DOWNBURSTS

Mark A. Rose

National Weather Service
Nashville, Tennessee

Abstract

A thorough summary of downbursts, their characteristics, and the atmospheric conditions in which they are generated is presented. An explanation of the equation of buoyancy and its inherent deficiency is made. A basic forecasting technique is proposed for wet microburst events, which are particular to the southeast United States. A basic hypothesis regarding the downward transport of higher momentum is established. It is this downward transport, induced by wind shear in the lower layers of the atmosphere, which is thought to be the primary forcing mechanism in the case of the wet microburst. A case study is presented which describes an equation developed for using low-level wind shear and average low-level velocity to calculate the maximum potential downburst velocity.

1. Introduction

During recent years, the topic of downbursts has received increased attention among meteorologists. Because of the enormous research which has been conducted on this topic within the last two decades, many characteristics regarding the downburst have been established. With the recent addition of the WSR-88D Doppler Radar at many sites across the country, scrutinous observation and research is not only possible, but inevitable. Downbursts have two primary impacts: (1) The straight-line winds which result from divergent surface outflow have been known to produce tornado force damage up to F3 intensity (Wakimoto 1985), and (2) Sudden, unexpected, and significant loss in altitude by descending aircraft resulting from wind shear caused by downbursts have resulted in numerous aircraft accidents. Although it is difficult to forecast downburst occurrences with any degree of reliability, it is imperative that environments which are conducive to downburst generation be recognized. With a thorough understanding of downbursts, their characteristics, and the environments in which they most often occur, it is possible that forecasters will be able to evaluate and report the potential for downburst occurrences in a given environment. Therefore, although surface damage will usually be unavoidable, injuries, loss of life, and aircraft accidents might be greatly reduced.

2. Downburst Definitions and Characteristics

In meteorology, the downburst as defined by Fujita (1985) and Wakimoto (1985) is a strong downdraft that causes an outflow of damaging winds at or near the surface. Downbursts may be categorized according to scale into macrobursts and microbursts (Wakimoto 1985). The macroburst is defined as a large downburst having an outflow diameter of 4 km or greater and damaging winds persisting for 5 to 20 minutes. The microburst is a small downburst having an outflow diameter less than 4 km and damaging winds persisting for 2 to 5 minutes. There exist two types of microburst: the dry microburst and wet microburst. Wakimoto (1985) describes the dry microburst as one coincident with little or no precipitation during the period of outflow and usually associated with virga from mid-level altocumuli or high-based cumulonimbi. The wet microburst, conversely, is often accompanied by heavy precipitation during the period of outflow and is usually associated with strong precipitation shafts from thunderstorms.

In aviation, a downburst is defined as a localized, strong downdraft with a downward vertical speed exceeding that of an aircraft during its landing operations (Fujita and Wakimoto 1981). At a height of 91 m (300 ft), which is the approximate decision height for opting to abort or continue a landing approach, the typical descent rate of a passenger jet is 3.6 m s^{-1} (12 ft s^{-1}) (Caracena and Maier 1987). An aircraft encountering a downdraft with a vertical speed exceeding 3.6 m s^{-1} would have a descent rate more than double the typical rate on landing approach.

Finally, the WSR-88D signature associated with a potential downburst is a divergent flow exhibiting a differential radial velocity of at least 10 m s^{-1} within a radius of 4 km (Knupp 1989).

3. Downburst Causes and Environmental Conditions

Favorable environmental conditions which correlate with microburst generation have been established (Table 1). Dry microbursts can occur in a variety of environments which exhibit convective instability. They frequently develop within environments exhibiting a deep, dry, atmospheric boundary layer (ABL) of at least 3 km in depth, the presence of which allows for the occurrence of virga (Knupp 1989). Thus, even weakly precipitating cumulus clouds can produce strong microbursts (McNulty 1991). Storms exhibiting a shallower dry ABL tend to be associated with only heavy precipitation. Therefore, evaporative cooling within the virga shaft is the primary forcing mechanism of the dry microburst.

Dry microbursts are most common in the western United States and over the High Plains where cloud bases are commonly as high as 500 mb with predominantly dry layers existing below (Wakimoto 1985). As precipitation descends below the cloud base and into the dry layer, it evaporates, causing the air to cool and become negatively buoyant. Therefore, dry microbursts may occur even when accompanied by little or no precipitation at the surface, and resulting peak downburst speeds are of the same magnitude as the resulting horizontal speeds.

