
Paul T. Schlatter
Warning Decision Training Branch, National Weather Service, Norman, Oklahoma

Thomas W. Schlatter*
NOAA/Earth System Research Laboratory, Boulder, Colorado

Charles A. Knight
National Center for Atmospheric Research,† Boulder, Colorado

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ABSTRACT

An unusual, isolated hailstorm descended on Boulder, Colorado, on the evening of 24 June 2006. Starting with scattered large, flattened, disk-shaped hailstones and ending with a deluge of slushy hail that was over 4 cm deep on the ground, the storm lasted no more than 20 min and did surprisingly little damage except to vegetation. Part I of this two-part paper examines the meteorological conditions preceding the storm and the signatures it exhibited on Weather Surveillance Radar-1988 Doppler (WSR-88D) displays. There was no obvious upper-tropospheric forcing for this storm, vertical shear of the low-level wind was minimal, the boundary layer air feeding the storm was not very moist (maximum dewpoint 8.5°C), and convective available potential energy calculated from a modified air parcel was at most 1550 J kg⁻¹. Despite these handicaps, the hail-producing storm had low-level reflectivity exceeding 70 dBZ, produced copious low-density hail, exhibited strong rotation, and generated three extensive bounded weak-echo regions (BWERs) in succession. The earliest of these filled with high reflectivities as the second one to the south poked up through precipitation-filled air. This has implications for low-density hail growth, as discussed in Part II.

1. Hail in Boulder

Severe hailstorms are rare in Boulder, Colorado, situated at the base of the foothills along the Front Range of the Rocky Mountains. They are far more common to the east, on the plains of Colorado. Yet, on the early evening of 24 June 2006, an intense hailstorm crossed the western edge of the city from north to south. Lasting only about 20 min, the storm dumped over 5 cm of slushy ice and nearly 5 cm of liquid-equivalent precipitation. So great was the volume of ice that the air temperature dropped from +27°C to +4°C at two locations (unofficial reports), and shallow ground fog formed in clearings at west Boulder parks after the storm passed. The hail stripped many leaves from trees and plants, streets and lawns alike had the appearance of freshly fallen snow (Fig. 1), driving in the slush was hazardous, and local flooding was common. Despite large balls of ice ranging from 6 to 8 cm in diameter in the early minutes of the storm, there was little damage to rooftops or automobiles because the ice balls splattered on impact. However, most vegetable and flower gardens near the center of the 1.5-km-wide hail swath were destroyed.

The large volume of ice was not the only unusual aspect of this storm. In advance of the storm, the surface dewpoint was relatively low, less than 10°C. The
convective available potential energy as computed 1 h before the storm from rawinsonde data at the National Weather Service (NWS) station serving Denver (KDNR), 48 km southeast of Boulder, was only 781 J kg$^{-1}$, not enough to attract attention. Strong low-level inflow, which would enhance convergence and updraft strength, was not evident in hourly surface aviation routine weather reports (METARs). Clearly, in situ observations did not indicate the likelihood of a large hail-producing storm on this day, even by midafternoon.

The storm formed in isolation near Pingree Park about 2200 UTC [1600 mountain daylight time (MDT)] and moved south-southeast, reaching Boulder about 2350 UTC. Figure 2 shows the storm total estimated precipitation, a good proxy for the storm track. The northern edge of this map is about 35 km south of the Wyoming border. Figure 3 shows the hail reports, taken from the Community Collaborative Rain, Hail and Snow (CoCoRaHS) Network (information online at http://www.cocorahs.org/) and from Boulder National Weather Service Forecast Office official spotter logs.

Doppler radar data, indicating updraft rotation and high reflectivity, prompted the National Weather Service to issue a warning for large hail at 2307 UTC, as the storm was crossing the Boulder–Larimer County line northwest of Lyons. A second warning at 2341 UTC extended the first one, which would have expired at 2345 UTC.

Section 2 of this paper examines the synoptic- and meso-alpha-scale meteorological conditions in the hours before the storm. WSR-88D radar data gave the first indication of a severe thunderstorm. In section 3, we correlate the radar images with ground reports of hail. Section 4 focuses on storm-scale features revealed by radar, in particular the strong rotating updraft and the bounded weak-echo region. We summarize the unusual aspects of this storm in section 5 and set the stage for Knight et al. (2008, hereinafter Part II), which discusses the results of examinations of hail collected during and immediately after this storm.

