DOPPLER RADAR OBSERVATIONS OF AN OKLAHOMA DOWNBURST*

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1. INTRODUCTION

"Downbursts", first discovered by Dr. T. T. Fujita, are small intense downdrafts at very low altitudes which impact the surface and cause a divergent outflow of wind. They can occur under a variety of meteorological conditions as was demonstrated during the JAWS 1982 field experiment which took place in the vicinity of Stapleton airport in Denver, CO. Many downbursts were detected but most of them were of the type now being called "dry" or "cumulus" or "virga" downbursts. A distinction must be made between these and the "wet" or "thunderstorm" downbursts which are the subject of this study. The two phenomena are very different. They are easy to distinguish: the former come from benign looking cumulus clouds and fall through a very deep and dry subcloud layer and the latter are associated with thunderstorms. Thunderstorm downbursts have been detected throughout the Great Plains and the Midwest, on the east coast, and in Florida, while the virga downbursts have been detected mainly over the high plains east of the Rockies.

The word "downburst" was first introduced by Fujita (1976) after the investigation of a plane crash at JFK airport, to describe the situation in which a thunderstorm downdraft becomes hazardous to the operation of jet aircraft on take-off or landing. At first, Fujita (1979) thought that the downburst and the well known thunderstorm downdraft were essentially the same but that, in the same way a funnel cloud aloft is not called a tornado, a mid-level downdraft in a thunderstorm would not be called a downburst. The concept was later refined when it was decided that the downburst must induce "an outburst of damaging winds on or near the ground" (Fujita and Wakimoto, 1981) where "damaging winds" refers to winds that can be estimated on the F-scale (for which the minimum threshold is 18 m/s). These damaging winds can be either straight or curved but they must be highly divergent (Fujita, 1981). Thus, even in its most recent and more meteorological definition, the term downburst is meant to signify a potential human hazard. Whether or not it also signifies a dynamically distinct phenomenon in thunderstorms is a matter of some debate and one which will be investigated in the current work.

2. RADAR ECHOES

Much effort has been spent relating specific radar echoes to ground damage and reports of severe weather. In the course of his investigation of the JFK accident Fujita (1976) associated damaging downburst winds on the ground with a "radar echo with a pointed appendage extending toward the direction of the echo motion" which he called a "spearhead" echo. "The appendage moves much faster than the parent echo which is being drawn into the appendage. During the mature stage, the appendage turns into a major echo and the parent echo loses its identity."

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" in the area of strongest winds. There is some question as to whether the downburst is simply associated with or actually causes these distinctive echo configurations. An extensive survey of the ground damage caused by a bow echo thunderstorm in Illinois by Forbes and Wakimoto (1983) revealed many downbursts, microbursts (downbursts with dimensions less than 4 km), and tornadoes. Their results consistently show the strong cyclonic curvature and tornado paths to be on the north side of the diverging wind pattern of the downbursts.

The Line Echo Wave Pattern (LEWP), defined by Nolen (1959) as a "configuration of radar echoes in which a line of echoes has been subjected to an acceleration along one portion and/or a deceleration along that portion of the line immediately adjacent, with a resulting sinusoidal mesoscale wave pattern in the line," is quite similar to the bow echo and has also been associated with reports of high winds and tornadoes. Hamilton (1970) was able to deduce a meso-low surface pressure area associated with the crest of the LEWP from the shape of the squall line as depicted on radar.

Fujita (1978) has documented downbursts associated with hook echoes, a distinctive configuration known to be a good indicator of at least a mesocyclone and often a tornado. He has documented a series of downbursts which all occurred on the south side of a mesocyclone

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moving from northwest to southeast across the Kansas-Missouri border, he has documented many twisting downbursts which show rotational as well as divergent wind patterns, and he has even inferred the existence of a downburst from the damage pattern left by a hurricane over land. It is difficult to ignore these coincidental occurrences of downbursts with strong cyclonic rotation. Yet most explanations for the downburst do exactly that.