The depth of dry air in a wet microburst environment over the southeast United States is typically more shallow than that found in a dry microburst environment. Thus, the comparable contribution to negative buoyancy induced by evaporative cooling within a wet microburst precipitation shaft is much less (Caracena and Maier 1987). However, there are other forcing mechanisms which are believed to induce and/or enhance the

Table 1. Dry vs. Wet Microburst Characteristics (from many sources)

Characteristic	Dry Microburst	Wet Microburst
Location of Highest Probability	Midwest/West	Southeast
Precipitation	Little or none	Moderate or heavy
Cloud Bases	As high as 500 mb	Usually below 850 mb
Features below Cloud Base	Virga	Shafts of strong precipitation reaching the ground
Primary Catalyst	Evaporative cooling	Downward transport of higher momentum
Environment below Cloud Base	Deep dry layer/ low relative humidity/dry adiabatic lapse rate	Shallow dry layer/high relative humidity/ moist adiabatic lapse rate
Surface Outflow Pattern	Omni-directional	Gusts of the direction of the mid-level wind

wet microburst phenomenon (Foster 1958), including melting of ice within the storm (Wakimoto and Bringi 1988).

One primary cause of wet microburst generation is thought to be precipitation loading. Precipitation loading occurs in thunderstorms when the weight of excessive water content within the cloud creates a downward force (Doswell 1985). This effect thereby either induces a downward current of air or enhances descending air within a downflow.

Another forcing mechanism which is thought to contribute to the strength of surface outflow is the downward transport of higher momentum (Duke and Rogash 1992). Here, strong horizontal winds exist in the mid levels. As the downburst parcel descends toward the surface, it has a horizontal component of the magnitude of the mid-level winds. This effect generates a corresponding horizontal momentum in the descending parcel, and it therefore conserves its own potential. As the parcel reaches the surface, the resultant divergent outflow is enhanced by the parcel's horizontal momentum and, in fact, surface wind gusts produced under this circumstance display a large component of motion in the direction of the mid-level winds and corresponding horizontal momentum. Downbursts generated in environments where the winds aloft are comparatively weak show considerable variability in gust direction.

Obviously, the downward transport of higher momentum does not necessarily induce the wet microburst. The wet microburst is thought to be initiated by evaporative cooling/melting aloft and/or precipitation loading. However, because environments in the southeast United States are much more moist than those over the High Plains, the effects of evaporative cooling would be much less significant than in the dry microburst. The downward transport of higher momentum is therefore hypothesized to not only accelerate an already descending parcel of air, but to be the primary contributor to the strength of surface outflow (in strongly sheared environments).

4. The Equation of Buoyancy

According to Foster (1958), wind gusts which accompany thunderstorms are produced largely by downdrafts that result from the negative buoyancy force acting upon an air parcel entrained into a thunderstorm at an upper level and evaporatively cooled. The temperature of the parcel then becomes less than that of its environment, and it begins to descend toward the surface. Aids in forecasting maximum wind gusts associated with thunderstorms have been developed which relate the intensity of wind gusts to the difference of the temperatures between the air within the downdraft and the environment. Downdraft speeds may be approximated using the equation of buoyancy. The equation of buoyancy is:

$$dw^2/dz = 2[(T_e - T_p)/(T_e)]g \qquad (1)$$

where w is the downward vertical speed, z is the height of the LFS (level of free sink, the source elevation of the downdraft, or the height at which the parcel first becomes cooler than its surroundings [Duke and Rogash 1992]), T_e is the temperature of the environment (degrees Kelvin), T_p is the temperature of the air parcel being evaporatively cooled, and g is the acceleration due to gravity. Thus, dw^2 is proportional to the size of the negative area below the LFS. Integration of the "gdz" term in the equation of buoyancy gives:

$$w = (2[(T_e - T_p)/(T_e)]gz)^{1/2} \qquad (2)$$

The LFS is most accurately determined by performing an equivalent potential temperature (θ_e, or theta-e) analysis utilizing atmospheric sounding data. Knupp (1989) suggests that downdraft parcels consist of low θ_e air. The presence of this drier, cooler air enhances evaporative cooling. Kingsmill and Wakimoto (1991) also associate minimum values of θ_e with the dry layer in thunderstorm-producing environments. Interestingly, Zipser (1969) notes that regions of lowest θ_e values may be coincident with regions of moderate to heavy precipitation falling from mid-level clouds. Therefore, the LFS may also be defined as the height in the lower atmosphere at which the minimum θ_e value is located.

It must be noted, however, that the equation of buoyancy is most useful in computing outflow velocities resulting from dry microbursts, since the equation considers only the thermal characteristics of a given environment (i.e., the effects of evaporative cooling). The equation does not consider the downward transport of higher momentum, and, for environments conducive to wet microburst generation, the equation of buoyancy represents only a partial velocity value (that due to evaporative cooling). Therefore, the resultant velocity value may not be representative of the wet microburst environment.

