DEEP HAIL:

Tracking an ELUSIVE Phenomenon

by Thomas W. Schlatter and Nolan Doesken

Weatherwise's "Weather Queries" column is sometimes presented with questions that require more space than can be devoted to them in the regular column to answer them fully. Recently, David Nolan of Mills Lake, Wisconsin, asked one such question—about deep hail. He queried: "What is the deepest hail accumulation over a one-square-mile area ever recorded in the United States, not drifted by wind or washed into piles?" Surprisingly, as posed, this question is unanswerable because there are no data on one-square-mile accumulations of hail. Even *Storm Data*, a monthly publication of the National Climatic Data Center that lists all severe storms observed in the United States, does not have information on deep accumulations of hail; until January 1, 2010, hail had to be at least three-quarters inch in diameter for a storm to be classified as severe. Now the criterion is one inch. Most occurrences of deep hail involve smaller hail, and thus they would not be recorded in *Storm Data* except accidentally. Neither is there a standard or widely accepted definition of "deep hail," so we propose one here:

> *Two inches or more of hail, measured on open, level ground, neither piled up by running water nor drifted by the wind.*

At one-inch depth, closely mowed grass such as the greens and fairways of golf courses are totally white, but other landscapes still show through. At an accumulation of two inches, the entire landscape begins to look like winter. Moreover, this much hail invariably damages vegetation, regardless of hailstone size. Finally, one inch of hail may occur in a few hail-prone areas as often as once a year, but a hail fall of two inches or more at a specific location is rare and may be considered an extreme event.

But why is it so difficult to find detailed information on storms that produce deep accumulations of hail? The simple answer is that witnesses are usually untrained observers who are in stressful situations (prolonged hailstorms are both damaging and frightening), and the evidence of such storms quickly disappears as the hail melts.

But we were determined to find out more about this meteorological phenomenon. We searched widely for documentation of large accumulations of hail, using the Internet, weather records, newspaper articles, state climatologists' knowledge, and public queries. In the end, we were able to paint a fairly comprehensive picture of this phenomenon, but we think we might have just scratched the surface. In fact, we suspect that that most occurrences of deep hail in the United States, especially those that occurred more than 20 years ago, are poorly documented.

Conditions Favorable for Deep Accumulations of Hail

Four conditions are necessary for deep accumulations of hail. First, copious atmospheric moisture combined with a low-level wind that continually feeds the moisture into the storm are essential.

Second, a storm or storms must generate prolonged hail falls over one locale, in extreme cases, for more than an hour. This can happen in several ways. Sometimes when winds aloft are light but moisture-laden surface winds are strong, the lateral spread of rain-cooled air is hindered by the inflow, and so the low-level convergence and the resultant updraft hardly move, and neither does the storm itself. Storms anchored to a terrain feature can stay put for an hour or two. Occasionally a thunderstorm produces multiple cells, each forming in roughly the same place, with the older cells propagating downstream from the point of origin. In this case, successive pulses of heavy rain and hail might affect the same area repeatedly over several hours.

Third, storm updrafts should not be choked by falling rain or hail. In short-lived, garden-variety thunderstorms, precipitation forms in the updraft and falls through it, exerting drag and eventually converting it to a downdraft, thus ensuring the storm's quick demise. In a tilted updraft storm, precipitation falls out of the updraft. In rotating thunderstorms, which may stand erect, the central updraft is so strong that large hydrometeors (raindrops and hail) do not have time to form; instead, they form at the outer edge. When they fall out of the storm, they do not choke the updraft.

