Statistical validation of a numerical snow cover model and preliminary experimental results to facilitate model improvement

by Christopher Charles Lundy

A thesis submitted in partial fulfillment' of the requirements for the degree of Master of Science in Civil Engineering
Montana State University

Abstract:
A computer model called SNOWPACK has been developed by the Swiss Federal Institute for Snow and Avalanche Research that simulates the evolution of a mountain snowpack. Using meteorological parameters measured at mountain weather sites, a prediction of snowpack stratigraphy is made by modeling snow characteristics such as snow depth, temperature, density, grain size, and crystal type. In order to evaluate the accuracy of the model, SNOWPACK was run using meteorological variables measured at a mountain weather station near Bozeman, Montana, and weekly snow profiles were conducted to provide a benchmark for the model output. A statistical analysis was then performed in order to objectively compare the predicted snowpack to the snow profile data.

While kinetic-growth metamorphism has been investigated in the laboratory previously, new technologies allow similar experiments to be performed with greater accuracy and efficiency. A methodology was developed that utilizes a computed tomography (CT) scanner to obtain cross-sectional images over time of a snow sample under a large temperature gradient. Using innovative stereological software, the microstructural properties of the snow can then be measured from the two-dimensional CT images.

SNOWPACK predicts snowpack temperatures with reasonable accuracy, but is less effective at simulating density. Different definitions of grain size utilized by the model and human observers resulted in large variations between the modeled and observed grain size. Predicted and observed grain types also demonstrated low correlation. Other aspects of the analysis suggest that the manner in which the surface energy exchange, wet snow metamorphism, and new snow density are modeled need refinement. Despite these deficiencies, SNOWPACK still provides the snow practitioner with a useful tool for simulating the mountain snowpack. The laboratory experiments succeeded in quantifying the changes in snow microstructure during kinetic-growth metamorphism, but are also applicable to equilibrium conditions. The presented methodology demonstrates that CT technology and stereological methods are improvements over previous techniques for investigating snow metamorphism. Since the metamorphism laws in SNOWPACK are based on snow microstructure, the results of future experiments could provide data permitting validation and improvement of these theories.

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This thesis has been read by each member of the thesis committee and has been found to be satisfactory regarding content, English usage, format, citations, bibliographic style, and consistency, and is ready for submission to the College of Graduate Studies.

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A computer model called SNOWPACK has been developed by the Swiss Federal Institute for Snow and Avalanche Research that simulates the evolution of a mountain snowpack. Using meteorological parameters measured at mountain weather sites, a prediction of snowpack stratigraphy is made by modeling snow characteristics such as snow depth, temperature, density, grain size, and crystal type. In order to evaluate the accuracy of the model, SNOWPACK was run using meteorological variables measured at a mountain weather station near Bozeman, Montana, and weekly snow profiles were conducted to provide a benchmark for the model output. A statistical analysis was then performed in order to objectively compare the predicted snowpack to the snow profile data.

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CHAPTER 1

INTRODUCTION

Introduction to Snow Metamorphism

The seasonal snowpack found in alpine environments has been the subject of both observation and organized research since at least the early 1800s (Colbeck, 1991). Much of these studies have been conducted in an effort to better understand and predict the release of avalanches, which are a significant threat to both life and property in the mountainous regions throughout the world.

In most mountainous environments, snow blankets the ground for large portions of the year. Storms throughout the fall, winter, and spring deposit fresh snow which accumulates over time to create the seasonal snowpack. Since these snowfalls are often separated by periods of contrasting weather, such as sunny, warm periods, cold snaps, or high winds, the snowpack is often observed to have a stratified configuration (Seligman, 1936). It is on these layers that avalanches often initiate and slide.

Once on the ground, the snow creates a complex granular aggregate comprised of ice grains and interstitial pore space. The porous nature of the snowpack is of great consequence as it allows the transference of water, either as a vapor or liquid, within the material. Dry snow is a three-constituent material composed of the solid and vapor states of water as well as air. If liquid water is present, as it often is during warmer periods of the winter and especially in the spring, the snow is classified as wet.

As soon as new snow lands on the snowpack, it begins a process of metamorphism that continues until it finally melts in the spring and summer. This phenomenon was first described in detail by Paulcke (1934), although it is commonly believed that the changes occurring within the seasonal snow pack have been observed since the 1800s. Metamorphic processes are complex and change the properties of the individual snow grain as well as its relation to the snow particles surrounding it. Snow crystals may become smaller or larger, change shape, and become more or less bonded to its neighboring grains. While similar metamorphic processes may be taking place in snow within a common horizontal layer, snow at different vertical levels will often be metamorphosing very differently. Frequently, this serves to further differentiate the successive layers of snow, intensifying the stratified structure of the snowpack. Other times, metamorphism causes portions of the snowpack to become more homogenous.

