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Investigating the thermophysical properties of the ice–snow interface under a controlled temperature gradient Part I: Experiments & Observations

Kevin Hammonds *, Ross Lieb-Lappen, Ian Baker, Xuan Wang

Thayer School of Engineering at Dartmouth College, Hanover, NH, USA

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ABSTRACT

Of critical importance for avalanche forecasting, is the ability to draw meaningful conclusions from only a handful of field observations. To that end, it is common for avalanche forecasters to not only have to rely on sparse data, but also on their own intuitive understanding of how their field-based observations may be correlated to complex physical processes responsible for structural instability within a snowpack. One such well-documented basis for mechanical instability to increase within a snowpack is that caused by the presence of a buried ice lens or ice crust. Although such icy layers are naturally formed and frequently encountered in seasonal snowpacks, very little is known about the microstructural evolution of these layers and how they contribute toward weak layer development. Furthermore, in terms of assessing the structural integrity of the snowpack, there is at the present time no consistent treatment for identifying these layers a priori as problematic or benign. To address this issue, we have created an idealized laboratory scenario in which we can study how an artificially created ice lens may affect the thermophysical and microstructural state of the interface between the ice lens and adjacent layers of snow while under a controlled temperature gradient of primarily -100 K m^{-1}. Utilizing in situ micro-thermocouple measurements, our findings show that a super-temperature gradient exists within only a millimeter of the ice lens surface that is many times greater than the imposed bulk temperature gradient. Such large temperature gradients on such a small scale would not be measurable by most field-based instrumentation and to our knowledge these laboratory-based in situ measurements are the first of their kind. Additionally, we have also investigated and characterized the microstructural evolution of the ice–snow interface with X-ray Micro-computed Tomography and Scanning Electron Microscopy. In our analysis, we have been able to identify distinct regions of simultaneous ice crystal growth, sublimation, and kinetic snow metamorphism. We hold that these observations are both consistent with previous laboratory studies and observations made in the natural environment.

1. Introduction

It has long-been observed in seasonal mountain snowpacks that it is often the natural formation of a snow or ice crust on the surface of the snowpack, that once buried, is responsible for dangerous and widespread avalanche conditions (Jamieson et al., 2001; Greene and Johnson, 2002). Crusts of nearly pure ice, termed ice lenses, can form from a variety of meteorological conditions including significant melt/freeze or freezing rain events (Fierz et al., 2009). Once formed, these ice lenses create both a sharp discontinuity in the thermal conductivity of the adjacent snow layers and a nearly impermeable barrier to the diffusion of water vapor through the snowpack (Adams and Brown, 1983; Fierz, 1998; Colbeck and Jamieson, 2001). Additionally, ice lenses once buried can also persist throughout the entire winter season and act repeatedly as an ideal sliding surface for slab avalanches (Jamieson and Johnston, 1997). Although recent progress has been made in modeling many snowpack properties, such as the anisotropic thermal conductivity (Shertzer and Adams, 2011), small-scale temperature gradients across pore spaces (Kaempfer et al., 2005), and temperature gradient metamorphism of dry snow (Schneebeli and Sokratov, 2004), it remains unclear as to how these thermophysical properties and processes are related to the more disjointed situation of a buried ice lens within a snowpack. This may be in part due to the tumultuous nature of naturally-formed ice lenses and crusts, as they are rarely created in a uniform or predictable enough fashion to warrant an accurate representation when considering areas of scale. Without the aid of broad field-based data collection, such as perhaps could be derived from co-located snow penetrometer measurements (Marshall and Johnson, 2009; Löwe and Van Herwijnen, 2012), it will likely remain very difficult

* Corresponding author at: Ice Research Laboratory, Thayer School of Engineering at Dartmouth College, 14 Engineering Drive, Hanover, NH 03755, USA. Tel.: +1 603 646 6511 (office); +1 970 481 2745 (mobile).
E-mail address: kevin.d.hammonds.th@dartmouth.edu (K. Hammonds).

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to estimate and parameterize the natural variability in the porosity, permeability, tortuosity, and thickness of such ice layers and crusts. Further compounding the issue, the same local variability also exists for the snow layers adjacent to the ice lens (Schweizer et al., 2008). Nevertheless, because these ice lenses have been linked to widespread avalanche activity in the past, it seems prudent to not overlook such a clear relationship of cause and effect. In this paper, we present a new and systematic laboratory approach to better understanding the thermophysical properties and processes taking place at the ice–snow interface. Using primarily an imposed steady state temperature gradient of -100 K m^{-1}, our laboratory technique involves both the time-dependent microstructural characterization of the ice–snow interface as well as the measurement of in situ temperature gradients from within 1 mm of the interface. In characterizing the microstructure, we documented the temporal evolution of the interface at 6 h intervals over a 48 h testing period using X-ray Micro-computed Tomography (μ-CT) and performed post-test analysis via Scanning Electron Microscopy. In order to capture sub-millimeter temperature gradients, we integrated a micro-thermocouple array into the housing of our laboratory prepared ice–snow samples. Obtaining these physical temperature measurements was a key objective of this work that we believe may also extend the findings of other previous studies related to the modeling of heat and mass transfer in dry snow (Kaempfer et al., 2005), modeling combined with μ-CT observations of snow metamorphism (Flin and Brzoska, 2008; Pinzer et al., 2012), estimation of small-scale temperature gradients with laboratory and field-based thermal imaging (Shea et al., 2012; Schirmer and Jamieson, 2014), and in situ investigations on the thermal conductivity of dry snow (Riche and Schneebeli, 2013). Furthermore, we contend in our working hypothesis that the empirical observations correlating buried ice lenses to widespread avalanche activity and weak layer development are due to sub-millimeter scale thermophysical processes, and that these processes are related to sub-millimeter scale temperature gradients not previously recorded. All laboratory experiments were conducted in the Dartmouth Ice Research Laboratory (IRL) or the Dartmouth Electron Microscope Facility (EMF).

