PERMAFROST - Seventh International Conference (Proceedings),
Yellowknife (Canada), Collection Nordicana No 55, 1998

BOREHOLE TEMPERATURES IN ALPINE PERMAFROST: A TEN YEAR SERIES.

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Abstract

A 60 m deep borehole drilled in 1987 through the active rock glacier Murtèl-Corvatsch (Upper Engadin, Swiss Alps) has enabled collection of a 10 year long series of temperature measurements within creeping mountain permafrost, representing a regional signal.

Between 1987 and 1994, the uppermost 25 m rapidly warmed up. Surface temperature is estimated to have increased from -3.3°C (1988) to -2.3°C (1994), thereby probably exceeding previous peak temperatures during the 20th century. After 1994, within only two years with very little snow enabling intensive cooling of the ground, the temperatures declined, reaching values similar to those of 1987.

The variability of the observed permafrost temperatures is caused by several processes: (1) shorter periods of negative temperatures within the active layer due to long-lasting zero-curtains in the autumn; (2) global radiation and air temperature influencing temperatures mainly in the summer; (3) the history of snow-cover during the winter.

Introduction

The distribution of permafrost in low-latitude mountain areas is quite different from circumpolar regions: it is mainly controlled by radiation and altitude (Hoelzle, 1994; Keller, 1994). Hence, there are important differences within short distances. The most typical and reliable indication for mountain permafrost are active rock glaciers. Since permafrost is defined by temperature, the investigation of the rock-glacier thermal regime is fundamental.

In 1987, a borehole through the active Murtèl-Corvatsch rock glacier created the opportunity to investigate the thermal regime in a creeping permafrost body (Haeberli et al., 1988; Vonder Mühll and Haeberli, 1990). The cores, borehole logs, instruments for long-term monitoring (borehole deformation, temperature) and a number of geophysical surveys contributed to a better understanding of the internal structure and ongoing processes. Moreover, the probable evolution and development of an active rock glacier can be reconstructed (Haeberli et al., 1998). Temperatures are usually measured twice every month. Since 1993, a logger has stored one set of values every day.

In 1990, two permafrost drillholes were completed at Pontresina-Schafberg within an avalanche protection project (Vonder Mühll and Holub, 1992). Combined with Murtèl-Corvatsch, this allows the comparison of two sets of drill sites, which are some 15 km apart. Because of difficult access, only one set of temperature readings per year was originally foreseen at Pontresina-Schafberg. Between December 1991 and September 1994 a datalogger furnished additional daily temperature data for every thermistor in each borehole.

There are several papers reporting borehole temperatures, especially in circumpolar permafrost (e.g., Lachenbruch et al., 1982; Balobaev et al., 1983; Lachenbruch et al., 1988). However, articles about time

Table 1. Overview of key temperature data from three boreholes in Alpine permafrost

	Murtèl-Corvatsch 2/1987	Schafberg 1/1990	Schafberg 2/1990
Elevation [m a.s.l.]:	2671	2755	2733
Surface temperature [°C]:	-2.5 to -3.0	~ -1.5	~ 0.5
10 m temperature, 1992 [°C]:	-2.15	-1.5	-0.6
10 m temperature, 1993 [°C]:	-1.73	-1.0	-0.4
10 m temperature, 1994 [°C]:	-1.34	-0.7	-0.2
10 m temperature, 1995 [°C]:	-1.98	-1.0	
10 m temperature, 1996 [°C]:	-2.60	-1.2	-0.4
10 m temperature, 1997 [°C]:	-1.82	-0.8	-0.3
Temperature gradient between 20 m and 30 m (1991) [°C/m]:	0.050	0.022	0.015

series of permafrost temperatures are quite rare (Lachenbruch et al., 1962; Lachenbruch et al., 1966; Osterkamp and Romanovsky, 1996). This paper summarises temperature measurements in permafrost of the rock glacier drillsite at Murtèl-Corvatsch between 1987 and 1997. Analysis of the most important effects and comparison to the Pontresina-Schafberg drill site are also presented.