Types of Snow Metamorphism

Generally, two distinct metamorphic processes are recognized; the first is termed equilibrium metamorphism and is characterized by the production of smaller, rounded snow grains that are well-bonded to neighboring crystals. Snow that has undergone equilibrium metamorphism is typically strong and fairly dense. The second type of metamorphism results in weaker, larger-grained snow and has been termed kinetic-growth metamorphism. The resulting snow grains are angular, hexagonal, or faceted in shape and often poorly bonded to surrounding snow particles. The extent of the intergranular bonding depends on the snow density, temperature, temperature gradient, and orientation of the bond relative to the temperature gradient.

The type and rate of metamorphism occurring within the layers of an alpine snowpack is dependent on several parameters, including the temperature, temperature gradient, overburden pressure, density, and crystal type of the snow layer. Of these factors, temperature gradient is the most critical in controlling which type of metamorphism dominates. Temperature gradients develop within the snow cover since the base of the snowpack in contact with the ground is held at a relatively constant 0 deg C due to stored summer heat, and the air temperature at the snow surface is often significantly colder. When the snowpack is deep and the ambient air temperature is warm, the temperature gradient within the snow cover will be small and equilibrium metamorphism will be the most prevalent. These conditions are common in coastal or maritime climate regimes. In the more inland, or continental, mountain ranges, the snowpack is typically shallow and the air temperature is colder. The result is higher temperature gradients which drive kinetic-growth metamorphism.

Overview of Kinetic-Growth Metamorphism

As a result of the large thermal differences within the snow cover, a gradient in vapor pressure forms so that water vapor diffuses within the snow pore space (Colbeck, 1983), a process which has been conceptualized for over forty years as the "hand-to-hand" delivery of water vapor (Yosida et al, 1955). This visualization conveniently describes the fundamental process of kinetic-growth metamorphism: the sublimation of water vapor from a "source" grain and the subsequent vertical diffusion and condensation onto a "sink" grain. As the diffusion process continues, larger crystals tend to grow rapidly at the expense of smaller grains. The result of kinetic-growth metamorphism is, in the early stages, angular ice grains characterized by flat faces and sharp edges. As the crystals reach more advanced stages of development, the growth of the crystals become oriented normal to the slope; the resultant snow grains are typically hollow, striated columns or cups. In the final stage of the metamorphic process, the crystals become columnar with the c-axis oriented perpendicular to the sope. These new crystal types are often called faceted grains, temperature gradient (TG) snow, kinetic-growth forms, recrystallized snow, or depth hoar.

During the formation of faceted snow, water vapor can move through the snow pore space either by diffusion or convection. While diffusion is generally accepted as the dominant process during metamorphism, the role of convection has been subject to conjecture. Trabant and Benson (1972) calculated vapor fluxes that were an order of magnitude higher than those predicted by early diffusion-only models (Bader, 1939; Giddings and LaChapelle, 1962). They attributed these higher rates to convection within the snowpack. However, these differences have been attributed to faults in the early models by Colbeck (1980), who points out that the one-dimensional diffusive vapor flow equations used by previous models can significantly underestimate the vapor flux. Experiments conducted by Akitaya (1974) demonstrated that convection was likely to occur only if the pore spaces in the snow were extremely large and the temperature gradients very high, and concluded conditions sufficient for convection were unlikely in natural snow covers. Indeed, most recent models (e.g., Sommerfeld, 1983; Colbeck, 1983; Gulber, 1985; Christon et al, 1993; Satyawali et al, 1999) do not account for convective action.

Since vapor flux through the interstitial pore space is fundamental to kinetic-growth metamorphism, the snow must be sufficiently porous to facilitate significant mass transfer. Large faceted crystals tend to grow most readily in new snow or lightly compacted snow of low density where a large air space is present (Akitaya, 1974). In snow with densities greater than about 350 kg/m^3, the kinetic-growth process is inhibited and a “hard” depth hoar forms (Akitaya, 1974; Marbouty, 1980). The resulting crystals are still angular, but differ from normal depth hoar in that they are much smaller and possess considerable strength derived from a higher degree of bonding.

