Modeling Convective Heat Transfer in the Porous Active Layer of an Alpine Rock Glacier

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Abstract: Permafrost is defined as ground, which stays frozen for at least two consecutive years. In the Swiss Alps it is a widespread phenomenon and it has an important impact on the landscape, especially regarding natural hazards. Rock glaciers are one of the most striking permafrost landform. Their ice-rich body is often covered with coarse blocks, which allow for air circulation within the porous active layer (the uppermost 3-4m that thaw each summer) and act as a strong thermal filter between atmospheric and ground temperatures. We present an explicit modeling approach on a 2D domain to represent the effects of air convection on the ground thermal regime. Modeling results show that convection influences the ground thermal regime considerably and leads to generally colder ground temperatures.

Keywords: Permafrost, rock glacier, convection, heat transfer, Darcy's law

1. Introduction

Permafrost covers substantial parts of the Swiss Alps. Climate change affects the behavior, the temperatures and the extent of permafrost in general. In recent years, several modeling studies have been carried out to predict the future development of permafrost in the Swiss Alps (e.g. Marmy et al. 2016, Scherler et al. 2013). The results show that the projected temperature increase in the Alps is also reflected in the permafrost temperatures and extension. At the lower altitudinal borders of the current permafrost extent, it may vanish in future. Terrain instabilities, rock falls or the occurrence of debris flows are possible consequences of permafrost degradation. Furthermore, permafrost landforms may contain significant water reserves.

Many permafrost landforms, such as talus slopes and rock glaciers, are covered by coarse blocky material. This coarse blocky material has a high permeability and allows air to circulate within the soil. The air circulation leads to convective heat transfer and influences the ground thermal regime. Many field work based studies have shown that, at least in some cases, convective (or advective – defined as lateral convection) processes are crucial to maintain sub-zero temperatures within the ground (e.g. Delaloye et al. 2003). However, current mountain permafrost modeling approaches do generally not reproduce these processes, as they are limited to one-dimensional soil column simulations. Hence, they are not able to reproduce 2-dimensional convective effects. Most modeling studies so far often either neglect air convection within the ground (Noetzli & Gruber 2009) or use a parametrization (Scherler et al. 2014, Luethi et al. 2017, Pruessner et al. 2018). In a previous study (Wicky & Hauck 2017), we have shown the importance of internal circulation for the ground thermal regime within a talus slope. Here, we extend this model approach to rock glaciers. Rock glaciers are well-studied permafrost features as they are clearly visible in the landscape. They consist of a frozen core with substantial ice content and an active layer at the surface (approx. 2-5m thick, depending on the site) which thaws each summer. The active layer is often characterized by a high permeability, which allows for convective heat transfer by air flow. Understanding the processes that influence the thermal regime of a rock glacier is crucial to successfully model their future development, which also important regarding their potential hydrological significance.

2. Model description

2.1 General

Our model approach is based on previous studies, which simulate convection within porous media in a permafrost context (Wicky & Hauck 2017) and on engineering studies, which simulate convection in porous media in road embankment and railway constructions to study their passive cooling effect (e.g. Goering & Kumar 1996, Guodong et al. 2007, Arenson et al. 2006). We use boundary and validation data from the Swiss Permafrost Monitoring (PERMOS) site Murtèl/Corvatsch (PERMOS 2016) in the Engadin, Switzerland. The model is implemented and solved within the finite element method software COMSOL Multiphysics.

2.2 Governing equations

We couple the COMSOL Multiphysics Modules Subsurface Flow – Darcy's law and Heat Transfer – Heat Transfer in Porous Media. This allows simulating explicitly convective heat transfer and taking into account density driven free convection effects. Heat transfer is described with eqs. 1 and 2, where q is the heat flux, Q is the storage term, q_0 the boundary flux, d_{xy} the distance in x/y direction, k the (effective) thermal conductivity, C_p the (effective) volumetric heat capacity, ρ the density, u the velocity, T the temperature and t the time.

$$d_{xy}\rho C_p \frac{\partial T}{\partial t} + d_{xy}\rho C_p u \nabla T + \nabla q = d_{xy} Q + q_0 \quad (1)$$

$$q = -d_{xy}\, k \nabla T \quad (2)$$

Air flow in the porous matrix is assumed to be of Darcy flow type described in eqs. 3 and 4, where ϵ_p is the porosity, ρ the density, u the velocity, Q_m the boundary flux, κ the permeability, μ the dynamic viscosity, g the gravity constant and p the pressure. Temperature change influences air density and thus allows natural convection (Oberbeck – Boussinesq approximation).

