The Cooling Effect of Coarse Blocks Revisited: A Modeling Study of a Purely Conductive Mechanism

Stephan Gruber, Martin Hoelzle
Glaciology, Geomorphodynamics and Geochronology, Geography Department, University of Zurich, Switzerland

Abstract

Coarse blocks are a widespread ground cover in cold mountain areas. They have been recognized to exert a cooling influence on subsurface temperatures in comparison with other types of surface material and are employed in man-made structures for ground cooling and permafrost protection. The contrast in heat transfer between the atmosphere and the ground caused by thermally driven convection in winter and stable stratification of interstitial air during summer is usually invoked to explain this “thermal diode” effect. Based on measurements and model calculations, we propose an additional cooling mechanism, which is independent of convection, and solely functions based on the interplay of a winter snow cover and a layer of coarse blocks with low thermal conductivity. The thermal conductivity of a block layer with a porosity of 0.4 is reduced by about an order of magnitude compared to solid rock. We use a simple and purely conductive model experiment to demonstrate that low-conductivity layers reduce the temperature below the winter snow cover as well as mean annual ground temperatures by comparison with other ground materials. Coarse block layers reduce the warming effect of the snow cover and can result in cooling of blocky surfaces in comparison with surrounding areas in the order of one or several degrees. The characteristics of this mechanism correspond to existing measurements.

Keywords: coarse blocks; heat transfer; mountain permafrost; rock glacier; snow cover; thermal offset.

Introduction

Coarse blocks are a common surface cover in many cold and temperate mountain ranges. They have a cooling influence on ground temperatures compared with fine-grained soil or bedrock in otherwise similar settings (cf. Haebelri 1973, Harris 1996, Gorbunov et al. 2004, Juliansen & Humlum 2008). This cooling effect makes blocky substrates interesting for construction in cold regions (e.g., Goering & Kumar 1996, Guodong et al. 2007) and it is a significant factor influencing the distribution and characteristics of permafrost (Haebelri 1975). Therefore, the understanding and quantification of this cooling effect is important for spatial modeling of permafrost, estimation of its characteristics, and assessment of its temporal evolution.

Measurements in coarse blocky substrate as well as their interpretation are faced with a number of difficulties. To begin with, it is difficult to define the surface of a blocky substrate. Point measurements are bound to either the interstitial air or large clasts and integral macroscopic properties of the blocky material, such as temperature or albedo, are difficult to determine. Similarly, on a macroscopic scale, snow is partly deposited in a volume rather than on a discrete surface because the geometric surface roughness and the depth of voids can have the same order of magnitude as snow thickness itself. Despite these difficulties, a number of processes that may be responsible for the cooling effect of coarse blocks have been proposed and analyzed (e.g., Hanson & Hoelzle 2004, Juliansen & Humlum 2008, see Herz 2006 for a comprehensive review).

These processes are: (a) free convection; (b) forced convection; (c) chimney effect; (d) evaporation/sublimation/ice melt; (e) snow deposition deep into the active layer; and (f) protruding blocks reducing the insulating effect of the snow cover. While all of these processes are plausible, little is known about their relative importance and about the dependence of this importance on environmental conditions. However, understanding the importance of each process is vital to further progress.

One way to achieve this is the joint analysis of model results and measured data. The deviation between model and measurements is bound to contain (among other errors) the error produced by not including an important process in the model. Using such experiments, we were surprised to find that the thermal conductivity of the near-surface material decisively controls ground temperatures below the snow cover. For example, the depression of winter temperatures measured on coarse block fields (cf. BTS on coarse blocks, Haebelri 1973, 1975) in the Murtel/Corvatsch area (Fig. 1) could be reproduced with two models (TEBAL, Gruber 2005; SNOWPACK, Bartelt & Lehning 2002) that do not include the process of air movement in blocks (cf. Frey 2007). This suggests that at this site, either convection is of secondary importance after an effect related to thermal conductivity, or, that errors in both models resulted in temperature depressions similar to those measured.

