NEW SNOW DENSITY ACROSS AN ELEVATIONAL GRADIENT IN THE PARK RANGE OF NORTHWESTERN COLORADO

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ABSTRACT

NEW SNOW DENSITY ACROSS AN ELEVATIONAL GRADIENT IN THE PARK RANGE OF NORTHWESTERN COLORADO

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A study was conducted to examine the spatial variability of new snow density across an elevational gradient on the windward side of a mountain. It was hypothesized that the density of new snowfall would decrease with an increase in elevation. Furthermore, it was hypothesized that select meteorological parameters could be utilized to explain variability and to create a predictive model of new snow density. A field campaign was conducted at the Storm Peak Laboratory in February, 2005 on Mt. Werner in northwestern Colorado. Snow sampling and in-situ meteorological measurements were conducted along an elevational gradient at five sites ranging in elevation from 2200 m to 3244 m above MSL. Snow was intermittently sampled during snow events from snow boards. New snow density was calculated from measurements of snow water equivalent and new snow depth. Meteorological measurements of air temperature, relative humidity, wind speed, and direction were continuously logged at five minute intervals throughout the month. In addition, supplemental observations of snow crystal habit, size, and degree of riming were noted at each sampling visitation.

The results indicated mean new snow density did not decrease with an increase in elevation. Observed mean new snow densities ranged from 83 kg m^{-3} to 101 kg m^{-3} with the lowest mean densities found at 2200 m and 2771 m. Individual densities measurements ranged from 26 kg m^{-3} to 188 kg m^{-3}. Considerable site specific intra-storm variability in density was observed. The results of correlation analysis indicated a direct relationship between new snow density and several explanatory meteorological variables, such as, approximated 700 millibar temperature (0.74), relative humidity (0.77), wind speed (0.55), lifted condensation level air temperature (0.59) and surface air temperature (0.55). Wind and degree of riming were concluded as being associated with higher densities values. Linear regression analysis utilizing the best single predictor variable (~700 millibar level air temperature) resulted in an $R^2 = 0.54$.

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INTRODUCTION

The density of new snowfall is an often overlooked, but important fundamental physical property of snow. It varies across both time and space, making it a considerable challenge to characterize and predict, especially in complex terrain. Snowfall density is not only important to the scientist, but to the winter motorist, snow plow operator, ski patroller, and winter sports enthusiast; to name a few. It represents the difference between effortlessly skiing "champagne" powder and experiencing the workout of a lifetime in the infamous "Sierra Cement or Cascade Concrete." To the winter motorist, it determines whether you easily back out of your driveway or get stuck in a foot of wet, dense snow. To the scientist, it serves as an essential input parameter in various modeling applications including: snowfall forecasting, snowpack evolution, snow transport, land surface modeling, avalanche control and forecasting (Wetzel et al. 2004; Roebber et al. 2003; Shulski and Seeley, 2004; Judson and Doesken, 2000; Holyroyd, 1999; Pomeroy et al. 1998).

Density is defined as mass per unit volume and is typically expressed as specific gravity. Whiteman (2000) terms specific gravity as the ratio of the density of any substance to the density of water. New snow density is the water content of snow divided by its depth and is expressed in grams per cubic centimeter (g cm^{-3}) or kilograms per cubic meter (kg m^{-3}). For example, the density of ice is equal to 917 kg m^{-3} while the density of water equates to 1000 kg m^{-3}. To put this in perspective, new snow densities found in the United States range anywhere from 10 kg m^{-3} to 350 kg m^{-3} (Judson and Doesken, 2000) with peak frequencies occurring between 60 kg m^{-3} and 90 kg m^{-3} (Doesken and Judson, 1996).

The density of new snow is characterized by a considerable degree of variability both in a spatial and temporal sense. Spatially, it varies across topographic position, elevation, aspect, and exposure (Judson and Doesken, 2000; Grant and Rhea, 1974). From a temporal perspective, it undergoes alteration from the moment it falls from the cloud. Upon reaching the ground, it is subject to even further modification by the prevailing surface conditions. On a broader temporal scale, snowfall density is influenced by various climatological features, such as seasonal temperature variability and the position of the jet stream (Shulski and Seeley, 2004). Higher density snow tends to fall during the fall and spring months while lower density snow is characteristic during mid-winter (Shulski and Seeley, 2004; Doesken and Judson, 1996).

Specifically, snowfall density is primarily a function of crystal habit and size; and is determined by the atmospheric conditions in-cloud where snow crystals are formed and by the sub-cloud conditions as the crystal falls to the surface (Roebber et al., 2003). Once on the ground, snow is affected by the prevailing surface conditions which further modify the initial density through compaction and metamorphic processes (Roebber et al., 2003).

This thesis research investigated the spatial and temporal variability of new snow density across elevation in order to gain a more comprehensive understanding of how density varies in complex, mountainous terrain. It was conducted in direct support of a cooperative project (funded by COMET- Cooperative Program for Operational Meteorology, Education, and Training) between Colorado State University, Desert Research Institute, and the National Weather Service Forecast

Office at Grand Junction, Colorado. The primary objective of the cooperative project is to improve snowfall QPF (quantitative precipitation forecasting) for the RAMS (Regional Atmospheric Modeling System) forecasting model for northwest Colorado. Overall, this thesis research served a dual purpose: 1) to understand the meteorological conditions that influence snowfall density across an elevation gradient; and 2) to verify RAMS forecast predictions of liquid-water equivalent and snow depth. Relationships between density and select meteorological variables were explored using linear regression and correlation analysis.

Storm Peak Laboratory (SPL), near Steamboat Springs, Colorado was chosen as the location for the field case study. SPL is situated in the Park Range at an elevation of 3210 m MSL on the west summit of Mt. Werner and is operated by the Desert Research Institute's Division of Atmospheric Sciences.

Background

Mt. Werner is located within the montane and subalpine life zones. The lower elevational extent of the mountain is forested primarily with lodgepole pine (*pinus contorta latifolia*) and quaking aspen (*populus tremuloides*). The higher elevations are forested by subalpine fir (*abies lasiocarpa*) and Engelmann spruce (*picea engelmannii*).

The general climate of the region can be described as a typical continental climate characterized by large diurnal and seasonal fluctuations of temperature (Whiteman, 2000). Winters are normally cold and summers are typically dry and moderate. Annual precipitation in the region varies based upon aspect, elevation, and terrain relief (Whiteman, 2000). In Steamboat Springs, the majority of annual precipitation falls in the form of snow, however; convective thunderstorms bring appreciable precipitation during the summer months. Winds aloft are predominantly out of the west due to the position of the jet stream over the Southern Rockies during the winter months (Whiteman, 2000).

Furthermore, three generalized winter storm tracks characterize the regional climatology. The *westerly track* is characterized by storm systems that are orographically lifted by the Wasatch Plateau and mountain ranges along the Continental Divide in Colorado (Cline, 1997). N*orthwesterly track* systems are influenced by the Uinta Mountains and ranges in north-central Colorado (i.e., Park Range) (Cline, 1997). S*outhwesterly track* systems are characterized as being orographically lifted by the San Juan Mountains of southwest Colorado (Cline, 1997).

The snow climate of the Park Range (central Rocky Mountains of Colorado) is considered continental and is characterized by cold temperatures and low-moderate snowfall (< 8 meters) (Mock and Birkeland, 2000, McClung and Schaerer, 1993). The Park Range has a north-south orientation and is generally perpendicular to the prevailing westerly winds (Borys and Wetzel, 1997). The topographic position of the range with respect to the prevailing winds increases its potential for production of enhanced precipitation by orographic lifting (McClung and Schaerer, 1993). Specifically, Mt. Werner sits approximately 1150 m above the Yampa Valley making it a significant obstacle for incoming airmasses. McClung and Schaerer (1993) noted that the orographic effects in mountainous terrain may account for 50% to 75% of winter precipitation. Snowfall data from Steamboat Springs and SPL demonstrate the degree of spatial variability within a short distance, presumably associated with the effects of orographic precipitation. This is illustrated by contrasting the snowfall records from the National Weather Service Coop station-Steamboat Springs (057936) and SPL. On the valley floor, Steamboat Springs receives an average annual total snowfall of approximately 420 cm, whereas, SPL averages from ~ 400 – 900 cm annually with a maximum recorded annual accumulation of 1138 cm (Borys and Wetzel, 1997).

In conclusion, knowledge of spatial and temporal characteristics of snowfall density (and its derivatives- snow water equivalent and snow depth) across elevation could assist with further advances of various operational models. Additional understanding of the spatial and temporal variability of snowfall density, snow water equivalency, and snow depth during storm events would likely provide helpful insights to the operational meteorologist predicting snowfall QPF and to the snow hydrologist (Mizukami, Decker, and Julander, 2003)

RESEARCH HYPOTHESES

The objective of this research was to observe the spatial and temporal variations of new snow density on the windward side of a mountain. The research attempted to explain variation by testing whether significant correlations existed between new snow density and several parameters including: a) ~700 millibar level air temperature, wind speed, and relative humidity; b) lifted condensation level air temperature; c) site-specific surface air temperatures; d) snow crystal habit/size, and degree of riming. Precisely, the research tested the following hypotheses:

1. Mean new snow density decreases with increase in elevation;
2. New snow density is related to an approximate 700 millibar level air temperature, wind speed, and relative humidity;
3. New snow density is related to lifted condensation level temperatures (LCL-T);
4. New snow density is not related to site-specific surface air temperature; and
5. New snow density is related to snow crystal habit, size, and degree of riming.

The first hypothesis is supported in the literature by findings presented by Grant and Rhea (1974) and Wetzel et al. (2004). Hypotheses #2 - #5 are based upon the documented relationship between temperature, snow crystal formation, and new snow density (aufm Kampe et al., 1951; Bossolasco, 1954; Gold and Power, 1954; Diamond and Lowry, 1954; Power et al., 1964; Grant and Rhea, 1974; McGurk et al., 1988, Judson and Doesken, 2000). Moreover, Hypotheses #2 - #4 are based upon previous attempts to correlate and predict new snow density using various meteorological parameters (Diamond and Lowry, 1954; Grant and Rhea, 1974; McGurk et al., 1988; Judson and Doesken, 2000; and Wetzel et al. 2004).

LITERATURE REVIEW

This review of the scientific literature entails an examination of related research on the topic of new snow density and the meteorological and topographical factors influencing its development. First, this review will present a brief synopsis of the history of snow science (late 1800's-1950) in order to lay a contextual foundation for the current research. Second, this review will examine several studies on snow crystal formation and its relationship to meteorological conditions that will assist in the understanding new snow density. Third, current research as it relates to this thesis research will be examined.

Snow Studies – A Brief History

The first systematic observations of the measurement of snow in the United States were conducted by an observer network overseen by the Smithsonian Institution in the mid 1800's (Henry, 1917). These early measurements of snow were primarily directed towards fine-tuning a method by which to collect falling snow and the calculation of its water equivalency as evidenced in the *Annual Report of the Chief Signal Officer of the Army* (Abbe, 1887). In the report, Cleveland Abbe (1887) outlined a methodology for measuring new snow depth and the determination of its water equivalency. He stated that in the absence of melting snow, the following estimation should be employed: ten inches of snow equals one inch of water. One hundred twenty years later this simple ratio is still commonly used, even though it was noted early on as having the potential for significant error. Abbe (1887) relates this error potential because of "wide variability of this ratio for different kinds of snow." By the phrase, "different kinds of snow" it can be inferred that Abbe was talking about the spatial variability of freshly fallen snow, thus marking a starting point for this thesis subject matter.

By the early 1900's, Dr. James Church (1914), a professor of classics at the University of Nevada-Reno, completed some of the most comprehensive snow related studies to date in the Sierra Nevada Range. Dr. Church made a substantial impact in the field of snow science and is considered the pioneer of snow surveying and forest-snow interactions (Stafford, 1959; Kattelmann et al, 1996). Some of his earliest work involved the establishment of the Mt. Rose Observatory (10,800 feet) located between Reno, Nevada and Lake Tahoe, California. Equipped with thermometers provided by the U.S. Weather Bureau, Church climbed Mt. Rose once a month to record temperature readings (Stafford, 1959). Soon after the observatory was established, Church (1914) invented the Mt. Rose sampler, a snow sampling instrument that efficiently calculates snow water equivalency for the purpose of snowmelt runoff predictions. A modified version of this device is still used operationally to this day.

Further research during this period focused on gaining a practical understanding of snow as it relates to avalanches and snow hydrology (Colbeck, 1987). Advances in other scientific fields, such as physics, also began to broaden the scope of research beyond the observational stage. Specifically, investigations included measurement of albedo, radiative absorption, heat transfer and evaporation, energy exchange, and the evolution of the snowpack (Colbeck, 1987).

The next period in the advancement of snow research occurred during the 1930's and 40's with the establishment of government funded laboratories, (Davos, Switzerland and Sapporo, Japan) as well as the formation of organizations and annual conferences, such as, the International Glaciological Society, the International Commission on Snow and Ice, and the Western Interstate Snow Survey Conference, the predecessor to the Western Snow Conference (Stafford, 1959; Colbeck, 1987). These organizations provided an arena for ideas to be exchanged and research to be published resulting in rapid advancements in snow science (Colbeck, 1987).

In the 1940's, the U.S. Army Corp of Engineers and the U.S. Weather Bureau began the Cooperative Snow Investigations in order to address runoff and flood forecasting problems in the mountain regions of the western United States (Kattelman et al, 1996). Out of this cooperative study, three snow laboratories were established: Central Sierra Snow Laboratory (near Donner Pass, California), the Upper Columbia Laboratory (Glacier National Park, Montana), and the Willamette Basin Snow Laboratory (western Oregon) (U.S. Army Corp of Engineers, EM 1110-2-1406). These laboratories conducted some of the most extensive research to date on the spatial variability of the snowpack within a particular catchment.

Early Studies of New Snow Density and Related Topics

Prior to the 1950's, early studies related to new snow density were primarily observational in nature. These studies focused on improving methods to better understand why the density of freshly fallen snow varies both spatially and temporally. During this period, the theory that the density of freshly fallen snow was dependent upon air temperature gained attention. This is evidenced in field studies conducted in Belgium, Germany, Sweden, Switzerland, and United States (Henry, 1917). These studies primarily highlighted density-temperature relationships as well as density-snow crystal size relationships (Henry, 1917).

However, the 1950's marked a point when efforts were undertaken to gain a more comprehensive understanding of the spatial variability of new snow density and its relationship to snow crystal size and shape, and the meteorological conditions in which snow crystals are formed (e.g. Diamond and Lowry, 1954; Gold and Power, 1954; Bossolasco, 1954). The understanding of snow crystal formation is of great importance to the study of snowfall density because the shape, size, and degree of riming of the crystal provide "evidence" of the conditions present in the cloud upon formation and act as a tool to help interpret initial snowfall density.

Significant laboratory studies on snow crystal formation were conducted by Nakaya (1951) and aufm Kampe et al., (1951) with the purpose of categorizing snow crystal shapes and explaining the effect of temperature on the shape of the crystal. Nakaya examined crystal formation at varying degrees of supersaturation and air temperature (Gold and Power, 1954). Laboratory experiments by Nakaya revealed that certain types of snow crystals formed under specific temperatures: needles and irregular crystals formed at temperatures of -5º to -8ºC; hexagonal plates and columns near -9ºC; dendrites at -14º to -17ºC; and hexagonal plate and columns below -20ºC (Gold and Power, 1954).

Similarly, aufm Kampe et al. (1951) grew ice crystals in a cold chamber while controlling humidity and air temperatures ranging from freezing to -40º C. Results displayed the degree to which certain crystal types could prevail at various temperatures. In particular, they identified that higher temperatures (0º to -10ºC) were dominated by various types of plates, columns, and needles while lower temperatures (-10º to -40ºC) were characterized by plates, dendrites, and irregular crystals. Also, it was noted that with decreasing temperature, the size of the crystal decreased and the shapes were more irregular (aufm Kampe et al. 1951). The authors acknowledged the limitation of their study noting that simulated laboratory conditions are not equal to those in the free atmosphere where an ice crystal travels through a cloud with varying temperatures and relative humidity (aufm Kampe, et al. 1951). Nonetheless, the laboratory research completed by Nakaya (1951) and aufm Kampe et al. (1951) greatly contributed to the understanding of the formation of ice crystals and its dependence upon temperature and degree of supersaturation.

Alternatively, Gold and Power (1954) addressed this call for further experimentation in the natural environment by taking a field based approach in their research on the dependence of snow crystal formation upon the prevailing meteorological conditions. Their research marked a starting point in the effort to verify laboratory experiments on snow crystal formation from the perspective of taking into account the influence of meteorological conditions. During the winter of 1951-52 at McGill University in Montreal, Canada, snow crystals were captured from numerous snow events during a 90 day period with the objective of trying to correlate snow crystals observed on the ground with an estimated cloud base temperature from which the crystal originated. Gold and Power (1954) made the following snow crystal observations related to temperature: needles and irregular crystals from 0º and

-11º C; dendrites from -7º to -18ºC; columns from -8º to -12ºC; and columns below -22ºC. Results yielded a moderate degree of similarity related to formation of specific crystal types by temperature in concert with the laboratory experiments previously cited. Furthermore, Gold and Power (1954) concluded that meteorologists, with some degree of certainty, would be able to estimate cloud base temperatures by identifying crystal types in the field. However, it was noted that certain crystal types, such as plates and columns, existed at various temperature ranges and may not be reliable in the determination of the temperature of the cloud from which they formed (Gold and Power, 1954).

Bossolasco (1954) analyzed 53 cases of fresh snowfall data collected at Weissfluhjoch (2540-2660m) near Davos, Switzerland. The results indicated that the density of freshly fallen snow reached a minimum density at an air temperature near -11ºC and its maximum from -20º to -25ºC and near freezing, however, considerable scatter in density was observed at -5º to -7ºC. In general, new snow density seemed to have a parabolic dependency on surface air temperatures (Bossolasco, 1954). Lastly, Bossolasco (1954) postulated that since the observatory (Weissenfluhjoch) was positioned near the top of the mountain and the free atmosphere, the air temperature values utilized in the correlation were representative of the altitude in which the snow was formed and that there was a direct relationship between mean air temperature and new snow density.

Likewise, Diamond and Lowry (1954) conducted measurements of new snow density at the Central Sierra Snow Laboratory during the winter of 1951-52. They hypothesized that the density of new snow is likely a function of snow crystal type and size; however, they made no attempts to test this assumption. Instead, they tried to establish a relationship between new snow density and upper air temperatures. This was achieved by trying to correlate density values measured during storms with air temperatures from surface and radiosondes from Oakland, California. Specifically, Diamond and Lowry (1954) attempted to correlate 500-mb and 700-mb level temperatures (taken 240 km away) as well as surface temperatures with density measurements taken on ground. Results illustrated that 700-mb level temperatures correlated (0.639) at a 99% confidence interval and surface temperatures correlated at 0.503. No relationship was found to exist between new snow density and 500-mb level air temperature. Furthermore, they generally found a somewhat linear relationship between new snow density and 700-mb level/surface temperatures. Despite the apparent lack of detail and discussion in their journal contribution, the study prompted further investigation testing the assumption that new snow density is a function of the predominant snow crystal type falling during a storm.

