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A New Data Set for Assessing the Cold Content of the Rocky Mountain West

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Abstract

Snowpack cold content (CC_{snow}) is the energy required to bring a snowpack to an isothermal temperature of 0.0°C. CC_{snow} is a complicated measure that integrates the response of a snowpack to components of the snow-cover energy balance. An improved understanding of the spatiotemporal variability of CC_{snow} may provide insight into snowpack dynamics and sensitivity of the snowpack to climate change. In this study, snowpit observations of snow water equivalent (SWE), snow temperature (T_{snow}) and snow density (ρ_{snow}) from the United States Geologic Survey Rocky Mountain Snowpack Chemistry Program (USGS RMS) were used to evaluate vertical CC_{snow} profiles over a 16-year period in Montana, Idaho, Wyoming, Colorado and New Mexico. Since 1993, USGS RMS has collected snowpack data throughout the Rocky Mountain region. Spatial grouping of locations based on similar CC_{snow} was evaluated, and trend analyses were performed. No clear geographical patterns in the vertical profiles of T_{snow}, ρ_{snow} or CC_{snow} is apparent; what stands out is the variability. At least in some cases, this variability can be related to differences in air temperature, precipitation, aspect, and elevation. In others, the causes appear to be more subtle.

1 Introduction

A critical variable in predicting river runoff across the western U.S. is peak snow water equivalent (SWE) of the mountain snowpack, which typically occurs around 1 April. However, the onset of spring snowmelt is variable and depends strongly on weather conditions and characteristics of the snowpack itself. A key component of a snowpack in this regard is its cold content, or CC_{snow}, which represents the amount of energy required to raise its temperature (T_{snow}) to the melting point. The CC_{snow} is a function of both T_{snow} and snow density (ρ_{snow}). As noted by Reba et al. (2011), management strategies based on historical relationships between snow deposition patterns from index sites and stream discharge may become unstable under a warming climate, which will significantly impact water resources management. Nimble decision making minimizes risk, and accurate forecasting of spring snowmelt volume and timing lets water

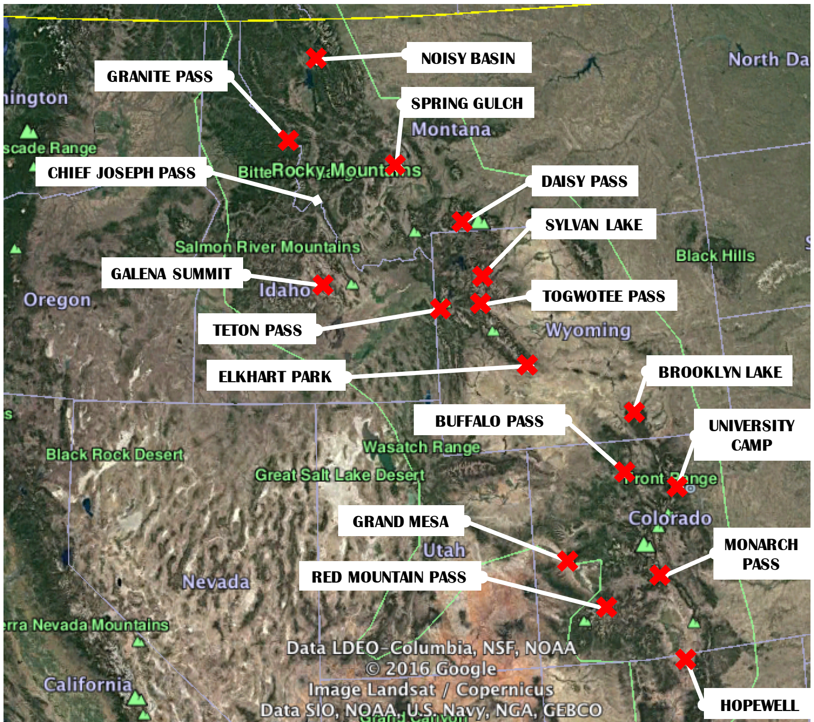


Figure 1: The 17 sites from USGS RMS used in this study, co-located with SNOTEL sites of the same name. See the appendix for coordinates and data table. The green line on the map encircles the Rocky Mountain west USGS RMS study area.

managers reduce this risk. Calculating CC_{snow} during the accumulation period could aid in estimating improving runoff prediction. Monitoring CC_{snow} also has climate change research. However, few data sets exist with which to assess CC_{snow} in U.S. snowpacks.

This study describes the compilation and analysis of a comprehensive, quality-controlled set of vertical profiles; T_{snow}, $\rho_{snow,}$ and CC_{snow} from 17 locations across the montane western United States (Figure 1). Data collected by the United States Geological Survey Rocky Mountain Snowpack Chemistry Program (USGS RMS) at or near 1 April form the basis for this study. The T_{snow} and ρ_{snow} data from paper field forms were first digitized. Following an extensive set of quality control procedures, data from each snow pit was then interpolated to 10 cm vertical layers. The objective of assessing this new CC_{snow} data set is to serve, explore and define the spatiotemporal characteristics of CC_{snow} in the Rocky Mountain west, based upon direct snowpack observations.

As noted, the assembled data set has applications to both streamflow modeling and climate research. Simple streamflow models do not even incorporate the CC_{snow}, while in others, bulk values are assumed. An example of a streamflow forecasting model that does not use CC_{snow} stratified or bulk is the Ensemble Streamflow Prediction approach discussed by Franz *et al.* (2003). Ignoring CC_{snow} can cause errors in predicting the timing of runoff. Hindcast experiments comparing systematic error in simulated melt onset against the CC_{snow} profiles offer a path for reducing such errors. The dataset also provides a baseline for assessing the evolution of the snowpack. The warming and particulate deposition are well studied and have resulted in earlier runoff initiation and less peak SWE over parts of the U.S. However, little is known about changes in CC_{snow} (Clow, 2010; Painter *et al.,* 2010). While the 16-years of data presently digitized is arguably too short to conduct a robust trend analysis, less than 50% of data have been digitized so far and USGS RMS is expected to continue into the future. This data publication and preliminary study support the usefulness of CC_{snow}, USGS RMS, and the importance of research focused on these data.

The 16-year average profiles at each site are broadly characterized by a minimum in CC_{snow} near the base of the snowpack, ρ_{snow} is often low and where there is a ground heat flux into the snowpack. Highest CC_{snow} layers are in the middle of the snowpack, where densities are higher than the layers above or below. However, the mean profiles mask high inter-annual variability in the vertical profiles of CC_{snow}; CC_{snow} appears to be more variable than either T_{snow} or ρ_{snow}. Near the top of the snowpack variability in CC_{snow} is especially pronounced. No clear geographical patterns in the vertical profiles of T_{snow}, ρ_{snow} or CC_{snow} are apparent; what stands out is the variability. At least in some cases, this variability can be related to differences in winter air temperature, precipitation, aspect, vegetation, latitude, and elevation. In others, the causes appear to be more subtle.

2 The USGS RMS Project and Data Digitization

2.1 Project Mission

The core mission of the USGS RMS Project is to assess and monitor the chemistry of precipitation at high elevations (> 1800 meters). Since 1993, USGS RMS has become the most expansive and comprehensive snowpack-chemical monitoring network of its kind. Beginning with sampling fewer than 20 sites in Colorado in 1993, the system has expanded to include more than 50 locations along the continental divide (Figure 1). In the process, techniques have been developed that use robust tracers to separate and quantify local and regional sources of atmospheric deposition of airborne pollutants. Non-digitized USGS RMS data are now becoming long enough (25-years, generally) to establish background levels against which one can determine elevated chemical concentrations at locations where deposition of acidic compounds is a concern. The project primarily monitors federally-managed lands in the Rocky Mountain region including several protected wilderness areas in National Forests and Parks. Applications of this regional snow-chemistry work include identifying regional trends in chemical concentration and deposition as well as monitoring sub-regional or local effects including power-plant emissions in Colorado, and snowmobile usage in Yellowstone and other areas (Ingersol *et al.* 2009).

The USGS RMS database includes the addition of new data annually or when historical data are digitized. Snowpits dug early in the project's history or data collected in conjunction with other projects may be a new source of data. The USGS requires that standard operating procedures be followed for any data collection program; therefore, field collection techniques must be verifiable before data are included in the USGS RMS dataset (Ingersol *et al.* 2009).

2.2 USGS RMS Study Area Description

USGS RMS study area is the Rocky Mountains region (Figure 1), and is on the order of 1000 km from the Pacific Ocean and 1,500 km from the Gulf of Mexico, the origins of moisture. The Rocky Mountains receive moist air by several pathways. These include low atmospheric pressure weather systems moving across the desert southwest, and systems coming from the North Pacific related low-pressure originating in the Gulf of Alaska and Aleutian Islands chain. The Sierra Nevada and basin/range of Nevada intercept much of the moisture moving directly east from the Pacific. Systems coming in from the North Pacific move across the Cascades and high deserts of the northwest, following the Snake River basin inland. Upslope lows happen when cyclones form in the four-corners area and when well-developed entrain moisture from the Gulf of Mexico, resulting in orographic uplift east of the continental divide. Upslope lows are most frequent in late winter and spring but may occur at any time of year. If lows stall, they can result in snowfall measured in feet over several days.

