Density of Freshly Fallen Snow in the Central Rocky Mountains

Arthur Judson* and Nolan Doesken+

ABSTRACT

New snow density distributions are presented for six measurement sites in the mountains of Colorado and Wyoming. Densities were computed from daily measurements of new snow depth and water equivalent from snow board cores. All data were measured once daily in wind-protected forest sites. Observed densities of freshly fallen snow ranged from 10 to 257 kg m^{-3}. Average densities at each site based on four year's of daily observations ranged from 72 to 103 kg m^{-3}. Seventy-two percent of all daily densities fell between 50 and 100 kg m^{-3}. Approximately 5% of all daily snows had densities below 40 kg m^{-3}. The highest frequency of low densities occurred at Steamboat Springs and Dry Lake. The relationship between air temperature and new snow density exhibited a decline of density with temperature with a correlation coefficient of 0.52. No obvious reversal toward higher densities occurred at cold temperatures, as some previous studies have reported. No clear relationship was found between snow density and the depth of new snowfalls. Correlations of daily densities between measurement sites decreased rapidly with increasing distance between sites. New snow densities are strongly influenced by orography, which contributes to density differences over short distances.

1. Introduction

Density is an important physical property of snow. It establishes the relationship between snow and its water content, correlates with snow strength and ease of removal, and is an input parameter in a snow accumulation algorithm used to estimate new snow depths with the NEXRAD WSR-88D radar (Super and Holroyd 1997). It is used to forecast snowfall from an orographic precipitation model employed in the western United States. Snow density is a contributory factor in avalanche occurrence and a consideration in snow management programs, runoff predictions, high speed snow removal, and snow safety.

Snow density varies with crystal size, shape, and the degree of riming. Crystals may be hexagonal or spicular, clear or opaque, partly obscured by rime, or so heavily rimed the original forms are unrecognizable. Crystal size varies constantly. Smaller crystals are generally associated with colder temperatures and larger ones with warmer conditions, but a large range of sizes occurs at all temperatures. In particular, tiny crystals occur with both warm and cold conditions. Small particle sizes sometimes contribute to higher densities because they pack better. Crystals that fall through clouds with high concentrations of supercooled water become rimed and produce high density layers. LaChapelle (1969) found a 15-cm deposit of heavily rimed needles a few hours old that had a density of 320 kg m^{-3}; this value is greater than the density of metamorphosed continental snowpacks months old. The event turned out to be more than academic because the occurrence caused widespread avalanching.

Density at the time of observation is a product of the initial density and further densification due to prevailing weather conditions, overburden pressure, and the amount of time between deposition and measurement. Densities increase with pressure and time. The process is temperature driven with the greatest density increases occurring at snow temperatures near 0°C, and the least with temperatures near –40°C. The process associated with crystal alterations in the snowpack is called metamorphism. The original forms are

*USDA Forest Service (retired), Rocky Mountain Research Station, Fort Collins, Colorado.
+Colorado Climate Center, Atmospheric Science Department, Colorado State University, Fort Collins, Colorado.
Corresponding author address: Nolan J. Doesken, Atmospheric Science Department, Colorado State University, Fort Collins, CO 80523-1371.
E-mail: nolan@ccc.atmos.colostate.edu

In final form 26 January 2000.

slowly destroyed and gradually metamorphose into more rounded shapes. These modifications result in decreasing snow depth with time as the amount of pore space decreases while density increases. This basic feature of snow is ever present, and it is the reason that short measurement intervals give larger new snowfall totals than longer measurement intervals do for the same event. The physics of the process dictates rapid settlement initially followed by slowing rates of change as density rises. The higher the density, the greater the resistance to further densification.

A simple rule of thumb has developed through history to quantify and describe the density of fresh snow. The "ten-to-one rule" used to convert snow depth from its water content likely originated from nineteenth-century snow density data from Toronto, Ontario, Canada (Potter 1965). Anyone who has spent time observing snowfall knows from experience that snow density varies greatly from one snow event to the next and even from time to time within a single storm. Yet the ten-to-one rule persists and is still used to determine snowfall from water content and vice versa at some weather stations. Abbe (1888) warned nineteenth-century weather observers concerning the large errors associated with such a simplification, but more than 100 years later the practice continues.

From studies that have been published, the density of freshly fallen snow in the United States varies from 10 to about 350 kg m^{-3} (Diamond and Lowry 1954; Wilson 1955; LaChapelle 1962; Judson 1965; Grant and Rhea 1974; McGurk et al. 1988; Doesken and Judson 1997). Other pertinent contributions to the literature came from Oda and Kudo (1941), Bossolasco (1954), Power et al. (1964), Gunn (1965), Stashko (1976), and Meister (1986). Most of these publications are not in mainstream meteorological literature, and the results have not been widely distributed among meteorologists. For this reason, and because of the general dependence of operational meteorologists on gauge data, snow density has not been available to most operational forecasters.

Gauge precipitation data are not used in place of water equivalent data because of undercatch problems (Goodison 1978). The difference between actual precipitation and catch from an unshielded gauge may exceed 50% for wind speeds of 3 m s^{-1} at gauge top. Gauge precipitation therefore differs from snow water equivalent by the amount of undercatch. This disparity varies from site to site and is a function of site exposure and protection from wind. Figure 1 shows an example of gauge catch as a function of core precipitation in a wind protected forest opening at Berthoud Pass, Colorado. More exposed sites suffer greater disparities.

Are density variations important? Suppose that 10:1 is used to estimate expected snowfall when the actual ratio is 40:1 in one instance or 3:1 in another? It takes more energy to shovel high density snow than low. A vehicle that rolls easily through fluffy snow founders in higher density deposits with more rolling resistance. New snow densities that depart widely from normal and certain density profiles in fresh snow favor avalanching. The product density times snow depth gives the weight of the overlying snow layers, and therefore the stress at any level in the snowpack.

