along the surface can easily become strong enough to cause an unmanageable loss of lift to an aircraft penetrating it (Figure 1). Figure 2 shows that the magnitude of the downdraft velocity has as much effect as the horizontal wind shear on the ability of a plane to maintain its speed and glide slope profile under shear conditions. But Figure 2 also shows that even performance increasing wind shear (increasing headwind) and updrafts, typically associated with gust fronts, can be unsafe when their magnitudes are large. The effect of turbulence on aircraft control is not captured by the F-factor hazard index, but the hazard can be extreme, especially at low altitudes.

3. THE DATA

As part of the development and demonstration of the Federal Aviation Administration Terminal Doppler Weather Radar (TDWR) system [8], MIT Lincoln Laboratory has measured thunderstorm-generated low altitude wind shear with a transportable pulsed Doppler weather radar testbed at five airports: Memphis (1985), Huntsville (1986), Denver (1987-88), Kansas City (1989), and Orlando (1990). The pencil beam TDWR testbed radar was used to gather surface data over the airport every 1.0 - 1.5 min to correctly capture the rapid thunderstorm outflow evolution. Systematic radar measurements aloft to 6.0 km AGL every 3 min were also made to detect any precursors to the microburst outflow events. In addition to this operational scan strategy, the TDWR testbed included advanced techniques to enhance data quality such as clutter filtering, clutter residue mapping, Doppler velocity dealiasing, and automatic selection of pulse repetition frequency to minimize range obscuration by out-of-trip weather echoes [9].

At each field site, a Doppler weather radar operated by the University of North Dakota was situated with an orthogonal viewing angle relative to the TDWR testbed radar, so that the Doppler data from the two radars could be combined to allow unambiguous recovery of the three dimensional windfield at the surface. In Denver, Kansas City, and Orlando, data were collected so that dual Doppler surface windfields could be derived over the airport every minute. A network of 30-40 surface weather stations was also sited with an average inter-station spacing of 1.4 - 2.1 km, to measure surface winds, temperature, relative humidity, pressure, and rainfall amounts every minute [10]. Because of the rapid (dual) radar update rate, the overall storm coverage, the minimization of data contamination, the supporting surface measurements, and the variety of climatic regimes sampled, the TDWR testbed low altitude wind shear measure-

AIRCRAFT ENCOUNTER WITH A MICROBURST

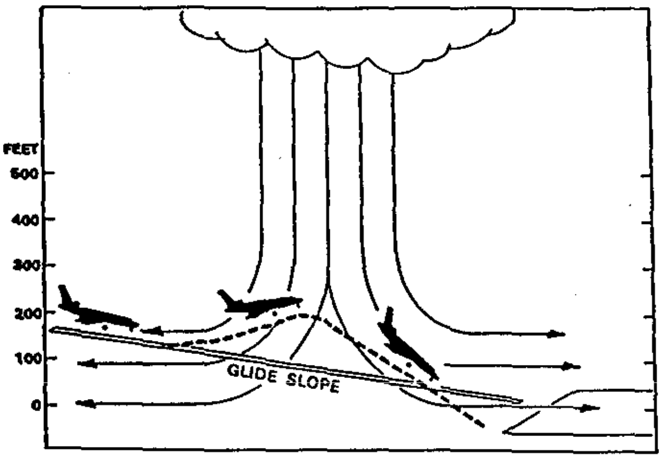

Figure 1. Schematic drawing of an aircraft encounter with a microburst. Notice that the increased headwind lifts the plane above its intended glideslope while the increased tailwind causes the plane to fall below its intended glideslope.

