A Summertime Tornado Outbreak in Colorado: Mesoscale Environment and Structural Features

EDWARD J. ZIPSER
National Center for Atmospheric Research1, Boulder, CO 80307

JOSEPH H. GOLDEN
Environmental Research Laboratories, NOAA, Boulder, CO 80303

(Manuscript received 2 March 1979, in final form 22 June 1979)

ABSTRACT

On 14 August 1977, there was a mini-outbreak of three tornadoes about 40 km east of Denver, Colorado. There were no significant synoptic-scale disturbances affecting Colorado on that day. Mesoscale analysis is used to establish several smaller scale systems that influenced storm development. The most notable feature of the mesoscale band of parent thunderstorms was the active growth along their northwest flank, in spite of cell movement toward the east. On the convective scale, the situation can be described as discrete propagation of multi-cell storms by new cell development on the left rear flank. Two of the three tornadoes were documented photographically, and post-analysis shows that they were of large size and long duration, but slow moving. Structural features of the largest tornado are analyzed in different portions of the life cycle, and compared with other cases in the literature. This tornado moved on a track curving toward the north-northwest, remaining at least 5–10 km distant from any significant precipitation. A dust band believed to represent an inflow jet was observed, which was in a different quadrant from similar features in other cases. Aspects of the tornadoes which could cause public confusion are noted, such as the disproportionately short condensation funnel from high-based cumulus clouds.

1. Introduction

The thunderstorms of the High Plains near the east slope of the Rockies are frequent hail producers, but they are not well known for their tornadoes. Recently, a number of papers have shown examples of Colorado tornadoes. Prosser (1976) suggested that Denver area tornadoes were characteristically weak and that the large vortex that he described was exceptional. Connell (1975) and Golden (1978) showed examples of large Colorado tornadoes. The frequency of tornadoes can be surprisingly high. Pearson et al. (1977) and Ostby et al. (1978) list 42 and 32 Colorado tornadoes during 1976 and 1977, respectively, a two-year total exceeded by just six other states.

In Colorado, a rapidly increasing population is expanding into High Plains areas where, previously, tornadoes would have crossed only rangeland. Although the recent totals may be anomalous, it would not seem prudent to regard High Plains tornadoes as either rare or unimportant.

On 14 August 1977, there was a mini-outbreak of three tornadoes near Bennett, Colorado, ~40 km east of Denver’s Stapleton Airport (Fig. 1). Our interest was especially aroused when, some weeks after the event, we were shown a set of excellent photographs of the largest tornado, taken by a state patrolman. When the evidence of these photographs was combined with other eyewitness accounts and pictures, that tornado was established to be of large size (200 m in diameter) and long lifetime (~36 min). Unfortunately, there was no aerial survey, but a ground survey was made several weeks after the event; our observations and interviews at that time led us to conclude that no structure suffered a direct hit, but that winds in the 45–55 m s⁻¹ range (i.e., an F3 damage estimate according to the scale developed by Fujita (1971)) were responsible for the considerable damage to trees and structures, and for the injury to one man pierced in the leg by a flying board. Statistically, most tornadoes of that size and longevity would be in the F2 or F3 class (Fujita and Pearson, 1973). Upon closer investigation, some anomalous attributes of the tornado emerged. In common with other Colorado tornadoes (Flavin, 1952; Connell, 1975; Prosser, 1976; Golden, 1978) forward motion was very slow, in this case about 4 m s⁻¹. But the largest Bennett tornado had a westward component
of motion, an extremely rare occurrence. Further, it was on the west flank of a band of cumulonimbus which was itself propagating toward the west, despite strong relative inflow of low-level moist air from the southeast, the more conventional flank for new growth.

An attempt to understand these facts led to subsynoptic analysis, and to the obvious conclusion that the antecedent conditions to these tornadoes were rather different from those usually cited for most tornadoes. Needless to say, these Colorado tornadoes often create forecasting problems. In this case, a severe thunderstorm watch was issued by the National Severe Storms Forecast Center for an area to the east of the actual location of the storms discussed in this paper, but only after the dissipation of the tornadoes. In actuality, all storms dissipated rather quickly without seriously affecting the warning area. Since none of the other Colorado tornadoes known to us fit the classical picture either, we believe that documentation of the mesoscale setting of the Bennett tornadoes is justified. In addition, this paper describes the size, the motion and certain structural features of the tornadoes.

2. Synoptic-scale and mesoscale environment of the Bennett tornadoes

On the day of the tornadoes, no major synoptic-scale disturbances were affecting Colorado. At 700, 500 and 300 mb, a large ridge of high pressure covered most of the central United States, with a rather weak extension westward along the Colorado-New Mexico border. At the surface, a diffuse quasi-stationary front was oriented from northeast to southeast, separating warm air over the mountains from cooler air over Kansas and Nebraska. The synoptic-scale gradients associated with the front were generally overwhelmed by those of mesoscale events (Fig. 2).