This paper presents density data on freshly fallen snow from several mountain sites in Colorado and Wyoming. Frequency distributions, the relationship between air temperature and density, the effect of snow depth on daily density, and spatial variations in 24-h new snow densities are considered.

2. Data

With the exception of data collected by the first author at his residence in Steamboat Springs and at nearby Dry Lake, all data used in this study were from avalanche stations. Some were maintained by the U.S. Forest Service Alpine Snow and Avalanche Research Project, now defunct. One station was operated by the Wyoming Department of Highways and is now closed.

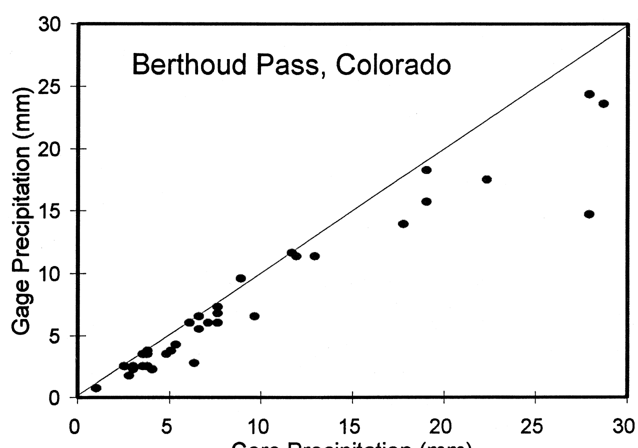

FIG. 1. Daily precipitation measurements from an unshielded 20.3-cm (8 in.) diameter precipitation gauge as a function of water equivalent from snow board cores at Berthoud Pass, CO, during the winter of 1971/72. The measurement site is an ideal exposure in a naturally sheltered clearing surrounded by a mature spruce–fir forest at an elevation of 3450 m MSL.

Two stations were administered by the University of Colorado; both have since closed. Others, still active, belong to the Colorado Avalanche Information Center. All observers were skilled avalanche forecasters trained in special snow measurements. The locations of all measurement sites, which cover 6° of latitude from southern Colorado to northwest Wyoming, are shown in Fig. 2 and described in Table 1.

Observations at all sites consisted of once daily, early morning measurements of new snow depth and water content. New snow depth was measured on white snow boards set flush with the snow surface. All water-equivalent data were from cores extracted from the boards. At Wolf Creek Pass, a plastic tube was used and samples were weighed. The remainder were cored using galvanized, 20-cm diameter cans. Cores were subsequently weighed or melted. Water from melted cores was poured into standard National Weather Service reduction tubes and measured. Sample age ranged from about 1 h to just under 24 h. All data were restricted to the 1 November through 30 April period to minimize radiation effects. The sites were located in wind-protected forest openings. The predominant stand types were spruce–fir, sometimes mixed with lodgepole pine and aspen. All samples involved new snow at least 2.5 cm in depth and free from wind effects, sleet, freezing rain, rain, freezing drizzle, drizzle, melt crusts, or other snow with visible melting effects.

Densities measured at Dry Lake, Steamboat Springs, and Wolf Creek Pass are from the matching winters 1994/95 through 1997/98. The other 4-yr sets used in the distributions are from the 1970s, with at least three matching winters each. Data used for interstation density plots are from the best data–observer combinations available.

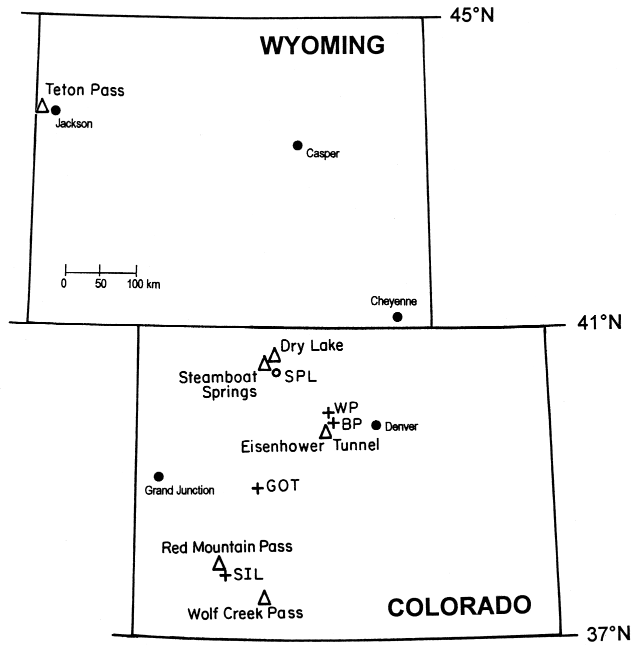

FIG. 2. Location of Colorado and Wyoming snow density measuring sites used in this study (open triangles). Cloud-level temperature data were obtained from the Storm Peak Laboratory (SPL; circle). Supplemental comparative density data (plus signs) were utilized from Berthoud Pass (BP), Gothic (GOT), Silverton (SIL), and Winter Park (WP) avalanche research sites.

3. Frequency distributions

Figure 3 histograms show the distributions of new snow densities for each observing site in the study. Densities ranged from 10 to 257 kg m^{-3} with individual station peak frequencies varying from 60 to 100 kg m^{-3}. Measures of central tendency and other statistical details of the distributions are shown in Table 2. The lowest elevation site, located in the city of Steamboat Springs, Colorado, had the lowest average density of 72 kg m^{-3}, a peak frequency (mode) of 70 kg m^{-3}, and a range from 15 to 168 kg m^{-3}. This site is sheltered by a young stand of lodgepole and ponderosa pine. It is often immersed in a deep and persistent temperature inversion throughout the winter months. The combination of the trees and the inversion results in snow deposition with little or no wind most of the time. Steamboat Springs shares with nearby Dry Lake a tendency for occasional very low density snowfalls of considerable depth. A daily fall of 36 cm of 23 kg m^{-3} snow was measured on 19 January 1996. The Dry Lake observation that day showed 45 cm of new snow with a density of 30 kg m^{-3}. Smaller diameter, unrimed stellar crystals and small, clear plates were observed during both low-density depositions.

