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ABSTRACT

The active dry microburst days during the 1982 JAWS (Joint Airport Weather Studies) Project in Colorado are examined for common characteristics. The environments on these days are shown to have similar thermodynamic structures in the vertical. In the morning, a shallow radiation inversion is capped by a deep, dry-adiabatic boundary layer. Moisture is present at midlevels. By evening the radiation inversion has been replaced by a superadiabatic layer at the surface. Solar heating of the boundary layer is shown to be important for producing an environment favorable for dry microbursts. A model is proposed that can be used by forecasters to issue a "wind shear watch" to the general public and aviation community.

Peak downdraft speeds associated with dry microbursts appear to be a result of negative buoyancy, owing to the evaporation of precipitation during the descent below cloud base. These downward velocities are of the same magnitude as the horizontal wind speeds. Entrainment of subcloud air into the downdraft is considered minimal.

1. Introduction

In the early 1970s, photographs taken during aerial surveys performed by the University of Chicago revealed divergent patterns of wind damage in cornfields and forests after severe storm activity (Fujita, 1981; Wakimoto, 1981; Fujita and Wakimoto, 1981; Forbes and Wakimoto, 1983; Wakimoto, 1983). These photographs suggest that some downdrafts, under certain conditions, could produce tornado-force damage up to F3 intensity (Fujita and Wakimoto, 1981) at the surface. In recent years a class of these violent outflows, called "microbursts," has received a great deal of attention and has been identified as a causal factor in a number of aircraft accidents (Fujita, 1976; Fujita and Byers, 1977; Fujita and Caracena, 1977; Fujita, 1983a; National Transportation Safety Board, 1983).

Devising a scheme to predict the likelihood of a microburst event over a particular geographic area is one of the important problems facing forecasters. Although there are many guidelines that have been developed in recent years for severe thunderstorm and tornado prediction, there has been little progress on the problem of forecasting strong wind events. The purpose of this paper is to document the environmental conditions that are favorable for dry microbursts over the High Plains.

The documentation of microbursts has begun only recently, and the definition of microbursts has been modified accordingly as new information from field projects and aerial photographs from damage surveys have been analyzed. In the spring and summer of 1982, the JAWS (Joint Airport Weather Studies) Project operated near Denver (McCarthy *et al.*, 1982). The JAWS network was designed to include a small triple-Doppler radar triangle (average baseline approximately 20 km) and surface Portable Automated Mesonet (PAM) stations that were densely distributed (average spacing approximately 4 km) in order to depict the three-dimensional structure of the microburst in space and time.

Section 2 of this paper discusses the present concept and definition of dry and wet microbursts. Analysis of the microburst activity during the JAWS Project is presented in Section 3. Section 4 presents the synoptic-scale and thermodynamic conditions associated with dry microburst activity over the High Plains and Section 5 discusses the mechanism through which the dry microburst attains its peak wind speed.

2. Concepts and definitions of the microburst

After investigating the crash of an aircraft at New York City's John F. Kennedy (JFK) Airport, Fujita (1976) proposed the term "downburst" to describe the wind which affected the airport.

Downburst: A strong downdraft which induces an outburst of damaging winds on or near the ground.

In 1978, it became apparent that there were various temporal and spatial scales of downbursts; as a result the term was subdivided into "macroburst" and "microburst."

Microburst: Small downbursts, less than 4 km in outflow diameter, with peak winds lasting only 2 to 5 min. They may induce dangerous tailwind and downflow wind shears which can reduce aircraft performance.

Macroburst: Large downbursts with 4 km or larger outflow diameter, with their damaging winds lasting 5 to 20 min. Intense macrobursts cause tornado-force damage up to F3 in intensity.

The discussions in this paper will be limited to the microburst event, with emphasis on the dry microburst.

Results from the JAWS Project reveal that some microburst winds are accompanied by heavy rain from thunderstorms, while others are associated with virga shafts from either altocumuli, or clouds that have been called shallow high-based cumulonimbi by Brown *et al.* (1982). The latter cloud type may not be an appropriate description, since there was no thunder or lightning present and the visual appearance of these clouds were shallow and innocuous. (It should be noted that the term cumulonimbus does not necessarily imply lightning and thunder although they are present in most cases.) Rising convective towers were not usually apparent and the clouds were often glaciated. In these virga cases, little or no rain accompanies the microburst winds at the surface. An example of an altocumulus cloud which produced a microburst is shown in Fig. 1. Normally strong downdrafts would not be expected from this cloud type. Another example of a virga-producing microburst is shown in the article by McCarthy and Serafin (1984, p. 120). In this case the peak wind speed was 23.5 m s^{-1} and no rain was detected at the surface.

The division of microbursts into two classes has been recognized by other scientists:

1) Rodi *et al.* (1983) presented results from a case study of a "dry" microburst, when blowing dust was observed at the surface;

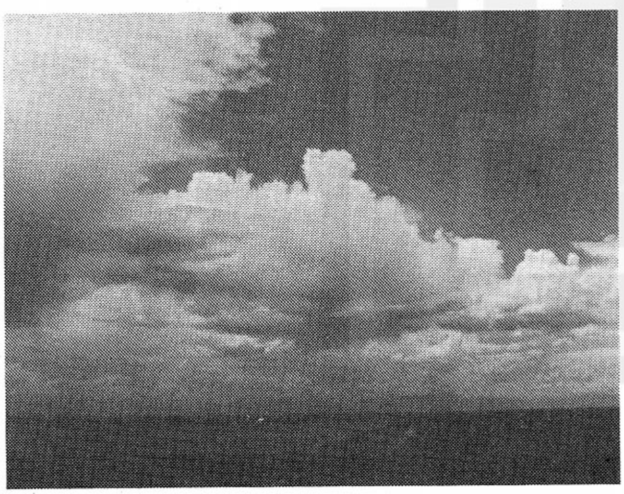

FIG. 1. An altocumulus cloud that spawned a microburst on 14 July 1982. Virga was pendant from the cloud base. (Photo by B. Smith, The University of Chicago.)

2) Wolfsen (1983) uses the terms "dry" (or "cumulus" or "virga") microburst and "wet" microburst, stating that the former comes from benign-looking cumulus clouds and the latter are associated with thunderstorms;

3) Caracena *et al.* (1983) use the terms "dry" and "wet" microbursts with basically the same definitions as Wolfsen (1983);

4) Wilson *et al.* (1984) claim that there are "dry" microbursts (virga-type) and "wet" microbursts, each having different forcing mechanisms.

Based on the past and present studies, the following definitions of dry and wet microbursts will be used:

Dry microburst: A microburst that is accompanied by little or no rain between the onset and the end of the high winds, including intermediate calm periods, if any. This type of microburst is usually associated with virga from altocumuli or shallow, high-based cumulonimbi.

Wet microburst: A microburst that is accompanied by heavy rain between the onset and the end of the high winds, including intermediate calm periods, if any. This type of microburst is usually associated with intense precipitation shafts from thunderstorms.