5. Proposed Forecasting Techniques for Wet Microbursts

Like many severe weather events, the exact time and location of microbursts are difficult to forecast with any appreciable accuracy. It must rather be the responsibility of the forecaster to determine the potential for microburst generation. The problem which forecasters in the southeast United States encounter when determining the probability of microburst production is that, unlike the case of the dry microburst, many factors should be evaluated in order to determine the likelihood of wet microburst generation (Table 2). The one tool which forecasters have and must utilize most in this endeavor is the atmospheric sounding.

The first determination that the forecaster should make is the degree of instability exhibited by the environment. Although

Table 2. Hypothesized Wet Microburst Forecasting Techniques

1. Determine the instability of the environment.
2. Determine the height of the LFS, as well as the height of the shear layer, which is the height at which winds cease to display large increases with height.
3. Determine the difference in the wind velocities and the average wind velocity within the shear layer.
4. Determine the velocity of thunderstorm motion.

hazardous downburst winds can be produced by environments that exhibit moderate and even weak instability, for a downburst to be generated, there must be sufficient instability to induce both updrafts and cumuliform development. Although a greater instability will generally correlate with a higher downburst potential, it is important to consider that the probability of downburst production is not a direct result of an environment's degree of instability. Therefore, weakly unstable environments must not be ignored.

The second determination that should be made, particularly in the southeast United States, is the height of the LFS and the shear layer. In determining the LFS, one must simply find the level of minimum θ_e. All National Weather Service offices have access to the SHARP Workstation (Hart and Korotky 1991), which automatically computes θ_e at 50 mb increments. Therefore, at those offices, the height of the LFS can be easily derived. Levels of free sink corresponding to minimum θ_e values are often present in environments conducive to wet microburst production, and these wet microbursts may, in fact, begin their descent at the LFS. However, their largest acceleration is thought to be initiated when they descend into the shear layer and the downward transport of higher momentum begins to act upon the parcel. The height of the shear layer must be determined using a method other than that used for determining the level of free sink (Fig. 1). Here, the height of the shear layer is the level at which winds cease to display significant increases in speed with height (less than 3 m s^{-1} km^{-1}, or $3 \times 10^{-3} s^{-1}$). Therefore, the layer exhibiting the maximum low-level wind shear gradient (referred to as the shear layer) would be bound by the level corresponding to the height of the shear layer and the surface.

The third consideration that should be made is the amount of wind shear exhibited within the shear layer. This parameter is necessary in determining the magnitude of the downward transport of higher momentum in the occurrence of a wet microburst event. There are two requirements that must be met for strong downbursts due to the downward transport method to occur. First, strong horizontal winds (at least 10 m s^{-1}) must exist at the top of the shear layer. Second, wind speeds near the surface must be relatively weak in order to maximize the magnitude of wind shear. Strong velocities which overlie comparatively weak velocities enhance an already descending parcel of air (Fig. 2). It is the magnitude of this downward current which the author theorizes to equate to the magnitude of downburst velocity due to the downward transport of higher momentum. This magnitude may be generalized by determining the difference in the horizontal speed of the winds at the top of the shear layer and at the surface. The author believes that the portion of the strength of surface outflow due to the downward transport of higher momentum would be determined by the

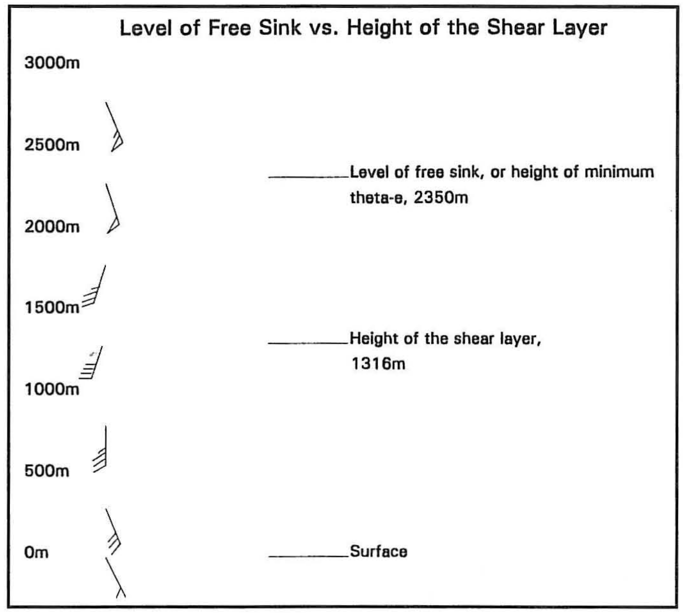

Fig. 1. Level of free sink vs. height of the shear layer, based on sounding taken at Nashville, TN (BNA), 1200 UTC 11 April 1995. Note: This environment produced a thunderstorm which generated a 60 knot wind gust at the surface.

