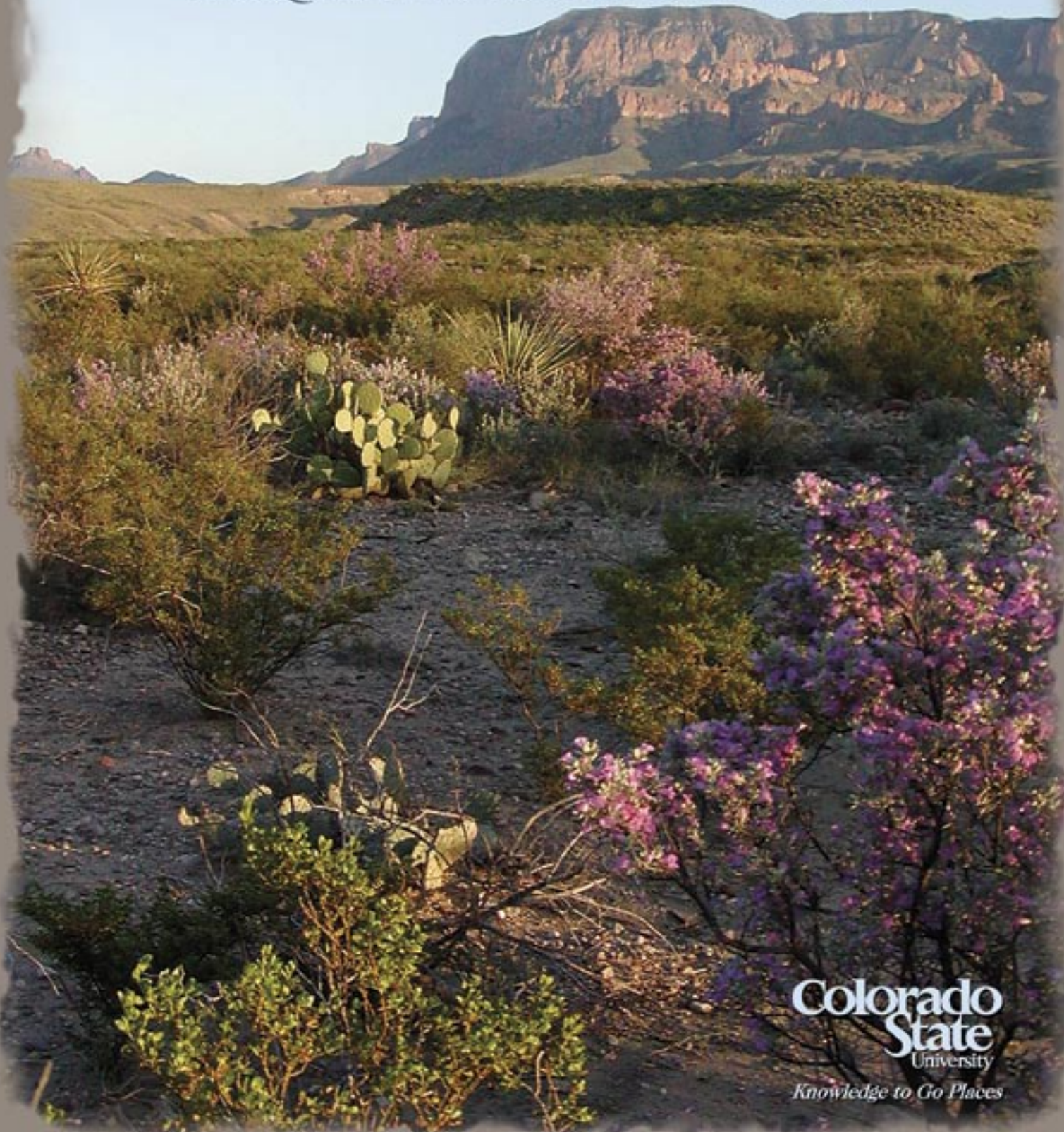


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Colorado
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Knowledge to Go Places