$$\frac{\partial}{\partial t}(\epsilon_p \rho) + \nabla(\rho u) = Q_m \quad (3)$$

$$u = -\frac{\kappa}{\mu}(\nabla p - \rho g) \quad (4)$$

2.3 Geometry

The geometry consists of a simplified two-dimensional schematic rock glacier (Figure 1) consisting of three domains with different material properties (Table 1). The active layer (AL) has a thickness of 4 m and the slope angle is 5°. The horizontal extent of 150 m is chosen to avoid boundary effects.

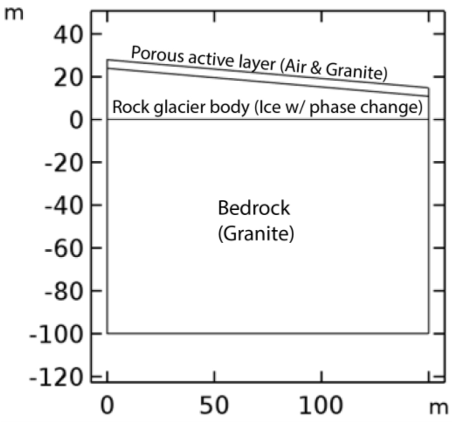

Figure 1: Geometry with three domains.

The mesh is composed of triangular elements and auto generated by COMSOL Multiphysics with some important restrictions: Mesh size in the AL is smaller than 0.5 m and increases to 15 m at the lower boundary in the bedrock. This results in a mesh with 8830 triangular elements. A mesh dependency study showed this as the best compromise between calculation time and result accuracy. Especially in the AL, where air circulation is possible, the mesh density plays a crucial role.

2.4 Material properties

Each domain from the geometry (Figure 1) has specific material properties described in Tab. 1. The respective properties are taken from the COMSOL Multiphysics material library. The porous active layer is defined by a granite matrix filled with air. Air density is temperature dependent and thus natural convection takes place. The rock glacier body allows a phase change from ice to water taking into account a latent heat of fusion of 333.5 kJ kg^{-1}. The bedrock is defined as granite, where heat transfer takes place by conduction only.

Table 1: Material properties of the three domains shown in Figure 1.

	Porous AL (Granite / Air)	Rock glacier (Ice / Water)	Bed-rock
Heat capac. [J kg^{-1} K^{-1}]	850 / temp. dep	2052 / 4179	850
Therm. cond. [W m^{-1} K^{-1}]	2.9 / temp. dep	2.31 / 0.613	2.9
Density [kg m^{-3}]	2600 / temp. dep	918 / 997	2600
Permeability [m^2]	1e-7	0	0
Porosity	0.5	0	0

2.5 Initial conditions

We obtain the initial conditions for the transient model run in a two-step procedure. First, we perform a steady state model run with a constant geothermal heat flux of 0.03 W m^{-2} at the lower model boundary, a temperature value of -2°C at the upper boundary and zero pressure over the whole domain. Second, the steady state run is followed by a 30-years spin up run using the daily mean value of the 16-years transient temperature boundary condition (*cf* 2.6) to reach a quasi-equilibrium state.

2.6 Boundary conditions

The upper thermal boundary condition (*Dirichlet*) is prescribed by a 16-years (2000-2015) temperature data series from the uppermost thermistor in the borehole COR087 close to the surface at Murtèl rock glacier (PERMOS 2016). Due to some problems with the measurement installations, the data series has some short gaps. To obtain a continuous temperature data series, we applied a gap filling algorithm based on either linear correlation for short gaps up to 5 days or quantile mapping for longer periods similar to Staub et al. (2017) to fill missing data. The lower thermal boundary condition (*Neumann*) is a constant geothermal heat flux of 0.03 $W\,m^{-2}$ (Scherler et al. 2014). The sidewalls of the model domain are isolated thus preventing lateral boundary fluxes. Pressure at the upper model boundary is open to atmosphere ($p = \rho g\, H_{p0}$), sidewall and bottom boundaries are closed (*No flow*).