Power et al. (1964) set out to test this assumption by collecting snowfall data over the course of the winters of 1960-61 and 1961-62 in Montreal, Canada. In addition to computation of new snow density; snow crystal samples were continuously captured by a snow crystal recorder throughout the course of each snow event. The snow crystal recorder functioned by capturing snow crystals on continuously advancing film. Prior to being exposed to snowfall, the film passed through a Formvar solution which produced a replicate of the general shape of the snow crystal. Results agreed with previous studies on crystal-temperature relationships displaying that certain basic crystal types were found to exist within specific density ranges. In general, dendrites were associated with the lowest density values, while needles, plates, spatial dendrites, and irregular crystals respectively were found as density increased. In addition, they observed the pronounced effect of riming upon the density of snow crystals, whereby, it was speculated that rimed crystals increased snowfall density by 30% to 100%.

In summary, it should be noted that a natural progression in the study of new snow density comes into fruition during this period. First, theories of snow crystal formation and their associated temperature relationships were established in a laboratory environment. Certain basic snow crystal types were identified as forming at particular temperature ranges. Second, these hypotheses were verified in the field. Field studies highlighted the need for further experimentation related to the conditions in the free atmosphere in which snow crystals are formed. Third, scientists tried to correlate new snow density measurements on the ground with air temperatures at the surface and in the upper atmosphere. Attempts were made to try to predict new snow density by correlating with parameters, such as, upper air temperatures and surface temperatures with mixed results. During this period, an integration of collective knowledge advanced the understanding of the properties of freshly fallen snow.

Current Research (1970-present)

The current state of research related to new snow density is one that has focused on several prevailing themes: spatial-temporal relationships, elevational, and meteorological controls affecting new snow density (e.g., Grant and Rhea, 1974; Meister, 1985; McGurk et al. 1988; Judson and Doesken, 2000); and improving snowfall forecasting models (e.g., Roebber et al. 2003; Wetzel et al. 2004). What becomes evident in the review of the current literature and pertinent to this thesis research is the divergence in results associated with elevational and meteorological relationships to new snow density and the need for a more comprehensive approach when looking at factors that influence new snow density.

To begin, one of the first to specifically address elevational controls on new snow density was Grant and Rhea (1974). Simply stated, they argued that new snow density decreased with an increase in elevation. Similarly, Wetzel et al. (2004) found a comparable pattern exemplified by greater densities at lower elevations. Although both of these studies were significantly different in method and focus, they found similar results related to the spatial variability of new snow density across elevation.

Specifically, Grant and Rhea (1974) investigated new snow density over eleven winters at three adjacent mountain passes in central Colorado. Data was collected at 64 closely spaced sites ranging in elevation from 2370 m to 3444 m. Samples of snow were taken from snow boards placed in large canopy gaps at approximately 0900 daily. Density was calculated using the standard technique by dividing the snow-water equivalent by the new snow depth. Results related to elevational controls showed that greater densities were found at lower elevations. Grant and Rhea hypothesized that greater density at lower elevations was associated with greater frequency and degree of riming as ice crystals traveled through lower and warmer portions of clouds. However, no actual experimentation was performed to confirm this.

Similarly, Wetzel et al. (2004) observed that greater densities were generally found at lower elevations when completing a case study as part of research to improve a snowfall forecasting model (RAMS) for the mountains of Colorado. As part of the case study, snow was sampled at multiple sites across an elevational gradient on Mt. Werner in Steamboat Springs, Colorado. Samples were taken from five locations along an east-west transect ranging in elevation from 2030m to 3170m. Special consideration in the sampling procedure was given in order to address the potential for obtaining a non-representative density sample due to further densification by metamorphic processes and wind. This was accomplished by sampling from protected sites multiple times throughout each storm event rather than at a fixed time. Although Wetzel was not expressly studying the elevation – density relationship, it was identified as an important aspect in trying to understand topographical influences on snowfall patterns in complex mountainous terrain. Similar to Grant and Rhea, Wetzel hypothesized that variation in density with elevation is likely related to the complex mixed-phase processes in orographic systems.

Studying the spatial variability of new snow density in the central Rocky Mountains, Judson and Doesken (2000) examined new snow density distributions over four winters from six sites in Colorado and Wyoming. Unlike smaller scale studies of Grant and Rhea and Wetzel et al., these specific site locations spanned over a considerable latitudinal extent and ranged in elevation from 2120m to 3400m. In contrast to previous studies, their results showed that the lowest mean density was found to exist at the lowest elevation site in their study; Steamboat Springs, Colorado

(2120m). Moreover, the greatest mean new snow density was found at a much higher elevation; Wolf Creek Pass, Colorado (3244m). These results contrasted with previous findings on elevation and illustrated the importance of spatial considerations in the interpretation and discussion of the variability of new snow density. Addressing the spatial component, Judson and Doesken (2000) analyzed interstation density relationships concluding that correlation coefficients decreased as distance between stations increased. Additional aspects noted to describe the observed variability of new snow density are as follows: aspect and exposure, timing and accuracy of measurements, degree of riming, and orography (Judson and Doesken, 2000). The apparent differences with regard to the relationship of elevation and new snow density do not necessarily present a problem; instead they highlight the importance of considering scale in the analysis and discussion of new snow density. Moreover, observed density differences over a large region should not be analyzed in the same manner as small scale studies because of differing influence related to synoptic and mesoscale (storm system origin) conditions, as well as microscale influences (complex topography).

Grant and Rhea (1974) and Judson and Doesken (2000) utilized similar sampling methodologies when collecting snow density data. Both sampled once daily in the early morning hours, thus raising the question of whether a single synchronous daily snow sample is an accurate measure of new snow density. Knowing the potential effects of metamorphic processes, the onset time of precipitation in relation to the sampling time is crucial. For example, if a sample was collected at 0900 hours and the onset of precipitation occurred at 1200 hours, twenty-one hours would elapse before the next snow sampling. During this period, the potential for obtaining a skewed sample may be accentuated by increasing air temperatures (snowpack settling) and further densification by the redistribution of snow by wind. Therefore, a more accurate representation of initial snowfall density may result from non time-dependent sampling methodology that is based upon the onset time of the precipitation.

Another key area of examination related to new snow density is the relationship of meteorological controls and density. Numerous attempts have been made to correlate initial density of snow with meteorological parameters, such as, surface and upper air temperatures, wind speed, and relative humidity. Most of the research has focused on the temperature-density relationship, with mixed results. For example, scatter plots displaying density as a function of various reference temperatures illustrate two prevailing trends: 1) a general parabolic relationship (Bossolasco, 1954; Grant and Rhea, 1974) with an increase in density at the high and low end tails; and 2) a non linear decrease in density with a decrease in temperature (Diamond and Lowry, 1954; McGurk et al. 1988; Judson and Doesken, 2000; Wetzel et al. 2004). Observed differences related to the above trends may be associated with the referenced temperature selected. Most studies have focused on upper air and surface temperatures (Diamond and Lowry, 1954; Bossolasco, 1954; Grant and Rhea, 1974; Meister, 1985; McGurk et al. 1988) while several utilized an approximate 700 millibar temperature (Judson and Doesken, 2000; Wetzel et al. 2004).

Addressing the utility of using surface observations to predict new snow density, McGurk et al. (1988) carried out snow sampling over a two year period at the

Central Sierra Snow Laboratory near Soda Springs, California. They sampled snow twice daily at 0800 and 1600 hours five days a week as well as measured air temperature, wind speed, and relative humidity. Results illustrated that surface temperatures were not a reliable predictor, exemplified in the wide range of densities found to exist at a given temperature. Surface temperature was found to be insignificant in regression analysis as evidenced in a coefficient of determination of $R^2 = 0.27$. Wind speed and humidity were also found to be insignificant. It was hypothesized that 700 millibar temperatures might serve as a better predictor of density because they are more representative of the temperature in which snow crystals are formed. However, it should be noted that a major shortcoming when utilizing upper air soundings is that radiosondes are launched twice daily, often considerable distances from the particular area of study.

Likewise, Meister (1985) found weak relationships to exist between surface air temperature and new snow density. Meister explored density relationships to wind speed and surface air temperature at seven monitoring stations throughout the Swiss Alps. Scatter plots of density versus air temperature displayed a nonlinear relationship. However, when reviewing the scatter plots by both Meister and McGurk, a general trend in the data is clearly present, displaying a general increase in density with increased temperature. This pattern is in contrast to the more or less parabolic curve present in the data of Bossolasco (1954) and Grant and Rhea (1974) and may be related the elevation of the reference temperature utilized.

Judson and Doesken (2000) and Wetzel et al (2004) utilized a different approach in trying to correlate density with temperature, using air temperature measurements from Storm Peak Laboratory (3221m) as an approximate 700 millibar level reference point. Because of its mountaintop location, Storm Peak Laboratory was considered to be representative of the in-cloud temperature in which snow crystals are formed. Both authors were able to explain 52% of the variation in new snow density when using temperatures from Storm Peak Laboratory as a reference temperature. These results are similar to early studies by Diamond and Lowry (1954) who attempted to correlate density with 700 millibar temperatures obtained from radiosondes (R^2=0.64).

Additional meteorological variables, such as wind speed and relative humidity have been shown to possess weak correlation to new snow density (McGurk et al. 1988). However, the influence of wind on the surface conditions of the snowpack cannot be understated. Wind exceeding a critical threshold serves to transport snow by rolling, saltation, and turbulent transport (McClung and Schaerer, 1993), thus, potentially leading to further densification of the snow at the surface.

In conclusion, various techniques and different approaches have been employed in attempt to explain both elevational and meteorological controls with new snow density. The results are somewhat diverse with differences linked to a range of variables including: sampling technique, accuracy of measurement, geographic location of the study, and data analysis procedures. What can be determined is the need for a more comprehensive approach integrating various substantiated methodologies

RESEARCH PLAN

The goal of this research was to address several gaps or unanswered questions identified in the literature as it pertains to new snow density. To this end, an integration of various field methods and analysis was utilized. This approach included: 1) consideration of the accurate measurement and assessment of meteorological conditions on the surface and in the upper atmosphere; 2) obtaining an accurate measurement of snow depth and snow water equivalent, bearing in mind the site location, timing and sampling interval in order to depict initial density before metamorphic processes and wind alter the snow; 3) categorization of crystal habit, crystal size, and degree of riming of the snow sampled in order to provide “clues” as to the conditions in the free atmosphere where the snow crystals were formed; 4) noting the timing of the onset and conclusion of the precipitation as well as observations of the surface condition of the snow (i.e., wind scoured, snow settling from trees); 5) careful analysis of the data; taking into account not only actual results, but the quality of the data being analyzed; and 6) finding practical methods which can be utilized in an operational setting to depict snowfall more accurately as well as providing valuable insights into the spatial distribution of new snow density and its derivatives (snow water equivalent and snow depth) for snowpack evolution models.

METHODS

In order to examine the spatial variability of new snow density across an elevational gradient, a mountain study area needed to be chosen that had easy accessibility and sampling sites with similar topographic characteristics. Moreover, an efficient sampling design and appropriate instrumentation was needed to derive new snow density data, as well as measurement of select meteorological parameters as a means to interpret the density dataset. Once the spatial data were collected, descriptive statistics were completed to quantify the snow sampling and meteorological data for each individual storm event as well as the entire month of experimentation. Finally, correlation and regression analysis were utilized as a tool to examine the relationship between density and the meteorological variables as well as to create a predictive model.

Study Area

The study was conducted during the month of February-2005 on the western slope (windward side) of Mt. Werner (2103-3221 meters) which is located in the 70 km long; north-south oriented Park Range of northwestern Colorado (Borys and Wetzel, 1997). Mt. Werner (Steamboat Ski Area) is located in Steamboat Springs, Colorado and is situated adjacent to the Yampa Valley. The particular study area was chosen for several reasons: first, past related research (Wetzel et al. 2004) was conducted on the mountain related to the understanding the properties of snowfall across elevation. Second, this location was selected to conduct a field case study for a COMET (Cooperative Program for Operational Meteorology, Education, and Training) project entitled, *Operational Use and Development of a High-Resolution Mesoscale Model in the Colorado Mountain Region for Wintertime and Other Forecast Applications*, which was the basis for this thesis research.

Precisely, this COMET project is an on-going collaborative effort between Colorado State University (CSU), Desert Research Institute (DRI), and the National Weather Service (NWS) Weather Forecast Office in Grand Junction, Colorado (GJT). The overall objective of the project is to improve forecast snowfall QPF for RAMS, a real-time mesoscale forecasting model operated by Colorado State University. The goal of the field case study was to get a more comprehensive understanding of the meteorological conditions that influence snowfall density and verification of RAMS predictions of new snow depth and accumulated precipitation for the area. This area is of particular interest because it is situated beyond the coverage extent of the WSR-88D Doppler radar in Grand Junction, Colorado, making snowfall QPF challenging for forecasters. Therefore, improvements to the RAMS model could assist forecasters in more accurate snowfall QPF for this region.

For this case study, RAMS forecasts were made at CSU twice daily utilizing a high-resolution 3 km nested grid (http://rams.atmos.colostate.edu/realtime/00z/crossmap.g3.html), which encompassed Mt. Werner. Forecasts of accumulated snow depth (cm) and accumulated precipitation (mm-liquid) were then verified by field measurements on the mountain, with the intent of getting a more comprehensive understanding of why RAMS over or under-predicts, and under what atmospheric conditions this occurs. The RAMS model grid point for the area is the ridge-top of Mt. Werner which was also the base of operations, Storm Peak Laboratory, for the case study and this thesis research.

Finally, the study area location was chosen because the field intensive nature of the case study would require extensive travel around the mountain during storm events. Logistically, this would not have been possible without use of the laboratory, ski lifts, and relative ease of access to sampling sites. Efficient access to the sites was critical in order to sample snow as closely as possible in a temporal sense. SPL provided a base from which to begin sampling runs early in the morning and after the ski area closed via snowmobile and skis.

Storm Peak Laboratory

Storm Peak Laboratory (40.45˚N, 106.74˚W) (http://stormpeak.dri.edu/) is located on the summit of Mt. Werner (3221 meters) and is operated by the Desert Research Institute's Division of Atmospheric Sciences. The facility is located within the Steamboat Ski Area and has over a 20 year history of basic research on cloud physics, high alpine radiation climatology, and cloud microphysics (Borys and Wetzel, 1997). The lab is instrumented with both atmospheric and meteorological instrumentation and collects five minute data of the following meteorological parameters on a 10 meter tower: barometric pressure, air temperature, relative humidity, wind speed and direction, solar radiation, precipitation, and aerosols. Data collected from these instruments are logged by a Campbell CR10X datalogger (Campbell Scientific Inc, Logan, UT) and are transferred via a local area network to the Western Regional Climate Center (WRCC) Reno, Nevada for display and archive.

Data can be accessed through the WRCC at:

http://www.wrcc.dri.edu/weather/strm.html.

In addition to meteorological instrumentation, SPL is equipped with a specially designed camera for ice crystal photography which was of interest in the study. This system allows for a time lapse history of snowfall at the lab and acts as a ground-truthing mechanism for the qualitative categorization of snow crystal habit during snow sampling. Lastly, the laboratory is equipped with high speed internet access, as well as bunk rooms and kitchen facilities which allowed for 30 days of continuous habitation for this study.

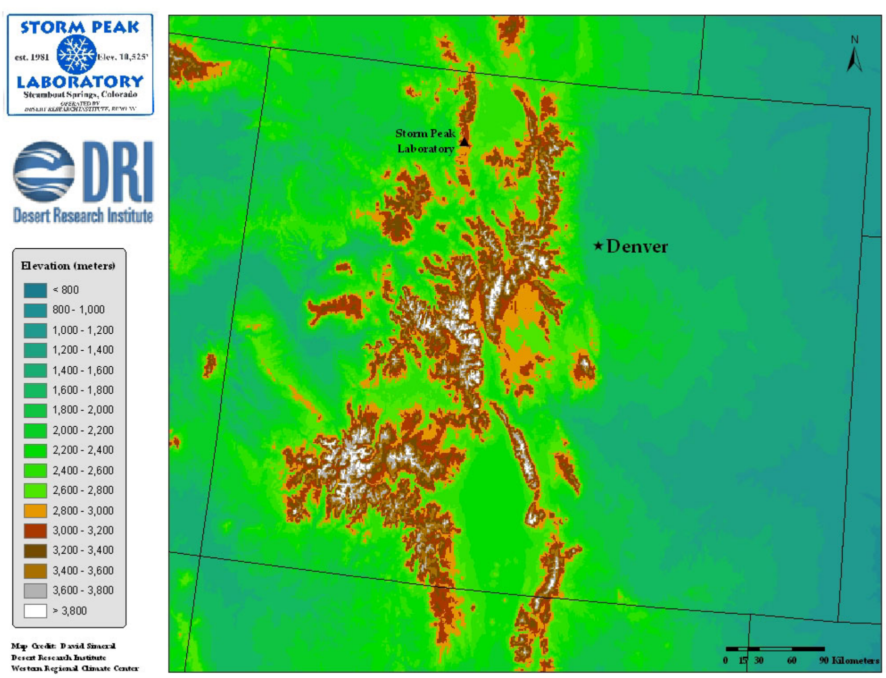


Figure 1 - Geographic location of Storm Peak Laboratory.

Figure 2 - Storm Peak Laboratory – February 2005.

Snow Sampling Site Locations

Snow sampling and meteorological data were collected at five sites along an elevational gradient on the western aspect of Mt. Werner. Site locations were east-west in orientation and started near the base of the mountain and continued to the summit. The site selection process involved finding evenly spaced, protected locations that were easily accessible on skis and/or by snowmobile. Further attention was paid to locating sites that possessed the following characteristics: a relatively flat surface, comparable canopy gap size, open exposure to receive incoming snowfall, and co-located near the ski area mesonet sites (discussed later in this section). The premise was to find locations where the canopy would act as a natural shield against wind transportation of snow via saltation (Borys and Wetzel, 2004). The following table summarizes the site characteristics for each site:

Table 1 – Site location metadata.