2. Synoptic- and meso-alpha-scale setting

At 1200 UTC (0600 MDT) 24 June 2006, west-northwest flow dominates the high troposphere over the central Rocky Mountains (Fig. 4). Wind speeds do not exceed 25 m s$^{-1}$. A weak short-wave trough lies over western Montana (off the map). At 700 hPa (Fig. 5), northwest flow prevails east of the mountains in Wyoming and Colorado. The air is dry over Colorado relative to climatology for late June. By 0000 UTC 25 June, the short-wave trough brushes northeast Colorado at 300 hPa (Fig. 6), but there is no upper-tropospheric cooling from morning to evening. The 700-hPa dewpoint at Denver rises from $-12^\circ$ to $+2^\circ$C between 1200 and 0000 UTC (Fig. 7). The northwest wind of the morning is replaced by a light south-southeast wind.

Denver (DNR) rawinsonde data give additional detail. The morning sounding (Fig. 8) depicts a subsidence inversion near 750 hPa with a shallow, moist boundary layer below. West-northwest or northwest winds extend from the high troposphere all the way down to this inversion. During the day, this inversion is negated through surface-based warming, and the base of the northwest flow retreats upward to 550 hPa. Though the moisture content below 700 hPa changes little at Denver during the day on 24 June, it rises substantially in the layer between 700 and 500 hPa. Riverton, Wyoming’s, 1200 UTC sounding (not shown) is moist in this layer, and it is very likely that this moisture advected toward Denver during the day. This can be seen in the evening sounding for Denver (Fig. 9), in which the precipitable water vapor (PWAT) has increased from 15.7 to 20.0 mm. The evening balloon launch time is about 2315 UTC, about 30 min before the storm reaches Boulder, 48 km to the northwest. The thin black line to the right of the temperature profile in Fig. 9 is the
trajectory of a parcel lifted from the surface. The boundary layer is very well mixed, almost up to 600 hPa. There is no convective inhibition. The calculated convective available potential energy (CAPE) is 818 J kg$^{-1}$, a modest value. The highest dewpoint measured prior to the storm was only 8.5°C (see Fig. 11, top-left panel). The prominent red curve in Fig. 9 follows a mixing ratio line up from a surface dewpoint of 8.5°C and then a moist adiabat up from the lifting condensation level. The CAPE associated with this modified surface parcel is considerably larger, 1550 J kg$^{-1}$, enough to sustain a strong updraft but still on the low end of the spectrum compared with values normally associated with hail larger than 2 in. (5 cm) in diameter (Edwards and Thompson 1998).

Integrated column water vapor is estimated from analysis of signal delays from global positioning system satellites (Bevis et al. 1992) at two locations in Boulder:

Fig 2. Precipitation from the hailstorm that struck Boulder on the evening of 24 Jun 2006. The storm formed about 1600 MDT northwest of Pingree Park, hit Boulder about 1745 MDT, and was due east of Morrison by 1845 MDT. The color scheme shows storm total precipitation estimated from WSR-88D data in inches. The radar (KFTG) is at lower right (black circle). Green indicates precipitation between 2.5 and 5.0 cm. The distance between the northern and southern borders of Boulder County is 40 km. County names appear in yellow.
the National Center for Atmospheric Research’s (NCAR) Foothills Laboratory on the north side of town and at the NOAA/Earth System Research Laboratory (ESRL) on the south side. Measurements for a 48-h period bracketing the storm are shown in Fig. 10. At both locations, the column water vapor rises in the 12 h prior to the storm, as corroborated by the Denver rawinsonde. A peak value of 2.25 cm occurs during the storm (center of the plot) at the NCAR Foothills Laboratory (red curve), near the eastern edge of the storm. The ESRL site is just 0.5 km west of the center of the hail swath. There, the intense precipitation interferes with the reception of the GPS signals causing a brief break in the record (blue curve), but both curves track very closely. For reference, the average value of the column water vapor for all of June 2006 is 1.51 cm, with a standard deviation of 0.37 cm, the extremes being 0.50 and 2.45 cm, both coincidentally visible in Fig. 10.

A time series of surface observations at the NCAR Foothills Laboratory and the University of Colorado campus (red stars in Fig. 3) is shown in Fig. 11. Prior to the storm, the surface dewpoint is 6°–8°C; the wind is light, generally from southeast to northeast at a few meters per second. Arrival of the outflow from the storm brings a sudden wind shift to the north, gusts of 13–16 m s⁻¹, and a temperature drop of 14°–16°C within minutes. The center of the hail core passes 2.2 km west of the Foothills Laboratory and 1.0 km west of
the University of Colorado campus, moving north to south. Both sites record a pressure jump: 3.5 hPa at NCAR and 3.8 hPa on campus.

