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# PROCESSES OF SNOW/PERMAFROST-INTERACTIONS AT A HIGH-MOUNTAIN SITE, MURTÈL/CORVATSCH, EASTERN SWISS ALPS

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**Abstract**

In a study on the surface of the active rock glacier Murtèl/Corvatsch, a system of vertical funnels (holes) was examined within the snow cover in early winter. Such funnels distributed along topographic depressions and following cold-air drainage patterns efficiently couple the active layer with the cold winter atmosphere, thereby reducing the thermal insulation effect of snow. For late-winter, spring and early summer conditions, repeated snow-depth point measurements were interpolated on the basis of topographic parameters and used in a model to simulate the melting of snow during the spring and early summer period over the entire rock glacier. The effects of late melting and of thick snow, causing delayed surface warming during spring and early summer, combine with the effects of enhanced mid-winter cooling in furrows, to cause colder ground temperatures and a shorter thaw season. This explains the pronounced decrease of active-layer thickness in deep furrows as documented by earlier seismic refraction soundings.

## Introduction

The winter snow cover and its melting exert a great impact on the development and occurrence of permafrost in polar and alpine regions (Ohmura, 1981; Keller, 1994). Snow is a poor heat conductor and short-term variations of air temperature rarely reach the snow-covered ground as they are dampened by the snow when the snow cover is thick enough. In the fall, strong cooling effects can be initiated by thin snow effectively conducting heat out of the underlying ground and intensifying the emission of long-wave radiation (Keller and Gubler, 1993). Yet, relatively little is known about the processes relating to the effect of winter snow cover on the heat balance of alpine permafrost. Equally sparse knowledge is available about the impact of permafrost on the melting of the snow cover. In order to improve the empirical knowledge base, a study on winter snow conditions was carried out at the surface of the active rock glacier Murtèl/Corvatsch (Bernhard, 1996; Sutter, 1996). This rock glacier has been the site of intensive previous studies (c.f. Barsch, 1975; Haeberli et al., 1988; Hoelzle, 1994; Keller, 1994; Vonder Mühll, 1993). It is approximately 400 m long and roughly 200 m wide and lies between 2620 and 2850 m a.s.l. Its surface is completely vegetation-free, consisting of coarse blocks and exhibiting a rugged microtopography with ogive-like transverse ridges and furrows several meters deep (Figure 1).

## Field measurements

During early winter 1994 and until 7 March 1995, the occurrence and development of snow funnels (Figure 2) was mapped in a representative field of about 60 x 160 m. Position, diameter, vertical profile, grain-shapes of

*Figure 1. Rock glacier Murtèl-Corvatsch (photo: S. Sutter, 1995).*

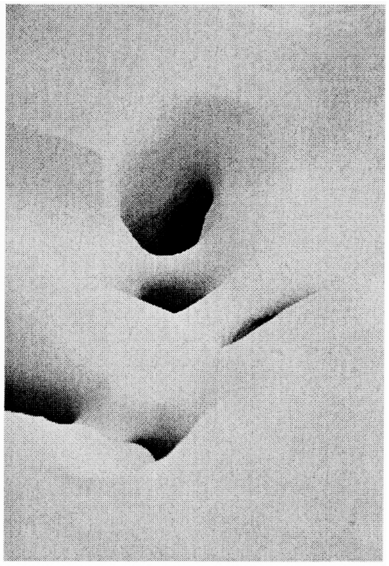

*Figure 2. Funnels on the rock glacier Murtèl-Corvatsch (photo: L. Bernhard, 1994).*