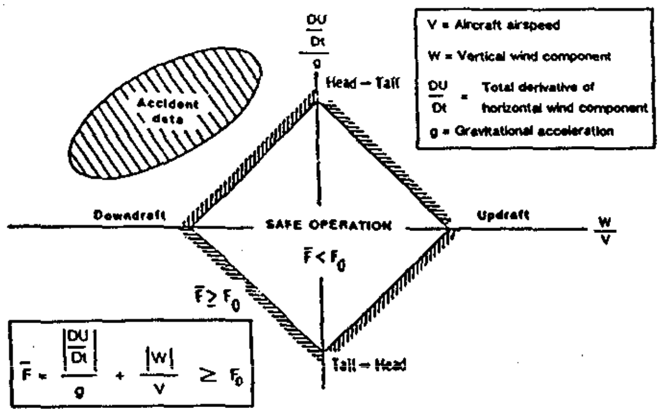

Figure 2. Definition of F-factor wind shear hazard index. Typical threshold values (F_0) for jet transport range from 0.10 - 0.15. Notice that all of the aircraft accidents have taken place in the quadrant associated with divergent horizontal winds and downward vertical velocities along the flight path. Adapted from [7].

ments provide a comprehensive, high quality data base for microburst and gust front research.

4. LOW ALTITUDE WIND SHEAR CHARACTERISTICS

4.1. MICROBURSTS

Recent work on aviation weather hazards and, in particular, on microbursts has focussed on the thunderstorm downdraft and outflow as the primary cause of low altitude wind shear. The precipitation-driven downdraft of a cumulonimbus cloud is now commonly called a microburst when its diameter is small (< 4 km) and its outflow is strong (> 10 m/s). Figure 3 shows the relative frequency of six different microburst characteristics at each of the five field sites.

Figure 3(a) shows the distribution of maximum surface radar reflectivity in microbursts. Surface reflectivity levels below 30-35 dBZ usually correspond to little or no measurable rainfall. In Memphis, Huntsville, Kansas City, and Orlando, microbursts were almost always associated with heavy rain at the surface. However, 78% of the Denver microbursts impacting the weather station network had reflectivity <30 dBZ. The semi-arid climate there is typical of the high plains region east of the Rocky Mountains. The associated microburst wind shear [Figures 3(b) and (d)] was quite similar at all the field sites, revealing that low reflectivity events are not necessarily weak. The distribution of microburst sizes [Figure 3(c)] shows that microbursts were somewhat smaller in Orlando and Denver than at the other field sites. The dry, ice-driven microbursts of Denver, and the highly unstable summer thunderstorms in Orlando are expected to be small based on theoretical considerations [12,13].

The size and strength of the downdraft, and the temperature of the outflow air play dominant roles in determining the outflow evolution. The surface temperature change associated with dry microbursts can be either positive or negative but is almost always small [Figure 3(f), Denver]. The outflow air will readily mix with ambient air after the initial momentum has dissipated. Wet microburst outflows are almost invariable cold, with the temperature changes typically ranging from -1 to -12 °C. These outflows continue propagating as gravity currents once the initial downdraft/outflow momentum has dissipated. The difference in associated microburst air temperature helps explain the difference in microburst event duration between Denver and the other field sites [Figure 3(e)]. Statistics on other microburst characteristics such as outflow depth, and cloud top height, are given in [14] for Huntsville and Denver.

The evolving three dimensional windfield near the surface in microbursts is perhaps the most important characteristic to quantify for wind shear studies. By combining the data from two or more Doppler weather radars scanning synchronously, and employing the mass continuity equation of fluid dynamics with the boundary condition that the vertical velocity equal zero at the ground, the three dimensional windfield near the surface can be accurately derived [15]. Figure 4(a) shows the surface reflectivity of a strong, isolated microburst observed with the TDWR testbed radar near the Memphis International Airport on 26 June 1985. Observers noted extremely heavy precipitation during this storm. Taking as time T the time shown in Figure 4(a) (1836:29 GMT), the evolution of the outflow at five times from T+1.5 min to T+5.6 min is shown in Figure 4(b). The high reflectivity (45-55 dBZ) main storm downdraft is located at a range of approximately 8 km northeast of the TDWR testbed radar in these cross sections. The strongest outflow winds are located approximately 100 m AGL. These cross-sections clearly show the development of a horizontal vortex or rotor associated with the leading gust front as the outflow spreads away from the storm center. This vortex eventually detaches and moves away from the main outflow.