A strong mesoscale high-pressure system (hereafter called the mesohigh), developed over Nebraska during the previous night in association with widespread thunderstorms, and moved southeastward at \( \sim 12 \text{ m s}^{-1} \) across Kansas during the day. It was accompanied by a pressure rise of about 4 mb relative to normal diurnal changes (Figs. 2a–2c), a temperature fall of \( \sim 10 \text{°C} \) relative to the normal diurnal trend (Figs. 2a–2f), and a wind velocity change of 10 m s\(^{-1}\) or more (Figs. 2a–2f). The western flank of the mesohigh, initially distinct in eastern Colorado (Figs. 2a, 2d), tended to reinforce and merge with the mountain-to-plain pressure and temperature gradients later in the day. At 2100 GMT, for example, there was a potential temperature gradient of over 20°C across eastern Colorado. Throughout the day, there was a general increase in upslope wind components.

The potential temperature is often highest over the mountains during clear middays, usually associated with a diurnal maximum of mesoscale upslope flow. In this case, the outflow from the mesohigh reinforced the orographic upslope flow tendency in eastern Colorado, as well as the weak synoptic-scale upslope flow.

There was a tongue of cool, moist air, only about 100 km wide, near the Colorado-Wyoming border, persisting beyond 1800 GMT. It was most obvious on the 1800 GMT chart, where the 30°C potential isotherm extends westward to Fort Collins (Fig. 2e). At first, we were inclined to ignore this feature, but we now believe that it was important to the mesoscale setting of the tornadic storm. While regions to the north and south were experiencing normal solar heating, fog, stratus and drizzle were maintained in the upslope flow until early afternoon. Somewhat higher surface pressure and diffused flow out of the region were noted throughout the day, as manifested by Cheyenne’s south wind and Denver’s north wind.\(^2\) The northerly wind in the Denver area was upslope with respect to the mesoscale terrain (Fig. 1), and reinforced a normal daytime northerly component. The net result of these developments was that significant mesoscale convergence and cyclonic vorticity existed between Denver and

\(^2\) The complete sequence of morning visible satellite pictures was examined in time-lapse mode (Purdom, personal communication). This sequence confirms our initial speculation that the low cloud cover was continuous and extensive beginning just to the north of Denver, and that the low cloud motions supported the divergent winds in this area as analyzed.
Limon just prior to the tornado development (Figs. 2c, 2f).

Others have pointed out the tendency for mesoscale regions of persistent low clouds in the morning hours to warm up more slowly than adjacent clear regions (Purdom, 1973; Purdom and Gurka, 1974; Weiss and Purdom, 1974). These papers also give clear evidence from the combination of surface analysis and satellite imagery that such areas are slow to develop cumulus clouds, while adjacent areas are favored for thunderstorm development. The suppressed convective development in the initially cloudy, cool regions is ascribed to greater stability, while the enhanced development along the edges is thought to be an analogue of the rising motion along the leading edge of a sea breeze.

3. Air mass characteristics

The tornadoes developed 40–50 km east of Denver between 2120 and 2142 GMT. We believe that for this case, the Denver sounding at 2300 GMT represented the thermodynamic properties of air west of the storm system rather well. However, there was strong low-level inflow of moist air into the storm system from the southeast. Ordinarily, the nearest available sounding in that direction would be Dodge City, 400 km distant. In this case, we were extremely fortunate to be able to obtain data from Limon3, only 80 km away.

The early morning sounding for Limon (Fig. 3) showed the 18°C saturated conditions at the surface, consistent with the upslope fog being reported, overlaid by exceedingly dry, stable air. By midday (1800 GMT) there was a moist layer about 600 m thick, still overlain by the dry stable layer, which appeared to be somewhat weakened by lifting, but still representing a formidable lid to development of surface-based deep convection. Extrapolating to 2100 GMT, using the observed surface temperature, one would expect a deeper moist layer, still capped by a weakening stable layer. In addition to the normal afternoon deepening of the boundary layer, the low-level air moving from Limon at 1800 GMT and approaching the Bennett area at 2100 GMT should have experienced strong mesoscale convergence (Figs. 2c, 2f). Therefore, substantial deepening of the moist layer, sufficient to permit the release of marked convective instability, is plausible. The strong stable lid capping the air flowing westward out of the mesohigh precluded premature development.

In a study of northeast Colorado soundings taken during the National Hail Research Experiment, Mahrt (1977) found that the mixed layer was significantly shallower on hail days than on days with only cumulus congestus. Our assumed mixed layer depth of 1500 m at 2100 GMT is close to Mahrt’s mean hail day value of 1300 m. Browning and Foote (1976) suggested that long-lived supercells appear to prefer an environment where weaker convection is suppressed. Mahrt’s data also suggest that east-southeast winds at low levels are most favorable for hail occurrence in northeast Colorado, in agreement with suggestions of Foote and Fankhauser (1973), Fankhauser (1976) and Chalon et al. (1976), all showing examples of significant storms preceded by confluent surface easterlies advecting moist air westward out of the plains. Modahl (1979) showed that not only are low-level easterlies favorable, but that easterlies increasing with time during the day are especially well related to hail occurrence on that day. The conditions in our case at Limon were similar to the above for hail days. One difference our case had from the usually accepted severe storm environment was in moisture distribution: a strong low-level moisture gradient is often found in locations of severe storm development, but the subcloud air was very moist at both Limon and Denver near the time of the Bennett tornadoes (Figs. 2c, 3).