In this paper we explore and describe this combined effect of near-surface thermal conductivity and snow pack using a simplified model. While subject to strong generalization with respect to the measured situation, the simple model used here allows to isolate and properly demonstrate the relevant process in a framework that is easily traceable. The cooling mechanism, which we propose, does not contradict existing and well-established research on convective heat transport in coarse blocks (e.g., Goering & Kumar 1996, Guodong et al. 2007). Instead, it offers an explanation of measured cooling where snow cover is thick and signs of significant convection are absent.
Model Experiment with Synthetic Data

Based on a model experiment, we intend to illustrate that a lower thermal conductivity of near-surface material causes lower temperatures below the winter snow cover and that this also affects mean temperatures at greater depth. The model is reduced to only conductive components and effects of, e.g., water percolation or phase change are neglected. That way, this mechanism can be studied in isolation from other effects.

Model description

The model contains a finite-difference Crank-Nicolson solution of the heat conduction equation with no treatment of phase change or advective heat transport. The snow pack and the uppermost 5 m of the ground are discretized with a spacing of 0.1 m. Below, the interval gradually increases down to 15 m. The snow cover is added and depleted in steps of 0.1 m. Available model parameters are: maximum snow cover thickness ($H_{\text{max}}$), duration of the accumulation ($D_{\text{acc}}$) and ablation ($D_{\text{abl}}$) periods, date of maximum snow cover thickness ($t_{\text{max}}$), phase lag of temperature cycle ($L$), mean surface temperature ($M$), surface temperature amplitude ($A$), and the thickness of the block layer ($B$).

Equation (1) describes the temporal evolution of the snow cover thickness $H$ (Fig. 2). The parameter $\Delta t$ ranges from 0 to 1 and describes the relative distance to $t_{\text{max}}$, where $\Delta t$=0 at the date of $t_{\text{max}}$, and $\Delta t$=1 at the dates of $D_{\text{acc}}$ and $D_{\text{abl}}$.

$$H = H_{\text{max}} \cdot \left(1 - \left(\frac{e^{-\Delta t^{2.5}} - 1}{e - 1}\right)\right) \quad (1)$$

The influence of the snow cover on ground temperatures in nature has three main causes: (a) thermal insulation; (b) reduction in albedo; and (c) advection of latent heat because melt energy is required to remove the snow. In this model, only (a) is considered because the effect of thermal insulation is of interest here.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure1.png}
\caption{Near-surface temperatures at the rock glacier Murtel. The solid line shows average daily temperatures 10 cm deep in bedrock adjacent to the rock glacier front. The dashed line shows daily temperature measurements about 50 cm deep within the blocky surface of the rock glacier. These measurements were taken around midnight and therefore have a cold bias during the snow-free time when significant diurnal amplitudes exist.}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure2.png}
\caption{Synthetic snow cover evolution using $H_{\text{max}}$ of 2.5, 1.5, 1.0, 0.5, 0.3, and 0.1 m.}
\end{figure}

Ground properties

The snow cover has a uniform density of 280 kg m$^{-3}$, a thermal conductivity of $k_s = 0.13$ W m$^{-1}$ K$^{-1}$, and a volumetric heat capacity of $c_s = 5.4 \times 10^5$. The thermal conductivity of the ground is $k_g = 2.5$ W m$^{-1}$ K$^{-1}$ and the volumetric heat capacities of the ground and block layers are $c_g = 1.6 \times 10^6$ J m$^{-3}$ K$^{-1}$ and $c_b = 0.8 \times 10^6$ J m$^{-3}$ K$^{-1}$. This is based on typical rock thermo-physical properties (Cermák & Rybach 1982) and a porosity of the block layer, which is assumed to be 0.4–0.5. For the block layer, different thermal conductivities $k_b$ are considered between that of pure rock (2.5 W m$^{-1}$ K$^{-1}$) and a rather low estimate (0.2 W m$^{-1}$ K$^{-1}$). The low values of thermal conductivity for the block layer are in accordance with values in the range of 0.3 W m$^{-1}$ K$^{-1}$ published for dry sand and for theoretical values when calculating a mixture of rock and air using the geometric mean that usually approximates random aggregates rather well.

