Analysis and Estimation of Snowpack Properties Using CLPX Data

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Abstract- An analysis of snow grain size behavior with respect to other snow parameters such as snow depth, density, and temperature was performed. From this analysis, a pattern was derived which can be used to approximate the range of grain size variations. Data used in this research are from NASA Cold Land Processes Field Experiment (CLPX) in Colorado. This intensive field survey was conducted in February and March of 2002 and 2003. The measurements include the grain size, density, and temperature in different layers of snowpack profiles. The analysis of snowpack profiles showed that the snow density usually tends to increase towards the bottom of the snow. Snow density is about 0.1 kg/m^3 for fresh snow and increase up to 0.4 kg/m^3 for the old snow, bottom layers. Snowpack temperature increases towards the snow-ground interface ranging between -1 ^{o}C to 0 ^{o}C. The very top layer temperature is usually very dependent to the air temperature in the area (-6 to -8 ^{o}C for our measurements). The grain size profile generally shows an increase in the snowpack profile. Fresh snow grains are around 0.1 mm which their size increases toward the lower layers of snow up to 2.5mm. It needs to be mentioned that the changes in grain size profile are not linear. In addition, there are cases where a layer of dense snow with large grain size is located between snow layers with smaller grain sizes which can be explained by melt and refreeze during the season. Overall, the snow grain size variation is highly correlated with both snow density, and temperature. The correlation is generally higher between snow grain size and snowpack temperature as compared with grain size and density. In order to better re-analyze evolution of snowpack properties, we excluded the very top layer of the fresh snow from the analysis. The results showed an increase in correlation between snowpack temperature and grain size. On the other hand, the snowpack temperature profile might be estimated by a function (possibly linear) by using the top and bottom temperature. The slope of the regression line indicates the dependency of the regression slope to the snow depth. The surface and body temperature of the snowpack can be obtained from NCDC and microwave channels. Using snowpack temperature, the grain size evolution can be approximated.

Introduction

Snow and its properties estimations are among NOAA's priorities from two perspectives: global scale, and regional /continental scale. On the global scale, high albedo snow plays a major role in the earth's energy balance. Seasonal snow covers more than thirty percent of earth’s land surface (Robinson et al., 1993). Also, an estimation of snowpack properties is significantly important at regional scales for various problems such as flood predictions and water resource management. Melting snow is responsible for the majority of spring floods. Satellites operating in the optical wavelengths have monitored snowcover over the Northern Hemisphere for more than forty years (Grody et al. 1996). Optical sensors can detect snowcover during daylight and under cloud-free conditions. In contrast, microwaves are sensitive to snowpack properties (depth, snow water equivalent, grain size, and wetness). Many studies have been conducted to establish a relationship between snowpack properties and microwave electromagnetic scattering signatures (Change et al., 1987, Goodison-Walker 1995). In a different approach, some scientists simulated the microwave emission of snowpack. Pullinainen et al. (1998) proposed a single layer snow emission model (HUT) for simulating the snowpack brightness temperature. Similarly, Wiseman and Matzler (1999) developed a multi-layer microwave emission model (MEMLS). This multi-layer and multi-scattering radiative transfer model uses six-flux theory to describe volume scattering and absorption. The scattering coefficient for both models, HUT and MELMS, was determined empirically from snow samples.

In the mentioned algorithms and models, there are key parameters of snow such as snow depth, density, water content, and grain size. These parameters play a significant role in the microwave emission and contribute to the measured emission by sensors. The goal of this study is to analyze the behavior of snow grain size variations with respect to other snowpack parameters such density, depth, and temperature which influence the microwave scattering of snowpack. In this study, data from the NASA Cold Land Processes Field Experiment (CLPX) in Colorado was used for this analysis.

Study Area

The Cold Land Process Experiment (CLPX) consisted of multiple sites in Colorado. The study area (Colorado) was selected because the central Rocky Mountains have large physiographic gradients and they provide different terrain, snow, soil, and ecological characteristics. CLPX design consisted of nested sites in Colorado, United States. In other words, the collection is designed in one area within another, based on a 5-level set (Fig.1). The different scales were designed to provide a "scale bridge" between the levels for better understanding of the relationship between one scale to another scale. It starts from the Large Regional Study Area (LRSA) which is 400km x 400km at 104 º- 108.5 ºW, 38.5 º- 42 ºN. This coordinate size was selected because it contained a broad range of physiographic characteristics and therefore a wide range of snow and freeze/thaw characteristics as well as suitable images for coarser-resolution spaceborne passive microwave remote sensors. Then, the scales zoom in to approximately 215km x 170km (105 º- 107.5 ºW, 39.5 º- 41 ºN) of Small Regional Study Area in north-central Colorado. This area still contains most of the physiographic characteristics and it is efficient to have high-resolution space-borne passive microwave remote sensors. Inside the Small Regional Study Area, there are three regions called Meso cell Study Areas (MSA, 25km x 25km).

