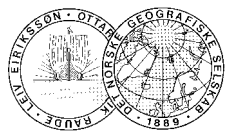


Thirty years of permafrost research in the Corvatsch–Furtschellas area, Eastern Swiss Alps: a review

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During the past 30 years, intensive permafrost research has been performed in the area of Corvatsch–Furtschellas, Eastern Swiss Alps. Main progress has been achieved by borehole observations in creeping permafrost, geophysical soundings, energy flux measurements above and within permafrost, photogrammetric determination of surface kinematics of creeping permafrost and permafrost distribution pattern modelling. The paper gives a review of principle results during the 30 years' research period.

Keywords: *Corvatsch–Furtschellas, models, permafrost, rock glacier*

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Introduction

The high-mountain cryosphere, consisting mainly of snow, glaciers and permafrost, is well known to react sensitively to climatic changes (Haerberli & Beniston, 1998). Present and potential future atmospheric warming is able to strongly affect the alpine glacial and periglacial belt with its large mass wasting potential. Therefore, process research and long-term monitoring are both necessary for the still young research discipline of mountain permafrost science. The main objectives in high-mountain permafrost research are:

- To better understand the processes of formation and decay of permafrost
- To document ongoing changes of permafrost
- To improve the basis for assessing consequences of future climate change on permafrost

Study site

The Corvatsch–Furtschellas area is one of the best-investigated mountain permafrost sites of the Alps. The research area lies in the Upper Engadin region in the Eastern part of the Swiss Alps. The climate is slightly continental mainly influenced by SW air masses with mean annual precipitation of 800 mm in the valley floors and 1,000 to 2,000 mm in the periglacial areas (Schwarb et al. 2000). The mean annual 0°C isotherm is at around 2,200 m a.s.l. The area is dominated by several well-developed rock glaciers, glacier forefields, and glaciers covering mainly the eastern slope of the Corvatsch mountain ridge (Fig. 1). On the NE side is a ski run of the Corvatsch ski resort. The described area extends from 1,800 to 3,400 m a.s.l.

Principal results from 30 years of research

Changes in permafrost take place at various scales of space and time. According to Haerberli et al. (1993), climate-

induced reactions of permafrost at individual points take place in a time sequence of three main steps:

- changes in active layer thickness and thaw settlement/frost heave in supersaturated material at the permafrost table as an immediate response (time scale years);
- disturbance of the temperature profile within the permafrost, i.e. between the permafrost table and the permafrost base as an intermediate response (time scale years to decades);
- displacement of the permafrost base as a definitive response (time scale decades to centuries or even millennia);

During this evolution, spatial changes occur:

- modification of permafrost distribution patterns
- adjustment of geomorphic, hydrological and nivo-glaciological processes such as permafrost creep, frost heave/thaw settlement, thermokarst, erosion and slope instability on thaw destabilised slopes (e.g. debris flows, rock falls), drainage characteristics and avalanche formation.

The above five reactions have been – and still are – the focus of the main research activities in the Corvatsch–Furtschellas area during the past three decades.

Borehole observations

The first borehole was drilled by (Barsch 1977) on the rock glacier Murtél. This hole was 11 m deep. A major step was accomplished in 1987 with a project funded by ETH Zurich (Haerberli 1990, Haerberli et al. 1988, Vonder Muehl & Haerberli, 1990): two boreholes of 58 m and 21 m depth were drilled. The project included three main aspects of borehole investigations: (a) documenting thermal conditions within the creeping permafrost, (b) studying creep processes at depth, and (c) analysing physico-chemical properties of the ice/rock mixtures.

Temperatures have been measured since 1987 in the 58 m deep borehole (Fig. 2). Between 1987 and 1994, the