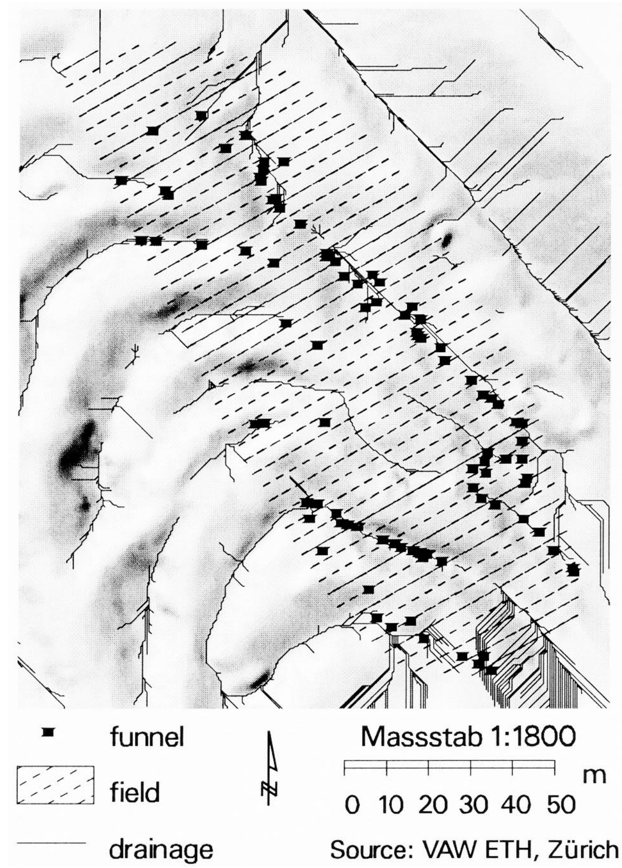


*Figure 3. Funnel positions in the field for December 8/9, 1994.*

surrounding snow crystals, snow and air temperature, and in places the flow direction of the air was determined for the funnels. In addition, BTS (bottom temperature of snow cover, Haeberli, 1973) measurements were carried out in a 20 m-grid and shallow ground-temperatures were measured at four positions on the surface and in front of the rock glacier. Fieldwork during late-winter, spring and early summer was conducted in the period between January and July 1994. Three transects were established perpendicular to the general rock glacier flow and two additional transects were arranged diagonally. This sampling pattern reflects the surface structure of the rock glacier and made it possible to revisit approximately the same points. Using a georeferenced model, the evolution and melting of the snow cover was investigated over the given time period as well as across the entire rock glacier. This improves the potential for detecting and explaining the interrelationships between various topographic and glaciological factors and processes.

## Data analysis

### Early Winter: Funnel Phases and Positions

In the examination of the funnels (Figures 2 and 3, Table 1), a division into initial, activating, and deactivating phases has proven useful, as the physical processes responsible for the funnel development change through time. During the initial phase, the funnel is formed a couple of days after the first major snowfall. At this time of year, large blocks break through the (still) thin snow cover. Snow erosion by strong winds leads to reduced snow depths around such blocks and favours the formation of funnels. The funnels are coupled with the air chamber system of the blocky active layer. During the activating phase with a more or less closed snow cover, only a few blocks remain visible. Funnels with and without hoar-frost crystals can be found. In funnels with long hoar-frost needles (sometimes up to five centimetres), warmer air temperatures are measured. During the deactivating phase, free-standing funnels are typically found in furrows, but become rare and finally disappear as the snow depth increases and the furrows fill up with snow. The funnel diameter decreases and funnels with hoar-frost crystals are the exception.

**Table 1. Number of funnels and their distribution**

| Date | Ridge | Slope | Furrow | Number |
|---|---|---|---|---|
| November 17, 1994 | 24% | 34% | 42% | 41* |
| December 8/9, 1994 | 23% | 17% | 60% | 97 |
| January 3/4, 1995 | 19% | 18% | 63% | 126 |
| January 18, 1995 | 32% | 45% | 23% | 45 |
| February 1/2, 1995 | 31% | 41% | 28% | 49 |
| March 7, 1995 | 41% | 35% | 23% | 17 |

### Mid-winter, Spring and Early Summer: Snow Depth Variability on a Rugged Surface

On the rugged topography of the rock-glacier surface, snow is usually removed from ridges and blown into furrows. Point measurements in the field indeed confirmed that snow-cover thickness is far greater and snow-cover duration far longer in furrows than on ridges. The original point samples must, however, be interpolated across the entire study area by means of a stochastic or deterministic model (Stüve, 1988). A digital terrain model (DTM) (Weibel and Heller, 1991) of the study area was used to calculate topographic parameters – gradient (slope), aspect and profile curvature - which were then used to characterise the terrain at sample points and establish a multiple regression model for extending the snow depth measurements across the DTM. Topographic parameters were determined according to the method proposed by Zevenbergen and Thorne (1987), which is implemented in the GRID module of ARC/INFO. Due to the rugged topography of the rock glacier surface and redistribution of snow by wind, the accumulated snow depth shows substantial spatial variation. Therefore, a multiple regression model (Chatterjee and Price, 1991) was used in an attempt to establish a relationship between the snow depth values measured at the sample points (dependent variable) and the topographic parameters calculated from the DTM (independent variables; cf. Bernhard, 1996, for a complete analysis of the regression model used).