The Denver sounding at 1200 GMT showed dry air and west wind components throughout the low troposphere. Hourly surface data revealed that very moist north winds prevailed throughout the day, which obviously must have replaced the dry air in the lowest level shortly after 1200 GMT. The 2300 GMT sounding was probably representative of this moist northerly current after daytime heating and vertical mixing have deepened the moist layer.

For both Denver and Limon, we estimated that surface temperature and dew point most likely to have been associated with convective cloud development if the air sampled at either location had moved to the Bennett area at 2100 GMT. The undilute parcel ascent associated with those estimates is plotted on each sounding sequence (Fig. 3). These two estimates of parcel ascent follow the same moist adiabat, suggesting that thermodynamically, the storms could have ingested low-level air from either direction, in distinct contrast to many storms which form along strong low-level moisture gradients.
In each case, cloud base as indicated by the lifting condensation level was near 700 mb, the level of free convection was near 625 mb, undilute parcel temperature excesses were several degrees Celsius, especially from 500–350 mb (the lifted index was −5°C), and equilibrium was near 220 mb (12 km MSL).

All soundings show moderate wind shear (3 × 10^{-3} s^{-1}) in the lowest few kilometers, very small shear in mid-troposphere, and again moderate shear (3 × 10^{-3} s^{-1}) between 7 and 12 km. Strong wind shears are generally thought to be typical of the tornado environment. Maddox (1976) constructed mean hodographs for several different categories of tornado and severe thunderstorm proximity soundings. Compared with these mean wind profiles, the shears in the present case were smaller, but not insignificant.

4. Development and evolution of convective storms

The storms associated with the Bennett tornadoes organized into a line, oriented NNE–SSW (Fig. 4). The first echo formed just before 1924 GMT, and by 2007 GMT three storms were in existence, about 25 km apart. (Unfortunately, radar scope photographs were not available between 2004–2205 GMT; however, manual radar logs were used to establish continuity of most of the significant echo cores.) Each of the original three storms had some continuity over a

---

Footnote:
4 Radar tops were reported at 14.2 km east of Bennett and 16.7 km south of Bennett.
period of 2½ to 3½ h, with little net displacement over that time. The tornadoes formed 5–15 km to the west and northwest of the northernmost storm, and during the middle to late stages of the parent storm’s lifetime.

The most remarkable feature of these storm echoes was their westward discrete propagation during part of their lifetimes. The two southern storms started to move eastward, then were found progressively farther west, then moved toward the east again before dissipating. The third storm associated with the tornadoes was harder to follow. It appeared to propagate westward between 2007–2135 GMT, with two cores reported at 2135 GMT, when tornadoes were on the ground near the northern core. Between 2135–2155 GMT, the northern core was nearly stationary and then moved eastward. (Little significance can be attached to the apparent storm splitting, because Fig. 4 is based only on operationally reported core locations and not on reflectivity maps; it is possible that several radar cores existed where only one core is depicted.)

A careful study of the satellite picture sequence and radar sequence combined enabled us to distinguish the new growth relative to the existing mesoscale band of storms. On the visible SMS 1 satellite sequence (Fig. 5), the northwest flank of the storms was marked by a line of active cumulus congestus or cumulonimbus calvus clouds. From 2100 to 2230 GMT, this line was the source region for convective storm development. The new storms developed intermittently in time and were not continuous along the band. Individual storms generally moved from 260° at 10 m s⁻¹, as reported by the Limon radar observer. Also individual storm tops could be seen to detach from the nearly stationary mesosystem and move rapidly toward the east-northeast. This behavior can be seen most easily by tracing the detached anvil top backward from its position just east of the northeast corner of the box outlined in white in Fig. 5 at 2230 GMT. That same exercise reveals the explosive nature of the storm development, from a cloud line no more than a few kilometers across at 2100 GMT to an anvil 40–50 km across at 2130 GMT. Similarly, explosive growth of cumulonimbus clouds on the northwest flank of the system near the Bennett area is strongly suggested on the 2130 and 2200 GMT pictures. This explosive growth of hard cumulus towers was observed by Golden from Denver during the hour preceding the tornadoes. In summary, on the convective scale, the storms appeared to be of the multicell, discretely propagating type, with new cell development on the left rear flank. The net effect on the mesoscale band of storms was a westward displacement with time.

There was apparent suppression of smaller convective clouds northwest of the thunderstorm group (extending north–south throughout the center of the box in Figs. 4 and 5). At the same time, the region to the southeast remained free of low clouds (Fig. 5). Nevertheless, since subcloud air favorable for deep convection was present on either side, we are especially interested in the question of why the northwest flank of the thunderstorms developed new growth and became very active while the southeast flank did not.

