



An integrated microstructural study of dry snow metamorphism under generalized thermal conditions
by Daniel August Miller, II

A dissertation submitted in partial fulfillment of the requirements for the degree of Doctor of
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Abstract:

Snow microstructure significantly influences the mechanical, thermal, and electromagnetic properties of snow. The microstructure is constantly evolving from the time it is deposited on the surface until it sublimates or melts. The resulting time variant material properties make the study of snow metamorphism of fundamental importance to a wide variety of snow science disciplines. Dry snow metamorphism has traditionally been classified by the thermal gradient encountered in the snowpack. Snow experiencing a predominantly equi-temperature environment develops different microstructure than snow that is subjected to a temperature gradient. As such, previous research has evaluated snow metamorphism based upon select thermal gradient dependent processes, when in reality, there is a continuum of physical processes simultaneously contributing to metamorphism. In previous research, a discrete temperature gradient transition between the two thermal environments has been used to activate separate morphological analyses. The current research focuses on a unifying approach to dry snow metamorphism that is applicable to generalized thermal environments. The movement of heat and mass is not prescribed, but is allowed to develop naturally through modeling of physical processes. Heat conduction, mass conservation, and phase change equations are derived in a simplified two-dimensional approach. Each differential equation is non-linearly coupled to the others through phase change. The microstructural network is then discretized into elements and nodes. Finite difference equations are developed for the network, and numerically solved using iterative techniques. The finite difference model provides a unique platform to study the influence of numerous geometric and thermodynamic parameters relating to dry snow metamorphism. Numerical metamorphism studies in an equi-temperature environment agree well with established trends and published experimental results. A smooth transition between equi-temperature and temperature gradient environments is defined and influencing parameters are examined. In the temperature gradient environment, a dominant grain theory based on crystallographic orientation is postulated through numerical modeling, and is supported by experimental observation. Several specific metamorphism applications, ranging from avalanche debris sintering to model integration in a full scale snowpack, are presented. The microstructural model has proven to be capable of evaluating metamorphism for a broad range of geometric parameters and thermal environments, yet is flexible enough to accommodate additional scenarios.

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Daniel August Miller II

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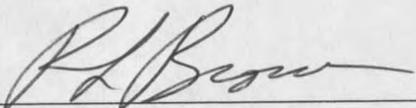
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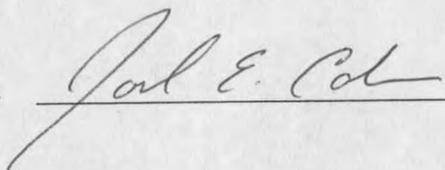
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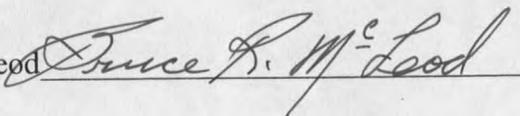
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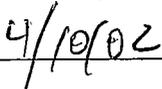


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ABSTRACT

Snow microstructure significantly influences the mechanical, thermal, and electromagnetic properties of snow. The microstructure is constantly evolving from the time it is deposited on the surface until it sublimates or melts. The resulting time variant material properties make the study of snow metamorphism of fundamental importance to a wide variety of snow science disciplines. Dry snow metamorphism has traditionally been classified by the thermal gradient encountered in the snowpack. Snow experiencing a predominantly equi-temperature environment develops different microstructure than snow that is subjected to a temperature gradient. As such, previous research has evaluated snow metamorphism based upon select thermal gradient dependent processes, when in reality, there is a continuum of physical processes simultaneously contributing to metamorphism. In previous research, a discrete temperature gradient transition between the two thermal environments has been used to activate separate morphological analyses. The current research focuses on a unifying approach to dry snow metamorphism that is applicable to generalized thermal environments. The movement of heat and mass is not prescribed, but is allowed to develop naturally through modeling of physical processes. Heat conduction, mass conservation, and phase change equations are derived in a simplified two-dimensional approach. Each differential equation is non-linearly coupled to the others through phase change. The microstructural network is then discretized into elements and nodes. Finite difference equations are developed for the network, and numerically solved using iterative techniques. The finite difference model provides a unique platform to study the influence of numerous geometric and thermodynamic parameters relating to dry snow metamorphism. Numerical metamorphism studies in an equi-temperature environment agree well with established trends and published experimental results. A smooth transition between equi-temperature and temperature gradient environments is defined and influencing parameters are examined. In the temperature gradient environment, a dominant grain theory based on crystallographic orientation is postulated through numerical modeling, and is supported by experimental observation. Several specific metamorphism applications, ranging from avalanche debris sintering to model integration in a full scale snowpack, are presented. The microstructural model has proven to be capable of evaluating metamorphism for a broad range of geometric parameters and thermal environments, yet is flexible enough to accommodate additional scenarios.

