EVALUATING THE IMPORTANCE OF CRYSTAL-TYPE ON NEW SNOW INSTABILITY: A STRENGTH VS. STRESS APPROACH USING THE SNOSS MODEL

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ABSTRACT: Understanding new snow instability is the key factor in predicting the release of direct action avalanches during storm cycles. The compaction rates, shear strengths and densities of various crystal-types were experimentally measured during a two winter field project in the Cascade Mountains of Washington State.

Cold-type crystals, such as bullets and sideplanes, showed relatively high density rates and moderate shear strengths. In contrast, warmer-type, dendritic crystals, such as dendrites and stellars, exhibited low shear strengths at very low densities. Warmer, non-dendritic types, such as needles and sheaths, were found to have moderately high densities and low to moderate shear strengths. Riming increased the density and shear strength of a given crystal type.

The SNOSS model has been developed as a tool in forecasting these types of avalanches but the model's present form does not incorporate crystal-type in its stability calculations. Our measurements show that the SNOSS model could be improved by adding crystal-type factors to initial density calculations and possibly to shear and densification rate equations as well.

New mesoscale weather forecast models which incorporate crystal habit parameterizations have the potential to greatly improve the forecasting of direct action avalanches when combined with a SNOSS-type stability model.

KEYWORDS: crystal-type, shear strength, densification, direct action avalanche, stability index

1. INTRODUCTION

In modeling natural releases in storm snow cycles (i.e., direct action avalanches) it is important to accurately parameterize some of the rheological properties of new snow. In particular how quickly new snow gains strength, whether it is through mechanical compression or metamorphic strengthening, is of critical significance to simple strength vs. stress models such as SNOSS (Hayes et al., 2004).

Previous studies have examined this basic relationship by computing a strength factor index (SFI) for individual layers within the snowpack (Perla et al., 1982, Fohn, 1986, Jamieson and Johnston, 1995). This index is defined as the strength of a homogeneous layer divided by the stress on the snow layer due to overburden, i.e. the slope-parallel shear force on the layer due to gravity. In the simplest models, a release is predicted to occur when the SFI index is less than one, i.e. the stress on the layer overcomes the layers strength. (Note: early empirical data, which assumes the SFI index is calculated using a standard methodology employing shear frames to measure strength, suggests that natural releases may actually occur at a ratio closer to 1.5. (Fohn, 1986 and Jamieson et al., 2007) This is partly due to scaling factors to be discussed subsequently.)

One of the main issues of complexity in calculating the SFI for a particular slope involves tracking the strength evolution of a weak layer. Specifically, this concerns estimating the initial strength of a weak layer and then predicting its increased strength over time due to such factors as destructive metamorphism and pressure sintering. The SNOSS model considers four factors affecting the rate of strengthening: the overburden pressure, the metamorphic stress, the temperature of the layer and the density of the layer. The actual instantaneous strength of the layer is assumed to be solely a function of density.

Most of the studies on snow shear strength have used density as the predictor for shear strength. Many studies have shown a relatively good correlation between shear strength

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and density. In their work with shear frames, Jamieson and Johnston evaluated many data sets and found reasonably well matched parameterizations for shear strength using density and basic crystal type as variables (Jamieson and Johnston, 2001). However, it should be noted that these studies have considered new snow as a single crystal type (i.e., precipitation particles), with the exception of graupel as a separate type. For its part, SNOSS parameterizes shear strength as a function of density squared which is slightly greater than the average of value of denstiy^1.92 for Jamieson and Johnston's two groups of crystal types combined.

This study will look at new snow crystal type and its role in determining a) new snow density, b) rate of densification, and c) new snow shear strength. Key questions to be answered include:

1) How well does crystal-type predict new snow densities compared with traditional measured parameters, such as air temperature?

2) Does the rate of densification depend entirely on snow temperature, overburden, type and rate of metamorphism or is crystal-type an important factor.

3) How well does density determine the initial shear strength for new snow? Is the change in density over time well correlated to the change in shear strength over time?

It can be hypothesized that shear strength is determined by the strength and number of bonds between snow crystals and that density is merely a proxy for these underlying variables. New snow crystals may have varying numbers of contact points and potential bonding sites depending on their shape or form (crystal habit) and their size. Thus, crystal-type may be a better predictor of new snow strength than density. The strength of the density/shear correlation from previous studies may be due in part to the correlation of high density to measurements of older snow layers which tend to densify as bonds increase, strengthen and grow over time due to destructive metamorphism and pressure sintering.