#### Spring and Early Summer: spatial patterns of snowmelt

Based on the measured snow depth distribution, the spring and early summer melting of snow on the rock glacier surface with its complex topography was calculated using an energy balance approach - as first applied in Norway (Sverdrup, 1936) - and compared to periodic observations. A simplified energy balance model was developed to estimate spatial patterns of snow melt, i.e., to attribute an individual value of snow melt for every point of the grid representing the study area. The conditions within the snow cover determine the start of the runoff process. The time when the surface of the snow cover reaches a temperature of 0˚C indicates the start of snow melt. Despite a positive energy supply, however, the temperature of the snow cover can continue to be negative. Only when the snow cover becomes isothermal, do runoff and mass loss start. In the model, the energy available for snow melting is represented by the direct short-wave radiation calculated for the preceding time period. Additionally, the specific latent heat must be known as well as the snow density. The latter was assumed to be constant (400 kgm$^{-3}$), as the density exerts a minor influence on snow melt.

The model is expressed as follows:

$$S_{0-n} = S_0 - \left( \frac{\sum_{i=0}^{n} E_m \left( / - \alpha_i - c_i \right)}{L_f \times \delta_s} \right) \qquad [1]$$

| | |
|---|---|
| $S_0$ | initial snow depth (value per grid cell) [$m$] |
| $n$ | Number of days [$d$] |
| $E_m$ | mean incident radiation (value per grid cell) [$MJ/m^2d$] |
| $a_i$ | Albedo at day $i$ |
| $c_i$ | Coefficient of cloud cover at day $i$ |
| $L_f$ | specific melt heat [MJ/kg] |
| $d_S$ | Mean snow density [kg/m$^3$] |

The cloud-cover coefficient was assumed to be proportional to the mean cloud cover (Müller, 1984): under clear sky conditions, the entire global radiation reaches the snow cover, while only 72% reaches the ground at 4/8 cloud cover, and still less (36%) for a completely overcast sky. In order to assess the performance of the proposed modelling procedure, the results were analysed qualitatively and quantitatively (see below).

### Discussion of results and interpretation

#### Coupling of the Atmosphere with the Permafrost Active Layer through the Development of Snow Funnels

At the beginning of snow-cover development, the highest frequency of snow funnels was found in furrows. Modelling cold air drainage over the digital terrain model of the rock-glacier surface by applying a hydrological ARC/INFO module (‘Hydrologic Modeling Tools’ ESRI, 1992; cf. Hutchinson, 1988) indeed indicates that the funnels primarily occur close to paths of cold air drainage (Figure 3). In the rock debris of the active layer, macropore and channel systems exist in which the air circulates. Along the furrows, the hidden coupling of this macropore and channel system with the funnels is visible. Through the relief, the air flowing down from higher rock-glacier parts in the channels and macropores of the active layer becomes confined and compressed. Compression of air favours the development of vertical air movement. As with the wind tubes in summer (Schaeftlein, 1962; cf. also Wegmann, 1995), downslope-flowing cold air prob-