2.3 Data Digitization

2.3.1 Challenges and Sites Selection

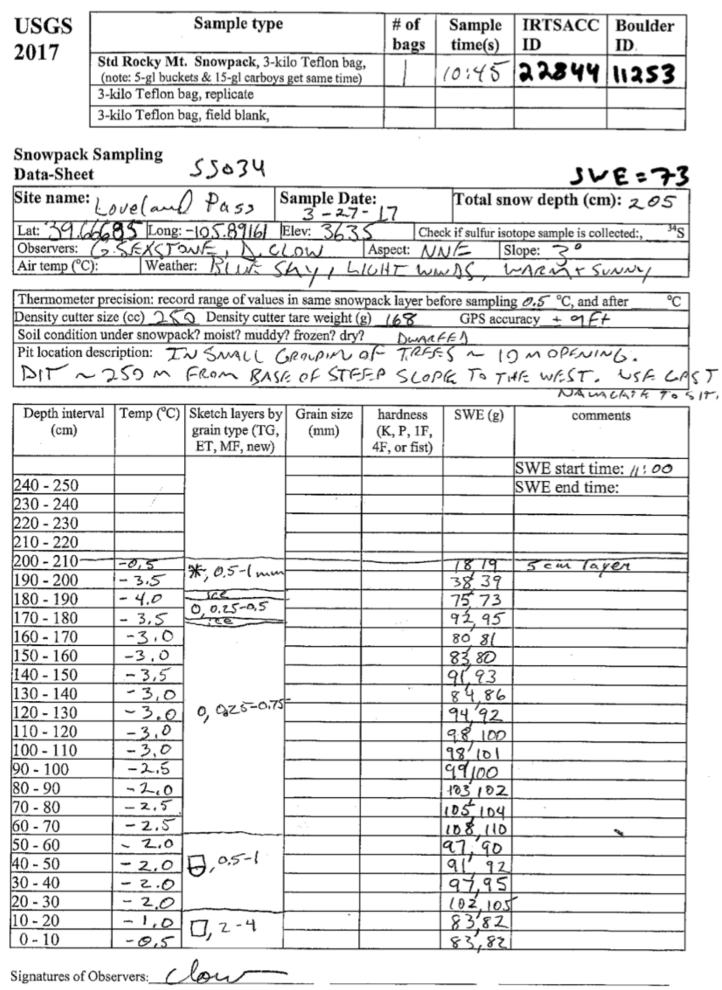
The USGS RMS snowpack chemistry and bulk snowpack properties data are currently available at National Water Information System web site (NWISWeb)[1]. All physical snow pit data collected as part of the USGS RMS were available as paper field forms, which were acquired, scanned and placed into PDF documents. T_{snow}, snow depth, and ρ_{snow} data were then digitized from paper field forms for 17 locations (Figure 2) encompassing the Rocky Mountain region. Graham Sexstone, the USGS RMS project leader, consulted the author on the scope of the effort and which sites to digitize. Data completeness, sampling from different snowpack environments and co-location with SNOpack TELemetry (SNOTEL) sites were among the selection criteria. SNOTEL is a network of automated stations that record snow water equivalent in mountain areas across the U.S. west.

There is a human element involved when digitizing from handwritten field forms. In most cases, it was not possible to contact the field personnel who collected the data to obtain clarification (e.g., to decipher unclear numerals). Field scientists use techniques to sample the snowpack which are described in the USGS RMS standard operation procedures manual. Field workers balance

[1] <http://waterdata.usgs.gov/nwis>

data quality with personal safety. Notes may be skipped, then filled in later. Blowing snow may disrupt work, and there are situations in which the best sampling location can't be reached. Such situations are typically noted on the field forms.

One downside of repurposing USGS RMS data relates to the core focus of the project on chemical assessment. When conditions are severe, physical snowpack (temperature, density) data are the first to be neglected. This human element makes the author of the present study well suited to the task of data digitization because he collected snowpit data for the USGS RMS project, knows current data collectors, and understands the project. Good note taking and the project leader's input, allowed for reconstructing events during field visits in many cases. The 17 selected sites include qualitative information on fields forms which is not digitized. A method for digitizing qualitative data along with metadata classification has not yet been devised for USGS RMS.


USGS 2017

Sample type	# of bags	Sample time(s)	IRTSACC ID	Boulder ID
Std Rocky Mt. Snowpack, 3-kilo Teflon bag, (note: 5-gl buckets & 15-gl carboys get same time)	1	10:45	22844	11253
3-kilo Teflon bag, replicate				
3-kilo Teflon bag, field blank,				

Snowpack Sampling Data-Sheet SS034 SWE=73

Site name: Loveland Pass | Sample Date: 3-27-17 | Total snow depth (cm): 205

Lat: 39.66685 | Long: -105.89161 | Elev: 3635 | Check if sulfur isotope sample is collected:, ___ ^{34}S

Observers: G. SEXSTONE, D. CLOW | Aspect: NNE | Slope: 3°

Air temp (°C): | Weather: BLUE SKY, LIGHT WINDS, WARM + SUNNY

Thermometer precision: record range of values in same snowpack layer before sampling 0.5 °C, and after ___ °C

Density cutter size (cc) 250 Density cutter tare weight (g) 168 GPS accuracy ± 9 ft

Soil condition under snowpack? moist? muddy? frozen? dry? DUNNO

Pit location description: IN SMALL GROUPING OF TREES ~ 10 M OPENING. PIT ~ 250 M FROM BASE OF STEEP SLOPE TO THE WEST. USE GPS NAVIGATE TO SITE.

Depth interval (cm)	Temp (°C)	Sketch layers by grain type (TG, ET, MF, new)	Grain size (mm)	hardness (K, P, 1F, 4F, or fist)	SWE (g)	comments
						SWE start time: 11:00
240 - 250						SWE end time:
230 - 240						
220 - 230						
210 - 220						
200 - 210	-0.5				18, 19	5 cm layer
190 - 200	-3.5	*, 0.5-1 mm			38, 39	
180 - 190	-4.0	ice			75, 73	
170 - 180	-3.5	O, 0.25-0.5 ice			92, 95	
160 - 170	-3.0				80, 81	
150 - 160	-3.0				83, 80	
140 - 150	-3.5				91, 93	
130 - 140	-3.0				84, 86	
120 - 130	-3.0	O, 0.25-0.75			94, 92	
110 - 120	-3.0				98, 100	
100 - 110	-3.0				98, 101	
90 - 100	-2.5				99, 100	
80 - 90	-2.0				103, 102	
70 - 80	-2.5				105, 104	
60 - 70	-2.5				108, 110	
50 - 60	-2.0				97, 90	
40 - 50	-2.0	⊟, 0.5-1			91, 92	
30 - 40	-2.0				97, 95	
20 - 30	-2.0				102, 105	
10 - 20	-1.0	□, 2-4			83, 82	
0 - 10	-0.5				83, 82	

Signatures of Observers: Clow

Figure 2: Standard field form used for USGS RMS data collection.

2.3.2 Vertical Interpolation and Data Accuracy

At each snow pit, the field scientist collects (along with chemistry) measurements of T_{snow} and ρ_{snow} at a series of levels. The standard operating procedure is to obtain snowpack measurements at 10 cm increments. For obtaining ρ_{snow}, the sample of a fixed volume is collected and then weighed. However, operating procedures are flexible; 20 cm intervals for the measurement of T_{snow} and ρ_{snow} are used with deep snowpacks (generally over 200 cm thick) to save time, but there are exceptions even to this guideline. For example, a coarse sampling interval speeds up field work in homogenous snowpacks. Extending sampled layers beyond 20 cm is rare, but must be looked for. Layers of snow near the ground or the snow surface may not fall precisely on the sample interval, and the ground surface may be interrupted by vegetation, rough surfaces or flowing water.

Given the desire to compare different profiles, data from all of the raw profiles were interpolated to 10 cm intervals, starting from the bottom of the snowpack. While interpolation allows for better data visualization, it, of course, does not increase the vertical resolution. In other words, a snowpack measured at 20 cm intervals after interpolation to 10 cm layers still must be considered 20 cm vertical resolution. In the database, values flagged with an "E" are estimated. Note that an issue arises at the top of the snowpack, as this final layer is typically less than 10 cm. For instance, a 77 cm thick snowpack would have a 7 cm top layer. This affects profile visualization and mathematical computation of all variables and a carefully weighted average must be applied.

In some cases, SWE was recorded in the paper field forms, as was the case on the example field form provided as figure 2. In other cases, it was not. In these latter cases, SWE was calculated using the interpolated ρ_{snow} and depth profiles. SWE is the depth of water left behind after melting of the snow column and is useful when a single dimension length unit is needed to represent the volume of water within an area.

Concerning data accuracy, T_{snow} in the early part of the record was reported to a tenth of a degree C. However; the nearest half degree is the best accuracy field thermometers can be read to and is hence the correct significant figure for the instrument. The data 0.5℃ was not adjusted to for this analysis and was used as provided. All field thermometers are calibrated against NIST certified thermometers before being deployed for field work and then again on return. Comparing T_{snow} readings at one point with two field thermometers is the method of bias checking used in the field. ρ_{snow} measurements are expected to be accurate to 2% (+/-) using the methods described by Ingersol *et al.* (2009). The field forms note any interference from vegetation, debris, ice lenses and hard surface crust on paper field forms but this information was not digitized. The final step was to calculate CC_{snow} from the interpolated 10 cm values of T_{snow} and ρ_{snow}. The CC_{snow} is reported in MJ m^{-3} and as mentioned is the energy that is required to raise the snow to 0˚C. Any further energy input would result in snow melt.

3 Results

Table 1 Database wide descriptive statistics.