Dry Lake had an average density of 77 kg m^{-3}. The range varied from a sample low of 10 kg m^{-3} to a maximum of 160 kg m^{-3} with the peak at 90 kg m^{-3}. This snow study plot is not quite as protected from wind as is the Steamboat Springs site, but blowing snow problems are minimal.

Snowfalls with densities below 40 kg m^{-3} are called wild snow. Several snowfalls of this type occur annually in the Park Range. Both Steamboat Springs and Dry Lake have reported at least 8% of their daily snowfall with these very low densities. These events appear to be somewhat unique to the region, although lake-effect snows near the Great Lakes sometimes show similar densities (Eichenlaub 1979). These snow lay-

TABLE 1. Site information for snow density data collection sites in Colorado and Wyoming used in this study.

Station name	Lat	Long	Elev (m)	Observer	Period of record
Primary stations for density comparisons					
Steamboat Springs	40°28'	106°49'	2120	A. Judson	1994–98
Dry Lake	40°32'	106°47'	2560	A. Judson	1994–98
Teton Pass	43°30'	110°57'	2440	W. Bassett	1970–74
Eisenhower Tunnel West Portal	39°41'	105°55'	3360	USFS Alpine Snow and Avalanche Research Project	1976–80
Red Mountain Pass	37°54'	107°43'	3400	University of Colorado, San Juan Avalanche Project	1972–76
Wolf Creek Pass	37°29'	106°47'	3244	Colorado Avalanche Information Center	1994–98
Supplemental data					
Silverton	37°49'	107°40'	2830	University of Colorado, San Juan Avalanche Project	1974/75
Gothic	38°58'	106°59'	2896	B. Barr	1975/76 1994/95
Berthoud Pass	39°48'	105°47'	3450	USFS Alpine Snow and Avalanche Research Project	1971/72 1975–78
Storm Peak Laboratory	40°27'	106°44'	3210	Desert Research Institute	1994–98
Winter Park	39°54'	105°46'	2825	E. Henion	1977/78

ers exhibit extremely low internal cohesion and present minimal resistance to travel. In terms of avalanches, wild snow sometimes flows silently down steep slopes unrestrained by stands of timber and becomes airborne after reaching a relatively low threshold speed.

Teton Pass, Wyoming, was the northernmost site in our sample. New snow densities there averaged 82 kg m^{-3} during the four winters ending in April 1974. The maximum daily value was 192 kg m^{-3}, the minimum recorded was 27 kg m^{-3}, and the peak frequency was 70 kg m^{-3}. This pass rises abruptly above the plains of Idaho and although the elevational change there is similar to that encountered farther south in Utah's Wasatch Front, densities are closer to those measured in Colorado.

The Eisenhower Tunnel West Portal site lies adjacent to Interstate 70 directly west of Denver. Here, densities averaged 76 kg m^{-3}, peaked at 80 kg m^{-3}, and ranged from 30 to 133 kg m^{-3}, the narrowest of our data. The shape of the distribution is similar to that at nearby Berthoud Pass (Judson 1965). On the summit of Red Mountain Pass in Colorado's San Juan Massif, densities averaged 75 kg m^{-3}, peaked at 60 kg m^{-3}, and ranged from 20 to 167 kg m^{-3}. Despite its more southerly latitude, the general range and limits of densities at Red Mountain are similar to data from Steamboat Springs, Dry Lake, and Teton Pass.

Wolf Creek Pass, Colorado, is located approximately 100 km southeast of Red Mountain Pass. The outstanding feature of new snow densities at Wolf

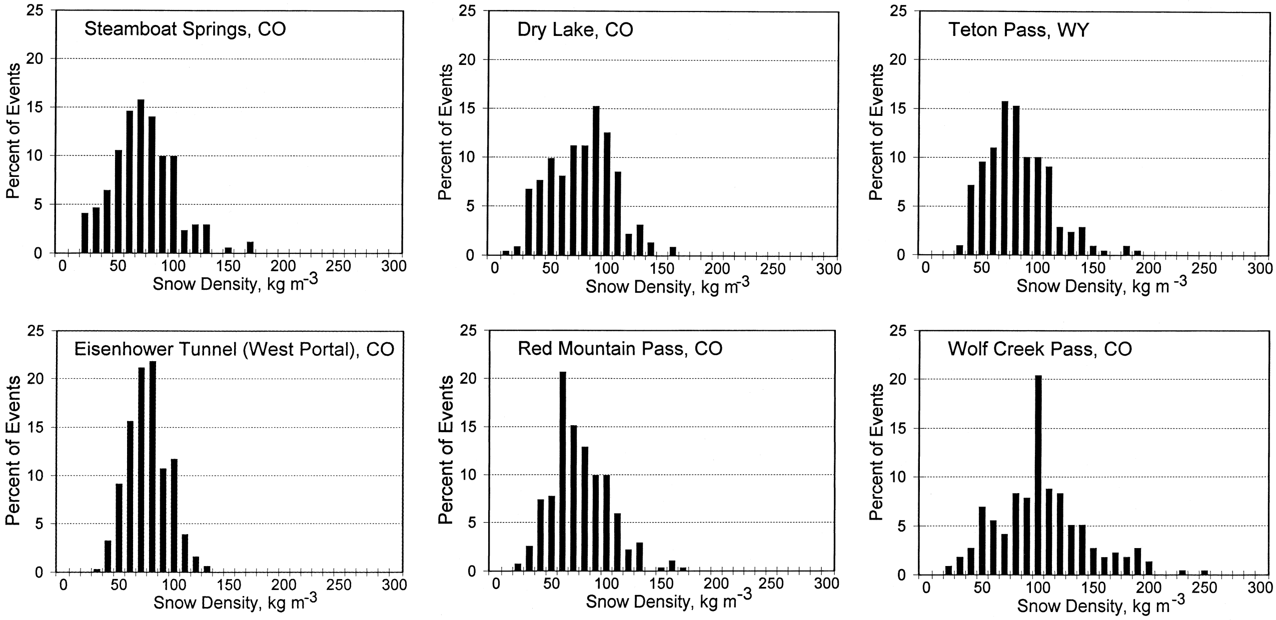

FIG. 3. New snow density distributions from the Colorado and Wyoming measurement sites.