The use of the terms "wet" and "dry" may seem ambiguous since both types of microbursts are associated with precipitation. However, results to be presented in this paper illustrate that evaporative cooling of the precipitation within the virga shaft appears to be the primary forcing mechanism of the dry microburst, in contrast to the wet microburst which appears to be a result of several forcing mechanisms.

Initially, this proposed hypothesis seems inconsistent since a wet microburst might be expected to have more evaporation than the dry microburst—owing to the larger liquid water content descending from cloud base which does not totally evaporate before reaching the surface. This would suggest a larger pool of negatively buoyant air; however, there are three important factors, two thermodynamic and the other microphysical, which must be considered.

First, as shown by Fujita (1983b), the environmental temperature sounding of a wet microburst is close to the moist-adiabatic lapse rate. This is in contrast to the results presented in this paper, which illustrates that a typical temperature sounding during a dry microburst is dry adiabatic. Clearly, the latter sounding-type is preferred for evaporative cooling of precipitation within the downdraft. Second, there is a difference in the relative humidity of the environment below cloud base for both types of microbursts. Wet microbursts tend to occur on days when the environment contains a substantial amount of water vapor relative to the environment of the dry microburst (Fujita, 1983b). Evaporative cooling within a downdraft would proceed more efficiently in a dry environment. Third, as first discussed by Brown *et al.* (1982), it is believed the stronger updrafts associated with thunderstorms that spawn wet microbursts produce graupel and small hail which subsequently melt, forming large raindrops. On the other hand, Fujita and Wakimoto (1983a,b) have shown that the parent cloud of the dry microburst can be an altocumulus cloud with relatively weak updrafts. Owing to these updrafts and the drier environment, these clouds contain less liquid water and therefore less precipitation. This observation is confirmed by radar measurements, which illustrate that the echo of the parent cloud of the dry microburst has maximum reflectivity values of approximately 30 dBZ (Fujita and Wakimoto, 1983a,b). The particles, however, are smaller and are easily evaporated during the descent from cloud base (Pruppacher and Klett, 1978). Das and Rao (1972) noted that a given liquid water content divided into a larger number of smaller drops is more efficient in supplying moisture to the downdraft than the same liquid water divided into a smaller number of larger drops. Several of these ideas, discussed in this section, will be expanded upon in Section 5.

It is interesting to note that a related phenomenon, the "dry" downdraft, has been discussed in the literature. Braham (1952) was the first to identify the "dry thunderstorm" of the semiarid regions which produces virtually no precipitation yet is characterized by gusty winds. Krumm (1954) discussed two critical elements for the production of destructive winds (which may have been a result of dry downbursts) from a dry thunderstorm: 1) a high cloud base (3–3.5 km AGL), and 2) a dry adiabatic lapse rate in a deep, dry subcloud layer. As previously mentioned, Brown *et al.* (1982) present a study of destructive winds from extremely shallow, high-based cumulonimbi for which the term "thunderstorm" no longer necessarily applies.

3. Microburst activity during the JAWS Project

In order to devise a forecasting scheme for the occurrence of dry microbursts over the High Plains, a technique to identify the active and nonactive microburst days was developed to analyze meteorological data recorded by the 27 surface PAM stations.

An algorithm was devised to inspect the wind speed data for the characteristic peak in wind speed over a short interval noted on many past microbursts studies (e.g., Fujita and Wakimoto, 1981). First, the pre- and post-mean wind speeds were computed using the following formulas,

$$\bar{W}_- = \frac{1}{6}\sum_{-2\text{ min}}^{-7\text{ min}} W = \text{pre-mean wind speed},$$

$$\bar{W}_+ = \frac{1}{6}\sum_{+2\text{ min}}^{+7\text{ min}} W = \text{post-mean wind speed},$$

where W is the one-minute mean wind speed (see Fig. 2). The averages were computed for all of the PAM stations for the entire three-month operational period. A computer listing was made of the time (day, h, min) of the wind event which simultaneously satisfied the following six conditions:

1) $W_c \geq 10\text{ m s}^{-1}$,
2) $W_c \geq \bar{W}_- + 5\text{ m s}^{-1}$,
3) $W_c \geq \bar{W}_+ + 5\text{ m s}^{-1}$,
4) $W_c \geq 1.25\bar{W}_-$,
5) $W_c \geq 1.25\bar{W}_+$,
6) $\bar{W}_+ \leq 1.5\bar{W}_-$.

Condition 1 specifies that the center wind speed, W_c, must be faster than 10 m s^{-1} in order to be identified as a microburst. Conditions 2 and 3 state that the center wind must be at least 5 m s^{-1} faster than the mean speeds before and after the center wind speed. Conditions 4 and 5 specify that W_c must be at least 25% faster than the mean wind speed before and after the center wind. These last four conditions isolate the peaks in wind speed such as shown in Fig. 2. Condition 6 excludes gust fronts which are often characterized by strong and persistent postfrontal winds.

After the computer search, a total of 436 suspected microbursts were noted. All of the known microbursts that were documented by meteorologists in the field or by analysis of Doppler radar data were included in this listing. However, there were many wind speed traces that resemble Fig. 2 which were caused by noise or momentary peaks in the wind speed on days when the speeds were high and the wind was from a uniform direction throughout the network. Subsequently, a second screening process was developed. The wind speed, wind direction, temperature, dewpoint temperature and station pressure were plotted on a network map along with 15 min time sections of the same data. The final selection of microbursts was made after analyzing the network maps and time sections, along with a careful review of the Doppler

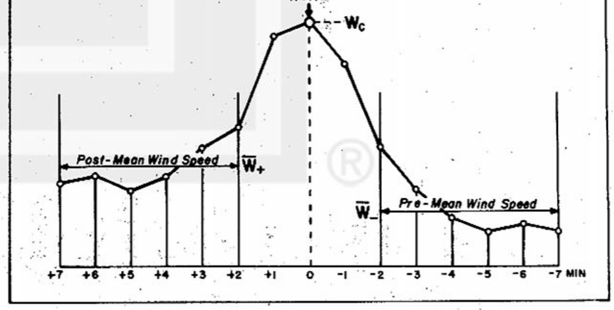

FIG. 2. A hypothetical microburst wind speed trace. The pre- and post-mean wind speeds are $\bar{W}_-$ and $\bar{W}_+$, respectively, and W_c is the center wind speed.

radar data, satellite imagery, and the log books maintained by meteorologists during the field phase of the project. This process reduced the total number of microbursts to 186.

The next step was to subdivide this total of 186 into the number of wet and dry microbursts. As previously mentioned, several researchers agree that dry microbursts are characterized by little or no rain reaching the surface and are often associated with virga shafts. Based on this observation, it was decided that a possible method for identifying dry and wet microbursts would be to examine the precipitation measured by the surface PAM stations. If the measured precipitation was less than 0.01 inches during the onset and end of high winds, it was classified as dry. If the measured precipitation was greater than or equal to 0.01 inches, it was classified as wet.