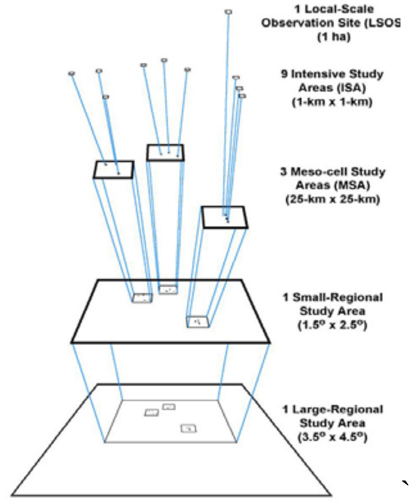

Fig 1: Schematic diagram of the nested study areas for the CLPX , www.nohrsc.nws.gov

The three MSAs are Fraser, North Park, and Rabbit Ear. These three MSAs represent four of the major snow cover classes, which are classified by Sturm et al., [1995]. Nine (3 in each MSA) Intensive Study Areas (ISAs) were selected. Each ISA (1km x 1km) included about 15 snow pits to measure of snowpack properties. Three MSAs (Fraser, North Park, and Rabbit Ear) have their own physiographical characteristics and therefore collected data such as snow depth, density, temperature, and snow grain size are distinguishable at each location (Table 1).

North Park (106.1º -106.4 º W, 40.6º- 40.8 ºN) is an inter-mountain glacial basin that opens toward north into Wyoming. The other sides are surrounded by high mountains, which develop deep snow packs in winter because of significant orographic precipitation effects. However, these surrounding mountains also cause the precipitation "shadow", therefore, there is a relatively small snow accumulation in North Park. It has a mean elevation of 2499m and a total elevation range of 312m. The type of snow cover in North Park is prairie and most of the vegetation is low-relief grassland with shrubs in wetter area. Snow pack in this area tends to be shallow, windswept snow cover and extensive frozen soils.

Rabbit Ears (106.5 º -106.8º W, 40.3 º- 40.6 ºN) includes low to moderately rolling hills extending north-south throughout the middle. It has a mean elevation of 2725m. The vegetation is moderate-relief area in woodland or Low Mountain with mixed coniferous/deciduous forest. Rabbit Ear has heavy snowfall during the winter and spring and it becomes the deepest snow pack in Colorado at the higher elevations. Also, the snow packs of this area have the characteristics and depth of a region influenced by orographically induced precipitation, and has only 10% of global seasonal snow cover [Sturm et al., 1995].

Then, Fraser (39.8º - 40º N, 105.7º - 106º W) is a topographically complex area, with High Mountain and high-relief areas that has a mean elevation of 3066m. The vegetation is predominantly coniferous and sub-alpine forests. Snow cover is moderate to deep and increases with elevation. Snow packs in this area are minimally modified by wind and have considerable deep hoar development.

Each of the MSAs (Fraser, North Park, and Rabbit Ear) described above includes 3 Intensive Study Areas (ISA) (Table 1). Each ISA represents a relatively homogeneous, major physiographic characteristic, and major landscape such as topography, vegetation, and snow cover and its size (1km x 1km) is the largest size that this can be covered as well as it is a common resolution for other geophysical data sets. Within the each ISA there are about 16 snow pits for intensive spatial sampling of snow and soil properties (Table 1).

The snow survey in the above locations was carried out during 4 Intensive Observation Periods (IOPs) during February and March of 2002 and 2003 in mid-winter (February) when frozen conditions and dry snow covers prevail and in early spring (March) when frozen and thawed conditions and wet snow covers are prevalent. Thus the measurements from 434 snow pits (3 MSAs x 3 ISAs x 16 snow pits x 4 IOPs) were available and analyzed.

Table 1: Characteristics of the different study areas, www.nohrsc.nws.gov

MSA	ISA	Characteristics
North Park	Potter Creek	Dry grassland with isolated shallow ponds, on a flat aspect with low relief; shallow windswept snow cover.
	Illinois River	Wet grassland with widespread meandering riparian areas, on a flat aspect with low relief; shallow windswept snow cover.
	Michigan River	Dry sage-grassland with moderate relief; shallow windswept snow cover.
Rabbit Ear	Buffalo Pass	Dense coniferous forest interspersed with open meadows; low rolling topography with deep snow packs.
	Spring Creek	Moderate density deciduous forest; moderate topography on west-facing slope, with moderate snow packs.
	Walton Creek	Broad meadow interspersed with small, dense stands of coniferous forest; low rolling topography with deep snow packs.
Fraser	St.Louis Creek	Moderate-density coniferous forest, on a flat aspect with low relief.
	Fool Creek	Moderately high-density coniferous forest, on wet north-facing slope
	Alpine	Alpine tundra, with some subalpine coniferous forest; generally north-facing with moderate relief.