CHAPTER 1

BACKGROUND AND LITERATURE REVIEW

Introduction

The snow that perennially or annually blankets temperate and polar latitudes has a significant impact on our everyday lives. Snow is a substance of extremes: providing unique recreational opportunity and beauty, yet threatening the safety of individuals and communities. Snow can paralyze major geographic regions by restricting travel, causing property damage, and by creating life-threatening avalanche hazards. Snowcover can influence local as well as global climate changes (Berry,1981) due to interactions with the atmosphere through emissive, reflected, and absorbed radiation (Warren, 1982; Dozier et al., 1988). Snow also provides vital moisture reserves for the world. It is estimated that three-quarters of the world's terrestrial water resources are currently stored in snow and ice (Committee on Opportunities in the Hydrologic Sciences, 1991) and that snow supplies one third of the world's agricultural irrigation water (Stephun, 1981). Snow's influence in vast and diverse areas of our world makes the study of snow mechanics a uniquely rewarding endeavor.

Microstructure Significance

The formal scientific study of snow dates back to the early 1800's (Colbeck, 1991). It was recognized early on that the response of snow to its environment depends upon its thermal, mechanical, and electromagnetic properties (Arons and Colbeck, 1995). Dry snow is composed of an ice network with interstitial pores filled with a mixture of air and water vapor. Wet snow includes a liquid phase of water that may occupy the bond areas or fill the pore spaces, depending upon the water content. This unique construction makes the microscopic details of the ice and pore spaces a major influence in snow's physical behavior. The microstructure of snow (defined as structures on the scale of individual ice grains, inter-granular bonds and pores) determines the mechanical (Yosida, 1963; Hobbs, 1965; Keeler, 1969; Yen, 1969; Kry, 1975; Gubler, 1978 a,b; Brown, 1980; Armstrong, 1980; St Lawrence and Lang, 1981; Adams and Brown, 1982a; Salm, 1982; Hansen and Brown, 1988; Brown and Edens, 1991; Edens and Brown, 1991; Mahajan and Brown, 1993; Shapiro, 1997; Johnson and Schneebeli, 1999), thermodynamic (Yosida, 1955, 1963; Colbeck 1980; Adams and Brown, 1990; Adams and Sato, 1993; Arons, 1994) and electromagnetic (Warren, 1982; McClung and Schaerer, 1993) properties of snow. The intergranular bonding of snow grains comprising a snowcover affects the strength, viscosity, creep, thermal, optical and electromagnetic properties (Adams et al., 2001).

Snow Metamorphism

Snow is a unique granular material. From the time it touches the earth until it either transitions to liquid (melts) or to vapor (sublimates), the snow microstructure is

continually changing in a process called metamorphism. The time-varying microstructural quantities result in nonlinear material responses, making the study, understanding, and prediction of snow metamorphism vital to nearly all areas of snow science. The critical dependence of snow properties on microstructure makes metamorphism an extremely important area of study. Microstructural changes were first described and documented in detail by Paulke (1934), although casual observations of snowpack metamorphism came much earlier (de Quervain, 1963). In recent times, efforts to understand the evolving microstructure in snow intensified. The combination of large crystal surface area to volume ratio and homologous temperature ($T/T_{\text{melt}} > 0.9$ generally) makes snow a very nonlinear and a highly temperature dependent material (Colbeck, 1983a). Because of the relatively warm temperatures in seasonal snow, water vapor is free to migrate and diffuse in the pore spaces of the ice matrix. Specific surface areas as large as $10,000 \text{ m}^2/\text{m}^3$ (Edens, 1997) result in snow continually trying to reduce that ratio, thereby reducing the overall surface free energy (de Quervain, 1963; Hobbs, 1965; Colbeck, 1980; Langham, 1981).