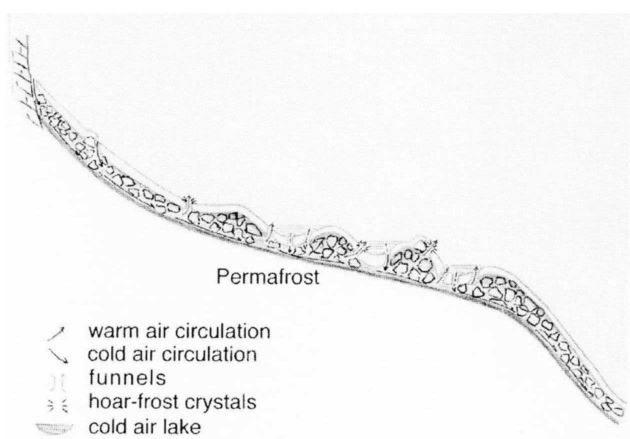


*Figure 4. Sketch of a possible air-circulation system.*

ably circulates at the base of the highly permeable active layer. The cold wind pushes the warmer air within the active layer upwards through the funnel and the cold air within the active layer above the permafrost surface can reach the snow cover where active-layer thickness is small (cf. Figure 4). Mechanical effects of the circulating air, as well as locally higher temperature gradients, could further help to open and uncover funnels in topographic depressions. Higher temperature gradients in depressions are due to stagnation of cold air at the snow surface and vertical drainage into the active layer through funnels. In fact, active-layer temperatures in furrows are known to closely follow short-term fluctuations of air temperatures even with an existing snow cover, whereas the rock debris on ridges continuously and nearly constantly cool down (Hoelzle et al., in preparation).

Permafrost active layer thickness is considerably larger, and BTS-temperatures higher on ridges than in furrows (Vonder Mühll, 1993); this would favour funnel formation on ridges. However, funnels on slopes and ridges were only found after snow depth had increased. In the active layer on ridges, not only is a greater amount of energy present, but it can also be better preserved for two main reasons: (1) a snow cover which has hardly been affected by funnel-formation, prevents upward-directed escape of the relative heat and (2) ridges are seldom influenced by cold-air drainage. Funnels with hoar–frost crystals can primarily be observed on the slopes of ridges. Due to the fact that warm air can absorb more water, the water drops condense when cooling down during the outflow from the funnel and become deposited on the funnel edge, which leads to the growth of hoar–frost crystals. The crystal growth is directed radially from the margins towards the centre of the funnel opening.

Once the funnels are formed, the colder external air masses sink into the rock debris through the funnels. On the other hand, currents of surface air become diverted by the large rocks and blow straight into the circulation system, which leads to increased circulation velocity. The currents as well as the shape and distribution of the rock debris determine the shape of the funnels and their opening. Inside the funnels, between the blocks, snow accumulates without cutting off the connection with the channel/macropore system. This snow accumulation could be caused by the funnel-forming process, during which snow particles fall through the snow cover and finally cause the snowcover to collapse within the funnel. This process may be initiated by the high permeability of freshly fallen snow, which would increase further through constructive metamorphism. During snow precipitation, the funnels can become snow-covered but may reopen by the above-described processes. Furthermore, snow always gets carried into funnels by wind.

Asymmetric cycles of air temperature were observed in connection with alternating air-flow directions in the funnels: during several minutes of out-streaming air, the thermistor in the funnel warmed up, whereas only a few seconds of in-streaming air were sufficient to cool it down again and compensate for the previous rise in temperature. The most plausible explanation for this 'in- and outbreathing' is to be found within the complex open circulation system of the active layer with its convective fluxes. When colder air sinks into funnels, the lighter, warmer air is pushed upwards through other funnels (Sutter, 1996).

Details of the processes are still unclear. Possible effects of wind pumping (Clarke et al., 1987; Colbeck, 1989), for instance, remain to be investigated. The most important factors for the formation of funnels, however, can be assumed to be:

- the high temperature-gradient in the snow covering the still relatively warm active layer in early winter, which favours constructive metamorphism and corresponding reduction in snow density and strength;

- the existence of many large, interconnected macropores in the blocky active layer, which leads to a high permeability of the rock-debris as a precondition for the development of air circulation and, especially, cold-air drainage between the permafrost table and the bottom of the snow cover;

- the topography of the surface and of the permafrost table, which governs the channeling of cold-air drainage at the snow surface and within the highly permeable active layer;

- the snow-depth (snowdrift included) influencing the position and life-time of the funnels;

- the weather affecting the heat balance in the ground and the entire air circulation system during all funnel phases.