Statistic	Density (kg m-3)	SWE (mm)	Depth (cm)	Average Snow Temperature (deg	Bulk CCsnow (MJ m-2)
Mean	295	542	181	-2.92	3.1
Median	296	503	165	-2.99	2.7
Standard Deviation	35	261	78	1.16	2.1
Range	183	1574	454	6.17	13.3
Minimum	210	106	39	-6.17	0.0
Maximum	393	1681	493	0.00	13.3
N	268	268	268	268	268

3.1 Bulk Characteristics

Bulk characteristics (weighted averages) of the snowpack are obtained by averaging data from all sites (Table 1). For example, mean bulk ρ_{snow} of 295 kg m^{-3}, combined with the bulk T_{snow} of -

2.99˚C and mean SWE of 542 mm yield a CC_{snow} of 3.1 MJ m^{-3}. However, it is seen that even for bulk values, there is considerable variability. As another example, the CC_{snow} ranges from a low of zero (the entire snowpack is at the melting point) to a maximum of 13.3 MJ m^{-3}. Spatial bulk characteristics of ρ_{snow}, T_{snow}, and CC_{snow} are examined below. The maps provided as figures 3 to 7 show the bulk values at each station. There is no clear spatial pattern in any of the variables; while one might expect, for example, that the bulk T_{snow} would be lower for the northern sites and warmer for the southern places, this is not borne out in the data.

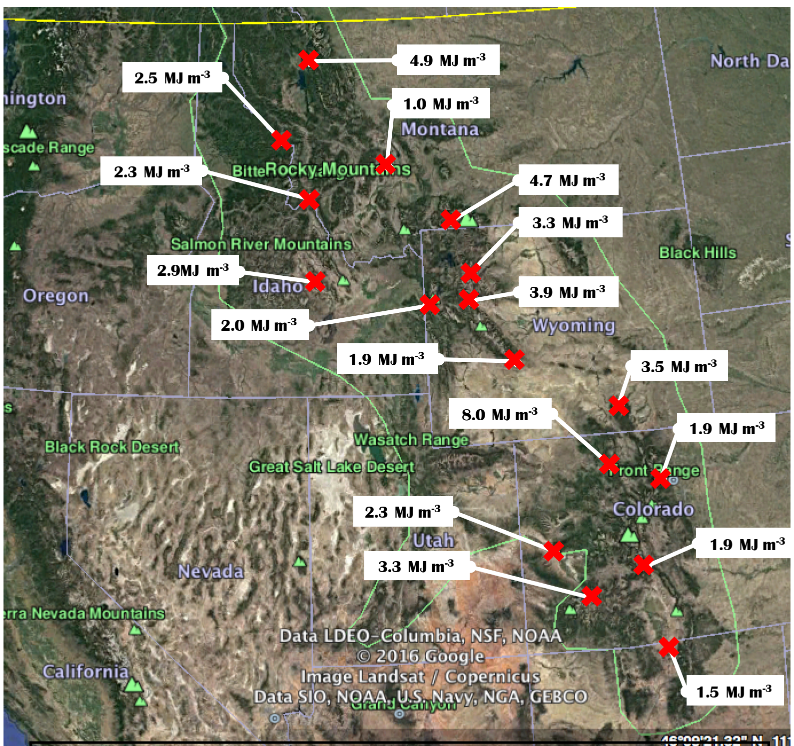


Figure 3. Spatial distribution of mean CC_{snow} in units of MJ m^{-3}.

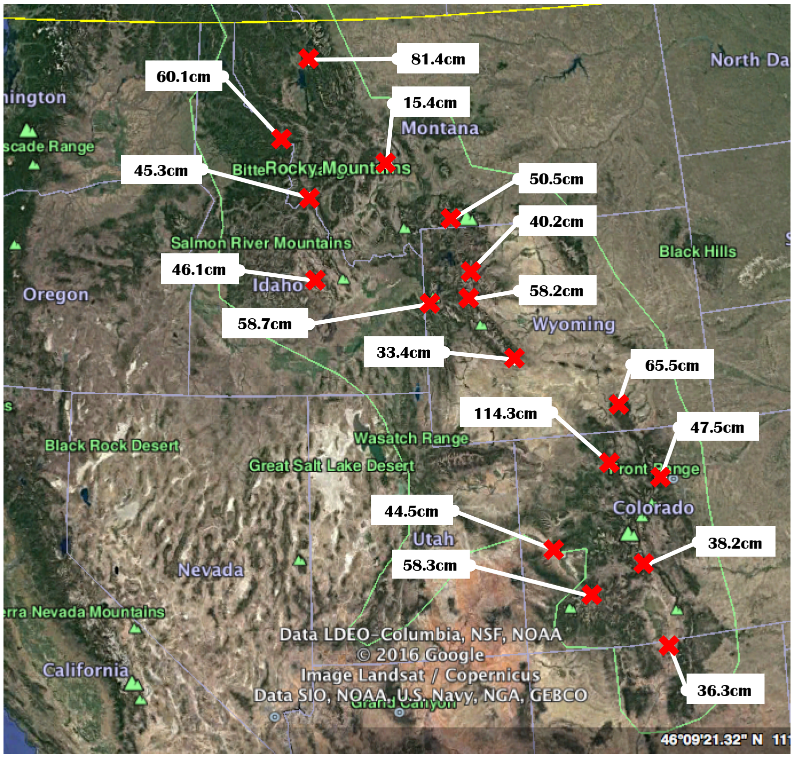


Figure 4: Spatial distribution of mean bulk SWE in units of cm.

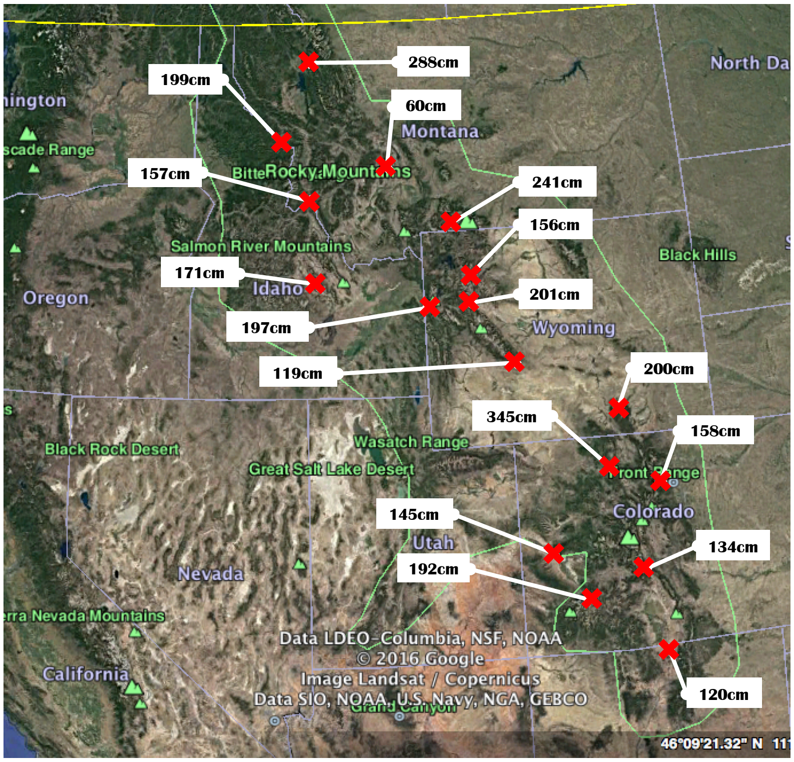


Figure 2: Spatial distribution of mean snow depth in units of cm.

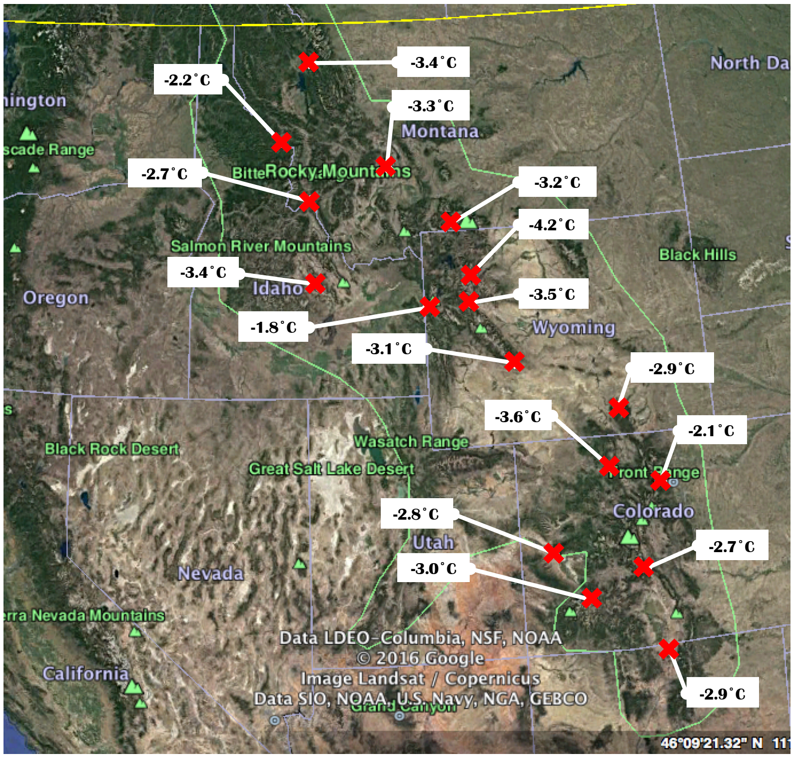


Figure 6: Spatial distribution of 16-year mean, bulk T_{snow}.