Given the substantial spread between surface temperature and dewpoint across Boulder County, the environment appears favorable for generation of strong downdrafts. One way to examine the downdraft potential is with the sounding parameter downdraft CAPE (DCAPE) (Emanuel 1994). The modified surface parcel in Fig. 9 results in a DCAPE value of 1293 J kg\(^{-1}\).

Evans and Doswell (2001) examined proximity soundings associated with 67 derechos, and a DCAPE of 1293 J kg\(^{-1}\) falls in the top 25% of all types of derecho environments they examined. Cohen et al. (2007) likewise found that DCAPEs over 1000 J kg\(^{-1}\) are favorable for severe wind-producing mesoscale convective systems. As portrayed in Fig. 11, however, severe wind gusts did not occur.

Finally, we examine surface observations from METAR sites in the vicinity of the storm (Fort Collins, FNL; Greeley, GXY; Broomfield, BJC; and Denver, DEN). All of these sites lie east of the storm track, BJC being the closest, about 10 km distant. At 2300 UTC (Fig. 12), light southeast winds blow along the entire Front Range urban corridor. West of the Continental Divide, winds are mostly from the northwest. A zone of converging winds in the foothills from early to late afternoon is a common feature of the mountain–plains diurnal circulation in summer (Toth and Johnson 1985). On this day, the convergence zone is present in late
afternoon and probably provides a source of vorticity for the storm as it develops over western Larimer County. At 2300 UTC, southeast winds of 5 m s\(^{-1}\) feed air with a dewpoint of 7\(^\circ\)C toward the storm. By 0000 UTC (Fig. 13), the surface winds at BJC and DEN have backed into the east and strengthened slightly at BJC. Surface moisture is the same. The storm is still west-northwest of Broomfield.

In summary, the data discussed here do not suggest an atmosphere primed for severe convection. There is, at best, only weak dynamic forcing from a short-wave trough aloft and moderate convective instability. The surface dewpoint seems low for a storm producing so much ice and liquid. Lower-tropospheric shear was not measured in the near vicinity of the storm, but the Denver rawinsonde, launched 48 km southeast of Boulder, showed little wind and almost no shear at all below the 600-hPa level (Fig. 9).

The NOAA Network Profiler at Platteville, Colorado, 45 km northeast of Boulder, might have provided valuable wind information, but it had been inoperable since late April 2006. The same is true of a boundary layer profiler at the Rocky Mountain Arsenal, a few kilometers west of Denver International Airport, part of the Cooperative Agency Profiler (CAP) network. Unfortunately, data from that network had ceased to be available just months before. Doppler radar data shed much more light on the storm dynamics than the conventional data just considered. That is the subject of the next section.

**FIG. 5.** A 700-hPa analysis for 1200 UTC 24 Jun 2006. Rawinsonde data are plotted in black, showing temperature (\(^{\circ}\)C), dewpoint depression (\(^{\circ}\)C), geopotential height (m) with leading 3 omitted, and wind vectors at each site. Small wind barbs represent 5 kt (2.6 m s\(^{-1}\)), and large barbs 10 kt (5.1 m s\(^{-1}\)). Yellow solid contours depict 700-hPa heights (dam), red solid contours depict temperature (\(^{\circ}\)C), and shaded areas represent dewpoint (\(^{\circ}\)C) as shown in color bar at top. Analyses are from the RUC.
3. Radar imagery and surface hailfall characteristics

Past studies of Colorado hailstorms using dual-Doppler radar analyses and/or dual-polarimetric radars have provided invaluable information about hail growth processes and storm morphology (Foote and Frank 1983; Blanchard and Howard 1986; Kennedy and Rutledge 1995; Conway and Zrnic 1993; Hubbert et al. 1998; Kennedy and Detwiler 2003; Tessendorf et al. 2005). Only the WSR-88D radar (KFTG) east of Denver, Colorado, collected data on 24 June 2006; thus, this section focuses on single-Doppler data from KFTG as the hailstorm traversed Boulder County from north-northwest to south-southeast. See Crum et al. (1993, 1998) for the specifications of the WSR-88D radar. Throughout the event, KFTG operated in Volume Coverage Pattern-11 (VCP-11), meaning that it produced volume scans approximately every 5 min. Updated plan position indicator (PPI) scans every 5 min are a primary limitation to the radar analysis of this hailstorm, as transient radar features may appear and disappear in a single minute or less. Despite the limitation, one can identify several important characteristics of the Boulder hailstorm. We examine this storm at its most intense stage as it crossed Boulder County and a dense network of spotters.

a. Storm initiation to classification as a supercell (2023–2156 UTC)