### Spatial Snow-melt Modelling - Qualitative and Quantitative Assessment

Photographs of the Murtèl rock glacier taken every second day by an automatic camera with 35 mm colour reversal film from a position in close vicinity to the middle station of the Corvatsch cable-car were used for comparison, along with qualitative checks of the applied modelling techniques (Figures 5a and 5b). In order to achieve a visual comparison with the results produced by the snow-melt modelling, three days were chosen during the snow-melt period: (1) June 18, 1994; (2) June 29, 1994; (3) July 7, 1994.

May 1 was determined as the start of the snow-melt phase. The snow loss accumulated between May 1, and

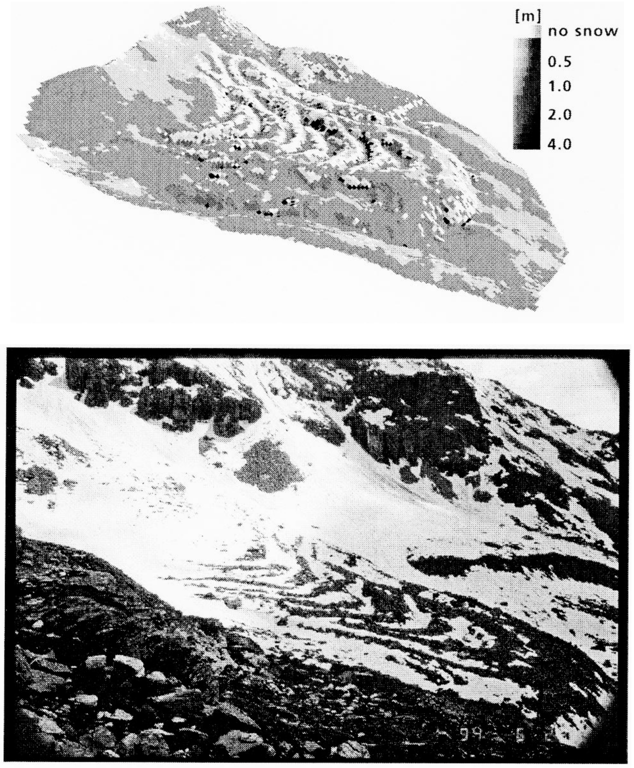


*Figure 5. (a) Calculated snow depth for June 29, 1994 viewed from the perspective of the automatic camera; (b) Corresponding photograph for the same day.*

the above-mentioned three selected dates was calculated using the described simplified energy-balance model. The continuous snow-depth grid interpolated by multiple regression from the measurements taken on April 27 provided the initial snow depth values. Although interpretation of the three visual comparisons is somewhat difficult, a clear trend can be seen. The model results for the first two dates clearly show that the characteristic pattern of long-lasting snow in furrows can be simulated well, but that an excess of snow-covered areas is calculated as compared with the photographs. On July 7, the furrows were computed to be entirely clear of snow in contrast to real conditions. The regression model of snow height as a function of microtopography obviously underestimated snow heights in furrows and overestimated corresponding values on ridges. This effect is due to the method of regression analysis which constructs a purely statistical relationship between the independent variables (topographic parameters) and the dependent variables (snow depth), averaging and smoothing the scatter of values occurring in reality.

Results of modelled changes in snow-cover thickness were quantitatively compared with results from field measurements on May 20 and June 20, 1994. Absolute and relative differences for both dates were computed. The absolute differences reveal the model error (in meters) much like the residuals of a regression model. The relative differences indicate the magnitude of the