This behavior is a fundamental characteristic of cold, axisymmetric outflows. As the cold air spreads radially, its volume covers a larger area and the outflow depth drops rapidly. This sets up a radial pressure gradient that accelerates the fluid outward. However, the acceleration of fluid just behind the front is limited by the front itself, so disturbances will propagate back away from the front. This "reflected" fluid is overtaken by fluid from farther upstream leading to an accumulation in a raised rim or leading vortex ring [5]. The popularly held notion that this feature is caused by the "spin-up" of a constant volume vortex that formed around the downdraft before it reached the surface, and "stretched" in length as the circumference of the outflow expanded, is incorrect. In a two dimensional cold outflow, a similar circulation forms but fluid does not accumulate in the slightly deeper gravity current "head" (Figure 5). Thus circular gust fronts are fundamentally different from their more straight line counterparts. The idealized outflow from an isolated cell with no leading vortex front (Figure 1) essentially never occurs.

The Doppler radar spectrum width (not shown) is very high in the leading vortex gust front shown in Figure 4, indicating strong turbulence at low altitudes. The downdraft speed on the backside of the vortex is comparable to that at low altitudes in the main storm downdraft coincident with the high reflectivity storm core, but the reflectivity is only 10-15 dBZ. Thus, even though this microburst is associated with heavy rain and high reflectivity, there is a low reflectivity region of severe aircraft hazard surrounding it. The hazard of the gust front is a significant part of the overall microburst hazard.

Detection of microburst aircraft hazard with ground-based Doppler weather radar relies on the divergence detected in the radial winds being comparable to the divergence in the azimuthal direction, so that estimates of wind shear along any runway will be accurate. Our studies indicate that this is not always true. The average strength asymmetry ratio (maximum over minimum outflow strength from any viewing angle) in Denver microbursts is almost 2:1; the cumulative frequency of strength asymmetry ratios is shown in Figure 6. Thus, the wind shear in a microburst could be anywhere from half to twice as strong as that detected by Doppler radar.

4.2. GUST FRONTS

As shown in Figure 4, the leading edge of a microburst is actually a gust front, which weakens as it expands outward. However, if the cold outflow from a number of cells pools together, and is continually freshened, the gust front can remain very strong and hazardous for long periods of time. Gust fronts are characterized by a convergent wind shear pattern and very strong low altitude updrafts. This upward moving air is often visually marked by a low altitude arc cloud or roll cloud (Figure 5).

In the following, a gust front event is defined as a single observation of a gust front (on a radar volume scan) as determined by subjective analysis. Gust front strength is determined by the change in Doppler velocity (ΔV) across the gust front. The relative frequency of weak, moderate, strong, and severe gust front events is shown in Figure 7(a). Kansas City exhibited the strongest events, followed by Denver and Orlando. About 84% of all gust front events had $\Delta V \leq 15$ m/s. The distribution of lengths of gust front events is provided in Figure 7(b). Orlando gust fronts tended to be slightly shorter than those in Denver and Kansas City. The average gust front lengths for Denver, Kan-

