Modeling Transient Permafrost Temperatures below Steep Alpine Topography

Jeannette Noetzli¹, Stephan Gruber¹ and Sven Friedel²
¹Glaciology, Geomorphodynamics and Geochronology, Department of Geography, University of Zurich, Switzerland,
²FEMLAB GmbH, Zurich, Switzerland
*Corresponding author: Winterthurerstrasse 190, CH-8057 Zurich, jeannette.noetzli@geo.uzh.ch

Abstract: Permafrost is widespread in the European Alps and its degradation following climate change is an important factor influencing the stability of steep rock. In order to assess current and future permafrost temperatures in the subsurface of steep mountain topography we developed a modeling approach that combines a surface energy balance model together with a numerical 3D heat conduction scheme solved within COMSOL Multiphysics. To create the geometry for the topography investigated a routine to import gridded elevation data has been written. The modeling chain bears potential for a number of studies addressing prevailing topics of mountain permafrost research.

Keywords: Permafrost, complex topography, transient temperature field, model integration

1. Introduction

Permafrost is abundant in the subsurface of high-mountain areas such as the Alps and a significant proportion is located in steep bedrock. Permafrost is defined as material of the lithosphere with temperatures below zero degrees during a whole year.

Permafrost degradation following climate change can be a crucial factor influencing the stability of steep rock (Haeberli et al., 1997; Davies et al., 2001), which is important for construction practices and natural hazards in Alpine areas. Knowledge about the distribution and evolution of permafrost temperatures is key to the discernment of sensitive zones. As permafrost is a thermal phenomenon of the subsurface, it is not visible and modeling is therefore one of the main topics in permafrost research, which is particularly challenging for the complex and highly variable conditions found in high mountains.

The investigation of ground temperatures beneath alpine topography needs to account for 2- and 3-dimensional effects, since strong lateral components of heat fluxes exist that are caused by geometry and variable surface temperatures, violating the common assumption of 1-D vertical heat transfer (Kohl, 1999; Gruber et al., 2004b). It has been shown that due to these effects surface conditions alone do not sufficiently indicate the thermal conditions at depth even for equilibrium conditions (Noetzli et al., 2007). Established permafrost distribution models, however, are typically based on the surface energy balance or selected proxy variables without considering the thermal conditions at depth and a 3-dimensional character of the subsurface heat flow.

In this paper we present a modeling approach for the investigation of subsurface temperatures in complex and steep mountain topography that combines a surface energy balance model and 3D heat conduction within COMSOL Multiphysics. As an example, below ground temperatures and permafrost evolution for the Matterhorn (4478 m) in the Swiss Alps are shown.

2. Modeling Permafrost Temperatures

2.1. General Approach

To model ground temperatures in alpine terrain we developed a modeling chain that considers the processes in the atmosphere (climate), at the surface (energy balance) and in the deeper subsurface (heat conduction) in a transient and 3-dimensional way: We combine a surface energy balance model with a 3-dimensional heat conduction scheme (Noetzli et al., 2007; Figure 1). Modeled ground surface temperatures are imposed as upper boundary condition for the numerical heat conduction scheme. Additionally, scenario climate time series from Regional Climate Models (RCMs) can be integrated to simulate future scenarios (Salzmann et al., 2007). The basic inputs for the modeling procedure are a digital elevation model (DEM)
that represents the topography of the area investigated (Data Source: Swisstopo), measured climate time series (Data source: MeteoSwiss), and information on surface and subsurface characteristics.

2.2. Rock Surface Temperatures

In complex high mountain topography a sound calculation of surface temperatures is particularly important as surface temperatures are highly variable in space and time, and they are the main cause for lateral heat fluxes in the underground. Surface temperatures are controlled by the energy balance at the surface and mainly depend on climatologic variables, on topographical factors and on surface characteristics. The TEBAL model (Topography and Energy BALance (Gruber, 2005) simulates hourly time series of surface energy fluxes and near-surface temperatures based on observed climate time series, topography, and surface and subsurface information. The model contains algorithms for the mountain-specific extrapolation and parameterization of meteorological variables and surface energy fluxes. Detailed information on the model design, its application, and thorough validation have been published previously (c.f. Gruber et al., 2004a; Gruber, 2005; Noetzli et al., 2007; Salzmann et al., 2007).

2.3. 3D Heat Conduction in the Subsurface

In steep rock slopes, heat transfer at depth mainly results from conduction and is driven by the temperature variations at the surface and the upward heat flow from the interior of the earth. Further processes are not considered: the effects of fluid flow can, as a first approximation, be neglected in bedrock permafrost (Kukkonen and Safanda, 2001), and radio genetic heat production only becomes important at greater depth. Accordingly, we considered a conductive transient thermal field under highly variable topography in an isotropic and homogeneous medium (Carslaw and Jaeger, 1959):

$$\frac{\partial T}{\partial t} = \kappa \nabla^2 T \quad (1)$$

where $T[K]$ is the temperature at times $t [s]$ and $\kappa [m^2 s^{-1}]$ is the thermal diffusivity, defined as the ratio of thermal conductivity $l [W m^{-1} K^{-1}]$ to volumetric heat capacity $\rho c_p [J m^{-3} K^{-1}]$.