Site Name	Elevation (m)	Position	Vegetation
Mt. Werner Summit (MTW)	3244	W 40˚ 27' 23.0" N 106˚ 44' 24.3"	Engelmann spruce
Patrol Headquarters (PHQ)	3176	W 40º 26' 59.1" N 106º 44' 57.3"	Engelmann spruce Subalpine Fir
Pumphouse BAR-UE (BAR)	2771	W 40˚ 27' 36.3" N 106˚ 45' 40.0"	Mixed conifers Aspen
Vagabond Saddle (VGB)	2557	W 40˚ 27' 44.0" N 106˚ 46' 29.0"	Aspen
Christie (CHR)	2200	W 40˚ 27' 35.8" N 106˚ 47' 39.9"	Aspen

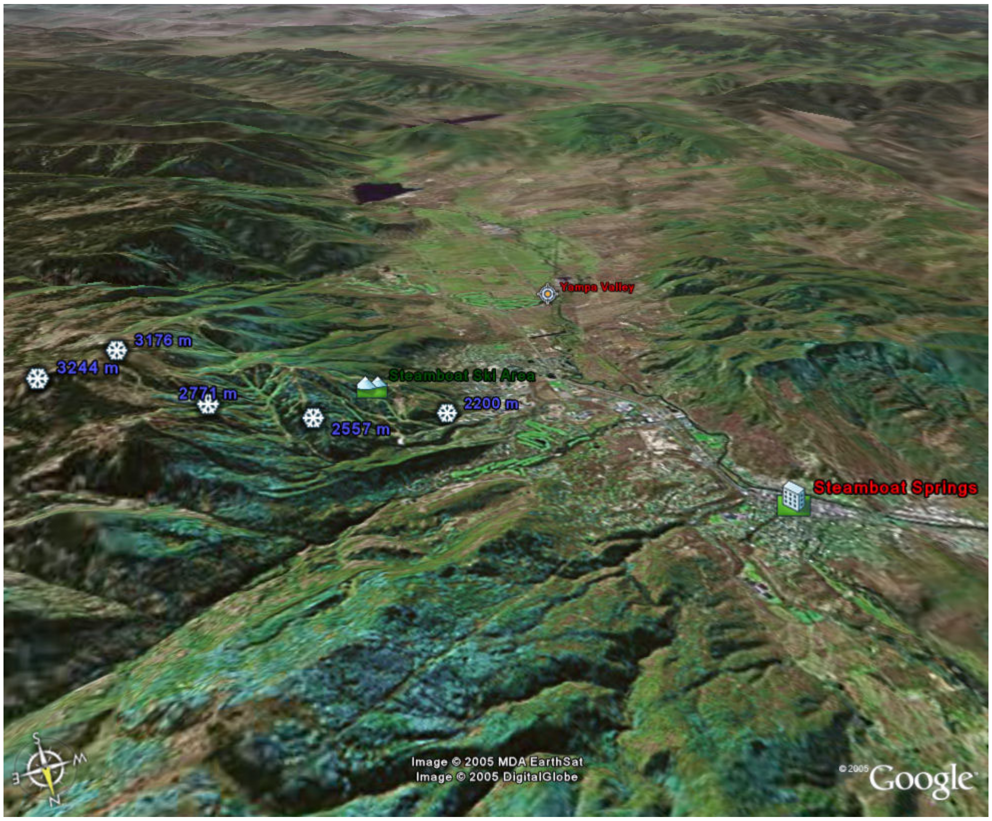
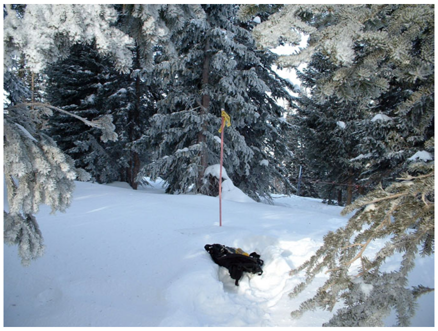


Figure 3 – 3-D map of Mt. Werner and study site locations.

MTW – 3244 meters



PHQ – 3176 meters

BAR – 2771 meters

VGB – 2557 meters

CHR – 2200 meters

Figure 4 - Photographs of snow sampling sites.

Snow Sampling Equipment and Meteorological Instrumentation

Site locations were outfitted with a 60 cm × 60 cm white snowboard, and a temperature-relative humidity sensor. Each snowboard was attached to a bamboo pole so it could be easily identified when snow covered. The temperature-relative humidity sensors were housed in a solar radiation shield and attached to a bamboo pole 2 meters above the snow surface.

Specifically, HOBO Pro Data Logger Series (Onset Computer Corporation, Bourne, MA) temperature/relative humidity sensors were utilized. The temperature sensor has a range of -30º to 50º C and accuracy of +/- 0.2 at 21º C. The relative humidity sensor has a range of 0 to 100% with an accuracy of +/- 3% or +/- 4% in a condensing environment. Each unit has a programmable start time and sampling rate. Data were collected from the HOBO sensors by a HOBO shuttle device which stores data, synchronizes the data logger clock with the PC clock, and re-launches the sensor according to its original specifications.

The HOBO sensors logged five minute point measurements in order to provide a site specific record of the surface conditions present during snowfall deposition. Additionally, comprehensive meteorological measurements were concurrently logged at SPL and throughout the ski area via a network of surface observation sites maintained by the Steamboat Ski Area. Hourly data (wind speed/direction, air temperature, relative humidity) from the mesonet were transferred electronically on a daily basis to SPL.

Snow Sampling Technique

A circuit of the sampling sites was completed in approximately a two-hour time frame. Sampling runs generally took place twice daily during storm events, except when the onset time (i.e., late afternoon or evening) of the precipitation did not allow multiple visitations. Otherwise, sampling was completed once in the early morning before the ski area opened and once in the late afternoon. The goal was to allow enough time to elapse in order to complete a sampling run, as well as to allow an appreciable amount of snow to accumulate. However, it was important not to allow too much time to elapse before metamorphic processes could alter the initial density significantly. LaChapelle (1961) noted that densification of freshly fallen snow begins at the time of deposition, and that density measurements made within 24 hours of deposition often reflects a density value that is higher than its initial value. Pomeroy et al. (1998) noted that within a cold prairie snowpack that initial density may increase on a magnitude of 8-13 kg m^{-3} within a storm event (12 hours).

In the field, measurements of new snow depth (cm) and snow water equivalently (mm) were taken in order to calculate a new snow density value (kg m^{-3}). New snow density represents a ratio of snow water equivalency to new snow depth (McClung and Schaerer, 1993). Depth and SWE measurements were completed with a Snowmetrics T1 sampling tube and hanging spring scale. The sampling tube was used to obtain new snow depth measurements to the nearest 0.1 cm at three locations on the snow board. Three samples were taken in order get a representative sample and to address the possible effect of snow transport by saltation onto the board. The snow sample was then weighed with a calibrated scale that converts weight into a water equivalency and the board was wiped clean. From the measurements obtained, a simple calculation (SWE/NSD × 1000) was used to derive a new snow density value in kg m^{-3}. The SWE and new snow density equations are as follows:

$$\text{Water Equivalent of New Snow} = [\text{New Snow Density (kg m}^{-3}) \times \text{New Snow Height (cm)}/100$$

$$\text{New Snow Density (kg m}^{-3}) = [\text{Weight New Snow (gm) / Sample Volume (cm}^{3})] \times 1{,}000$$

(McClung and Schaerer, 1993).

It should be noted that snow sampling involved a degree of uncertainty related to the measurement process and natural variation. To this end, measurement error can result from the difficulty in reading the depth (to the tenth) on the sampling tube while is it snowing and from compaction of snow in the tube. Furthermore, the scale utilized to determine SWE requires regular calibration and special attention to eliminate any snow/ice build-up on the spring. The other area of uncertainty, natural variation, is harder to pin down. Variations in depth on a sampling board may be related to the natural spatial distribution of snowfall or from redistribution of snow by saltation, or sloughing from trees. While saltation and sloughing are part of the natural processes, they make obtaining a representative sample of new snow density more difficult. In order to address this uncertainty, careful inspection and notation of the surface conditions was necessary as well as consistent calibration and cleaning of the scale and sampling tube.

Lastly, snow crystal samples from the surface were visually examined at each site visitation. The snow crystals sampled were only representative of the time in which they were sampled. Crystals were identified utilizing a 30x magnifying loupe and a crystal card and logged into a field notebook. Crystals were classified by crystal habit, crystal size, and degree of riming. Snow crystals were classified by the following basic morphology: plates, stellar, columns, needles, spatial dendrites, capped columns, irregular particles, graupel, ice, and hail. Riming classification (scale 0-5 with 0=unrimed, 1=lightly 2=moderately, 3=densely, 4=heavily, 5= graupel) was based upon work by Mosimann et al. (1994). Lastly, the following supplemental observations were logged at each visit: date, time, sky conditions, wind speed, wind direction, and barometric pressure.

Supplemental Data Collection

In addition to field measurements, the following supplemental information was collected in order to characterize individual storm events: GOES satellite imagery, forecast discussions from NWS-GJT, and RAMS forecast plots.

Figure 5 - Snow sampling equipment.

Figure 6 - Snow sampling on Mt. Werner summit.

Data Analysis

The overall strategy for data analysis was to investigate the data on a variety of scales. Macro scale analysis involved qualitative assessment of the synoptic and mesoscale conditions present during each snow event. Micro scale analysis included investigating elevational profiles of snow sampling data and meteorological data. To address the specific research hypotheses, descriptive statistics were utilized to address the first research hypothesis: mean new snow density will decrease with an increase in elevation. The remaining hypotheses were addressed using correlation analysis between the response variable (new snow density) and several explanatory variables. The explanatory variables included: site specific surface temperatures; SPL temperature, relative humidity, and wind speed (~700 millibar level); and lifted condensation level temperatures (LCL-T from GJT upper air soundings). Furthermore, regression analysis was utilized to create a model of the specific variables that would be the best predictor of new snow density. Data were statistically analyzed using the statistical software package, SPSS 13.0 and Microsoft Excel.

Moreover, an analysis of snow crystal data and meteorological data were examined to attempt to explain the conditions in the free atmosphere where the snow crystals were formed and describe the conditions at the surface. Data collected from each snow event were analyzed individually and combined for all storm events. Because of the limitation presented by the fact that the snow sampling dataset consisted of point measurements and the meteorological dataset continuous data, a method needed to be devised to address this concern. In response, meteorological data were averaged for the time period when the precipitation started and the initial snow sample was taken. Each successive sampling period was averaged for the time period between site visits. This resulted in one meteorological value for temperature, relative humidity, and wind speed for each period for comparison to the new snow density value for correlation and regression analysis.

Analysis of the snow crystal data deviated slightly from the methods utilized for the previously mentioned parameters. While new snow density values were representative of a period of time between samples, snow crystal samples were only representative of the time in which they were observed. In response, analysis involved pairing crystal data with individual point measurements of air temperature at the specific time of sampling. Furthermore, analysis included utilization of the SPL air temperature dataset since it was most likely to be representative of the conditions in which the snow crystals were formed.

Upper Air Data

Upper air data was used in the statistical analysis to see if it would act as a reliable predictor of new snow density. Specifically, lifted condensation level temperatures were used because it has been theororized that 700 millibar temperatures may correlate well with new snow density (Diamond and Lowry, 1954; McGurk, 1988; Judson and Doesken, 2000). Upper air sounding data was obtained from archived data from the University of Wyoming, Department of Atmospheric Sciences. Data were obtained from weather balloons launched from the National Weather Service Forecast Office at Grand Junction twice daily. GJT (~169 km west-southwest from Steamboat Springs) data was chosen over Denver because of its upwind proximity to Steamboat Springs. Additional data was analyzed from Salt Lake City, Riverton, and Flagstaff, however; it was decided that the data would be of little value because of the distance from Steamboat Springs. Furthermore, attempts to utilize interpolated upper air data from Denver and Grand Junction proved to be problematic in previous studies (Grant and Rhea, 1974). Lastly, another limiting factor of using upper air data is that observations are only taken twice daily.

SPL Temperature Data

During winter storm events, SPL (~700 millibar level) is typically enveloped in a cloud making it a logical site to investigate the conditions present when snow crystals form (Borys and Wetzel, 1997). Temperature data from SPL was utilized in the linear regression analysis as a potential explanatory variable. This method was used by Judson and Doesken (2000) and Wetzel et al. (2004) with reasonable success.

Summary

The methodology outlined here represented a means to answer the five research hypotheses set forth. Answering the first hypothesis involved the direct approach of measuring snow water equivalent and snow depth to determine initial snow density across an elevational gradient. Descriptive statistics were used to calculate mean density values across elevation for the entire sampling period.

Inferential statistical methods were utilized to explain variation in density and to create a predictive model of new snow density addressing Hypotheses #2-#5.

RESULTS & DISCUSSION

The subsequent results are based on intermittent snow samples and continuous meteorological observations collected on Mt. Werner during four winter storm events in February 2005. The number of snow samples taken throughout each storm varied depending upon the onset timing and duration of the event. Results are presented for each individual snow sampling variable including: new snow density and its derivatives new snow depth and snow water equivalency. The snow density results and discussion section includes a description of the sample across elevation as well as a summation of pertinent trends in the meteorological conditions. Results are presented in chronological order (case by case) followed by a summary for the entire month. Next, the supplemental variables of snow depth, snow water equivalent (SWE), and snow crystal data are presented as a monthly summary. Finally, results of correlation and regression analysis are presented in order to address several of the research hypotheses set forth.

Overall, results related to the specific research hypotheses were mixed. Generally speaking, new snow density did not decrease with an increase in elevation, thus not supporting Hypothesis #1. Results from Pearson's correlation displayed significant linear relationships existed between density and several meteorological variables including: LCL-T (0.59), SPL-air temperature (0.74), SPL-relative humidity (0.77) and SPL-wind speed (0.55) and site-specific air temperature (0.55) at p=.00, thus supporting Hypotheses #2 and #3 but not Hypothesis #4. Linear regression analysis yielded a highly significant model at p=.00 and explained 54% (R^2 = 0.54) of the variability in new snow density at all sites on the mountain.

New Snow Density

February 7-8, 2005

Results displayed mean event densities ranging from 57 kg m^{-3} to 67 kg m^{-3}. The lowest mean density was found at the Bar-UE Pumphouse (BAR) (2771m) and the highest density at Vagabond Saddle (VGB) (2557 m). The lowest and highest individual densities (40/100 kg m^{-3}) were also observed at BAR (2771m). Overall, mean densities across the entire mountain varied only 10 kg m^{-3}. The following tables and graphs summarize these findings:

Table 2 - Case summaries for new snow density – February 7-8.

	3244m	3176 m	2771 m	2557 m	2200 m
N	9	9	9	9	6
Mean (kg m^{-3})	61	58	57	67	64
Median	57	47	48	70	59
Minimum	50	43	40	49	52
Maximum	75	94	100	89	80
Range	25	51	60	40	28
Std. Deviation	9	21	22	14	13

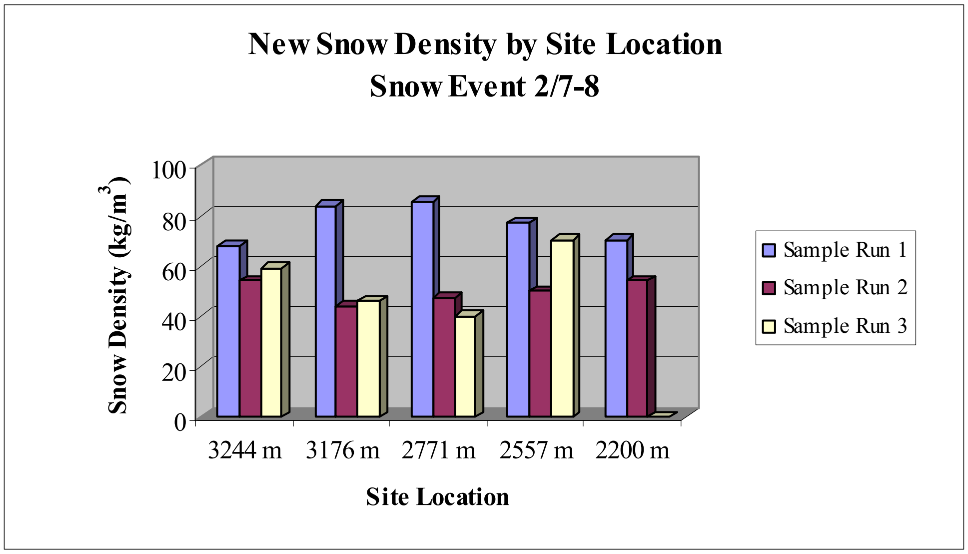


Figure 7 - Representation of mean new snow density by elevation. Each bar represents an average of three samples taken per site visit - February 7-8.

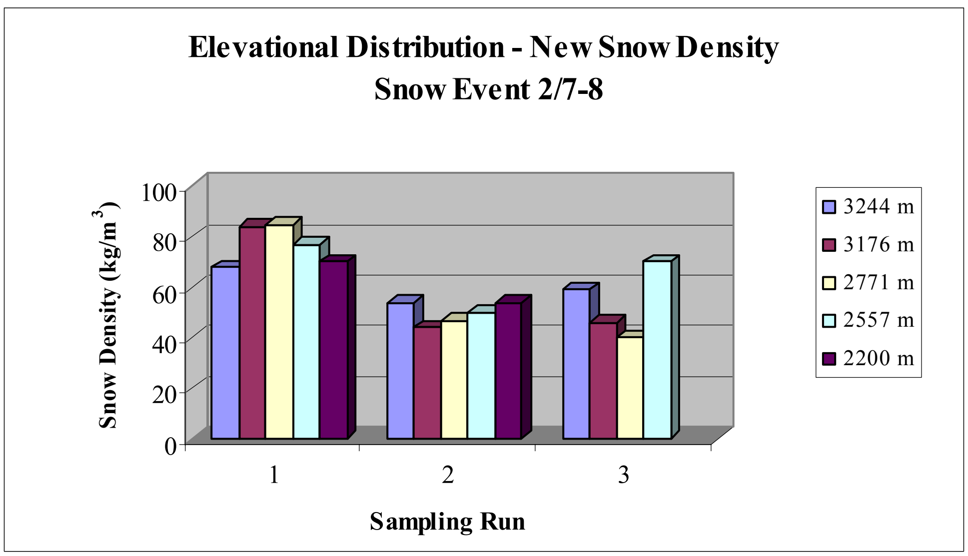


Figure 8 - Mean new snow density values obtained from three sampling runs – February 7-8.

Profiles of air temperature across elevation displayed a decrease in temperature with elevation across the mountain throughout the event. The greatest range in temperature (16.2º C) was observed mid-mountain at VGB (2557 m) and the least variability was found at the summit (8.5º C). From top to bottom, mean temperatures for the event ranged from -11º C to -6º C. Relative humidity measurements showed that the mountain was generally in-cloud overnight between the first and second sampling period. Relative humidity was > 90% across the mountain throughout the night and air temperatures from top to bottom displayed less dispersion (~5º C) than during the daylight hours where mean air temperatures varied ~8º C. This may explain the why less variability in density was observed on the mountain during the second sampling run.

Snow crystal data collected showed that heavily rimed crystals fell in the earlier portion of the storm as evidenced in the relatively high densities. There was a large degree of variability in crystal habit observed in the higher elevation sites which included: plates, stellar, columns, needles, and spatial dendrites. Stellar crystals (2-4mm) were the dominant habit found in the lower elevations. This occurrence suggests that conditions were present which favored the formation of crystals which occur in a mixed water and ice cloud at -12ºC, when supersaturation with respect to ice is near its maximum (Figure 9).

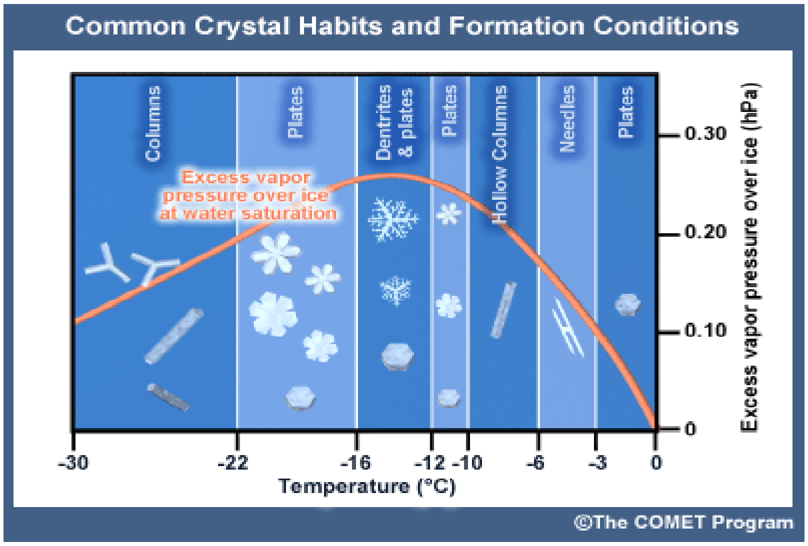


Figure 9 – Relationship between crystal habit and conditions in the free atmosphere (This figure was obtained from the Cooperative Program for Operational Meteorology, Education and Training).