MICROBURST CHARACTERISTICS

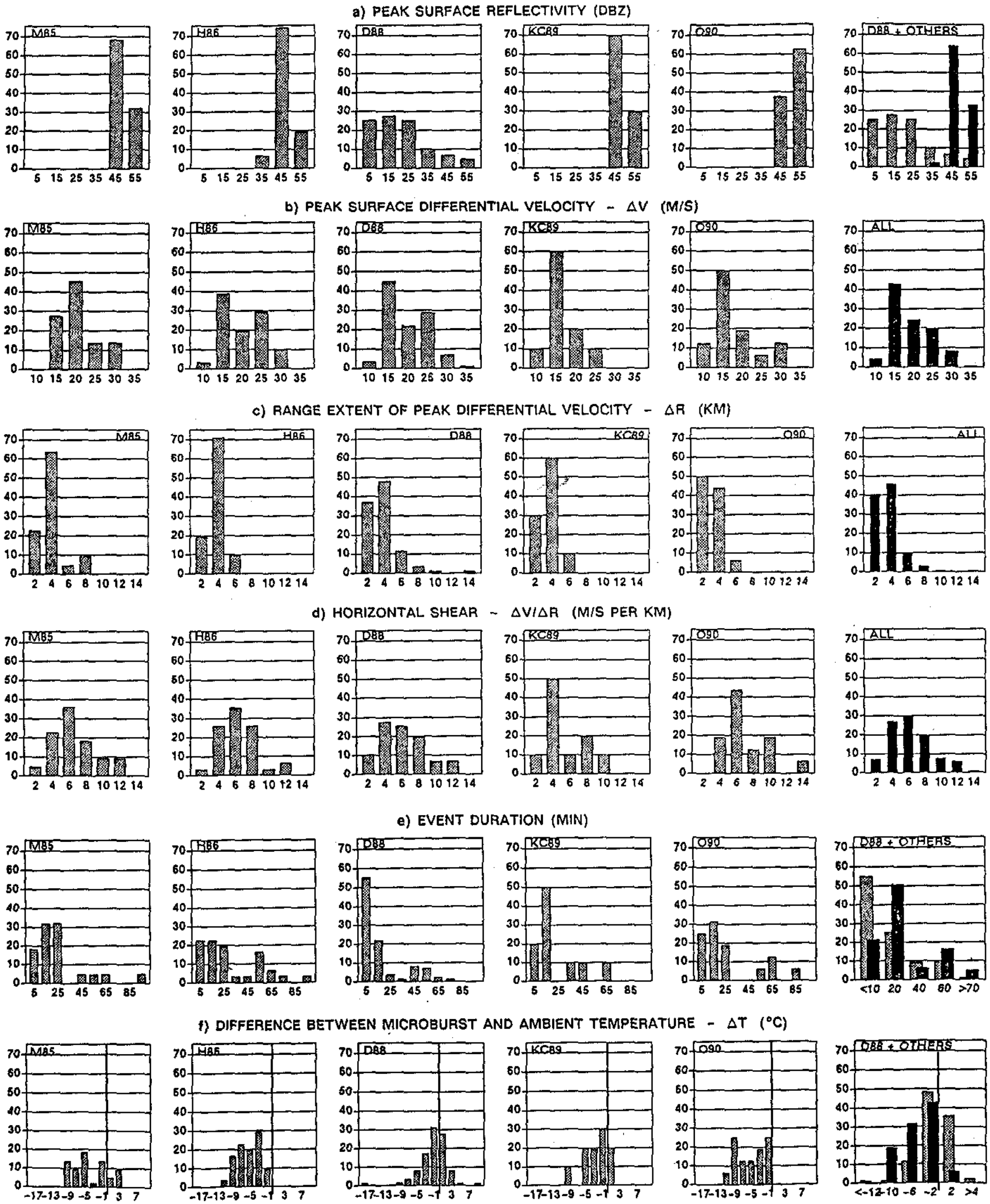

Figure 3. Characteristics of microbursts (MB) are represented by relative frequency of events at each airport (M85: Memphis – 22 MB; H86: Huntsville – 31 MB; D88: Denver – 87 MB; KC89: Kansas City – 10 MB; O90: Orlando – 16 MB) with the measured variable. The rightmost chart in each row shows the relative frequency of the measured characteristic for all microbursts if only black bars are shown (ALL: 166 MB); if both grey and black bars are shown, the grey bars represent the Denver distribution, and the black bars represent the average distribution found by combining data from all sites except Denver (OTHERS: 79 MB). In e) and f), the sampling intervals were combined in the rightmost chart for legibility. Only microbursts impacting the weather station network were used in the sample. TDWR testbed radar data were used in charts a)–d), mesonet data in e) and f).

sas City, Orlando and all gust fronts were 29 km, 31 km, 26 km and 29 km, respectively.