At the very least, it could be hypothesized that new snow density is directly related to crystal type since the size of the pore spaces between crystals (or how tightly packed the crystals are) is likely determined primarily by crystal type and size. Even if density proves to be a reliable measure for the evolution of shear strength, crystal type information may be useful for calculations of initial density and initial shear strength.

2. FIELD WORK

In 2006 an NSF grant was received by the University of Washington Dept. of Atmospheric Sciences Cloud Physics Unit. This grant provided funding for the study of snow crystal habits and densities for the purpose of improving model parameterizations of cloud microphysical processes. The field work supported by this study promised the potential for acquiring a large data set of detailed meteorological and snow crystal measurements. Thus, by co-locating with an existing meteorological study there existed a unique opportunity for avalanche research involving the study of crystal-types and new snow instabilities.

The field work for this study occurred during two winter seasons (2006-7, 2007-8). During the first season a snow lab research trailer was located at Snoqualmie Pass in the Washington Cascade Mountains. At an elevation of 921 meters this east-west pass receives significant snowfall despite its relatively low elevation, primarily due to cool easterly flow generally preceding frontal passage of synoptic scale systems. It also occasionally receives abundant snowfall form convergence zone effects due flow around and over the Olympic Mountains to the west.

Figure 1: Stevens Pass Study Area. Note: shear tables to the right of trailer and settlement tube shelter attached near trailer door.

For the 2006-7 season the snow lab research trailer was located just east of the crest of Snoqualmie Pass at an elevation of 870 meters. The trailer contained a cold lab in which to observe and record snow crystals via a high-powered stereoscopic microscope and camera. It also contained a warm section for monitoring incoming storms and sensor output via computer.

At the trailer site various meteorological data were continually recorded including precipitation rate, wind speed and direction, temperature, humidity, particle size and particle fall speed. Next to the trailer, snow pit data was recorded and shear frame tests were performed. Due to the low elevation of the pass, the research site frequently received a rain/snow mix of precipitation following frontal passage. This unfortunately limited the amount of shear frame data collected for the 2006-7 season.

A higher location in the Washington Cascades was chosen for the 2007-8 season. The research trailer was located at east/west oriented Stevens Pass, elev. 1238 meters, which is about 80 km north of Snoqualmie (see Figure 1). Meteorological data similar to last seasons was collected in addition to more controlled shear frame data and information on snow densification.

A study area located directly adjacent to the trailer allowed shear measurements to be performed on elevated tables, thereby ensuring measurements in new snow only. Densification measurements were performed in a shelter attached to the north side of the trailer using snow tubes. (Procedure details to be discussed in the subsequent section on methodology.) A total of 393 shear measurements were completed and 50 densification time series were obtained for the two winter seasons combined. Detailed crystal observations were recorded for 54 days throughout both the winter seasons.

3. METHODOLOGY

3.1 *Observing crystal-type and new snow density*

Snow crystal observations were made every 15 minutes during storms. The crystal-types were categorized on an approximate mass-percentage basis. The various degrees of riming were also noted for each crystal-type (or for the sample as a whole in the standard case of uniform riming). Classification was based on the meteorological classification of snow crystals established by Magono and Lee (1966).

New snow density was calculated by measuring snow height with a standard snow board and weighing samples collected via a snow bag system. The weighing system involved collecting snow with a plastic bag inserted in a large metal cylinder with a height of 20 cm and diameter 88 cm. At 15 minute intervals coincident with the crystal observations, the snow bag was removed and weighed and a height measurement was obtained. This allowed density and crystal-type changes to be calculated on a relatively fine temporal scale.

3.2 *Measuring snow densification rate*

Settlement tubes were constructed for measuring the compaction of snow samples due to the application of an overburden stress. The tubes were manufactured from 25 cm sections of 7 cm diameter acrylic tubing. Each tube was fitted with a low friction plastic plunger with a hollow shaft which allowed weights to be added incrementally to increase the compactive force. Height gradations were added to the tube to determine changes in piston height to the nearest 1 mm.

Snow samples were taken from a snow board adjacent to the standard snow board for crystal observations. This allowed an accurate extrapolation of crystal-type and degree of riming to the settlement tube sample. Samples were weighed and piston heights measured to determine an initially density. Weights were gradually added to the pistons over a 30 min. period to limit mechanical breakage of crystals and to avoid too much deviation from the effects of a natural snowfall.