VOLUME 22, FALL 2004

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Heavy Snowfall . . . in the Midst of a Drought

John Weaver

On the morning of 19 March 2003, residents living just east of the Rocky Mountains in north-central Colorado awoke to find themselves buried under two-to-four feet of extremely wet, heavy snow. The snow was so heavy that in Fort Collins alone 37 structures were completely destroyed and more than 200 severely damaged as roofs, walls, and entire buildings collapsed. Had this been a large tornado outbreak, the massive amount of destruction that occurred in dozens of Colorado cities up and down the northern Front Range¹ would have made national news for days. However, other than for a couple of thirty second spots on the networks, very little national attention was given the event. In large part, the lack of interest in the wide ranging impact of this record-breaking snowstorm² prevailed locally. Perhaps the explanation lies in the absence of violence that characterized the two-day-plus affair. After all, snow is nothing more than white crystals floating to earth. Ironically, the storm occurred during the worst drought in Colorado history, so most local residents were simply glad to have the moisture.

From a forecast point of view, the storm was not a surprise. The occurrence of a heavy snow event was accurately predicted, as was the fact that the storm would last for at least 48 hours. Computer model guidance correctly indicated that the heavier precipitation would begin over the Front Range on the evening of Monday, 17 March, and continue for at least 48 hours (Figs. 1, 2). The guidance even hinted at two periods of heavier activity. The first would start on the evening of the 17th, and taper off late the next morning. A second round would begin on the late afternoon of the 18th, and continue into the morning of

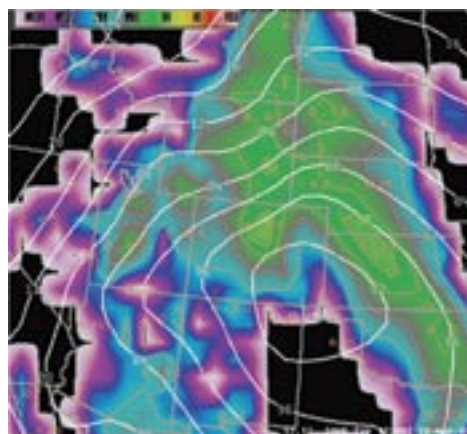


Figure 1. Computer-model output (eta 24-hr, forecast from 12:00 UTC, 17 March 2003) depicting forecast precipitation and surface pressures. The precipitation forecast is for the period 11:00 pm on 17 March through 5:00 am LST on 18 March 2003. The output shows 0.95" of liquid precipitation, or around 10"-12" at the snow: liquid ratios that were expected to occur. The interim, 6-h map (not shown) indicates that the precipitation would be spread evenly over the 12-h period. (1 in = 25.4 mm)

the 19th. That's pretty much what occurred, though the model forecast precipitation amounts were significantly understated for the populated areas along the Front Range corridor (Fig. 2).

There were misgivings among forecasters as to when (and in some cases whether) the changeover from rain to snow would occur. All of the computer models predicted that the 1000-500 hPa thickness (a measure of the "coldness" of the lower and middle layers of the atmosphere) was theoretically too high (i.e., too warm) to allow frozen snow crystals to reach the ground. In fact, several indicators suggested that snow levels would go no lower than about 6,000 feet (1830 m). The majority of the larger northern Front Range cities are

situated about a thousand feet lower than that. Nevertheless, most Colorado forecasters ultimately agreed that diurnal cooling, combined with the cold precipitation, would chill things sufficiently to allow the changeover to occur just after sunset. My own assessment was that the rain would turn to snow around 6:00 pm, with snow totals reaching upwards of 10"-15" (25-38 cm) by the time the storm was over.