Temperatures with depth

The thermal regimes of the three borehole sites are quite different (Figure 1 and Table 1), although elevation, surface conditions and lithology are similar. Surface temperature estimated by a linear extrapolation of the gradient below the zero annual amplitude (ZAA) to the surface is about 1 to 2°C colder at Murtèl-Corvatsch than at the Pontresina-Schafberg localities. A big difference exists in the temperature gradients of the two drill sites as well: the high value at Murtèl-Corvatsch is caused by the two boundary conditions: one at the surface (surface temperature: -2.5°C), the other at about 50 m depth (talik, see below: 0°C). The values of about 0.2°C/10m at Pontresina-Schafberg is typical for this area (Bodmer and Rybach, 1984).

Thermal conductivity of cores from the Murtèl-Corvatsch drilling, determined in a cold laboratory, is between 2.3 and 3.0 W/m°C. Values calculated from amplitude attenuation and phase lag with depth scatter slightly more, but most are between 2.0 and 3.0 W/m°C as well (Vonder Mühll and Haeberli, 1990).

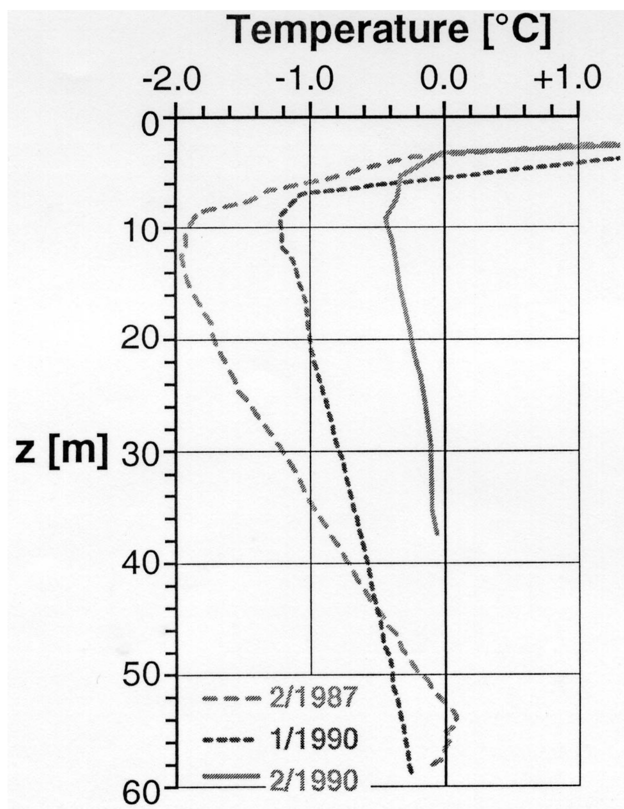

Figure 1. Permafrost temperatures in the Upper Engadin in September 1991 from the bore-holes Murtèl-Corvatsch (2/1987) and Pontresina-Schafberg (1/1990 and 2/1990).

Intrapermafrost talik

A special feature is observed at Murtèl-Corvatsch as described by Vonder Mühll (1992): seasonal temperature variations occur not only down to a depth of roughly 20 m but also within a layer between 51 and 57 m depth. Every year, at the end of June or the beginning of July, the temperatures rise within a few days from 0.05°C to about +0.15°C. Temperatures remain positive until late September and drop within a short period of time towards -0.1°C during the winter and spring. Above 51 m and beneath 57 m, the values do not vary and have been negative since 1987. The measured maximum temperature in summer increased slightly between 1989 and 1993. During the last four years the warming has accelerated (0.1°C in 1994; 0.3°C in 1997).

Recent evolution of the temperature at various depths

A fundamental question for the assessment of the distribution of mountain permafrost concerns the representativeness of the permafrost temperatures. Do the measurements show the particular thermal regime at the drill sites (is it a local signal ?) or are they characteristic for the region or even a larger area? Therefore, three comparisons between the two localities were made:

(1) temperature records just below the permafrost table (boreholes 2/1987 Murtèl-Corvatsch and 2/1990 Pontresina-Schafberg from 1992 to 1994, when a data-logger was used at Pontresina-Schafberg; Stucki, 1995);

(2) the 10 m temperature in August/September (when measurements are available from all three boreholes; see Table 1);

(3) the temperature data in the uppermost 20 m in general.