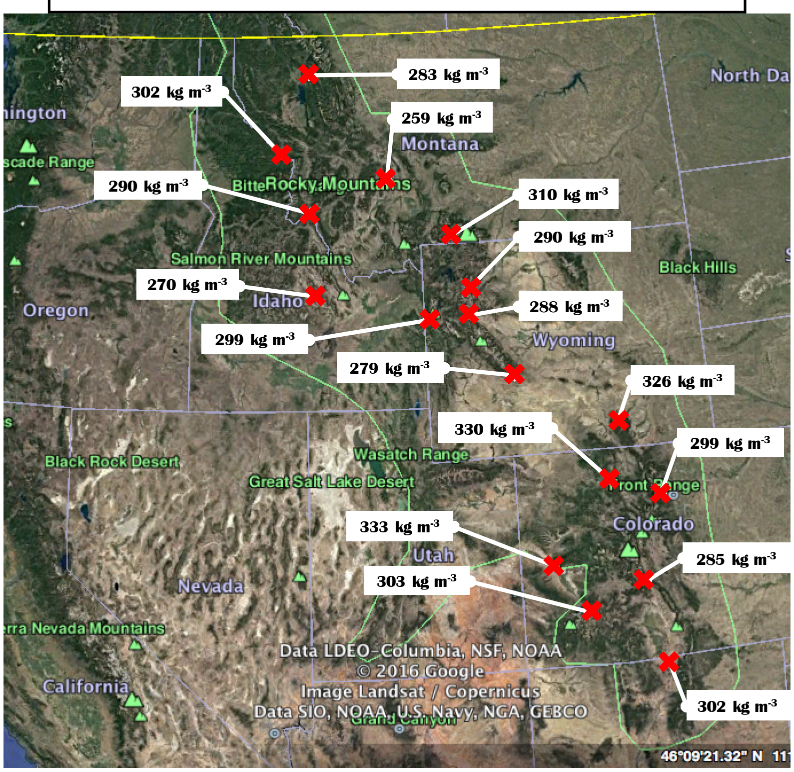


Figure 7: Spatial distribution of 16-year mean, ρ_{snow}.

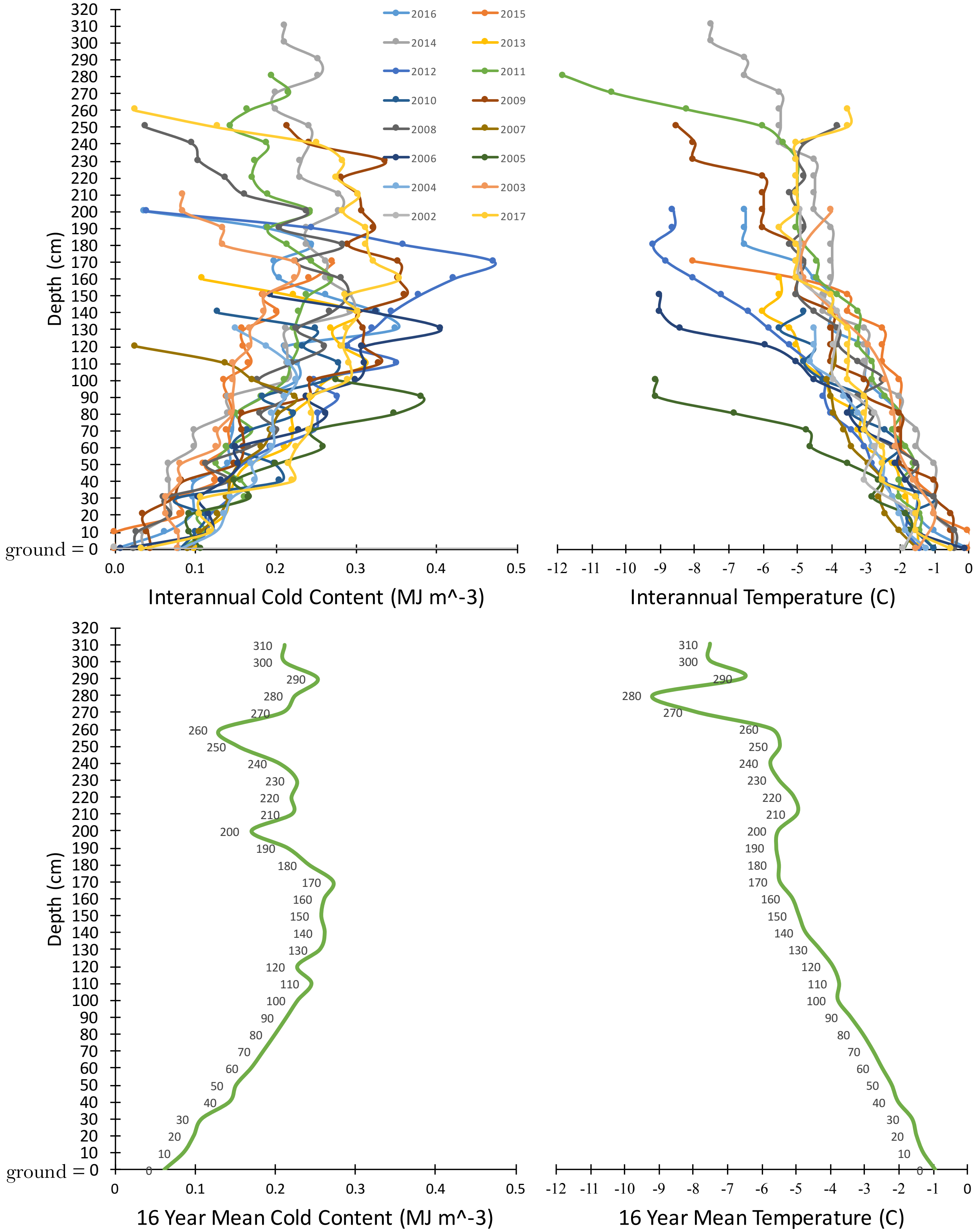


Figure 8: Profiles CC_{snow} and T_{snow} at Togowtee Pass, WY for each year from 2002 to 2017 (top) and for 16-year averages (bottom).

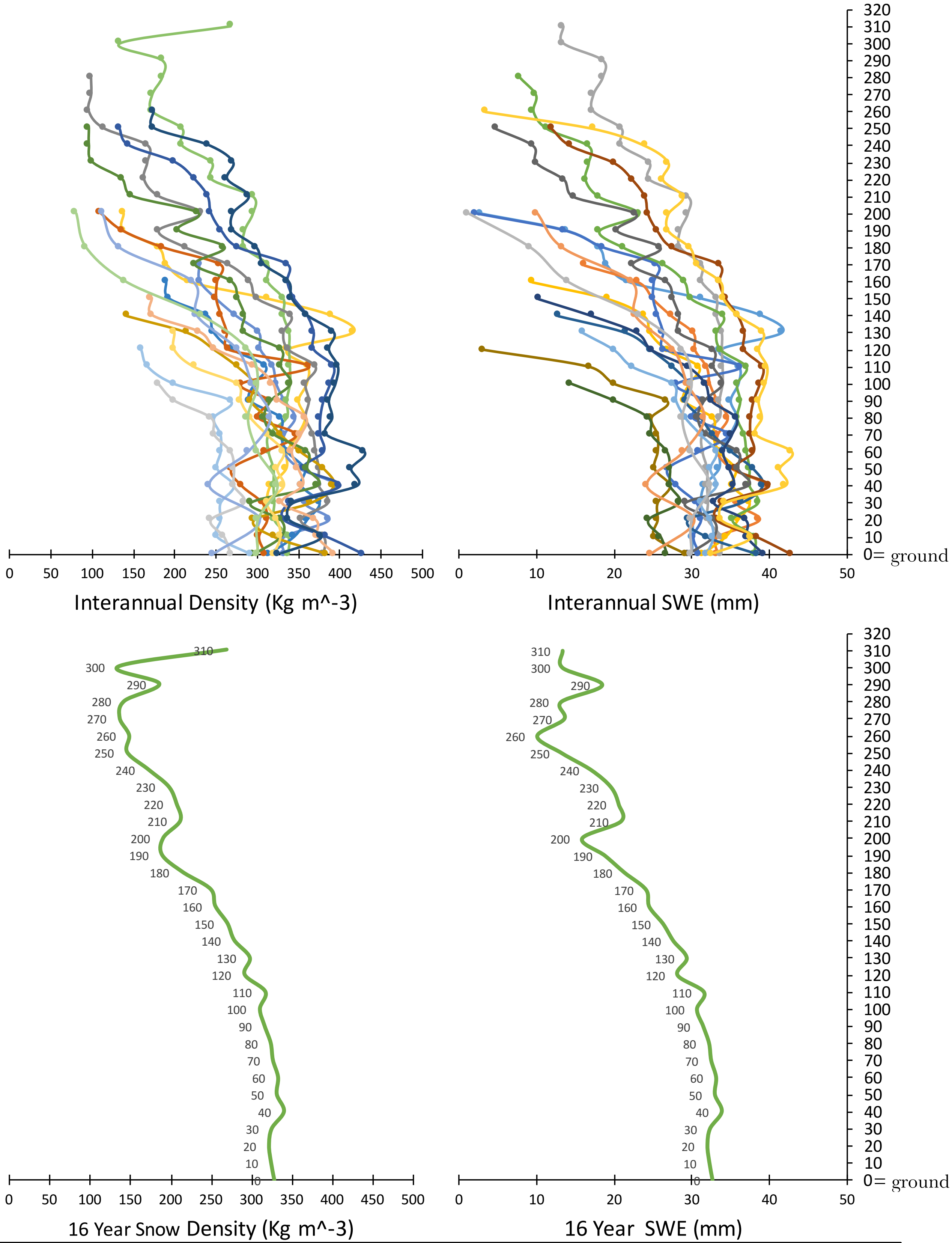


Figure 9: Profiles ρ_{snow} and SWE at Togowtee Pass, WY for each year from 2002 to 2017 (top) and for 16-year averages (bottom).