Data Acquisition

During the IOPs, the value of snow depth, density, temperature, and mean grain size were collected along with the vertical profile of the snowpack within all ISAs. Snow depth is measured in centimeters by inserting probe vertically into the snow pack and recorded at the interface of snow and air. The probe is left in place against the pit wall for reference of other measurements. Snow pack is sampled out with the snow cutter in 10cm increments, and recorded as snow density with the scale. Snow temperature is measured on the same 10cm intervals and simultaneously with the density measurements over the entire profile using a thermometer. Solar radiation and shade problems were

Figure 2: Measurements in snow pits, (NSIDC)

concerns, so equilibration of thermometer was performed before the measurements. Snow grain size is measured for each homogeneous layer in the snow profile. To determine major grain boundaries, instruments such as paintbrush, putty knife or hand are used, and samples are collected randomly with the crystal card. Then, loupe-style hand lenses are used to determine size of snow grains along their long axis (Fig 2).

Data Analysis

To understand the large scale snow characteristics in of MSAs (Meso-cell Study Area) and ISA (Intensive Study Area), the means and standard deviations of snow depth (height), snow temperature, density, and snow grain size were computed over ISAs and MSAs by averaging the measured values from the snow pits (Fig 3).

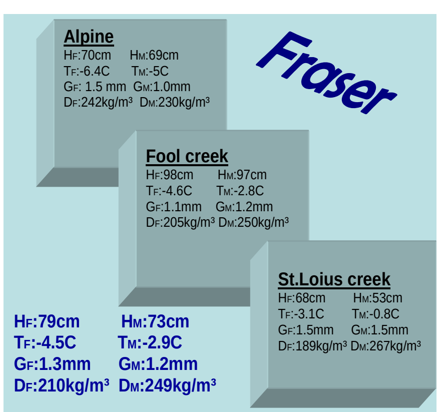

Figure 3: Average of snow parameters in Fraser (IOP 1-IOP2) HF=Height of snow in Feb, HM=Height of snow in Mar., TF=Snow temperature in Feb., TM=Snow temperature in Mar., GF=Grain size in Feb.

Fraser has moderate snow depth ranging from 53 cm in ISA, St Luis Creek to 97cm I Fool Creek. The mean temperature is lower than North park (-6.4 ^{oC} to -3.1 ^{oC}). The average density in different ISAs varies between 189kg/cm^3 to 301kg/cm^3. In North Park, snow depth is relatively shallow (less than 20cm) with high mean temperature (-2.4 ^{oC}) and low density (197kg/m^3) during the dry period of February. The mean density and temperature tend to increase during thaw and refreeze period of March (315kg/m^3, and -0.5 ^{oC}). Rabbit Ear has the highest average of snow accumulation and consequently its snow has high density compare to the other two ISAs. The average snow depth exceeds 200 cm. In Buffalo Pass and the snow density reaches 364kg/cm^3 during the thaw re-freeze period in March.

A more detailed analysis of snow data shows the variation of snowpack properties in different ISAs within MSAs (Fig 4). It is observed that in ISAs within North park where snow depth is shallow, the average temperature is high with a high standard deviation. The large standard deviation indicates that the average temperature of snow is very much dependent on air temperature which has a large range. In North Park's ISAs and the snow density tends to be low (less than 250kg/cm^3). On the other hand, the average snow grain size is relatively high (more than 1.2mm) with a very large standard deviation in size of the gains. Considering the fact that in a shallow snow like North Park's snow covered area there won't be many layers of snow, then this large high average of snow grain size and its variation can be explained by thaw and re-freeze process which is due to oscillation of air temperature. In Rabbit Ear the snow is deeper and the density is higher but the average grain size is low for two of the ISAs (Buffalo and Spring).

Profile of Snow Properties:

In order to have a better understanding of snowpack properties and their behavior with respect to each other, the profiles of snow depth, density, temperature, and grain size were analyzed. Since the snow depth was shallow in North Park, the profile analysis was only applied to Fraser and Rabbit Ear.