Creek Pass is the shift to higher values throughout the distribution. No location in Colorado or Wyoming has reported higher new snowfall densities in the literature, and the average of 103 kg m^{-3} is the highest reported in the Rocky Mountains. The minimum density there was 20 kg m^{-3} and the relatively long tail extended to 257 kg m^{-3}. The extended peak frequency at 100 kg m^{-3} may be an artifact of rounding. There would be no physical reason for such a prominent peak with sharp declines on either side. To test this assumption, a separate distribution for this station based on 10 cm and greater snowfalls was made. That distribu-

TABLE 2. Comparative snow density characteristics.

Station	No. of winters sampled	Daily snow events ≥ 2.5 cm	Density characteristics (kg m^{-3})							Percent of events with densities	
			Least	Greatest	Mean	Median	Mode*	Standard deviation	Weighted mean**	< 40 kg m^{-3}	≥ 110 kg m^{-3}
Steamboat Springs	4	171	15	168	72	70	70	28	72	8.8	9.9
Dry Lake	4	223	10	160	77	81	90	29	77	8.0	16.0
Teton Pass	4	209	27	192	82	77	70	29	81	1.0	20.3
Eisenhower Tunnel West Portal	4	307	30	133	76	75	80	18	76	0.3	6.2
Red Mountain Pass	4	271	20	167	75	72	60	26	77	3.3	13.0
Wolf Creek Pass	4	216	20	257	103	100	100	41	108	2.8	42.3

*Mode in intervals of 10.
**Weighted by depth of fresh snow for each event.

tion showed a steady buildup to a less pronounced 100 kg m^{-3} peak followed by a slow but steady frequency decline into the higher densities.

Large storms occur at Wolf Creek Pass with densities above 100 kg m^{-3}, making this a snow climate of its own. Such storms repeatedly occur with southwest flow aloft bringing moisture from the Gulf of California and the subtropical Pacific. Heavily rimed crystals and graupel (snow pellets) are typical at Wolf Creek. Only one major barrier with elevations above 2000 m above mean sea level (MSL) stands between the pass and its southern moisture sources. This, together with orographic blocking of northerly and northwesterly flow by upstream mountains, is probably the reason for the higher densities measured here. Rhea (1972) reported that the Wolf Creek area averages eight times more precipitation with 700-mb southwest flow than it receives with north-northwest wind at that pressure level. These orographic influences combine to make Wolf Creek Pass snows atypical of most of the Colorado and Wyoming mountains much of the time. Occasionally, lower-density snows occur at the pass for extended periods.

The Colorado–Wyoming data were compared with the only other comparable density data available. This second group included records from North Danville, Vermont, and avalanche station data presented by LaChapelle (1962). LaChapelle's data came from Alta, Utah; Berthoud Pass, Colorado (not included in pooled data); Squaw Valley, California; Stevens Pass, Washington; and Girdwood, Alaska. These data were pooled with the Vermont data and compared to pooled data from Colorado and Wyoming. The pooled sets appeared similar up to 90 kg m^{-3} (70th percentile). Medians and modes were similar, but the LaChapelle–Vermont data showed stronger positive skew toward higher densities. This attribute alone separates the two groups and makes them fundamentally different. The Vermont data were almost normally distributed and showed no skew toward higher densities that were characteristic of data from Alta and stations farther west.

4. Relation of density to temperature

Crystal type and degree of riming are temperature dependent. Since these factors are partial determinants of the density of fresh snow, the relationship between density and temperature has been studied in hopes of finding a means of predicting density in advance of snowfalls. Results of previous work show two recurring patterns: 1) a nonlinear decrease in snow density with decreasing temperature (LaChapelle 1962; McGurk 1988) or 2) a parabolic relationship with density increasing at both warm and cold ends of the curve with a density minimum in between (Grant and Rhea 1974). The density minimum, when adjusted for temperatures near the ground, coincides with the dendritic growth range of snow crystals. Dendrites have been assumed to give the lowest densities, but recent observations at both Steamboat Springs and Dry Lake show that while unrimed stellar crystals are observed in very low density snowfall, unrimed plates and small diameter assemblages of plates mix with stellars in such snows. Fresh snow density–temperature correlations, excepting work by Stashko(1976), who stratified his data by snowflake size, have been weak, showed considerable scatter, and had r values below about 0.6.

We tested four winters of new snow density at Dry Lake, Colorado, with air temperature at nearby Storm Peak Laboratory (SPL) (Borys and Wetzel 1997). SPL is 9.5 km southeast of and 640 m higher than Dry Lake. SPL is frequently immersed in heavy clouds during the synchronous snowfalls that occur at the two sites. It is slightly above the average 700-mb level. Free air sounding temperatures were not used in this density study because of their limited availability (twice daily) and because of uncertainties that arise from interpolating between distant upper air stations. Grand Junction, Colorado; Salt Lake City, Utah; Lander, Wyoming (recently moved to Riverton); and Denver, Colorado, are pertinent stations, but the closest one, Denver, is 200 km distant and east of the mountain barrier. Since temperatures often change with time during snow events, temperatures at SPL were chosen to coincide with the centroid of each day's most intense snowfall in order to most closely match air temperature with the new snow strata's density. A recording precipitation gauge trace 50 m from the snow board was used for timing. By using in-cloud temperature data from a nearby site, it was hoped that scatter associated with using ground-based temperatures or interpolated upper-air temperatures from distant stations could be reduced.