The actual echo pattern was traced from films

---

5 It is significant that the motion of the particular cell associated with the tornadoes at 2135 GMT was reported by the Limon observer to be from 170°, 4 m s⁻¹, in sharp contrast to those for the preceding several hours. From 2155 GMT on, cell motion from the west-southwest, but slower than before, was observed. No hook echo or other distinguishing radar signature was noted, even though the radar operator was aware of the tornadoes in progress.
Fig. 6. Tracings of radar echo distribution from LIC scope photographs at 2024 and 2205 GMT. The actual area is overestimated by an unknown amount because of “bloom” due to overexposure of the film. The cross-hatched areas are echo cores located by the radar operator at 2155 GMT, with height in hundreds of feet.

of the Limon radar scope at 2024 and 2205 GMT (Fig. 6). The radar echoes on the scope at 2024 were less than 30 min old, except the large echo in the middle (along 39° 30’N), which was 1 h old. The echoes near the southwest corner were forming on the east–west ridge (Fig. 1) separating the Platte and Arkansas valleys, an extremely common “hot spot” for new echo growth (Henz, 1973; Karr and Wooten, 1976). The NNE–SSW mesoscale band of storms between Denver and Limon was not in any of the recognized geographical areas preferred for convective development; thus, considering its rapid intensification as well as the associated tornado development, it requires some other explanation. We have already suggested reasons for the mesoscale convergence zone to be in that general area; the sparse data available do not justify any more exact analysis. Comparison of Figs. 4, 5, and 6 suggests that the tornadoes developed just northwest of a very active portion of the radar band, where new cell growth was protruding well into the clear area to the northwest. Subsequent photographs confirm this general description of northwest flank development, with the surface position of the tornado vortices well northwest of any precipitation, but sloping toward the east or southeast with height.

5. Tornado evolution and structural details

A detailed map which can be used for location of the tornado photographs is given in Fig. 7. The second and third tornadoes (T2 and T3) definitely spent their entire lifetimes 5–10 km or more away from significant precipitation. We speculate that T1 formed along the western cloud edge, as was the case for T2 and T3; however, the radar core shown in Fig. 7, with its associated precipitation, accelerated T1’s decay. At the same time, the cloud line and subsequent tornado development was displaced toward the west.

The first tornado (T1) occurred from 2120 to 2140 GMT northwest of Strasburg, close to the large radar-echo core indicated on Limon radar. The tornado was observed through heavy rain and hail by a sheriff’s officer at Strasburg, who reported that the tornado appeared to be embedded within a curtain of heavy precipitation. We also note that heavy rain was reported to the ESE at Byers (see Fig. 7), both prior to and during the first tornado development. No eyewitness photos of the first tornado have been found.

The second and third tornadoes (T2 and T3) formed near the western cloud edge depicted in Fig. 7. The western cloud boundary is also sharply defined in the sequence of high-resolution satellite photographs given in Fig. 5. This boundary is located by two white arrows along the narrow, bright, rapidly growing line of cumulus congestus in Fig. 5. The second tornado (T2) occurred from 2135 to 2154 GMT about 15 km NNE of Bennett over open farm terrain. An eyewitness account from a Colorado state patrolman indicated that T2 had a slow northeastward motion during its mature stage (Fig. 8a) but may have slowed in forward speed and looped during its decay stage (Fig. 8b). The mature T2 (Fig. 8a) had a condensation funnel which tilted eastward with height and a large amorphous dust cloud at its base (viewed from

Fig. 7. Detailed map of the Bennett vicinity, locating the three tornadoes (T1, T2, T3) and the location of all tornado photographs (P1–P5) used in Figs. 8 and 9. The edge of the low clouds is sketched rather accurately, as it moves only slowly toward the northwest during the period covered by the photographs (2140–2210 GMT). Note that T1 and T2 probably moved, but they are shown as large dots, because no good evidence has been found of their actual tracks.
P3). This tornado was clearly pendant from the northwestern edge of the congestus cloud line shown in the SMS satellite sequence. In fact, it appears from close inspection of the original color photograph of Fig. 8a that the tornado developed beneath a flank of relatively shallow cumulus clouds, with the deeper convection (darker cloud bases) adjacent to the east. Note the clear sky in the upper left of Fig. 8a. Fig. 8b shows tornado T2 in its decay stage, photographed at least 10 min later at closer range from P5.

Some characteristic dimensions of tornadoes T2 and T3 have been determined photogrammetrically in Figs. 8 and 9 using an estimated cloud base of 1520 m AGL from the Denver and Limon soundings (Fig. 3) and hourly surface observations (Fig. 2). Knowledge of camera angles and location was also employed, mainly as a consistency check. The calculations are summarized in Table 1. We should not expect agreement better than a factor of 2 among dimensions calculated for the same tornado feature, even in pictures taken close together in time, because 1) tornadoes undergo changes in size and shape during their life cycles, especially during the decay stage, 2) cloud-base determination on the photographs was often difficult and arbitrary, and 3) there is an uncertainty of a few minutes in the time of each picture. We note in Table 1 that the funnel diameter of tornado T2 shrank while the debris cloud more than doubled in size as the tornado entered its decay stage. At the same time, tornado T2 evolved from a smooth narrow column (Fig. 8a) to a ropelike, contorted funnel which exhibited greater tilt toward the southeast with height (Fig. 8b). There is also some indication of at least one secondary vortex in the debris cloud of the decaying tornado (center of Fig. 8b, to right of funnel).