The use of a discrete measuring system at the surface to establish a division between dry and wet microbursts is not an ideal data source. Doppler radar reflectivity and velocities would certainly provide the most comprehensive information; however the exclusive use of radar data to objectively determine the active microburst days is not possible, for the following reasons:

1. There were several days when the JAWS Project shut down their entire field operations.
2. Radar observations were made only during the day and into the early evening, with no data collected before 0800 MST or after 2300 MST.
3. The statistics gained from radar are highly dependent on the geographic area in which the scanning is taking place, which changes according to storm movement.
4. There is always an unintentional bias toward scanning high-reflectivity cores, while dry microbursts are associated with relatively weak echoes.

Using the criteria of measured precipitation at the surface, 155 of the total of 186 microbursts were classified as dry. During the field phase of the JAWS Project, meteorologists were stationed at all three Doppler radar sites to log weather events, note cloud types, and take pictures of microburst events (approximately 3500 pictures were taken during the three-month period). A total of 41 microbursts within the PAM network were noted by the meteorologists and subjectively classified as either wet or dry based on the visual appearance of the rainshafts, the parent-cloud type, and the real-time Doppler radar information. All 41 cases were in perfect agreement with the subdivision obtained from the PAM data. Although this is only approximately 22% of the total number of microbursts within the PAM network, it raises the confidence level of the results. In addition, comprehensive radar reflectivity data were available for 12 microbursts within the PAM network. Examination of this data at a height of 500 m suggests that a maximum reflectivity of approximately 25 dBZ is a threshold that can be used to distinguish wet and dry microbursts. The maximum reflectivity at 1 km for two dry microbursts analyzed by Roberts and Wilson (1984) was 32 and 37 dBZ.

The daily count of JAWS microbursts is shown in Fig. 3. The 186 microbursts occurred on 49 days (155 dry microbursts occurred on 47 of these days and 31 wet microbursts occurred on 15 days). The large number of dry microbursts suggests, as expected, that dry microbursts occur frequently over the High Plains where cloud bases are high and the subcloud environment is dry enough that it is not uncommon for very light rain or no rain at all to reach the ground. The highest number of microbursts occurred in mid-July, although late May had several active days. It is surprising that the JAWS network experi-

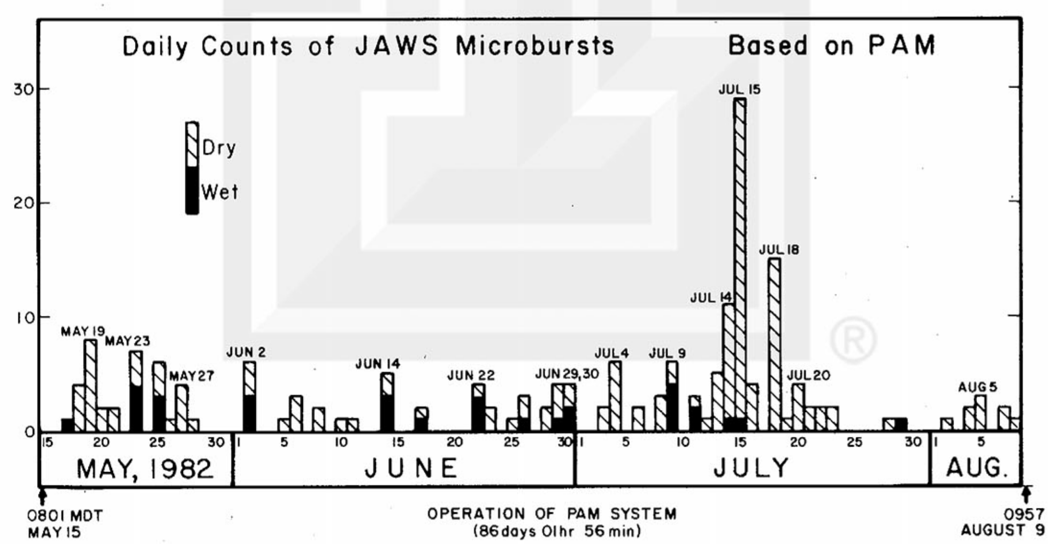

FIG. 3. Daily count of JAWS microbursts determined by computer analysis. The number of wet and dry microbursts is shown on the figure (MDT + 6 h = GMT).

enced such a large number of microbursts during the project even though it covered an area of approximately 500 km^2.

4. Forecasting dry microburst activity

During the field phase of JAWS it was the general agreement among scientists that the environmental conditions prior to the formation of microbursts were not clearly understood. An example of this lack of knowledge occurred on 18 July 1982, when a nowcast (0–24 h) was made in the early morning hours. After a careful examination of the synoptic charts and the rawinsonde data, a decision was reached by the principal scientists that 18 July would not be an active day and as a result the JAWS Project was shut down for the entire day. To our dismay, as illustrated in Fig. 3 and confirmed by a storm chase team working on their own (Joe Golden, personal communication, 1983) 18 July was the second most active microburst day.

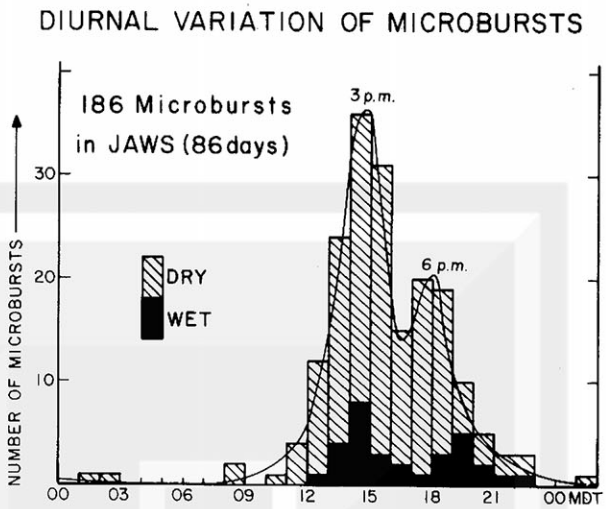

FIG. 4. Diurnal variation of the 186 microbursts during the JAWS Project. Most of the activity occurs during daylight hours with two peak periods at 1500 and 1800 MDT (MDT + 6 h = GMT).

a. Factors controlling the spring and summertime weather over Denver

It is a well-known fact that the nature of the spring and summertime weather over Denver is diurnal. This observation was noted by Cook (1939) and Beckwith (1957, 1960) during their analyses of thunderstorm activity over the Denver region. In general, there is a lack of thunderstorm development during the night and early morning hours.