3. PROPOSED THEORETICAL EXPLANATIONS

Fujita (1976) and Fujita and Byers (1977) developed a model of the downburst which accounted for the spearhead echo. They proposed that the downburst is caused by the collapse of an overshooting top on a large tall cell. The potential energy of the cloud top is converted into kinetic energy of the descending air which, by virtue of its large horizontal momentum, moves faster than neighboring parts of the same echo. The downward motion is accelerated by the evaporation of water droplets into the dry air that must be entrained along the way.

The main downdraft in a mature thunderstorm is a result of the cooling of dry midlevel air within the storm and/or the cooling of sub-cloudbase air by evaporation. The downdraft produces an outflow of air beneath the storm but the vertical velocities are weak when the cooled air reaches the surface. There is often a gust front at the edge of the outflow with associated wind shear and a dramatic temperature drop. The similarity between Fujita's proposed mechanism for downbursts and the mechanism known to produce the thunderstorm downdraft led some scientists to the conclusion that Fujita was observing ground damage caused by the gust front itself. As observations accumulated, it became clear that the gust front was one of the key ingredients but that the downburst was a smaller scale, separate phenomenon. Caracena (1978) suggests that a large downdraft may naturally contain an ensemble of small impulsive components of various intensities, and that downbursts and microbursts may simply be the stronger ones of these. He also notes that they may occur more commonly than one might expect from the relatively few published case studies.

A study was done by Caracena and Maier (1979) of a microburst associated with a thunderstorm which passed over the Florida Area Cumulus Experiment surface mesonetwork. They concluded that the spearhead echo was "symptomatic of strong boundary layer forcing and moisture flux convergence". This, however, did not explain why or how microbursts occurred. The authors noted that a technique by Foster (1958), based on moist adiabatic descent of downdraft air consisting of a mixture of midlevel air and updraft air, failed to account for the strength of the observed winds. They suggest that the necessary additional sources of negative buoyancy might be "the unmixed entrainment of environmental air into the rain shaft and/or the melting of a large quantity of precipitation".

Although downbursts come in many different sizes (Caracena, 1978; Fujita and Wakimoto, 1981) ranging from 1 km to 40 km with extremes of 0.1 km and 200 km, most documented downbursts are on the order of 5 km across and are much smaller and stronger than the main downdrafts. This discrepancy led Emanuel (1981) to speculate that downbursts may be due to a dynamically distinct mechanism. He suggests that downbursts are manifestations of the "penetrative downdraft" which could account for their strength and small scale. The potential for penetrative downdrafts inside a thunderstorm exists when cool dry air overlies cloudy air of high liquid water content. The updraft-downdraft configuration in a supercell thunderstorm may provide this setting. Emanuel is the first theoretician to suggest some connection between the storm rotation and the downburst although, in his scenario, the rotation serves only to trap air of high liquid water content and small vertical velocity directly below a region of inflowing potentially cold air, thus setting up a conducive environment for penetrative downdrafts.

None of the aforementioned mechanisms have been demonstrated to be the actual cause of downbursts although they are all plausible. They do provide some suggestion of what to look for in the observations.

In summary, the recurring parts of the puzzle appear to be: a particularly strong cell within a line of thunderstorms; a bow echo or LEWP in the mature stage of the cell; a gust front; some small scale rotation; decay of the parent cell as the echo shape begins to resemble a spearhead; strong surface winds, the downburst, and maybe a tornado; and a possible weak echo trench in the vicinity of the strongest winds. In these latter stages, the storm is decaying rapidly. The rest of this work will be concerned with trying to recognize these phenomena in the radar observations of an Oklahoma thunderstorm and with understanding just how they combine to produce the downburst.

4. OVERVIEW OF THE SYNOPTIC SITUATION

On 13 April 1981 during the NSSL Spring Program a warm humid southerly airflow was present over Oklahoma, with a cold front oriented southwest to northeast moving into the state from the northwest. Surface and upper air analyses can be found in the more detailed descriptions by DiStefano (1983) and Wolfson (1983).