The third tornado was the largest, longest-lived and apparently most intense in this mini-outbreak. The tornado’s damage track was extensively surveyed by the authors several weeks after the event. Our best estimate of the T3 tornado track (dashed) the photographic sites (P1–P5) and the primary damage locations are given in Fig. 7. The third tornado was spotted by the state patrolman from P5 as he watched T2 toward the northeast in its decay stage.

T3 was first observed at 2142 GMT as a very large swirling cloud of dust and small debris on the northeast side of Bennett. As the tornado intensified and
Fig. 9h.

Fig. 9i.

Fig. 9j.

Fig. 9k.

Fig. 9. Photographs of the third Bennett tornado (T3) from locations specified in Fig. 7 as P1–P5.

(a) T3 viewed from P3, looking south about 2142 GMT, just after its formation.
(b) T3 viewed from P5, looking south-southwest about 2151 GMT. Photo courtesy of Colorado State Patrol. A transient vortex is visible just to the right of the tornado.
(c) T3 viewed from P1, about 2151 GMT. On the original photograph a transient vortex is visible (dotted arrow), then T3, then T2 (white arrow, distant right).
(d) T3 viewed from P1, about 2153 GMT. T2 is still visible on the original photograph (arrow to right).
(e) T3 viewed from P3 at close range, looking south-southeast about 2154 GMT. Note that the tornado is on the east side of the highway (Colo. 79).
(f) T3 viewed from P2, about 2158 GMT.
(g) T3 viewed from P2, about 2159 GMT.
(h) T3 viewed from P4, about 2159 GMT. Photo courtesy of Colorado State Patrol.
(i) T3 viewed from P4, about 2203 GMT. Photo courtesy of Colorado State Patrol.
(j) T3 viewed from P4, about 2204 GMT. Photo courtesy of Colorado State Patrol.
(k) T3 viewed from P4, about 2210 GMT. Photo courtesy of Colorado State Patrol.
moved slowly northward, the dust cloud circulated upward in a cyclonic helical fashion. The earliest eyewitness photographs, taken from P3 and P5, are shown in Figs. 9a and 9b. As mentioned above, the photographs show that both T2 and T3 were well to the west and northwest of any significant precipitation, and were along the major western boundary of the building cumulus congestus cloud system. During the early stages of T3’s life cycle no condensation funnel was evident. The vortex was manifested at lower levels by a rising, hollow column of dust which increasingly tilted toward the southeast with height. We also note in Figs. 9b and 9c some indications of transient vortices off to either side of T3. The dust column had an average diameter of ~175 m in the early stages (Table 1). Figs. 9c and 9d show the intensifying tornado as it was turning toward the NNE (observed from P1). At this time, a long tilted column of dust extended from the surface to cloud base with a prominent bulge in the middle (diameter ~380 m in Fig. 9c). Shortly after the mature tornado had crossed Colorado State Road 79 (see Fig. 7), it was photographed (Fig. 9e) from a distance of less than 1 km by an observer at P3. Again, Fig. 9e clearly illustrates the tilted, hollow column of dust, with some striking asymmetries at low levels suggestive of outflow in the northwest quadrant (right side of picture). Figs. 9f and 9g were taken from P2, looking northeast. These are the only photographs which show the complete vortex column, including the ropelike funnel which descended only about one-third of the distance from cloud base to the ground, and the dust-debris cloud below. Figs. 9f and 9g also show clearly the apparent southeastward tilt of the tornado with height, the northeast–southwest orientation of the parent congestus cloud line, and the suppressed cumuli and blue skies (on original color print) in the north background. We also note the enlargement of the debris cloud diameter at the ground between Figs. 9f and 9g, from 170 to 340 m (Table 1).