Based on the statistics obtained from the PAM data, the diurnal variation of microbursts during JAWS was examined (Fig. 4). This figure illustrates that there is also a diurnal influence on the microburst activity over Denver, which is clearly related to solar heating. During JAWS, both dry and wet microbursts increased rapidly around noon, reaching a significant peak at approximately 1500 MDT (MDT + 6 h = GMT). A secondary peak of dry microburst activity occurred at 1800 MDT. The dependence of microburst activity on solar heating over Denver suggests that the rawinsonde data at Denver may be the key to understanding the environmental conditions favorable for wind shear events over the High Plains.

Although rawinsonde data is envisaged as being important for predicting dry microbursts, there were several synoptic features that were noted on most of these active days. A weak cold or stationary front with waves was near Denver during the day. In the morning, a weak to moderate 500 mb trough was generally located near the Pacific Northwest with the accompanying ridge in western Nebraska. Positive vorticity advection (PVA) was either weak or absent over Denver during the day. No upper-level jet streak of significance was noted on these days and, in general, the upper-level winds were only of moderate intensity, with only one case when the winds exceeded 50 kt on the Denver sounding. Surface winds in the morning were calm or of light intensity from a southwesterly direction.

b. Denver soundings

Based on the discussion in the previous section, the rawinsonde data at Denver for the active dry microburst days were carefully examined for common characteristics. Upon examination of Fig. 3, five days were identified as representative of dry microburst activity: 19 May and 4, 14, 15 and 18 July. These five days are not only characterized by the highest total number of dry microbursts but also by the highest wind speed values—values that exceeded the approximately 20 m s^{-1} headwind–tailwind wind speed differential that the Pan American airline encountered when it crashed at Kenner, Louisiana, in 1982 (NTSB, 1983).

Although these days are dominated by a large number of dry microbursts, Fig. 3 illustrates that wet microbursts occurred on 14 and 15 July. Thus the criteria that will be developed in this paper does not exclude the possibility of a wet microburst event. This is especially true in the lee of the Rocky Mountains where thunderstorm probability, and therefore wet microbursts in the spring and summer, is high owing to the orographic effects to be discussed later. This should not, however, affect the usefulness of the results. A related example would be a tornado forecast that is issued and verified for a particular day. Obviously, many of the thunderstorms on that day would not be severe. In that instance, we do not consider a tornado forecast as misleading since environmental conditions would also be favorable for nonsevere thunderstorms.

For each of the days listed before, the soundings at 1100 and 2300 GMT were plotted on a thermodynamic diagram (Figs. 5 and 6). Amazingly, the temperature and moisture profiles on these days for both time periods are remarkably similar. The question of how these soundings differ from the days when no microbursts occurred is addressed in the next section.

At 1100 GMT,[1] the temperature sounding is characterized by a shallow radiation inversion owing to nocturnal cooling at the surface. Typically, this layer is no deeper than 40–50 mb. Above this layer is an extremely deep dry-adiabatic layer with a top near 500 mb. The lapse rate above this mixed layer is slightly less than the moist adiabatic lapse rate up to the tropopause. Note, as expected, that the tropopause on 19 May is significantly lower than on the microburst days in July. The dew-point temperature sounding is characterized by two types of moisture profiles. At the surface, both profiles have moisture present, with the dew-point temperatures ranging from 2 to 9°C. In one profile (Type A), the mixing ratio decreases with height but approaches saturation at midlevels. In the other profile (Type B), the air is dry just above the surface but approaches saturation at midlevels, similar to Type A.

At 2300 GMT the temperature sounding is characterized by a shallow superadiabatic layer, usually less than 10 mb in thickness, near the surface owing to solar heating. Above this layer the temperature lapse rate is still dry adiabatic up to 500 mb. Since this layer is well mixed, the moisture profile is nearly parallel to the constant mixing ratio line, except near the surface where the moisture content increases. However, the Type B sounding still exhibits some drying in the layer above the surface. The surface dew-point temperatures have dropped compared to the morning, ranging from −2 to 3°C. The height where the dew-point depression approaches zero aloft is close to the cloud base reported by the Denver office of the National Weather Service.

During the JAWS Project, soundings were also launched at 1700 and 2000 GMT. An example of the evolution of the dry microburst environment on 14 July 1982 is shown in Fig. 7. The microburst activity in the JAWS network occurred between 1944 to 2356 GMT during this day. Upon examination of the soundings in Fig. 7, it appears that the first microburst reached the surface soon after the convection temperature was reached. The reported clouds and cloud bases are indicated on the figure.

The preference for the sounding type (shown in Figs. 5 and 6) over the High Plains is understandable when one considers the affect of the orography on the atmospheric flow patterns. The high elevation of

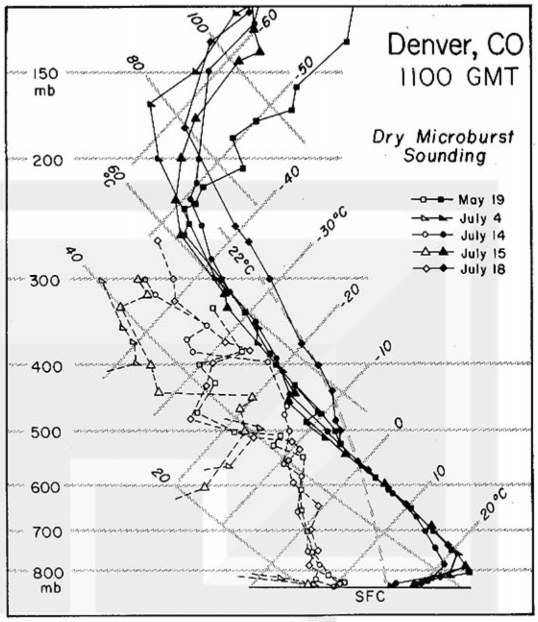

FIG. 5. Morning soundings launched at Denver, Colorado, on five dry-microburst days.

the surface combined with the tendency for subsidence on the eastern slopes of the Rocky Mountains favor a deep dry layer in this region. In addition, insolation tends to produce a deep dry-adiabatic layer which frequently generates convection. This convection is often concentrated by the daytime upslope flow that is part of the mountain–valley orographic and diurnal circulation (Orville, 1964; Henz, 1972; Raymond and Wilkening, 1980). Dry microbursts are a daytime phenomena, since it is hypothesized that dry microbursts are favored when a certain type of precipitation falls into a deep dry-adiabatic layer and daytime is when such optimal environmental conditions normally occur.

The dry-microburst sounding should be relatively dry, except at midlevels, in order to have a greater evaporative cooling potential. Of great importance is the orographic effect, which helps generate some convection on these days when it normally might not occur. This convection is not always a thunderstorm. If the sounding is too dry, it is unlikely that clouds and hence precipitation will form and, if the sounding is too moist, numerous thunderstorms may develop (Beckwith, 1960). It is believed that these moist days would be more conducive to wet-microburst generation. As previously mentioned, the wet microburst is usually embedded within the main precipitation shaft of a thunderstorm.