While an exact value for the critical temperature gradient necessary for kinetic-growth metamorphism is difficult to determine due to its dependence on temperature as well as snow density and structure (Adams and Brown, 1983; Colbeck, 1983), a vapor pressure gradient of 5 mb/m was found to be sufficient to initiate growth of faceted snow (Armstrong, 1985). Throughout the literature, a threshold temperature gradient between 10-20 deg C/m is typically cited.

A variety of conditions can exist within the snowpack that give rise to temperature gradients large enough to drive kinetic-growth metamorphism. The most common situation for permitting the growth of large faceted crystals occurs during early winter when the snowpack is shallow, air temperatures are cold, and the snow on the ground is often of low density. These conditions are especially prevalent in continental, high-altitude climates where depth hoar is observed to grow nearly every season. Since the rate of metamorphism is an increasing function of temperature, the strongest faceting usually occurs near the ground at the base of the snowpack. Under these circumstances, the thermal gradient would be considered negative; that is, the temperature decreases in the direction of the snow surface causing a net upward transfer of water vapor. Field researchers (Perla and Martinelli, 1976) have also observed that faceted grains are often found above and below high-density crust layers formed from sun, rain, or wind action. This has been attributed to local increases in temperature gradient due to the higher thermal conductivity of the dense layer (Adams and Brown, 1983). Recently, more attention has been given to faceted snow that forms in the upper regions (top .20-.30 m) of the snowpack. These grains, which have been reported by many snow researchers and avalanche practitioners, are termed near-surface faceted crystals (Birkeland, 1998) and are typically much smaller than depth hoar. Birkeland (1998) identified three different sets of surface conditions which can give rise to very large temperature gradients in excess of 100 deg C/m.

In addition to altering the original crystal shape and size, kinetic-growth metamorphism significantly changes the thermo-mechanical properties of the snow. As the original snow crystals disappear during the recrystallization process, their bonds are also lost (Colbeck, 1983). Thus, bond formation cannot keep up with bond loss (de Quervain, 1963), and the bonds that do exist will be smaller relative to the new crystal. Furthermore, the majority of bonding that does occur takes place between grains that are above or below each other, forming vertically-oriented chains of depth hoar crystals. While the snow maintains considerable compressive strength, shear strength rapidly decreases as kinetic-growth metamorphism progresses. The end result is a fragile "house of cards" scenario where the entire snowpack is weakly supported by depth hoar, often requiring only a small additional load to cause complete failure of the layer. As long as the snowpack remains cold, faceted grains are very resistant to rounding or bonding which would ultimately strengthen the snow. As a result, once faceted snow forms, it often remains a persistent threat in the mountain snowpack. Depth hoar resulting from kinetic-growth metamorphism is responsible for very large and destructive avalanches, often causing the entire snowpack to fail right down to the ground.

Kinetic-Growth Metamorphism Research

Kinetic-growth metamorphism has been the subject of more formal research than perhaps any other phenomena associated with the alpine snowpack. There has been a tremendous amount of investigative and experimental work done in both laboratory and field settings (i.e. de Quervain, 1963; Akitaya, 1967, 1974; Marbouty, 1980; Trabant and Benson 1972; Bradley et al,1977; Adams and Brown, 1982), in addition to theoretical studies attempting to model the complex physical processes involved with metamorphism (i.e. Colbeck, 1983; Adams and Brown, 1983; Christon et al, 1987; Gray and Morland, 1993). Early observations from field workers and snow practitioners identified depth hoar as a major cause of avalanches, thus underscoring the necessity of such research.

The conditions necessary for kinetic-growth metamorphism have been duplicated in the laboratory (de Quervain, 1963; Akitaya, 1967, 1974; Marbouty, 1980) and the resulting faceted crystals have been analyzed. The prevailing conditions in Fairbanks, Alaska, are very conducive to depth hoar formation, and detailed field observations, experiments, and analyses have been performed in this environment by Trabant and Benson (1972). Work has been done by Birkeland et al (1998) to measure the strong temperature gradients near the snow surface which often result in faceted snow occurring in the upper regions of the snowpack.