A pre-event, light rain, began falling in northern Colorado early on the morning of 17 March (Fig. 3), and continued generally light-to-moderate throughout most of the day. It tapered off completely just before 4:00 pm

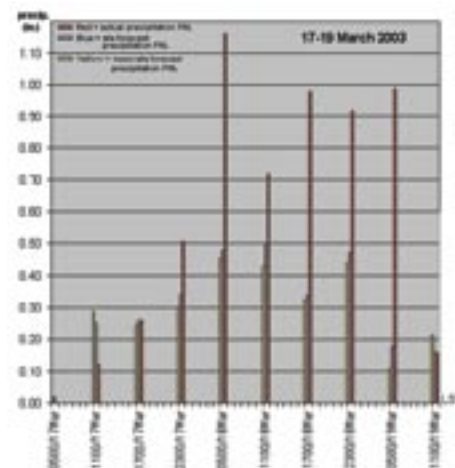


Figure 2. a) Meso-eta model (amounts from the eta-12 km grid output, extrapolated to a 29 km grid increment), and standard 80 km eta model (amounts from the eta-12 km grid output, extrapolated to an 80 km grid) precipitation forecasts (in inches) from the morning of 17 March 2003, plotted in yellow and blue, respectively. Plotted in red are actual liquid-equivalent precipitation amounts in 6-hr increments from observations taken at the Colorado State University Campus in central Fort Collins (FCL). (1 in = 25.4 mm)

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¹ The geographical designation "Front Range" refers to the easternmost range of peaks of the Rocky Mountains, but the terms "Front Range," or "Front Range corridor" will apply.

² The March 2003 snowstorm has erroneously been called a "blizzard," and there was certainly enough snow involved to qualify. However, to meet the official definition there would have to have been either sustained winds, or frequent gusts, to at least 35 mph (56 km/h) for a significant period of time, and there were not.

Heavy Snowfall *(continued from page 8)*

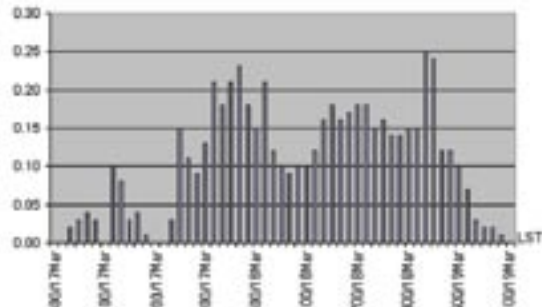


Figure 3. Hourly precipitation (in inches) measured at the Colorado State University site (FCL) in central Fort Collins. Amounts shown are for the hour ending at the times appearing on the abscissa. (1 in = 25.4 mm)



Figure 4. One line of convection moves off to the west of Fort Collins (squall lines were moving westward) as a second line forms to the east. Figure shows the 0.5 degree tilt, PPI reflectivity scan taken from the Denver, Colorado WSR-88D at around 6:00 pm on the evening of 17 March 2003.

local standard time (LST), but showers began again around 7:00 pm, as several north-south-oriented bands of convective precipitation moved across the area from east to west (Fig. 4). The new showers were heavier than those which had occurred earlier (Fig. 2), even producing a small, short-lived tornado about 25 miles (~40 km) east of Denver. However, as dusk transitioned to dark, all of the precipitation on the plains continued to fall as rain. Just fifty miles to the north – across much of southeastern Wyoming – it had been snowing most of the afternoon. This was troubling, since the region where it was snowing is situated at elevations of 6,000 feet, or greater. This is the precise elevation where the models predicted the rain/snow line would be

found. As temperatures and dewpoints hovered in the upper 30s (Fahrenheit) throughout northern Colorado, forecasters began to worry about their predictions of heavy snow. Denver television stations had played up the coming winter weather, but by this time there seemed a strong possibility that the official National

Weather Service forecast for a 12-20" (~30-50 cm) snowfall could turn to nothing more than 2-3" (~50-75 mm) of cold rain.

The problem may have been in the anticipated, versus actual, location of key synoptic features. Here, the computer models were only a few miles off, but it was a critical few miles. The eta-model presented a scenario wherein a so-called “warm conveyor belt” (i.e., a warm, moist stream of air being drawn into a developing extratropical cyclone) would move moist air up from the Gulf of Mexico into southeast Wyoming. The developing extratropical cyclone would then



Figure 5. GOES, 6.7 μm water vapor image taken at 7:45 pm on 17 March 2003. The image shows the moisture associated with the warm conveyor belt stretching from northeastern Oklahoma, across most of Kansas, and westward into northern Colorado. At this time the surface low pressure is moving into southeast Colorado.