2. Background

2.1. Previous work

While several theoretical and laboratory studies have been conducted in the past to investigate heat and mass transfer mechanisms related to snow metamorphism (Kaempfer et al., 2005; Flin and Brzoska, 2008; Pinzer et al., 2012; Riche and Schneebeli, 2013; Wang and Baker, 2014) and snowpack stability (Adams and Brown, 1990; Colbeck, 1991; Fierz, 1998; Colbeck and Jamieson, 2001) few have been able to mesh the two. One study that did successfully combine both field and laboratory experiments, to which the work being presented here is closely related, was that of Greene (2007). In order to investigate the effects of buried ice lenses and crusts in a snowpack, Greene conducted a series of laboratory experiments with both naturally collected and artificially created ice lenses and crusts. After imposing an applied steady-state temperature gradient, Greene utilized a serial sectioning and three-dimensional reconstruction technique which allowed him to make several interesting observations indicative of an increase in the temperature gradient near these layers. Some of these observations included 1) vertical chains of faceted and hollow particles growing from the bottom (warmer) side of the ice lens, 2) sublimation and smoothing from the upper (cooler) surface of the ice lens, and 3) development of microcavities directly above the ice layer. In the end, however, Greene was not able to quantify the potential mechanisms responsible for these observations, citing that there was “no consistent signal from the ice layer in the temperature data”. Greene notes in his conclusions that some potential reasons for this may have been simply due to insufficient thermocouple sensitivity (± 0.5 K), too large of a distance between the thermocouple probes (1.0 cm), or thermocouple probes that were too large in diameter (255 μm). Greene also remarks that detecting occurrences of new ice crystal growth or sublimation at the ice–snow interface would be difficult with standard field techniques.

2.2. Thermophysical considerations

Within any homogeneous snowpack, it is the thermodynamic processes of both conduction and the release of latent heat that are generally responsible for the overall metamorphic state and resulting microstructure of the snowpack (Armstrong, 1985). In this sense, homogeneity is defined by the thermal conductivity remaining constant from point to point. Should there be any variation in the thermal conductivity, such as could be due to the introduction of a physical barrier or a change in the porosity, then the material would be inhomogeneous (Kakac and Yener, 1993). Mathematically, either relationship is best described by the three-dimensional heat equation as shown in Eq. (1), where ρ is taken to be the density, c_p is the specific heat capacity at constant pressure, $\boldsymbol{q}$ the heat flux via conduction or latent heating, T the temperature of the conductive medium, and t the time over which the temperature is changing (Greene, 2007).

$$\rho c_p \frac{\partial T}{\partial t} = -\nabla \cdot \left(\boldsymbol{q}_{conduction} + \boldsymbol{q}_{latent\ heat}\right). \tag{1}$$

In this treatment we have chosen to neglect $\boldsymbol{q}_{convection}$ based on the calculation of Grashof and Knudsen numbers, although it should be noted that large scale free convection has been observed in natural snowpacks (Sturm and Johnson, 1991) and in other laboratory experiments under very large temperature gradients (≥500 K m^{-1}) and high permeability snow types (Akitaya, 1974; Powers et al., 1985).

2.2.1. Grashof number

The thermal variant of the Grashof number Gr_L, a dimensionless parameter commonly encountered in heat and mass transfer problems, is the ratio of buoyancy forces to viscous forces that would be required for a thermally convective boundary layer to exist via purely free convection (Bergman et al., 2011). In this study, we use a more general variation of the Grashof number Gr_C, in which both mass and heat transfer are included (Bergman et al., 2011). This allows for concentration gradients, such as water vapor in air, to also be considered for free convection. The potential for free convection to occur at an interface is generally thought to be important when $Gr_L \geq 1000$ (Holman, 2002; Greene, 2007), but it should be noted that the significance of Gr_L or Gr_C is heavily dependent on flow direction, geometry, and the characteristic length selected (Levenspiel, 1998). Both Gr_L and Gr_C are given in Eqs. (2) and (3), respectively, where g is the acceleration due to gravity, β is the volume coefficient for expansion of the fluid, ΔT_c is the temperature difference between the surface and the edge of the boundary layer ($\Delta T_c = T_s - T_\infty$), L_c is the characteristic length, ν_f is the kinematic viscosity of the fluid, ρ_f is the density of the fluid, $\Delta\rho_c$ is the difference in the fluid density between the surface and the edge of the boundary layer ($\Delta\rho_c = \rho_s - \rho_\infty$), and ν_f is the kinematic viscosity of the fluid (Bergman et al., 2011).

$$Gr_L = \frac{g\beta\Delta T_c L_c^3}{\nu_f^2} \tag{2}$$

$$Gr_C = \frac{g\Delta\rho_c L_c^3}{\rho_f \nu_f^2}. \tag{3}$$

In these equations, the cubic exponent on L_c gives a particular significance to how L_c is determined. The selection of L_c is typically defined in heat and mass transfer problems as the ratio of the solid's volume to surface area, thickness of a plane wall separating two fluids, or the ratio of the surface area to the perimeter of the solid (Bergman et al., 2011). Fig. 1 demonstrates this significance, where L_c has been plotted