Seventy-seven Denver (1988), 66 Kansas City (1989), and 13 Orlando (1990) cases were chosen for analysis of gust front duration [Figure 7(c)] and propagation speed [Figure 7(d)]. About 82% of Kansas City gust fronts had durations of less than 60 minutes, as compared to 52% of Denver and 31% of Orlando gust fronts. The mean duration of Denver gust fronts was 71 minutes, Kansas City - 42, and Orlando - 117 minutes. Thus, Orlando gust fronts were the longest-lived gust fronts. The mean duration of all gust fronts was 63 minutes. The distribution of gust front propagation speed indicates that Kansas City gust fronts propagated faster than Denver and Orlando gust fronts. The average propagation speeds of Denver, Kansas City, Orlando gust fronts were 7 m/s, 10 m/s, and 8 m/s, respectively.

The distribution of the direction *toward* which the gust fronts propagated is given in Figure 7(e). In both Denver and Kansas City, the preferred direction of propagation was from the northwest quadrant to southeast quadrant. In Orlando, the preferred propagation direction was southwest to northeast. About 73% of all gust fronts exhibited an eastward propagation component.

Outflow depth determined from radar data for each of the three sites is given in Figure 7(f). The deepest outflows were found in Kansas City, where an average outflow depth of 1.4

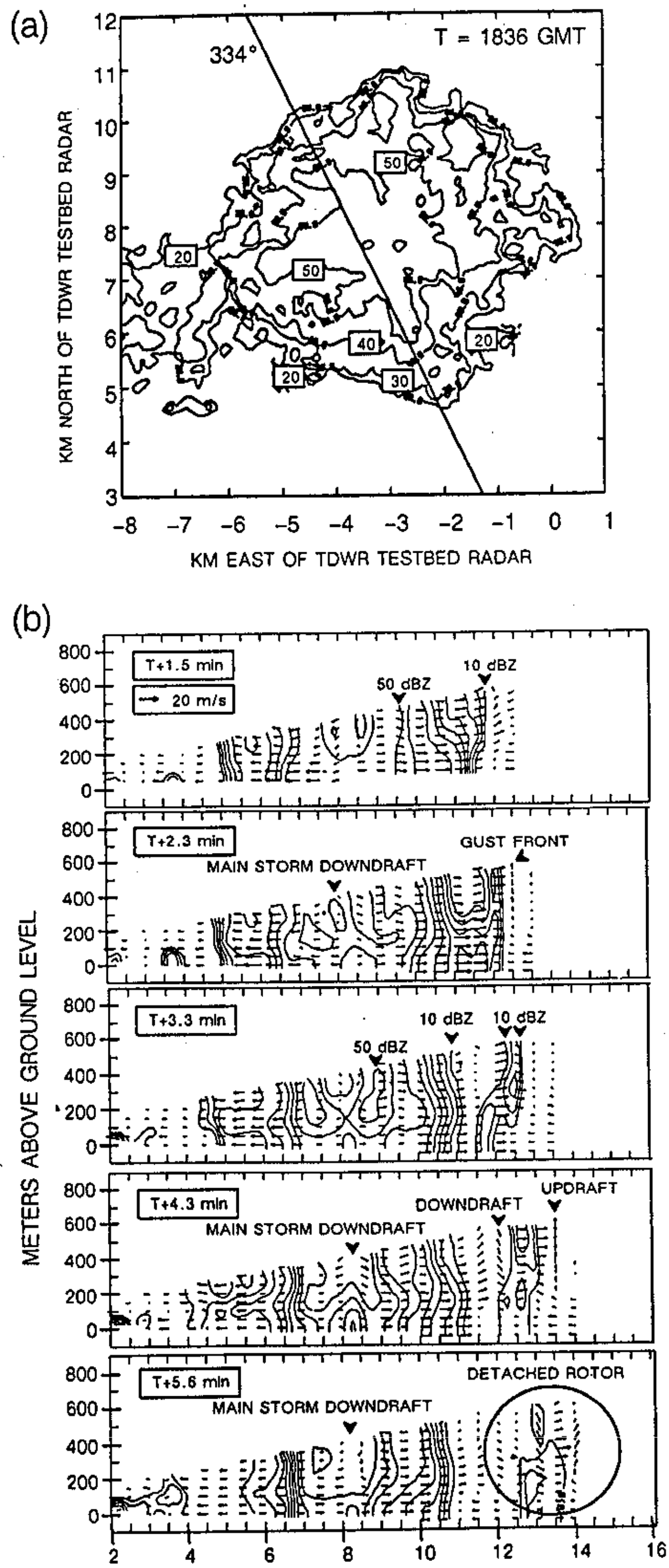

Figure 4. (a) TDWR testbed radar 0.5° elevation scan at time T, 1836:29 GMT, on 26 June 1985. Data were collected near Memphis, TN. Reflectivity is contoured at 20, 30, 40, and 50 dBZ (selected contours are labelled with boxed numerals). (b) Vertical cross-sections along azimuth 334° [shown in (a)], at five sequential times. Reflectivity is contoured every 5 dBZ from 10 dBZ.

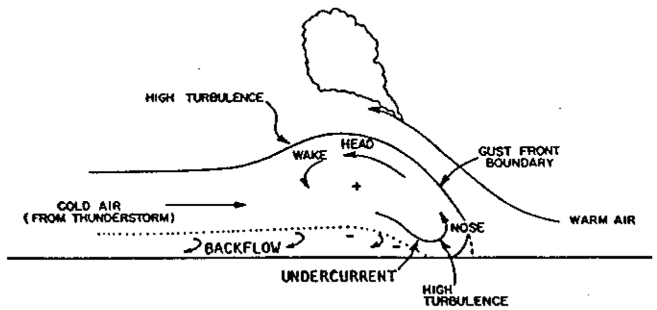

Figure 5. Schematic representation of an atmospheric density current. An aircraft flying into the outflow would experience an increase in head wind, and an aircraft exiting the outflow would experience a decrease in tailwind. Both situations result in a performance gain. Strong turbulence and vertical air motions occur within the shear zone and in the wake of the gust front head. From [16].

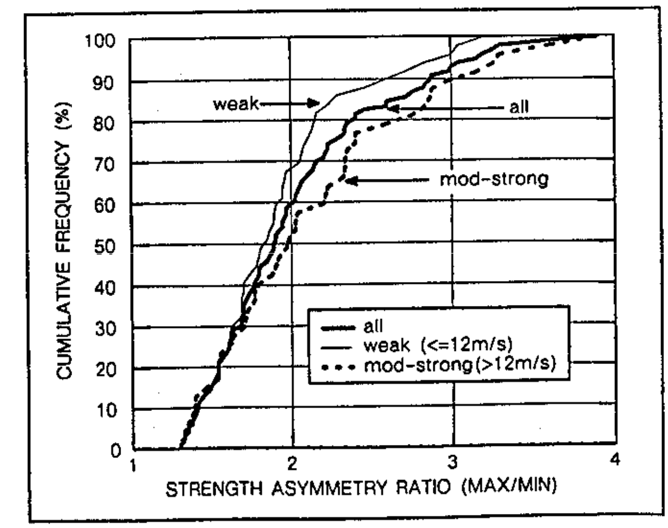

Figure 6. Cumulative frequency of strength asymmetry ratios for various maximum strength classes, for 96 observations of 27 microburst events measured in Denver, 1987 with dual Doppler radar. From [17].