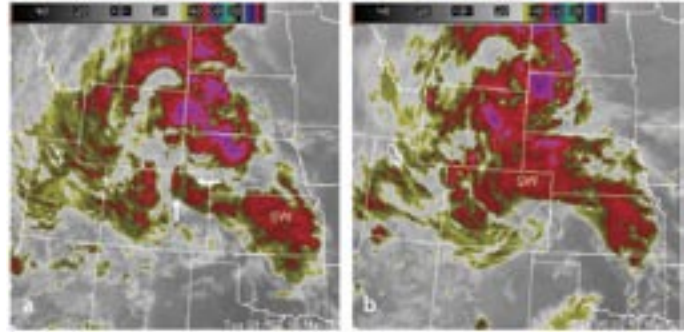


Figure 6. GOES, 10.7 μm infrared window images taken on the evening of 17 Mar 2003. a) image taken at 6:45 pm LST showing infrared view of banded convection in northeastern Colorado (arrows) and approaching shortwave disturbance to the east-southeast, over Kansas (SW), and b) image taken at 10:00 pm LST showing infrared view of shortwave at the time the rain changed over to snow along the Front Range in northern Colorado.

wrap heavy precipitation over the top of the cold air, and back into Colorado from the north (recall Fig. 1). GOES satellite imagery showed that the center of the developing system was actually a little further south than expected, and that the warm conveyor belt was feeding directly into northeast Colorado (Fig. 5). By 9:00 pm, as a second line of relatively heavy convective rain moved across the northern Front Range, a failed forecast was beginning to look more and more likely. It was raining steadily – relatively hard at times – but the temperatures and dewpoints were all staying well above freezing.

Satellite imagery offered a clue that changes were on their way. Figure 6 presents two GOES 10.7 μm images that reveal an enhanced area of colder cloud tops associated with a shortwave trough (marked SW in the figure) approaching from the east. This disturbance didn't arrive along the Front Range until about 10:00 pm LST, but its arrival had a profound effect. It was at that time when most reliable observers at elevations around 5,000 ft. reported a changeover from mostly rain to 100% snow. By this time, FCL (on the Colorado State University campus in central Fort Collins) had reported 0.76" (~19 mm) of rain. There'd been a little ice mixed in with the rain off-and-on throughout the evening, though it all melted on contact. But at 10:00 pm, the changeover took place, and snow began in earnest. By 7:00 am on Tuesday, 6"-12" (15-30 cm) were measured at various locations in Fort Collins, and it

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Heavy Snowfall *(continued from page 9)*

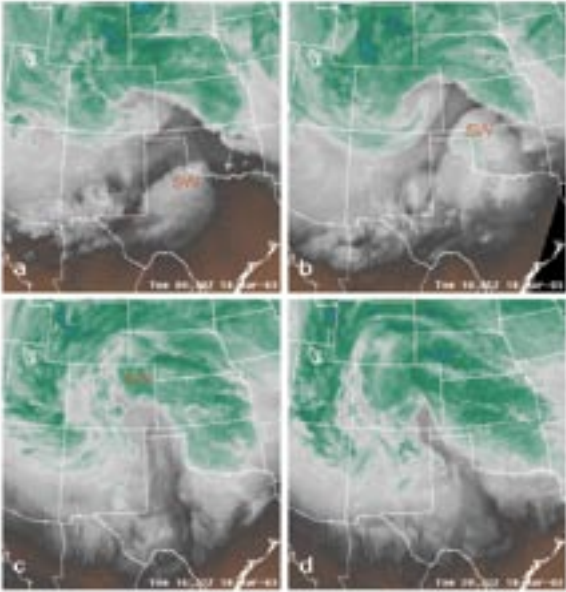


Figure 7. GOES, 6.7 μm water vapor image taken at a) 9:30 pm on 17 March, b) 3:05 am on 18 March, c) 9:22 am on 18 March, and d) 1:22 pm on 18 March 2003 showing an intensifying shortwave (marked SW in red) as it makes its way around the deepening cyclone which is still centered over southeast Colorado. Snow rates increased dramatically as this feature arrived along the Front Range. Note the expanding warm conveyor belt, especially over Kansas and Oklahoma.

