Impact of Heat Convection Induced by Topography-Driven Air Ventilation on Snow Surface Temperature

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INTRODUCTION

Exchange of energy between the atmosphere and the snowpack drives most snowmelt (Male and Granger, 1981; Gray and Landine, 1988). The snow-atmosphere boundary is a permeable wall that permits penetration of wind flow. Air ventilation in snow and firn has been observed in both natural and artificial snowpacks (Albert and Hardy, 1995; Clifton et al., 2008; Drake et al., 2017). Airflow through pore spaces impacts the thermal regime of ice sheets and snowpacks by transporting heat and water vapour (Clarke et al., 1987; Powers et al., 1985), as well as the transport of chemical species (Waddington and Cunningham, 1996). Albert and Hardy (1995) conducted a field experiment to induce wind flow at the surface of a snowpack whilst measuring temperature distributions within the snowpack. They observed highly non-uniform internal snow temperature distributions.

Some models have represented snow-air exchange by 2D advection-conduction heat transfer algorithms (Albert and Hardy, 1995) or other schemes (Colbeck, 1989, 1997; Clarke and Waddington, 1991, Albert, 1993). However, in most numerical models of snow-atmosphere exchange, assumptions are made to simplify the energy balance; for instance, turbulent fluxes are represented by 1st order theories and the snow surface is considered an impermeable and flat boundary. Some studies have used the radiative snow surface temperature as an index to assess snow model performance (Lapo et al., 2015; Conway et al., 2018). This index has exposed the under-estimation of turbulent fluxes by the current theories under stable atmospheric conditions that are often encountered above snow (Cullen et al., 2007). In particular, Helgason and Pomeroy (2012) observed that the measured sensible flux could not offset heat loss through longwave radiation during clear sky conditions, which resulted in unrealistic drops in simulated snow surface temperature using the SNTHERM model. Helgason and Pomeroy (2012) suspected that forced convection into the snowpack under the presence of sastrugi might have influenced measured snow surface temperature. To resolve this issue in models, a numerical strategy of adding a ‘windless coefficient’ to increase estimated sensible heat flux under stable conditions is often employed (Brun et al., 1989; Jordan et al., 1999; Brown et al., 2006). This method, however, lacks physical realism.

This study investigates the impact of thermal convection induced by topography-driven pressure fluctuations at the snow surface coupled with surface energy balance on simulated near snow surface temperature.

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METHOD

Snow Energy Balance

Pomeroy et al. (2016) developed an energy balance model to solve for the radiative snow surface temperature, assuming that the snow surface is thermally disconnected from the underlying snow (i.e. there is no heat conduction between the snow surface and the underlying layer). Their model considered a no-mass “snow surface skin” of zero internal energy. In this study, the energy balance at the snow surface is applied to an exchange layer of a few centimetres. This exchange layer is also assumed to have no mass, but in contrast to Pomeroy et al.’s model, is linked to the snowpack via a heat conduction term.

A first-order closure was applied to estimate the vertical fluxes of momentum, sensible heat, and latent heat, i.e. that these fluxes are proportional to the vertical gradients of wind speed, temperature, and specific humidity, respectively. To account for atmospheric stability, the Monin-Obukohv similarity theory is used (Monin and Obukhov, 1954).

Thermal Convection in Porous Media

The topography-driven airflow theory is taken from previous studies of airflow through snow (Bartlett and Lehning, 2011). The velocity of the air phase was estimated using Darcy's law. The pressure at the snow surface was divided into a stationary, homogeneous ambient pressure and a time-varying, inhomogeneous pressure fluctuation of smaller magnitude. The pressure fluctuation at the snow surface depends on the length and height of snow dunes. For simplicity, a flat surface was approximated, following Bartlett and Lehning (2011).

Heat Transfer

Liquid water within the pore space was neglected. Thus, the snowpack is only composed of ice and air. Assuming incompressible airflow and thermal equilibrium between the gas and solid phases, heat transfer through snow was estimated using the convection-conduction heat equation.

Model Design

A 2D model was developed to simulate the energy balance near the snow surface and heat transfer through advection and conduction within the snowpack. An explicit upwind finite volume method was applied to solve for the 2D heat convection-conduction equation. The snowpack temperature profile was initially assumed to be linear, ranging from -10°C at the surface to 0°C at the bottom. A constant temperature was assumed at the bottom of the snowpack (=0°C) and periodic boundary conditions were specified at the lateral boundaries.

The meteorological inputs were assumed constant and are summarized in Table 1.

RESULTS

Impact of Dune Height

To investigate the impact of the height of snow dunes on simulated snow surface and internal temperature, the wavelength of the snow dune was kept constant at 2 m. Snow properties, domain boundaries, and atmospheric inputs for the reference case are summarized in Table 1. The height of the snow dune was increased from 5 cm to 15 cm by increments of 5 cm for two different air temperatures (-20 °C and -10 °C). All other variables were held constant and the simulations were run until steady state conditions developed. Figure 1a presents the lateral (horizontal) distribution of the simulated snow surface temperature for three different dune heights, at an air temperature of -20 °C. The snow surface temperature was not homogeneous. At each dune height, the location of maximum snow surface temperature corresponded to the location of minimum pressure at the snow surface. Inversely, the lowest snow surface temperature was estimated where the pressure at the surface was maximal (i.e. where the air moved downward within the snowpack). For increasing
dune height, the maximum value of the snow surface temperature increased, while the minimum value remained similar at all dune heights. The difference between the maximum and minimum values of the estimated snow surface temperatures over the snow surface (ΔT_s), which symbolizes the heterogeneity in the lateral distribution of snow surface temperature, for all three dune heights and at the two different air temperatures, are shown in Fig. 1. At all dune heights, ΔT_s decreased with increasing air temperature.