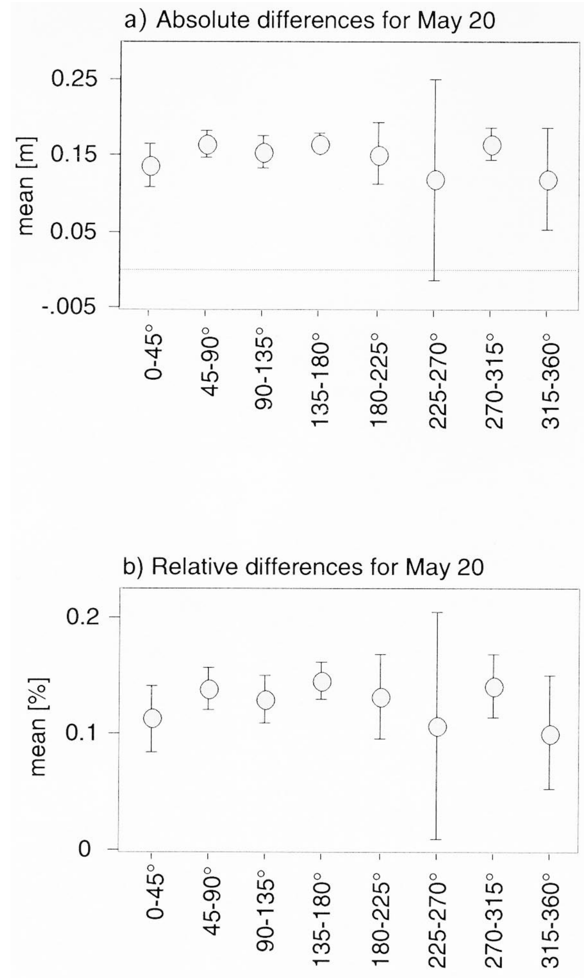


*Figure 6. (a) Absolute and (b) relative differences between measured and simulated snow heights for May 20, 1994, grouped into eight aspect classes[degree].*

error in relation to the actual value. In order to accomplish a more differentiated analysis of the errors expressed by the computed differences, the individual sample points on the rock glacier were classified according to topographic parameters. As an example, the absolute and relative snow-height differences for May 20 have been assigned to eight equidistant classes of slope aspect (Figures 6a and 6b). The other analyses show similar results. The mean differences exhibit similar values for all classes. On average, snow melt was overestimated by 12-17 cm, corresponding to snow depth values which are 10-15% too low in relative terms. The standard deviations are usually in the range of a few centimetres. The greatest absolute differences are for NW-NE exposures. These aspect classes also display very slight scattering. Similarly high median values are observed for SW-W exposures (225-270°), but the large scatter in this class reflects locally extreme snow accumulation recognisable in the field but not reproduced by the regression model.

## Conclusions

Field investigations and spatial modelling using GIS-techniques indicate that a number of processes are involved with the important snow/permafrost-interactions on rock-glacier surfaces during wintertime. Following the special effects of enhanced ground cooling by thin snow in fall, the active layer of rock-glacier permafrost can be effectively coupled with the cold atmosphere during early winter by a system of snow funnels forming along cold-air drainage patterns which predominantly follow furrow systems of the rock-glacier surface. During later stages of winter, the furrows are filled up with snow due to snow redistribution by wind, the funnel system disappears and the active-layer/atmosphere coupling vanishes. Melting of the redistributed snow leads to a characteristic pattern of long snow-cover duration in furrows; this snow cover preserves cold ground temperatures by minimizing the effects of incoming solar radiation (Harris and Corte, 1992). These processes influence ground temperatures and patterns of active layer thickness as a function of the characteristic microtopography of rock-glacier surfaces.

Numerical modelling of snow melt in a spatially differentiated way for complex terrain gives results proving the feasibility of the approach taken. It is, however, not yet a practical tool for glaciologists or snow physicists. This is primarily due to the fact that some critical input parameters – in particular snow depth and the snow cover composition – must be measured at sample points in the field and subsequently interpolated across the entire study area.

## References


**Barsch, D.**(1975). Photogrammetrische Bewegungsmessungen am Blockgletscher Murtèl I. Oberengadin; Schweizer Alpen. *Zeitschrift für Gletscherkunde und Glaziologie*, **XI (2)**, 111-142.

**Bernhard, L.** (1996). Modellierung der Ausaperung der Schneedecke mit GIS in Abhängigkeit der Strahlung und des Reliefs. Masters thesis, Department of Geography, University of Zurich, 90 pp.

**Chatterjee, S. and Price, B.** (1991). *Regression analysis by example*. New York, Wiley, 278 pp.

**Clarke, G.K.C., Fisher D.A. and Waddington, E.D.** (1987). Wind pumping: a potentially significant heat source in ice sheets. In *International Association of Hydrological Sciences*, Publication **170** (Symposium at Vancouver 1987–The Physical Basis of Ice Sheet Modelling), pp. 169–180.