The storm originated northwest of Boulder in extreme northwest Larimer County, Colorado. Clusters of weak thunderstorms formed along the Medicine Bow Range. The first radar echo of what would become the Boulder hailstorm appeared 50 km northwest of Pingree Park, Colorado (see Fig. 2), at 2036 UTC. Most cells formed and moved east-southeast, dissipating within 30 min. However, a persistent cluster of multicell storms moved slowly east-southeast and was 30 km...
northwest of Pingree Park at 2101 UTC. At the same time, a faster-moving supercell with a history of severe hail approached the multicell cluster of storms from the north-northwest. This supercell generated a radar-identified gust front extending west from its reflectivity core. When the gust front reached the multicell cluster at about 2115 UTC, new cores of reflectivity formed on the west side of the cluster, along a west to east line. By 2141 UTC, the previously severe supercell weakened considerably while the southernmost cell in the cluster rapidly increased in size and strength through 2215 UTC. Though too far from the radar to verify for certain, it appears that intensification was aided via low-level convergence generated by the supercell gust front.

Less than 10 min after the rapid intensification at 2141 UTC, a mesocyclone developed. It became well defined at 2156 UTC over Pingree Park. This mesocyclone satisfied criteria first defined by Donaldson (1970) for a single-Doppler radar: radial velocity shear values $\geq 6 \text{ m s}^{-1} \text{ km}^{-1}$, differential radial velocity (defined as the difference between the maximum out-bound and inbound velocities) $\geq 30 \text{ m s}^{-1}$, depth $\geq 3$ km, base height $< 5$ km above radar elevation, and persisting for $\geq 10$ min. Many of these same criteria were used to create the mesocyclone detection algorithm applied to WSR-88D radar data (Stumpf et al. 1998). As early as 2156 UTC, the rotational signature in the Boulder hailstorm had a velocity shear of $\sim 7 \text{ m s}^{-1} \text{ km}^{-1}$, a differential velocity of $26 \text{ m s}^{-1}$, a depth of $\sim 3$ km, a base height of $\sim 2.5$ km above the radar level, and had persisted for well over 10 min. Davies-Jones et al. (2001) defined a supercell qualitatively as a long-lived (>1 h) thunderstorm with a high degree of spatial correlation between its mesocyclone and updraft. As will be discussed, based on the Davies-Jones et al. criteria, the Boulder hailstorm was a supercell from 2156 UTC until past 0000 UTC, when it exited Boulder County. Incidentally, both the algorithm described by Stumpf et al. and a newer, more restrictive version identified mesocyclones as the storm traversed Boulder County.
Fig. 8. Skew $T$–log$p$ diagram with a plot of Denver rawinsonde data for 1200 UTC 24 Jun 2006.

Fig. 9. Skew $T$–log$p$ diagram with a plot of Denver rawinsonde data for 0000 UTC 25 Jun 2006. The thin black line represents the trajectory of a parcel lifted from the surface. The red curve follows a constant mixing-ratio line up from a surface dewpoint of 8.5°C, the maximum observed prior to the storm, and then a moist adiabat up from the lifting condensation level.
FIG. 10. Total column water vapor (cm and in.) as inferred from analysis of signals received from GPS satellites. Dual-frequency receivers are located in north Boulder at the NCAR Foothills Laboratory (red curve) and in south Boulder at ESRL (blue curve). The figure spans 48 h, time is in UTC, and the storm occurred close to 0000 UTC 25 Jun 2006. The two purple dots indicate the column water vapor calculated from the Denver rawinsonde data displayed in Figs. 8 and 9.

FIG. 11. A 90-min time series, bracketing the hailstorm, of surface parameters measured at the University of Colorado campus (solid lines) and the NCAR Foothills Laboratory (dashed lines). (top left) Temperature (red) and dewpoint (green). (top right) Station pressure; the campus site is at slightly higher elevation. (middle left) Five-min wind (blue) and gust speed (black). (middle right) Five-min wind direction. (bottom left) Rainfall accumulation. All times are UTC. The NCAR and campus locations are shown in Fig. 3. Note that the sudden changes occur slightly earlier at NCAR, consistent with storm motion from north to south. Precipitation after 0030 UTC at the campus location is explained by melting hail in the precipitation gauge.
b. Storm characteristics prior to reaching Boulder County (2156–2300 UTC)

