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Coupled water and heat transfer in permafrost modeling

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Abstract

Permafrost degradation in high mountain environments is one of the effects of climate change in the Alpine region (IPCC, 2007). The consequences may be manifold, ranging from rock falls and debris flows, to structural damages in infrastructures located on high mountains. The exceptional rock-fall activity during the summer 2003 is likely an indication of this rapid destabilization that takes place as an almost immediate reaction to extreme warming (Gruber et al., 2004a).
The understanding and prediction of such phenomena requires first the localization of permafrost affected areas, and then the monitoring of permafrost sites through proper measurement and modeling techniques. However, the modeling of alpine permafrost is not an easy task because of a variety of causes that contribute to increase the complexity. In particular, the crucial factors dominating alpine permafrost are (1) topography and soil type heterogeneity, (2) snow insulating effect, (3) presence of ice in the ground and (4) high thermal inertia for temperature change at depth. These disturbances could be dealt with through a physically based approach that accounts for the topographical characteristics of the basin, allows heterogeneous parameterization of thermal and hydraulic properties of the ground, solves snow accumulation and melting, and calculates temperature, water and ice content in the ground.
GEOtop (Rigon et al., 2006) is a distributed physically-based hydrological model that appears suitable to deal with the above outlined requirements, as it solves coupled water and energy bud- gets, allows heterogeneous input parameters in the form of maps and includes a snow module that calculates accumulation-melting of snow through a multilayer discretization of the snowpack (Endrizzi, 2007). The model, at the beginning of this work, was lacking of a freezing-soil module capable to account for phase change and heat advection in the soils, extremely important in permafrost affected areas (Roth and Boike, 2001). The inclusion of this part, however, needs a deep thermodynamical analysis of the system, in order to derive the relations between pressure and temperature in a ground subject to freezing conditions.

Furthermore, the solution of the energy equation requires a robust numerical scheme, which has to cope with the high non-linearities present in the apparent heat capacity formulation for phase change (Hansson et al., 2004). Finally, the snow-soil thermal interactions require a special attention, as they command the energy flux in input to the ground when the snow is present.

The objectives of this thesis are to develop a new freezing soil module inside GEOtop, to test the model against analytical solutions, experimental data and field observations, and to apply the model to investigate the influence of coupled heat and water flow in arctic and alpine permafrost areas.