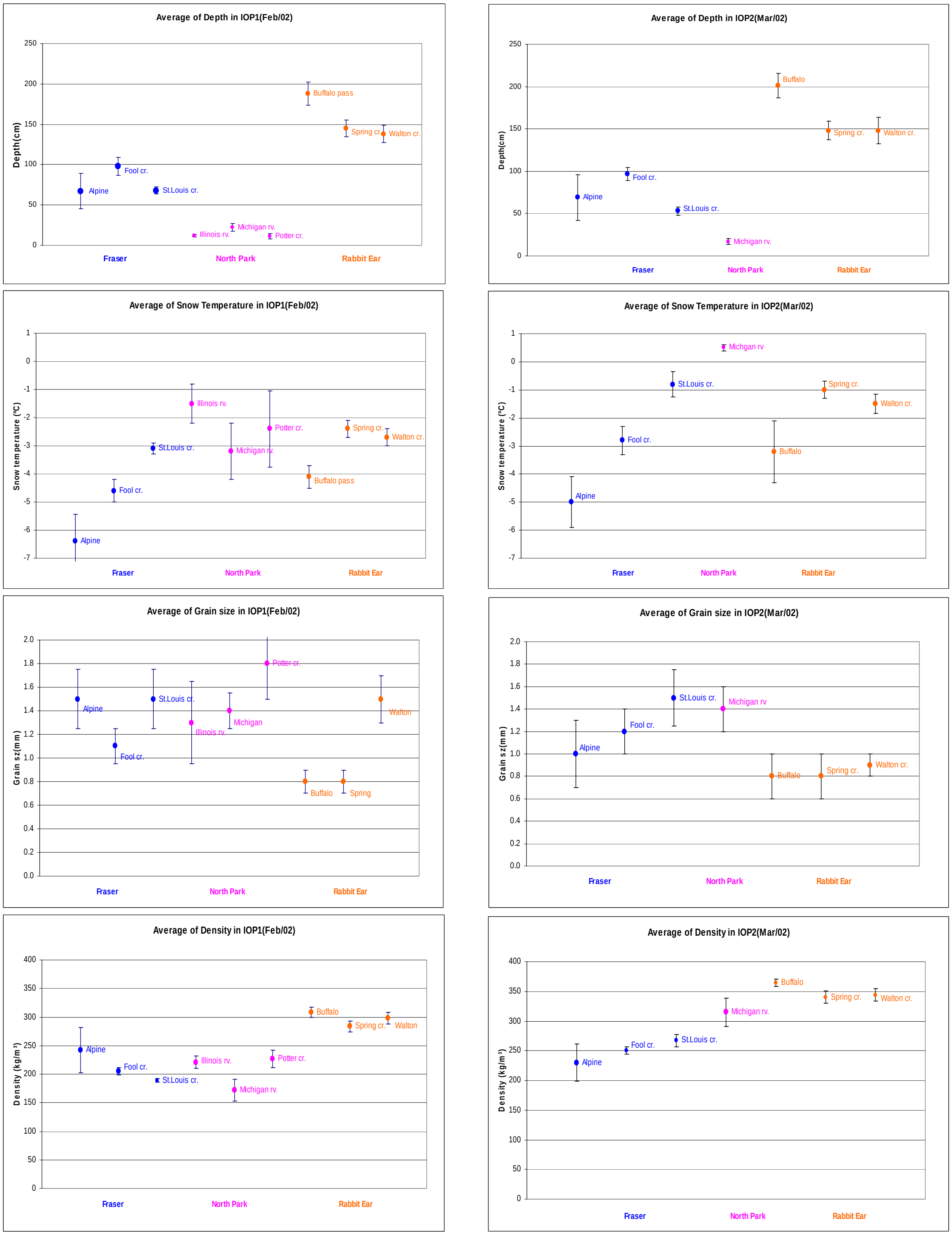

Figure 4: Variation of snow mean and standard deviations of parameters

The profile of snow temperature, density, and snow grain size for various snow pits in all ISAs located in Fraser and Rabbit Ear were drawn. Figure 5 illustrates changes in snowpack characteristics (density, temperature and grain size). It is observed that, with except to very top layer of snow, the snow temperature, density, and averaged grain size increase towards the snow-ground interface. The older snow has larger grain sizes and the fresh snow on top has smaller grain size. But, the very top layer of the snow (top 10cm) shows different characteristics. In cases, the snow grain size is larger in very top layer as compared with the underlying layer. This can be explained by daily fluctuations air temperature. During the day the temperature of air increases resulting in acceleration of snow grain size increase.