February 12-13, 2005

Results displayed rather high mean densities ranging from 126 kg m^{-3} to 168 kg m^{-3}. The lowest mean density was observed near the base of the mountain at VGB (2557m) and the highest mean was recorded at Patrol Headquarters (PHQ) (3176m). The greatest intra-station variability was found at PHQ (3176 m) while the least was found at BAR (2771 m). The highest individual density (188 kg m^{-3}) for the entire month was measured at PHQ on the morning of 13 Feb 05. The following table and graphs summarize these findings:

Table 3 - Case summaries for new snow density - February 12 -13.

	3244m	3176 m	2771 m	2557 m	2200 m
N	6	6	3	3	3
Mean (kg m^{-3})	152	168	131	126	134
Median	155	161	132	131	139
Minimum	141	154	129	112	125
Maximum	159	188	133	134	139
Range	18	34	4	22	14
Std. Deviation	7	15	2	12	8

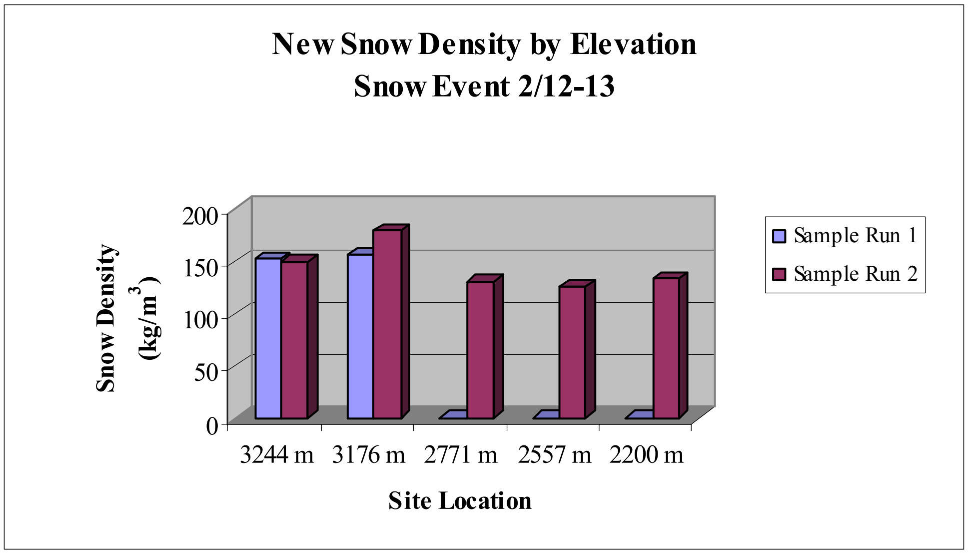


Figure 10 - Representation of mean new snow density by elevation. Individual bars represent an average of three samples taken per site visit – February 12-13.

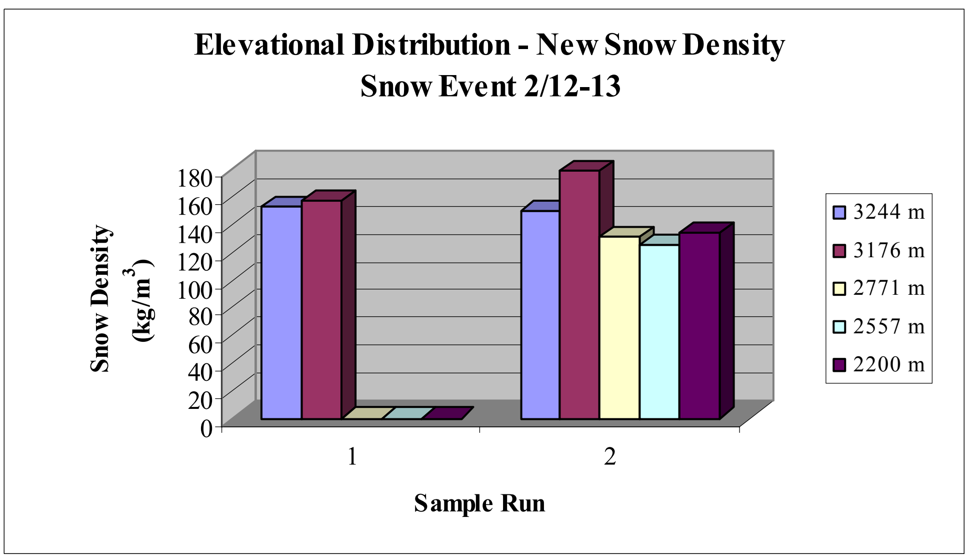


Figure 11 - Mean new snow density values obtained from three sampling runs – February 12-13.

Surface observations illustrated that the lower portion of the mountain was near or above the freezing level for most of the event. Mean air temperatures for the event ranged from -6º C at the summit to 0º C at the base. Interestingly, large spikes in temperature were observed on 13 Feb 05 in the lower three sites (< 2771 m) from approximately 1100 – 1530 hours. During this period, temperatures at VGB (2557 m) rapidly increased from near freezing level to approximately 10º C within a two hour period while the summit remained largely unaffected by this trend.

The summit region was in-cloud (>95% RH) for the entire 48-hour period while the lower portion was sporadically in cloud. The high density snow observed at upper elevations was associated with the elevated degree of riming present on the crystals as well as signs of wind deposited snow on the boards. Crystal habits sampled at the upper elevations included heavily rimed 1-2 mm needles and ice pellets while moderate to heavily rimed stellar crystals and needles were found at lower elevations. The presence of needles suggests that the crystals were formed under a low degree of supersaturation at -3º to -5º C (McClung and Schaerer, 1993) and this coincides with surface conditions on the summit which displayed nearly an identical temperature range as well as relative humidity > 95%. This suggests that the crystals were formed in the cloud near the same elevation as the mountain summit while the stellar crystals observed at lower elevations had origins at a higher altitude (lower temperature) in the atmosphere.

February 14-15, 2005

Results displayed mean densities ranging from 66 kg m^{-3} to 99 kg m^{-3}. The lowest mean density was recorded at PHQ (3176m) while the mean highest density was at VGB (2557m). The lowest individual densities (26 and 28 kg m^{-3}) for the entire month were observed in the summit region. Overall, a considerable degree of variability was found throughout the mountain during this snow event. The following table and graphs summarize these findings:

Table 4 - Case summaries for new snow density – February 14-15.

	3244m	3176 m	2771 m	2557 m	2200 m
N	9	9	9	9	6
Mean	81	66	73	99	68
Median	86	80	74	80	68
Minimum	28	26	53	60	64
Maximum	133	94	98	167	74
Range	105	68	45	107	10
Std. Deviation	43	29	16	42	4

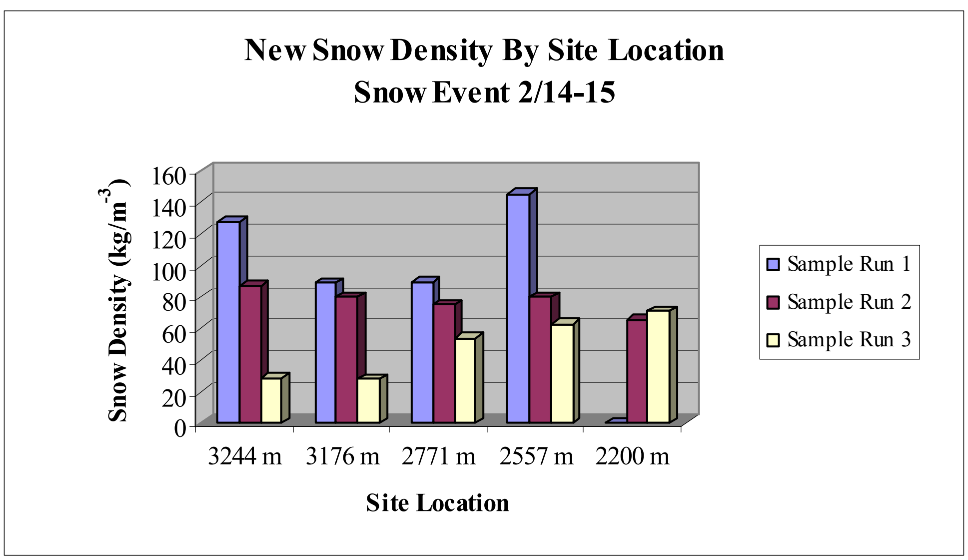


Figure 12- Representation of mean new snow density by elevation. Each bar represents an average of three samples taken per site visit – February 14-15.

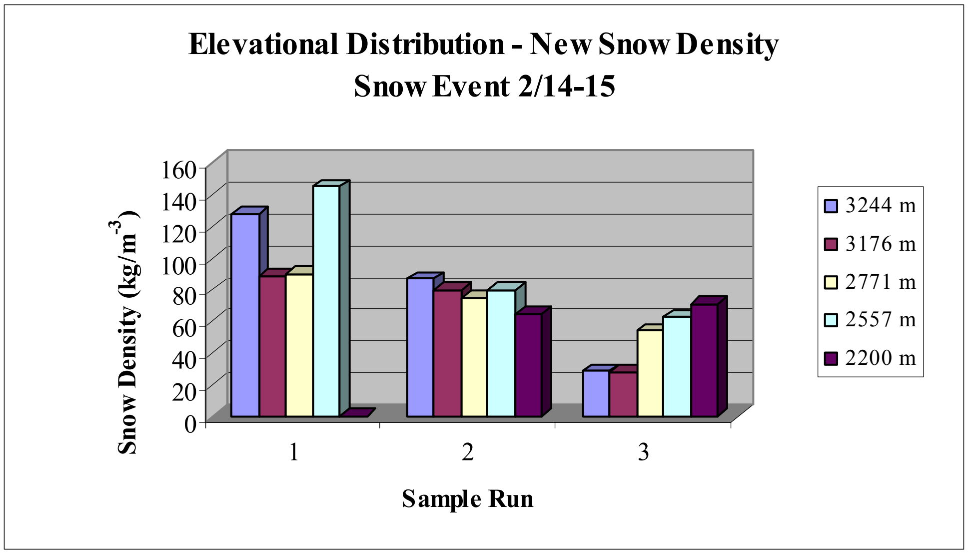


Figure 13 - Mean new snow density values obtained from three site visits – February 14-15.

Meteorological conditions during this event mirrored the density trends observed, exemplified by a wide range in temperatures throughout the mountain. Temperatures hovering near freezing prevailed on the middle and lower portion of the mountain throughout the first 24 hours of the event, followed by rapid cooling beginning in latter 24 hours (Figure 14). Temperatures dropped approximately 12º C in the final 24 hours of the event resulting in lowest snow densities observed for the month.

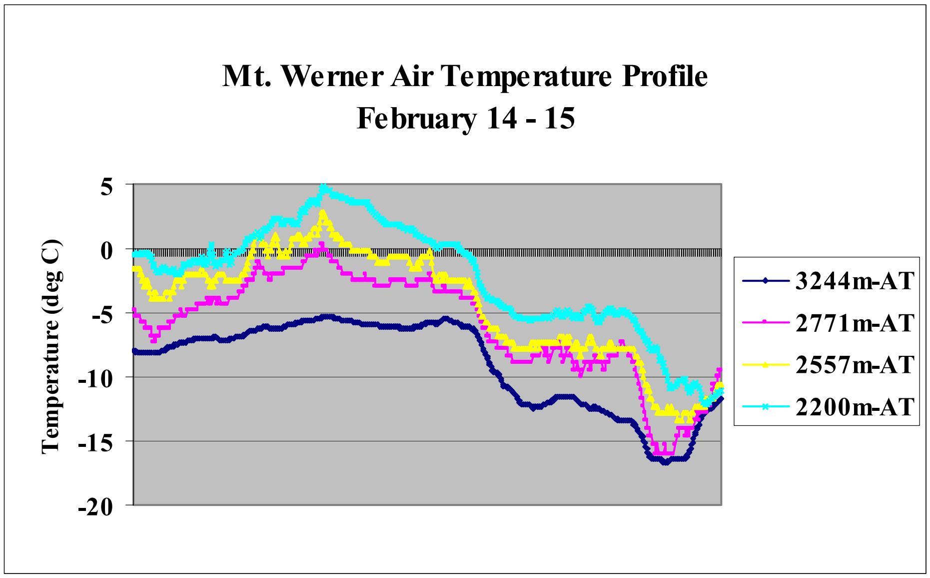


Figure 14 - Time series representation of air temperature profile on Mt. Werner – February 14-15.

Relative humidity measurements displayed that the higher elevation sites were in-cloud for nearly the entire event while the lower elevations were intermittently in-cloud, primarily during the evening hours.

Small stellar crystals (2-3 mm) were the predominant type present throughout the mountain during this event. Air temperatures throughout the morning and afternoon of 15 Feb 05 averaged approximately -11º C at the summit, and -5º C near the base suggesting that the crystals originated at roughly the same elevation as the summit. Additionally, moderate to dense riming (2-3) was present on all crystals observed.

February 19-21, 2005

Results displayed mean densities ranging from 93 kg m^{-3} to 132 kg m^{-3}. The lowest density snow was found at the base of the mountain (2200m) and the highest density was observed at VGB (2557m). A considerable range in density was observed at both the summit (3244m) and VGB. The subsequent table and graphs summarize these findings:

Table 5 - Case summaries for new snow density – February 19-21.

	3244m	3176 m	2771 m	2557 m	2200 m
N	9	9	9	9	6
Mean	114	112	104	132	93
Median	113	111	103	136	88
Minimum	83	106	88	86	79
Maximum	150	125	125	182	111
Range	67	19	37	96	32
Std. Deviation	23	6	13	39	15

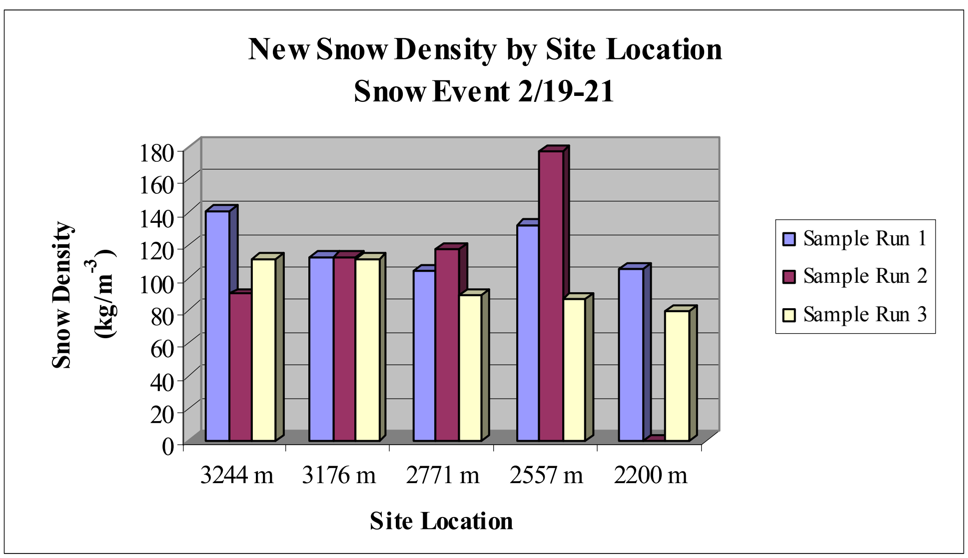


Figure 15 - Representation of mean new snow density by elevation. Each bar represents an average of three samples taken per site visit – February 19-21.

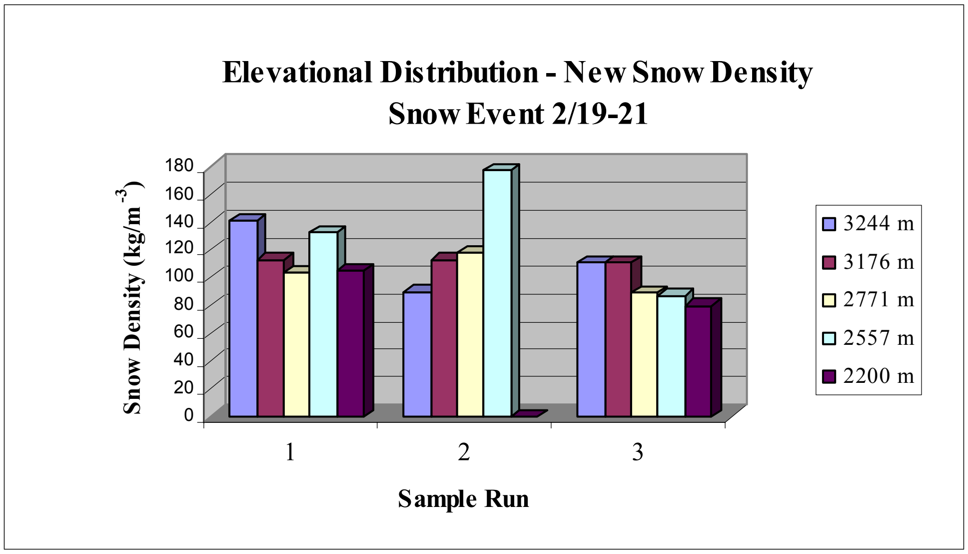


Figure 16 - Mean new snow density values obtained from three sampling runs – February 19-21.

Surface air temperatures fluctuated only 3º C on the summit during the entire three day event. For the same period, the mid mountain region of BAR (2771 m) and VGB (2557 m) ranged 10º C and 12º C respectively. Mean temperatures hovered around the freezing point from VGB to the base. Relative humidity trends suggest that the summit region was in-cloud nearly the entire storm while the mid and lower portions were not in-cloud during most of the event.

A wide variety of snow crystal types were observed during the event. The summit (3244 m) received heavily rimed 2 mm spatial dendrites while nearby PHQ (3176 m) received 1-2 mm heavily rimed stellar, irregular, and graupel on 20 Feb 05. Likewise, graupel and irregular particles were observed at both the mid and lower elevations. On 21 Feb 05, 2mm stellar crystals dominated the higher elevation while 1-2 mm plates, stellar, and spatial dendrites were found at BAR (2771 m). The lower elevations received 2mm, moderately rimed stellar crystals.

Density Summary - February 2005

In summary, no clear pattern was found to exist as it relates to the elevational component of this study. Even though surface air temperature profiles clearly showed that normal adiabatic lapse rates were present during all events, the spatial distribution of new snow density across did not vary directly with temperature and elevation. These results are a departure from findings of Wetzel et al. (2004) who generally found greater densities at lower elevations on Mt. Werner during January – February 2002. Similarly, Grant and Rhea (1974) concluded that new snow density was greater at lower elevations, relating this to a higher frequency and degree of riming at the lower elevations. However, frequency distributions of crystal data from this study show that a greater degree of riming was present at the higher elevations and may be associated with higher densities (Figure 17).