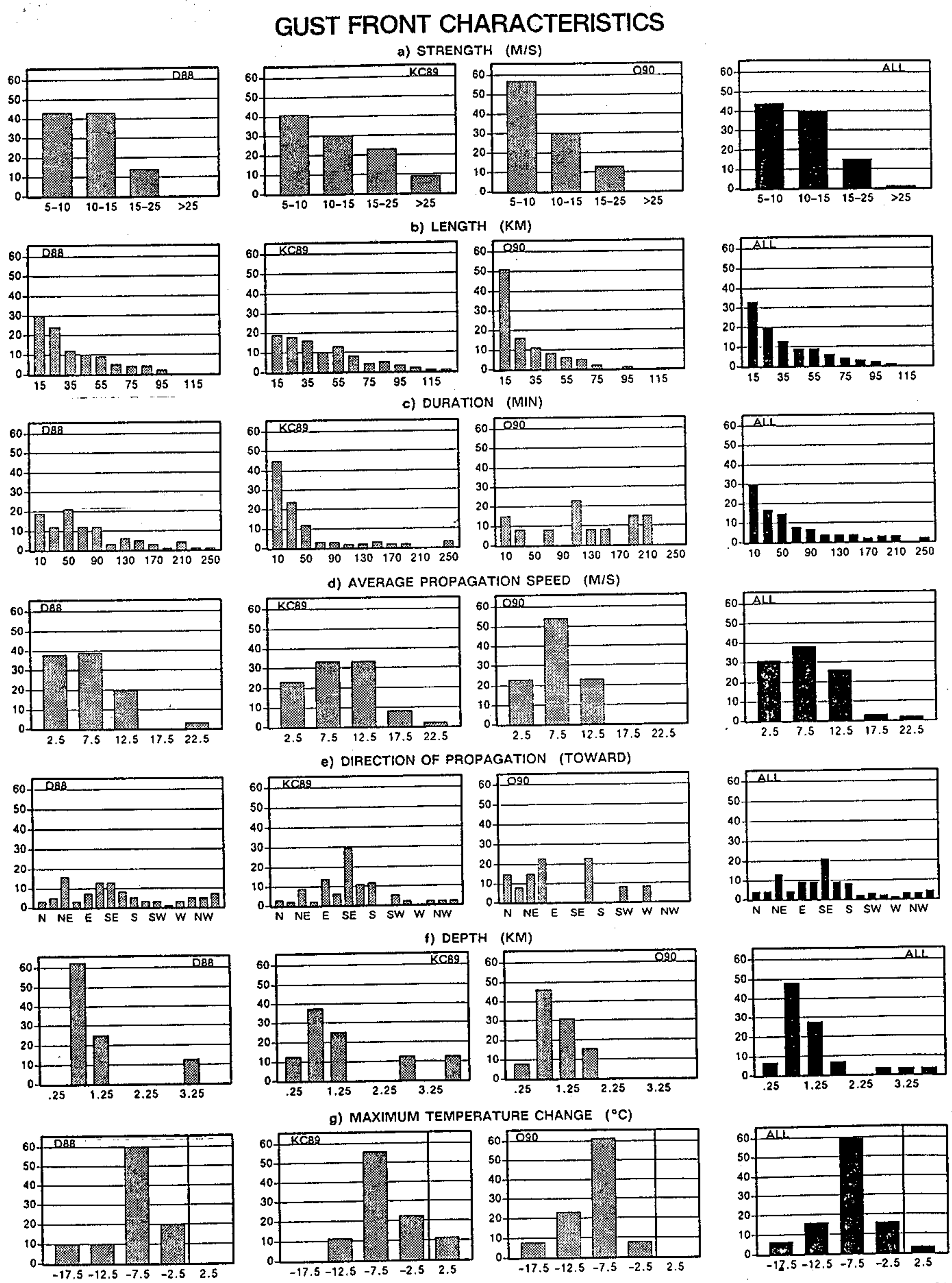

Figure 7. Characteristics of gust fronts are represented by relative frequency of events at three airports (D88: Denver; KC89: Kansas City; and O90: Orlando) with the measured variable. The rightmost graph in each row shows the relative frequency of the measured characteristic for all gust fronts (ALL).