3. Results

3.1 Temperature

The simulation results show that the explicit formulation of convective air flow in the model leads to a significant effect of convective heat transfer in the active layer and on the thermal regime of a rock glacier (Figure 2). Winter temperatures are highly influenced by convective heat transfer due to the unstable thermal stratification of the air. This leads to free convection and allows a pronounced convective cooling. The stronger the thermal gradient between the boundary and the active layer temperature, the more effective is the cooling. Summer temperatures show almost no sensitivity to convective heat transfer, because heat conduction dominates, as the thermal stratification of the air is stable. The comparison to the results of a “conduction only” simulation, where only the heat transfer equations (eqs. 1 and 2) have been solved, shows that convection in the AL influences the ground temperature even at a depth of 24.56 m. The cooling effect at the lowermost thermistor seems to be rather small, but at these depths temperatures are stable and react only very slowly to changes in the energy balance in the subsurface. Small temperature changes can then have a significant influence on the persistence of permafrost and its spatial distribution, as permafrost temperatures in Switzerland are at many sites close to zero degree (PERMOS, 2016). This is especially for sites with low ice content and therefore small latent heat content critical.

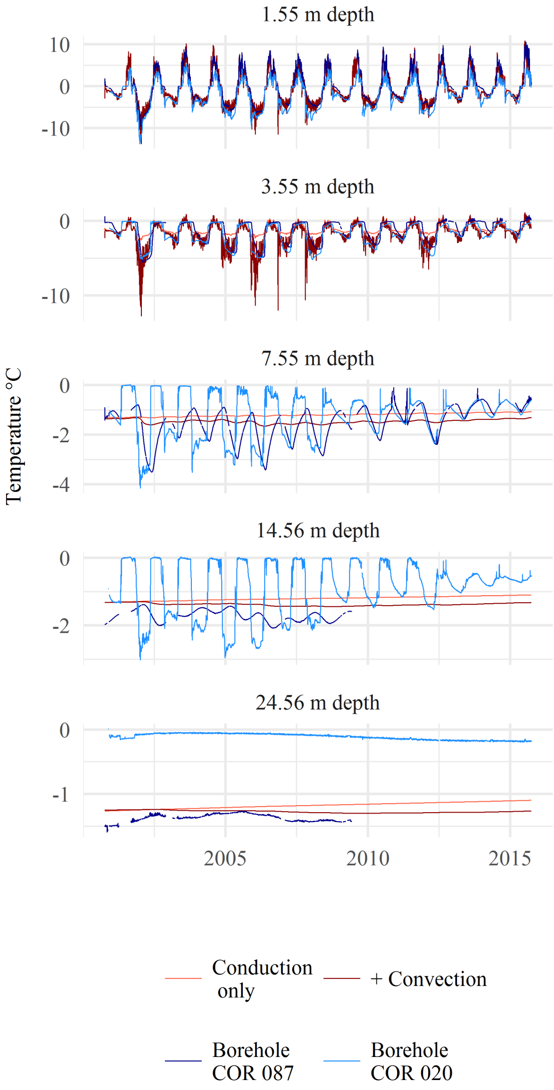

Figure 2: Temperature evolution for modelled (red) and measured (blue) values over 16 years for different depths at the Murtèl rock glacier. Model data are extracted from a virtual borehole in the center of the calculated domain. Measured data are from two boreholes (COR087 and COR020), which are next to each other on the Murtèl rock glacier (PERMOS 2016).

3.2 Air circulation

Over a yearly cycle, two different air circulation patterns can be observed within the AL of the rock glacier. During late autumn and winter until early spring (Figure 3A) the thermal stratification of the air is unstable and leads to the development of multiple vertical convection cells. These convection cells are the result of free convection induced by temperature dependent density differences in the air-filled pore space and are responsible for the colder temperatures compared to a “conduction only” simulation (red lines in Figure 2). During summer (Figure 3B), a gravity-driven gentle down flow of air can be observed in the AL. Its influence on the ground thermal regime is small and conductive heat transfer dominates.