On the other hand, the bottom layer (approximately 10cm above the snow-ground interface) has different characteristics in terms of snow grain size, temperature, and density. The average grain size, snow temperature, and density of the bottom layer are larger than other layers. In addition, the snow temperature in the bottom layer falls in a certain range with a

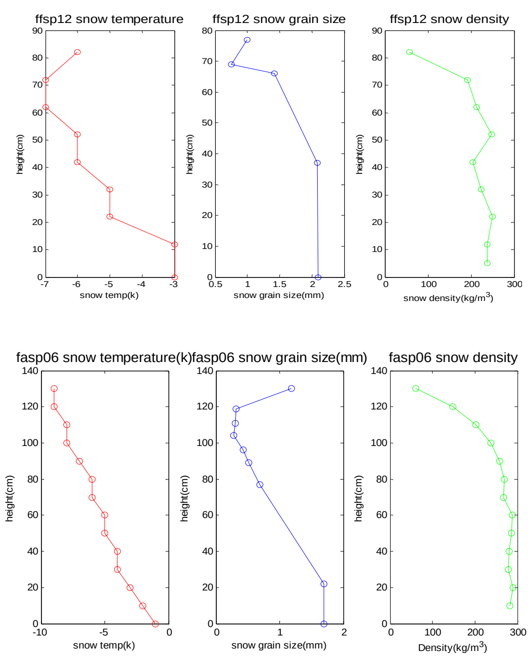

Figure 5: Variation of snow temperature, grain size, and density in the snow profile Fraser Alpine (pits 6 and 12)

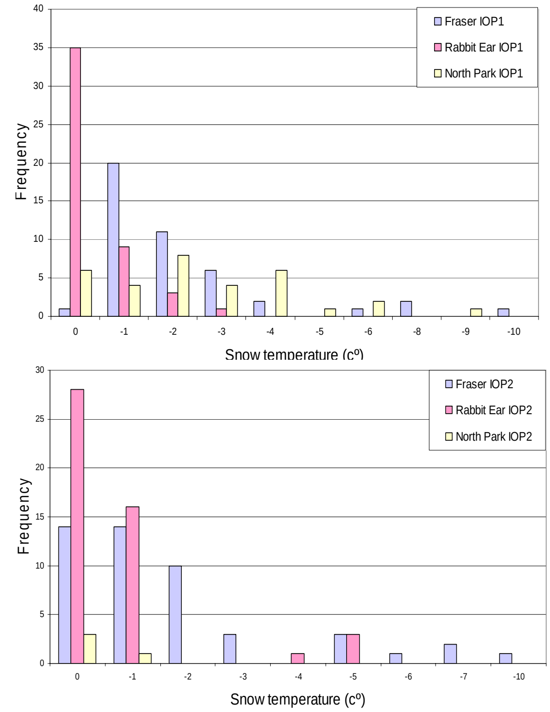

Figure 6: Temperature of snow bottom layer in various snow pits for IOP1 (top), and IOP2 (bottom)

relatively small deviation. For example, in Rabbit Ear, the temperature of bottom layer is between 0^{oC} and -1^{oC}. Figure 6 illustrates the variation of temperature of snow-ground interface.

To quantify the variation of all snow parameters (density, temperature, and grain size) with respect to each other, the correlation coefficients between those parameters over the profile was calculated for all the snow pits within ISAs of Fraser and Rabbit Ear. Figure 7 shows the correlation coefficients between snow grain size, and temperature and snow grain size and density for the snow pits located in Fraser and Rabbit Ear. In Rabbit Ear, both density and temperature show significant correlations with grain size. In Fraser, correlations between the density and the grain size changes but the snow temperature shows high and consistent correlations with grain size.

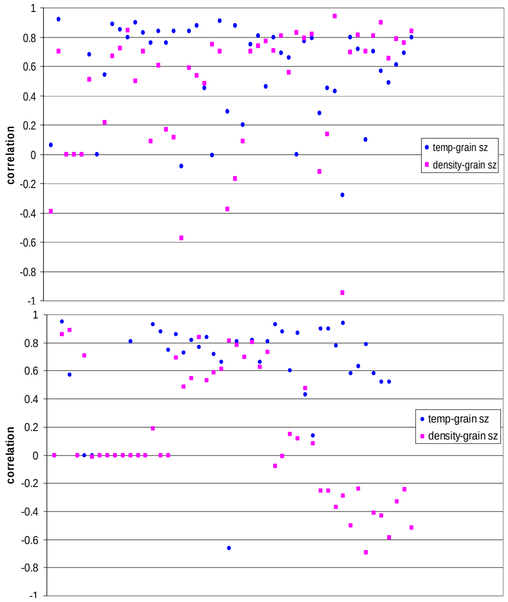

Figure 7: Correlation coefficients between snow grain size and temperatures and snow grain size density for different snow pits in Rabbit Ear (top) and Fraser (bottom)

Methodology

As shown in the previous section, the snow temperature and snow grain size are highly correlated in the profile of snowpack. Thus, using the temperature, the grain size profile can be estimated. Also, it was shown that the temperature for the bottom layer of snow tends to be in a certain range. Thus, the intercept of the regression line can be a fixed value which is determined based on the characteristics of the snow covered area. In this study, we derived the regression line between snow grain size and snow temperature for each of the snow pits located in all ISAs for selected IOPs. Then, we defined a new regression line by averaging the slope of the regression lines for all the snow pits. Finally, we examined the derived regression line for estimating the snow grain size using snow temperature profile for different IOPs in various locations.