The modeling package COMSOL Multiphysics was used for forward modeling of subsurface rock temperatures. The simulations are conducted within the heat transfer module in transient 3D mode. The upper boundary condition (UBC) simulated by the energy balance model is defined as a function $UBC = f(x,y)$, and interpolated from a file. A uniform lower boundary condition heat flux of 80 mWm$^{-2}$ was set (Medici and Rybach, 1995). For simplicity, and due to the lack of information, homogenous isotropic material properties were chosen based on published values.

The topography of the area under consideration is imported by a routine within COMSOL Script. The routine reads gridded elevation data from a common format used in Geographic Information Science (GIS; Format GRIDASCII), typically with a spatial resolution between 10-50 m, and generates the geometries (Figure 2). The geometry is meshed with increasing vertical refinement from 250 m at depth to ca. 10 m for elements closest to the surface. In order to avoid effects from the model boundaries, a roughly discretized rectangle box of 1000 m height and thermal insulation across its sides is added below the topography.
Figure 2. Geometry of the Matterhorn (CH, 4478 m) imported to COMSOL Multiphysics. For the modeling, a 1000 m rectangle box was added below the topography.

2.2. Transient Temperature Fields: Paleo-Effects and Climate Change

To allow for transient effects of the late and post glacial period the model can be initialised using a temperature history at the surface. For this purpose a surface temperature history is prescribed in terms of a function that interpolates the current surface temperature for each time step from a file. Transient effects from the last glacial period, however, were found to be small for depths where permafrost exists (up to some 1000 m; Noetzli et al., in prep.). This is mainly attributed to the accelerating effect of steep topography where, unlike in flat terrain, changes in surface conditions intrude from many sides. For the simulation presented in this paper, we do not consider the temperature effects of the past ice ages.

In contrast, the past century warming and predicted future temperature evolution significantly alter the subsurface thermal field. To simulate future surface temperatures, the energy balance model can be driven by time series gained from regional climate models (RCMs, cf. Salzmann et al., 2007).

2.3. Latent Heat Effects During Phase Change

Water contained in the pore space and crevices of rock delays the response to surface warming by consuming latent heat, which may influence the time and depth scales of permafrost degradation by orders of magnitude even in low porosity rock (Wegmann et al., 1998; Kukkonen and Safanda, 2001). In a finite-difference heat transport model this effect can be handled by an apparent heat capacity $\rho c_a$ (Eq. 2) which substitutes the volumetric heat capacity $\rho c_p$ in the heat transfer equation (Eq. 1) for temperatures below the melting point. In this study, we used the approach described by Mottagy and Rath (2006). The apparent heat capacity augments the volumetric heat capacity by the energy needed for phase change during a time step:

$$
(\rho c)_a = (\rho c)_p + \rho_i L_f \Phi \frac{d\Theta}{dT}
$$

Here, $\rho_i$ is the density of ice, $L_f$ is the specific latent heat of fusion for ice, $\Phi$ is the porosity of the material and $\Theta$ is the volumetric unfrozen water content (the parameter $\omega$ describes the steepness of the unfrozen water content curve). In our model, only the temporal deviation of $\Theta$ needs to be implemented:

$$
\frac{d\Theta}{dT} = \frac{2(T - T_L)}{\omega} \exp\left(-\frac{T - T_L}{\omega}\right) \quad \text{if } T \leq T_L
$$

$$
0 \quad \text{if } T > T_L
$$

The apparent heat capacity was assigned with the subdomain properties. The temperature- and phase-dependent variation of the bulk density is assumed negligible for such low porosity material. For bedrock, we consider a porosity of 3% according to Wegmann (1998).

3. Results for the Example Matterhorn

In Figure 3 the subsurface temperature field of the Matterhorn is visualized in a cross section for current (steady state) and for a scenario of future conditions in 100 and 200 years, respectively, assuming a linear and uniform warming of surface temperatures of +3 °C/100 yr.
Figure 3. Modeled subsurface temperatures for the Matterhorn visualized in a cross section. The 0 °C-Isotherm corresponds to the permafrost boundary and is shown with a black line. (a) corresponds to equilibrium conditions, (b) depicts a temperature field after 100 years, and (c) after 200 years, respectively.

The steady state temperature field is significantly influenced by mountain sides having different temperatures: The isotherms are steeply inclined in the top part, a strong lateral heat flux exists from the warmer to the colder side, and the influence of the geothermal heat flux is marginal.

The scenario temperature fields deviate strongly from equilibrium conditions. Projected future warming leads to deep reaching and long-term changes in the permafrost conditions, after 200 years changes have reached a depth of approximately 250 m. Due to the steep topography a temperature signal intrudes into the mountain from different sides, which significantly accelerates the warming of the subsurface. This, together with the low ice content, makes bedrock permafrost very sensitive to climate change.

4. Conclusions and Perspectives

An energy balance model has been successfully combined with numerical 3D heat conduction in COMSOL Multiphysics and an import routine for digital elevation model has been written to import topographic geometries in order to model ground temperatures and permafrost distribution below complex topography.

The model chain applied may be established for future studies on the subsurface distribution and evolution of mountain permafrost, such as the re-analysis of recent periglacial rock fall events or the study of the present transient state of thermal fields below complex topographies. A validation study testing the modeling approach presented with measured temperature data and geophysical soundings for a test site in Switzerland is underway.

References