Snow Density and its Underlying Variables

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ABSTRACT

The facilities and tools available at the Desert Research Institute Storm Peak Laboratory in Steamboat Springs, Colorado were used to asses the relationship between snow density and environmental variables including ice crystal structure, temperature, relative humidity, and wind speed. In-situ measurements were recorded and analyzed to reveal which variables had the most significant impact on snow density throughout the snowfall period which lasted from 12 March 2006 to 14 March 2006. Prior to my research, snow densities were expected to increase as temperature increased. The importance of understanding and predicting snow density can be applied to snow emergency situations and avalanche forecasting. Research completed at the Storm Peak Laboratory is applied to prior studies which had varying results. A study completed by Doesken and Judson [2002] found that snow densities decline between certain temperatures and are extremely variable between other temperatures. Finally, in agreement to the hypothesis formulated prior to the research completed in Steamboat Springs, CO, Wetzel et al. found that snow densities tended to increase as temperature increased. These studies failed to apply ice crystal structure and size to the temperature data they recorded. An application of ice crystal structure to density provides motivation for further research.

I. Introduction

Snow density establishes a relationship between snow and water content which correlates with many situations that depend on forecasting. Snow density forecasting is very important for avalanche forecasting, snowmelt runoff forecasting, snowdrift forecasting, and it is also an important parameter involved in Weather Surveillance Radar. Further, it is also involved in snow management programs which help aid in high speed snow removal and snow safety. Forecasting snow accumulations is a difficult task that is commonly aided by the erroneous "ten-to-one-rule" (Ten inches of snow to one inch of rain). According to Doesken and Judson [2000], the "ten-to-one-rule" is a rule of thumb that has been used throughout history to describe the density of snow. In the work of Bruening et al. [2003], he adds that the "ten-to-one-rule" is a snow ratio which is defined by the density of water (1000 kg m^{-3}) to the density of snow (100 kg/m^{-3}). This rule developed from nineteenth century snow data in Toronto, Ontario. Despite the fact that this rule is inaccurate, it is still commonly used. One poorly understood component of snow depth forecasting is determining the snow ratio. The snow ratio is inversely proportional to the snow density [Ware et al. 2006]. Snow density tends to vary greatly from one snow event to another, and it also varies within a single storm depending on its convective nature. A compilation of measurements has detected that snow densities vary from 10 kg m^{-3} to roughly 350 kg m^{-3} [Doesken and Judson, 2000]. Due to the significance of snow density and its affects on society, In my research at Storm Peak Laboratory I conducted measurements from which I analyzed snow density and the variables in which it depends upon including ice crystal structure as well as temperature, relative humidity and wind speed.

A study by Doesken and Judson [2000] assessed the relationship between air temperature and snow density and the effect of snow depth on density. Data was collected throughout several mountain sites in Colorado and Wyoming. A nearby sight recorded in-cloud temperature data to diminish error that would have resulted from data taken from ground based sites. Daily measurements of new snow depth, water content and temperature were recorded. The study concluded that snow densities decline with temperature over the range of 0 to -20° C. However there was a considerable amount of scattered data. The warmer temperatures had the largest amount of variability. Densities at temperatures between 0 and 5°C had densities which ranged from 160 to 70 kg m^{-3}. The method of recording data for this study may be the reason that Doesken's study proved to be somewhat conclusive. Many other studies failed to find a trend and part of the reason for this was that many of the studies had a poor method for taking measurements. Nevertheless there are still many factors that affect snow density that may be hindering a direct relationship between snow density and temperature. For instance, the Judson study failed to apply the temperature and snow density data to the ice crystal structure.

An additional study was completed by Wetzel et al. [2004] over the course of the winter of 2002. The study focuses on the limitations of forecasting in the mountains due to radar interference. Wetzel et al. propose that to improve short term forecasting much greater use can be made of specific observations. One of the methods of improving snowfall forecasts includes the analysis of snow density and the variables that affect it.

The study was based at the Desert Research Institute's Storm Peak Laboratory in Steamboat Springs, Colorado. However, measurements were taken from the floor of the Yampa Valley, which is 10 km from the base of the Steamboat Springs mountain range, to the ski are patrol headquarters located near the top of the mountain. New snow depth from each precipitation event was measured as a total accumulation on a snowboard. The snow was then measured in a cylindrical tube and weighed. Other observations including temperature, relative humidity and wind were concurrently recorded. Many of the measurements were taken while the snow event was still occurring, which reduced the effects of snowpack metamorphosis.