3.2 Snow Profile Characteristic Examples from Togowtee Pass Wyoming

Snow profiles can be thought of as signatures of geography and climate. As an example, vertical profiles from Togowtee Pass are first considered. Figures 8 and 9 show profiles for individual years along with the 16-year site-specific means for all variables. The different profiles for each year manifest the influence of varying environmental conditions from the preceding winter up until peak SWE, and each winter pattern is unique. These include the air temperature at the surface and T_{snow} at the ground, which influence heat conduction into or out of the snowpack. Kinetic metamorphism from vapor pressure and T_{snow} gradient alters the stratified ρ_{snow} and snow structure. Snowpack structural adjustment over time change the snow thermal conductivity which in turn influences water vapor and energy flows; therefore, anisotropic and heterogeneous snow conductivity is quite typical in Rocky Mountain snowpacks. Precipitation in turn influences the depth of the snowpack and compression of its lower layers. If a location has a snow profile that deviates sharply from the site-specific16-year mean profile, it suggests winter weather conditions were likely unusual.

Looking first at the mean values in figures 8 and 9, ρ_{snow} tends to increase upwards in the snowpack, then turns back to lower ρ_{snow} near the surface; SWE naturally shows the same basic pattern. T_{snow} decreases in each layer nearer to the snow surface. The vertical profile of CC_{snow} largely mirrors the vertical profile of T_{snow}; clearly, the effects of T_{snow} on CC_{snow} dominate over variations in ρ_{snow} for this site. Togowtee Pass has an exceptionally cold snowpack, which may be the reason for T_{snow} playing a more significant role than ρ_{snow}. By comparison, nearby Teton Pass Wyoming (about 1000 feet lower) has the same 16-year mean snow depth and SWE, but half of the CC_{snow} (2.0 Mj m^{-3} compared to 3.9 Mj m^{-3} for Togowtee Pass). Hence, with roughly the same SWE, nearly twice as much energy is needed to initiate melt at Togowtee Pass than at Teton Pass. Phrased differently, the snowpack at Togowtee pass would start to melt later in the spring than at Teton Pass. As discussed later, a regression analysis reveals a reasonably strong relationship between CC_{snow} and SWE - as SWE increases so does the CC_{snow}. All physical processes determining T_{snow} and ρ_{snow} profiles at either site can not be measured or known. The contrast in CC_{snow} between Teton Pass and Togowtee Pass according to USGS RMS data is explained by the T_{snow} alone, which will certainly help determine snow melt onset at both passes.

Looking now more closely at the individual years, the averages at Togowtee Pass mask considerable variability in ρ_{snow} throughout the snowpack, with near ground values ranging from 250 to 400 kg m^{-3}. Values in the middle of the pack range from 100 to 425 kg m^{-3}, and at the surface ρ_{snow} drops to as low as 100 kg m^{-3}. When ρ_{snow} is below 200 kg m^{-3}, it must be new snow. It appears that often the majority of the CC_{snow} exists in the top 50% of the snowpack at Togowtee Pass. The top 50% of the snowpack also seems to have the most variability in CC_{snow}. Based on results at Togowtee Pass and other sites in the Rocky Mountain region, bulk CC_{snow} values seldom exceed 9 MJ m^{-3} at $\lesssim$11,000ft. Note that the profiles shown in figures 8 and 9 are but a snapshot in time; the CC_{snow} is continuously evolving, forced by heat conduction and the addition or removal of snow mass.

SWE is less intuitive when plotted as a profile (Figure 9) as opposed to the integrated value for the entire snowpack (which is of relevance to water resources). The water depth in a 10 cm layer is perhaps difficult to envision. When discussing SWE, the bulk term is most common.

3.3 Variability in CC_{snow} Between Sites

The mean profile of CC_{snow} by combining all sites is plotted along with medians and standard deviations in figure 10 while mean profiles for the individual sites follow in figure 11. The means in figures 10 and 11 extend up to 380 cm; Buffalo Pass, with a maximum depth of 490 cm, is the only extreme outlier and is hence omitted. Five isothermal snowpacks were also removed from this calculation because there is no CC_{snow} in those conditions. Around 272 values are used to calculate the mean value in any given 10 cm layer. There is less confidence in each 10 cm layer above 3.5 m total depth because the sample size is much smaller.

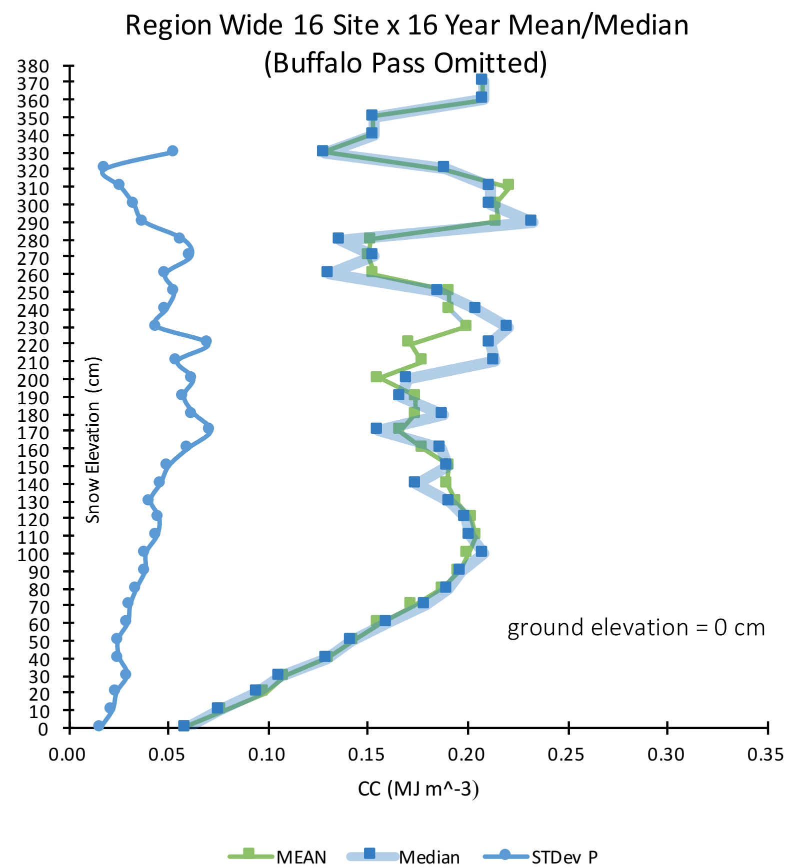


Figure 10: Mean CC_{snow} profile based on all sites, excluding Buffalo Pass, along with the median values and standard deviation.

In figure 10, low CC_{snow} at the base of the snowpack is observed (0.06 MJ m^{-3} at 0 cm up to 0.2 MJ m^{-3} at 100 cm) and from 0 cm up to 100 cm, there is a linear slope of increasing CC_{snow}. This feature points to the fairly warm ground surface (near 0˚C) initiating an upward conduction of heat into the snowpack as well as upward vapor diffusion, resulting in the formation of layers of fairly low density depth hoar with faceted crystals.

Above 100 cm snow depth, CC_{snow} seems to vary by depth. The mean and median deviate erratically from the 100 cm level up to the 370 cm depth (Figure 10). This is probably due to the top 30 cm of the snowpack being highly coupled to the atmosphere, which can be seen in T_{snow} profiles as the sharp hooks to the left. The CC_{snow} ranges from 0.13 to 0.27 MJ m^{-3} for each 10 cm layer. Removing the hooks to the left smoothens the erratic profile between 100 cm and 370 cm. The sharp left hooks in the top 30 cm of the snowpack are a result of maximum incoming shortwave radiation at the time of snowpack observation.

CC_{snow} profiles at individual sites tend to have similar shapes but differ most in the magnitude of the bulk values. While the bulk values, of course, depend in part on T_{snow} and to a lesser extent ρ_{snow}, differences in CC_{snow} between snow pits are often dominated by differences in the total mass (and depth) of the snowpack. Phrased differently, while CC_{snow} tends to be proportional to SWE, SWE also tends to be proportional to snow depth. For instance, Buffalo Pass is omitted because (eliminated from figures 10 and 11) it is an extreme outlier in terms of snow depth. Buffalo pass experiences the dataset maximum snow depth of 490 cm and a CC_{snow} of 13 MJ m^{-3} while at Sylvan Lake, the snow depth is around 150 cm and the CC_{snow} is much smaller at 3 MJ m^{-3}, profile shape between the two is quite similar.