A schematic model summarizing the characteristics of the morning and evening soundings for dry microburst activity over the High Plains is shown in Fig. 8. The morning Type B sounding is similar to the 1200 GMT sounding deduced by Caracena *et al.*

[1] The thermodynamic data is correct only for the 15 July sounding. The other soundings have been shifted so that the temperature curves of the dry-adiabatic layer overlap. This adjustment was made to emphasize the similarities between the soundings.

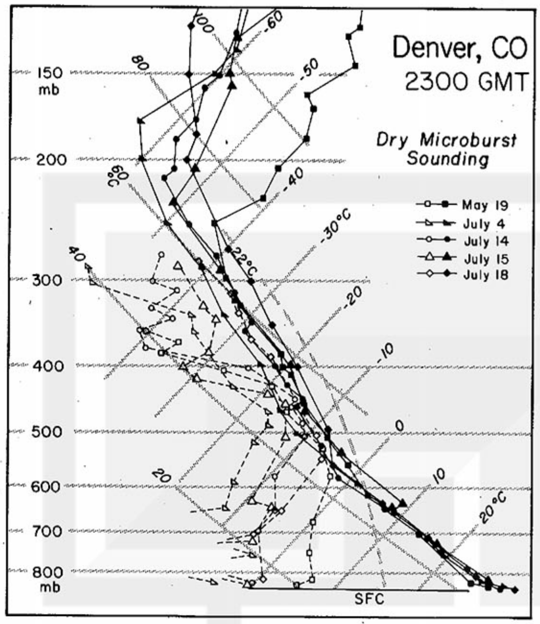

FIG. 6. As in Fig. 5 but for evening.

(1983), which they claim is typical of the dry microburst environment. The evening Type A sounding is similar to the 0000 GMT sounding at Denver for extreme wind events from shallow, high-based cumulonimbi, deduced by Brown *et al.* (1982), and the heat burst sounding by Johnson (1983) on a day when downburst-type winds occurred in Oklahoma. It should be mentioned that although dry microbursts may occur whenever a sounding similar to the model in Fig. 8 is present, it may be difficult to initiate convection under these environmental conditions without the orographic forcing.

Table 1 summarizes the lifted index, subcloud lapse rate at 2300 GMT and the variation of wind direction from the surface to cloud base. The indices suggest that the soundings are stable in the morning and subsequently become neutral or slightly unstable by evening, except for the sounding on 15 July. The temperature lapse rate at 2300 GMT below cloud base is close to the dry adiabatic rate and surprisingly, is superadiabatic on three of the five days owing to the heating in the surface boundary layer. The subcloud winds are an indication of the change in stability. At 1100 GMT the veering and subsequent backing of the winds with increasing height on three of the days suggests a destabilization of the temperature lapse rate while the veering of the winds on the other two days occurs at the lowest levels, which is still an indication of destabilization. The backing of the subcloud winds with increasing height at 2300 GMT is a result of the overall cooling of the layer after sunset.

Based on the observations from the JAWS Project, the following conditions can be considered necessary for an environment to be favorable for dry-microburst activity:

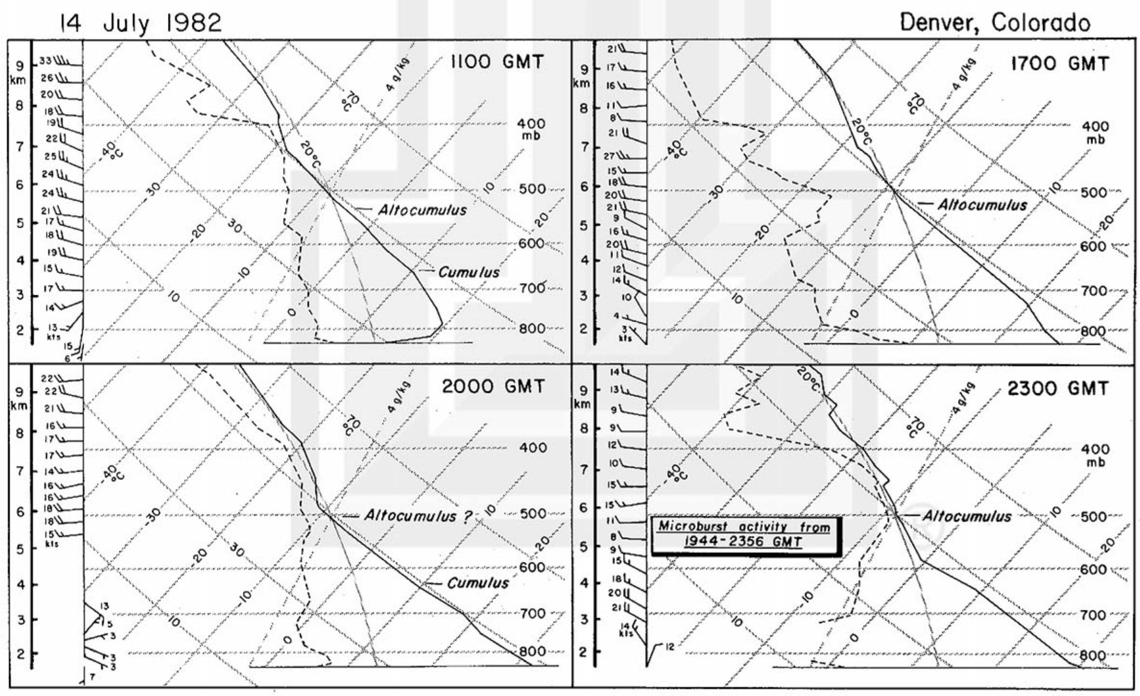

FIG. 7. Evolution of the dry microburst environment on 4 July 1982. Reported clouds and cloud bases are indicated on the figure. Microburst activity in the JAWS network occurred between 1944 and 2356 GMT.