The scatter plot of grain size versus temperature in a snow pit is shown in Figure 8. Other snow pits follow a similar pattern for variation of temperature versus snow grain size. The regression line between snow grain size and temperature is derived for all the snow pits. Figure 9 illustrates that for ISA Fool Creek in Fraser. For each of the snow pits in ISA Fool Creek the scatter plot of snow temperature versus grain size was drawn. The regression line between temperature and grain size is shown (Fig 9). In order to derive an equation that represents the ISA, the regression lines were averaged (Fig 9). Similarly, other ISAs located in both MSAs (Rabbit Ear and Fraser) show the same pattern. Table 2 shows the equations derived for the six ISAs located in Rabbit Ear and Fraser. The process was repeated for other IOPs too.

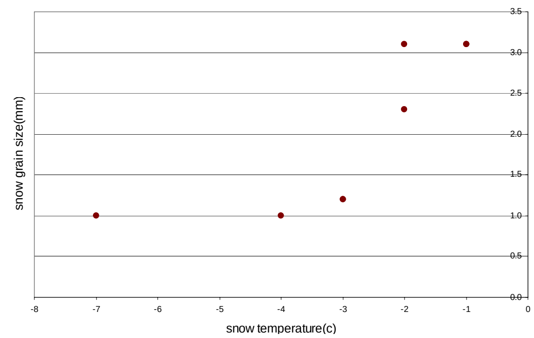

Fig 8: Snow grain size vs. snow temperature (Fool Creek, Fraser, IOP1, pit #13)

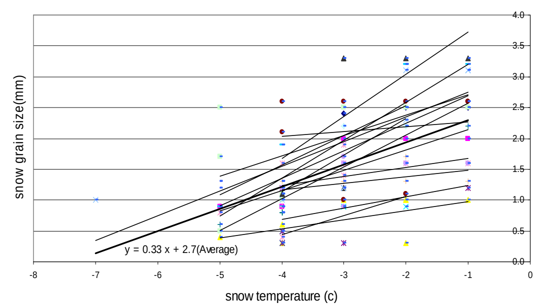

Fig 9: Snow grain size vs. snow temperature (Fool Creek, Fraser, IOP1, 16 pits)

Table 2: Equations to estimate snow grain size using snow temperature, H is snow depth, T is snow temperature and Z is snow grain size.

	FRASER			
IOP1	Alpine	Fool creek	St.Louis creek	AVERAGE
f(snow temperature)	T=-0.0663H-2	T=-0.058H-2	T=-0.0467H-2	T= -0.057H-2
f(snow grain size)	Z=0.198T+2.48	Z=0.21T+2.06	Z=0.33T+2.7	Z=0.246T+2.413
	Rabbit Ear			
IOP1	Buffalo pass	Spring creek	Walton creek	AVERAGE
f(snow temperature)	T=-0.0458H	T=-0.0356H	T=-0.0453H	T= -0.042H
f(snow grain size)	=0.1076T+1.265	Z=0.107T+1.06	Z=0.13T+1.826	Z = 0.115T+1.384

Results and Discussion

The derived equations for different IOPs were used to estimate the snow grain size. First, the equations were examined over different ISAs during different IOPs. In Alpine which is located in MSA Fraser the estimated and measured grain size show high correlations and the Root Mean Square Error (RMSE) is low too. The difference between the average of estimated and measured grain size is about 2mm (Fig 10). Similarly in Fool Creek in Fraser there is a satisfactory correlation between estimated and measured grain size. However, in Fool Creek the correlation coefficient is lower. In Fool Creek the measured snow grain sizes have higher standard deviation compared with Alpine. The equation shows higher error in estimating the larger grain size (Fig 11).