All comparisons confirm that the evolution of the temperatures is synchronous in all three boreholes although there are differences in absolute values as well as in the temperature gradient. In the following, only data from Murtèl-Corvatsch are discussed, because the highest temporal resolution is available here.

Figure 2 shows the temperature measurements at the most interesting depths between July 1987 and September 1997. In addition to the raw data, a running mean of a one year interval is plotted. Temperature data from the borehole Murtèl-Corvatsch are available on the CD-ROM which is to be distributed at the VII International Conference on Permafrost in Yellowknife (Canada).

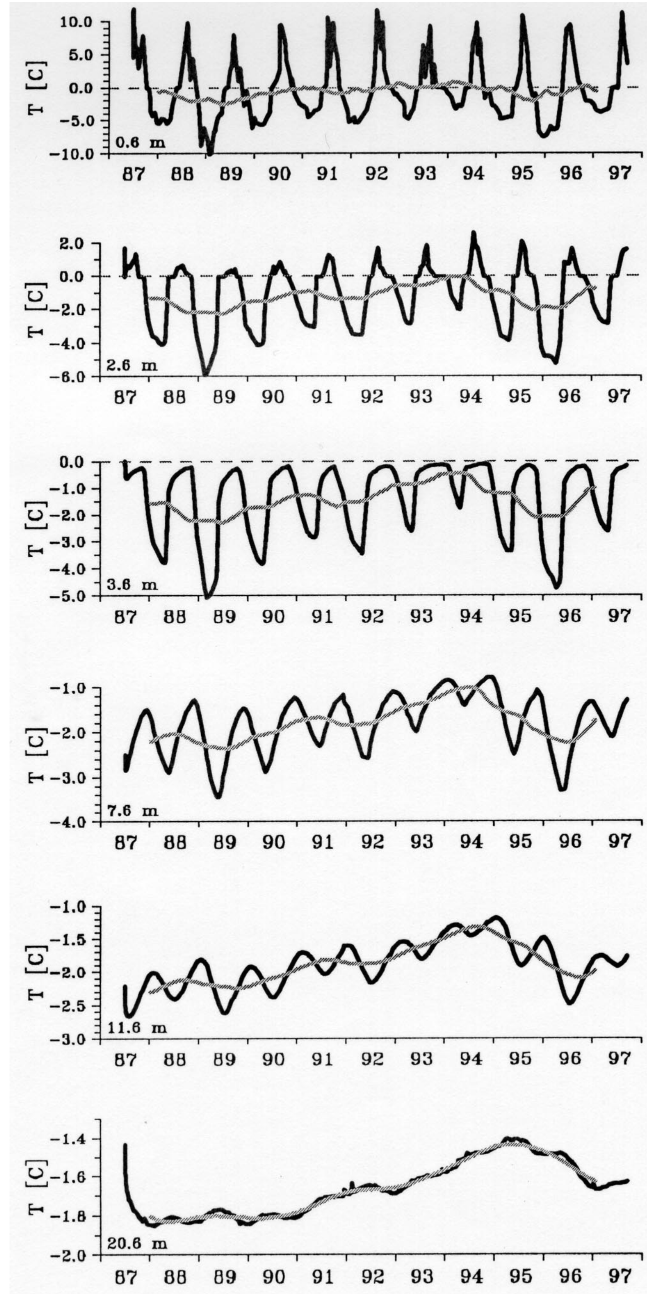

Figure 2. Time series of borehole temperatures in Alpine permafrost of Murtèl-Corvatsch between 1987-1997.