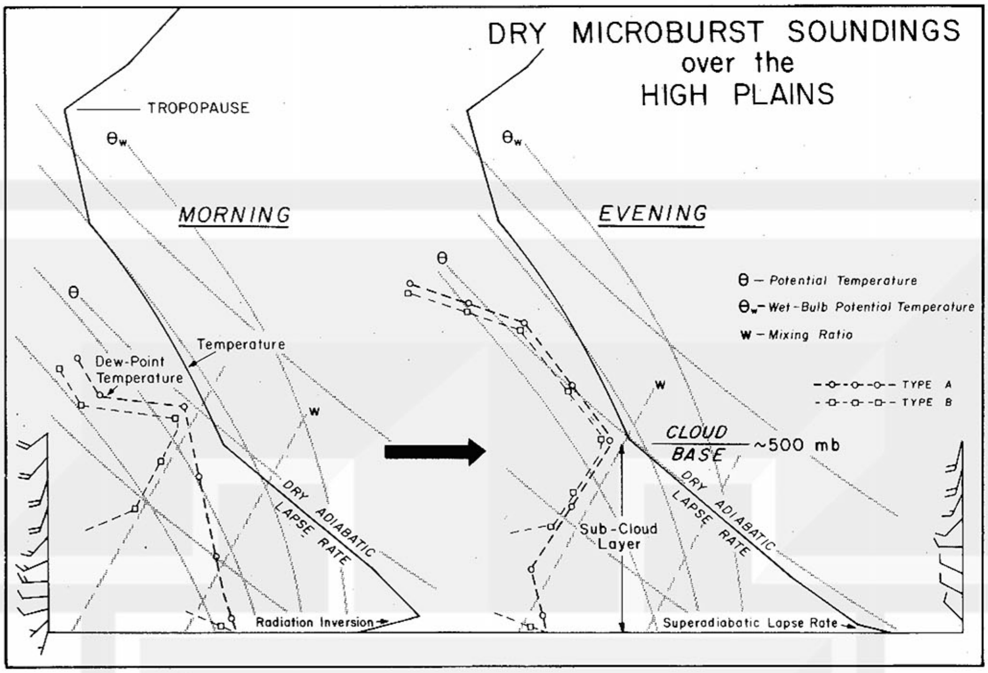

FIG. 8. Model of the characteristics of the morning and evening soundings favorable for dry-microburst activity over the High Plains.

1) In the morning there is a shallow radiation inversion at the surface (approximately 40–50 mb in thickness) beneath a deep dry-adiabatic layer.

2) The dry-adiabatic layer must extend to approximately 500 mb.

3) The mean subcloud mixing ratio is approximately 3–5 g kg^{-1}, with midlevel moisture present as shown in Fig. 8.

4) The convection temperature must be reached during the day.

c. Days with no microbursts

When attempting to isolate the environmental conditions favorable for dry microbursts, it is important to consider the days when no wind shear events were present. As shown in Fig. 3, there were 37 days when no microbursts occurred in the PAM network during the JAWS Project. These days can be divided into the following four categories:

1) Seven days were characterized by stratiform rain owing to easterly winds forcing air up the Front Range of the Rocky Mountains.

2) Thunderstorms were present on 15 days.

3) Ten days would be classified as "fair weather" days.

4) Five days were characterized by virga from clouds similar to the ones that produce dry microbursts.

TABLE 1. Dry microburst soundings.

DATE	Lifted Index 1100/2300 GMT	2300 GMT Sub-Cloud Lapse Rate	Wind Direction Surface→Cloud base 1100 GMT	2300 GMT
May 19	3.0 / -0.5	9.75 °C/km	backing ↓ veering	backing
July 4	4.0 / 0.0	9.99 °C/km	backing ↓ veering	backing
July 14	3.5 / -0.5	9.55 °C/km	veering	backing
July 15	2.5 / 2.0	8.99 °C/km	veering	veering ↓ backing
July 18	2.5 / 1.0	10.27 °C/km	backing ↓ veering	veering

Before discussing each of the four categories, we should consider one day in particular—17 July that provides some insight into the problem of forecasting dry-microburst activity. This day falls under the second category when thunderstorm activity was present.

Although the synoptic conditions over the Denver area did not change drastically between 14–18 July, the 17th was an inactive day between several very active dry microburst days (see Fig. 3). To understand this behavior, the morning soundings on the 17th and the 18th were plotted in Fig. 9. At first glance, the soundings appear similar; however, a shallow cold layer originating from the north propagated through the JAWS network in the early morning on 17 July

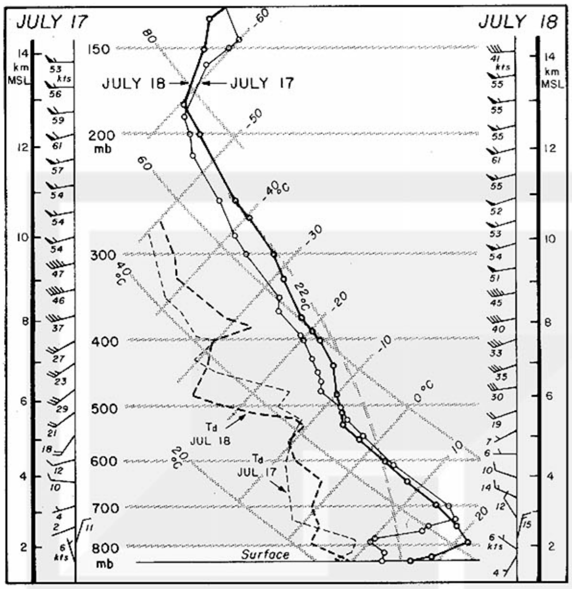

FIG. 9. Soundings at 1100 GMT over Denver on 17 and 18 July. Note the shallow, cool layer on the 17th, capped by an inversion between the 730 and 780 mb levels.

(note the northerly winds at the low levels). This air mass produced a significant stable layer capped by an inversion between the 730 and 780 mb levels. Solar heating, which has been shown to be important for producing an environment favorable for dry microbursts, could not remove this inversion. As previously mentioned, thunderstorms did form over the mountains and propagated eastward through the JAWS network; however, since the thermodynamics of the boundary layer were not ideal, no significant wind shear event was noted. By the morning of the 18th, the shallow radiation inversion had returned, along with the intense dry-microburst activity during the day.

Of the four categories, the first situation is common in the Denver area and is frequently referred to as "upslope conditions." The temperature soundings are usually moist adiabatic and saturated from the surface to approximately the 500–600 mb levels. Under these conditions, evaporated cooling of precipitation would not be expected to occur efficiently. Based on analyses of many case studies and two field projects, it has been concluded that the parent clouds of microbursts are convective; a stratiform cloud producing a microburst has never been documented.

The second situation can be separated into two categories, i.e. days when thunderstorms occurred a) within the network, and b) outside the network. Wet microbursts may have been present on days when the thunderstorm activity was outside of the network. However, based on log books maintained by the observing meteorologists, 11 of the 15 days had thunderstorms within the PAM network. These storms produced rain and/or hail, but no significant outflow. Clearly there is a need to understand the differences between thunderstorms that produce wet microbursts and those that produce precipitation and weak downdrafts. On 10 of these 15 days the soundings were similar to those deduced by Fawbush and Miller (1953) and Beckwith (1960) for hailstorms. The other five days that did not appear to be favorable for thunderstorm development were apparently related to the orographic circulation that can initiate convection over the mountains which subsequently propagates over the High Plains if sufficient moisture is present. None of the soundings on these 15 days were similar to Fig. 8, although the sounding on 17 July was not drastically different.

The third group of days were characterized by either clear skies, scattered cumulus humulis or thunderstorm activity restricted to the mountains. There was a spectrum of sounding types for these days but none were similar to Fig. 8. In all but two cases the temperature sounding was not dry adiabatic. In the other two cases the dry-adiabatic layer was not deep enough and there was insufficient moisture present, especially at midlevels.

