STATISTICAL ANALYSIS OF MOUNTAIN PERMAFROST TEMPERATURES

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Summary

The consequences of climate change are clearly visible in the Swiss Alps. In the past decades, increasing air temperatures have induced pronounced glacier retreat and permafrost thawing. Thawing permafrost in steep terrain is a potential natural hazard, as it can become unstable and trigger mass movements such as settlement, debris flows or rock fall. The WSL Institute for Snow and Avalanche Research SLF has been measuring ground temperatures and displacements in permafrost boreholes for more than a decade. This thesis aimed to analyse these ground temperatures with statistical methods, assessing possible changes, trends and physical coherencies.

In a first step, temporal changes in daily ground temperatures measured in two adjacent boreholes at Muot da Barba Peider in the Eastern Swiss Alps were analysed. Statistical models, which could for example describe changes in the amplitudes or in the mean, were used to estimate possible trends. The results for the period 1996 - 2008 revealed increasing summer temperature for the upper ground layers, whereas winter temperatures had decreased. For the frozen rock below 10 m however, a general temperature increase was found. Although increasing summer temperatures were consistent with the development of the air temperatures, decreasing winter temperatures could be attributed to a thin early winter snow depth. The general warming trend in the deeper layers was assigned to increased heat transfer through the mountain ridge of Muot da Barba Peider induced by warming air temperatures and lower snow depths. These results confirm that permafrost temperatures in the Alps are influenced by factors such as snow cover, surface properties, hydrology and topography. Increasing air temperatures do not necessarily induce permafrost thawing.

Special attention was paid to the so-called “active layer”, the topmost ground layer above permafrost, which seasonally thaws in summer. An increase in its thickness implies a potential increase of the material which might be released in a mass movement. Typical active layer characteristics have been analysed and compared for ten different permafrost sites. Whereas over the past decade, the active layer remained rather constant at the individual sites, significant differences due to local terrain properties were visible. The comparison of the daily development of the active layer thickness with that of the thawing degree days revealed that ice-rich ground layers delay the active layer development efficiently and thus isolate the permafrost from warm air temperatures. Two of the ten sites, however, revealed abrupt active layer deepening due to lateral air and/or water flows.

Further investigation of the dependence between air and ground temperature was performed. Transfer function models were used to quantify the relation between air and ground temperatures measured at 0.5 m depth at seven different permafrost sites. The results showed that the delay between daily changes in the air and ground temperature ranges from one to six days, depending on

the site. The most efficient relation was found for a very coarse-blocky rock glacier site, whereas scree slopes with smaller grain sizes showed a weaker and more prolonged relation.

The main heat transfer mechanism in permafrost is conduction, but due to phase change, air or water flows, heat can also be transferred non-conductively. A statistical procedure including spectral analysis, order-restricted inference and a false discovery rate procedure has been developed to detect depths and frequencies at which significant non-conductive heat transfer processes occur. The application of the procedure to two-hourly borehole temperatures measured at Muot da Barba Peider revealed significant non-conductive heat transfer for the period 2005 - 2009 only in an ice-rich layer between 1 and 1.9 m depth. To gain deeper insight into the processes occurring shorter (three-week) periods have been analysed. The results showed non-conductive heat transfer processes that could be attributed to phase changes at the freezing front and at the base of the active layer in autumn, to convective air and vapour flows through the frozen scree in winter, and to phase changes and meltwater infiltration during the thawing period in spring.

Analyses of borehole temperatures also revealed special phenomena. A case study for the famous permafrost site at Flüela Pass showed that the permafrost body inside the scree slope, close to the lake has degraded from 7 m to 3.5 m thickness within four years. This rapid permafrost degradation could be attributed to a seasonal ventilation system inside the scree, leading to condensation which melts the permafrost body from below. Increasing lake water temperatures might accelerate the phenomenon.

The ground temperatures analysed in this work include about one decade of measurements and therefore are too short for climate-related statements. However, the statistical analyses performed give an interesting insight into the development of permafrost ground temperatures during the past ten years and their interaction with air temperature and local properties. The presented results furthermore emphasize the strong spatial variability of the ground thermal regime in mountain permafrost.