**Colbeck, S.C.** (1989). Air movement in snow due to wind-pumping. *Journal of Glaciology*, **35, 120**, 209–213

**Haeberli, W.** (1973). Die Basis-Temperatur der winterlichen Schneedecke als möglicher Indikator für die Verbreitung von Permafrost. *Zeitschrift für Gletscherkunde und Glazialgeologie*, **IX,** 221–227

**Haeberli, W., Huder, J., Keusen, H.R., Pika, J. and Röthlisberger, H.** (1988). Core drilling through rock glacier permafrost. In *V. International Conference on Permafrost*, **2**, pp. 937-942.

**Harris, S.A. and Corte, A.E.** (1992). Interactions and Relations between Mountain Permafrost, Glaciers, Snow and Water. *Permafrost and Periclacial Processes*, **3**, 103-110.

**Hoelzle, M., Wegmann, M. and Krummenacher, B.** (in preparation). Continuous measurements of bottom temperatures of the winter snow cover with miniature temperature dataloggers.

**Hoelzle, M.** (1994). *Permafrost und Gletscher im Oberengadin. Grundlagen und Anwendungsbeispiele für automatisierte Schätzverfahren*. Mitteilungen der Versuchsanstalt für Wasserbau, Hydrologie und Glaziologie der ETH Zürich, No. 132.

**Hutchinson, M.F.** 1988. Calculation of hydrologically sound digital elevation models. In *Proceedings of the 3rd International Symposium on Spatial Data Handling*, pp. 117-133.

**Keller, F.** (1994). *Interaktionen zwischen Schnee und Permafrost*. Mitteilungen der Versuchsanstalt für Wasserbau, Hydrologie und Glaziologie der ETH Zürich, No. 127.

**Keller, F. and Gubler, H.U.** (1993). Interaction between snow cover and high mountain permafrost at Murtèl/Corvatsch, Swiss Alps. In *Sixth International Conference on Permafrost, Beijing*, **1**, 332-337.

**Müller, H.** (1984). *Zum Strahlungshaushalt im Alpenraum*. Mitteilungen der Versuchsanstalt für Wasserbau, Hydrologie und Glaziologie der ETH Zürich, No. 71.

**Ohmura, A.** (1981). *Climate and energy balance on arctic tundra*. Zürcher Geographische Schriften, ETH Zürich, No. 3.

**Schaeftlein, H.** (1962). Ein eigenartiges Hochmoor in den Schladminger Tauern. *Mitt. des Naturwissenschaftlichen Vereins für Steiermark.* **92**, 104–119.

**Stüve, P.** (1988). Die Schneeschmelze eines nordskandinavischen Einzugsgebietes ermittelt über die räumlich-zeitliche Variation des Strahlungs- und Energiehaushalts. PhD thesis, Institut für Physische Geographie der Freien Universität Berlin, 123 pp.

**Sutter, F.** (1996). *Untersuchung von Schloten in der Schneedecke des Blockgletscher Murtèl am Corvatsch*. Masters thesis, Department of Geography, University of Zurich, 86 pp.

**Sverdrup, H.U.** (1936). The eddy conductivity of the air over a smooth snow field. *Geophys. Publ.*, **11**, 5-69.

**Vonder Mühll, D.** (1993). *Geophysikalische Untersuchungen im Permafrost des Oberengadins*. Mitteilungen der Versuchsanstalt für Wasserbau, Hydrologie und Glaziologie der ETH Zürich, No. 122.

**Wegmann, G.** (1995). *Permafrostvorkommen auf geringer Meereshöhe. Eine Fallstudie im Brüeltobel (AI)*. Masters thesis, Department of Geography, University of Zurich, 80 pp.

**Weibel, R. and Heller, M.** (1991). Digital terrain modelling. In *Geographical Information Systems: Principles and Applications*. New York: John Wiley & Sons, pp. 269-297.

**Zevenbergen, L.W. and Thorne, C.R.** (1987). Quantitative analysis of land surface topography. *Earth Surface Processes and Landforms*, **12**, 47-56.