In general, we will consider two categories of metamorphism depending upon the thermal environment. In a snowpack where the temperature is nearly uniform, metamorphism is termed "equi-temperature". If a significant temperature gradient is applied (frequently found in alpine snow), then "temperature gradient" metamorphism results. Traditionally, each of these conditions has been treated as separate and distinct since each results in a unique microstructure (Sommerfeld and LaChapelle, 1970). Use of the temperature environment to describe the metamorphic process is not universally accepted. In fact, the categorization of metamorphism has resulted in heated discussion

and debate. Colbeck (1980, 1982, 1983a) used crystal forms and driving forces to describe metamorphism. The current research reported here does not require a distinction between the different types of metamorphism, rather it (as a preview) uses physical processes common to both. The resulting unified approach makes the discussion somewhat obsolete and irrelevant. But, in order to present past efforts in a logical manner, the equi-temperature and temperature gradient terminology will be used with no opinion offered on its validity.

Equi-temperature Environment. "Equi-temperature" or "radius-of-curvature" metamorphism results when only very small microscale temperature gradients exist in a snowpack. The characteristic microstructure resulting from this environment is smooth rounded grains connected by smooth reverse curvature necks. An example is given in figure 1 in chapter 2. The resulting snow tends to strengthen and densify with time. In the absence of a macroscopic temperature gradient, ice particles are observed to sinter by growing the bonds between the individual grains. This sintering process is commonly referred to as equi-temperature metamorphism. Colbeck (1980) correctly pointed out that truly equi-temperature metamorphism is impossible for any process involving phase change: Heat must flow in order for phase change to occur, thereby requiring microscopic temperature gradients. Colbeck (1980) introduced the term "radius-of-curvature" metamorphism (for reasons that will be obvious later). "Equi-temperature" metamorphism will be used here with the understanding that some (even though very small and highly localized) temperature gradients must exist for phase change metamorphic processes to take place.

There are several physical processes available for the movement of water molecules in snow metamorphism. Maeno and Ebihara (1983) summarized six potential mechanisms that contribute simultaneously to the growth of necks between sintering ice particles: surface diffusion from a surface source (Kuczynski, 1949), volume diffusion from a surface source (Kuczynski, 1949), vapor transport from a surface source (Hobbs and Mason, 1964), boundary diffusion from a grain boundary source (Johnson, 1969; Colbeck, 1998; Adams et al., 2001), volume diffusion from a grain boundary source (Ashby, 1974), and volume diffusion from dislocation sources (Ashby, 1974). The question that arises is which (if any) are predominant and can any of these mechanisms be neglected? Several studies, theoretical and experimental, have addressed this issue.

Kingery (1960) showed ice particles brought together at subfreezing temperatures remain together even when the unifying force was removed. He claimed that surface diffusion from the grain surfaces to the newly formed bonds resulted in "regelation" of the particles. It was previously believed that pressure melting or a liquid-like surface layer was required for bonding, but Kingery disproved this. Kuroiwa (1961) conducted experiments similar to Kingery, but came to different conclusions on the mass transport mechanisms. Kuroiwa concluded that volume diffusion was dominant above -10°C with surface diffusion emerging and then dominating below -15°C . Hobbs and Mason (1964) and Hobbs (1974) also conducted ice sintering experiments with entirely different interpretation of results. They brought together several sizes of uniform spheres in a vapor-saturated environment. They then observed particles optically and measured bond sizes in time. Each mechanism was assumed to conform to the following law:

$$\left(\frac{r_b}{r_g}\right)^n = \frac{B(T)}{r_g^m} t$$

where t is time, $B(T)$ is a temperature dependent function, r_g is the grain radius, r_b is the bond radius, m and n are integers that depend upon the mass transport mechanism. Hobbs and Mason (1964) claimed that it is impossible to experimentally distinguish (find independent m and n coefficients) between the sintering rates of vapor, surface, or volume diffusion. In fact, they show similar rate dependence for each case. Hobbs and Mason presented convincing arguments pointing to vapor diffusion as the dominant sintering mechanism (by four orders of magnitude) based on the size of the respective coefficients. Maeno and Eblnuma (1983) confirmed the vapor transport dominance except under certain temperature and geometric conditions where surface diffusion may be significant. The small bond size required for significant surface diffusion would be very short-lived since the sintering rates are so high with small bonds. As a consequence, experiments and analysis have focused on the vapor diffusion regime. Maeno and Eblnuma (1983) have shown (analytically) the significance of surface diffusion when $r_b/r_g < 0.06$, yet Hobbs and Mason (1964) didn't report measured ratios less than 0.1. The sintering progressed so quickly (a few minutes), that the very small bond to grain ratios were not visually captured. Until recently, the prevailing consensus, over at least the previous 20 years, is that vapor diffusion is the primary sintering mechanism during metamorphism of a macroscopically equi-temperature snow pack. Other mechanisms are probably at work, but at rates much lower than vapor diffusion. The only exception is the potential short-term contribution of surface diffusion under specific temperature and geometrical conditions.

Recently, grain boundary diffusion has been given more attention as a potential sintering mechanism. Grain boundary diffusion is a sintering process that occurs at the interface of two crystals, whereby mass migrates from the center of the contact to the surface of the bond. Sintering takes place when surface tension forces pull the grains together resulting in a stress gradient from the center to the surface of the bond. Colbeck (1998;1997) applied a grain boundary diffusion model (Zhang and Schneibel, 1995) to ice. His model assumed the presence of a grain boundary stress gradient producing molecular flux, which redistributes mass evenly onto spherical ice grain surfaces. Intergranular necks were not considered. Colbeck's analysis raised the question of grain boundary diffusion significance, but did not attempt to provide physical evidence of its existence. He recognized the need for better physical constants defining grain boundary molecular mobility before the significance of grain boundary diffusion can be evaluated. Adams et al. (2001) used a scanning electron microscope to examine bonds between sintering ice grains. They discovered a grain boundary "ridge" protruding into the pore at the grain boundary surface. This ridge is thought to result from the migration of molecules from the bond center to the surface, providing the first physical confirmation of grain boundary diffusion in ice. Adams et al. (2001) also presented a mass balance analysis which brought into question the validity of grain boundary physical parameters and, potentially, our understanding of sintering.

For the current effort, sintering due to vapor diffusion is the accepted dominant mechanism, conforming to current data. Colbeck (1980) suggested a process of vapor diffusion between surfaces of different radii of curvature. He derived the vapor pressure

over curved surfaces as a function of surface curvature through the chemical potential.

Vapor pressure over curved surfaces is given by the familiar form of Kelvin's equation:

$$P = P_0 \exp \left[f \left(\frac{1}{\rho_s} \right) \right],$$

where P is the equilibrium vapor pressure over the surface, P_0 is the equilibrium vapor pressure over a flat surface at a reference temperature, and ρ_s is the average surface curvature. ρ_s is defined by:

$$\frac{2}{\rho_s} = \frac{1}{r_1} + \frac{1}{r_2},$$

where r_1 and r_2 are radii of curvature measured in any two orthogonal planes on the surface separating the phases (Colbeck, 1980). Vapor sintering takes place when vapor sublimates from a high surface energy site (a convex grain), diffuses through the pore space and then condenses on a lower surface energy site (concave bond). For convex surfaces, radii are positive; conversely, radii are negative for concave surfaces. At a given temperature, vapor pressures over convex surfaces are greater than vapor pressures over concave surfaces. Molecules will sublime from the convex surfaces, travel through the vapor, and deposit on the concave neck between grains. This is also the mechanism for the rapid decay of dendritic snow particles when they initially fall on the snowpack. The sharp convex corners have very high vapor pressure compared to the surrounding vapor and other surfaces. These sharp features decay quickly and rounded forms develop. The same processes are responsible for the sintering of grains. This process was described by Colbeck (1980) as "radius of curvature" metamorphism.