Surface and active layer

The uppermost thermistor at 0.6 m depth furnishes a reference value for the BTS (bottom temperature of the winter snow cover; Haeberli, 1973). The variation of the winter temperature from one year to the other is remarkably high (between -3° and -9°C). However, in every year, temperatures indicate 'permafrost probable' in terms of BTS. The amplitude of the temperature signal (half the difference between minimum and maximum values) at the lowest thermistor in the active layer (at 2.6 m, 4°C) is about half that of the highest (9°C). A zero curtain effect can be observed in various years (e.g., 1993, see Figure 3). Sometimes it hardly occurred, especially when the first snowfall came late (autumn)

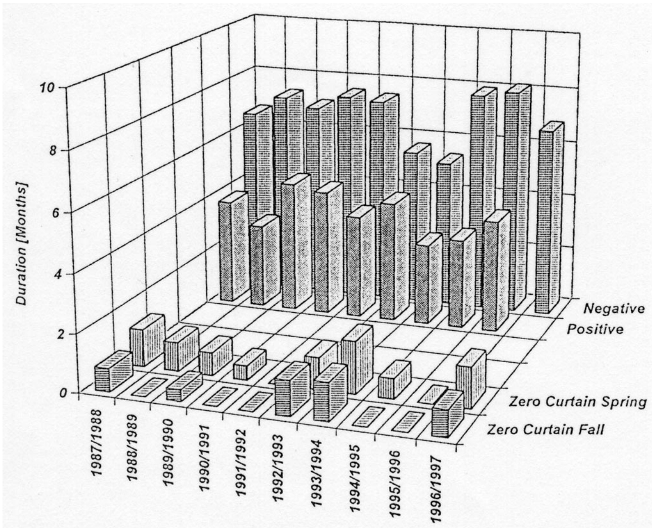

Figure 3. Analysis of the time series from the uppermost thermistor (0.6 m below the top of the inclinometer tube; actually just within the debris). Periods of positive and negative temperatures and duration of an observed zero curtain in fall and in spring separated for each year (fall 1987 to spring 1997).

or when the snow melted quickly (spring). The running mean with a one year interval shows variations between -2°C and +1°C. The uppermost thermistor even reveals a positive annual mean for periods of several months. The period between 1991 and 1995 was particularly warm.

3.6 M DEPTH

The uppermost thermistor in permafrost reveals that the warmest temperatures are almost constant (between -0.29°C and -0.11°C) throughout the ten year period while the coldest values are governed by the active layer temperatures. Consequently the running mean remains negative and its behaviour is similar to that of the thermistors above. The warming phase in summer is very consistent: after a fast warming in late spring to roughly -0.5°C only a small temperature increase is observed during the following few summer months because of latent heat processes. Hence, the shape of the summer peak is asymmetrical (a slow increase in temperature followed by a fast cooling). In addition, the shape is quite different from one year to the next: in 1991 the peak is quite sharp, whereas in 1993, the temperature remained near the maximum temperature for almost half a year. This means that a large of heat amount penetrated into the frozen ground, which of course strongly influences the running mean.

7.6 M DEPTH

The signal is still slightly asymmetric but more closely resembles a sine curve superposed by an amplitude variation and by a long-term fluctuation. The amplitude ranges between 0.3°C and 1.2°C and the phase lag is of the order of some 4 to 5 months. The running mean ranges from -2.4°C (1989) to -1.0°C (1994).

11.6 M DEPTH

The shape of the temperature signal is symmetrical, in particular the maximum peak. Amplitude (0.1°C to 0.6°C), phase lag (about half a year) and fluctuation of the running mean (-2.3°C in 1989 to -1.3°C in 1994) are easily detectable because the absolute accuracy of the used sensors is on the order of +/- 0.05°C.

20.6 M DEPTH

Seasonal temperature variations are visible but they are smaller than 0.1°C. Dissipation of the drilling heat took about half a year. The signal shows a temperature trend integrated over about one year (the annual running mean corresponds to the measured values). However, temperature at 20.6 m depth rose by 0.4°C within 4 years (1991 - 1995).

Analysis

RUNNING MEANS

Figure 4 shows the running means with a running interval of 365 days for temperature readings at various depths in the uppermost 20 m. Characteristic features of heat conduction are present: phase lag, amplitude attenuation and filtering of high frequencies with increasing depth. At depths of 7.6 m and 20.6 m, mean temperatures over the last 10 years are about the same (-1.7°C). In general, mean temperatures decrease with depth in the uppermost 15 m, indicating an ongoing warming trend. In fact, in steady state conditions one would assume the contrary (the deeper the warmer).