A sounding taken at Tuttle, OK (Tuttle is marked with a triangle in figure 2) shows warm, moist surface air, a slight capping inversion at 850 mb and an approximately dry adiabatic lapse rate up to 500 mb (figure 1). This sounding was taken at 2005 CST, an hour before the thunderstorm arrived, and is representative of the pre-storm environment. The surface winds are light from the southwest but at slightly higher levels a southerly low level jet is present. The winds turn gradually to become more westerly and stronger with height.

5. DOPPLER RADAR DATA ANALYSIS

Much information can be gained by examining the reflectivity and radial velocity fields observed by the Norman, OK Doppler radar (NRO) while the downburst was occurring. Ten tilt sequences were recorded during the fifty minutes between 2045 and 2135 CST and the rapidly changing nature of this storm required that all of them be analyzed. Both the Cartesian and radial coordinate systems centered at NRO, as well as the location of the storm at various analysis times are shown in figure 2. A series of maps showing the evolution of the reflectivity and Doppler velocity fields at 1.0 km above the ground is presented in figure 3. Negative values of Doppler velocity signify radial motion toward the radar.

The storm is very strong at 2047 CST and 2050 CST when reflectivity values greater than 55 dBZ can be found. Based upon analyses of much larger extent (not shown here) it is clear that there is a very well defined gust front oriented in approximately the east-west direction, as evidenced at 2047 by the east-west line or arc of enhanced reflectivity which intercepts the right border at y=35. The gust front curves to become more parallel with the cold front slightly farther to the east. It is not clear which thunderstorm cell has produced the outflow responsible for this east-west oriented gust front but it is probably a cell to the northeast of the one depicted at 2047, or perhaps it is a number of different cells along the front whose outflows have merged. There is another gust front present which is definitely due to the outflow from the depicted cell. It is oriented northeast to southwest and is evidenced by the tight reflectivity gradient from 15 to 40 dBZ (Wakimoto, 1982) on the southeast side of the high reflectivity core. In the following discussion I refer to these as two separate gust fronts although, as the cell evolves, this distinction becomes somewhat artificial.

At 2047 CST there is a closed 15 dBZ contour on the east-west gust front. By 2050 this has grown to a 25 dBZ closed contour and at 2057 CST there is no longer any distinction between this region and the main echo. The main echo has, however, changed shape considerably. The rapid growth of this cell was probably due to the increased convergence of inflowing air near the junction of the gust fronts. In a less detailed view, this behavior might suggest the formation of a spearhead echo with the parent echo being drawn into the appendage. At the same time there is a southward protrusion and a suggestion of cyclonic turning of the outflow air behind the north-south gust front. This motion is particularly evident is the -25 m/s isodop (line of constant Doppler velocity) and in the increasing velocity gradient between 2047 and 2057.

By 2102 CST the cell looks very different. The east-west gust front is still present and a new closed 15 dBZ contour has appeared. A "hole" has developed in the 45 dBZ contour behind the north-south gust front close to the increased area of maximum Doppler velocity. The eastern portion of the -25 m/s isodop has become more rounded and extended southeastward while the northern edge has been deflected strongly southwestward suggesting a substantial increase in the cyclonic rotation. Note that the reflectivity field is less than 20 dBZ at the western edge of the depicted domain around y=25 and that a cell of greater than 45 dBZ is evident on the southern edge of the domain around x=-68.

At 2106 the "hole" in the 45 dBZ contour is still evident but the 40 dBZ contour has now protruded southeastward and a small bullet shaped region of high radial velocities has developed in the same place. The east-west gust front is characterized by a reflectivity cell of greater than 25 dBZ. The outflow air behind the gust fronts appears to be merging, suggesting an occlusion process. The weak reflectivity region at the southwestern side of the picture has grown and curved in an anticyclonic sense, although this does not appear clearly in the Doppler velocity field. Notice also the anticyclonic hook in the 40 dBZ contour.