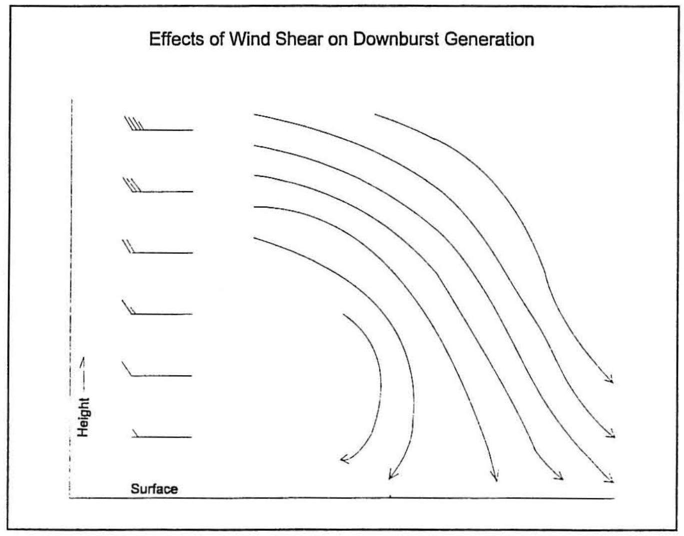

Fig. 2. Effects of wind shear on downburst generation, where strong velocities which overlie comparatively weak velocities in an unstable environment enhance an already descending parcel of air.

combination of this difference in speeds and the average wind speed exhibited in the shear layer (Fig. 3).

(Obviously, in weakly sheared environments, especially those which often exist during the summer months in the southeast United States, the downward transport of higher momentum cannot be supported, and steps two and three described above would not apply. Therefore, this method is only applicable to those environments which exhibit the significant wind shear which produces multicell and supercell thunderstorms.)

A fourth consideration which should be made is the velocity of thunderstorm motion. It is theorized that thunderstorms

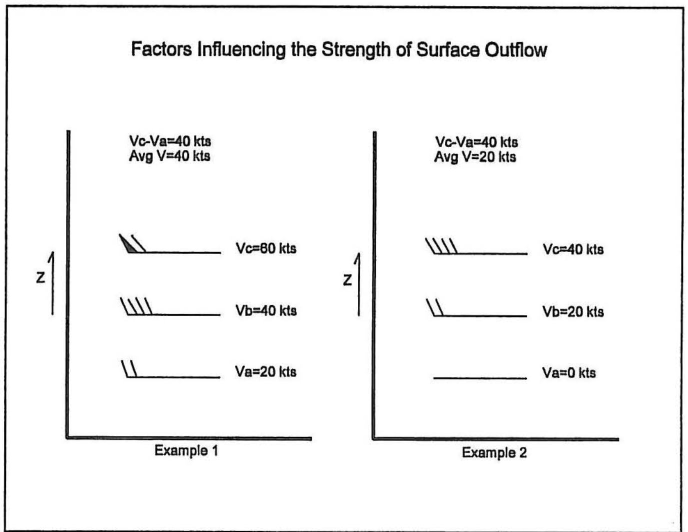

Fig. 3. Factors influencing the strength of surface outflow. Although the wind shear gradient in each layer is equal (Vc-Va = 40 kt, with each layer assumed to be of equal depth), the wind profile in example 1 would exhibit the potential for greater surface outflow than that in example 2, since the average velocity is greater than in example 2.

which exhibit rapid movement do so because of strong mid-level winds. Strong mid-level winds which overlie relatively weak winds at the surface would create a strong low-level wind shear gradient, and would thereby increase the effects of the downward transport of higher momentum. According to Duke and Rogash (1992), downbursts that are generated in environments where the winds aloft are comparatively weak show considerable variability in surface gust direction. Also, such outflow winds are relatively weak. Therefore, slow moving, or stationary thunderstorms are less likely to generate strong microbursts than fast moving thunderstorms. Also, the direction of thunderstorm motion is most often determined by the mid-level winds. These winds also determine the general direction of surface outflow since, under most circumstances, the peak gust generated by a wet microburst will reflect the direction of the mid-level winds rather than the prevailing surface wind direction observed before the onset of outflow winds.