The remaining four photographs of tornado T3 were taken from P4 by the state patrolman, looking south (Figs. 9h–9k). Note in Fig. 9h that the tornado had crossed the highway a second time and was headed on a NNW track for the remainder of its lifetime. The dense dust and debris cloud grew both vertically and horizontally during the picture sequence Figs. 9f–9i as shown in Table 1. Of course, some of the variations in size or appearance of the dust cloud may be due to inhomogeneities of the underlying surface. Most important, a pronounced band of dust developed during this stage (Figs. 9h–9i), which we interpret as a feeder band which apparently spiraled into the base of the vortex from the east and southeast. A similar structural feature was first noted by Golden and Purcell (1977) in the Great Bend, Kansas, tornado of 30 August 1974, and was also discussed by Umenhofer et al. (1977). It was demonstrated by analyses of motion pictures that the dust-band was essentially an inflow jet which spiraled into the Great Bend vortex. Connell (1975) presented some interesting data and speculations on a large tornado which occurred near Sterling, Colorado, on 6 July 1972, in which debris-cloud features greatly resembled those noted above in the third Bennett tornado and in the one at Great Bend (Golden and Purcell, 1977). The dust band in the Bennett tornado (T3) resembled similar structural features in the Great Bend and Sterling, Colorado, cases, except that the dust band/debris cloud geometry was rotated by 90–180° from the Great Bend system; that is, the dust band in the Bennett tornado denoted a concentration of inflow into the base of the vortex from the east and southeast, while the tornado was moving towards the NNW. Relative to the direction of motion, the dust band was in the right rear quadrant of both the Bennett and Great Bend tornadoes. Finally, we note the helical-upward growth of the tornado’s debris column in Figs. 9h–9j and the short-lived development of a rare double-walled condensation funnel in Fig. 9i. Golden (1974a,b,c) found that the appearance of a double-walled funnel in waterspouts is relatively rare and occurs during the mature stage of the most intense waterspot developments. Fig. 9k shows a close-up of the Bennett tornado illustrating the apparent outflow of debris in the northwest quadrant of the vortex and the very turbulent structure of the lower vortex circulation. Similar features were also noted at times in the Great Bend tornado’s mature stage by Golden and Purcell (1977).

6. Unusual aspects of the Bennett tornadoes and comparisons with recent tornado events

As noted in earlier sections, the three tornadoes near Bennett had some unusual characteristics: they formed on a synoptically quiescent day in summer; they developed on the western edge of a high-based cumulus congestus cloud line, at least 5–10 km away from the nearest significant thunderstorm or precipitation; and the largest tornado formed well to the northwest of the nearest radar echo and moved slowly toward the N and NNW. The third tornado was bathed in bright sunlight during most of its lifetime and exhibited a pronounced dust band similar to that previously documented by Golden and Purcell (1977) for the Great Bend tornado. The largest tornado did not produce much damage, although photos clearly indicate a structure and size capable of producing extensive damage. (At times the diameter of the third Bennett tornado’s debris cloud was over twice that of the Great Bend tornado.) It was probably fortuitous that the Bennett tornadoes all remained away from the town, that just one injury was suffered, and that only a few
structures were damaged along the highway to the north of Bennett.

Golden (1978), Prosser (1976) and Flavin (1952) all documented tornadoes in an area of apparently high tornado incidence on the northeast fringe of metropolitan Denver. In all three cases, the tornado had a relatively slow forward speed (under 5 m s⁻¹) toward the N or NE and was visible mainly by its large diameter and tall debris cloud; only a short condensation funnel was visible in all cases. No hook echoes were observed on the WSR-57 radar at Limon (~100 km away) in any of these cases. Golden (1978) found that the Denver tornado of 30 May 1976 developed from a thunderstorm cell which exhibited rapid vertical growth during the hour preceding the tornado, reaching a maximum height of 14.5 km—all of the tornadoes appeared to be pendant from rapidly growing congestus clouds.

The westward component in the Bennett tornado’s path (see Fig. 7, T3) appears to be another very unusual feature. Notis and Stanford (1973) found that about 70% of Iowa tornadoes travel NE, 30% travel SE, and none have a westward component. Similarly, Golden and Purcell (1977) found that for a dozen or more tornadoes which they documented on 30 August 1974, all but one moved toward the northeast; the largest tornado of that outbreak, noted above near Great Bend, had a sinusoidal track toward the southeast. Recently, two Iowa tornadoes exhibiting westward motion have been described. The cyclonic-anticyclonic pair reported by Knupp and Brown (1977) moved toward the north-northwest during a portion of their track. Stanford (1974) studied a July tornado which moved WNW at about 4–5 m s⁻¹ for ~30 min in weak thunderstorm outflow. Stanford attributed the unusual motion of the tornado to the westward expansion of its parent cumulonimbus; the center of the radar echo of the latter remained essentially stationary during this time. Golden (1973, 1974a,b) has shown that the Florida Keys’ waterspouts are qualitatively similar to Midwestern tornadoes and that their translation averages only ~3–8 m s⁻¹ during the mature stage. Moreover, Golden found that the direction of waterspout motion is largely determined by location relative to a neighboring rainshower; waterspouts tend to move away from the shower and eventually are overtaken by shower outflow.

7. Tornado life cycles

There seems to be emerging in the recent literature on tornadoes and related convective vortices the concept of a fairly regular vortex life cycle. Golden (1973, 1974a,b) clearly documented a characteristic five-stage life cycle for waterspouts, but noted that not all waterspouts evolve through every stage. Likewise, the careful synthesis of observations and photographs taken of the large, destructive tornado at Union City, Oklahoma, by meteorologist chase-teams (Golden and Purcell, 1978a,b) led to a tornado life cycle of four distinct parts: organizing, mature, shrinking and decaying stages. Golden and Purcell (1978a) demonstrated that the Union City tornado’s life cycle fit well with descriptions of previously reported tornadoes (e.g., Agee et al., 1977; Beebe, 1960). Moreover, the Union City tornado life cycle resembled, in most important respects, that typical of Florida Keys waterspouts.