In ISAs; Walton Creek and Spring Creeks in Rabbit Ear, the estimated snow grain size shows lower correlations with the measured grain size. The error occurs where snow grain size is very small (<0.5mm) or very large (>1.5mm) (Fig 12). Although the average grain size for estimated and measured grain size are the same and the RMSE and bias are low but the correlation coefficient is low. This is due to high range of grain size variations in the ISA (Walton and spring Creek) which ranges from 0.5 to 3 mm. To derive the source of the error the derived equation for estimating the grain size was applied to each of the snow pits located in Walton and Spring Creeks separately (Fig 13). Table 3 shows the performance of the equation for each of the snow pits. It is observed that in a few of snow pits the error estimations increase, which results a decrease in the correlation coefficients. This decrease in correlation originates from insufficient measurements of snow grain size in those pits. For example in snow pit 8 in Spring Creek, we had only one snow grain size measurement for the bottom 80cm of snow (0.75mm) (Fig 14). This value was assumed constant for the whole 80cm which in reality may not be correct. On the other hand, we observed that the temperature increases towards the snow-ground interface. Similar problems exist in ISA, Walton Creek. Figure 14 illustrates those there actually only 5 grain size measurements for the all layers of snowpack which is deeper than 160cm.

By excluding those snow pits with inadequate snow grain size measurements, a higher correlation between estimated and measured snow grain size is observed (Fig15).

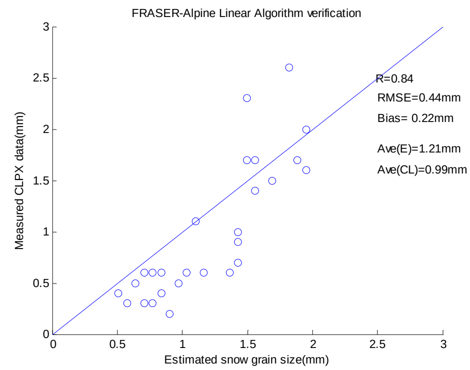

Figure 10: Measured vs. Estimated snow grain size (Fraser, Alpine)

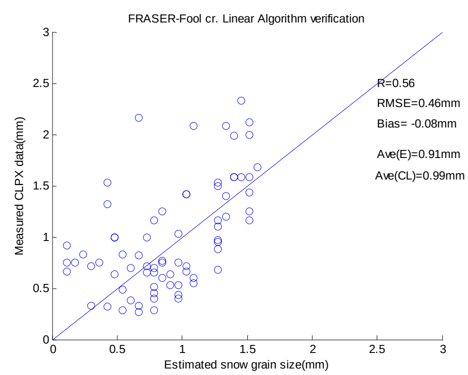

Figure 11: Measured vs. Estimated snow grain size (Fraser, Fool Creek)

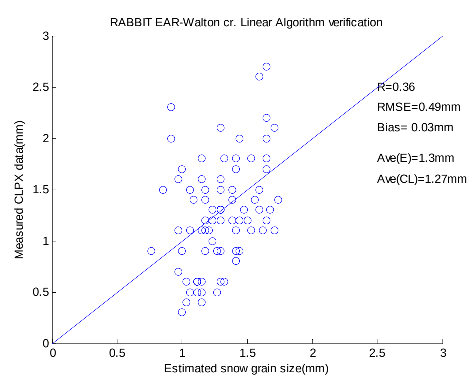

Figure 12: Measured vs. Estimated snow grain size (Rabbit Ear, Walton)

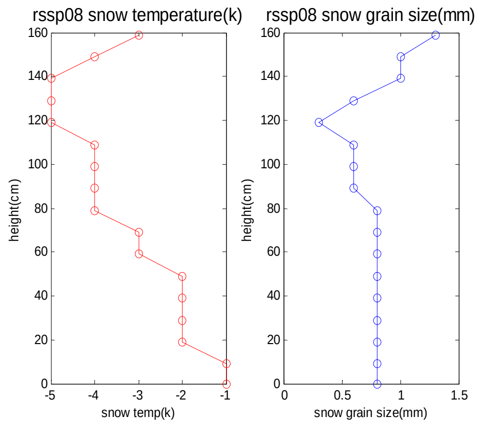

Figure 13: Variation of snow temperature, and grain size, and density in the snow profile Rabbit Ear, Spring Creek, snow pit 8

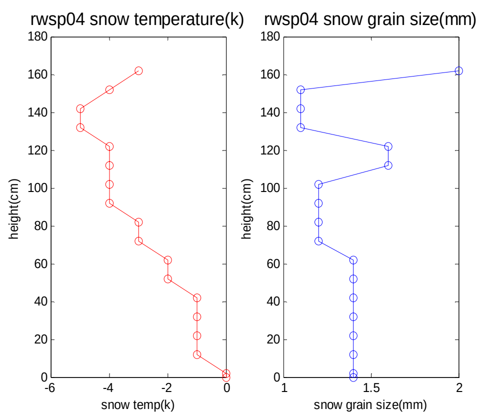

Figure 14: Variation of snow temperature, and grain size, and density in the snow profile Rabbit Ear, Walton Creek, snow pit 4