### Table 1. Snow properties, model boundaries, and atmospheric inputs for the reference case.

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density</td>
<td>300 kg m(^{-3})</td>
</tr>
<tr>
<td>Grain size</td>
<td>1 mm</td>
</tr>
<tr>
<td>Temperature at snow-soil interface</td>
<td>0 °C</td>
</tr>
<tr>
<td>Initial snow surface temperature</td>
<td>-10 °C</td>
</tr>
<tr>
<td>Dune height</td>
<td>5 cm</td>
</tr>
<tr>
<td>Dune wavelength</td>
<td>2 m</td>
</tr>
<tr>
<td>Roughness length</td>
<td>1 mm</td>
</tr>
<tr>
<td>Height of measurement</td>
<td>2 m</td>
</tr>
<tr>
<td>Air temperature</td>
<td>-20 °C</td>
</tr>
<tr>
<td>Wind speed</td>
<td>5 m s(^{-1})</td>
</tr>
<tr>
<td>Relative humidity</td>
<td>80%</td>
</tr>
<tr>
<td>Incoming shortwave radiation</td>
<td>100 W m(^{-2})</td>
</tr>
<tr>
<td>Incoming longwave radiation</td>
<td>200 W m(^{-2})</td>
</tr>
</tbody>
</table>

Heterogeneity in snow surface temperature can be explained by looking at internal snow temperature distribution (Fig. 2). For taller dunes, airflow within the snow was faster, resulting in greater thermal convection flux. This caused the cold front on the left-hand side of the snowpack (where the air flowed downward from the surface) to be colder and reach deeper snowpack layers. Conversely, the velocity of the upward airflow (on the right-hand side of the snowpack) increased with dune height and more thermal energy was transported from the warm ground-snow interface to the snow surface, resulting in a warmer internal snow temperature just below the surface on the right-hand side of the snowpack. This corresponded with higher snow surface temperatures simulated on the right-hand side of the snowpack for increasing dune height.

A similar analysis was conducted for two different wind speeds (5 m s\(^{-1}\) and 10 m s\(^{-1}\)) whilst the other variables were kept constant (Table 1). The new results were similar to the previous observations. The minimum value of snow surface temperature varied very little with wind speed and dune height, and the highest value of snow surface temperature increased with dune height and agreed with the location of the smallest pressure at the snow surface. ΔT_s increased with wind speed and dune height (Fig. 1b).

### Impact of Dune Wavelength

In this section, the impact of dune length on simulated snow temperature is studied. Simulations were first run for two different air temperatures (-10 °C and -20 °C) at a fixed dune height of 5 cm. All the other model inputs and initial conditions were kept constant (Table 1). The results are presented after steady state was reached.
Figure 1. a) Horizontal distribution of simulated snow surface temperature for three dune heights (5 cm, 10 cm, and 15 cm) at an air temperature of -20 °C and a dune length of 2 m. b) Difference between the maximum and the minimum values of the distributed snow surface temperatures (dTs) for two different air temperatures (-20 °C and -10 °C) and increasing dune height (from 5 cm to 15 cm) with a constant dune length of 2 m.

Figure 3a shows the simulated lateral distribution of snow surface temperature for three different dune lengths (1 m, 5 m, and 10 m) and an air temperature of -20 °C. For longer dunes, the minimum value of snow surface temperature increased, while the maximum value decreased: snow surface temperature became more homogeneous. Figure 2b presents the variation of $\Delta T_s$ with air temperature and dune length. $\Delta T_s$ was greater for a colder air temperature. The distributed surface temperature flattened with increasing dune length; this was caused by lower air convection from a more uniform pressure gradient at the snow surface.

Wind speed was increased from 5 m s$^{-1}$ to 10 m s$^{-1}$ for a fixed air temperature of -20 °C. The variations of $\Delta T_s$ for these two wind speeds and the three different dune lengths are presented in Fig. 3b. Unexpectedly, $\Delta T_s$ was non-monotonic with dune length: at the highest wind speed, the maximum value of snow surface temperature was higher for a 5 m wavelength than for a 1 m and 10 m wavelength (Fig. 3b). This was caused by higher heat convection in 5 m wavelength dune, resulting in more transport of energy from the bottom of the snowpack (warm) to the snow surface.

CONCLUSIONS

The impact of thermal advection initiated by topography-induced airflow on snow internal and near surface temperatures was investigated. The input heat flux was estimated by solving for the energy balance at the snow surface, using meteorological data to drive the model. Increasing dune height resulted in an increase in heat convection and therefore in more spatial variability in estimated snow surface temperature. Heat convection within the snowpack decreased with increasing dune wavelength, resulting in a more homogeneous snow surface temperature. The near snow surface temperature was, however, more varied for a colder air temperature and a higher wind speed above the snow surface.
Figure 2. Simulated snow internal temperature with the values from the reference case (Table 1) for three different dune heights (5 cm, 10 cm, and 15 cm from top to bottom) and a constant dune length of 2 m. The top graph shows the topography of the snow surface and the pressure perturbation \( (p') \) generated by it.

Figure 3. a) Horizontal distribution of snow surface temperature for three dune lengths (1 m, 5 m, and 10 m) and an air temperature of \(-20^\circ\text{C}\), a wind speed of 5 m s\(^{-1}\), and a dune height of 5 cm. b) Difference between the maximum and minimum values of the distributed snow surface temperature (\(\Delta T_s\)) for two different air temperatures (-10 \(^\circ\text{C}\) and -20 \(^\circ\text{C}\)), two different wind speeds (5 m s\(^{-1}\) and 10 m s\(^{-1}\)) and an increasing dune wavelength (from 1 m to 10 m), with a fixed dune height of 5 cm.
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REFERENCES