The five nonmicroburst days when virga was present from parent clouds that were similar to the active dry-microburst days are the most interesting cases. On three of the five cases, the temperature sounding was not dry adiabatic. In addition, these soundings had considerable amounts of moisture present, especially at the low levels. These two factors would not be favorable for strong evaporative cooling to occur below cloud base. On the other two days when a deep, dry-adiabatic layer was present, the convective temperature was never achieved during the day. As a result the subcloud layer was not well mixed, as was evidenced by the moisture curves at 2300 GMT. In both cases the mixing ratio decreased with height, in contrast to active dry microburst days.

Two conclusions can be drawn from these virga case studies:

1) Virga appears to be an essential ingredient for dry microburst only when the subcloud moisture and temperature profiles are similar to Fig. 8.

2) The forecaster must be aware of the expected maximum temperatures in the afternoon.

It is interesting that results from the JAWS Project reveal that microbursts can be absent on active thunderstorm days. A summary of the relationship between thunderstorms and microbursts during the 86-day period is shown in Table 2. The numbers within parentheses represent days when thunderstorms formed within, or propagated through, the PAM network. This table clearly illustrates that a microburst forecast is not the same as a thunderstorm forecast.

TABLE 2. Relationship between microburst and thunderstorm days.

	Days with microbursts	Days without microbursts	Total
Days with thunderstorms	36 (21)	15 (11)	51
Days without thunderstorms	13	22	35
Total	49	37	86

5. Determination of peak windspeeds

An important consideration is the mechanism through which the dry microburst attains its peak wind speed. Hookings (1965), Kamburova and Ludlam (1966) and Ludlam (1980) have studied the maintenance of downdrafts by the evaporation of falling precipitation as a function of drop size, rain intensity and downdraft speed. One of their conclusions is that the principal factors in the production of strong downdrafts are the intensity of rainfall and steepness of the environmental lapse rate. However, if the environmental lapse rate was approximately equal to the dry-adiabatic lapse rate, then the microphysics of evaporation places little restriction on downdraft magnitude; and even in a moderate or light rain, strong downdrafts may be generated.

Although past studies suggest that microphysics plays a minor role when the temperature lapse rate is dry adiabatic, it is believed that weak updrafts (supported by the lifted indices in Table 1) within the parent clouds of dry microbursts produce a precipitation type that is easily evaporated in the downdraft. This agrees with the hypothesis of Brown *et al.* (1982) that weak updrafts result in an abundance of lightly rimed snowflakes. These particles evaporate rapidly and completely during descent from cloud base. This is confirmed by measurements from Knight *et al.* (1974) who have shown that rimed snowflakes are observed in virga from Colorado cumulus. In addition, Rodi *et al.* (1983) measured small particle sizes between 10^{-5} and 10^{-3} m within a virga shaft of a dry microburst during JAWS.

Based on these past studies, it is not surprising that the dry-adiabatic lapse rate in Fig. 8 would be conducive of strong downdrafts; however, it does not explain the short temporal and small spatial scales of the microburst. In this regard, cloud base detrainment instability (CBDI) as discussed by Emanuel (1981) could be the mechanism for initiating the dry microburst. In particular, he suggests that CBDI must be limited to clouds resulting from the horizontal advection of cloudy air over clear air. This scenario frequently occurs in the Denver area, where clouds form above the mountains and subsequently advect eastward over the High Plains.

To test the importance of evaporative cooling within the downdrafts, simple thermodynamic calculations were performed. The buoyancy equation can be written as

$$\frac{dw}{dt} = g\frac{T' - T}{T}dz - \text{precipitation drag}, \qquad (1)$$

where T' and T are the virtual temperatures of the parcel and that of the environment, respectively. Dry microbursts are characterized by light rainfall which often does not reach the ground, so for our purposes the drag by precipitation can be ignored, as Krumm (1954) has suggested. If it is assumed that the conditions are steady state, and the horizontal advection of w is negligible, Eq. (1) can be rewritten as

$$\frac{1}{2}w^2 - \frac{1}{2}w_0^2 = -R\int_{p_0}^{p}(T' - T)\frac{dp}{p}. \qquad (2)$$

Equation (2) expresses the well-known fact that the gain of kinetic energy of the parcel is proportional to the area between the parcel path and the environmental sounding on a thermodynamic chart which has ln P and T as its coordinate axes (e.g. an Emagram).

Although (2) has frequently been applied to compute updraft speeds within convective phenomena, there are relatively few cases when it has been used to compute downdraft speeds. Fawbush and Miller (1954), Foster (1958) and Markus (1980) all used variations of the parcel theory for estimating gusts from thunderstorms. In each case they assumed that the descending parcel remained saturated during its descent to the surface. It is questionable whether this applies to the downdraft of a dry microburst. Over the High Plains, Krumm (1954) noted that since most of the raindrops evaporate before reaching the surface, the parcel descent could not continue moist adiabatically. Calculations by Das and Rao (1972) show that the circumstances that cause greater subsaturation in the downdraft occur when the temperature distribution is close to the dry-adiabatic rate.

Figure 10 was constructed to model the descent of a parcel within a dry microburst over the High Plains. This model is similar to one proposed by Krumm (1954) for dry thunderstorms. The mixing ratio and dry-adiabatic path of the parcel is determined by the surface temperature and dew-point temperature within the microburst recorded by the PAM stations. This model does not account for entrainment, which will be subsequently examined.

The model in Fig. 10 was applied to the five dry-microburst days. On each of these days, the surface thermodynamic characteristics of the strongest microburst was used, since it was believed that they would suffer the least entrainment. The sounding (launches at 1100, 1700, 2000 and 2300 GMT) closest to the microburst time was used in the calculation of the

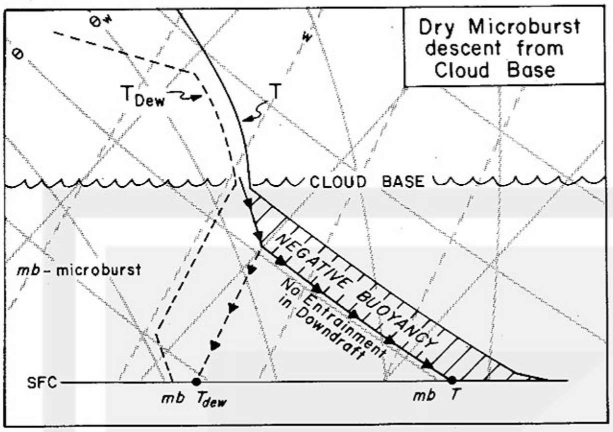

FIG. 10. Model of the thermodynamic descent of a dry microburst from cloud base. Surface temperature and dew-point temperature within the microburst are determined from PAM data. No entrainment into the downdraft is assumed.