Reexamining Figs. 9a and 9b, we note that the shrinking and decay stages of Bennett tornado T2 are illustrated. Likewise, an incomplete life cycle of tornado T3 was documented by the photographs: Figs. 9a–9e show the organizing stage, when the condensation funnel was not visible and probably remained a short pendant hanging from the high cloud bases above; Figs. 9f–9k illustrate T3’s mature stage, with peak tornado (debris cloud) size and density near the end of the picture sequence. We note the great similarity to the life-cycle picture sequence shown for the Great Bend tornado by Golden and Purcell (1977) and Umenhofer et al. (1977). Both cases suggest that the visible funnel lengthens and broadens appreciably only after vortex rotational speeds exceed a certain threshold, thereby lowering core pressures sufficiently at low levels for condensation to occur.

The fact that the condensation funnels can be short and inconspicuous in High Plains storms is significant. In many severe tornadoes farther east, the cloud base can be within a few hundred meters of the ground, so that a modest pressure drop of 20–30 mb in the core should bring a funnel to the surface, although the intense Xenia, Ohio, tornado (Fujita, 1975; Golden, 1976) is a perplexing counterexample. The Bennett tornadoes descended from a cloud base of about 1500 m, so that a modest pressure deficit of, say, 20–30 mb would have taken the funnel only 15–20% of the way to the ground. Combined with the large tilt of the vortex, the potential for underestimation of the true strength of a vortex, especially in its early stages, is very great. Umenhofer et al. (1977) made a similar point from pictures of the Great Bend case, where cloud base was above 1500 m.

8. Summary and conclusions

The Bennett, Colorado, tornadoes of 14 August 1977 formed in an environment considered favorable for severe local storms in northeast Colorado (usually considered to be hailstorms) in these
respects: (i) the synoptic-scale low-level flow was from the southeast and became stronger with time during the daytime hours, (ii) the mixed layer was relatively shallow, and (iii) there was ample low-level moisture. Compared with most tornado proximity soundings, tropospheric wind shear and thermodynamic instability, although present, were less extreme than usual. In contrast to many severe local storm situations, no significant synoptic-scale weather disturbance was noted at any level. We suggest that in many situations, most common in summer, severe weather develops in the absence of strong synoptic-scale forcing if the mesoscale setting is favorable.

Features of the subsynoptic environment included the following:

- The moist low-level southeasterly flow, partly synoptic-scale and partly orographic, and strongly enhanced by outflow from the mesohigh to the east of Colorado.
- On a somewhat smaller scale, a strong convergence zone developed between southeast and north or northwest flow.
- This inflow from the northwest was closely related to the outflow from a 100 km scale cool, moist region where low clouds were slow to dissipate during the day.
- In spite of strong actual and relative inflow of moist air from the southeast, the storms developed new growth of flanking cumulus congestus and cumulonimbus clouds on their west and northwest flanks, where the tornadoes were observed and therefore apparent inflow from the northwest.
- In contrast to many severe weather situations, there was no significant moisture gradient; the low-level air on both sides of the storms had very similar thermodynamic properties.
- The mesoscale cloud system, including its tornado-bearing active northwest flank, propagated slowly toward the northwest, while individual storm cells (with one apparent exception) moved toward the east-northeast. The tornadoes' motion was more nearly that of the propagation of the mesoscale radar complex (Figs. 4 and 6) than that of the motion of most individual cells.

It may be questioned whether the long-lived Bennett tornado was associated with a supercell. The absence of a hook echo or other distinguishing severe weather radar signature suggests the absence of persistent weak echo region (WER). Together with the obviously discrete mode of growth of new cumulonimbus cells, the preponderance of available evidence argues in the negative. Indeed, the presence of discrete new growth on the rear flank recalls the feeder clouds described by Dennis et al. (1970) or Browning's (1978) daughter clouds in the multi-cell storm, although it is unusual to find these on the left rear flank (Marwitz, 1972a). Thus far, we have referred to the Marwitz (1972b) description of a supercell; emphasizing the steady-state WER, resulting from a continuously propagating quasi-steady strong updraft. Browning (1965, 1978), Lemon et al. (1977), and others, describe the archetypical supercell as having not only quasi-steady draft characteristics, but also rotation and a mesocyclone. The undoubted importance of this classic supercell has led some to conclude that any storm with a tornado is also a supercell, and vice versa. We believe that such a conclusion is premature and probably incorrect, as it implies that all storms, and only those storms, with quasi-steady updrafts and WER's, possess mesocyclones and tornadoes. If there is observational evidence in support of this sweeping conclusion, we are unaware of it.

Notable aspects of the tornadoes themselves included the following:

1) For the third time in three years, tornadoes of respectable size have been photographed near the Denver metropolitan area. The dimensions of the large Bennett tornado were about the same as those of the Great Bend case in which horizontal velocities of over 70 m s⁻¹ were measured (Golden and Purcell, 1977).

2) The third Bennett tornado was observed continuously for about 35 min. Its mean path was toward the north at 4 m s⁻¹, but after its initial stages it moved mainly toward the north-northwest.