The downburst, characterized by low equivalent potential temperature (EPT) and maximum wind gusts, is known to have hit the surface mesonet station just south of CIM (-30, 25) at 2110 CST (DiStefano, 1983). I suggest that the velocity maximum and 40 dBZ protrusion at 2106 are due to the downburst. The reflectivity minimum or "hole" at 2102 appears to be related to the downburst and may be an indication of a newly formed updraft. Note that these features are quite distinct horizontally from the dry region in the southwest.

At 2112 CST there is continued dry intrusion from the west and a suggestion of a "weak echo trench" or "spearhead trench" with the spearhead being the deflection of the reflectivity contours probably due to the downburst. It is not at all clear that the dry air to the west and the spearhead are causally connected. The storm has weakened greatly and even the 50 dBZ region is breaking up and shrinking in size. The lobe of high reflectivity extending southeastward with dry air behind it is the old east-west gustfront. There may actually be another downburst occurring at this time at x=-33, y=35 where the reflectivity minimum exists in approximately the same place relative to the core of the storm and the gustfronts as did that at 2102 CST.

In the series of pictures from 2117 to 2132 not shown here (see Wolfson, 1983) the main echo continues to elongate and curve, developing into a bow shape while increased cyclonic rotation is evident in the Doppler velocity field. This cyclonic rotation is confirmed in the wind field from a 2-Doppler analysis at 2130 CST. The weak reflectivity region in the west continues to infiltrate in an anticyclonic manner what was the main core of the cell and the gustfront structure gradually disintegrates.

RHI's constructed from sector scans of the storm taken while the downburst was occurring clearly show the low level (below 2.5 km) high speed outflow current, a strong gradient of Doppler veloctiy across the gustfront, and a leading patch of high speed air at the head of the outflow which corresponds to the downburst. Dry air entering the storm from the rear above 6 km is also evident.

6. A NEW HYPOTHESIS

In this section I present a new hypothesis, developed using the preceding Doppler radar observations as a guideline, for thunderstorm

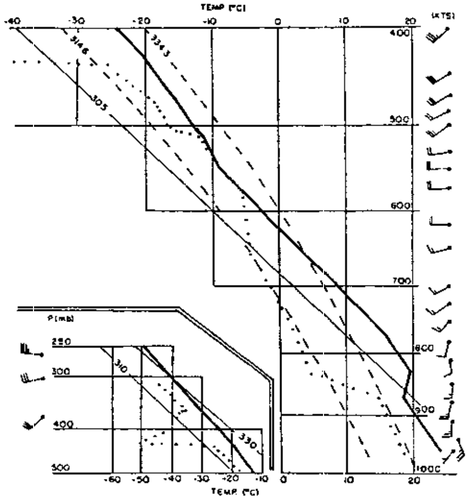


Fig. 1. (left) Tuttle sounding at 205Z, 14 April 1981. The solid line represents temperature, and the dotted - dewpoint temperture.