After 30 min., a constant overburden stress was obtained in each of six cylinders. Two cylinders each had the same weight applied to limit variability due to measurement technique. This allowed the testing of three artificial snow loads at the same time on a single mix of crystal-types all with the same initial density. Settlement heights were measured on all tubes initially every 15 minutes and then less frequently depending on the rate of settlement and whether a perceptible height change was observed.

Shielded from solar radiation in the settlement tube shelter, a temperature gage/data logger allowed measurements of temperature effects upon settlement rate.

3.3 *Measuring new snow shear strength*

The standard method for obtaining a quantitative measure of shear strength involves the use of a shear frame, most commonly either 250 cm^2 or 100 cm^2. The frame is placed in the superstratum approx. 2-5mm above the weak layer (AAA Guidelines, 2004). However, for typical new snow densities (40-160 kg/m^3), the snow is too weak to support the standard shear frame.

To circumvent this difficulty a new, light-weight plastic frame was developed. To prevent the frame's settling through the low-density new snow, a light, corrugated plastic top was incorporated into the frame design. Also, to minimize the stress concentrations at the cross sections of the frame, 7 cross members were used with a depth to width ratio of 5:6, which is similar to standard sized frames (Jamieson and Johnston, 2001). This design along with a much larger frame size kept the new snow layer from being compacted by the weight of the shear frame and allowed shear measurements of sufficient magnitude so as to be measurable by a standard force gage (approx. 10-100 N).

The large frame size also helped to eliminate ambiguity concerning application of the Daniels' strength correction factor (Sommerfeld, 1980). This is the scale factor used to account for the small frame sample size in relation to the size scale of the weaknesses being tested. Essentially, the large frame size helps ensure that small scale weaknesses will be captured in the sample area allowing the layer to fail with the same shear stress as the slope as a whole. The required frame size has been estimated from data compiled by Fohn (1987). .

Performing shear tests on tables, instead of directly on the snow pack, ensured that only new layers were tested and allowed for an easy "reset" between measurements by brushing snow off of the tables. Density measurements were made at the bottom of the frame/snow interface for comparison to density measurements taken at the research trailer as a quality control check. Temporal height and crystal-type data from the research trailer allowed for precise determination of shear layer composition on the snow collection tables. Rough shears which occurred below the shear frame/snow interface were rejected due to ambiguity concerning the specific failure layer.

4. RESULTS

4.1 Effects of crystal type on density

Even from the initial observations of crystal type at 15 minute intervals during the first season of field work, it became quite apparent that crystal types changed frequently within a storm cycle and almost always involved a mix of types at any given time. It was rare to find a snow sample where a single crystal type made up more than 90% of the sample mass. Frequently crystal types progressed from cold-type polycrystals to more dendritic types and back again multiple times within a single storm. Often the samples included various amounts of graupel and graupel-like snow.

To add to the complexity of the observations the degree of riming on crystals also changed significantly within 15 minute intervals. Occasionally, densely rimed and unrimed crystals were even observed in the same sample.

Despite this variability in crystal type, there were occasions in which a single crystal type or mixture of crystals remained almost constant (variations less than 10%) for two 15-minute observation periods. This enabled a reasonably reliable density calculation to be made using the snow height and mass of snow collected for this time interval. Of course, this assumes no intermediate crystal type reversals during the observation period. Performing this type of quality control check for consistent observations substantially reduced the data set to about 20-30 density/crystal type pairings for each winter season.

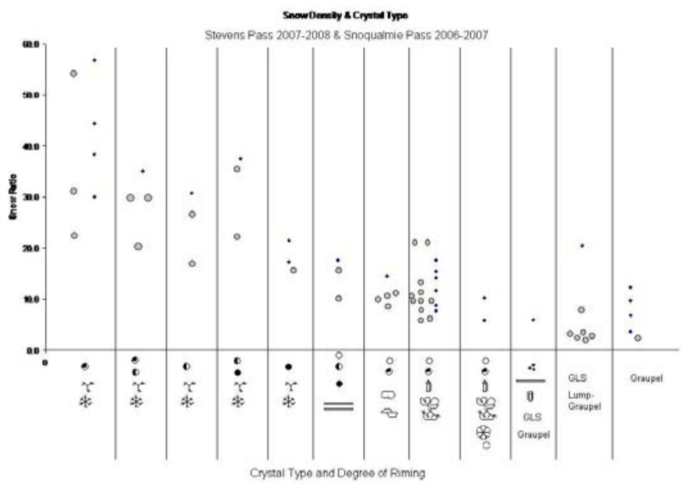

Figure 2: Snoqualmie Pass data (larger grey circles) and Stevens Pass data (smaller dark dots) for observation periods with consistent 15 min. crystal-types. Data ordered by crystal-type and degree of riming (dendrites to graupel, light riming to dense riming). Snow Ratio=1000kgm^{-3}/density.