Another interesting fact is the distance between the curves. In the active layer, effects of advection and convection can be expected. Therefore, large differences ('jump') in mean temperatures from above to below the permafrost table would not be a surprise. However, a jump of more than 0.5°C can be observed between 1.6 m and 2.6 m. Just above and below the permafrost table the maximum difference is less than 0.4°C. The major part of advective processes presumably occurs around 2 m depth.

ACTIVE LAYER

The surface of mountain permafrost often consists of coarse blocks and boulders of different size, generating self protecting micro-climate conditions: in early winter and especially when the snow cover is thin, cold air entering through natural funnels circulates in the voids between the scree (Keller and Gubler, 1993; Sutter, 1996; Bernhard et al., 1998) and reduces the mean annual surface temperature (MAST). Big boulders are free of snow for a long time, conducting heat out of the ground. Moreover, in spring, the snow lasts much longer between the boulders than at vegetated sites of comparable elevation and aspect.

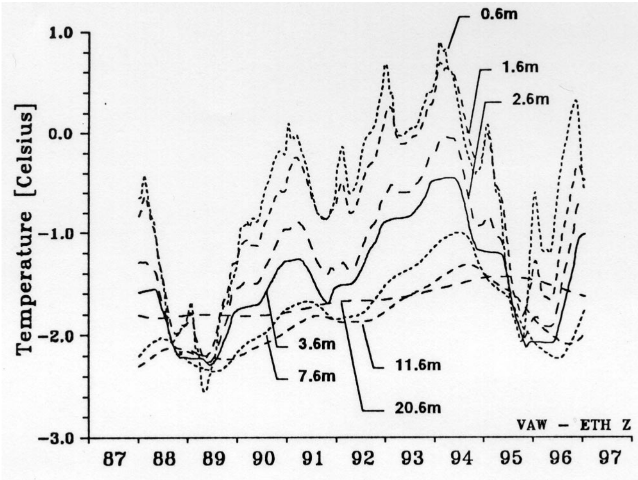

Figure 4. Running means of borehole temperature with time at various depths (Murtèl-Corvatsch).

The influence of advection (by air and / or water) in the active layer is obvious. Nevertheless, the temperature signal from the active layer is one boundary condition for the measured permafrost temperatures farther down, where heat conduction is the dominant process

Several processes are to be observed, which are important for the thermal regime of Alpine permafrost:

a) First major snowfall. Besides the overall thickness of the snow cover, the date of the first major snowfall is most important. In 1988/1989 for instance, after a first small snowfall in early December, no precipitation was registered until the end of February. At the end of April, snow-cover thickness was higher than the long-term average. The thin snow cover during the first part of the winter allowed rapid heat loss from the ground. Consequently, ground temperatures during this winter were the coldest since measurements began.

In October 1993, snow-cover thickness had already reached almost 1.0 m. Between New Year and April, more than 1.5 m of snow protected the ground from cooling. In addition, the snow fell on warm ground (as indicated by a long-lasting zero curtain). The heat stored in the active layer during summer could not escape because of the insulating snow cover. In early November 1996, a heavy snowfall of more than 1.5 m had a similar effect. The winters of 1993/1994 and 1996/1997 are - in terms of permafrost temperature - the warmest, although the mean annual air temperatures were not particularly warm.

b) Duration of positive and negative temperatures (Figure 3). After a thick snow cover in winter that generally warms the permafrost, a late melting of the snow follows. As long as snow covers the ground, the temperature is below or at 0°C. This in turn reduces the time of positive temperature and hence the heat introduced into the ground in summer. The same is true if the first snowfall occurs early. This extends the duration of negative temperature. Average durations over the last ten years are 3.8 months for positive temperatures and 7.0 months for negative ones.

c) Zero curtain. As mentioned above, a long-lasting zero curtain can be observed only under special circumstances. In principle, a zero curtain in the fall shortens the duration of negative temperatures in the following winter, and in spring, the zero curtain causes a shorter period of positive temperatures in the following summer. The latter effect is less pronounced than the former as Figure 3 indicates: the shorter the duration of the zero curtain in fall, the longer the period with negative temperatures. In contrast, a zero curtain in spring does not necessarily cause a shorter period of positive temperature values.