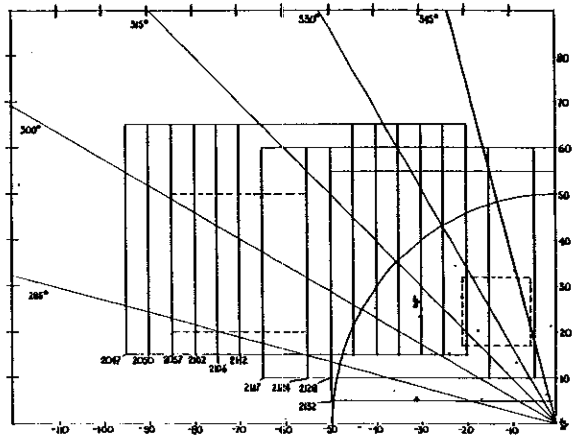
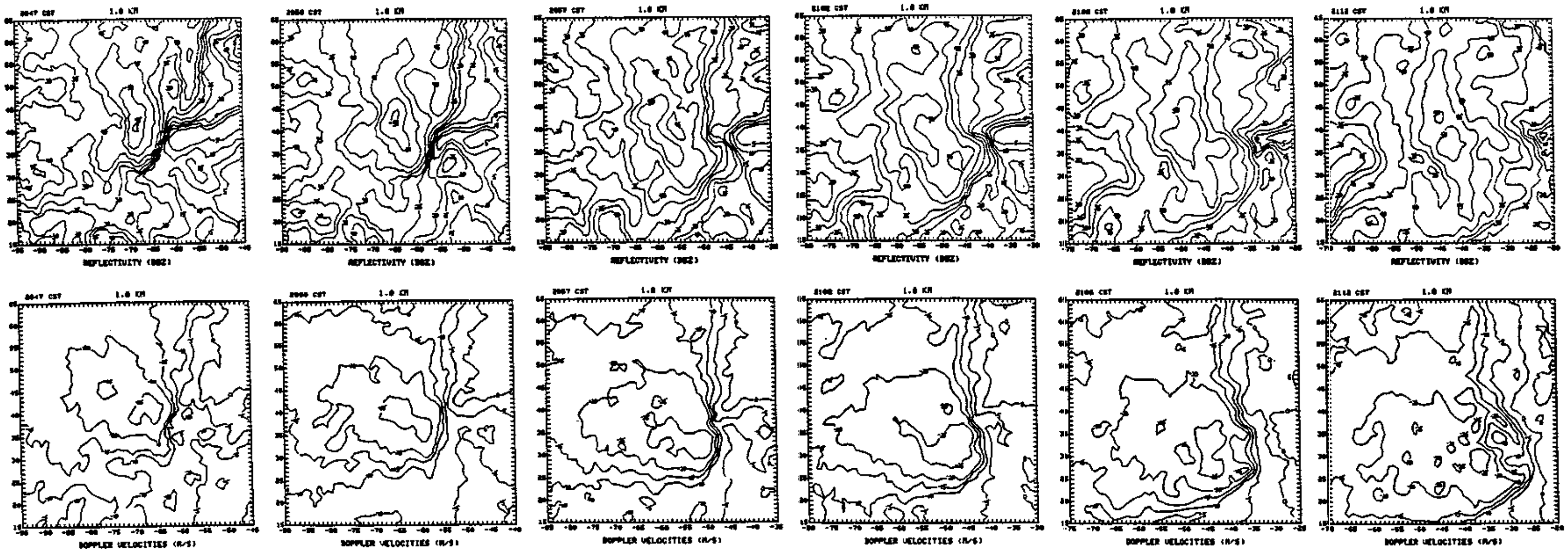


Fig. 2. (right) Coordinate system with origin at Norman, OK Doppler radar (NRO), labelled in km. The lower left corner of each 50 x 50 km analysis box is marked with the time (CST) shown in figure 3.

Fig. 3. (below) CAPPI displays at 1.0 km height of reflectivity and Doppler velocity for 13 April 1981.



downbursts. It is different from previous hypotheses in that dynamic rather than thermodynamic processes are proposed to be responsible for the downbursts. This new hypothesis accounts well for the rotational characteristics of downbursts reported in other observational studies which have not been explained by the earlier proposals and it makes the connection between the LEWP, the bow and spearhead echoes, the cyclonic rotation to the north and the anticyclonic rotation to the south, the gust front, the hook echo, and the tornado. The proposed mechanism differs little from the mechanism determined, in a fine mesh (.25 km) numerical simulation by Klemp and Rotunno (1983), to produce a small scale "occlusion downdraft" near the tornadic region in a supercell thunderstorm. This new hypothesis is simply stated below and not proved, for although diagnostics may be performed, they are beyond the scope of this work.