It is reasoned that the correlation of all the above discussed environmental characteristics is necessary for the potential of wet microburst generation to be maximized. (For PC-GRIDDS users, a macro written by the author which isolates areas displaying instability, high low-level moisture, and strong low-level wind shear has been placed in Appendix 1.) The pronounced absence of one or more of these particular characteristics in an environment may greatly reduce the potential for the occurrence as well as the resultant magnitude of a wet microburst event, although hazardous outflow winds may still result.

6. Case Study

An equation (hereafter termed the equation of downward transport) has been developed by the author which assesses the magnitude of the low-level wind shear and calculates the maximum potential downburst velocity due to the downward transport of higher momentum. During 1995–1996, 22 downburst events which occurred at or near Nashville, Tennessee were analyzed using this equation. The equation of downward transport is:

$$v_{max} = (v_d v_{avg} g z)^{1/4} \qquad (3)$$

where v_{max} is the maximum potential downburst velocity (in m s^{-1}), v_d is the differential velocity, or the wind speed at the top of the shear layer minus the surface wind speed, v_{avg} is the average wind speed within the shear layer, g is the acceleration due to gravity, and z is the height (in m) above the surface of the shear layer.

This equation was developed using a simple procedure. An equation which accounted for four parameters (wind shear, average speed within the shear layer, gravity, and height of the shear layer) was desired. When these four parameters are multiplied, the resultant product is of the dimension $m^4 s^{-4}$. In order to reduce this product to a velocity, i.e., a product with the dimension m s^{-1}, the fourth root must be extracted. The equation was not designed to account for phenomena such as precipitation loading, since it is hypothesized that the downward transport of higher momentum is the primary forcing mechanism contributing to the strength of surface outflow in thunderstorm environments exhibiting strong vertical wind shear.

The results are shown in Table 3. It must be noted that all V_{max} calculations were obtained using data from the last atmospheric sounding before each event. The maximum observed wind speeds were obtained from the Nashville observation site (BNA), the nearby Rutherford County Airport (MQY), or were inferred from damage reports in or near the Nashville area.

That the majority of the cases analyzed show a definite correlation between the maximum calculated and maximum observed wind speeds gives further support to the hypothesis that the downward transport of higher momentum plays a significant role in the generation of the majority of wet microbursts, especially in the southeast United States.

Obviously, all four steps described in the wet microburst forecasting techniques are not included in equation 3. Only steps 2 and 3 are used. The first step, which is to determine the instability of the environment, must be performed in order to determine whether the equation is applicable to a particular environment. The fourth step, which is to determine the velocity of thunderstorm motion, is useful in determining the direction of outflow winds.

In order to obtain more favorable results from this downward transport equation, the author derived a regression equation using the two data sets v_{max} calculated and v_{max} observed. The regression equation derived is:

$$v_{max}regr = (0.296)v_{max}calc + 20.6 \qquad (4)$$

where v_{max}regr is the maximum potential downburst velocity derived using the regression equation, and v_{max}calc is the maximum potential downburst velocity calculated using equation (3). Combining equations (3) and (4) gives:

$$v_{max} = (0.296)(v_d v_{avg} g z)^{1/4} + 20.6 \qquad (5)$$

The results from applying equation (5) to the data are given in Table 4. The significance of this equation is in greatly reduced errors. In fact, the standard deviation of the errors in all 22 cases using equation (3) is 5.09. When equation (5) is applied to the same data, the standard deviation decreases to 2.63. (See Figs. 4 and 5.)

Obviously, further research is required for two primary reasons. First, much more data is required in order to establish a reliable regression equation. Second, it is not known whether this regression equation is universal or site specific. Therefore, local studies should be conducted at each site before determining an optimal regression equation.