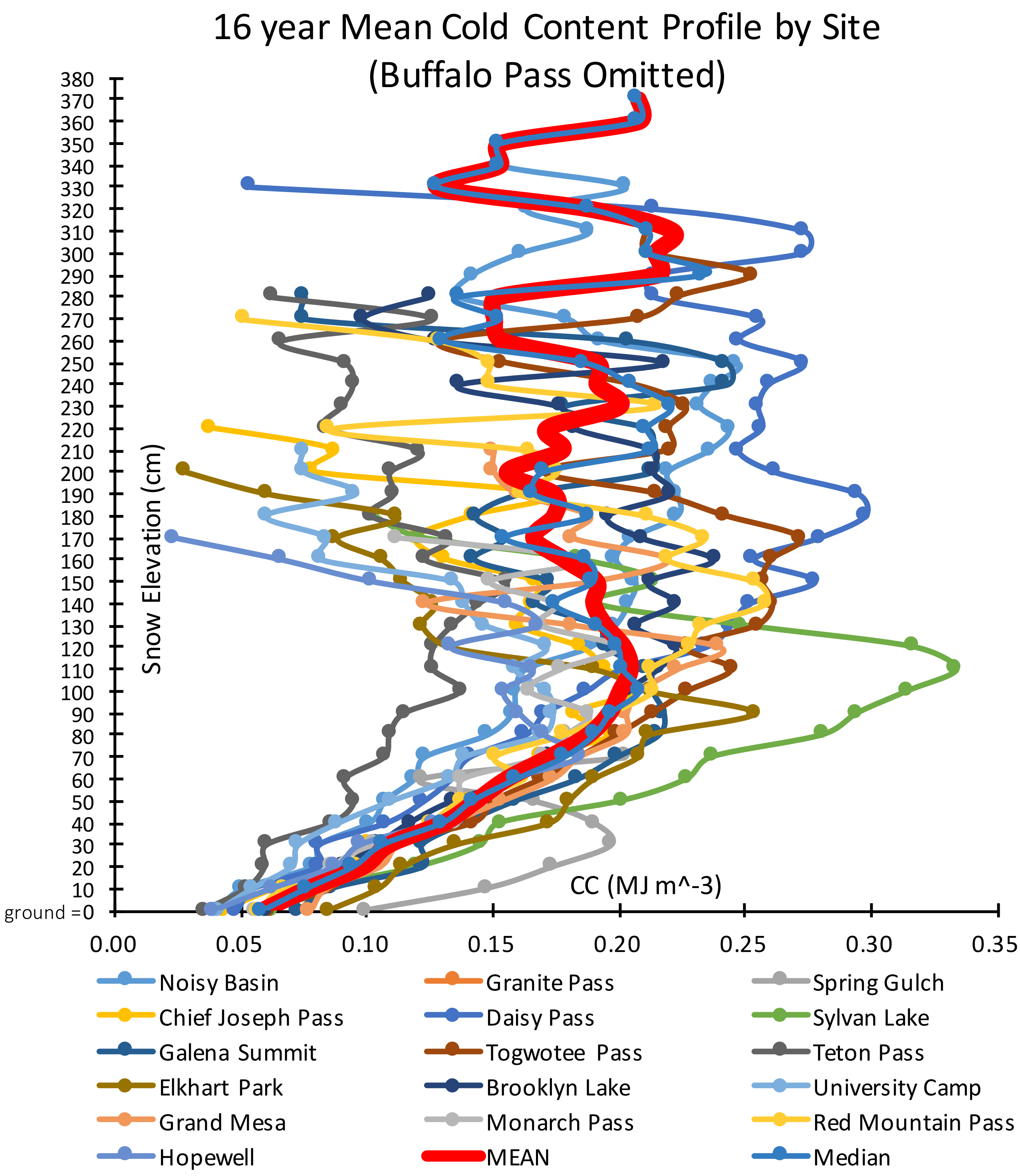


Figure 11: 16 yr. Mean CC_{snow} profiles at each station.

3.4 Regression Analysis

When plotting linear regressions of snowpack characteristics, the two most highly correlated values are snow depth and SWE (Figure 12). These 272 field observations show a nice tight relationship, with a high r^2 of 0.93. A regression of CC_{snow} against SWE shows more spread (Figure 13). However, the r^2 of SWE and CCsnow correlation is still fairly high (0.65). Using excel regression analysis, t-stat was found to be -2.45 and P-value of 0.01488. Also, residuals were well randomized, which point to a robust mathematical relationship. These results indicate that by knowing SWE, one can obtain a reasonable bulk CC_{snow} estimate, which could be useful for predicting the onset of melt.

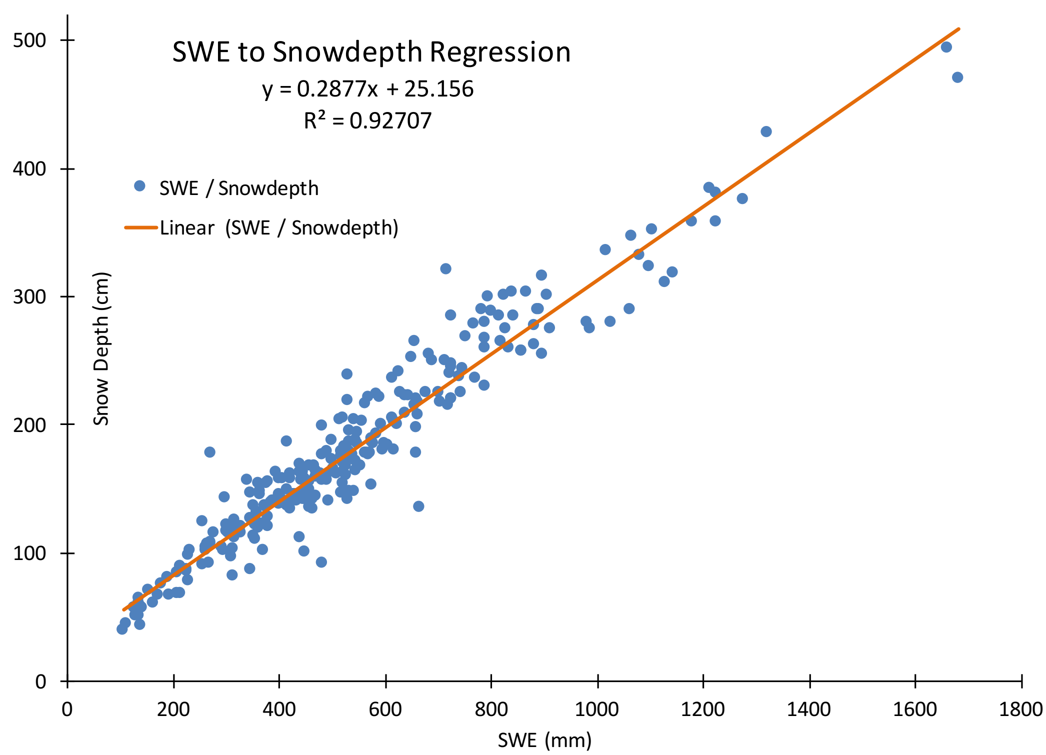


Figure 12: Regression between snow depth and bulk SWE, n=272. This is a very strong correlation, often used to estimate SWE from snow depth. Comparing this regression to Figure shows CC_{snow} to SWE may also produce useful estimates.

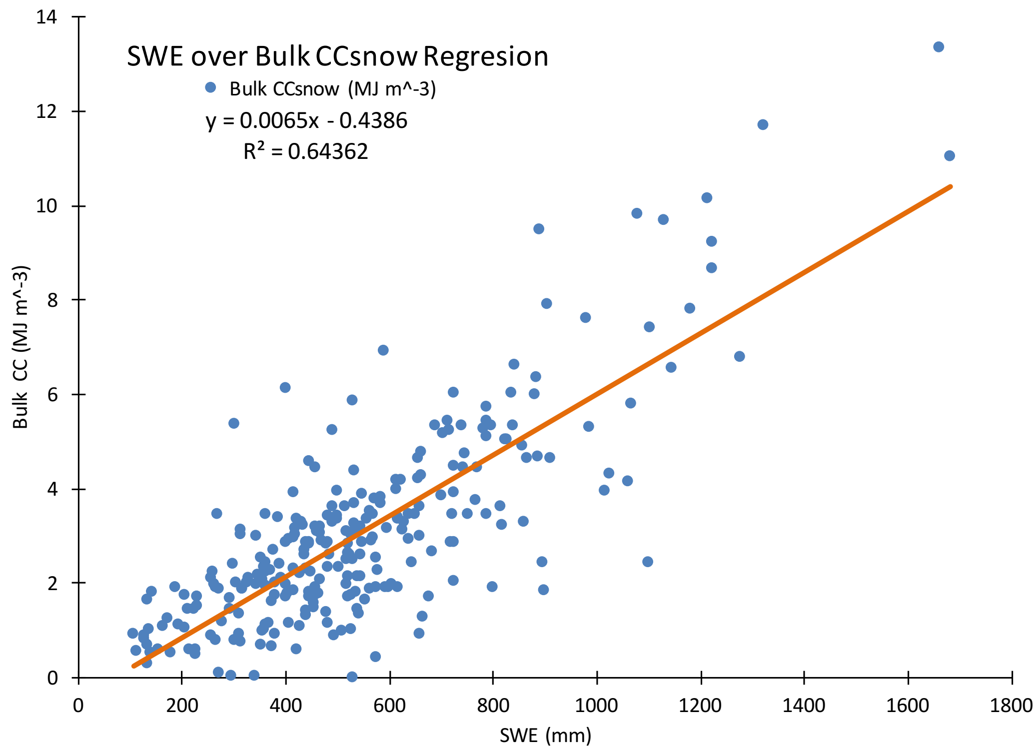


Figure 13: Regression between bulk CC_{snow} and bulk SWE. There is scatter but the data have correlation; more analysis is needed to know if this regression could be useful for producing estimated data. Each dot represents the mean value of an individual site, n=272.