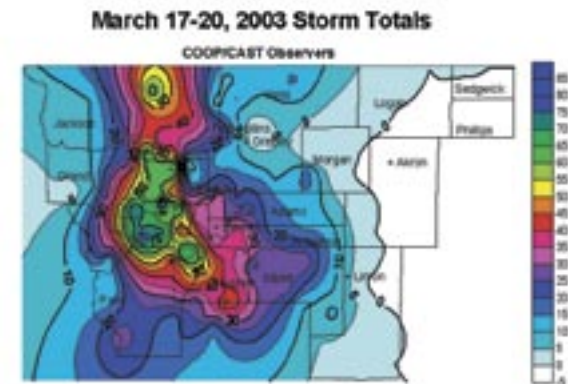


Figure 8. Map showing total snowfall (in inches) for the March 2003 snowstorm in north central Colorado. Observations were collected by National Weather Service (NWS) co-operative observers and members of the Colorado All-Season Spotter Team (CAST) – a volunteer spotter network that provides real-time weather information, year-round, to forecasters at the NWS office in Boulder, Colorado. Map courtesy of the Boulder, Colorado, NWS forecast office. (1 in = 2.54 cm)

was still coming down³. The liquid equivalent at FCL (where 8" fell overnight) was 1.5" – yielding a snow/water ratio of about 5:1. Other observers in the region all reported ratios ranging from 5:1 to 7:1. These included

several experienced observers who are part of the Colorado Climate Center's CoCo RaHS (Community Collaborative Rain and Hail Study) project. CoCo RaHS is a network of trained volunteers with observers in most of the cities affected by the storm.

The intensity of the snowfall trickled off to less than half an inch per hour over the next four hours, but a second shortwave was rotating around the now extremely robust cyclone (Fig. 7). This second disturbance – accompanied by deeper moisture in a reinvigorated warm conveyor belt – arrived in central Colorado around noon local, and snow rates increased dramatically. This was the beginning of the second, and most persistent, segment of the event. As the hours passed, and the snow continued up and down the Front Range corridor, tree limbs began snapping, wide-expanse roofs bowed downward, and cars on the street morphed into massive white mounds. Heavy snow continued for another 24 hours, with some particularly heavy convective bursts just after midnight on the 19th. When it was over, central Fort Collins had received an additional 24" of snow, and several foothills observers reported more than 40".

By midday on Wednesday, 19 March, north central Colorado was buried (Fig. 8). Roads throughout the region were impassable, and most businesses were closed. The northern Front Range had been hit with its second largest snowfall in the region's history (Wilson 2003), and, according to *Claims* magazine, Colorado sustained the highest nationwide insured losses for the entire first quarter of 2003 as a result. The snow itself was so heavy that municipal snow plows in most cities were at first unable to clear roads. Many plows were damaged while

trying. Thousands of residents in Jefferson County (west and southwest of Denver) were trapped in their homes for several days, and deep snow closed the major interstates. Yet – other than for hospitals and emergency responders – no one that I've spoken with locally ever felt any real sense of danger. From a more personal perspective, I certainly didn't feel threatened at any time. The storm, to most, seemed more of an interesting phenomenon – partly fun, and partly an inconvenience. Figures 9 and 10 illustrate the absurdity of the situation. I broke two snow shovels, and finally succeeded in shoveling out my driveway, only to find deep, extremely heavy snow blocking the street. Figure 11 is an example of building damage in Fort Collins. And this was one of the salvageable structures.