3) The tornadoes were pendant from rapidly growing cumulus congestus clouds on the northwest flank of strong thunderstorms but 5–10 km distant from any significant precipitation.

4) The cloud base was ~1500 m above the ground, and the condensation funnel was relatively short and inconspicuous in most of the photography, absent in others.

5) A pronounced dust band was a conspicuous, although transient, feature during the mature stage of the tornado. Relative to north, it was in a different quadrant from similar features noted in the Great Bend (Golden and Purcell, 1977) and Sterling (Connell, 1975) cases; relative to the unusual northwestward propagation of the Bennett cases, it was similarly located.

If large tornadoes should also occur fairly regularly near populated areas of the High Plains in future years, we suggest that the rarity of significant damage to date may have been fortuitous and may not continue indefinitely. Certain aspects of the Bennett case also suggest that there is potential for public confusion. The areas struck by the two largest tornadoes experienced no precipitation, insignificant wind and mostly bright sunshine prior to the event. The condensation funnel was short and inconspicuous during the first 15 min of the larger
tornado's life cycle, and only the spectacular dust cloud provided a few minutes of warning to people in the path. Finally, the unusual direction of tornado motion, compared with the 'normal' eastward movement of storms, as well as with individual storm movements on that day, would hardly fit the expectations of either a trained radar operator or a threatened individual. As one of the eyewitnesses said, 'the storm went east, while the tornado cloud went west!'

Note added in proof: There was abundant tornadic activity over the High Plains and in the foothills of the Rocky Mountains during summer 1979. On 24 June the first well-documented tornado to occur in the mountainous terrain of the foothills formed in mid-afternoon over Manitou Springs, CO (elevation 2000 m MSL) and tracked east-south-eastward, unroofing several homes and uprooting large trees. This tornado was extensively photographed and a research study is underway by Golden. On 16 July a tornado killed one person and injured dozens of others on an extensive track through Cheyenne, WY; damage estimates exceed $20 million. Photographs of the Cheyenne tornado reveal a turbulent dust column and very short condensation funnel, with striking similarities to the Bennett and Great Bend tornadoes.

Acknowledgments. This paper was made possible by the superb photographs and excellent recall of detail of Colorado State Patrolman Matthew White. He was able to reconstruct the events of 14 August many weeks later on our survey trip, made together with Patrolman Ernest Anderson, who brought the pictures to our attention. We appreciate the fine work of Clyde Gall and Chuck Herbert of the State Patrol's photo lab, as well as the full cooperation of many others in the Colorado State Patrol, including Capt. Lindquist and Lt. Harrington. Pictures and eyewitness accounts provided by Mrs. Copeland and Mrs. Saylor of Bennett were of great value. We thank officers Ard, Saylor and Tweeden of the Bennett station of the Adams County Sheriff's Office for eyewitness accounts. We appreciate the cooperation of all the following individuals who supplied or loaned data: James Purdom, NOAA/NESS; Dane Clark, NOAA/NESDIS; Ed Ferguson, Chief, SFSS/NESS at Kansas City; Ellis Burton, MIC of NOAA/NWS office at Denver; Tom Lewis, OIC of Limon NOAA/NWS Station; Gerry Klazura, Bureau of Reclamation, Denver. John Brown, Jim Fankhauser, Bob Maddox and three thorough, anonymous reviewers, read the manuscript and offered a number of useful suggestions. We thank a reviewer for raising the issue of supercell versus multi-cell storms.

REFERENCES
Lemon, L. R., R. J. Donaldson, Jr., D. W. Burgess and R. A. Brown, 1977: Doppler radar application to severe thunder-
storm study and potential real time warning. Bull. Amer.
Mahrt, L., 1977: Influence of low-level environment on severity
of high plains moist convection. Mon. Wea. Rev., 105,
1315–1329.
Marwitz, J. D., 1972a: The structure and motion of severe hail-
storms. Part II. Multi-cell storms. J. Appl. Meteor., 11,
180–188.
——, 1972b: The structure and motion of severe hailstorms. Part
Modahl, A. C., 1979: Low-level wind and moisture variations
preceding and following hailstorms in northeast Colorado.
Notis, C., and J. L. Stanford, 1973: The contrasting synoptic
and physical character of northeast and southeast advancing
Ostby, F. P. Jr., A. Pearson and L. Wilson, 1978: The tornado
Pearson, A., F. P. Ostby, Jr., and L. Wilson, 1977: The tornado
season of 1976. Weatherwise, 30, 3–9, 17.
Purdom, J. F. W., 1973: Satellite imagery and the mesoscale
convective forecast problem. Preprints 8th Conf. Severe
——, and J. J. Gurka, 1974: The effect of early morning cloud
cover on afternoon thunderstorm development. Preprints
5th Conf. Weather Forecasting and Analysis, St. Louis,
Stanford, J. L., 1974: Analysis of a rare, westward-advancing
tornado in Iowa. Weatherwise, 27, 202–205, 211.
Great Bend tornadoes of August 30, 1974. Preprints 10th
Conf. Severe Local Storms, Omaha, Amer. Meteor. Soc.,
457–462.
102, 400–402.