One might expect the regression shown in figure 13 to produce r^2 near100 based on equation 1, but it does not. The CC_{snow} variance must be explored closely to find what is responsible. As a good example, as noted earlier, while Togowtee Pass and Teton Pass have about the same peak SWE, the snowpack at Togowtee Pass tend to have almost twice the cold content; at least part of the explanation is that it lies at a higher elevation. However, departures from the regression line could also reflect factors other than elevation, such as aspect, vegetation, and latitude. CC_{snow} is accurate and precise when measured in a snowpit and takes into account the entire snow accumulation season's weather and geography. Perhaps the location itself causes variation in CC_{snow} and therefore, the timing of snow melt onset. Future studies will focus on linking difference in the regression (Figure 13) to physical processes.

4 Discussion and Conclusion

16-Years of quality controlled snowpit profiles and snowpack characteristics from the Rocky Mountain west of North America have been digitized, collated, and consolidated. Such a dataset will likely prove useful for runoff and climate change interpretation. Characteristic snowpack profiles at high vertical resolution may be helpful as climate change reference points. Stratified CC_{snow} is best put to use when other variables are difficult to measure or do not exist and should be considered for any snowpit data collection program.

This is the first data set that the author is aware of enabling a detailed analysis of the cold content of snowpacks across the Rocky Mountain region of North America. Preliminary analysis shows CC_{snow} can help determine discrepancies in the snowpack to streamflow relationship. CC_{snow} can be used to evaluate differences in melt timing between watersheds with the same SWE and depth. Measured CC_{snow} at a point in time reflects all processes acting on the snowpack, even those not yet accounted for in the snow-cover energy balance equation (appendix equation 2).

The 16-year average profiles at each site are broadly characterized by a minimum in CC_{snow} near the base of the snowpack, where ρ_{snow} is often low (via the development of depth hoar) and where there is a ground heat flux into the snowpack. The middle of the snowpack has the highest CC_{snow} because ρ_{snow} is highest and T_{snow} is relatively high as well. The mean profiles mask high inter-annual variability in the vertical profiles of CC_{snow}; CC_{snow} appears to be more variable than either T_{snow} or ρ_{snow}. The stratified 16-year mean profiles may be useful in providing a benchmark to detect climate change. No clear geographical patterns in the vertical profiles of

T_{snow}, ρ_{snow} or CC_{snow} are apparent; what stands out is the variability. At least in some cases, this variability can be related to differences in winter air temperature, precipitation, aspect, and elevation. In others, the causes appear to be more subtle.

USGS RMS is the first regional data set with which one can explore and define the character and magnitude of CC_{snow} across Rocky Mountain west of North America. Preliminary analysis shows CC_{snow} can help determine discrepancies in the snowpack to streamflow relationship. CC_{snow} can be used to evaluate variability in the timing of spring melt between snowpacks with the same SWE, such as at Togotwee Pass and Teton Pass.

5 Contributions

Many thanks to Graham Sexstone, USGS Colorado Water Science Center, USGS RMS project manager, encouraged me to take on this project, supplied raw data on paper field forms, reviewed early drafts and donated many hours. Mark Serreze took an early interest in this project when others did not. Thank you, Mark, this project is a leap forward in my education and career. Discussions with Matthew Granitto, Holly Barnard, Katherine Hale, Michael Dwyer and Noah P. Molotch kept me motivated to brush aside doubt and added critical advice.

Appendix

Dig Site Geocoordinates

Field workers recorded waypoints in NAD 83 projection at the location of each dig site. There are some inconsistencies to be aware of depending on the intended use of these data. Spatial snow distribution effects of digging a snowpit each year and site access also would determine where to excavate a snowpit. Recording of coordinates is of some concern; degrees, minutes, and seconds or decimal degrees are used interchangeably depending on the preference of the data collector or the default of the GPS. Converting coordinates to decimal degrees was not yet performed.

Coordinates represent the dig site in several ways. First, the coordinate SNOTEL uses for the metrological tower, while consistent, it is not often accurate for describing the dig site. These SNOTEL coordinates are used in the SOP from the USGS as well. (Ingersol *et al.* 2009) In reality, although the USGS tries to sample very close to the same location, snowpits are dug at a new place each year, while balancing quality of the dig site snowpack verses annual and spatial consistency on each visit. Another issue to be aware of is when a default dig site coordinate from a previous year are carried over to the next. Uncertainty exists with these coordinates, and it can be difficult to spot them within the data set. Recorded exact values for multiple years have a high probability the coordinate was carried over from a previous year. With handheld GPS, an error is inherent, making it unlikely to duplicate coordinates or elevation; therefore, exact duplication of coordinates is a clue something may be wrong. GPS error when recorded can help reconstruct field location. Users may want to focus on consistency when representing the dig site, in which case the SNOTEL coordinate may be useful, but watch out for snowpits dug a significant distance from the SNOTEL tower, then determine if that difference is acceptable.

For some users, precise and accurate representation of each snowpit location may be paramount. There is no perfect solution when survey grade coordinates are needed. Most often the error associated with each handheld GPS coordinate will provide a large enough footprint to include all snow pits and the SNOTEL towers. A statistical approach is then recommended to replace default coordinates with estimated coordinates. Plot each coordinate that is non-default for the site, forming a point cloud, then calculate the spatial mean of the point cloud. If the point cloud doesn't have too much variance, it may be useful to replace the default coordinates with this estimated mean coordinate, which in most cases will be advantageous beyond default values.

One more option when choosing the best dig site coordinate is to use the spatial mean from the point cloud discussed above, as the default coordinate. A more balanced approach would be to giving some weight to the dig site in reality but adding a level of consistency. Thus, an improvement to SNOTEL tower position coordinates, because the tower causes interference with the snow under and near it, which field workers avoid. The dig site is a separate location than the tower geocoordinate. Avoiding the tower and anti-freeze pressure pillow is a high priority for field workers; any disruption of the snowpack around the tower and snow pillow could adversely affect SNOTEL data and would best be avoided by field workers. The SNOTEL tower and equipment force snowpack redistribution nearby and is also a concern for field workers. The coordinate of dig site representation should be determined by the user, keeping in mind information provided in this section. For additional information on dig site, location coordinates contact USGS RMS project manager.

Sampling Time Notes

The recorded site visit time stamp uses a 24-hour clock set to mountain standard time (MST) which has a -7 hours offset from UTC, after daylight savings time starts, somewhere around March 12 each year. Before daylight savings time goes into effect, -6 hours offset from UTC. Thankfully all of the sites digitized here are in the MST. Field workers recorded local time on the field sheets and therefore take into account these issues. However, it would be worth checking time records on or near the daylight savings time change, around March 12, if the time of day is critical to users. Changing over to UTC eliminates any discrepancy in time zone offset and daylight savings. Migrating to UTC is one change needed if the future scope of the project is expanded to include physical observations with the goal of better spring runoff forecasting.

A site visit takes time to finish, and so a "beginning" and "end" of site visit are usually recorded. Noting the time of events during site visits has not been recorded very often; it is proposed that field workers do so in future data collection efforts. Field worker error in time recording shows up most often as; absence of time value and only arrival time entered on the field sheet. Field forms prompt field workers to enter both arrival and end times.

When dealing with the time window of a site visit, it is proposed that a mean time is used as the time stamp for an individual snow pit. Subtract the start time from the end time, then divide by two; add that much time to the start time, to get the timestamp for a specific snow pit. By changing SOP a little all timestamps can be recorded, and a site visit meantime can then be used for snowpit timestamp, any ambiguity would be avoided as people unfamiliar with the dataset and field protocol use the data. The vast diurnal CC_{snow} swings make accurate and precise time records vital. Stratified CC_{snow} has been shown to change drastically from one hour to the next.

While time is not usually considered critical with snowpit field data collection; with the new research in energy balance quantification and CC_{snow}, time will become more critical than it was in the past. Accurate time stamps could be a deciding factor on whether a dataset is suitable for forecasting ablation and runoff. Consistent sampling near 1 April is essential to minimize the impact of differences in solar radiation on the seasonal scale. Sampling the snow at a similar time of day is also important for the same reason. The consistency of sampling in both annual and daily time is shown in figures 14 and 15 adding some confidence in the SOP and the claim of 1 April site visit target date and arriving near the same time each day. Considering the vast areal extent of the USGS RMS project, figures 14 and 15 show the majority of sampling happens as claimed.