Correlation between radiation and ground temperature

The relationship between monthly means of global radiation and temperature in the active layer (0.6 m depth) was also investigated. The values from January to December are scattered and do not show any significant correlation. The separation into summer (July and August) and winter (November to June) reflects the influence of the snow cover discussed above. The correlation for July and August is 0.8, for November to June it is 0.4. Especially in summer, radiation is an important factor for the permafrost temperature.

Correlation between snow-cover thickness in November and December and permafrost temperature in March and April

As shown above, the snow cover is an important factor for the evolution of permafrost temperatures. A snow cover with a thickness of more than about 80 cm acts as insulation. It preserves the heat introduced in summer and protects the permafrost from cold winter

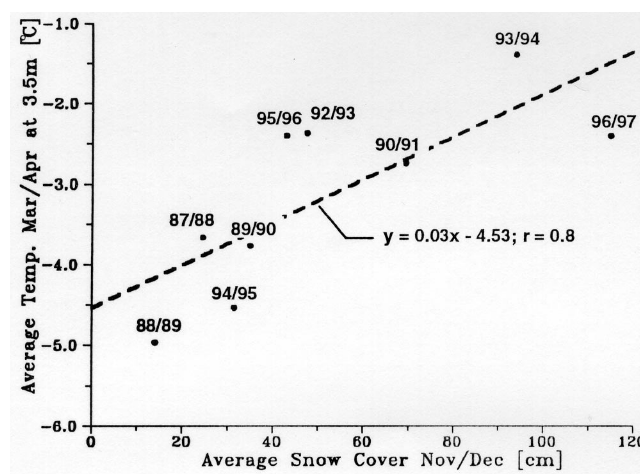

Figure 5. Correlation between the averages of snow depth in November / December (x) and temperature at 3.6 m depth in March / April (y).

air temperature. In contrast, a thin (5 to 15 cm) snow cover in late autumn allows efficient cooling of the ground (Keller and Gubler, 1993).

The correlation coefficient r for the relation between the mean snow-cover thickness in November and December and the mean permafrost temperature at 3.6 m depth in March and April is 0.8 (Figure 5). A decrease of snow-cover thickness by 10 cm causes a cooling in permafrost temperature by 0.3°C. Haeberli (1985) calculated a similar value by correlating the mean snow-cover thickness in November and February with the mean permafrost temperature at 3 m depth in February and May at Gruben rock glacier (6 years, r=0.97).

These relationships statistically confirm the influence of the snow-cover thickness in early winter on permafrost temperatures. Local effects such as variations of snow cover distribution as a function of boulder size or local climate cause particular conditions for every site.

Conclusions

The analysis of the ten-year series of borehole temperatures within the permafrost of the active Murtèl-Corvatsch rock glacier revealed that

• temperatures in the uppermost 20 m showed remarkable interannual variations;

•a trend of rapid warming by about 1°C/decade until 1994 was largely compensated by rapid cooling in 1994/1995 and 1995/1996;

• snow conditions - especially in early winter - exert an important influence on ground temperatures; and

• the documented ground thermal signals probably reflect conditions and temporal evolution characteristic of regional rather than local scales.

The measurements will continue into the future and serve as a basis for comparison with additional boreholes already existing or to be drilled in mountain permafrost.

Acknowledgments

The drilling was funded by a special grant from ETH Zürich (permafrost core drilling, project 0230.70). A number of colleagues helped with the recording of the time series, especially Paul Gnos, Martin Hoelzle, Felix Keller, Sepp Luthiger (all VAW), Catherine Mittaz (University of Zürich), Theo Gianotti and Bruno Paganini (both Luftseilbahn Surlej-Corvatsch).

References

Balobaev, V.T., Devyatkin, V.N. and Kutasov, I.M. (1983). Contemporary geothermal conditions of the existance and development of permafrost. In *Final Proceedings 4th International Conference on Permafrost, Fairbanks, Alaska.* National Academy Press, Washington, DC, pp. 8-12.

Bernhard, L., Sutter, F., Haeberli, W. and Keller F. (1998). Processes of snow/permafrost-interactions at a high-mountain site, Murtèl-Corvatsch, eastern Swiss Alps. In *Proceedings 7th International Conference on Permafrost, Yellowknife, Canada*. This volume.