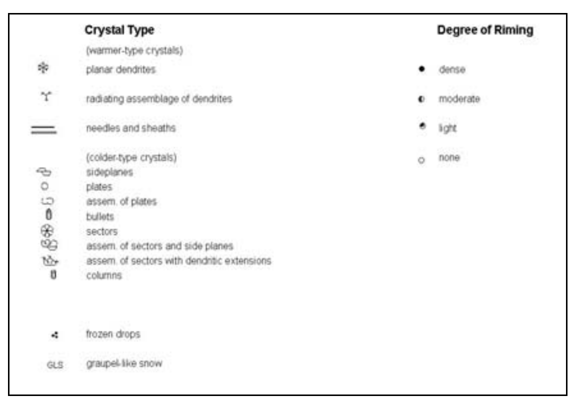

Figure 3: Guide to symbols for Figure 2.

Examining the graph of snow crystal data for Stevens Pass and Snoqualmie Pass (Figure 3), there is clearly a general trend for dendritic forms (planar dendrites and radiating assemblages of dendrites) to have low densities (high snow ratios), followed by colder type crystals (sideplanes, bullets, assemblages of sectors and plates) having higher densities (lower snow ratios). On average, observations with the highest densities consisted mostly of graupel, graupel-like snow and, in one instance, frozen drops. Within these categories there is some indication that density increases with a corresponding increase in the degree of riming. For needles and sheaths it appears that their densities may lie somewhere between the colder and dendritic types but the limited number of observations makes this rather speculative.

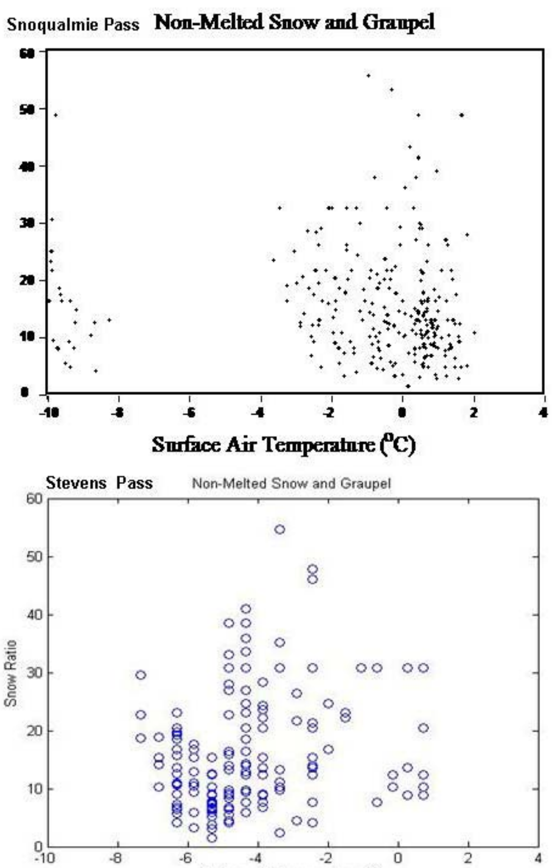

Figure 4: Surface temperature plots for all data from both winter seasons (2006-7 and 2007-8).

Predicting density from surface temperature observations would seem difficult given the large scatter in the temperature/density plot (see Figure 4). For this data there is no obvious correlation between surface air temperature and snow temperature. In general, there were observed many storms in which temperature showed very little fluctuation (frequently only 1-2 degrees Celsius) while crystal-types and densities exhibited very large and frequent fluctuations.

4.2 Densification rate (compactive viscosity)

One of the goals of this study was to determine if there is a connection between the rate of a snow layer's densification and its initial crystal type. First in addressing this link it is worthwhile to study the correlation between density and compactive viscosity (essentially the ease with which a material can be compacted). Formulations for the compactive viscosity of snow have been proposed at least since the 1950's where snow was modeled as a visco-elastic material(Kojima, 1954). Primarily, modeled as a function of density, equations for compactive viscosity have more recently incorporated a temperature dependence (Conway and Wilbour, 1999).