Boundary conditions

A harmonic temperature boundary condition (Dirichlet) representing seasonal variation drives the heat conduction scheme at its upper boundary for the duration of several hundred years. This condition ($T_{\text{surface}}$) is prescribed at the snow surface during winter and at the ground surface during summer. It is described by Equation (2), where $\varphi$ is the duration of one seasonal cycle (one year). Similar to conditions at Murtel/Corvatsch, we assume $M = -2.5^\circ$C, $A = 10^\circ$C, $L = 45$, $J_{\text{max}} = 105$, $D_{\text{abl}} = 50$, $D_{\text{acc}} = 170$, where $D_{\text{abl/acc}}$, $J$, and $L$ are given in days and days of the year, respectively.

$$T_{\text{surface}} = \sin\left(-(t + L)\frac{2\pi}{\varphi}\right) \cdot A \cdot M \quad (2)$$

Results

The insulating influence of the winter snow cover increases with thicker snow cover (Fig. 3). The temperature $T_0$ refers to the temperature at the ground surface. Changing the thermal conductivity of the block layer modifies the warming influence of the snow cover (Fig. 4A) and, in accordance with observations (Fig. 1), lower temperatures are modeled under the snow when using lower thermal conductivities of the near-surface, which are characteristic of the block layer. During winter, the heat conduction through the snow pack is very small and, as a consequence, the heat conduction from deeper ground layers...
dominates the temperatures at the snow/ground interface. The BTS method (Haeberli 1973) exploits this effect. If the thermal conductivity of the near-surface ground layer is significantly lower, then the relative importance of heat transfer through the snow increases and temperature at the snow/ground interface will respond more to atmospheric forcing. This is also visible in Fig. 1, where both time series contain similar temperature fluctuations in winter and where these fluctuations are more pronounced in the blocks.

It is now important to know whether this effect only results in lower temperatures under the snow cover, or, whether it also influences mean ground temperatures. In Fig. 4B we can see that over the course of about 450 modeled years, all temperatures have warmed with respect to Figure 4A, indicating exactly this effect over the longer term. This is also visible in the transient response of temperatures at 10 m depth (Fig. 5). After initialization with a temperature of $M = -2.5^\circ C$ and constant boundary conditions having the same mean, temperatures equilibrate at much higher levels due to the insulating effect of the winter snow. This insulating effect is modulated by the thermal conductivity of the blocky layer. These results can be explained as follows: The mean annual ground temperature (at some shallow depth) in first approximation contains a weighted average of surface temperatures. The weight and relative importance of winter temperatures in this average is reduced by the insulating effect of the snow cover (cf. Zhang et al. 2001) that impedes the heat transfer between the (snow) surface and the ground. Where the thermal conductivity of the near-surface layer is low, the heat transfer in snow-free conditions is already slow. As a consequence, the contrast between summer and winter conditions is smaller than for situations with high thermal conductivity of the subsurface. The relative cooling effect of blocky material (compared to many other surfaces) is essentially an effect of reduced warming. This effect is a thermal filter with an effectiveness that is dependent on the thermal contrast between summer and winter conditions. A block layer reduces the overall thermal conductivity of the ground-atmosphere interface and thus reduces the contrast between summer and winter.

Discussion

This experiment illustrates that the temperature below the winter snow cover as well as mean annual ground temperatures at greater depth can be significantly reduced solely based on the low thermal conductivity of blocky material. The use of a one-dimensional scheme together with macroscopic properties of block layers is a challenging concept because the size of individual clasts can exceed the vertical discretization interval by far. Nevertheless, as long as the majority of clasts do not exceed the thickness of the block layer, this approximation should produce acceptable results, because the overall conductive heat transfer is impeded by the small surface of the contacts between individual pieces of rock. The comparison of modeling results with measurements, however, has to employ either spatial averaging or deeper measurements in order to average lateral variability (cf. Frey 2007, Hoelzle & Gruber 2008). Using the geometric average as an approximate mixing model (Clauser & Huenges 1995), the thermal conductivities of coarse blocks (cf. Binxiang et al. 2004) and sand should be the same because both materials have similar constituents and a similar porosity. This is only true for completely dry material because sand or other soil material usually holds significant amounts of water due to capillary forces in the more abundant small pores. This likely
results in a distinctly higher overall thermal conductivity in fine-grained soil than in coarse material.