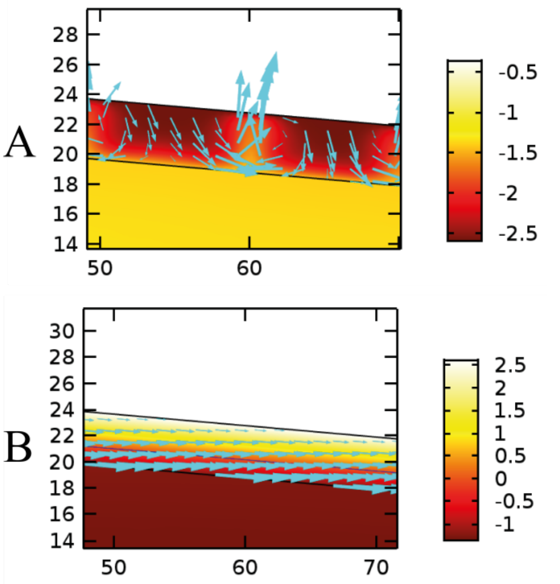

Figure 3: Active layer circulation snapshot. (A) Multicellular convection during winter (cooling). (B) Gentle down flow during summer. Scale in °C, distance in m.

3.3 Comparison to borehole data

Compared to borehole data, the model performs relatively well. The effect of convection is best visible during winter at a depth of 3.55 m (Figure 2), where modelled temperatures without convection are far too warm. At depth, the model shows some discrepancy to measured data. The general warming tendency and the mean temperatures are well represented, whereas the amplitude is much bigger in the measured data. This may be due to convection at depth within the rock glacier body (fractures, clefts), which is not represented in the model or due to uncertainties in the material properties. Furthermore, it is very likely that there is some form of convection or percolating water in the borehole casing of COR 020, which is just next to borehole COR 087 on Murtèl rock glacier, but shows a very different behavior (Arenson et al. 2010).

3.4 Sensitivity

Figure 4 shows a brief sensitivity analysis over one year simulation time. The prevailing air circulation pattern and the efficiency of cooling strongly depend on the material properties, especially on the permeability of the porous AL. The permeability of the AL is set to 1e-5 m^2, 1e-6 m^2 and 1e-8 m^2. Standard literature values are of magnitude 1e-7 m^2 (Goering und Kumar 1996, Guodong et al. 2007). A simulation with the lowest permeability shows an almost conductive behavior and ground temperatures are not influenced by convection anymore. Especially during wintertime, the low permeability prevents the occurrence of multicellular convection, which is crucial for an efficient cooling. In contrast, higher permeability leads to a more pronounced ground cooling because of a more efficient circulation. Care has to be taken while interpreting the results with a very high permeability, as the flow velocity and thus the Reynolds number gets higher and Darcy's law may not be valid anymore.

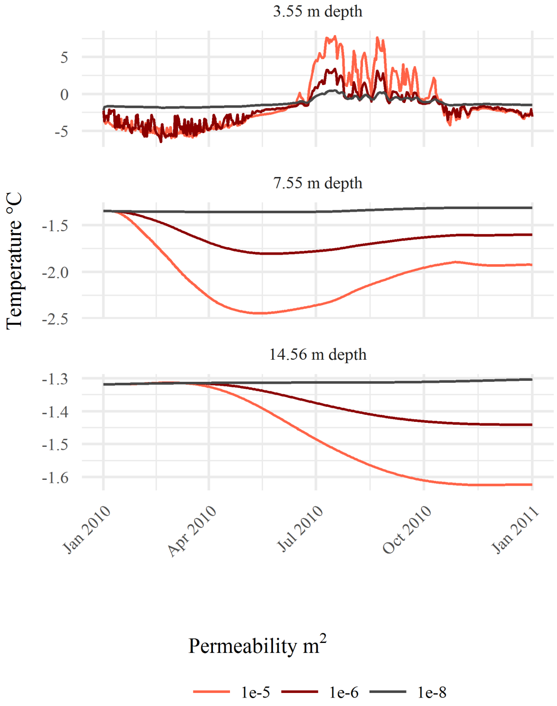

Figure 4: Temperature evolution during one modelled year (2010) with different permeability (1e-5 m^2, 1e-6 m^2 and 1e-8 m^2). Higher permeability leads to a more efficient cooling.

4. Conclusion and Outlook

The explicit modeling of 2D air convection within the soil is a novel approach in mountain permafrost research. The results clearly show that convection cannot be neglected in the modeling of ground temperatures and plays an important role in the thermal regime of a rock glacier. Ground convection leads to generally colder ground temperatures and might delay the degradation of permafrost in some places, as it was hypothesized in model approaches where convection was included through a simple parameterization (Scherler et al. 2014). In future, we aim to extent the model to further geometrically more complex rock glaciers or talus slopes and to solve for Brinkman or Stokes flow as Darcy's law may not be valid anymore with high permeability.

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