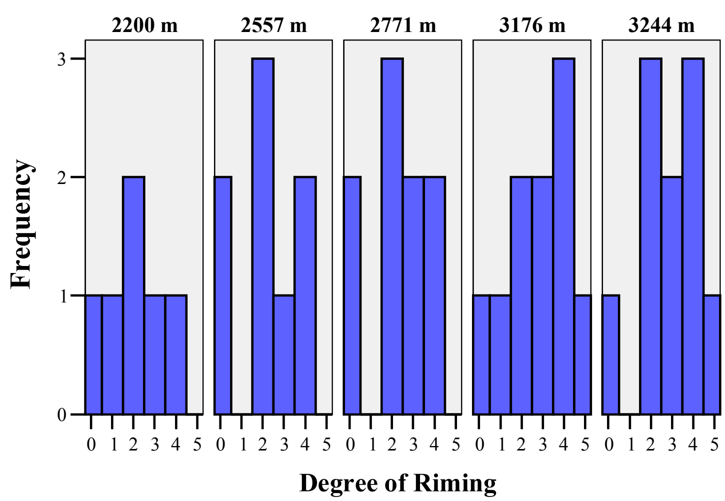


Figure 17 - Frequency distributions of snow crystal riming across elevation. Riming classification is based on a scale (0-5) presented by Mosimann et al. (1994).

Qualitative assessment of density data illustrates the high degree of intra-storm variability in density at each site. For example, the mean density value reported for a storm event may not accurately portray the density values observed throughout the storm. What is important to note is that a site with the highest individual density value recorded for an event may also be the location of the lowest density snow observed (i.e., 14-15 Feb at 3244 m). This further demonstrates the complexity in making generalizations regarding the relationship between density and elevation.

Overall, mean new snow densities across elevation for the month ranged from 83 kg m^{-3} to 101 kg m^{-3}. Monthly mean densities were based upon the mean of mean density values taken from each visitation. The highest overall mean density was found at VGB (2557m) while the lowest was observed at the base of the mountain CHR (2200m) as well as at BAR (2771m). The lowest (28 kg m^{-3}) and highest (179 kg m^{-3}) storm event mean densities were found near the summit at PHQ (3176m). However, two events affecting the overall mean density values should be noted. First, several high density observations at MTW (2/13-14, 2/19, 2/21) were likely associated with the redistribution of snow by wind. The exact degree to which they increased density is somewhat uncertain, however, a comparison to the PHQ observations (68 m lower in elevation) puts into question two observations at MTW (2/14, 2/19) because they were, respectively, 39 kg m^{-3} and 28 kg m^{-3} greater than observations at PHQ for the same period. Data for these sampling periods show 10-minute average wind speeds and 10-minute maximum gusts were in excess of thresholds for the transport of dry snow (7.7 m s^{-1}) (Li and Pomeroy, 1997) and suspension (>15 m s^{-1}) (McClung and Schaerer, 1993). Moreover, data illustrate that shortly before sampling on 14 Feb 05, maximum wind gusts exceeded 18 m s^{-1} and on 19 Feb 05 maximum gusts exceeded 22 m s^{-1} (Figures 18 and 19).

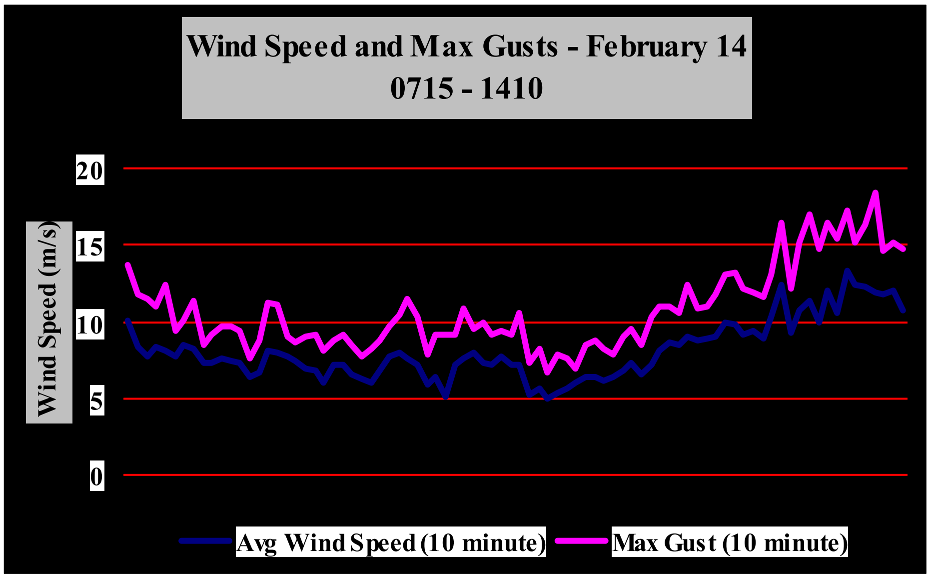


Figure 18 – Average wind speeds and maximum gusts at SPL – February 19 (0800 – 1000).

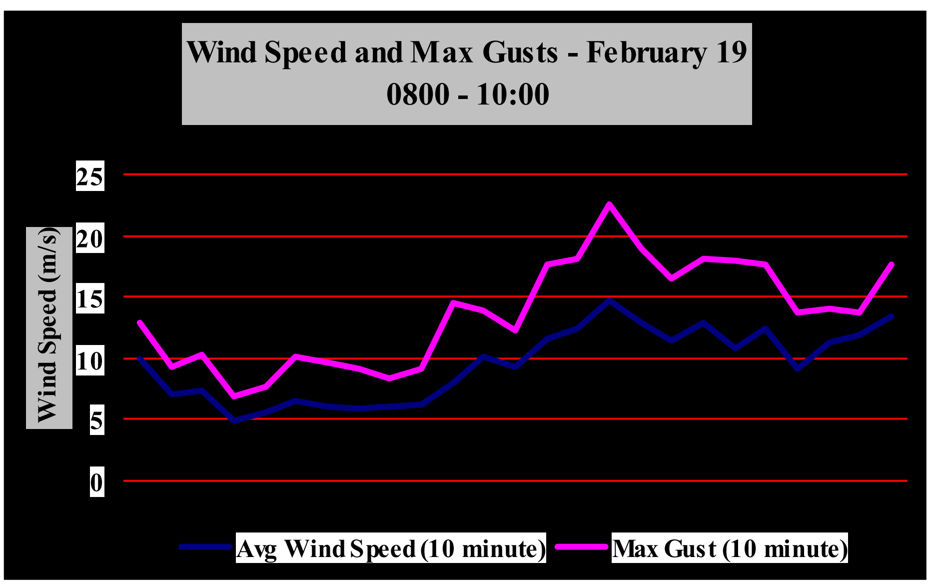


Figure 19 – Average wind speeds and maximum gusts at SPL – February 14 (0715 – 1410).

The second event possibly affecting overall mean density was that the lowest elevation site had less overall observations because snow sampling could not be executed upon several visitations. This occurred because snow on the board had melted before it could be measured (Appendix F).

Comparing density data with that of Judson and Doesken (2000) and Wetzel et al (2004), some similarities were found. For example, Judson and Doesken (2000) reported a mean new snow density of 72 kg m^{-3} (std. dev =28) at Steamboat Springs, CO (2120 m), the lowest elevation site in their study. Similarly, a mean new snow density of 83 kg m^{-3} (std. dev = 28) was observed at the lowest elevation site, CHR (2200 m). Moreover, data collected over four winters at Wolf Creek Pass (3244 m) in southern Colorado showed a mean new snow density of 103 kg m^{-3} with a standard deviation of 41 (Judson and Doesken, 2000). Correspondingly, a mean new snow density of 97 kg m^{-3} (std. dev = 42) was observed at the same elevation on summit of Mt. Werner (3244 m) for this study. Wetzel et al (2004) reported mean new snow densities across elevation ranging from ~60 kg m^{-3} to ~85 kg m^{-3} over a two-month period (January-February) on Mt. Werner. These similarities suggest that it may be possible to obtain a representative density population from only sampling a month-long period.

Measures of central tendency and other descriptive statistics for the month are summarized in the following table:

Table 6 - Descriptive statistics for new snow density -February 2005.

	3244 m	3176 m	2771 m	2557 m	2200 m
N	11	11	10	10	7
Mean	97	95	83	101	83
Median	90	89	87	83	71
Minimum	29	28	40	50	54
Maximum	153	179	131	177	134
Range	124	151	93	127	80
Std. Deviation	42	46	30	41	28
Kurtosis	-1.32	-.36	-.90	-.739	1.02
Std. Error of Kurtosis	1.28	1.28	1.33	1.33	1.59
Skewness	-.076	.36	.03	.66	1.25
Std. Error of Skewness	.66	.66	.69	.69	.79

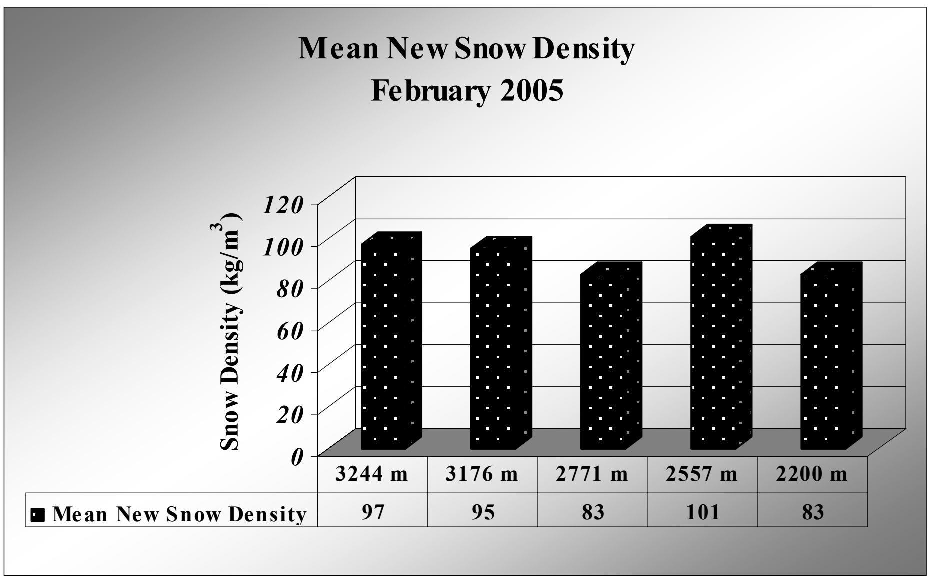


Figure 20 - Mean new snow density distribution – February 2005.

Investigating representativeness, histograms of density data (Figure 21) were examined for asymmetry of the density distributions. Skewness values from individual sites show some departure from symmetry. However, the standard error of skewness values fell within the -2 to +2 range, thus assuming normality. Likewise, the standard error of kurtosis values further reinforced normality assumptions necessary for linear regression analysis. An additional area of concern in the regression analysis was associated with the small sample size. However, this was recognized in the experimental design phase of the project and it was deemed acceptable because of the inherent limitations involved with intensive snow sampling.

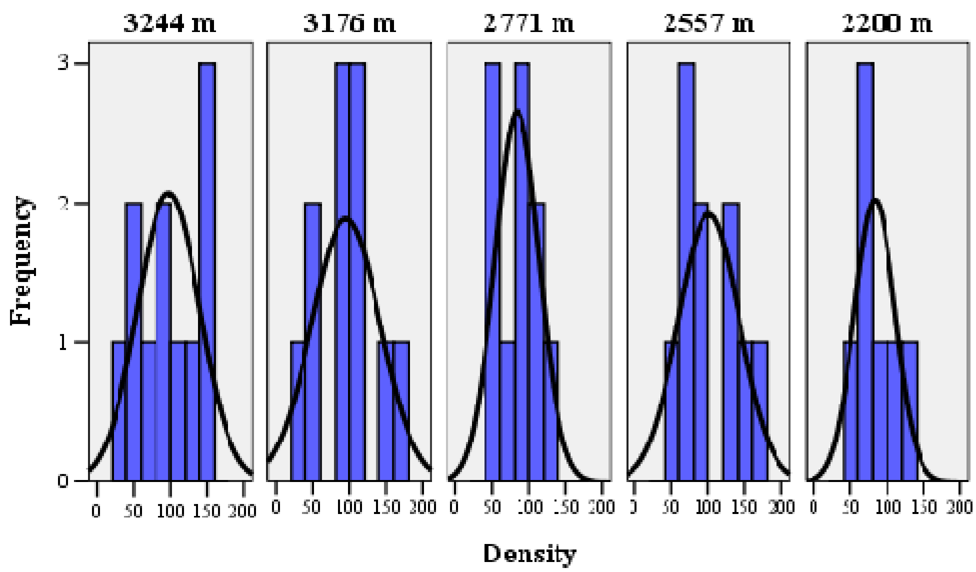


Figure 21 - Frequency distributions of mean new snow densities by site location – February 2005

New Snow Depth & Snow Water Equivalent

New Snow Depth – February 2005

Measurements of accumulated snow depth obtained from snowboards at each location resulted in total snowfall amounts ranging from 70 cm to 120 cm. Generally speaking, the total accumulation of snowfall increased with an increase in elevation. Additional graphical representations of individual snow events can be found in Appendix B. Figure 22 summarizes the monthly totals:

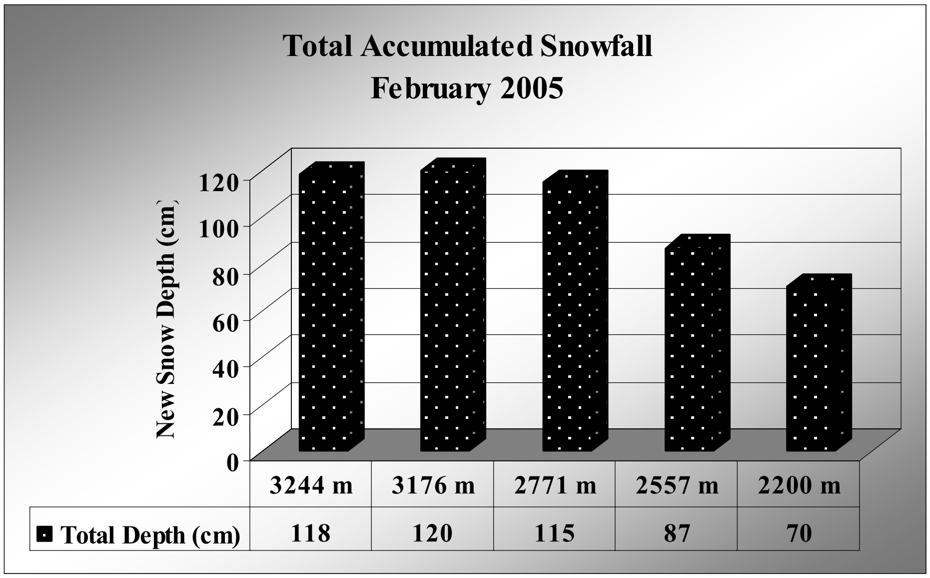


Figure 22 - Total accumulated snowfall – February 2005.

Snow Water Equivalency – February 2005

SWE measurements obtained from the Snowmetrics T1 sampling tube and calibrated scale ranged from 49 mm to 92 mm of accumulated liquid precipitation (Figure 23). Results of individual storm events can be found in Appendix C. In concurrence with snowfall data, SWE increased with elevation.

Measurement of SWE in the field, and to a lesser extent snow depth, required some degree of acceptance of the uncertainty involved the measurement process. To address this concern, a coefficient of variation (CV) was calculated for each snow sampling visitation to provide a means by which to assess variability in the measurement process due to either sampling error or natural variation. Overall, low CV values (<10%) were found for most of the observations (Appendix F).

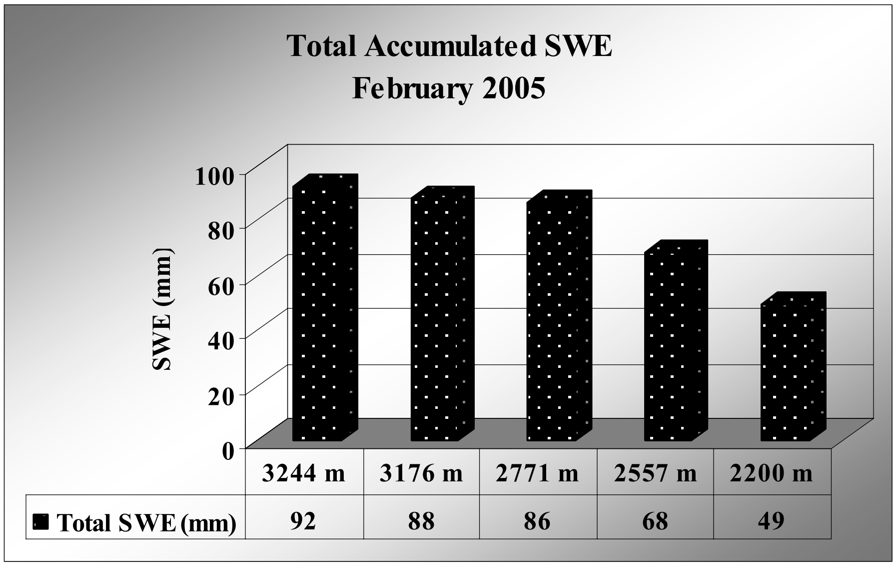


Figure 23 – Total Accumulated SWE – February 2005.

Snow Crystal Data

Snow crystal data including habit, and degree of riming were collected during each site visit. Cumulative results from all sampling sites illustrate that stellar crystals were the predominant crystal habit accounting for 54% of total observations, followed by spatial dendrites (12%), plates (9%), needles (7%), irregular particles and graupel (5%). The most prevalent crystal size sampled was 2mm (61%) followed by 1mm (20%) and 3mm (14%) (Appendix F). However, it should be noted that multiple crystal types and sizes were present in many samples. Therefore, analysis was based on the predominant crystal habits and sizes sampled.

Another important variable related to the initial density is the degree of riming of the snow crystal. Noteworthy, was the observation that 84% of the snow crystals sampled were rimed (>1) and the occurrence of dense to heavy riming (3-5) was noted in 49% of the samples. This occurrence indicates the presence of supercooled liquid water in the clouds in which these rimed crystals were formed and crystal growth by accretion.

The following figures summarize the analysis of density relationships to the degree of riming, crystal habit, and crystal size:

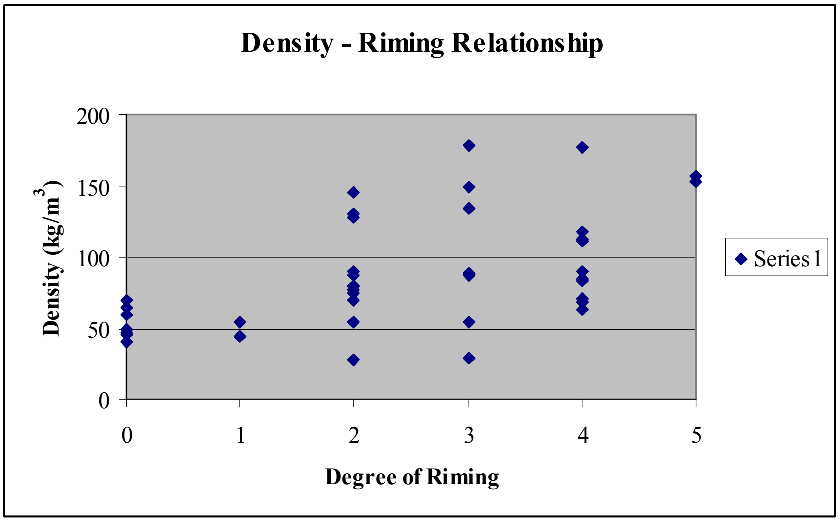


Figure 24 - Scatterplot of the relationship between new snow density and degree of riming.