Bodmer, Ph. and Rybach, L. (1984). Geothermal map of Switzerland (heat flow density). *Commission Suisse de Géophysique. Materiaux pour la géologie de la Suisse,* **22**, (47pp).

Haeberli, W. (1973). Die Basis Temperatur der winterlichen Schneedecke als möglicher Indikator für die Verbreitung von Permafrost. *Zeitschrift für Gletscherkunde und Glazialgeologie,* **9**, 221-227.

Haeberli, W., Huder, J., Keusen, H.-R., Pika, J. and Röthlisberger, H. (1988). Core drilling through rock glacier-permafrost. In *Proceedings 5th International Conference on Permafrost, Trondheim, Norway.* Tapir, **2**, pp. 937-942.

Haeberli, W., Hoelzle, M., Keller, F., Vonder Mühll, D. and Wagner, S. (1998). Ten years after the drilling through the permafrost of the active rock glacier Murtèl, eastern Swiss Alps: answered questions and new perspectives. In *Proceedings 7th International Conference on Permafrost, Yellowknife, Canada.* This volume.

Hoelzle, M. (1994). Permafrost und Gletscher im Oberengadin - Grundlagen und Anwendungsbeispiele für automatisiserte Schätzverfahren. *Mitteilung der VAW-ETH Zürich*, **132**, (121pp).

Keller, F. (1994). Interaktion zwischen Schnee und Permafrost: Eine Grundlagenstudie im Oberengadin. *Mitteilung der VAW-ETH Zürich*, **127**, (145pp).

Keller, F. and Gubler, H.U. (1993). Interaction between snow cover and high mountain permafrost Murtèl-Corvatsch, Swiss Alps. In *Proceedings 6th International Conference on Permafrost, Beijing, China*. South China University of Technology Press, **1**, pp. 332-337.

Lachenbruch, A.H., Brewer, M.C., Greene, G.W. and Marshall, B.V. (1962). Temperatures in permafrost. *Temperature - its measurement and control in science and industry*, **3**, 791-802.

Lachenbruch, A.H., Cladouhos, T.T. and Saltus, R.W. (1988). Permafrost temperature and the changing climate. In *Proceedings 5th International Conference on Permafrost, Trondheim, Norway.* Tapir, **3**, pp. 9-17.

Lachenbruch, A.H., Greene, G.W. and Marshall, B.V. (1966). Permafrost and the geothermal regimes. *Environment of the Cape Thompson region, Alaska.* USAEC Division of Technical Information, pp. 149-165.

Lachenbruch, A.H., Sass, J.H., Marshall, B.V. and Moses Jr, T.H. (1982). Permafrost, heat flow, and geothermal regime at Prudhoe Bay, Alaska. *Journal of Geophysical Research,* **87 (B11)**, 9301-9316.

Osterkamp, T.E and Romanovsky, V.E. (1996). Characteristics of changing permafrost temperatures in the Alaskan Arctic, USA. *Arctic and Alpine Research*, **28**, 267-273.

Sutter, F. (1996). *Untersuchungen von Schloten in der Schneedecke des Blockgletschers Murtèl-Corvatsch.* Unpublished Masters thesis, Geographical Institute, University of Zürich.

Stucki, T. (1995). *Permafrosttemperaturen im Oberengadin.* Unpublished Masters thesis, VAW-ETH Zürich, Department of Earth Sciences (110 pp.).

Vonder Mühll, D. (1992). Evidence of intrapermafrost groundwater flow beneath an active rock glacier in the Swiss Alps. *Permafrost and Periglacial Processes*, **3**, 169173.

Vonder Mühll, D. and Haeberli, W. (1990). Thermal characteristics of the permafrost within an active rock glacier (Murtèl/Corvatsch, Grisons, Swiss Alps). *Journal of Glaciology*, **36**, 151-158.

Vonder Mühll, D. and Holub, P. (1992). Borehole logging in Alpine permafrost, Upper Engadin, Swiss Alps. *Permafrost and Periglacial Processes*, **3**, 125-132.