From initiation at 2156 UTC until reaching the northern Boulder County line at 2300 UTC, the storm developed cyclically as new updrafts formed on the upshear (south) side. The mesocyclone persisted at midlevels but remained weak and at times ill defined. Typical of mesocyclonic supercells, the storm moved to the right of the mean wind after the mesocyclone de-
veloped. Storm motion was \(-8\ m/s\) from 310° before mesocyclone development and remained steady at 11 m s\(^{-1}\) from 345° afterward. Note that Doppler radial velocity data used in this study are storm relative, meaning that the radial component of the storm motion vector (11 m s\(^{-1}\) from 345°) is subtracted from the radial velocity vector at every range gate, allowing for easier interpretation of rotation and convergent–divergent radial velocity signatures associated with the storm. Reflectivity was never higher than 61 dB\(Z\) through 2300 UTC, and the highest reflectivity was below the freezing level (~4.3 km MSL). A bounded weak-echo region (BWER) first became evident at 2255 UTC, nearly simultaneous with the mesocyclone velocity difference peaking at 35 m s\(^{-1}\). Figure 14a shows the reflectivity and Fig. 14b the corresponding storm-relative velocity as the radar beam hits the storm at a range of 89 km from KFTG and 3.5 km AGL at 2300 UTC. The first surface hail report of 19-mm diameter came from 7 km west-northwest of Drake, Colorado (see Fig. 2), at 2245 UTC. Two more surface hail reports, the larger being 25 mm, came from extreme southern Larimer County as the leading edge of the storm reached the Boulder County line. These three reports all lie north of the map in Fig. 3.

c. Hailfall across Boulder County (2300–0004 UTC)

Part II of this study focuses on an examination of hailstones collected from three locations within the city of Boulder during and shortly after the storm. In addition to that detailed analysis, we also examined spotter reports from two sources. It is fortunate that Boulder County has many volunteer spotters who contribute to the CoCoRaHS Network. Many of these observers note the timing, hardness, and the average and maximum size of the hail, and all data are publicly available on the Internet. The data are reliable and robust for hail studies. We also used hail-size data from the official storm reports logged by the Boulder National Weather Service Forecast Office. From the plot of maximum reported hail size (Fig. 3), it is apparent that the largest hail fell along and west of U.S. 36 north of Baseline Road (at 40°N), and along Broadway just south of Baseline. The largest reported hail, 64 mm in diameter, fell in southwest Boulder. Two reports of golf-ball-size hail (44 mm) were received, one very near the 64-mm report and the other in the northeast part of the city. All told, 24 Boulder and Larimer County spotters reported hail sizes ranging from less than 1 to 64 mm, and six of those reports were at least 25 mm. Not only were some of the hail balls large, but the sheer volume of slushy ice was extraordinary (Fig. 1). Several spotters within the city mentioned hail accumulations near 50 mm. It is thus of little surprise that peak reflectivity values were extreme, at times exceeding 70 dBZ as the storm crossed the city. A detailed radar analysis of the storm is covered next.
4. Radar analysis of storm-scale features

a. High-resolution radar data

The Boulder hailstorm was 85 km from the KFTG radar when it entered northern Boulder County and 61 km from the radar when it exited southern Boulder County, allowing for good data resolution in azimuth and elevation while avoiding the effect of the radar’s cone of silence. At 50–100-km range, BWERs and mesocyclones are well resolved by the WSR-88D (Wood and Brown 2000). Data resolution in the radial direction is 1.0 km for reflectivity and 0.25 km for velocity, while the azimuthal resolution at a distance of 67 km (corresponding to the range from KFTG to south Boulder) is approximately 1.2 km for both reflectivity and velocity. The height of the center point of the lowest available elevation angle is approximately 850 m above the average surface elevation of the city of Boulder.

b. Characteristics of the hail core

A time–height plot of reflectivity for the Boulder hailstorm as it traversed Boulder County is shown in Fig. 15. This plot was produced as follows: At each elevation angle from 2300 to 0014 UTC, the maximum value of the reflectivity and its corresponding height above mean sea level (MSL) were recorded. The hailstorm had only one dominant hail core during the time period of Fig. 15.

Fast-moving storms may appear to tilt with height because the lowest reflectivity scan (0.5°) occurs roughly 4 min before the final scan (19.5°) for VCP-11, and in that time a fast-moving storm may have traveled several kilometers. However, the Boulder hailstorm moved at approximately 11 m s\(^{-1}\) (22 kt), and the highest-elevation scan needed to investigate this storm was only 10.0°. Between the 0.5° and 10.0° scans, roughly 3.5 min elapsed, during which time the storm moved about 2.3 km, an important point to remember but not a hindrance in tracking the reflectivity core.