The result of previous research has been a thorough understanding of the physical processes that occur during kinetic-growth metamorphism. However, little work has been done to quantitatively describe the changes in snow microstructure (i.e. grain size, bond size, neck length, coordination number, etc.) during metamorphic processes. Consideration of snow microstructure has been shown to be important to accurately model kinetic-growth metamorphism, as well as other types of snow properties including viscosity and thermal conductivity (Brown, personal communication, 1999). The microstructural quantities used to describe the granular network of snow are numerous and diverse. Parameters that appear frequently in the literature include bond radius, neck length, number of bonds per grain, number of bonds per unit volume, volume of a single grain, intercept length, surface area per unit volume, and coordination number (Kry, 1975; Gubler, 1978; Perla, 1986; Hansen and Brown, 1986; Edens and Brown, 1994). The relative importance associated with each of these quantities seems to depend on the author and the formulation of the model that utilize them.

Despite the important role snow microstructure plays in metamorphic processes, very few laboratory investigations have attempted to measure the change in microstructural parameters of snow over time. In Switzerland, depth hoar was grown in a laboratory, and surface sections of samples taken from this depth hoar were analyzed in order to see how the snow microstructure changed with time (Brown, personal communication, 1999). A similar experiment was performed by Fierz and Baunach (2000), and while certain microstructural properties were measured, important parameters describing the nature of bonding between the snow grains were not taken into account.

Computed Tomography

A major impediment to research of this nature has been the destruction of the snow specimen that is being examined. Current techniques of snow sample analysis, whether looking at individual crystals under magnification or performing surface or thin sections,

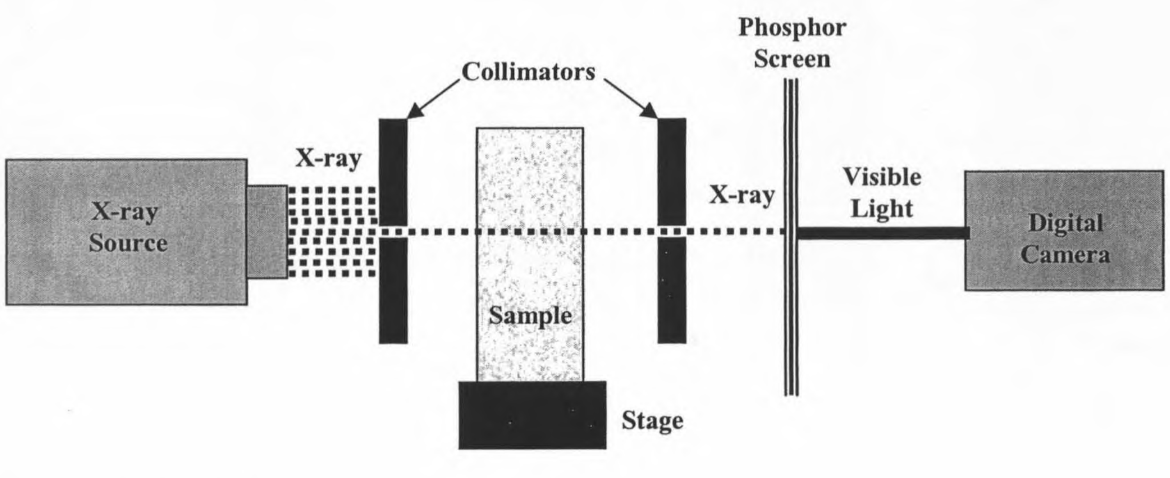

Figure 1. Illustration of CT scanner operation.

necessarily alter the specimen irreversibly. Up to this point, it has not been possible to continually analyze the properties of the *same* sample of snow during metamorphic processes. Many scientists have attempted to observe changes in snow properties over time by removing specimens of snow from a larger sample at regular intervals, but this introduces significant error due to spatial variation since each specimen is taken from a different location. Regarding recent metamorphism experiments, Brown reported significant scatter in their data because of this variability (personal communication, 1999). However, recent acquisition of CT scanners by several major research facilities worldwide have led to the development of a new tool for examining snow microstructure, one that allows nondestructive analysis of a snow sample.

Overview of Computed Tomography

Computed tomography (CT) uses an X-ray beam and digital camera to examine a cross-sectional slice of an object. The primary components of a CT scanner include an x-ray source, a sample stage, and a detection system (Figure 1). As the x-ray leaves its source, it travels through a collimator – two parallel lead plates – that narrow the beam into a flat, horizontal plane. This "plane" of x-ray transects the sample mounted to the stage and passes through another collimator before reaching the detector. The detection system consists of a phosphor screen that converts the x-ray into visible light and a high-resolution digital camera. The result is a very thin digital radiograph. This process is repeated, typically on one degree steps, as the sample or x-ray source is rotated through a full revolution. By taking many closely-spaced horizontal CT cross-sections along the vertical axis of a sample, it is possible to reconstruct its three-dimensional internal structure.