And finally, the altitude at which the wet-bulb temperature is 0°C (32°F) must be low enough, and the hail large enough, that it doesn't melt before reaching the ground. The wet-bulb temperature is the lowest temperature to which air can be cooled by evaporating water into it. Once a hailstone falls to where the temperature is above freezing, it begins to melt. In unsaturated air (below cloud base), the liquid coating on the hailstone evaporates. The latent heat involved in this process comes from the air, which cools. As long as the well-ventilated hailstone is passing through air whose wet-bulb temperature is below zero, evaporation will keep the stone at 0°C. The hailstone will lose mass from its surface, but only a small fraction of the total. Once it passes below the wet-bulb 0°C level, the hailstone loses ice mass more quickly through both evaporation and melting.

Aftermath

A long-lasting storm that drops huge volumes of hail rips leaves from trees and ornamental shrubs, ruins crops, and crushes flower gardens. In extreme cases, the weight of ice causes structural damage to and even collapses roofs with minimal slope. On highways, deep hail greatly slows or even stops traffic; snow plows must clear the roads before vehicles can proceed. During prolonged hail fall, the temperature drops impressively, often to 40°F, rarely to within a degree or two of freezing. If the wind is light following the storm, shallow, dense fog often forms as humid air comes in contact with the icy surface. The ground is white, as after a substantial snowfall. Flash floods often accompany large hail falls and, because ice floats on water, the hail may be washed into huge piles many feet deep.

Examples of Deep Hail

As we conducted our research, we determined that accounts of deep hail can be divided into three categories: credible historic accounts but with sketchy documentation, photo documentation, and scientific investigation of storms producing deep hail.

Credible Historic Accounts, Sketchy Documentation

We found two early reports of deep hail in *The New York Times* archives. An article appearing on July 11, 1877, described a severe hailstorm that occurred on the previous day in small towns just south of Watertown, New York. Large hail, some stones weighing half a pound, fell for 30 minutes, reportedly covering the ground nearly a foot deep. Several people were injured before they could find shelter. "Horses and cattle were killed in the fields … dead chickens, geese, pigs, and dogs were strewn on every side," downed tree branches littered streets and yards, and all types of vegetation were destroyed.

A shorter *Times* article published on June 23, 1906, mentioned that "hail fell to a level of 14 inches" on June 22 in parts of Clarke and Oconee Counties, Georgia, near Athens. "Pine trees for miles were stripped of their foliage."

In his long out-of-print *Weather Record Book* (Weatherwise, Inc., Princeton, NJ, 1971), the late David Ludlum briefly discussed hail accumulations. He wrote, "In a storm at Maryville in northwest Missouri on September 5, 1898, when hail fell 12 inches deep, lanes in fields were still closed two weeks after the storm." The Web site http://www.andthensome.com/weather/hail.htm also mentions this storm, adding, “On 27 October, enough hail still remained in ravines to be used by local residents to make ice cream.”

Photo Documentation

Some of the more interesting accounts of deep hail we found involved photo documentation. Figure 1, courtesy of Tony Laubach, shows hail three inches deep covering the grasslands of Arapahoe County, just east of the Denver, Colorado, metropolitan area, following an afternoon storm on August 17, 2009. The most interesting feature in this photo is the ground fog, a frequent occurrence when hail lies on the ground, provided that the wind is nearly calm. A dewpoint near or above 50°F is typical when thunderstorms rumble across eastern Colorado. When air this moist comes in contact with ice-covered ground, it cools, and some of the water vapor condenses into fog.

Graham Thompson contributed the photo in Figure 2, of a Colorado hailstorm in progress at 7:00 p.m., on May 31, 2006. The location is near the southern border of Douglas County on the Palmer Divide north of Colorado Springs. Note the pine needles, stripped from the trees and strewn atop the hail. Also note the large pile of hail collecting below a corner in the roof line. Graham estimated that this storm deposited two or more inches of hail on the ground in an area of about two square miles. The following morning dawned clear, but the ground was still white with hail.

The next photo, Figure 3, courtesy of Tony Laubach, is one frame extracted from his video at http://www.americantowns.com/co/springfield/videos-page2. The image illustrates why snow plows occasionally have to be called out in late spring and summer. This storm, in Baca County in extreme southeastern Colorado, covered the ground with hail four to five inches deep. In such a storm, driving conditions become treacherous much more quickly than in a heavy snowstorm.