The resulting scattergram (Fig. 4) shows new snow densities decline with temperature over the range 0° to −20°C, but with considerable scatter. The correlation is weak with correlation coefficient $r = 0.52$. Results are similar to those achieved by Diamond and Lowry (1954), LaChapelle (1962), McGurk et al. (1988), and Super and Holroyd (1997). While there is a hint of a second population below −15°C where density appears to increase somewhat with lower temperature, the main core of data continues to decline with temperature through −20°C.

There is some evidence here that densities of 100 kg m^{-3} or higher occur at cold temperatures (−15°C and colder) as suggested by Grant and Rhea (1974). However, a reversal to higher densities at lower temperatures, if it occurs, is not the dominant mode at the Dry Lake observing site. Neither is there evidence to support a continued linear decrease in density with decreasing temperatures as is currently shown in the National Weather Service Handbook Number 7 (U.S. Department of Commerce 1996).

The large variability in densities at warmer temperatures is also of interest. Dry Lake density variations associated with cloud temperatures of 0° to −5°C (as represented by the SPL readings) have ranged from 160 to 70 kg m^{-3}. While warm temperature snows may have mean densities near 100 kg m^{-3}, that value is an average of a widely dispersed population. Further improvement in the correlation might occur by stratifying the data by degree of crystal riming and by snowflake (or crystal) size, following the work of Stashko (1976). The density versus temperature question will not be resolved easily, and there is still room for further observations, analysis, and discussion.

5. Effect of new snow depth on density

Deep snowfalls are supposed to give higher 24-h density readings because the weight of the upper layers acts to densify the lower part of the deposit. This overburden pressure effect has been difficult to demonstrate (LaChapelle 1962; Meister 1986) because deep low-density 24-h snowfalls occur from time to time. Some examples from the U.S. Forest Service Westwide Network (Judson 1970) are 46 cm of 44 kg m^{-3} at Gothic, Colorado; 71 cm of 50 kg m^{-3} at Stevens Pass, Washington; 60 cm of 60 kg m^{-3} at Red Mountain Pass, Colorado; 60 cm of 70 kg m^{-3} at Wolf Creek Pass, Colorado; and 165 cm of 75 kg m^{-3} at Crystal Mountain, Washington. As previously mentioned, there were cases of 36 cm of 23 kg m^{-3} at Steamboat Springs, Colorado, and 45 cm of 24-h new snow with a density of 30 kg m^{-3} at Dry Lake, Colorado.

From five measurement sites in the central Rockies with similar density regimes, we compared a group of 70 daily snowfalls exceeding 30 cm with a group of 381 snowfalls less than 15 cm in depth. Average density of the first group was 75 kg m^{-3} while the latter group averaged 74 kg m^{-3}. A subset of the over-30-cm group, with water equivalents above 25 mm, gave an average density of 87 kg m^{-3}. Density range within this subset varied from 58 to 146 kg m^{-3}. The elevated density of the subset may indicate some pressure effect in 24-h snows with large water equivalents.

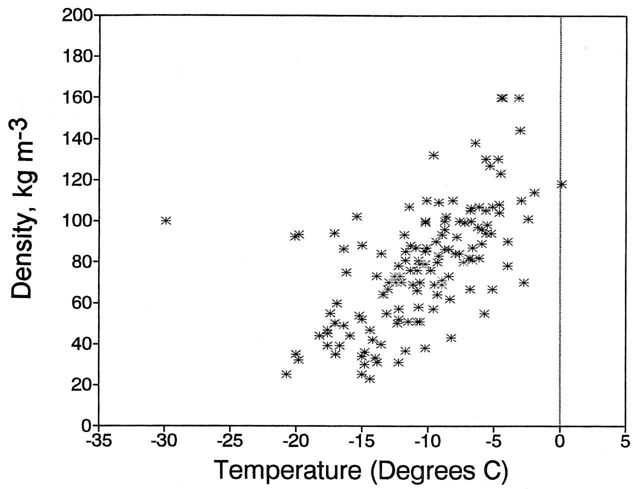

FIG. 4. Daily new snow densities at Dry Lake, CO, as a function of temperature at Storm Peak Laboratory, winters 1994/95 through 1997/98.

6. Spatial variation of new snow density

Work by LaChapelle (1958, 1962, 1969), McGurk et al. (1988), and Super and Holroyd (1997) shows that new snow density varies with snow climate. It varies within snow climates (Fig. 3) and it changes over distances on the order of a few kilometers. There are myriad causes for the observed disparities, but is operator error one of them? McGurk et al. (1988), with identical technique and equipment as used in this study, found average density differences between samples from adjacent boards in a forest clearing to be 0.13%. Our data, tested separately, show an average difference of 0.5% in samples taken from snow boards 1 m apart. As long as good equipment is used with reasonable care, density differences between operators should be minimal. The disparities must be attributable to other factors.

The smallest separation between measurement sites in our work was 7.2 km between Dry Lake and Steamboat Springs. The average new snow density difference between these sheltered sites was 11%. During the first winter of observations at Dry Lake, 62% of the densities paired with those measured at Steamboat Springs were within ±10 kg m^{-3}. The maximum disparity was 37 kg m^{-3}.

Figure 5 shows r values decreasing with increasing separation between measurement sites in Colorado. The value $r = 0.99$ was derived from snow boards 1 m apart in Steamboat Springs. Beyond about 10 km, correlation coefficients were uniformly below 0.7 and reached 0.34 at 335 km (Dry Lake/Wolf Creek).