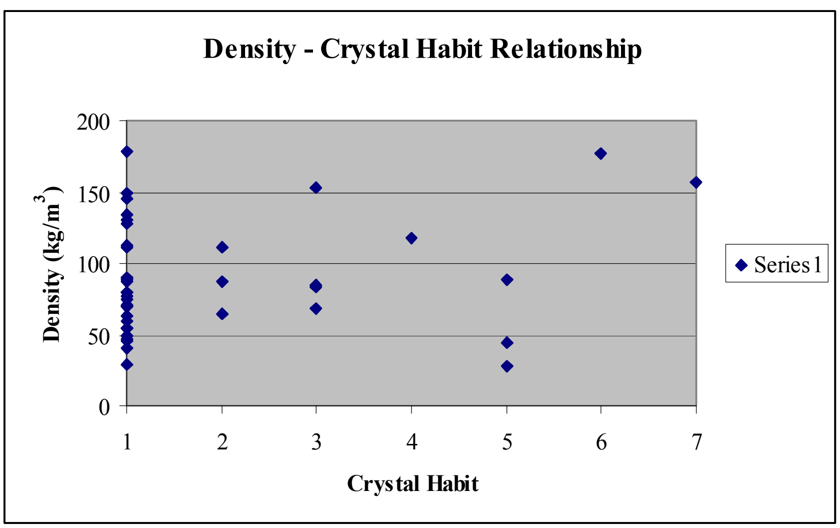


Figure 25 – Scatterplot of the relationship between new snow density and crystal habit. Crystal habit re-classification is based on the bulk density of various snow crystals (Pruppacher and Klett, 1997).

Crystal habits utilized in Figure 25 were re-classified from the original field classification and the new classification was based upon the bulk densities for various snow crystal habits (Pruppacher and Klett, 1997). The following description summarizes these changes: stellars-1 (least dense), dendrites-2, columns-3, irregulars-4, plates-5, graupel-6 and hail-7 (most dense).

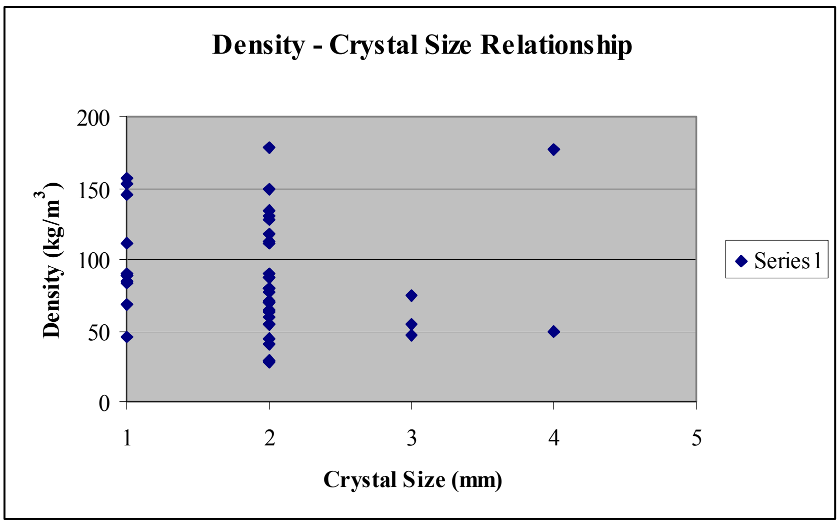


Figure 26 - Scatterplot of the relationship between new snow density and crystal size.

Overall, the variable that showed the strongest relationship influencing new snow density was the degree of riming (Figure 24). Data related to crystal habit (Figure 25) and size (Figure 26) displayed considerable scatter with no distinct pattern.

Bivariate Correlations

Pearson's correlation analysis was utilized to determine if relationships existed between the response variable (new snow density) and several explanatory meteorological parameters. Results illustrate that new snow density is highly correlated with the following variables: LCL-T (0.59), SPL-air temperature (0.74), SPL-relative humidity (0.77), SPL-wind speed (0.55), and site-specific surface air temperature (0.55). However, it should be noted that these variables are also highly correlated with each other. Table 7 summarizes these correlation results:

Table 7 – Pearson's Correlation matrix for response (density) and explanatory meteorological variables.

		Density	LCL-T	SPL-AT	SPL-RH	SPL-WS	Surface-AT
Density	Pearson Correlation	1	**.59(**)**	**.74(**)**	**.77(**)**	**.55(**)**	**.55(**)**
	Sig. (1-tailed)		.00	.00	.00	.00	.00
	N	49	49	49	49	49	49
LCL-T	Pearson Correlation	.59(**)	1	.76(**)	.69(**)	.22	.51(**)
	Sig. (1-tailed)	.00		.00	.00	.07	.00
	N	49	49	49	49	49	49
SPL-AT	Pearson Correlation	.74(**)	.76(**)	1	.88(**)	.53(**)	.70(**)
	Sig. (1-tailed)	.00	.00		.00	.00	.00
	N	49	49	49	49	49	49
SPL-RH	Pearson Correlation	.77(**)	.69(**)	.88(**)	1	.67(**)	.63(**)
	Sig. (1-tailed)	.00	.00	.00		.00	.00
	N	49	49	49	49	49	49
SPL-WS	Pearson Correlation	.55(**)	.22	.53(**)	.67(**)	1	.47(**)
	Sig. (1-tailed)	.00	.07	.00	.00		.00
	N	49	49	49	49	49	49
Surface-AT	Pearson Correlation	.55(**)	.51(**)	.70(**)	.63(**)	.47(**)	1
	Sig. (1-tailed)	.00	.00	.00	.00	.00	
	N	49	49	49	49	49	49

Regression Modeling

Linear regression analysis was utilized to create a predictive model for new snow density. This type of model assumes that there is a linear relationship between the dependent variable (density) and the predictive variables (LCL-T, SPL-AT, SPL-RH, SPL-WS, and surface-AT). Multiple combinations of the predictive variables were tested; however, the best fit resulted from all the previously mentioned variables excluding surface-AT. Results from this model were highly significant F (17.67, p=.00). The subsequent model explained over half of the variation in density with an $R^2 = 0.62$ (Table 8). Furthermore, qualitative assessment of the regression standardized residual histogram and normal P-P plot of the regression standardized residuals indicated that the assumption of normality was not violated (Figures 27 and 28).

Table 8 – Multiple linear regression model summary.

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.78(a)	.62	.58	24.8

a Predictors: (Constant), LCL-T, SPL-WS, SPL-AT, SPL-RH

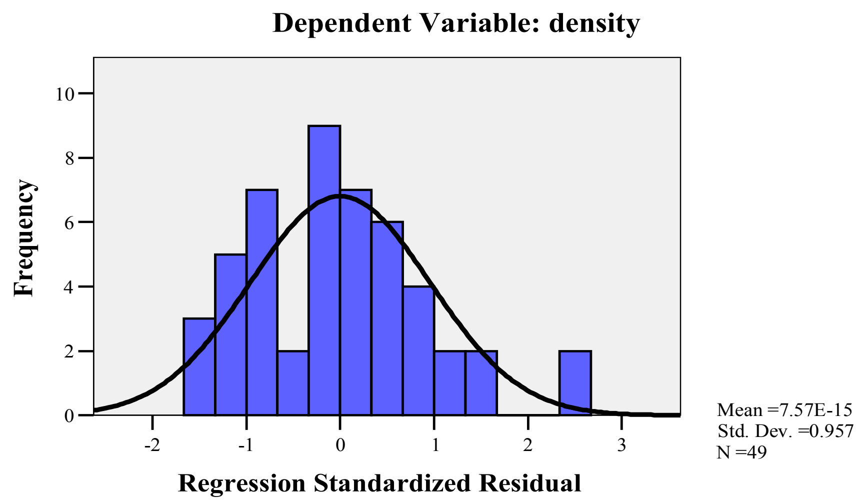


Figure 27 - Histogram of the regression standardized residuals.

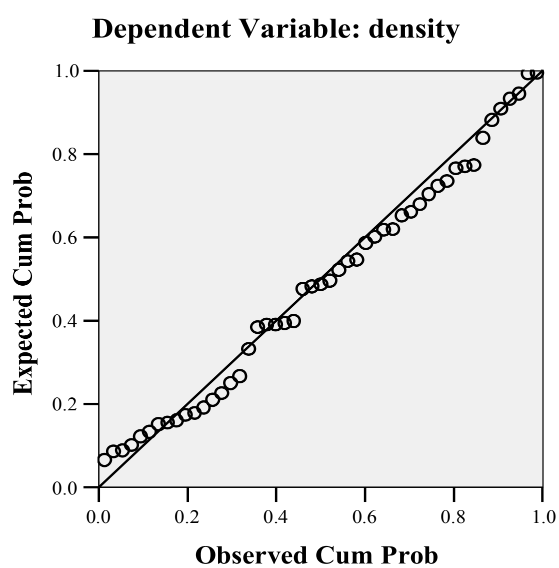


Figure 28 - Normal P-P plot of the regression standardized residuals.

However, analysis of collinearity diagnostics yielded that serious problems existed related to multicollinearity, whereby, the independent variables are a linear function of other independent variables. This was identified by tolerance values near zero and variance inflation factors >2. Furthermore, Eigenvalues near zero further indicated that the predictors were intercorrelated. Therefore, a stepwise linear regression model using the best single predictor variable, SPL air temperature, was utilized. The model results were highly significant (F 55.5, p=.00) and $R^2 = 0.54$ (Table 9, Figure 29). Moreover, assessment of the regression standardized residual histogram and normal P-P plot of the regression standardized residuals indicated that the assumption of normality is not violated (Figure 30). The resulting regression model equation for density is as following:

$$Density\ (y) = 9.9x + 170.3$$

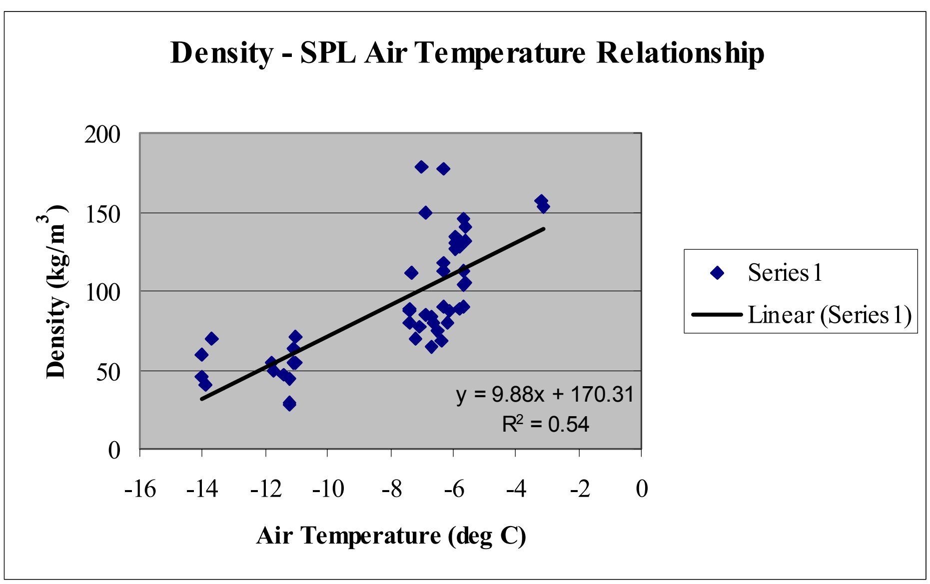


Figure 29 - Scatterplot of density as a function of air temperature at Storm Peak Laboratory.

Table 9 – Stepwise linear regression model summary.

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.74(a)	.54	.53	26.2

a Predictors: (Constant), temp spl

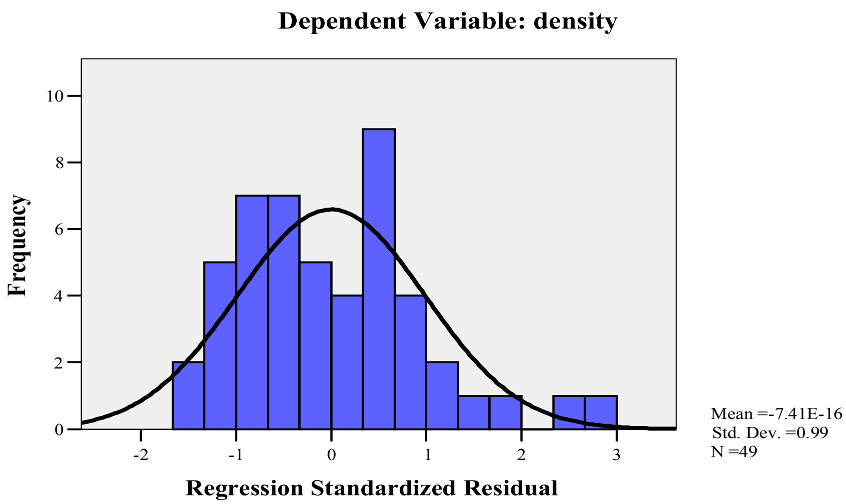


Figure 30 – Histogram of the regression standardized residuals.

The regression results using SPL air temperature to forecast density across the entire mountain were comparable to that of Wetzel et al. (2004) and Judson and Doesken (2000) who explained 52% of the variability in density utilizing SPL air temperatures (~700 millibar temperature) as a predictive variable. Furthermore, an attempt to utilize site-specific air temperature as a predictive variable resulted in a weak $R^2 = 0.30$ (Figure 31). These results are similar to those by McGurk et al. (1988) who reported an $R^2 = 0.27$ for surface air temperature.

Similar success was found in examining the relationship between new snow density and SPL wind speed; resulting in an $R^2 = 0.30$. However, it should be noted that a distinct trend can be observed in the scatterplot of density as a function of wind speed (Figure 32).

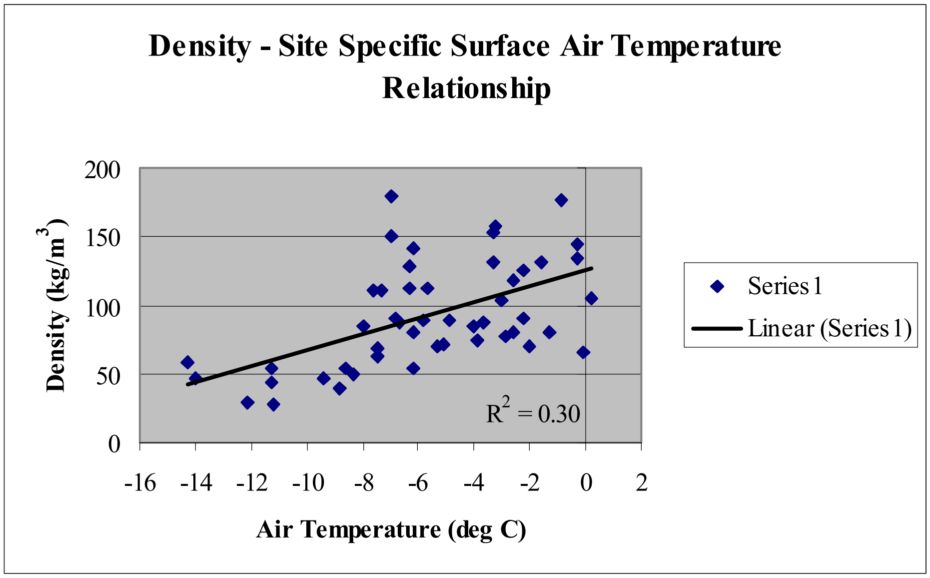


Figure 31 – Scatterplot of density as a function of site-specific surface air temperature.

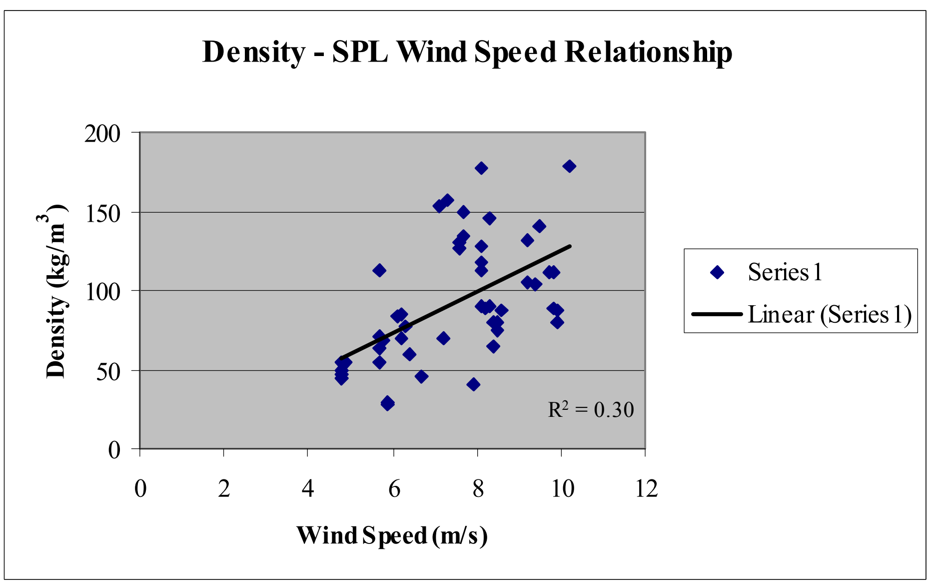


Figure 32- Scatterplot of density as a function wind speed at SPL.

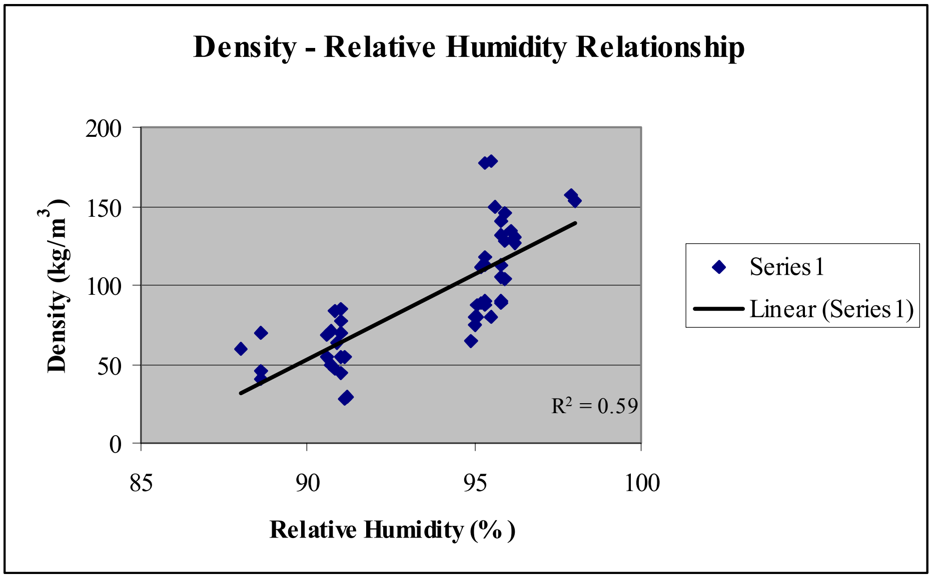


Figure 33 – Scatterplot of density as a function of relative humidity (MTW).