Another storm with deep hail was documented by John Farley, who was chasing a storm outside of Las Vegas, New Mexico, on May 27, 2009. John snapped a number of photos of the hail after the storm moved through Las Vegas, including Figure 4. John estimates that at least four inches of hail, mostly penny-sized, remained on the ground for more than 45 minutes after the storm. From his earlier vantage point, John estimated that the storm moved little between 1:30 and 3:00 p.m., giving it plenty of time to drop large amounts of hail on the ground. You can find his detailed narrative and photos at http://www.johnefarley.com/chase52709.htm.

TONY LAUBACH, STORM CHASER

Fig. 1. Hail covers the fields and generates ground fog in Arapahoe County, Colorado, on August 17, 2009.

GRAHAM THOMPSON

Fig. 2. At the height of a hailstorm, 7:00 p.m., May 31, 2006, near the southern border of Douglas County, Colorado. Note hail piling up below an inside corner of the roof.

TONY LAUBACH

Fig. 3. Hail covering a highway in Baca County, extreme southeast Colorado, June 13, 2009.

JOHN E. FARLEY

Fig. 4. Hail covering the streets of Las Vegas, New Mexico, late afternoon, May 27, 2009.

Allen Dutcher, the Nebraska State Climatologist, informed us of a massive hailstorm in the early afternoon of June 10, 2009, in farming country east of Scottsbluff in the Nebraska Panhandle. The slow-moving storm affected an area 25 miles long by five miles wide, mostly north of the North Platte River. Flash flooding occurred, and hail accumulated to a depth of six inches. Gary Aschenbrenner captured several images with his cell phone. Figure 5 shows a bleak landscape three miles north of the town of Minatare in late afternoon, about three hours after the storm ended. By this time the road had been plowed. Note the farmhouse on the distant ridge surrounded by trees completely stripped of leaves.

Dierdre Kann, a meteorologist at the NWS Forecast Office in Albuquerque, New Mexico, alerted us to observe a spectacular deposit of hail that occurred in extreme northeastern New Mexico in Union County between Clayton and Sedan. The storm hit near midnight on August 13, 2004. Pea- and marble-sized hail accumulating up to 12 inches deep was followed by as much as five inches of rain. Water washed the hail into a small tributary of Sand Draw. Pea- and marble-sized hail accumulating up to 12 inches deep was followed by as much as five inches of rain. Water washed the hail into a small tributary of Sand Draw. The icy flow was restricted by a 12-16 foot culvert that couldn't accommodate the flood, and hail piled up behind it, filling the draw to depths of up to 15 feet. The next morning presented a surreal scene, as ice cliffs 10-15 ft high lined both sides of the normally dry draw. In one place, floodwater had cut a tunnel in the ice. Figure 6 is a photo taken by Terry Martin, staff photographer with the *Union County Leader*, the weekly newspaper in Clayton. Ice remained in the draw for nearly a month, despite the warm sunny days of late summer. *New Mexico Geology* featured this storm in an article shortly after the storm: http://geoinfo.nmt.edu/publications/periodicals/nmg/26/n4/gallery.pdf.

The previous example, of an extraordinary amount of hail washed into a small area the size of a football field, gave only indirect evidence of a large accumulation of hail on the level. The next example is a very well documented storm that deposited the greatest accumulation of hail on the level that we could find.