A sample of interstation snow density scattergrams is shown in Fig. 6. No outliers were removed. A band of scatter some 60 kg m^{-3} wide was common to all plots. The high value outlier in Fig. 6d came from a localized fall of nearly 100% graupel at Gothic. Graupel from that storm produced a spot density of 169 kg m^{-3} at a nearby measurement site, the highest new snow density reading recorded in more than two decades of record in the Gothic–Crested Butte area. Gothic's daily new snow densities are poorly correlated ($r = 0.36$) with those at Dry Lake 175 km farther north. The apparent ceiling on Gothic densities near 80 kg m^{-3} in Fig. 6e is an artifact resulting from nonsynchronous snowfalls at Gothic and Dry Lake. Higher densities at Gothic were recorded that winter, but those occurred when Dry Lake was terrain shadowed from southwest flow aloft, so corresponding snowfall was absent at the more northerly site. A 10:1 data point is at the intersection of the dashed lines in Fig. 6 for the convenience of the reader. Clearly, neither a 10:1 ratio nor any other single ratio is appropriate in Colorado.

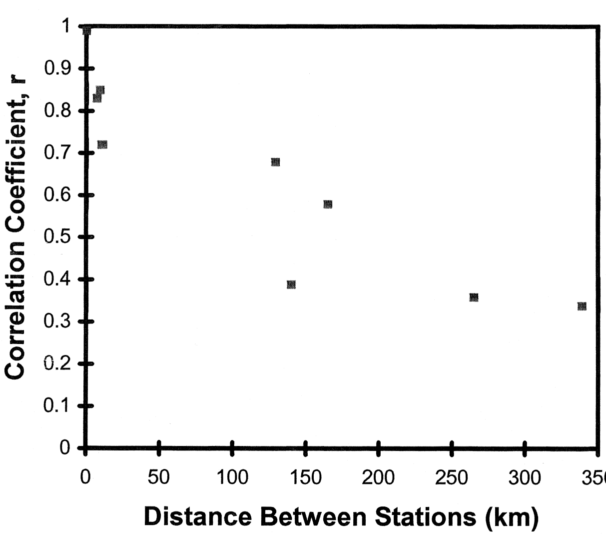

FIG. 5. Correlation coefficient r for synchronous daily observed snow densities as a function of distance between density measurement sites.

Scatter in interstation relationships derives from several sources. Some known primary causes for variation are site location and the ever-important exposure and protection from wind. Since our sites are all well protected, this discussion centers on variations related to accuracy of measurement, timing, and orography.

a. Accuracy of measurement

Snowfall at some avalanche stations used in this work was measured to the nearest 1.3 cm. Dry Lake and Steamboat Springs snow depth measurements were made to the nearest 0.2 cm. The seemingly small difference in precision is inconsequential given deep snowfalls, but it adds scatter when new snow depths are below about 10 cm. Rounding a new snow depth to 4 cm when it actually is 3.6 cm with 2-mm water equivalent yields a density difference of more than 10%. Use of the old National Weather Service direct conversion weighing scales (for 8-in. gauge precipitation) gives ±2.5 mm accuracy on water equivalent due to stick–slip in its mechanism. The largest error percentage from this source occurs with shallow, low-density snows. Additional error derives from minor reflective differences on snow boards that have been observed to cause depth differences up to 30% during warm conditions. Even the material beneath a snow board affects new snow depth on a board when temperatures are near 0°C. A snow board on warm bare ground at Steamboat Springs has been observed to have snow depths of about 1 cm below those on an adjacent board resting on snow.

b. Timing

Density samples should be time matched, but due to various constraints, simultaneous sampling is seldom achieved. The time of observation at Dry Lake was usually an hour earlier than the Steamboat Springs reading because of travel time. The problem appears when heavy snowfall occurs at observation time. Density from the site read earliest can be quite different from that of the stratum deposited in between observation times as new snow density varies with atmospheric conditions. Obviously, the shallower the layer affected and the more intense the between reading precipitation, the greater the potential difference in the two observations. Scatter in the density relationships between Steamboat Springs and Dry Lake is thus greater than would occur with simultaneous sampling.

As the distance between measurement sites increases, the time distribution of snowfall at those sites changes. This affects settlement rates and ultimately

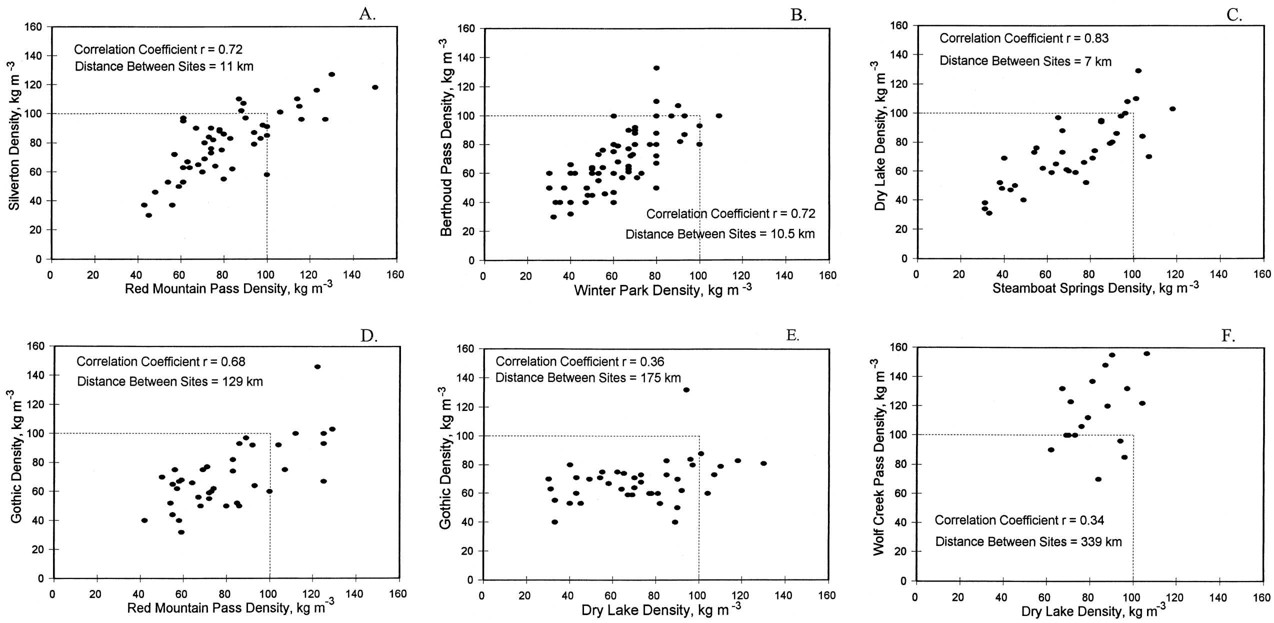

FIG. 6. Interstation snow density scattergrams. The dashed lines intersecting at 100 kg m^{-3} are identical with a 10:1 ratio of snow to liquid water.