Until now, compactive viscosity has not been closely examined for a correlation to new snow crystal-type. If a correlation exists between crystal-type and density then clearly an indirect relationship will exist for crystal type and compactive viscosity, but the question remains whether compactive viscosity for snow at a given density will vary with crystal-type.

To test this hypothesis, the results of densification tests were compared to the predicted results from the current version of the SNOSS model. SNOSS parameterizes compactive viscosity (η_{zz}) as a function of density (ρ) using an Arrhenius function of temperature consistent with the theory on generalized creep behavior for materials (Hayes et al., 2004 and Conway and Wilbour, 1999):

$$\eta_{zz} = (A)\left(\rho^4\right)\exp\left(\frac{E}{RT_s}\right) \quad (1)$$

E = activation energy, R = gas constant, T_s = snow layer temperature.

For each experimental compaction test performed with the settlement tubes, the SNOSS model's densification equations were run with one minute time steps using temperature readings from the gage/data logger in the tube shelter. The SNOSS density was initialized with the measured value from the tube sample. The equilibrium metamorphism stress factor (σ_m =75 Pa) was used for all model runs which, given the lack of temperature gradient during the test procedure, seems reasonable. By using this value we are assuming that some snow densification occurs due to destructive metamorphism although the short measurement time periods may make this effect negligible.

Figure 5 can be interpreted as a measure of how well SNOSS parameterizes densification due to overburden while taking in to account temperature and metamorphism. For seven test runs at Stevens Pass the compactive viscosity constant (A from equation 1) was determined experimentally for all six settlement tubes on a 12 minute time interval using a smoothed linear interpolation of the data points. These values were then compared to the SNOSS value initialized with observed density and run with temperature data synchronized to the test runs. Each test contained approximately 400 data points which are plotted in the box and whisker diagrams.

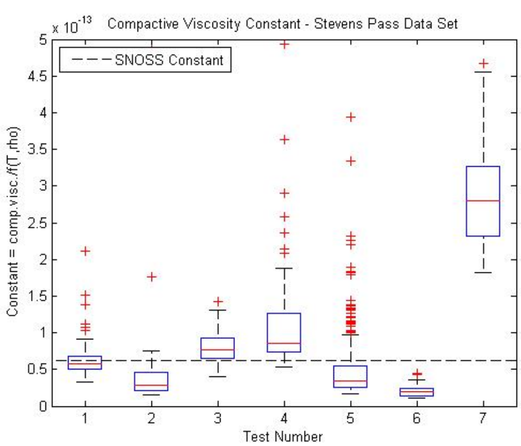

Figure 5: Compactive viscosity constant plotted against a specific mix of crystal-types (test number). Dashed horizontal line is the SNOSS model value for A . For each test, the top and bottom of the box represent the upper and lower quartiles respectively. The center line in the box is the median value. Whiskers extend to 1.5 IQR.

From examination of the graph it appears that the SNOSS parameterization of densification is reasonably accurate. Most of the median values for the seven tests fall close to the SNOSS value for the compactive viscosity constant. In a couple of cases the values are significantly different, most notably for test numbers six and seven. In these cases the SNOSS values fall outside the range of all the data points. With only two tests it cannot be determined whether the SNOSS error is due to crystal-type, temperature variations or some other effects, but it is worth noting that test number seven had the highest percentage of dendritic crystals while test number 6 had one of the lowest percentages. A SNOSS value lower than the observed value implies that the SNOSS densification rate is too high since the compactive viscosity constant term inside of η_{zz} appears in the denominator of strain rate calculations:

$$\frac{\partial \rho}{\partial t} = \rho\left(\frac{\sigma_m + \sigma_{zz}}{\eta_{zz}}\right) \qquad (2)$$

σ_{zz} = overburden stress

(Hayes et al., 2004).

4.3 Comparing initial shear strength to SNOSS

Measurements of shear strength can be analyzed in a similar way to measurements of densification by evaluating the constant factor (A_1) in the SNOSS equation (Hayes et al., 2004):

$$\sigma_{fz} = A_1 \rho^2 \qquad (3)$$

In this case a perfect fit to the data would be represented by a horizontal line for the plot of test number vs. shear constant. From figure 6 it is obvious that shear constant term is not, in fact, constant but instead varies with a strong correlation to variations in density. Thus, it would appear that a different shear strength density relation would improve the accuracy of new snow strength predictions.