In the *Weather Record Book*, mentioned earlier, David Ludlum talks about a hailstorm that occurred in the town of Seldon, Kansas, on June 3, 1959. Ludlum gives few details other than the fact that about 18 inches of hail accumulated on the level. It turns out that this storm is well documented in the August 1959 issue of *Monthly Weather Review* (pp. 301-303). Hail began falling about 5:15 p.m. with strong shifting winds, breaking many windows. The wind soon abated, but the hail continued to fall without interruption for 85 minutes. An aerial survey (see Figure 7, courtesy of the *Norton Telegram*) indicated that hail covered an oval area oriented northeast-southwest, about nine miles long and up to six miles wide, with the center of the storm near the southwest corner of Seldon. Most of the hail was pea- or marble-sized. It was so deep and heavy on U.S. Highway 83 that cars were stalled for four hours. The temperature fell from near 80°F to 38°F during the storm. Trees were denuded. Several roofs with little or no slope collapsed from the weight of the hail (see Figure 8).

Remarkably, someone had the presence of mind to measure the weight of accumulated hail on a truck scale: 28,000 pounds on a 10-ft by 45-ft scale, which comes to 62.2 pounds per square foot. If one assumes that the truck scale is in a flat area and no extra hail washes onto the scale, this is a phenomenal figure, in that a foot of liq-

GARY ASCHENBRENNER

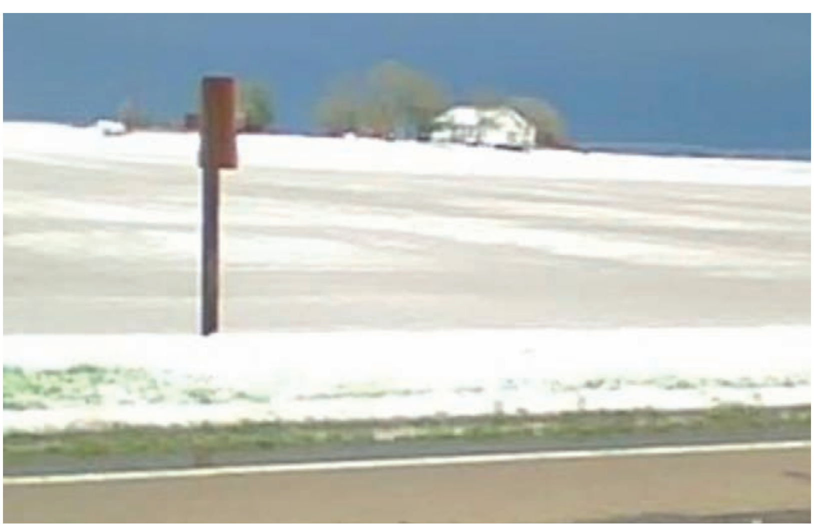


Fig. 5. Deep hail in farm country of the Nebraska Panhandle, late afternoon, June 10, 2009.

uid water exerts about the same pressure: 62.4 pounds per square foot. The world record 60-min rainfall is 12", listed for both Holt, Missouri, on June 22, 1947, and Kilauea Sugar Plantation, Hawaii, on either 24 or 25 January, 1956. This suggests that the Seldon, Kansas, hailstorm, accompanied by an estimated 3-5" of rain_all in 85 minutes_may be a close contender for the world record.