density at observation. If snowfall is concentrated solely in the first part of the measurement period at one station and solely in the last part of said period at another station, density differences between sites caused by differing settlement rates can amount to 8%, according to Meister's (1986) calculations. A 15% density difference due to settlement can occur with identical water equivalents when the snowfall distribution is evenly distributed throughout the measurement period at one station but occurs only during the last part of the period at another site.

c. Degree of riming

The presence or absence of rime on snow crystals strongly affects density. Pure falls of well-developed graupel produce initial densities in the range from about 120 to 250 kg m^{-3}. Experience with data from western avalanche stations indicates that such episodes are small-scale phenomena (such as occurred at Gothic, Colorado) restricted to small sections of a mountain range. Rarely does more than one avalanche station report consequential layers of graupel on a given day. Whenever there are differences in riming between reporting sites, the densities will be dissimilar.

d. Orography

Mountain barriers modify airmass properties that create special snow climates. New snow density distributions within snow climates are somewhat unique to each mountain range. Highest U.S. new snow densities are found in the Olympic Mountains of Washington where average daily new snow densities of 250 kg m^{-3} have been recorded (LaChapelle 1958). Lower densities occur in the Cascades and the Sierra Nevada with even lower densities in the Rocky Mountains. New snow densities from stations in different snow climates produce low correlations and high scatter. Comparison of the density of daily snowfalls between Alta, Utah, and Dry Lake produced r values of 0.25. Those between Dry Lake and Wolf Creek resulted in $r = 0.34$. The fact that there is any correlation at all may be significant, relating, perhaps, to the broader airmass characteristics of temperature and humidity.

7. Summary and conclusions

Large variations in daily new snow densities have been observed at sites in the central Rocky Mountains in Colorado and Wyoming. Daily new snow densities from sheltered snow study plots ranged from 10 to 257 kg m^{-3} while peak frequencies were distributed from 60 through 100 kg m^{-3}. Steamboat Springs and Dry Lake, located on the west flanks of Colorado's Park Range, have occasional very low density snowfalls with depths exceeding 30 cm. Part of the observed crystal mix in these wild snow episodes included small, unrimed stars and plates, and assemblages of tiny plates. While other high-elevation reporting sites experience wild snow occasionally, accompanying depths are normally under 10 cm. Deep low-density deposits in the Park Range are a special feature of the snow climate there. Wolf Creek Pass appears to have a snow climate of its own, featuring higher-density snowfalls with southwest flow aloft. Colder lower-density snows, which would occur with northwest through northerly flow at Wolf Creek, are blocked by upwind mountain ranges. Complex orographic influences combine to make Wolf Creek Pass snows atypical of most of the Colorado and Wyoming mountains.

Cloud-level air temperature is a factor in explaining some of the observed variation in snow density. Density at Dry Lake was observed to be weakly related to temperatures at SPL with temperature variations explaining only about one-fourth of the observed variance. The general pattern is a decrease in density with temperature, similar to findings by LaChapelle at Alta, Utah, and McGurk at the Central Sierra Snow Laboratory. It appears from other research that the temperature–density relationship in mountainous areas may be site specific with a parabolic relationship applying to some sites and the nonlinear decrease with temperature applying to others. A better relationship might be obtained by stratifying the data by snowflake (or crystal) size and degree of crystal riming.

New snow densities are not rigorously associated with new snow depth, a conclusion in agreement with the results presented by LaChapelle (1962) and Meister (1986).

Interstation density correlation decreases with increasing distance between measurement sites. The r values for station separations beyond 10 km were uniformly below 0.7. Daily density disparities on the order of ± 10 kg m^{-3} are common at sites less than 10 km apart, but values from adjacent snow boards have average differences below 1%, indicating that time-honored techniques for obtaining cores from snow boards produce consistent results. Although shelter from wind is fundamental at any snow measurement site, accuracy of measurement, timing, orography, and degree of crystal riming—especially with graupel versus other types of crystals—are important factors determining the degree of disparity between new snow density readings at adjacent stations.

Data used in this study were gathered by highly trained personnel. Accuracy of both new snow depth and its water equivalent was high. Unfortunately, such data are not presently available from most U.S. weather stations because of poor site exposure, inconsistent snowfall measurement technique, and heavy reliance on gauge data without supplemental snow core information. This is a serious shortcoming in U.S. climate data, and one that deserves attention today. Because of the importance of snow density for many applications and the difficulty of inferring it from other standard observations, it is critical that more effort be made to collect accurate snow density data.

With a concerted but relatively small effort, observers could easily gather the necessary data, specifically, an accurate daily measurement of new snow accumulation from an appropriate and representative exposure at a consistent time of day at all stations and an accurate core measurement of the water content of that snow accumulation. With that type of data, snow density and its variations can be documented, and applications can be made. Up to this time, most density measurements have been taken by snow scientists and avalanche specialists. Now it is time for meteorologists and climatologists to join in. From an economic perspective, we need to improve our knowledge and appreciation of snow density variations at low elevations and in urban areas as well as in avalanche-prone mountain ranges of the West. This is important for improved planning and management of snow removal activities for which several billion dollars are currently being spent annually (Minsk 1998), and for the monitoring of structural snow loads and the design of future structures. The recent automation of airport weather observations across the United States has ended most airport snowfall observations and degraded winter precipitation measurements. But with a little conviction and creativity, solutions can be found. For the benefit of the myriad of climate data users in this country, it is time to make snow density a part of the observation program.