Table 3. The Equation of Downward Transport Comparison

Event Number	Date of Event	v_{max} calculated (in m s^{-1})	v_{max} observed (in m s^{-1})	Error (in m s^{-1})
1	11 Apr 1995	35.2	30.9	+4.3
2	18 May 1995	44.5	38.7	+5.8
3	04 Jul 1995	32.2	33.5	−1.3
4	22 Jul 1995	28.9	32.2	−3.3
5	24 Jul 1995	28.1	29.6	−1.5
6	18 Jan 1996	51.9	36.1	+15.8
7	20 Apr 1996	28.0	30.9	−2.9
8	20 Apr 1996	30.2	36.1	−5.9
9	29 Apr 1996	35.4	28.4	+7.0
10	06 May 1996	31.3	30.9	+0.4
11	26 May 1996	25.7	25.8	−0.1
12	27 May 1996	25.4	28.4	−3.0
13	03 Jun 1996	25.6	28.4	−2.8
14	07 Jun 1996	28.6	25.8	+2.8
15	11 Jun 1996	27.4	28.4	−1.0
16	12 Jun 1996	30.0	25.8	+4.2
17	07 Jul 1996	33.9	30.9	+3.0
18	14 Jul 1996	23.3	28.4	−5.1
19	29 Jul 1996	34.0	28.4	+5.6
20	16 Sep 1996	42.3	30.9	+11.4
21	27 Sep 1996	37.5	25.8	+11.7
22	18 Oct 1996	21.8	25.8	−4.0

Table 4. Downward Transport Comparison Using a Regression Equation

Event Number	Date of Event	v_{max} calculated using regression equation (in m s^{-1})	v_{max} observed (in m s^{-1})	Error (in m s^{-1})
1	11 Apr 1995	31.7	30.9	+0.8
2	18 May 1995	34.9	38.7	−3.8
3	04 Jul 1995	30.6	33.5	−2.9
4	22 Jul 1995	29.5	32.2	−2.7
5	24 Jul 1995	29.2	29.6	−0.4
6	18 Jan 1996	37.5	36.1	+1.4
7	20 Apr 1996	29.2	30.9	−1.7
8	20 Apr 1996	29.9	36.1	−6.2
9	29 Apr 1996	31.8	28.4	+3.4
10	06 May 1996	30.3	30.9	−0.6
11	26 May 1996	28.3	25.8	+2.5
12	27 May 1996	28.2	28.4	−0.2
13	03 Jun 1996	28.3	28.4	−0.1
14	07 Jun 1996	29.4	25.8	+3.6
15	11 Jun 1996	28.9	28.4	+0.5
16	12 Jun 1996	29.8	25.8	+4.0
17	07 Jul 1996	31.2	30.9	+0.3
18	14 Jul 1996	27.5	28.4	−0.9
19	29 Jul 1996	31.3	28.4	+2.9
20	16 Sep 1996	33.1	30.9	+2.2
21	27 Sep 1996	31.7	25.8	+5.9
22	18 Oct 1996	27.1	25.8	+1.3

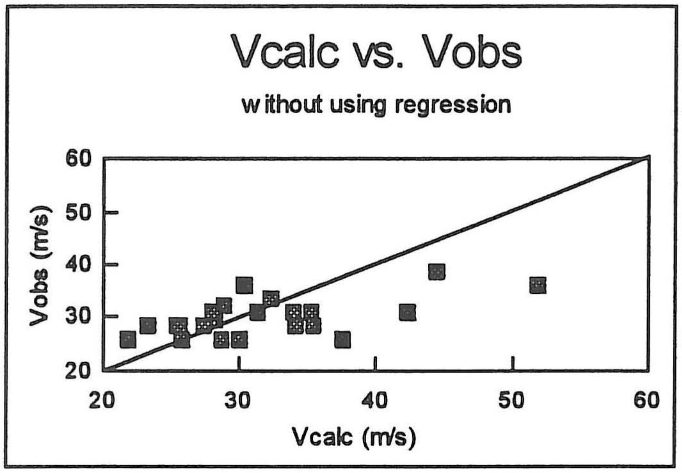

Fig. 4. Vcalc vs. Vobs without using regression (applying equation (3) and data from Table 3).

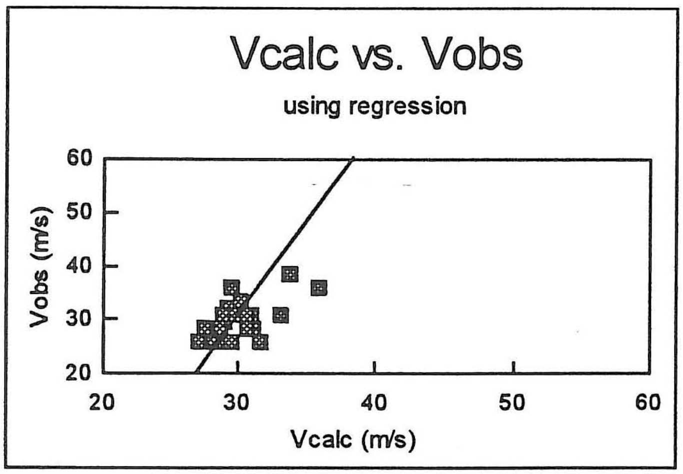

Fig. 5. Vcalc vs. Vobs using regression (applying equation (5) and data from Table 4).