Lastly, relative humidity measurements taken from MTW were utilized to investigate the relationship between density and relative humidity. MTW data was chosen over SPL because the relative humidity sensor at SPL often is covered with rime ice when the summit is in-cloud (temperatures below freezing). Results showed an R^2=0.59, however, this result is somewhat questionable because of error (+/- 3-4%) associated with relative humidity measurements in a condensing environment (Figure 33).

CONCLUSIONS

Mean new snow densities on Mt. Werner ranged from 83 kg m^{-3} to 101 kg m^{-3}. Individual density measurements ranged from 26 kg m^{-3} to 188 kg m^{-3}. A considerable degree of intra-storm variability in new snow density was observed (Appendix A). Mean new snow density did not decrease linearly with an increase in elevation. Overall dispersion in mean new snow density (February 2005) was moderate; and varied only 19 kg m^{-3} between the highest mean density (101 kg m^{-3} at 2557 m) and the lowest (83 kg m^{-3} at 2771 m and 2200 m).

Moreover, it was determined that high density snow was directly linked to effects of saltation and the degree of riming. Quantitatively, the data did not suggest a strong relationship between wind speed, and density; however, field observations of wind deposition of new snow (and associated higher densities) confirmed the influence of wind upon density at the surface. Furthermore, the occurrence of moderate to heavy riming during nearly half of the observations, particularly at the highest elevations, suggest a relationship between higher density snowfall and riming.

Statistical analysis has shown significant correlations existed between new snow density and several explanatory variables, such as, approximated 700 millibar level air temperature, relative humidity, and wind speed (Storm Peak Laboratory), and lifted condensation level temperature. Attempts to create a predictive model of density resulted in a moderate degree of success, whereby 54% of the variability was explained by the model utilizing an approximated 700 millibar level temperature (Storm Peak Laboratory air temperature). These results are in concurrence with previous attempts to create predictive models utilizing an approximated 700 millibar air temperature as a means to explain variation in snowfall density. Utilization of an approximated 700 millibar air temperature to predict density at various elevations resulted in significant models for high elevation sites (Appendix D). Use of multiple predictive variables in linear regression models proved problematic related to multicollinearity. Additionally, results from regression analysis using surface air temperature as a predictive factor showed a weak coefficient of determination (R^2=0.29).

In conclusion, further research on snowfall density should be directed towards how the three generalized winter storm tracks (northwest, west, and southwest) may be associated with snowfall density. This could be especially useful for snowfall prediction models that rely upon an accurate estimation snowfall density. Lastly, additional research should focus on the depiction of the spatial distribution of new snow density across elevation and aspect which could be particularly useful to snowpack evolution modeling efforts.

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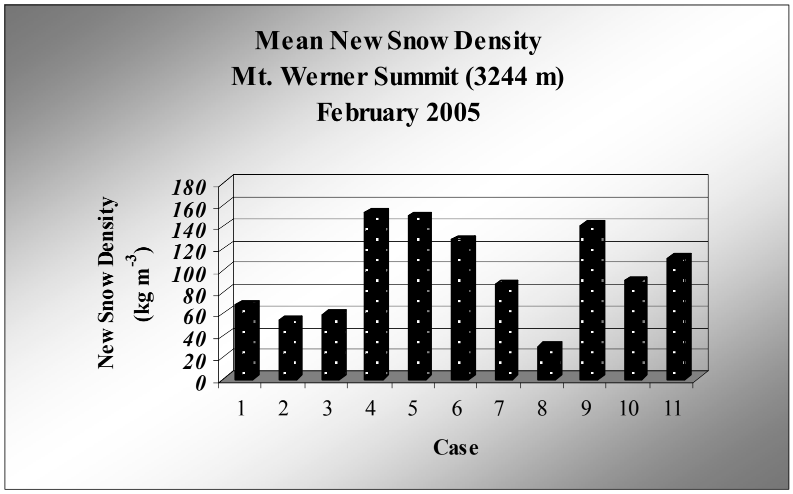
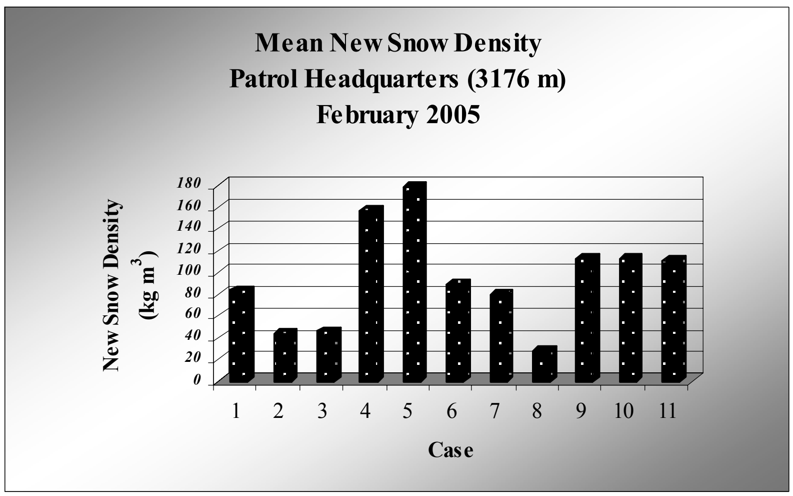
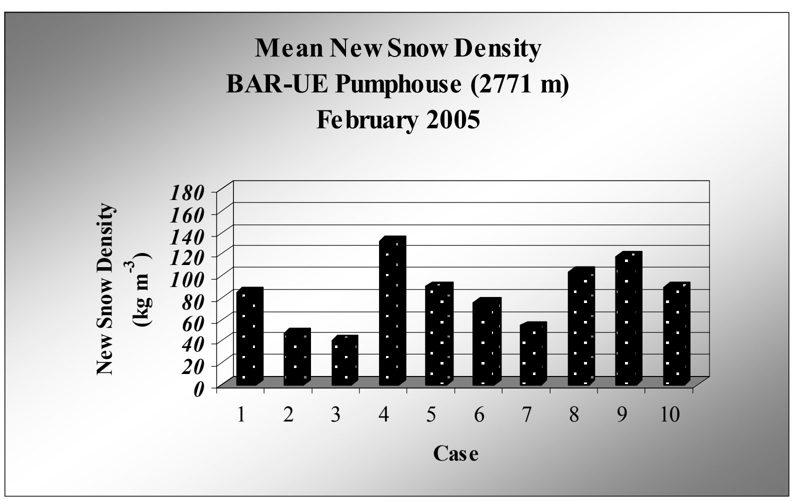
APPENDICES

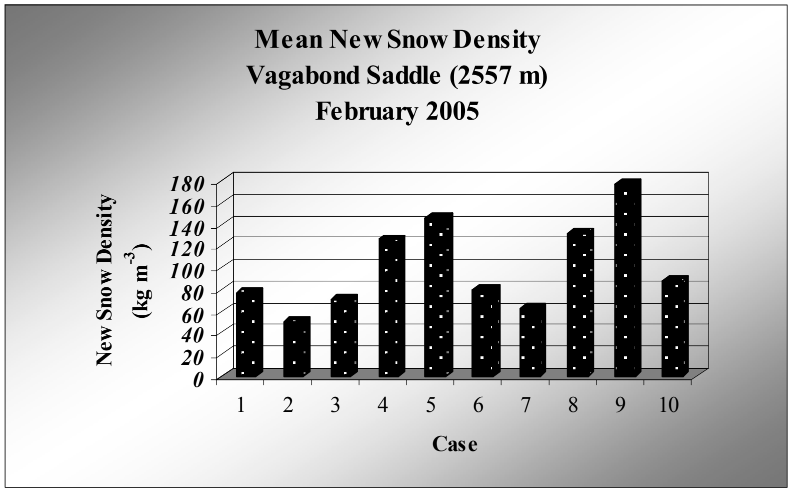
APPENDIX A

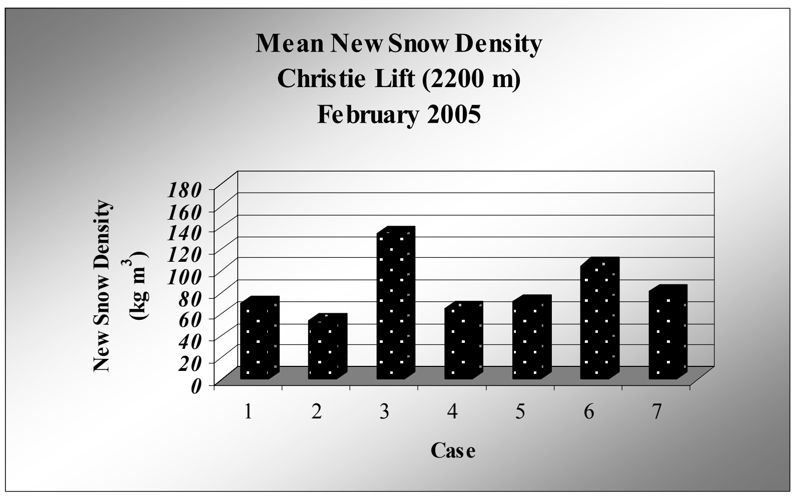
NEW SNOW DENSITY PLOTS


Mean New Snow Density
Mt. Werner Summit (3244 m)
February 2005
New Snow Density (kg m-3)
0
20
40
60
80
100
120
140
160
180
1 2 3 4 5 6 7 8 9 10 11
Case


Mean New Snow Density
Patrol Headquarters (3176 m)
February 2005
New Snow Density (kg m3)
0
20
40
60
80
100
120
140
160
180
1 2 3 4 5 6 7 8 9 10 11
Case


Mean New Snow Density
BAR-UE Pumphouse (2771 m)
February 2005
New Snow Density (kg m-3)
0
20
40
60
80
100
120
140
160
180
1 2 3 4 5 6 7 8 9 10
Case

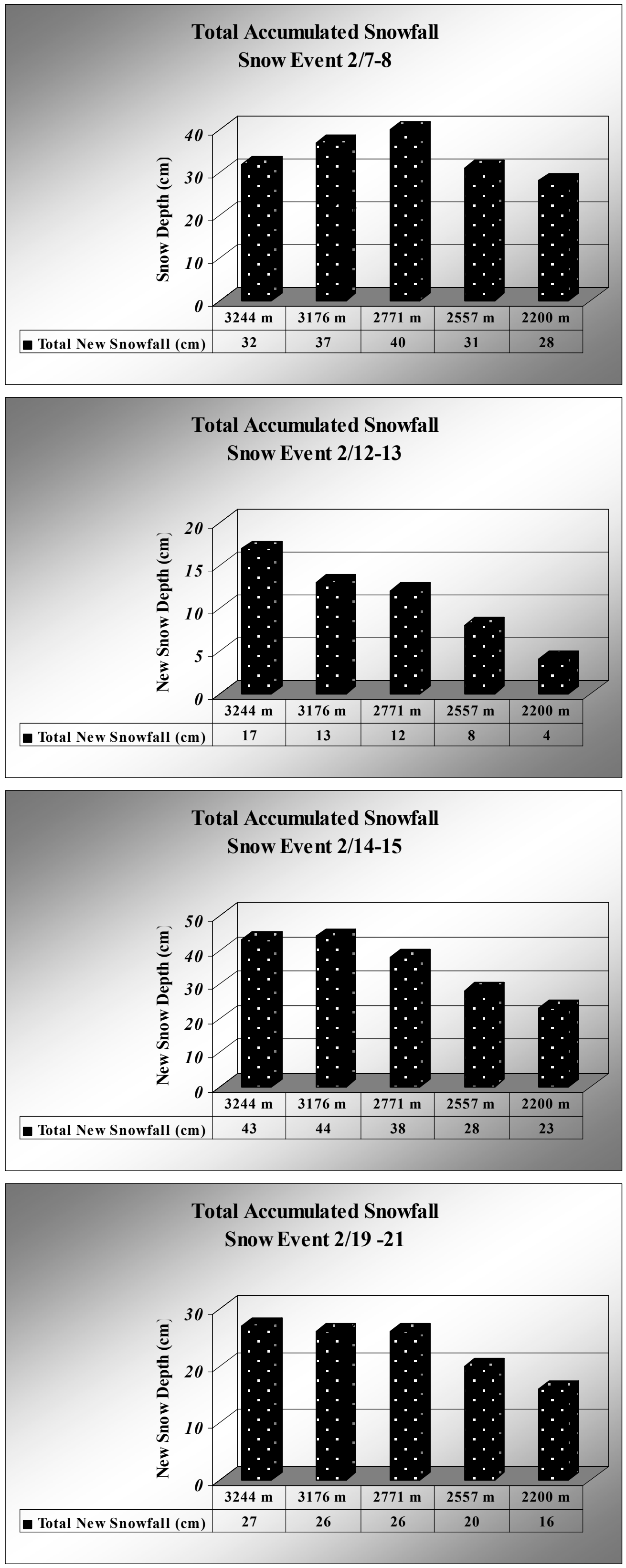




Mean new snow density at each sampling site – February 2005.

APPENDIX B

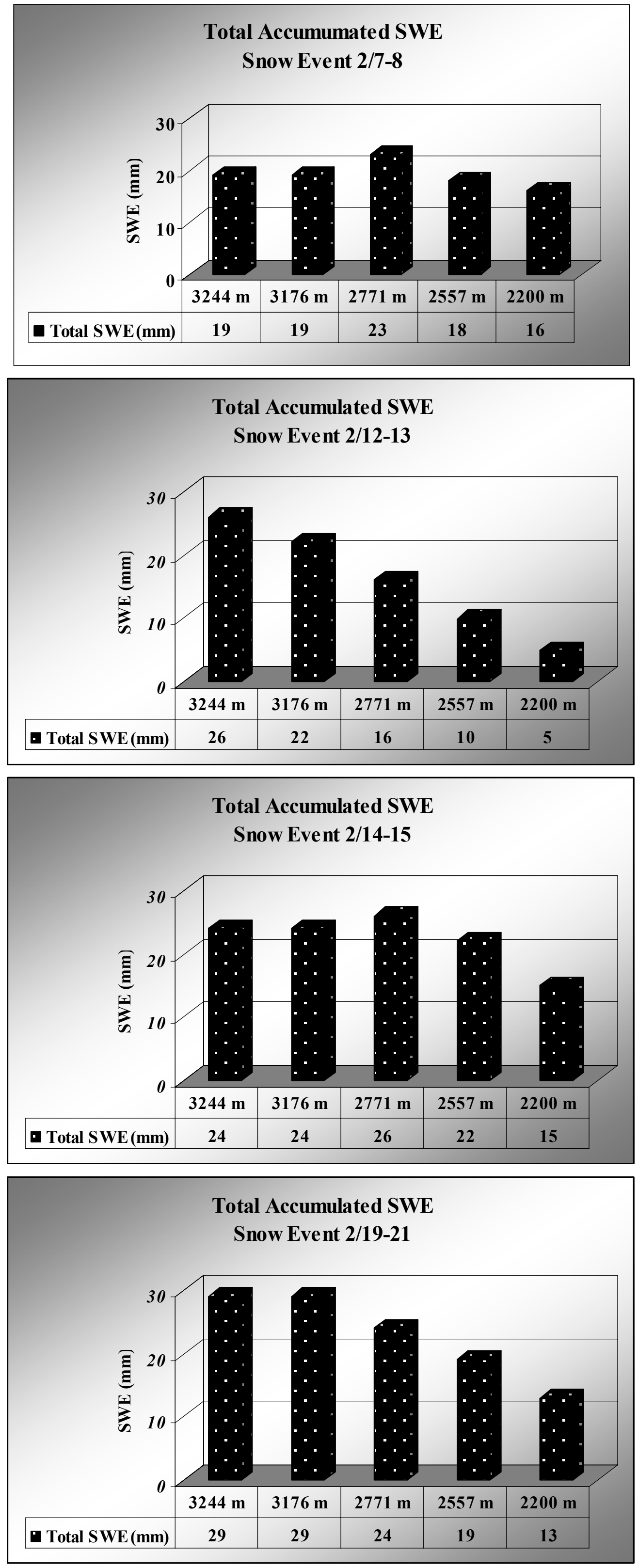
SNOW DEPTH PLOTS



Accumulated snowfall totals for each individual snow event in February 2005.

APPENDIX C

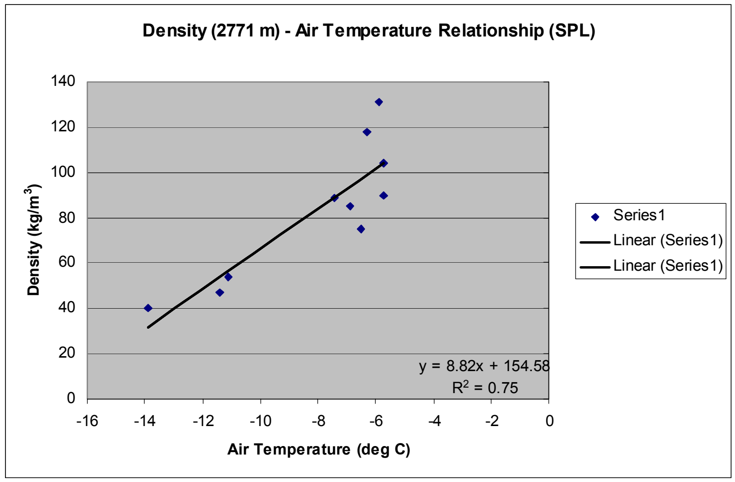
SNOW WATER EQUIVALENCY PLOTS

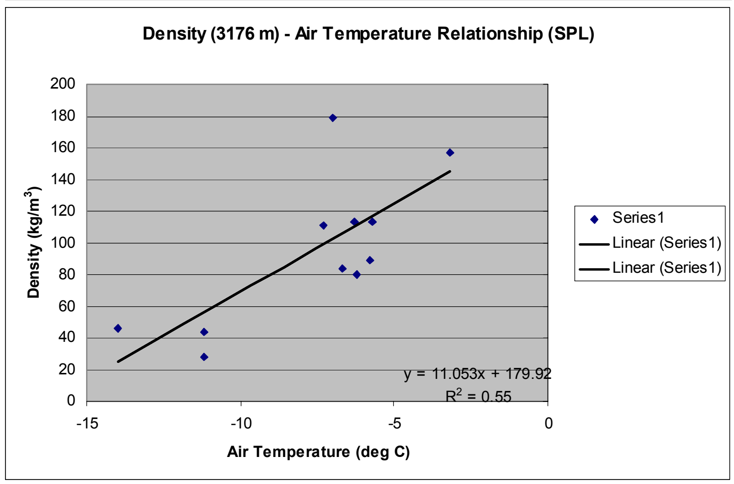


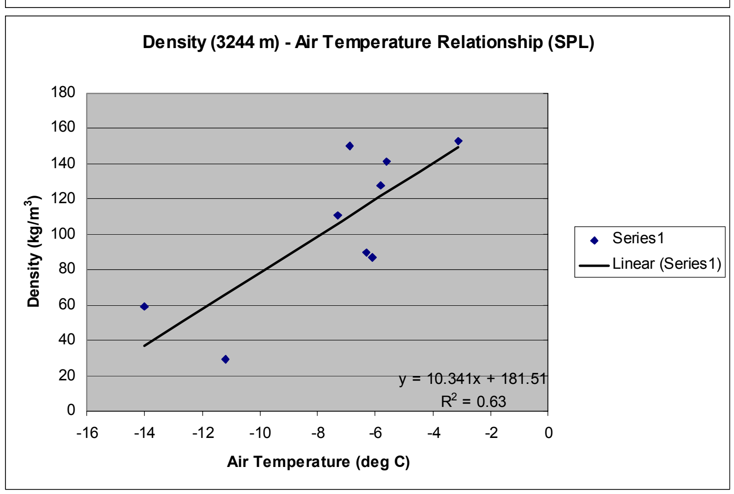
Accumulated SWE totals for each individual snow event in February 2005.