CIRA research associates working for the Virtual Institute for Satellite Integration Training (VISIT) have been tasked with developing a winter weather teletraining course for National Weather Service forecasters. The course is meant to focus on satellite imagery as a value-added tool within the short-range forecast/nowcast suite of products. The March 2003 storm is one of the examples chosen for presentation. Two questions concerning the case remain partially unanswered. First, and most important, why was the changeover from rain to snow delayed for so many hours (alternatively, why did it change, at all)? Second, why did precipitation amounts right along the Front Range exceed all of the model forecast values by nearly a factor of two? The solution to neither is trivial. The "late" changeover probably had to do with the fact that northeast Colorado was directly beneath the feed of warm, moist Gulf air aloft. The warmer rain may have been modifying the cold air that was trying to move in from the north. The changeover was probably due to layer lifting (and consequent adiabatic cooling) associated with the arrival of the shortwave disturbance illustrated in Fig. 6. Once the changeover occurred, the colder air from the north gained a foothold, and the precipitation never changed back.

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³ Interestingly enough, this first round of snow didn't present much of a problem for motorists along the urban corridor. In the week prior to the storm, daily high temperatures had ranged in the high 60s to low 70s (F), and the 2" (5 cm) soil temperatures had reached 50°F (10°C) the day before the storm. By early Tuesday morning, however, snow was finally beginning to accumulate on the roads.

Heavy Snowfall *(continued from page 10)*



Figure 9. Now what?! Shoveling the driveway doesn't help very much when the street has nearly thirty inches (~75 cm) of snow blocking it. Photo taken by the author in northeast Fort Collins late on the morning of 19 March 2003.

Thousands of buildings were damaged, and five people were killed. The largest snowstorm in north-central Colorado history occurred on 1-5 December 1913 (Wilson 2003). It dumped 30"-45" of snow onto communities all along the northern Front Range, including Fort Collins and Denver, and that storm was accompanied by strong, gusty winds. It

was a true blizzard. Worse, since it occurred near the beginning of winter, the snow was slow to melt off. The aftermath caused serious continuing problems for nearly two months.

The March 2003 snowstorm would certainly be classified as an extreme event anywhere in the country. A three-foot-deep, one-foot-square column of snow, at a snow-to-water ratio of 5:1 to 7:1, weighs from 27-38 pounds (12 - 17 kg). Putting that much weight on every square foot of a wide-expanse roof challenges even the most advanced engineering. As a witness to the event, I find it surprising that more structures

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It is likely that model underestimates of precipitation amounts just east of the foothills are directly related to local topography. The excessive precipitation in this region most probably resulted from a locally deepened boundary layer associated with cold air damming along eastern slopes of the Front Range – a phenomenon that occurs regularly in upslope precipitation situations (Richwien 1980, Gage and Nastrom 1985, Dunn 1987, or Wesley et al. 1990). The “piling up” of cold, moist air serves to extend the effect of the foothills several miles eastward. In Weld County – whose western border is just a few miles east of the mountains – both snow and liquid precipitation totals were closer to the model-predicted values. For the VISIT training, that aspect of the case will be heavily emphasized when the session participants include offices near mountainous terrain.

The March 2003 snowstorm was a wonderful example of the extreme weather events that occur frequently on the High Plains of the United States. The average annual precipitation along most of the Front Range corridor runs around 15" (~380 mm) per year, yet exceptionally heavy precipitation occurs somewhere in the region nearly every season. The most notable event for the City of Fort Collins was a flash flood which took place on the evening of 28 July 1997 (Petersen et al. 1999). That remarkable weather system dropped 14.5" (~370 mm) of rain onto portions of the urban area in less than 30 hours; 10.5" (267 mm) fell in just over five.