The basic premise is that when a cell along a line or front becomes very strong and organized it begins to take on some supercell characteristics, particularly in its post-mature stage. Horizontal vorticity, which is present in the low level environmental shear and which is generated by the horizontal buoyancy gradients in the storm, is tilted into the vertical near the main updraft. Strong low level convergence, caused by the downdraft outflow from the collapsing cell, forces stretching of the now vertically oriented vortex tubes. Significant cyclonic rotation begins at low levels and, as a result, the gust front begins to occlude. Anticyclonic vorticity is also generated but the cyclonic vorticity appears to be favored. The horizontal curvature of the flow resulting from the cyclonic rotation promotes downndraft intensification along the backside of the gustfront, especially near the circulation center, by dynamically inducing a vertical pressure gradient. This acts to rapidly accelerate air downward causing the downburst. The downburst might even form first at low levels and then extend upward as the flow adjusts to the dynamic pressure gradient. A schematic diagram depicting the proposed mesoscale circulation responsible for distorting the radar echo and inducing the downbursts is presented in figure 4.

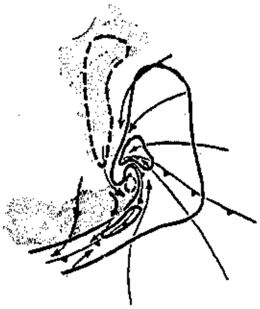


Fig. 4. Proposed circulation inducing downbursts. Dashed contours indicate downdrafts, solid contours, updrafts and the stippled area represents reflectivity greater than 30 dBZ. The small scale downdraft near the center of circulation is the downburst. After Klemp and Rotunno, 1983.

The configuration of the gustfront, marked by the cold front boundary in figure 4, is very much like that shown at 2102 CST. There is an updraft denoted by a solid contour near the occlusion point of the gustfront in 4 which is in a region of strong convergence. It was in a comparable region of the 13 April storm that cells ahead of the main storm cell were growing and subsequently merging with the main cell. It was also in this region that an updraft was inferred from the observations. The downburst, denoted by the small circular dashed contour in figure 4, is close to but south and west of the updraft and is behind the north-south oriented portion of the gustfront, just as in the analysis at 2106. Notice also the cyclonic curvature of the flow around the updraft-downburst area and the anticyclonic curvature south and west of there.

The potentially cool and dry air (low EPT) thought to characterize the downburst may well be a property of the entire thunderstorm outflow. It is likely that the low EPT air is already in the boundary layer when the downburst occurs.

In summary, I view the thunderstorm downburst as an inherently low level phenomenon, with essentially all of the important ingredients contained in the lowest 3 to 4 km of the atmosphere. It will appear in the post-mature to collapsing phase of the cell's evolution. Dynamic vertical accelerations could well be an order of magnitude larger than thermodynamic (buoyancy) accelerations at low levels. It is apparently misleading to look for the source height of the downburst. It is induced by a horizontal mesoscale circulation at low levels which nearly, or actually does, become tornadic. Although commonly thought to be mainly divergent, the downburst is really a rotational phenomenon. It is also apparently misleading to use conserved properties such as EPT or horizontal momentum to trace the downburst air; those properties only help indicate the source height of the outflow air from the whole storm.

This is a novel view of the thunderstorm downburst and it has not been proved. It does account for the observations and link phenomena which were known to occur simultaneously but were thought to be disconnected. Calculations must be done before its real relevance can be determined.

7. CONCLUSIONS AND FUTURE WORK

The major thrust of this work has been the analysis and presentation of detailed Doppler radar data collected during an Oklahoma thunderstorm in which downbursts developed. The distinctive bow or wavelike radar echo associated with this type of thunderstorm was determined to be caused by the low level cyclonic rotation. The spearhead echo, identified as a pointed appendage in the direction of motion, was determined to be a cell growing along an occluded gust front ahead of the main storm cell. The growth of this cell is an indication of the increased convergence in the region of gust front occlusion.

Careful examination of the data at different times has led to the identification of low level convergence and vorticity as major factors in downburst development. A new hypothesis was presented which identifies tilting of horizontal vorticity into the vertical and a subsequent increase in cyclonic rotation as the crucial elements in creating the dynamic pressure gradient proposed to be responsible for the downburst.