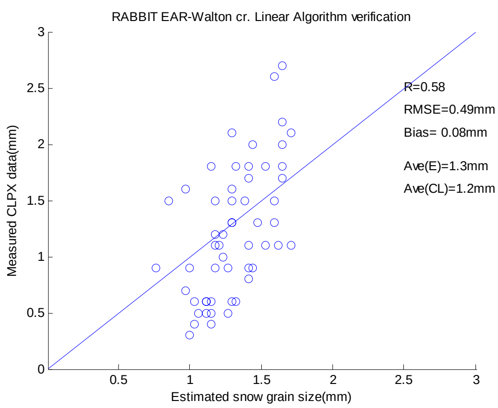

Figure 15: Modified (snow pits 4, 5, and 7 excluded) Measured vs. Estimated snow grain size (Fraser, Fool Creek)

Conclusion

In this research we analyzed the behavior of different characteristics of snowpack. We used the data from NASA Cold Land Processes Field Experiment (CLPX) in Colorado. The measurements include the grain size, density, and temperature in different layers of snowpack profile. It was observed that except for the very top layer of snow, the snow temperature, density, and averaged grain size increase towards the snow-ground interface. The older snow has larger grain sizes and the fresh snow on top has smaller grain sizes. The bottom layer (approximately 10cm above the snow-ground interface) has different characteristics in terms of snow grain size, temperature, and density. The average grain size, snow temperature, and density of the bottom layer are the larger than other layers. Using the results form the analysis, we derived an equation to estimate snow grain size using snow temperature. The results were satisfactory over ISAs located in MSA Fraser. While in MSA Rabbit Ear, the error of the estimations increased. The spatial changes in snowpack properties in this area add to the complexity of the problem. In addition, the changes in the snow profile could be due to existence of a very stratified layer in the bottom and a layer of recently fallen fresh snow on the top. In short, the approach for estimation of snow grain size using the snow temperature was relatively successful and the source of the errors was identified.

Acknowledgement

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Table 3: Comparison and analysis of snow grain size estimations for snow pits located in Spring Creek and Walton Creek in MSA Rabbit Ear

	Snow pit #	Depth(cm)	Average of CLPX data	Average of Estimated	CC	RMSE	BIAS
Spring Creek	rssp01	157	0.89	0.74	0.12	0.32	-0.14
	rssp02	154	0.93	0.78	-0.44	0.5	-0.27
	rssp03	116	0.88	0.79	0.71	0.72	-0.63
	rssp04	148	0.67	0.69	0.19	0.87	-0.82
	rssp05	180	0.78	0.62	0.17	0.8	-0.77
	rssp06	135	0.73	0.70	0.78	0.81	-0.8
	rssp07	150	0.75	0.70	0.84	0.82	-0.84
	rssp08	159	0.77	0.63	-0.32	0.79	-0.7
	rssp09	88	1.20	0.86	0.52	0.98	-1.04
	rssp10	143	0.85	0.77	0.16	0.93	-0.86
	rssp11	156	0.90	0.65	0.61	1.21	-1.63
	rssp12	128	0.70	0.72	0.22	1.13	-1.33
	rssp13	142	0.76	0.72	0.88	1.24	-1.64
	rssp14	144	0.66	0.68	0.62	1.25	-1.62
	rssp15	163	0.75	0.68	0.95	1.14	-1.42
	rssp16	161	0.65	0.66	0.73	1.4	-2.11
Walton Creek	Snow pit #	Depth(cm)	Average of CLPX data	Average of Estimated	CC	RMSE	BIAS
	rwsp01	141	0.98	1.22	0.99	0.39	0.24
	rwsp02	181	1.75	1.10	0.97	0.77	-0.49
	rwsp03	106	1.55	1.39	0.97	0.96	-0.89
	rwsp04	162	1.38	1.27	-0.20	0.82	-0.55
	rwsp05	134	1.20	1.33	0.03	0.91	-0.5
	rwsp06	145	1.13	1.35	0.88	1.43	-0.95
	rwsp07	161	1.58	1.20	-0.79	1.23	-0.86
	rwsp08	110	1.33	1.38	0.76	1.51	-1.23
	rwsp09	110	1.80	1.38	0.99	1.85	-2.05
	rwsp10	147	1.63	1.33	0.94	1.65	-1.83
	rwsp11	139	0.68	1.25	0.95	1.76	-1.26
	rwsp12	138	0.79	1.37	0.94	1.46	-0.13
	rwsp13	139	0.66	1.30	0.99	1.84	0.46
	rwsp14	104	1.70	1.41	0.87	2.1	0.28
	rwsp15	140	1.03	1.21	0.96	2.43	0.54
	rwsp16	151	1.25	1.36	0.93	2.14	0.52

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