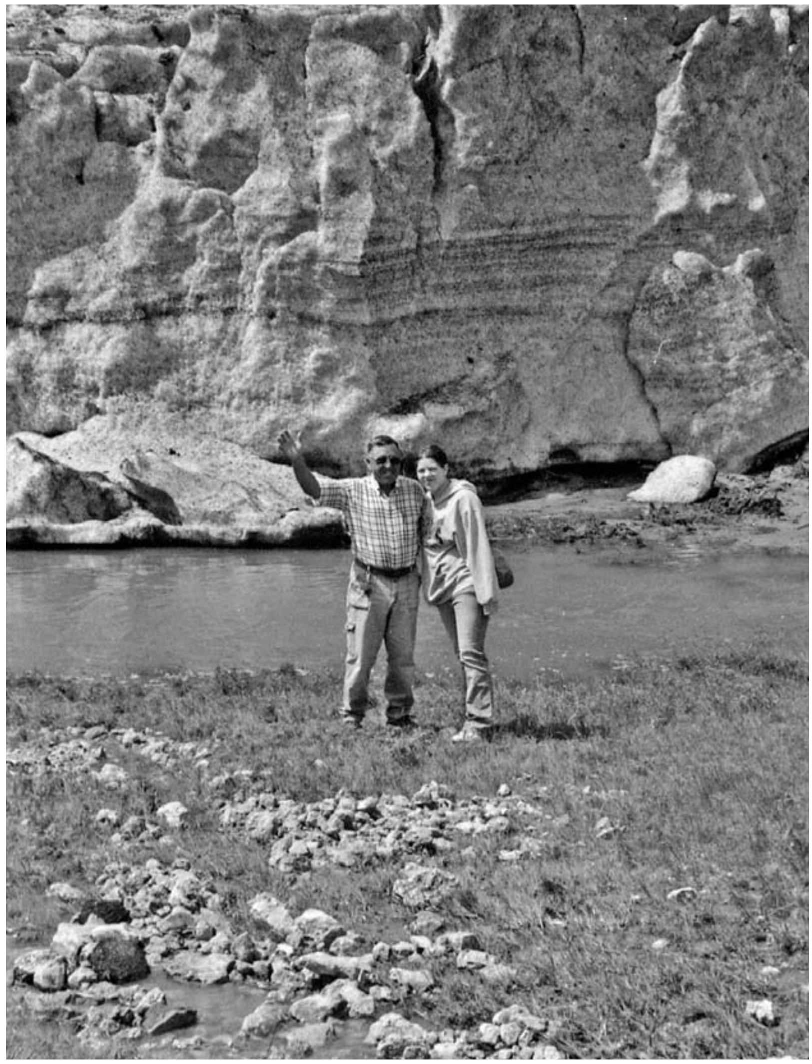
Scientific Investigations of Storms Producing Deep Hail

One can find many scientific papers describing severe storms. More often than not, however, the focus is on tornadoes, flash floods, or large hail. Rarely is the focus on unusual accumulations of hail. We present three exceptions here.

The Royal Meteorological Society in the United Kingdom published a special issue on hail and snow in the October 2009 edition of *Weather*. One article, "An Exceptional Hailstorm Hits Ottery St. Mary on 30 October 2008" (pp. 255-262), describes an early morning storm that produced about 7.9 inches of precipitation, including 9-10 inches of hail, in about two hours. Though this storm occurred in the United Kingdom and the focus here is on U.S. hailstorms, we highlight it anyway because the documentation is superb. The authors carefully examine weather conditions preceding the storm, digital radar images during the storm, and local observations collected after the storm. They even try to replicate the storm after the fact with computer prediction models.

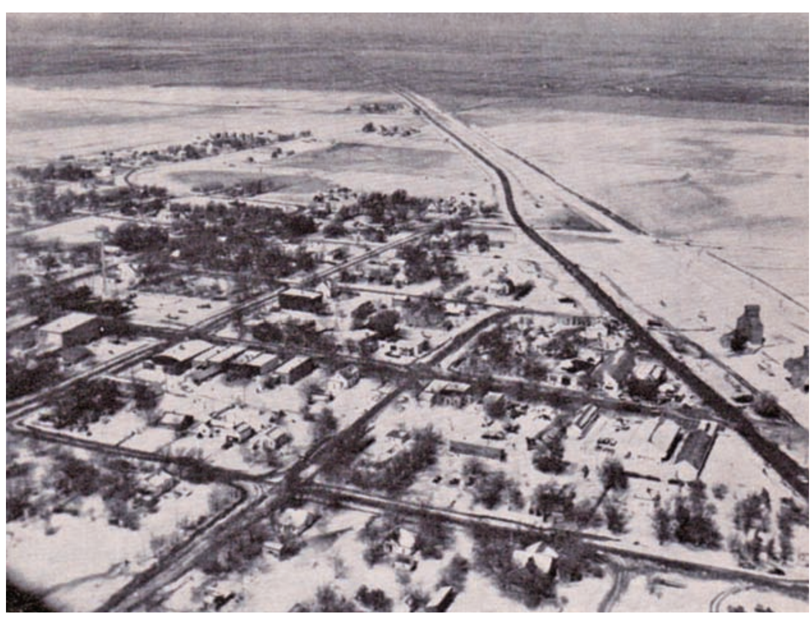
The second example is domestic. A hailstorm and flash flood broke over Cheyenne, Wyoming, during the evening of August 1, 1985. Over a period of about three hours, 6.06 inches of rain fell at the National Weather Service Office, breaking the state record for 24-hour precipitation that had stood since 1927. Of that amount, 3.50 inches fell in one hour, also setting a new state record. Hail stones up to two inches in diameter accumulated to depths of 11-12 inches. The hail washed into low-lying areas, where it piled up as high as six feet (see Figure 9). The storm is documented in "Meteorological Analysis of the Cheyenne, Wyoming Flash Flood and Hailstorm of 1 August 1985," a 51-page NOAA Technical Report (ERL 435-FSL 1).