Figure 2 depicts the snow densities for the different data collection sites throughout the winter of 2002. The measurements from individual precipitation events are shown as well as the period average values which are

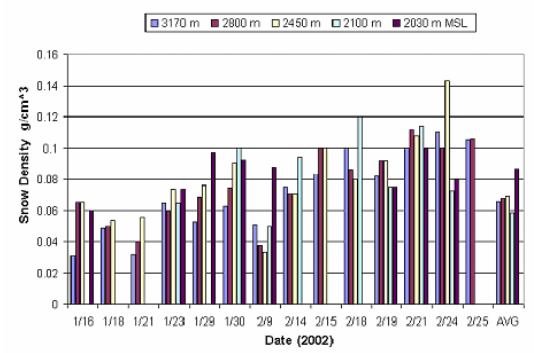


Figure 2: Snow density for sampling sites at elevations from 2030 to 3170 m

shown at the right edge of the table. The data shows that the average snow densities were relatively low with greater densities at lower elevations and increasing snow densities with the progression of the season. Measurements made earlier in the season might be expected to show a decrease in snow density from late fall toward mid-winter due to air mass characteristics.

The snow density data was then applied to temperature. Figure 3 shows a comparison of the air temperature and the snow density for the three highest sampling stations.

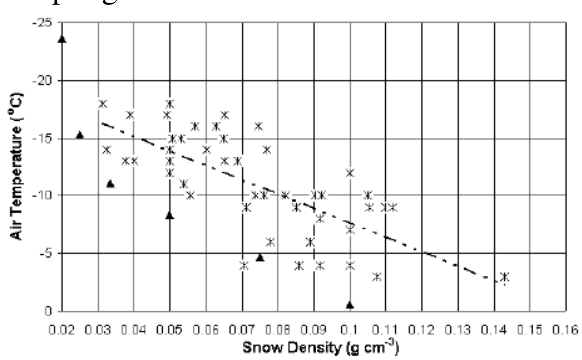


Figure 3: Scatterplot showing the relationship between air temperature and snow density (stars). Also shown are breakpoints (triangles) obtained from the NWS meltwater conversion table.

Figure 3 shows a linear relationship between snow density (stars) and air temperature. According to the linear curve (dashed line), the snow density generally decreases as the air temperature decreases. This relationship was consistent with my hypothesis prior to research completed at the Storm peak Laboratory in Steamboat Springs, CO from 12 March 2006 to 17 March 2006. I expected snow densities to increase as temperatures increased. Also shown in Figure 3 are breakpoints (triangles) obtained from the NWS meltwater conversion table. The meltwater conversion table is used to estimate new snow density using local air temperature. The data provided by the meltwater conversion table underestimates the density of new snow. This reiterates that the "ten-to-one rule" is not reliable. Correlation between the measured air temperature and new snow density explained 52% of the variance which means that although the snow densities are largest for warmer temperatures, there was still a considerable amount of scattered data. This is a similar relationship to the study completed by Judson.

III. Methodology

The research I completed was aimed at understanding the relationship between snow density and the variables including ice crystal structure, temperature and relative humidity. The study was based at the Desert Research Institutes Storm Peak Laboratory located in Steamboat Springs, Colorado, at the same location as the Wetzel study. Upon arrival to the laboratory, two suitable stations for snow density measurements were selected. The sites were chosen based upon areas enclosed by trees to minimize exposure to winds and drifting snow. Station 1 was located at 10, 359 ft while station 2 was located at 10, 569 feet. Snow boards which were approximately 2 ft by 2 ft were set at these locations and snow was measured and collected during and after snow events. Snow depth was first measured using a standard ruler. A plastic cylinder which was 12" in height and 3 and 14/16" in diameter, was then pressed onto the plywood with the open end facing downward, a metal plane was then slid under the cylinder to capture the snow inside the cylinder. The snow from the cylinder was then transferred to a plastic bag of known weight and the snow boards were wiped to set up the next snow density measurement. Next the bag of snow was transferred back to the lab where its weight was measured using a standard scale. The same process was then completed for the other station. The density of the snow sample was calculated by the equation:

$$\boldsymbol{\rho_{SNOW} = M_{SNOW}/V_{SNOW} = (M_{SNOW} - M_{BAG})/Pi * r_{CYL}^2 * h}$$

where $\boldsymbol{\rho_{SNOW}}$ is the density of the snow and $\mathbf{M_{SNOW}}$ is the mass of the bag and the snow and $\mathbf{M_{BAG}}$ is the mass of the bag itself. $\mathbf{V_{SNOW}}$ is the volume of the snow while $\mathbf{r_{CYL}}$ represents the radius of the cylinder and $\mathbf{h}$ is the height.