Since most observations to date have been viewed with thermodynamic mechanisms in mind as the cause of the downbursts, I believe it would be fruitful to review them in light of this new hypothesis. Estimates need to be made of the rate of vorticity production, the curvature of the flow, the vertical gradients of vorticity and dynamic pressure, and the total vertical acceleration in the vicinity of the downburst. A detailed, general scenario needs to be developed for the evolution of the thunderstorm downbursts for, although the thunderstorms themselves are fairly predictable and easy to track, the accurate prediction of the downbursts has eluded meteorologists.

The theoretical work on thunderstorm downbursts has barely begun. Although the analogy is not complete, it may be possible to exploit some of the work which has been done on supercell storms, mesocyclones, and tornadoes, with a few modifications, to help understand the line cell circulation. Once the downburst pattern is well recognized, future data gathering experiments can be designed specifically to observe them. I caution the meteorological community against drawing sweeping conclusions about downbursts in all parts of the country from the results of the JAWS experiment. The virga microbursts observed there are hazardous and very difficult to predict but they are perhaps characteristic of that local environment. Theoreticians must not channel all of their efforts into understanding virga microbursts while the more common and equally hazardous thunderstorm downbursts go unexplained.

REFERENCES

Caracena, F., 1978: A comparison of 2 downbursts of different size scales. Preprints, Conference on Weather Forecasting and Analysis and Aviation Meteorology. Silver Springs, MD, 293-300.

Caracena, F. and M. Maier, 1979: Analysis of a microburst in the FACE meteorological mesonetwork. Preprints, Eleventh Conference on Severe Local Storms, Kansas City, MO, 279-286.

DiStefano, J., 1983: Analysis of a thunderstorm downburst. Master's Thesis, Massachusetts Institute of Technology.

Emanuel, K., 1981: A similarity theory for unsaturated downdrafts within clouds. J. Atmos. Sci., 38, 1541-1580.

Forbes, G., and R. Wakimoto, 1983: A concentrated outbreak of tornadoes, downbursts, and microbursts on 6 August 1977. Mon. Wea. Rev. 111, 220-235.

Foster, D. S. 1958: Thunderstorm gusts compared with computed downdraft speeds. Mon. Wea. Rev., 86, 91-94.

Fujita, T. T., 1976: Spearhead echo and downburst near the approach end of a J. F. Kennedy airport runway, NYC. SMRP Research Paper 137, Univeristy of Chicago.

Fujita, T. T., 1978: Manual of downburst identification for Project NIMROD. SMRP Research Paper 156, University of Chicago.

Fujita, T. T., 1979: Objectives, operation, and results of project NIMROD. Preprints, Eleventh Conference on Severe Local Storms, Kansas City, MO.

Fujita, T. T., 1981: Tornadoes and downbursts in the context of generalized planetary scales. J. Atmos. Sci., 38, 1511-1534.

Fujita, T. T., and H. Byers, 1977: Spearhead echo and downburst in the crash of an airliner. Mon. Wea. Rev., 105, 129-146.

Fujita, T. T., and R. Wakimoto, 1981: Five scales of airflow associated with a series of downbursts on 16 July 1980. Mon. Wea. Rev., 109, 1438-1456.

Hamilton, R. E., 1970: Use of detailed intensity radar data in mesoscale surface analysis of the July 4 1969 storm in Ohio. Preprints, Fourteenth Radar Meteorology Conference, 339-346.

Klemp, J. B. and R. Rotunno, 1983: A study of the tornadic region within a supercell thunderstorm. J. Atmos. Sci., 40, 359-377.

Nolen, R. H., 1959: A radar pattern associated with tornadoes. Bull. Amer. Met. Soc., 40, 277-279.

Wakimoto, R., 1982: The life cycle of thunderstorm gust fronts as viewed with Doppler radar and rawinsode data. Mon. Wea. Rev., 110, 1060-182.

Wolfson, M., 1983: Doppler radar observations of an Oklahoma downburst. Master's Thesis, Massachusetts Institute of Technology.