In essence, Fig. 15 is a subjective analysis of the maximum reflectivity values associated with the primary hail core at each elevation angle as the storm crossed Boulder County. Reflectivity was as high as 60 dBZ up to 10 km MSL, where the in-cloud temperature was close to −38°C, indicating the possibility of hail at very high altitudes. Reflectivity values peaked in mid- and upper levels over north Boulder at 2344 UTC, just minutes before the largest hail reached the ground in south Boulder. In their review of previous hail studies, Knight and Knight (2001) found that the bulk of the hail growth occurs roughly between the −10° and −30°C levels, which for this storm correspond to ~6.5 km (−10°C in cloud) and ~9.3 km (−30°C in cloud). The in-cloud temperatures are estimated from the red parcel ascent curve in Fig. 9. Above −40°C height (~10.6 km in cloud), ice is the only contributor to reflectivity.
The level of neutral buoyancy (LNB) for this event was near the −53°C level (~12.0 km). The presence of reflectivity more than a kilometer above the LNB points to an overshooting top.

Figure 15 shows reflectivity greater than 70 dBZ below the 0°C level during several volume scans. This is not surprising given the combined effects of the large diameter and high volume of hail reported at the surface. Reflectivity greater than 65 dBZ occurred above the −20°C level as the hail core moved over Boulder (i.e., 2335–2359 UTC), far exceeding what is thought to be indicative of severe storms (Lemon 1980; Witt et al. 1998).

The high reflectivity values at altitudes above the −20°C level would normally indicate the presence of very strong updrafts, but in this case that would need to be qualified by the likelihood that most of the hydrometeors might be low-density ice (as discussed in Part II) and, therefore, have considerably lower than normal fall velocities.

c. Radar interpretation of storm updrafts

The low-level wind field ahead of the hailstorm during its traverse of Boulder County showed interesting Doppler radial velocity signatures. Mean storm motion was 11 m s$^{-1}$ from 345° while 10-m surface winds in Boulder 30 min prior to the arrival of the gust front had an easterly component and were very light at 1.5 m s$^{-1}$ gusting to 5 m s$^{-1}$ (Fig. 11). Many signs pointed to the potential for a storm with strong near-surface outflow winds: a prestorm surface dewpoint depression of nearly 20°C, DCAPE of >1200 J kg$^{-1}$, light inflow surface winds against a mean storm motion of 11 m s$^{-1}$ from 345°, the rapid accumulation of slushy hail, up to 5 cm of liquid equivalent precipitation in 20 min, and large temperature drops within the hail core. Yet, the radial velocity data and the surface data in Fig. 11 do not indicate unusually strong low-level winds (>20 m s$^{-1}$).

Figure 16 shows the reflectivity and radial velocity at 2344 UTC as the hail core passes over Boulder. In Fig. 16, KFTG (a) 0.5° base reflectivity (b) base radial velocity, and (c) storm-relative radial velocity from 24 Jun 2006 at 2344 UTC as the hail core passes over Boulder. Storm motion of 11 m s$^{-1}$ from 345° was subtracted from the radial velocities of (b) to produce (c). White rectangles (lines) in (b) and (c) indicate strongest region of outbound (inbound) velocities with respect to the radar. Color scale and data in (a) are in units of reflectivity decibels, while (b) and (c) are in knots. Green or blue velocities are inbound with respect to the radar, while red or pink velocities are outbound. Radar beam is ~800 m AGL over Boulder.
16b, the radial velocity is with respect to the radar, whereas in Fig. 16c the radial component of the storm motion has been subtracted out. Note that the lowest elevation beam is 800 m above the city. If the outflow wind direction at 800 m matched that at the surface ($\alpha$ 340° in Fig. 11), the radar, pointing along a 300° radial, would underestimate the strength of the outflow by nearly 25%. Even so, in Fig. 16b the radial velocities painted red (toward the storm) nearly match the radial velocities painted green (outflow from the storm). Several volume scans prior to and following Fig. 16 show that the low-level convergence remained anchored to the gust front along the south flank of the storm; thus, the gust front did not become widely separated from the main precipitation cascade.

From 2344 UTC and for an elevation angle of 4.3°, Fig. 17a hints at the presence of a BWER and Fig. 17b a mesocyclone. Both are well defined in the middle and upper levels of the storm; in particular, the BWER is better defined at higher-elevation angles than is shown in Fig. 17. Interestingly, much of the mesocyclone lies within the enhanced reflectivity region of the storm, with the maximum inbound velocities well south of the hail core and in weak reflectivity associated with the BWER (where the updraft is), while the maximum outbound velocities reside within the strongest reflectivity. A mesocyclone may augment an updraft via the formation of an upward-directed perturbation pressure gradient force coincident with the strongest rotation, typically in the midlevels of a storm (Rotunno and Klemp 1982). The subjectively analyzed center of the mesocyclone in the Boulder hailstorm was south of the reflectivity core and at least partially associated with the BWER (surrounding the Xs in Figs. 17a and 17b).