7. Conclusion

* The environmental conditions which lead to dry microbursts and those which lead to wet microbursts are often quite different. Whereas dry microbursts are caused primarily by evaporative cooling, wet microbursts are the result of multiple environmental conditions.

* One hypothesis regarding the cause of wet microburst is the downward transport of higher momentum. The downward transport is thought to be the result of wind shear in the lowest levels of thunderstorm environments (termed "shear layer"), and it is also thought to contribute greatly to the magnitude of the resulting surface outflow.

* An equation has been developed which attempts to quantify the downward transport of higher momentum by accounting for wind shear as well as the average wind speed within the shear layer. A table comparing the computed downburst speeds and observed speeds in 22 cases has also been presented. A regression equation has also been derived which reduced the error between the computed downburst speeds and observed speeds. This equation is only applicable in strongly sheared environments.

Not only is the knowledge of downburst characteristics imperative to the effective forecasting of downburst potential, but also the recognition of environments which are most conducive to the occurrence of the phenomenon. In the future, forecasters must not only be familiar with these parameters, but must also conduct local analyses of strong wind events to ensure that local criteria are established. Analyses should include multiscale reviews consisting of such factors as synoptic and upper air conditions, local atmospheric sounding data, multilevel thunderstorm analysis, and surface outflow patterns. These detailed analyses are presently possible, and thorough research of future events will help ensure that further and more scrutinous recognition of downburst characteristics and particular environmental parameters are established. Such research is necessary in order to further reduce loss of life and injury and aircraft mishaps due to strong wind events associated with thunderstorms.

Acknowledgments

The author thanks Henry Steigerwaldt, Science and Operations Officer, National Weather Service (NWS) Office, Nashville, TN, Richard P. McNulty, Chief, Hydrometeorological and Management Division, NWS Training Center, and Kevin J. Pence, Science and Operations Officer, NWS Forecast Office, Birmingham, AL for their thorough and most helpful reviews of this paper. The author also thanks Darrell R. Massie, Meteorologist, NWS Office, Nashville, TN for his suggestions.

Author

The author is currently a meteorologist intern at the National Weather Service Office in Old Hickory, TN. One of his primary duties is forecaster training, which includes preparing forecast/model discussions, short term and extended forecasts, and aviation forecasts. Other duties include assisting the service hydrologist in daily data collection and preparation of monthly hydrographs. Mr. Rose graduated in May 1994 from the University of Memphis with a Bachelor of Science degree in Geography, with a concentration in Meteorology and a minor in Mathematics. His interests include hydrology and statistics.

References

Caracena, F., and M. W. Maier, 1987: Analysis of a microburst in the FACE mesonetwork in southern Florida. *Mon. Wea. Rev.*, 115, 969–985.

Doswell, C. A. III, 1985: The operational meteorology of convective weather volume II: Storm scale analysis. *NOAA Technical Memorandum ERL ESG-15.*

Duke, J. W., and J. A. Rogash, 1992: Multiscale review of the development and early evolution of the 9 April 1991 derecho. *Wea. Forecasting,* 7, 623–635.

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

Fujita, T. T., 1985: *The Downburst.* The University of Chicago.

_______________, and R. M. Wakimoto, 1981: Five scales of airflow associated with a series of downbursts on 16 July 1980. *Mon. Wea. Rev.,* 109, 1438–1456.

Hart, J. A., and W. D. Korotky, 1991: The SHARP workstation-V. 1.50. *A Skew-T/Hodograph Analysis and Research Program* *for the IBM and Compatible PC, User's Manual,* NOAA/NWS Forecast Office, Charleston, WV.

Kingsmill, D. E., and R. M. Wakimoto, 1991: Kinematic, dynamic, and thermodynamic analysis of a weakly sheared severe thunderstorm over northern Alabama. *Mon. Wea. Rev.,* 119, 262–297.

Knupp, K. R., 1989: Numerical simulation of a low-level downdraft initiation within precipitation cumulonimbi: Some preliminary results. *Mon. Wea. Rev.,* 117, 1517–1529.

McNulty, R. P., 1991: Downbursts from innocuous clouds. *Wea. Forecasting,* 6, 148–154.

Wakimoto, R. M., 1985: Forecasting Dry Microburst Activity over the High Plains. *Mon. Wea. Rev.,* 113, 1131–1143.

_______________, and V. N. Bringi, 1988: Dual polarization observations of microbursts associated with intense convection: The 20 July storm during the MIST project. *Mon. Wea. Rev.,* 116, 1521–1539.