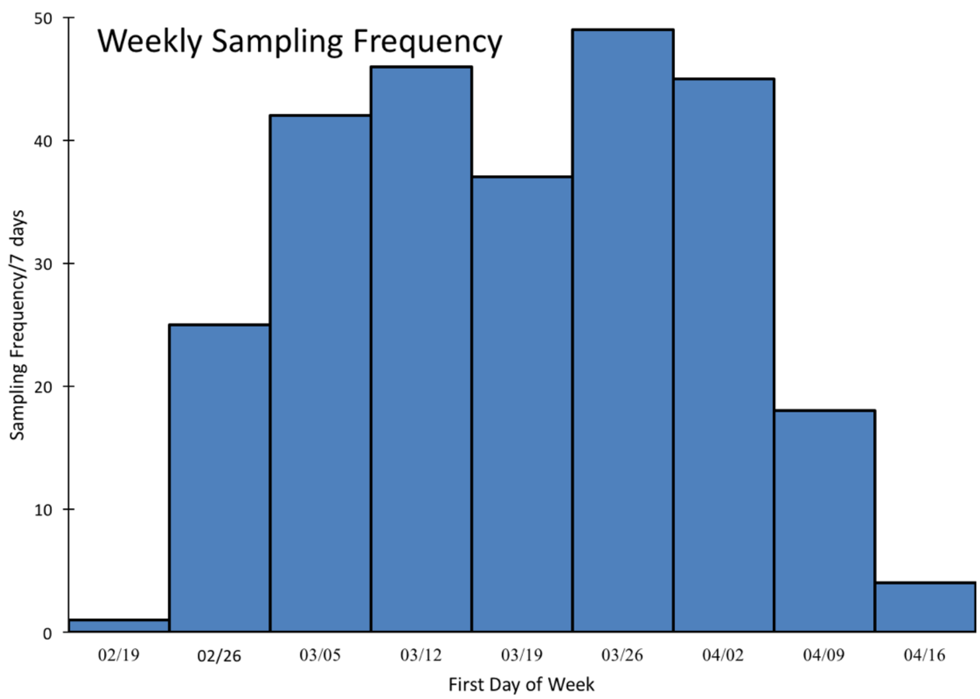


Figure 14: Success of USGS RMS in sampling on or before SWE_{peak} around 1 April.

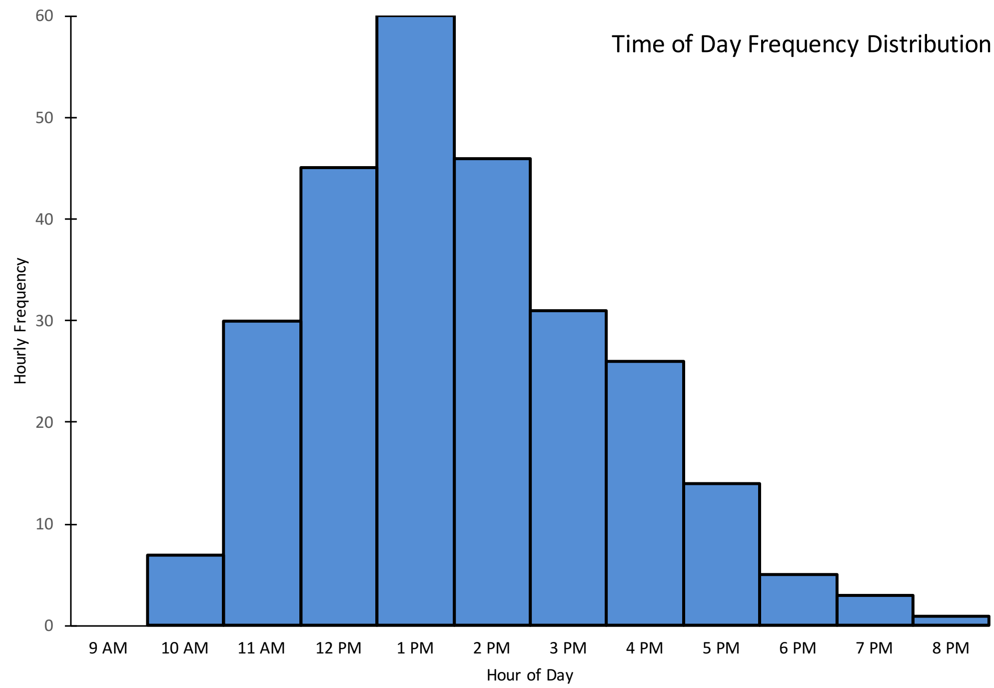


Figure 15: Time of day maybe useful to consider if data users are looking for diurnal trends or sublimation flux.

Important Equations

"Bulk Cold Content"

$$\mathbf{CC_{snow} = -C_i \times \rho_{ice} \times SWE \times (Ts\text{-}Tm)} \quad (1)$$

Where C_i is the specific heat of ice (2102 J kg^{-1} K^{-1}), T_{snow} is the average temperature, T_m is the melting point of ice (273.2K), ρ_{ice} is the density of ice (approximately 1000 kg m^{-3}), and SWE is the snowpack water equivalent in meters." (Serreze M.C., 2016 lecture notes)

"Snow Cover Energy Balance"
The snow-cover energy balance can be expressed as:

$$\mathbf{CC_{rate/time\ step} = dU\ dt^{-1} = Q^{*}+Q_G+Q_A-Q_E-Q_H} \quad (2)$$

where dU dt^{-1} is the net rate change of internal energy within the snowpack, Q^* is the net radiation, Q_G is the ground heat flux, Q_A is the advective energy flux (i.e. energy from precipitation onto the snowpack), and Q_E and Q_H are positive when the flux is directed from the snowpack to the atmosphere, while all other energy terms are positive when directed into the snowpack. Snowpack sublimation is represented within the snow-cover energy balance by Q_E and is calculated by dividing Q_E by the latent heat of sublimation (L_S), which is determined as a function of the T_{snow} of the surface." (Sexstone, G.A. *et al.*, 2016)

USGS RMS Network Summery By Location

Table 2: Quick reference details by location for USGS RMS

USGS NWIS Site ID	Name	Lat	Long	State	Elevation (ft)	16yr Mean Depth (cm)	16yr Mean TEMP (℃)	16yr Mean Density (kg m^{-3})	16 yr Mean CC (MJ m^{-3})	Mean SWE (mm)	Missing Year
480919113563600	Noisy Basin	48.0919	113.5636	MT	6150	287	−3.4	283	4.9	814	
463828114364600	Granite Pass	46.3828	114.3646	MT	6540	199	−2.2	302	2.5	601	
463900111280000	Spring Gulch	46.3900	111.2800	MT	5900	60	−3.3	259	1.0	154	
454147113560900	Chief Joseph Pass	45.4147	113.5609	MT	7370	157	−2.7	290	2.3	453	
450303109571100	Daisy Pass	45.0303	109.5711	MT	9530	241	−3.2	310	4.7	505	
442828110091700	Sylvan Lake	44.2828	110.0917	MT	8450	156	−4.2	290	3.3	442	
435228114425200	Galena Summit	43.5228	114.4252	ID	8860	171	−3.4	270	2.9	461	2009
434452110031300	Togwotee Pass	43.4452	110.0313	WY	9590	201	−3.5	288	3.9	582	
433006110575700	Teton Pass	43.3006	110.5757	WY	8190	197	−1.8	299	2.0	587	
430010109452500	Elkhart Park	43.0010	109.4525	WY	9400	119	−3.1	279	1.9	334	
412229106144100	Brooklyn Lake	41.2229	106.1441	WY	10600	200	−2.9	326	3.5	655	
403240106410000	Buffalo Pass	40.3240	106.1441	CO	10375	345	−3.6	330	8.0	1143	
400200105340000	University Camp	40.0200	105.3400	CO	10350	158	−2.1	299	1.9	475	
390158107583901	Grand Mesa	39.0158	107.5839	CO	10360	145	−2.8	333	2.3	445	2012
383100106193000	Monarch Pass	38.3100	106.1930	CO	10610	134	−2.7	285	1.9	382	
375350107420000	Red Mountain Pass	37.5350	107.4200	CO	11260	192	−3.0	303	3.3	583	
364233106145100	Hopewell	36.4233	106.1451	NM	10050	120	−2.2	302	1.5	363	

Works Cited

Clow, D. W. (2010). Changes in the timing of snowmelt and streamflow in colorado: A response to recent warming. *Journal of Climate, 23*(9), 2293-2306.

Ensemble Streamflow Prediction (ESP) (n.d.). Colorado Basin River Forecast Center. Retrieved from https://www.cbrfc.noaa.gov/wsup/doc/cbrfc_ws_esp.pdf

Franz, K. J., H. C. Hartmann, S. Sorooshian, and R. Bales, 2003: Verification of National Weather Service ensemble stream- flow predictions for water supply forecasting in the Colorado River basin. *J. Hydrometeor.*, 4, 1105–1118.

Ingersol, G.P., Campbell, D., Mast, M.A., Clow, D.W., Nanus, L., Frakes, B. (2009), Snowpack Chemistry Monitoring Protocol for the Rocky Mountain Network; Narrative and Standard Operating Procedures, USGS Standard Operating Procedure., Administrative Report, 58.

Painter, T. H., Deems, J. S., Belnap, J., Hamlet, A. F., Landry, C. C., & Udall, B. (2010). Response of colorado river runoff to dust radiative forcing in snow. *Proceedings of the National Academy of Sciences of the United States of America, 107*(40), 17125-17130. doi:10.1073/pnas.0913139107

Reba, M. L., D. Marks, A. Winstral, T. E. Link, and M. Kumar (2011), Sensitivity of the snowcover energetics in a mountain basin to variations in climate, *Hydrol. Processes*, 25(21), 3312-3321.

Sexstone, G. A., D. W. Clow, D. I. Stannard, and S. R. Fassnacht (2016), Comparison of methods for quantifying surface sublimation over seasonally snow-covered terrain, *Hydrol. Processes*, 30(19), 3373-3389.

Statistical Water Supply (SWS) (n.d.). Colorado Basin River Forecast Center. Retrieved from https://www.cbrfc.noaa.gov/wsup/doc/cbrfc_ws_sws.pdf