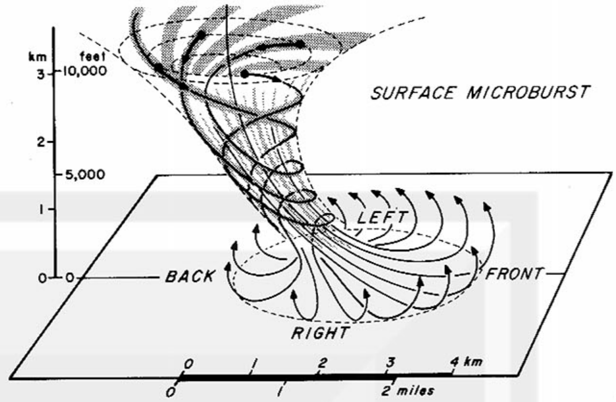

FIG. 11. Model of the descent of a microburst from cloud base. A rotating downdraft was frequently observed by the Doppler radars (from Fujita and Wakimoto, 1983b).

negative buoyancy. If it is assumed that $w_0 = 0$ at cloud base, Table 3 presents the calculated vertical velocities just above the surface. Also included in the table are the observed peak horizontal wind speeds of the microburst. It should be noted that owing to the large depth of the subcloud layer, a relatively small negative buoyancy may result in a significant integrated negative area on a thermodynamic chart.

The results from Table 3 suggest that the vertical wind speeds within a dry microburst are of the same magnitude as the horizontal wind speeds. If a small amount of entrainment had been incorporated into the downdraft the difference in the wind speeds would be smaller. The neglect of entrainment is based on results from Fujita and Wakimoto (1983a,b) taken from Doppler radar measurements during the JAWS Project. Figure 11 of their article illustrates the observation that microbursts have rotating downdrafts as they descend from cloud base. Apparently this rotation reduces entrainment and allows the vertical momentum to be preserved as it approaches the surface. The vertical wind speeds derived from thermodynamic calculations in Table 2 support this idea. Weisman *et al.* (1983), with the aid of a three-dimensional cloud model, hypothesize that this vertical vorticity is produced by the interaction of the storm with the environmental vertical wind shear and is stretched in an accelerating downdraft.

TABLE 3. Comparison of calculated vertical wind speeds and observed horizontal wind speeds within a dry microburst. Vertical speeds are based on negative buoyancy from evaporative cooling of precipitation particles.

Day	Calculated vertical speeds (m s^{-1})	Observed horizontal speeds (m s^{-1})
May 19	26.7	24.6
July 4	37.5	24.4
July 14	36.0	28.3
July 15	32.4	29.5
July 18	37.8	29.6

Although evaporative cooling of precipitation appears to be the logical mechanism for the prediction of wind speeds within a dry microburst, it is doubtful whether this could be applied to a wet-microburst event. Fujita (1983b) analyzed a wet microburst which struck Andrews Air Force Base, when the recorded peak horizontal wind speeds were greater than 67 m s^{-1}. The related vertical wind speeds could not be attained by negative buoyancy alone. The nearby sounding for his case study was saturated with the temperature profile close to the moist-adiabatic lapse rate from the surface to near the tropopause. It is believed that the wet microburst intensity may also be a function of either upper-level momentum descending to lower levels as described by Forbes *et al.* (1980) or strong motions produced by dynamically-induced pressure gradients discussed by Wolfsen (1983). The dynamics of the wet microburst is still a topic for future research.

6. Conclusions

The days which are characterized by dry-microburst activity over the High Plains have a common thermodynamic structure in the vertical. Interestingly, the synoptic conditions on these days does not play a major role in setting up favorable environmental conditions. The model in Fig. 8 can be used by National Weather Service forecasters to issue a "wind shear watch" to the general public and also would be important to disseminate to airline pilots who would become alert and cognizant of possible hazards during takeoff and landings. These results are in agreement with Wilson *et al.* (1984), who state that general area-wide alerts for dry microbursts can be made based

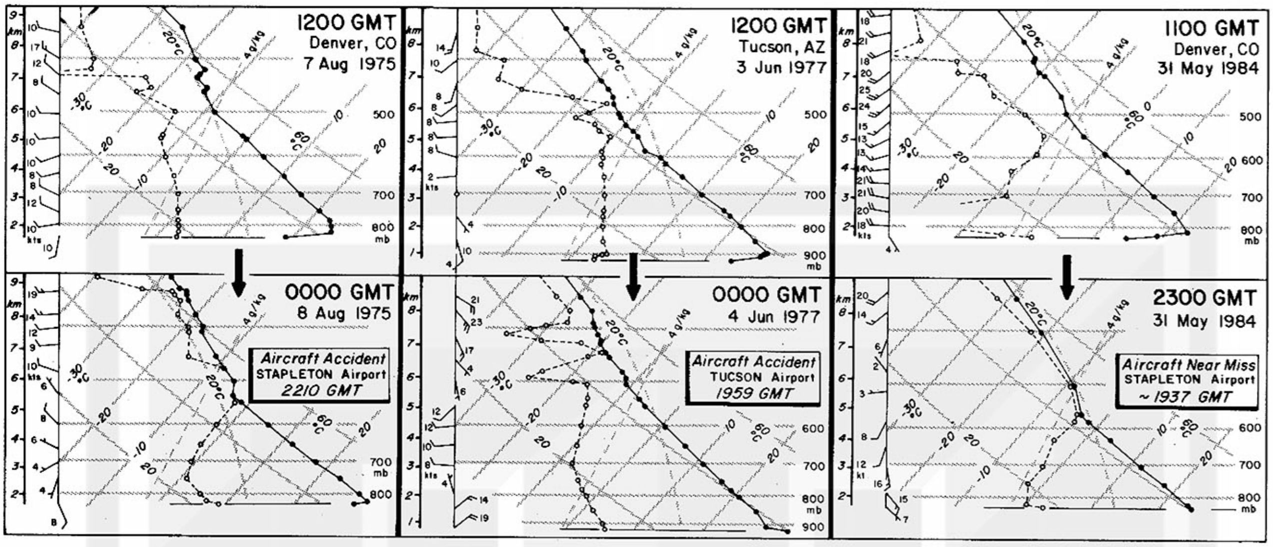

FIG. 12. The morning and evening rawinsonde soundings on the days when there were two aircraft accidents and one near miss. Note the similarities between these soundings and Fig. 8.

on vertical moisture and temperature profiles. It is unfortunate that the magnitudes of the wind speed cannot be anticipated since this would require advance knowledge of the surface temperature and dew-point temperature within the microburst.

Peak downdraft speeds associated with dry microbursts appear to be a result of negative buoyancy, owing to the evaporation of precipitation during the descent below cloud base, and are the same magnitude as the horizontal speeds. Entrainment into the downdraft is considered minimal. The relatively dry environment and the small updraft vertical velocities on dry microburst days apparently produce a preferred precipitation type—rimed snowflakes. These snowflakes can readily evaporate during the descent below cloud base.

To make an assessment of the forecast criteria presented in this paper, the sounding information from two past aircraft accidents at Denver, Colorado, and Tucson, Arizona, and a near miss at Denver, were plotted in Fig. 12. These events were all attributed to wind shear. Note the similarities between these soundings and Fig. 8. Meteorologists should be aware of this thermodynamic profile.

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