The third and final example is a case of serendipity. An early evening hailstorm on June 24, 2006, lasted no more than 20 minutes yet dumped up to two inches of hail in a one-mile-wide swath, north to south, across Boulder, Colorado. The storm began with scattered large, flattened, disk-shaped hailstones and ended with a deluge of slushy hail. One of the authors of this article, Tom Schlatter; his son Paul Schlatter,



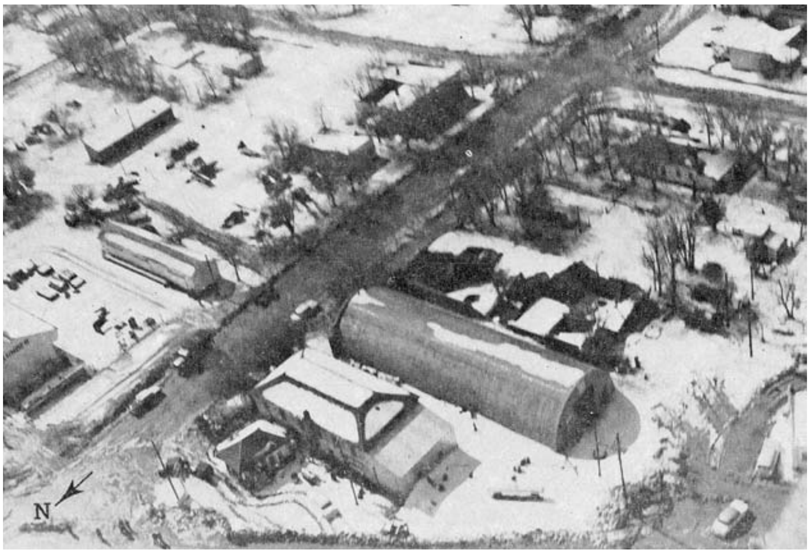
TERRY MARTIN

Fig. 6. Hail piled high by a storm near midnight, August 13, 2004, then cut through by floodwater, south of Clayton, New Mexico. Note layering of sediment in the ice "cliff" on the opposite bank.



NORTON TELEGRAM, NORTON KANSAS

Fig. 7. An aerial view of hail that fell up to 18 inches deep over Seldon, Kansas on the evening of June 3, 1959.