The first snow density measurements were taken on 13 March 2006. The snowboards had been set and cleared on the prior day at 5:30 at station 1 and at 5:40 at station 2. As mentioned earlier, station 2 was the measurement site at the highest elevation. Intense snowfall fell throughout the night of 12 March 2006 and persisted throughout the day on 13 March 2006. Upon arrival at station 1 at 9:00 on the 13th, a measurement of the snow depth from the plywood board indicated that 13 and 14/16" of snow had fallen since 5:30 on the previous day

Further analysis of the ice crystal structure during the snow event on 13 March was competed at the Storm Peak Laboratory using the Desert Research Institute snow video spectrometer system. This system consisted of a standard video camera which was enclosed in a rectangular wooden box. When observations were taken, the top of the box was removed and the camera was turned on. A square sheet of glass rested just above the camera lens. As ice crystals fell on the glass the camera recorded the ice crystal structure. Furthermore, every few minutes the glass was mechanically cleared to prevent large amounts of snow from accumulating on the glass. This allowed the camera to capture the ice crystal structure throughout a snow period. Unfortunately, camera malfunctions only allowed observations to be recorded during the snow event on March 13th.

IV. Results

Data recorded at station 1 is shown in Table 1. Five measurements were recorded over the course of two days. The table shows the temperature at the time of the snow density measurement as well as the average

Date	Time	Temp (F)	Avg. Temp (F)	RH(%)	Avg. RH(%)	Wind Speed (mph)	Avg. Wind Speed (mph)	Snow Density (kg/m3)
13-Mar	9:00	4.5		89		10.8		79.075
13-Mar	9:53	6.5	5.5	89	89	10.9	10.85	81.56
13-Mar	13:15	9.2	8.6	83	85	13.2	12.13	40.73
13-Mar	16:40	5.3	7.2	91	86.4	14.8	13.72	29.63
14-Mar	8:40	6.7	3.5	92	92.6	14.8	16.27	42.15

Table1: Data collected from the Storm Peak Laboratory for snow density observations at station

Date	Time	Temp (F)	Avg. Temp (F)	RH (%)	Avg. RH (%)	Wind Speed (mph)	Avg. Wind Speed (mph)	Snow Density (kg/m3)
13-Mar	9:15	4.5		89		10.8		141.08
13-Mar	12:15	10	7.45	83	86.5	11.9	11.55	40.44
13-Mar	4:25	6.2	8.14	89	84.8	13.4	13.14	52.47

Table 2: Data collected from the Storm Peak Laboratory for snow density observations at station 2

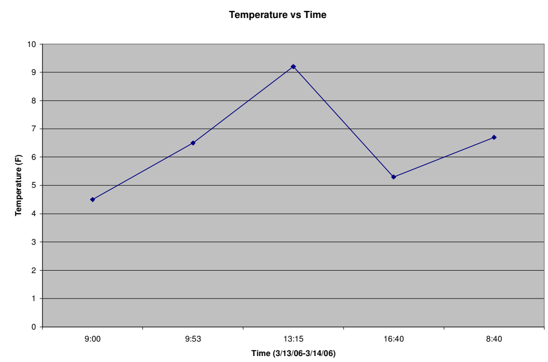
temperature between density measurements. The same was the case for relative humidity and wind speed. The data collected at station 2 is given in Table 2. There are fewer data points for station 2 partially because wind was more of a factor in creating drifting snow for this station. As opposed to data from station 1, station 2 only consists of data from 13 March.

Observations from the Desert Research Institute snow video spectrometer revealed that the snow event on 13 March 2006 was characteristic of dendritic aggregations which are very common in the Rocky Mountains [Tripoli 2006]. The ice crystals viewed included ordinary dendritic crystals, fernlike crystals and plates with dendrite extensions.

V. Discussion

An interesting an unforeseen trend found at station 1 and station 2 revealed that the snow density was generally greater at colder temperatures. However it must be admitted that an explicit correlation can't be determined here because there are few data points to make an assertion on. For this reason The relationship between snow density and temperature will only be referred to as a trend.

At station 1, the trend between snow density and temperature applies best to the first and third data points. A comparison of temperature with time and snow density with time is shown in Figure 4.