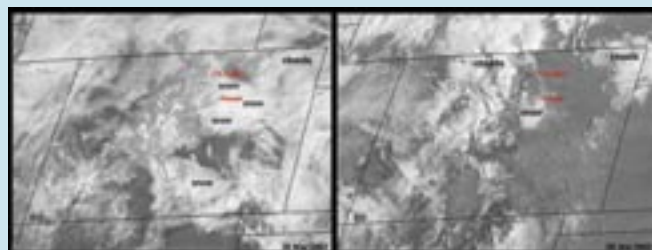


Figure 10. Ironically, the athletic fields at Colorado State University had been closed until the Fall term due to drought conditions. Watering restrictions made it impossible to revitalize the dry, brittle grass. This photo of a six-foot sign was taken on the morning of 19 March 2003. Photo courtesy of Stacey Seseske (NOAA/FSL), former CSU graduate student.

Comparing Two Storms

Not only did the all-time record blizzard of 1-5 December 1913 produce more total snowfall over a slightly larger area than did the 2003 storm, but it also occurred at the beginning of the cold season instead of near its end. According to Wilson (2003), persistent cold following the December 1913 storm caused deep snow to linger well into the following year. Its effects were adversely affecting various aspects of life in Denver well into February of 1914. The deep snow associated with the 2003 event, coming as it did at the beginning of spring, disappeared quickly.

Within a week, most of the snow along the Front Range was gone. The quick melt-off is evident in the two visible wavelength satellite images taken one week apart. On the left is a GOES-12 visible image taken at 17:45 UTC on 20 March 2003 showing snow cover along the eastern Front Range of Colorado the day after the storm. A cloud field covers extreme northeast portions of the state. On the right is a GOES-



12 visible image taken at 15:45 UTC on 26 March 2003. More than 80% of

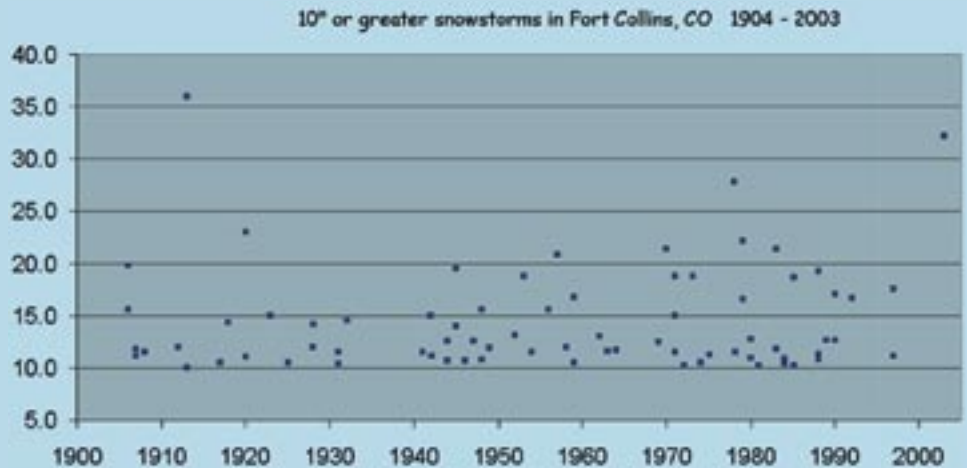
the snow cover along the Front Range has vanished.

Heavy Snowfall *(continued from page 11)*

What Constitutes the “Worst Storm?”

It is nearly impossible to rank snowstorms in any general way, simply because there are so many ways to do it. Trying to assess a storm’s intensity in terms of so-called human impact is a serious challenge. For example, you might decide to compare storm-related deaths/injuries as a measure of severity, but this would lead to a long series of questions. One would need to consider differing and/or changing population densities, time of day that the storm hits (nowadays, a one foot snow during rush-hour would have much more impact than the same storm in the middle of the night), available communications technology, response and rescue resources, and many others. Dollar damage assessment might be another part of the equation, but then one would have to consider such variables as inflation, differing/changing building codes, the size of the urbanized area affected, and so on.