d. BWER characteristics

Weak-echo regions were first identified in the 1960s and 1970s (Browning 1965; Chisholm 1970; Marwitz et al. 1972), and are an easily recognized reflectivity feature of severe storms. The Glossary of Meteorology (Glickman 2000) defines a BWER as “a zone of weak reflectivity a few kilometers wide associated with a strong updraft, typically found in the mid- and upper-levels of severe thunderstorms (3–10 km AGL).” The updraft responsible for a BWER is sufficiently strong that hydrometeors often have little time to grow before being ejected laterally in the anvil, thus explaining the low reflectivity in the low to midlevels of a given storm. However, flanks of the updraft can contain large hydrometeors so that the weak-echo region becomes completely surrounded or “bounded” by higher reflectivity.
values. A literature search for crude estimates of maximum heights and horizontal dimensions of BWERs led to Table 1.

An eyewitness with a background in meteorology described the sky conditions and, in particular, the appearance of the base of the updraft as it approached the south side of Boulder: “Getting off the bus at Dartmouth and Broadway [2335–2340 UTC; refer to Fig. 3 and the asterisk with 35 mm hail in southwest Boulder], I could readily see that this was no ordinary storm. Thunder was continuous, not loud, and clearly aloft—no cloud-to-ground lightning. The precipitation to the north seemed to be mostly transparent, but with some intense shafts still over the foothills that could have been hail [they were dark against a light background]. Most impressive, however, was the large precipitation-free base, elliptical, rippled on the bottom, from up Boulder Canyon a short distance west of Boulder out over central and north Boulder. This probably covered an area of 5–10 km². There was a smaller, connected base of like appearance over and behind Green Mountain [directly west of the southern part of Boulder],” (J. M. Brown 2006, personal communication). The large precipitation-free base was the visual manifestation of the BWER shown by the triangle in Fig. 18 with its apex pointing up.

The Boulder hailstorm had one and sometimes two BWERs as it traversed Boulder County. Figure 18 provides a fine example of the double-BWER structure at 2330 UTC, just as the hail core at midlevels reached northwest Boulder. The younger (older) BWER subjectively identified at 7.5 km MSL (Fig. 18e) is marked by a black triangle with its apex pointing up (down) and surrounded by a black square. These two locations are overlaid onto the remaining images in Fig. 18. The reflectivity structure reveals that the older BWER (farther north) is occupied by the extreme reflectivities of the primary hail core below 7.5 km MSL. The younger BWER (farther south) is precipitation free below 7.5 km MSL but is capped by high reflectivities at 10.0 and 11.5 km (Figs. 18g and 18h). This supports the hypothesis that younger updrafts formed on the south flank of the storm while older updrafts decayed, perhaps collapsed, and became filled with extreme reflectivities. The storm-relative radial velocities near the storm top (Fig. 18i) show a strongly divergent signature centered very near the younger BWER (dividing line between red and green), as might be expected.

The cross section taken along the component of the storm motion (Fig. 19a) at 2330 UTC shows the younger, very broad BWER centered at \(X = 21\) km. The remnants of the previous BWER, now several kilometers north of the younger BWER, are at \(X = 16\) km. An west-to-east cross section (Fig. 19b) displays the width and extent of the younger BWER located on the leading edge (south-southeast side) of the storm and south of the hail core. Earlier volume-scan cross sections (not shown) indicated a single well-defined BWER that was still farther north of the younger BWER shown in Fig. 19a, evidence that the feature at \(X = 16\) is a decaying updraft, and new, vigorous updraft development is occurring along the leading edge of the storm. The younger updraft on the south side of the storm in Fig. 18 and on the right (south) side of Fig. 19a appears to have formed beneath the overhanging echo from the older, northern BWER. This has implications

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**Table 1. Previous studies of BWERs, listing the average diameter and top of the BWER as mentioned or inferred from the study. Location of the storm or storms is also indicated.**