In many publications, the effect of ground cooling in block slopes is referred to as thermal offset, in analogy to common terminology in the Arctic. The thermal offset described in the Arctic is caused by seasonal differences in the properties of the active layer, which are due to the contrast in thermal conductivity between water and ice. This usually results in a curved temperature profile and a marked temperature difference between the top and bottom of the active layer. Convection of air would be similar to a temporary increase in the thermal conductivity and resembles this pattern. The mechanism we propose here, produces no temperature difference between the top and bottom of the active layer, and this behavior corresponds with several existing measurements (Juliussen & Humlum 2008, Hoelzle & Gruber 2008).

A block layer of very low thermal conductivity results in a strong thermal gradient with depth in the presence of a geothermal heat flux. This effect can reduce the relative ground cooling (Table 1) and varies with the thickness of the block layer and with the heat flux across it. In mountain areas, the deeper heat flux is usually reduced (Kohl 1999) and spatially highly variable (Gruber at al. 2004). Additionally, the advection of subsurface ice (moving rock glacier) and transient effects can reduce or even invert the heat flux in the uppermost tens of meters.

The effect of reduced warming by the snow cover as proposed here does not preclude the presence of additional processes that lead to relative ground cooling. Depending on environmental conditions, other processes may even be more important. The most prominent other process that is described in the literature is the circulation of air caused by temperature-driven free convection. This effect and the effect proposed in this paper are complementary in some way: conditions of little snow cover favor the effect of advection and reduce the purely conductive mechanism described here, whereas a thick snow cover inhibits convection and gives rise to the full effect of low thermal conductivity. Conditions may vary on a continental scale (low/high precipitation areas), locally (wind-swept ridge or snow-filled depression) or with time (dry winter, climate change). Because the proposed effect is “relative cooling by reduced warming,” it cannot result in ground temperatures significantly below the MAAT as has been observed for block surfaces with strong air movement (e.g., Gorbunov et al. 2004, Delaloye et al. 2003).

Table 1. Example of the net effect of diverse near-surface layers.

<table>
<thead>
<tr>
<th>Block layer thermal conductivity</th>
<th>Heat flux at lower boundary condition</th>
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<tbody>
<tr>
<td></td>
<td>0.0 W m⁻²</td>
</tr>
<tr>
<td></td>
<td>0.06 W m⁻²</td>
</tr>
<tr>
<td>(k_\text{B}=2.5\ W\ m^{-1}\ K^{-1})</td>
<td>4.6 °C</td>
</tr>
<tr>
<td>(k_\text{B}=1.2\ W\ m^{-1}\ K^{-1})</td>
<td>4.1 (0.5) °C</td>
</tr>
<tr>
<td>(k_\text{B}=0.5\ W\ m^{-1}\ K^{-1})</td>
<td>3.2 (1.4) °C</td>
</tr>
<tr>
<td>(k_\text{B}=0.2\ W\ m^{-1}\ K^{-1})</td>
<td>2.3 (2.3) °C</td>
</tr>
</tbody>
</table>

Subsurface warming for a 3 m thick near-surface layer with diverse thermal conductivities and two different lower boundary conditions. The second column (zero heat flux) represents the conditions shown in Fig. 5. Warming values refer to final subsurface warming at a depth of 3 m with respect to the mean (prescribed) surface temperature (M). Numbers in brackets express this warming as relative cooling with respect to pure rock (2.5 W m⁻¹ K⁻¹).

Conclusion and Outlook

We have presented a simple and purely conductive mechanism that can cause lower temperatures at the snow/ground interface as well as lower mean ground temperatures in coarse blocky surfaces as compared to bedrock or fine-grained material. This mechanism is not an alternative but rather an extension of existing theory, and it can at least partly clarify previously unexplained measurement results.

The quantitative understanding of the influence of each proposed mechanism and its sensitivity to material properties and environmental conditions is an important topic for future research. This will determine, for instance, which processes have to be included in a specific model and which are of secondary importance, only. The creative combination of both modeling and measurements is expected to be a viable means to achieve this. Additionally, methods for the delineation of block fields (cf. Heiner et al. 2003, Gruber & Hoelzle 2001) are important because this can strongly improve the quality of simulations, even with simple methods.

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References