Making comparisons based on objective weather variables might (at least at first glance) seem a better approach, but in this arena the problems can be even more complex. Is a two-foot snow, at a 20:1 snow-to-water ratio, “worse” than a one-foot snow at a heavier, 5:1 ratio? Should one simply consider the greatest snow depths reported for large storms, or should the assessment include the size of the total area affected? Is one storm “worse” than another if it is followed by a period of very cold weather that causes snow to linger an inordinate amount of time, instead of melting away quickly? Would a one-foot snow, accompanied by strong winds and six-foot drifts, be “worse” than a three-foot snow with modest winds and small drifts?



What constitutes a single “storm?” Should a break in snowfall of some arbitrary length of time suffice to represent the “end” of one storm, and the beginning of another? Should meteorologists make the determination based on whether a restart of snowfall is part of the same weather system?

Some climatologists contend that the snowstorm which occurred during the first week in December 1913 was actually two separate events. Snow fell on the 1st and 2nd, then there was a period on the morning of the 3rd where the precipitation stopped entirely. By this time there was 16.5" (42 cm) of new snow on the ground in Fort Collins. Light snow began again late in the day, and continued to increase until it became heavy on the 4th and 5th. By the time the five day period was over, a total of 36" (91 cm) had fallen. Looking back at the crude surface maps available for 1913, my guess is that both snows were part of the same low pressure system that moved up from the southwest. It’s a judgment call, but in the point-data shown below, I’ve chosen to classify the entire five day event as a single storm. My criteria, for this case and a few others, was as follows: 1) if there were two or three consecutive days

upon which similar amounts of snow fell (within the same order of magnitude), I would classify these days as a single event, and 2) if there were *more* than three days in a row with snow, then I would try to find maps that would confirm or deny a “single storm” interpretation. There were only five cases in category (2), and none seemed ambiguous.

The graph below shows snowstorms which produced 10" (25 cm), or greater, snowfall in Fort Collins over the period 1904 through 2003. Of the one hundred years compiled, 49 had at least one such event, and several produced deep snow events. The months in which double-digit snowstorms occurred were as follows: March (17 times), April (15), December (10), November (9), February (8), January (7), October (5), May (2), and September (1). The graph clearly shows that, for Fort Collins, the March 2003 snowstorm (32.2", or 82 cm) was second only to the blizzard of 1913 (36.0", or 91 cm). The third greatest total shown on the graph occurred in early May 1978, when a total of 27.8" (71 cm) was recorded.



Figure 11. Collapsed roof of the large Bed, Bath, and Beyond store on south College Avenue in Ft. Collins, CO. The roof on this structure was replaced and the store re-opened several months later. Photo courtesy of Ron Phillips, City of Fort Collins.

were't damaged. It was a large and quietly-ferocious beast.

But another way to look at it is to remember that the March 2003 snowstorm brought 5" (~127 mm), or more, of welcome precipitation to large portions of a drought parched state, and may have represented the first glimmers of hope for an end to Colorado's long and deadly drought.

Acknowledgments

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Implications

There is no single answer to the question of what sources are responsible for the haze at Big Bend National Park. Sources in both the U.S. and Mexico have been found to be responsible. Mexican SO₂ emissions contribute to the sulfate haze most frequently, but the haziest events that occur in the late summer and fall include contributions from Texas and the eastern U.S. The largest single contribution to haze is from the Carbon power plant in northern Mexico. Substantial reductions of that facility's emissions would likely result in small but noticeable improvements in Big Bend haze on many days, but it would not make much difference to the worst haze episodes during late summer and early fall. SO₂ emission reductions in both Texas and the eastern U.S. would likely reduce the worst haze episodes during the late summer and fall. Emission reductions southeast of Big Bend on both sides of the Rio Grande River have a potential to reduce haze at Big Bend during the June through September period when transport from this region is most frequent.

The clearest days at Big Bend have low sulfate concentrations. The visual scene on a clear day is more sensitive to small changes in haze than a hazy (or moderately hazy) day. On these clear days, the Carbon I & II power plants and other sources in northeast Mexico appear to be the largest contributors to Big Bend's sulfate haze. Thus, reduction in emissions from Carbon would likely result in creating more clear days. However, growth along this border region will probably further reduce the number of clear days.

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