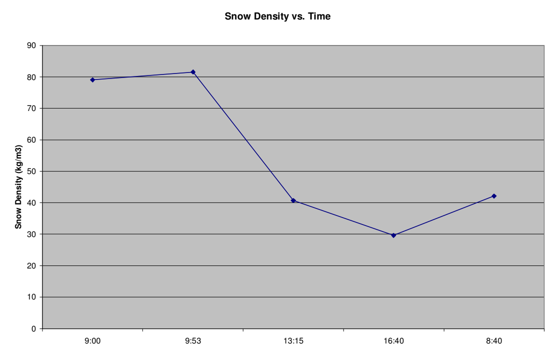
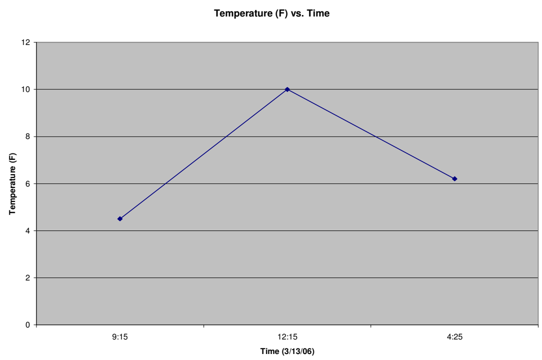


Figure 4: Temperature vs. Time (top) and Snow Density vs. Time (bottom) at station 1

The other data from Table 1 didn't seem to have any significant relationship. The wind speed and the relative humidity remained quite constant and this is the primary reason that no relationship was defined. Whether this relationship is one of causality or coincidence remains to be determined through further work involving snow events of longer duration.

Data from station 2 continued to support the trend that higher snow densities were associated with colder temperatures. Figure 5 provides a comparison of temperature with time and snow density with time. The trend is the most obvious for the first and second data points. Nevertheless, more data points are necessary to find a dominant correlation between the snow density and the air temperature.



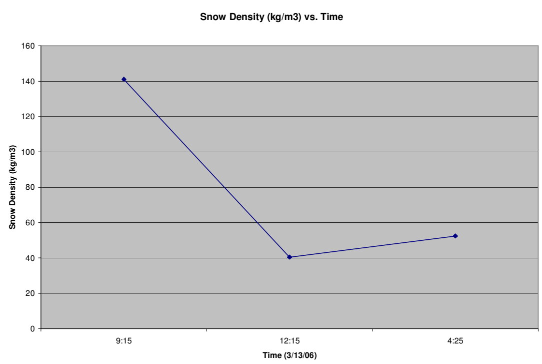


Figure 5: Temperature vs. Time (top) and Snow Density vs. Time (bottom) at station 2

The results from station 1 and station 2 which found the most significant correlation between air temperature and snow density, are contrary to that discovered by Doesken and Judson [2000] which found that snow density tends to decrease as temperature decreases. Doesken and Judson [2000] also mention that the size of the ice crystal contributes to the snow density. Smaller ice crystals tend to provide higher snow densities because they can be packed together tighter while larger crystals have gaps which don't allow the snow to pack together as well. With this stated the reason for the contradiction between the results from my research and Doesken and Judson's research [2000] may have been due to the size of the ice crystals. Smaller ice crystals in my research would suggest higher densities at cooler temperatures. However, the ice crystal size was neglected in my research at the Storm Peak Laboratory so this hypothesis will remain unproven.

The information observed regarding ice crystal structure gave no leads as to how the ice crystal structure affects the snow density. Research conducted over a longer period with the help of additional researchers would have allowed this part of the research to be improved. Taking the snow density measurements and monitoring the ice crystal structure became a difficult task for a single researcher.

VI. Conclusion

Research conducted at the Storm Peak Laboratory in Steamboat Springs, Colorado from 12 March 2006 to 14 March 2006 yielded a trend between snow density and air temperature. Prior to my research I expected snow density to increase as temperature increased. While this hypothesis was in agreement with a previous study completed by Wetzel et al. [2004], it opposed the results of the data conducted in my research. In my research, a trend between snow density and temperature found that snow density tended to increase as temperature decreased. Whether this relationship is one of causality or coincidence remains to be determined through further work involving snow events of longer duration. No specific relationship was found between snow density and relative humidity or wind speed. Also, the ice crystal structure was analyzed and had no apparent relationship to the snow density. It is suggested that future snow density studies should use a similar procedure in the collection of measurements but for a longer period of time. A study conducted over a period with highly varying temperatures may also present a better correlation between snow density and air temperature. Also, it is recommended that observations of ice crystal size be completed along with snow density measurements. Snow density is an important atmospheric variable in regards to avalanche and snowfall forecasting to name a few. For this reason further research on the topic is necessary.

Works Cited

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