Acknowledgments. This work was conducted with support from the U.S. Bureau of Reclamation, Contract 1425-97-PG-81-65337, and the Colorado Agricultural Experiment Station.

References

Abbe, C., 1888: 1887 Annual Report of the Chief Signal Officer of the Army under the direction of Brigadier-General A. W. Greeley, Appendix 46. U.S. Govt. Printing Office, Washington, DC, 385–386.

Borys, R. D., and M. A. Wetzel, 1997: Storm peak laboratory: A research, teaching, and service facility for the Atmospheric Sciences. *Bull. Amer. Meteor. Soc.,* **78,** 2115–2123.

Bossolasco, M., 1954: Newly fallen snow and air temperature. *Nature,* **174,** 362–363.

Diamond, M., and W. P. Lowry, 1954: Correlation of density of new snow with 700-millibar temperature. *J. Meteor.,* **11,** 512–513.

Doesken, N. J., and A. Judson, 1997: *The Snow Booklet: A Guide to the Science, Climatology, and Measurement of Snow in the United States.* 2d ed. Colorado State University, 87 pp.

Eichenlaub, V., 1979: *Weather and Climate of the Great Lakes Region.* University of Notre Dame Press, 335 pp.

Goodison, B. E., 1978: Accuracy of Canadian snow gauge measurements. *J. Appl. Meteor.,* **27,** 1542–1548.

Grant, L. O., and J. O. Rhea, 1974: Elevation and meteorological controls on the density of snow. *Adv. Concepts Tech. Study Snow Ice Resourc. Interdisciplinary Symp.,* Monterey, CA, National Academy of Science, 169–181.

Gunn, K. L. S., 1965: Measurements on new-fallen snow. McGill University Stormy Weather Group Scientific Rep. MW-44, prepared for U.S. Air Force, Contract AF19(628)-249, Bedford, MA, 27 pp. [Available from Dept. of Atmospheric and Oceanic Sciences, McGill University, 805 Sherbrook St. W., Montreal, PQ, H3A 2K6, Canada.]

Judson, A., 1965: The weather and climate of a high mountain pass in the Colorado Rockies. Research Paper RM-16, USDA Forest Service, Fort Collins, CO, 28 pp. [Available from Rocky Mountain Research Station, 240 W. Prospect, Fort Collins, CO 80526-1891.]

——, 1970: A pilot study of weather, snow, and avalanche reporting for western United States. Ice Engineering and Avalanche Forecasting and Control, National Research Council of Canada Tech. Memo. 98, 123–134. [Available from National Snow and Ice Data Center User Services, Campus Box 449, University of Colorado, Boulder, CO 80309-0449.]

LaChapelle, E. R., 1958: Winter snow observation at Mt. Olympus. *Proc. 26th Annual Meeting,* Bozeman, MT, Western Snow Conference, 59–63.

——, 1962: The density distribution of new snow. USDA Forest Service, Wasatch National Forest, Alta Avalanche Study Center, Project F, Progress Rep. 2, Salt Lake City, UT, 13 pp. [Available from USDA Forest Service, Wasatch-Cache National Forest, 8236 Federal Bldg., 125 South State St., Salt Lake City, UT 84138.]

——, 1969: *Field Guide to Snow Crystals.* University of Washington Press, 101 pp.

McGurk, B., D. Azuma, and R. Kattelmann, 1988: Density of new snow in the central Sierra Nevada. *Proc. 56th Annual Meeting,* Kalispell, MT, Western Snow Conference, 158–161.

Meister, R., 1986: Density of new snow and its dependence on air temperature and wind. *Proceedings of Workshop on the Correction of Precipitation Measurements,* B. Sevruk, Ed., Eidgenossische Technische Hochschule Zurich, 73–80.

Minsk, L. D., 1998: *Snow and Ice Control Manual for Transportation Facilities.* McGraw-Hill, 289 pp.

Oda, T., and K. Kudo, 1941: Properties of snow and its density. Seppyō 3, 109-121. SIPRE Translation 14, U.S. Army, Wilmette, IL, 21 pp. [Available from Librarian, USACRREL, 72 Lyme Rd., Hanover, NH 03755-1290.]

Potter, J. G., 1965: Water content of freshly fallen snow. CIR-4232, TEC-569, Meteorol. Branch, Dept. of Transport, Toronto, ON, Canada, 12 pp. [Available from National Snow and Ice Data Center User Services, Campus Box 449, University of Colorado, Boulder, CO 80309-0449.]

Power, B. A., P. W. Summers, and J. D'Avignon, 1964: Snow crystal forms and riming effects as related to snowfall density and general storm conditions. *J. Meteor.,* **21,** 300–305.

Rhea, J. O., 1972: Interpreting orographic snowfall patterns. M.S. thesis, Atmospheric Science Department, Colorado State University, 135 pp. [Available from Morgan Library, Colorado State University, Fort Collins, CO 80523-1371.]

Stashko, E. V., 1976: Water in freshly-fallen snow. *Proc. 44th Annual Meeting,* Calgary, AB, Western Snow Conference, 20–22.

Super, A. B., and E. W. Holroyd III, 1997: Snow accumulation algorithm for the WSR-88D radar: Second annual report. U.S. Dept. of Interior, Bureau Reclamation Tech. Rep. R-97-05, Denver, CO, 77 pp. [Available from National Technical Information Service, Operations Division, 5285 Port Royal Rd., Springfield, VA 22161.]

Wilson, W. T., 1955: The density of new-fallen snow. *Weekly Weather Crop Bulletin,* Vol. **42,** No. 51, 7.

U.S. Department of Commerce, 1996: National Weather Service Handbook No. 7. NOAA, NWS, Office of Systems Operation, Washington, DC, A-21, 260 pp. [Available from U.S. Government Printing Office, 710 N. Capitol St., NW, Washington, DC 20401.]