Zipser, E. J., 1969: The Role of Organized Unsaturated Convective Downdrafts in the Structure and Rapid Decay of an Equatorial Disturbance. *J. Appl. Meteor.,* 8, 799–814.

Appendix 1

PC-GRIDDS Macro "wetm.cmd"

```
loop
eras
txt1
txt2          *** Wet Microburst Macro ***
txt3
txt4 This macro is designed to assist in locating areas with a high potential
txt5 for wet microburst generation. In order for most wet microbursts to occur,
txt6 three conditions must be present: 1). strong low-level wind speed shear,
txt7 2). high low-level relative humidity, and 3). instability adequate for
txt8 thunderstorm development.
txt9
txta This macro presents three parameters to be analyzed and correlated in
txtb order for the wet microburst potential to be assessed. Low-level wind
txtc speed shear is depicted as the difference between the 1000 mb and 850 mb
txtd wind speeds. Low-level moisture is depicted as the average relative
txte humidity in 850-1000 mb layer. And lifted indices are used to depict
txtf instability.
txtg
txth Obviously, the correlation of a high degree of all of three parameters
txti will provide the highest potential for wet microburst occurrence. This
txtj macro will hopefully provide a simple method for locating areas where
txtk these conditions are most favorable. Although wet microbursts may occur
txtl in areas where all three parameters do not correlate, optimal areas are
txtm those in which these conditions are met.
endl
loop
area 36 87 10
emap
slyr 1000 850
f0
wspk gt20 ci02 ldif
relh gt50 ci10 lave/
lndx lt01 ci01/
txt4 850 mb wind speed minus 1000 mb wind speed (white)
txt5 1000-850 mb average layer relative humidity (red)
txt6 lifted index (green)
endl
loop
f6
wspk gt20 ci02 ldif
relh gt50 ci10 lave/
lndx lt01 ci01/
txt4 850 mb wind speed minus 1000 mb wind speed (white)
txt5 1000-850 mb average layer relative humidity (red)
txt6 lifted index (green)
endl
loop
f12
wspk gt20 ci02 ldif
relh gt50 ci10 lave/
lndx lt01 ci01/
txt4 850 mb wind speed minus 1000 mb wind speed (white)
txt5 1000-850 mb average layer relative humidity (red)
txt6 lifted index (green)
endl
loop
f18
wspk gt20 ci02 ldif
relh gt50 ci10 lave/
lndx lt01 ci01/
txt4 850 mb wind speed minus 1000 mb wind speed (white)
txt5 1000-850 mb average layer relative humidity (red)
txt6 lifted index (green)
endl
loop
f24
wspk gt20 ci02 ldif
relh gt50 ci10 lave/
lndx lt01 ci01/
txt4 850 mb wind speed minus 1000 mb wind speed (white)
txt5 1000-850 mb average layer relative humidity (red)
txt6 lifted index (green)
endl
loop
f30
wspk gt20 ci02 ldif
relh gt50 ci10 lave/
lndx lt01 ci01/
txt4 850 mb wind speed minus 1000 mb wind speed (white)
txt5 1000-850 mb average layer relative humidity (red)
txt6 lifted index (green)
endl
loop
f36
wspk gt20 ci02 ldif
relh gt50 ci10 lave/
lndx lt01 ci01/
txt4 850 mb wind speed minus 1000 mb wind speed (white)
txt5 1000-850 mb average layer relative humidity (red)
txt6 lifted index (green)
endl
loop
f42
wspk gt20 ci02 ldif
relh gt50 ci10 lave/
lndx lt01 ci01/
txt4 850 mb wind speed minus 1000 mb wind speed (white)
txt5 1000-850 mb average layer relative humidity (red)
txt6 lifted index (green)
endl
loop
f48
wspk gt20 ci02 ldif
relh gt50 ci10 lave/
lndx lt01 ci01/
txt4 850 mb wind speed minus 1000 mb wind speed (white)
txt5 1000-850 mb average layer relative humidity (red)
txt6 lifted index (green)
endl
loop
eras
txt1
txt2 In order to determine the level of free sink (i.e., the height at which
txt3 a microburst might originate due to evaporative cooling), the following
txt4 time section theta-e depiction should be used. Simply find the height at
txt5 which the minimum theta-e value exists at a certain time. This level
txt6 represents the approximate height of the level of free sink.
endl
loop
plan
tinc 2
xlvl
tsct 36.1 86.4
stof
nclb pres clry
xlbl last &
xlbb hour &
hour clry &
thte ci03/
txt2 Time Section (Nashville, TN)
txt3 theta-e (K)
endl
```