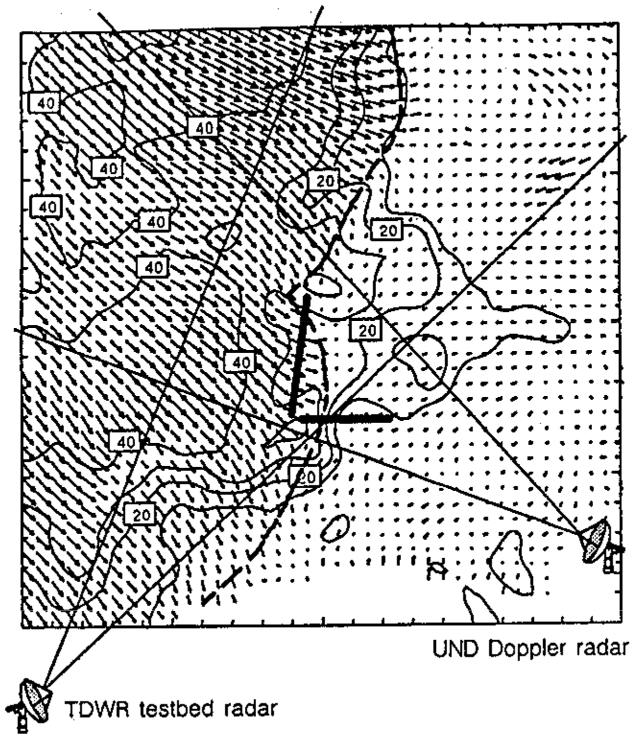

Figure 8. Dual Doppler wind vector plot showing the colliding gust fronts (dashed lines) from two large cells in a line storm as they impact the Kansas City International Airport on 15 August 1989. The airport runways are illustrated by the nearly orthogonal heavy lines near the center of the figure. A vector length of the grid spacing represents a 15 m/s wind speed. Axis tick marks are placed at 1 km intervals. Reflectivity is contoured in 10 dBZ increments from 10 to 50 dBZ. Notice that the University of North Dakota (UND) Doppler radar, located southeast of the airport, has a much better viewing angle than the TDWR testbed radar for observing the strong convergence associated with this gust front.

km was found. Outflows in Denver and Orlando had approximately the same average depth of 1.0 km.

In order to determine the thermodynamic characteristics of gust fronts, 10 gust fronts from Denver, 10 from Kansas City, and 13 from Orlando that passed through the weather station network were chosen for analysis. The maximum temperature change across the gust front for these cases is shown in Figure 7(g). Negative numbers indicate that the outflow air was cooler than the ambient air. Only one outflow (from Kansas City) was warmer than the ambient air. The majority of outflows were about 7.5°C cooler than the ambient air. The average temperature drops accompanying Denver, Kansas City, Orlando, and all gust fronts were -7.6°C, -5.9°C, -8.8°C, and -8.0°C, respectively. In general, Denver and Orlando gust fronts resulted in greater temperature drops than Kansas City gust fronts.

The asymmetry problem encountered in Doppler radar detection of microbursts is even more severe for gust fronts. One striking example of this is shown in Figure 8. This dual Doppler surface windfield analysis of a strong gust front at the leading edge of the pooled outflow from cells within a line storm shows how different the orthogonal views of the radial velocity can be. Essentially no gust front signature was detected in the radial windfield from the TDWR testbed radar in this case. We are actively exploring advanced techniques for detecting gust fronts in unfavorable viewing geometries with Doppler weather radar [18].

5. SUMMARY

Accurate detection of aviation-hazardous low altitude wind shear generated by thunderstorms relies upon its accurate characterization. The meteorological understanding of microbursts and gust fronts is rapidly growing, even as we develop the automated algorithms to ensure their detection. This survey of data from very different climatic regimes demonstrates the growth in our understanding of these events, and allows new insights into the analysis of the fatal US microburst aircraft crashes. This new understanding can now be used to enhance pilot and ATC personnel training, and exploited in the development of wind shear detection systems.

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