NORTON TELEGRAM, NORTON KANSAS

Fig. 8. Close-up aerial view of hail in Seldon, Kansas, June 3, 1959. Note trees stripped of leaves, and the building just right of center with the roof collapsed because of the weight of hail.

an interpreter of digital Doppler radar data; and Charles Knight, a cloud physicist and hail expert, co-wrote a paper on the storm in the August 2008 issue of *Monthly Weather Review*. The storm passed directly over Knight's home, and he collected hail samples! He determined that the hail grew by collecting supercooled cloud droplets, which froze quickly to the surface of the hail. This is called "dry growth" (the surface of the hail is not coated with liquid), and it can result in hail of unusually low density. The low-density hail in this storm, up to two inches in diameter, could be supported by a weaker than usual updraft, consistent with the marginal instability observed prior to this storm. Much of the hail splattered rather than bounced when it hit the ground, accounting for less than expected damage to cars, roofs, and windows for hail of this size.

The Need for Good Documentation

Storms producing deep hail are rare. As we noted earlier, hailstorms are not defined as severe unless hail diameter is at least one inch, and so many hailstorms do not make it into the official severe storm archive. To remedy this situation, we recommend broadening the definition of a severe storm to include hail that covers the ground to a depth of two inches or more, regardless of hail size. This much hail invariably causes damage to vegetation.

Here are some guidelines for documenting storms that produce deep hail.

- As soon as it is safe to go outside, measure the hail depth with a ruler. As with snow cover, measure at several spots in open, level areas where the hail is neither drifted by the wind nor piled up by running water. Take an average of the measurements. Hail melts quickly, so prompt measurements are essential.
- Measure the depth of drifts and hail piles, too, but keep in mind that this is not a good measure of how much hail fell.

DAILY CAMERA, BOULDER, COLORADO

Fig. 9. Aftermath of the Cheyenne hailstorm and flash flood, which occurred on the evening of August 1, 1985.

- Record the beginning and ending times of hail fall and hail size. Note how much wind accompanied the hail and how far the temperature dropped during the storm.
- Hail bounces out of most rain gauges. Measure the liquid water catch in the gauge, but try to measure the water content of the hail on the ground as well. A four-inch cylindrical gauge works fine for this purpose, but a small cylindrical bucket works, too. You can take a small plastic cutting board, slide it gently under the hail, then invert your rain gauge, push it down onto the cutting board, then carefully invert both the gauge and the cutting board to capture the hail inside the gauge. Once the hail has melted, you can measure its water content. The Web site for CoCoRAHS (mentioned at the beginning of this article) has detailed instructions, illustrated with color photos, for measuring the liquid equivalent of snow. These instructions apply to hail as well. Go to http://www.cocorahs.org/media/docs/Measuring%20Snow-National-Training%201.1.pdf and look at the segments on "Melting Snowfall" and "Measuring Snow Water Equivalent (SWE)."
- Photograph the scene. At the very least, show a ruler sticking out of the hail. Also photograph the surroundings to show streets and yards white with hail, leaves stripped from trees, damage to flower and vegetable gardens, dents on cars, broken windows, and, if applicable, structural damage. As a practical matter, insurance companies will want documentation of roof damage if you make a claim for repairs.
- Write a narrative of the storm, including any details that seem relevant.

The experience of seeing hail whitening the ground during the warm season is not soon forgotten. The incessant and deafening din of hail beating on rooftops and windows, the large volume of ice falling from the sky, and the destruction of gardens and crops within minutes are hard to grasp. If witnesses can spring to action quickly when the storm subsides and document what happened, meteorologists can look at the storm retrospectively, and bringing to bear radar, satellite, wind profiler, and other observations to better understand what causes these freakish storms. W

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We thank John Osborn for help in preparing many of the figures. Archivist Johanna Hardin put us in touch with people along the Front Range Urban Corridor of Colorado who had experienced hailstorms and taken photographs. Meteorologist Dierdre Kann of Albuquerque submitted color photos and some older black-and-white photos of New Mexico hailstorms and put us in touch with sources familiar with the hailstorm south of Clayton. Cheryl Griffith in the Department of Agricultural Economics, University of Nebraska, gave us contacts for the hailstorm near Scottsbluff. Thanks to John M. Brown and Ann M. Reiser for reviewing the manuscript.