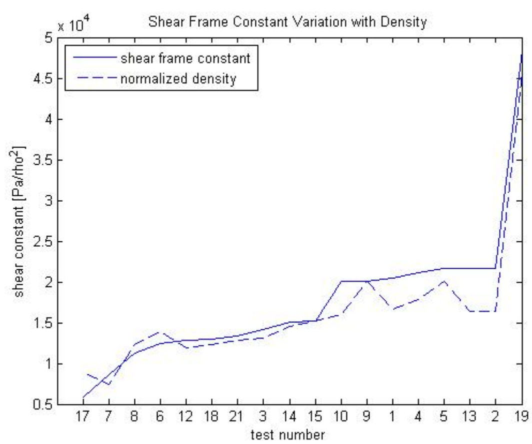

Figure 6: Variations in the value for the SNOSS shear constant (A_1) for various mixes of crystal-types (test numbers). Density has been normalized to the average shear constant value. Constant value in equation 3 for $A_1 = 1.95X10^4$.

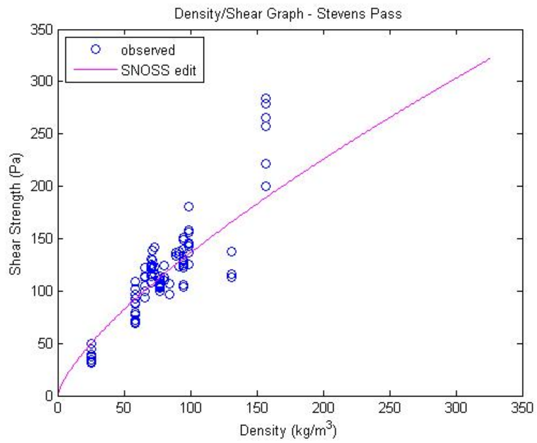

Figure 7: Best fit power law relation of density to shear strength using the edited SNOSS equation(4).

Using a power law best fit relation similar to previous studies (Jamieson and Johnston, 2001) yielded the following equation for predicting shear strength (σ_{fz}): $\sigma_{fz} = B\,\rho^{0.88}$ (4)
where B = 1002. Fitting this equation to the observed values resulted in an r-square value of 0.47 (see Figure 7). If this equation is accurate, it would indicate much easier shears in new snow than previous studies. However, it should be remembered that the technique used for measuring shear strength on these tests differed somewhat from previous studies. Nevertheless, there is reason to suspect that the SNOSS equation 3 for calculating initial shear strength before overburden may produce values that are too high.

There are a large number of previous studies measuring shear strength in older snow layers yielding a density relationship similar to SNOSS (e.g., Perla et al., 1982, Jamieson and Johnston, 2001). Thus, it may be the case that as snow ages and densifies it gains strength quickly in a relation similar to that as described in the SNOSS parameterization. However, upon initially falling without much overburden, snow shear strength may be much less than previously predicted. Of course, without overburden from a denser layer, no slab structure exists for avalanche concerns. It remains to be determined how quickly new snow gains strength towards a regime where a SNOSS-type parameterization applies.

As for crystal-type and shear strength, it appears that the new shear/density relation (equation 4) combined with a crystal-type/density relation should indirectly allow shear strength to be predicted from cystal-type. For example, low density dendrites and assemblages of dendrites exhibit low shear strengths. As expected from figures 5 and 6, cold-type crystals had higher densities but more moderate shears as predicted by the new shear/density relationship. Needles and sheaths, as mentioned earlier, may have densities between the other two types and correspondingly intermediate shear strengths.

5. CONCLUSIONS

One of the most promising results from this study is the potential for parameterizing a link between crystal type and new snow density. Previous studies on new snow densities have hinted at connections between crystal-types and densities (Judson and Doesken, 2000), but this relationship has yet to be explicitly defined in an equation. Surface air temperature alone proved to be a very poor predictor of density. Performing regression analysis on the crystal type data from this study will hopefully lead to a direct prediction of new snow density solely based on crystal type. This could potentially improve the accuracy of the initialization of avalanche forecast models which rely on density as a predictor of snow stability.

The SNOSS model's equations for snow densification seem reasonably accurate but could be improved with better predictions for initial density. Also, corrections for dendritic crystal-types may need to be added to the densification equations. A new initial shear strength parameterization may further improve the performance of the model.

An important point to consider is that the use of crystal type information is predicated on the ability of weather forecast models to accurately predict the quantity, spatial distribution and type of precipitation particles. Successful results from the weather research half of this study will hopefully lead to improved micro-physical weather models with abilities at high spatial scale resolution. A useful future project would involve using weather model output on crystal-type and applying it to the SNOSS model for a site specific area in the Washington Cascades.

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