<table>
<thead>
<tr>
<th>Reference</th>
<th>BWER size (km)</th>
<th>BWER top (km)</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>Marwitz (1972a)</td>
<td>12</td>
<td>8</td>
<td>NE CO</td>
</tr>
<tr>
<td>Marwitz (1972b)</td>
<td>4</td>
<td>7</td>
<td>AB</td>
</tr>
<tr>
<td>Marwitz (1972b)</td>
<td>3</td>
<td>Near summit 11</td>
<td>NE CO</td>
</tr>
<tr>
<td>Browning and Foote (1976)</td>
<td>10</td>
<td>−40°C, 10 MSL</td>
<td>NE CO</td>
</tr>
<tr>
<td>Donaldson (1978)</td>
<td>3.5</td>
<td>8.1 MSL</td>
<td>OK</td>
</tr>
<tr>
<td>Lemon (1980)</td>
<td></td>
<td>11 MSL</td>
<td>OK</td>
</tr>
<tr>
<td>Weaver and Nelson (1982)</td>
<td>7</td>
<td>&lt;10 MSL</td>
<td>OK</td>
</tr>
<tr>
<td>Knight (1984)</td>
<td>5</td>
<td>10</td>
<td>NE CO</td>
</tr>
<tr>
<td>Kraus and Marwitz (1984)</td>
<td>10</td>
<td>5 MSL</td>
<td>AB</td>
</tr>
<tr>
<td>Blanchard and Howard (1986)</td>
<td></td>
<td>−8 MSL</td>
<td>CO Front Range</td>
</tr>
<tr>
<td>Musil et al. (1986)</td>
<td>−10</td>
<td>−11</td>
<td>MT</td>
</tr>
<tr>
<td>Nelson (1987)</td>
<td>10–15</td>
<td>&gt;8</td>
<td>OK</td>
</tr>
<tr>
<td>Roberts and Wilson (1995)</td>
<td>4</td>
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<td>CO Front Range</td>
</tr>
<tr>
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<td>2–3</td>
<td>9–10 MSL</td>
<td>TX Panhandle</td>
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<tr>
<td>Hubbert et al. (1998)</td>
<td></td>
<td>6 MSL</td>
<td>NE CO</td>
</tr>
<tr>
<td>Stills et al. (2004)</td>
<td>3</td>
<td>8 MSL</td>
<td>Sydney, NSW, Australia</td>
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<td>MacGorman et al. (2005)</td>
<td>8</td>
<td>7 MSL</td>
<td>NE CO</td>
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</table>
for hail growth and hailfall characteristics that will be discussed in Part II of this study.

Several aspects of the Boulder hailstorm’s BWERs set it apart from those studied previously. The size of the BWER before and during the surface hail reports was extraordinary, at one point nearly 14 km wide along its major axis (in Fig. 19b it is ~10 km wide), as wide as any previously documented BWERs (Table 1). Determining the width and location of any BWER is inherently subjective, and for the purposes of this study, it was taken as continuous reflectivity of less than 40 dBZ bounded by reflectivities greater than 40 dBZ in the midlevel of the storm. In addition, this BWER was, at times, not capped by strong reflectivity, which is
atypical (Lemon 1980) but not unprecedented (Marwitz 1972b).

An example of an uncapped BWER is shown in Figs. 20a and 20b. “Uncapped” implies a lack of high reflectivity normally associated with the top of a BWER. Radar-identified, low-level convergence and upper-level divergence are associated with this BWER. The BWER persists for several consecutive volume scans. The two volume scans preceding Fig. 20 show that the BWER in Fig. 20 formed via an updraft beneath an existing echo overhang on the south side of the storm. The updraft was likely so strong that 1) no sizable hydrometeors could form in its core (based on reflectivity values of less than 35 dBZ) and 2) it “punched through” the existing echo overhang, which had contained reflectivity greater than 40 dBZ. Because this process occurred in less than 10 min (the time it takes for two volume scans), it is unlikely that the higher reflectivities making up the ring of the BWER were due to growth within the core of the updraft, but rather from preexisting hydrometeors that were “pushed aside” by the new, vigorous updraft. The implications of this rarely observed characteristic are discussed extensively in Part II of this study (in this issue).

5. Conclusions

The Boulder hailstorm of 24 June 2006 was highly unusual in the following aspects:

- The storm produced a kilometer-wide swath of water-soaked, low-density hail (a few hail balls reaching 60 mm in diameter) in a rather dry, moderately unstable, and weakly sheared environment.
- Surface outflow wind gusts (measured as high as 15 m s$^{-1}$) were not as strong as environmental parameters might have led one to expect.
- At times, the hailstorm had two BWERs, with the younger and stronger BWER forming on the southern flank of the storm. At one point, one of the young BWERs was up to 14 km across, east to west, and as wide as any BWER previously documented. At times, the newest BWER was not capped by high reflectivity.
- Reflectivity values greater than 65 dBZ extending well above the $-20^\circ$C level typically suggest very strong updrafts. In this case, because of the presence of low-density hail with lower fall speed, the updrafts needed to loft the largest hail in the storm would be weaker than normally expected.
- The mesocyclone of the hailstorm was strong but very broad, larger than the BWER and including it.

This paper, Part I of two parts, has focused mainly on the synoptic and radar data from the Boulder hailstorm. Part II discusses the unusual characteristics of the hailstones and employs the features of the radar
data to develop a hypothesis about the formation of large, low-density hailstones.

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