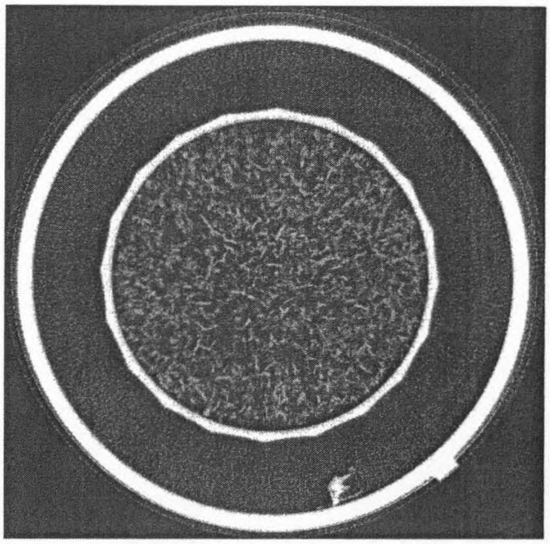

Figure 2. Two-dimensional CT image of faceted snow.

The variation in X-ray absorption of the sample is dependent on the density and, to a lesser extent, the chemical composition of the object, and it is represented by different intensities of light reaching the camera. By recording the plane of an object at many different angles through a full revolution, it is possible to mathematically extract the density of each point within the plane. This two-dimensional density map constitutes a CT image (Figure 2) and provides accurate information about the internal structure of an object. The utilization of computed tomography in the medical field is well known and its prevalence among other branches of science is increasing.

Application of Computed Tomography to Snow Research

Naturally, CT imaging is a promising tool to explore the internal structure of snow and ice. To date, its use in this regard is not well documented; however, several research institutions throughout the world have begun to explore its potential. The Swiss Institute for Snow and Avalanche Research (SLF) is currently in the process of acquiring a CT scanner (Lehning, 2000, personal communication), and in Japan, it has been used as a tool for investigating the structure and three-dimensional density of sea ice (Kawamura, 1990). To date, the largest advances made in this area have been achieved by French researchers at the Centre d'Etudes de la Neige (CEN) (Coleou et al, 2000). Using computed tomography and a powerful reconstruction software, three-dimensional images with a resolution of 10 μm were obtained of a small snow specimen (9mm × 9mm cylinder). However, to achieve these results required over 200 hours of scanning for each sample, in addition to an unspecified amount of time for image reconstruction and analysis. At Montana State University, scientists have used a CT scanner to search for biological matter in Antarctic ice cores and to investigate deformation of snow under axial loads (Adams, personal communication, 1998), and have demonstrated the utility of CT technology to collect nondestructive, two-dimensional images of snow microstructure (Lundy and Adams, 1998).

Stereology

The characterization of snow microstructure has been neglected by the majority of laboratory studies; a likely reason is because it is exceedingly difficult to quantify. Not only are the microstructural features of snow challenging to measure accurately, the values of these parameters can vary widely within a single snow sample. In addition to a large number of measurements, statistics are needed to provide information regarding the variation of the microstructural parameters within the snow specimen.

Historical Background of Stereology

Stereology, which literally means "knowledge of space," is a term coined by Hans Elias in 1961 to describe the emerging branch of science that allowed observations made from thin cross-sections of a specimen to be interpreted in terms of the specimen's spatial structure. Weibel (1980) defined stereology as "A body of mathematical methods relating three-dimensional parameters defining structure to two-dimensional measurements obtained on sections of the structure." These techniques that yield three-dimensional information from two-dimensional observations are becoming prevalent in biology, geology, and material science. Stereological methods are statistical in nature and provide estimates of spatial structure.

In 1847, French geologist Auguste Delesse introduced the concept of determining volume density by measuring areal density of a random two-dimensional cross-section (Weibel, 1980). A. Rosiwal, another geologist, furthered this concept in 1898 when he computed the volume fraction of a certain constituent by measuring the fraction of a randomly drawn line that intersected the particular component. Stereological methods were introduced to biological research in 1943 by Harold Chalkney at the National Cancer Institute in Bethesda. Since then, these techniques have been used extensively to investigate the internal structure of organs from microscope slides and also to quantify various parameters of bacterial colonies. In general, the evolution of stereology tended to be pragmatic: as new applications posed unique problems, solutions were found that added to the body of stereological techniques (Weibel, 1980).