APPENDIX D

LINEAR REGRESSION PLOTS



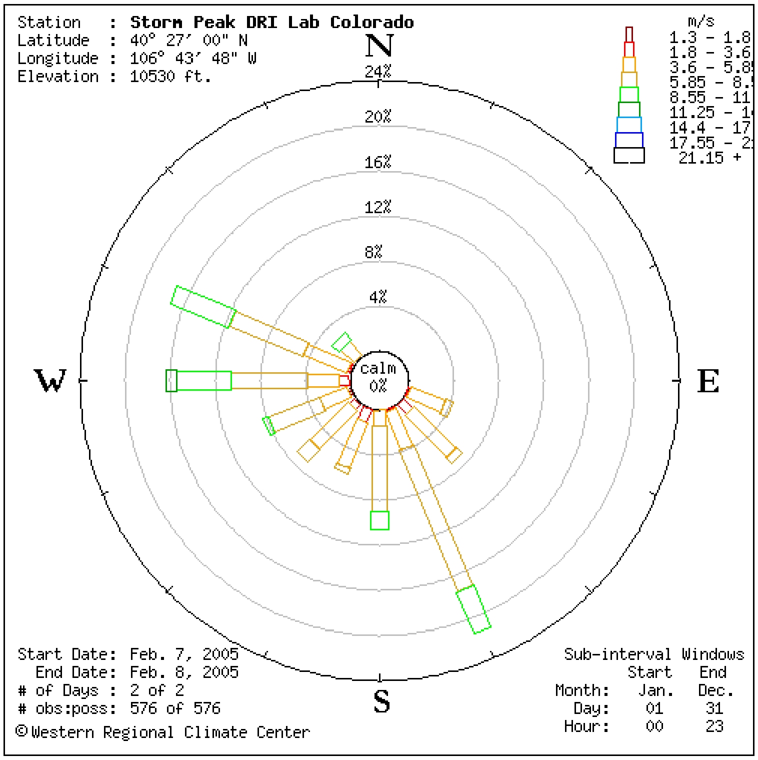


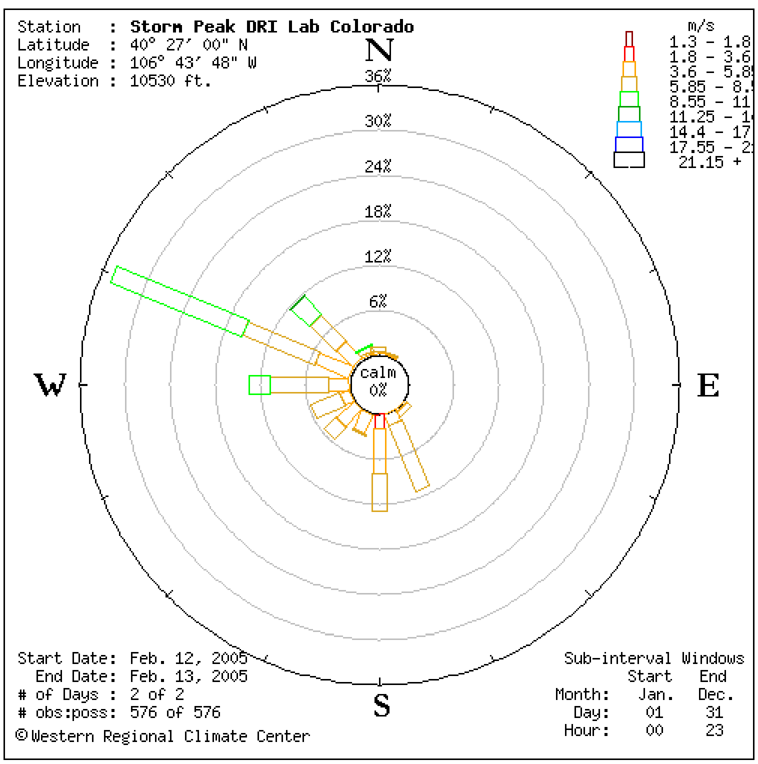


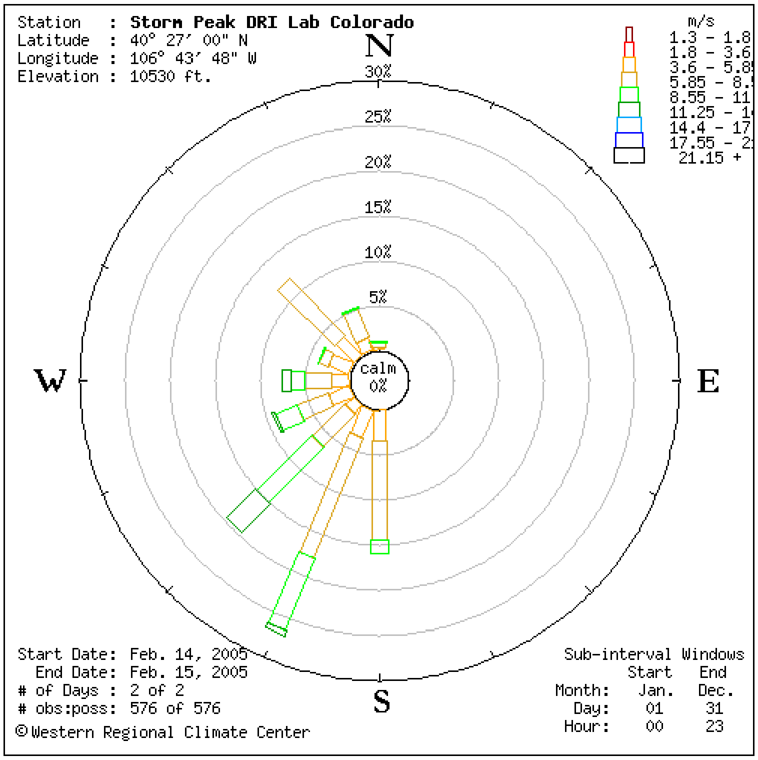
Scatterplots of density at various elevations as a function of SPL air temperature – February 2005.

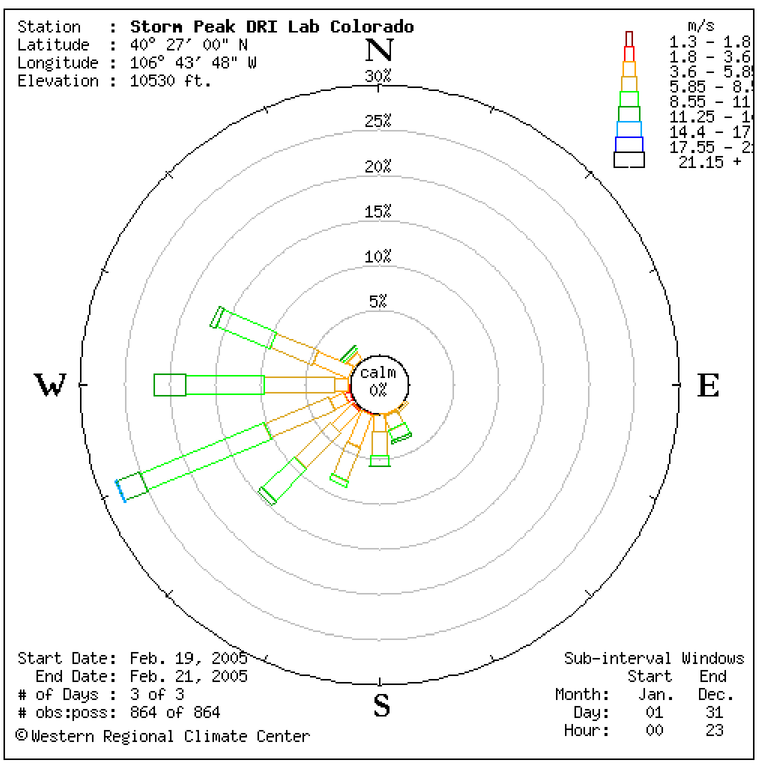
APPENDIX E

WIND ROSE GRAPHS


Station : Storm Peak DRI Lab Colorado
Latitude : 40° 27′ 00" N
Longitude : 106° 43′ 48" W
Elevation : 10530 ft.
N
E
S
W
24%
20%
16%
12%
8%
4%
calm
0%
m/s
1.3 - 1.8
1.8 - 3.6
21.15 +
Start Date: Feb. 7, 2005
End Date: Feb. 8, 2005
# of Days : 2 of 2
obs:poss: 576 of 576
©Western Regional Climate Center
Sub-interval Windows
Start End
Month: Jan. Dec.
Day: 01 31
Hour: 00 23


Station : Storm Peak DRI Lab Colorado
Latitude : 40° 27′ 00" N
Longitude : 106° 43′ 48" W
Elevation : 10530 ft.
N
E
S
W
36%
30%
24%
18%
12%
6%
calm
0%
m/s
1.3 - 1.8
1.8 - 3.6
21.15 +
Start Date: Feb. 12, 2005
End Date: Feb. 13, 2005
# of Days : 2 of 2
obs:poss: 576 of 576
©Western Regional Climate Center
Sub-interval Windows
Start End
Month: Jan. Dec.
Day: 01 31
Hour: 00 23





Wind rose graphical representations each snow event – February 2005.

APPENDIX F

SNOW SAMPLING DATA TABLES

KEY	Unit of measure
Date	month/year
Time	24 hr
Wind Speed (WS)	m/s
Wind Direction (WD)	0-360
Barometric Pressure (BP)	millibar
Precipitation (Precip)	S = Snow, –S = light snow, +S = heavy snow, PC = partly cloud
Density	kg/m^3
Depth	cm
Snow-water Equivalent (SWE)	mm
Crystal Size	mm
Crystal Habit	1=plates, 2=stellar, 3=columns, 4=needles, 5=spatial dendrites, 6=capped columns,7=irregular, 8= graupel, 9=ice, 0=hail
Riming	0-5
Saltation	Yes or No
Coefficient of Variation (CV) - density	%

	3244m			3176m			2771m			2557m			2200m		
Date	2/7	2/8	2/8	2/7	2/8	2/8	2/7	2/8	2/8	2/7	2/8	2/8	2/7	2/8	2/8
Time	15:00	08:00	14:45	15:30	08:35	15:05	16:00	09:00	15:30	16:30	10:00	15:45	16:40	10:30	16:00
WS	2	1.6	2.4	4	calm	0.3	calm	0.3	0.2	2.4	0.2	0.2	1.2	calm	0.4
WD	245	240	200	270	0	300	0	260	240	225	180	140	225	0	260
BP	675	678	679	681	684	685	718	713	723	737	742	742	770	779	776
Precip	S	-S	-S	S	S	-S	-S	S	PC	S	S	PC	S	S	PC
Density															
#1	65	54	50	69	44	47	100	45	40	74	50	70	62	52	0
#2	75	54	71	89	45	47	78	48	40	68	49	83	80	56	0
#3	64	57	55	94	43	45	76	48	40	89	52	70	78	53	0
Depth															
#1	7.6	20.2	4.0	7.2	25.0	4.2	5.0	28.4	5.0	5.4	24.0	1.4	4.8	23.0	0
#2	8.0	20.2	4.2	7.8	24.0	4.2	6.4	29.0	5.0	5.8	24.4	1.2	5.0	23.0	0
#3	7.8	21.0	3.6	7.4	25.2	4.4	6.5	29.0	5.0	5.6	24.8	1.4	5.1	22.4	0
SWE															
#1	5.0	11.0	2.0	5.0	11.0	2.0	5.0	13.0	2.0	4.0	12.0	1.0	3.0	12.0	0
#2	6.0	11.0	3.0	7.0	11.0	2.0	5.0	13.0	2.0	4.0	12.0	1.0	4.0	13.0	0
#3	5.0	12.0	2.0	7.0	11.0	2.0	5.0	14.0	2.0	5.0	13.0	1.0	4.0	12.0	0
Crystal Size	1	2	2	1	2	1	1	3	2	2	4	2	2	3	*
Crystal Habit	4,5	2	2	4,5	1,2,5	2,6	4	2	2	2,4	2	2	2	2	*
Riming	4	2	0	4	0,1	0	3,5	0	0	2	0,1	0	2	1	*
Saltation	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No
CV (density)	8%	3%	18%	15%	2%	2%	15%	3%	0%	14%	3%	10%	13%	3%	*

	3244m		3176m		2771m	2557m	2200m
Date	2/12	2/13	2/12	2/13	2/13	2/13	2/13
Time	14:45	09:10	15:30	09:35	10:00	10:30	10:45
WS	0.4	0.8	0.8	calm	calm	Calm	calm
WD	10	340	260	0	0	0	0
BP	677	683	683	689	726	745	778
Precip	+S	-S	-S	-S	-S	PC	PC
Density							
#1	146	141	158	186	133	112	139
#2	155	155	158	188	129	131	139
#3	159	154	154	163	132	134	125
Depth							
#1	4.1	12.8	3.8	8.6	12.0	8.0	3.6
#2	4.2	12.9	3.8	8.5	12.4	8.0	3.6
#3	4.4	13.0	3.9	9.2	11.0	8.2	3.2
SWE							
#1	6.0	18.0	6.0	16.0	16.0	9.0	5.0
#2	6.5	20.0	6.0	16.0	16.0	10.5	5.0
#3	7.0	20.0	6.0	15.0	14.5	11.0	4.0
Crystal Size	1,2	2,3	1	2,4	2,3	2	2
Crystal Habit	4,9	2,1	9	2	2,3	2	2
Riming	5	3,4	5	3	2,3	*	3,4
Saltation	No	Yes	No	No	No	No	No
CV (density)	4%	5%	1%	7%	1%	9%	6%

	3244m			3176m			2771m			2557m			2200m		
Date	2/14	2/15	2/15	2/14	2/15	2/15	2/14	2/15	2/15	2/14	2/15	2/15	2/14	2/15	2/15
Time	14:10	07:45	14:20	14:30	08:00	14:40	14:50	08:45	15:00	15:00	09:15	15:10	15:15	09:30	15:30
WS	5.4	calm	0.2	0.3	0.2	Calm	0.5	0.2	calm	2.7	0.1	1.6	5.0	0.6	0.2
WD	250	0	280	310	300	0	250	260	0	220	240	200	180	330	175
BP	680	680	682	685	686	688	721	723	726	740	743	745	771	776	778
Precip	-S	S	-S	PC	+S	-S	PC	+S	PC	PC	+S	PC	PC	S	PC
Density															
#1	133	86	29	83	80	26	83	74	53	143	84	53	0	65	69
#2	132	85	30	94	79	27	88	78	53	150	77	53	0	64	69
#3	119	89	28	91	81	30	98	72	55	167	80	55	0	67	74
Depth															
#1	3.0	14.0	24.0	4.8	16.2	23.0	4.2	17.6	16.0	1.4	15.4	10.8	0	15.4	7.2
#2	3.8	14.2	24.6	4.8	16.4	23.8	4.0	18.0	16.0	2.0	15.6	11.0	0	15.6	7.2
#3	4.2	14.6	24.8	4.6	16.0	23.6	4.1	18.0	16.4	1.8	15.0	10.8	0	15.0	7.4
SWE															
#1	4.0	12.0	7.0	4.0	13.0	6.0	3.5	13.5	8.5	2.0	13.0	6.5	0	10.0	5.0
#2	5.0	12.0	7.5	4.5	13.0	6.5	3.5	14.0	8.5	3.0	12.0	7.0	0	10.0	5.0
#3	5.0	13.0	7.0	4.2	13.0	7.0	4.0	13.0	9.0	3.0	12.0	7.0	0	10.0	5.5
Crystal Size	2	2	2	1,2	2	2,3	1	3	2	1	2	2	*	2,3	2
Crystal Habit	2	5	2	2	2	1,2	2	2	2	2	2	2	*	1,2,5	2
Riming	2	2	3	2,3	2	2	2	2	3	2	2	4	*	0	4
Saltation	Yes	No	No	No	No	No	No	No	No	No	No	No	No	No	No
CV (density)	6%	2%	3%	6%	1%	7%	8%	4%	2%	8%	4%	2%	*	2%	4%

	3244m			**3176m**			**2771m**			**2557m**			**2200m**		
Date	2/19	2/20	2/21	2/19	2/20	2/21	219	2/20	2/21	2/19	2/20	2/21	2/19	2/20	2/21
Time	10:00	14:00	08:00	10:20	14:20	08:20	10:40	14:40	08:40	11:10	15:00	09:05	11:20	15:15	09:25
WS	3.2	0.8	0.1	1.3	calm	0.1	0.9	0.8	0.5	2.1	0.8	1.1	calm	0.8	calm
WD	240	260	260	100	270	340	250	270	260	200	210	230	200	250	200
BP	678	679	683	684	685	689	720	721	726	738	740	745	769	773	778
Precip	-S	PC	S	PC	S	S	PC	S	-S	PC	+S	-S	PC	-S	-S
Density															
#1	138	83	107	106	107	109	100	125	88	125	182	86	94	0	79
#2	150	104	113	117	125	111	103	114	90	136	182	88	111	0	81
#3	135	83	114	115	107	114	109	114	89	136	167	86	111	0	80
Depth															
#1	4.0	2.4	19.6	4.7	2.8	18.4	3.0	2.0	19.4	2.4	1.1	15.2	1.6	0	14.0
#2	4.0	2.4	20.0	4.7	2.8	19.0	3.4	2.2	20.0	2.2	1.1	17.0	1.8	0	14.2
#3	4.8	2.4	20.2	4.8	2.8	18.0	3.2	2.2	20.8	2.2	1.2	16.8	1.8	0	15.0
SWE															
#1	5.5	2.0	21.0	5.0	3.0	20.0	3.0	2.5	17.0	2.0	2.0	13.0	1.5	0	11.0
#2	6.0	2.5	22.5	5.5	3.5	21.0	3.5	2.5	18.0	3.0	2.0	15.0	2.0	0	11.5
#3	6.5	2.5	22.5	5.5	3.0	20.5	3.5	2.5	18.5	3.0	2.0	14.5	2.0	0	12.0
Crystal Size	*	2	2	*	2	1,2	*	2,4	1,2	*	4	2	*	*	2,4
Crystal Habit	*	5	5	*	2,7,8	2	*	7,8	1.2,5	*	8	2	*	*	2
Riming	*	4	4,5	*	4	4,5	*	4	3	*	4,5	3,4	*	*	2
Saltation	Yes	No	Yes	No	No	No	No	No	No	No	No	No	No	No	No
CV (density)	5%	13%	3%	5%	9%	2%	4%	5%	1%	4%	4%	1%	9%	*	1%

Field observation data for each storm event – February 2005.