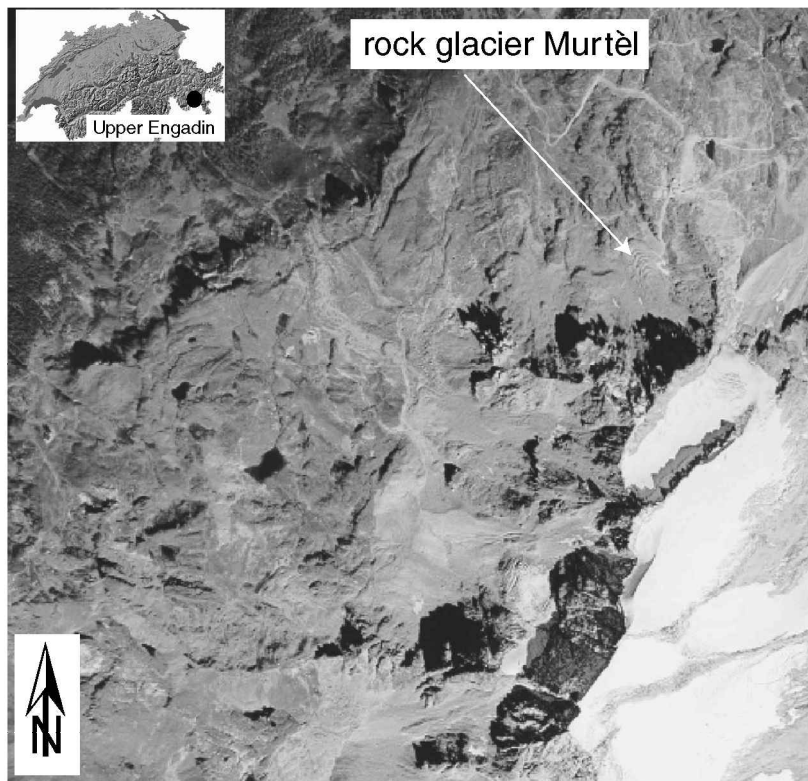


Fig. 1. Infrared aerial photograph of the Swiss Federal Office of Topography from 7.9.1988. Aerial-photograph archive FD/KSL, Flight-line: 061 161, Image-no: 4770 from the Corvatsch-Furtschellas area in the Upper Engadin area, Eastern Switzerland.

uppermost 25 m warmed rapidly (Vonder Muhll & Haeblerli 1990, Vonder Muhll et al. 1998). Mean annual 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. During the 2 years 1994 to 1996, when winter snowfall was low, intensive cooling of the ground occurred, the temperatures reaching values similar to those in 1987. Since 1996, permafrost temperatures increased, followed first by a cooling, later again by a warming.

The variability of the observed permafrost temperatures is caused by several processes, including: (1) a reduced period of negative temperatures within the active layer due to long-lasting zero-curtains in autumn; (2) global radiation and air temperature changes influencing ground temperatures mainly in summer; and (3) variations in the duration of winter snow cover. 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 temperatures (Smith 1975). In contrast, a thin (5–15 cm) snow cover in late autumn is most efficient in allowing cooling of the ground (Keller & Gubler 1993).

The correlation of the mean measured snow-cover thickness in November and December and the mean measured permafrost temperature at 3.6 m depth in March and April

has an $r^2 = 0.64$ (Vonder Muhll et al. 1998). Taking the linear relation from (Vonder Muhll et al., 1998), then a decrease in snow-cover thickness by 10 cm causes a cooling in permafrost temperature by 0.3°C . The trend can be seen at several depths, and a strong correlation exists between early autumn snow-cover development and permafrost temperatures. The influence of the snow-cover thickness in early winter on permafrost temperatures is confirmed by statistical and physical model analysis (Vonder Muhll et al. 1998; Zhang et al. 2001). Local effects such as variations of snow-cover distribution as a function of boulder size or local climate cause particular conditions for every site.

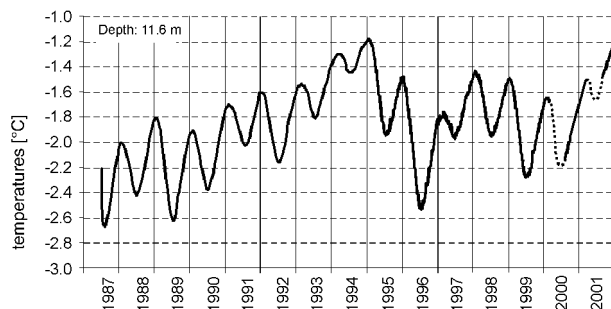


Fig. 2. Permafrost temperature in the rock glacier Murtèl at a depth of 11.6 m, dotted line means interpolated values due to data gaps.

Table 1. Target layers / boundaries and applied geophysical methods applied at Murtél rock glacier.

Target	Method
Active layer, permafrost table	Refraction seismics, 2-D DC resistivity tomography
Shear horizon	Ground penetrating radar (GPR), Gravimetry
Bedrock	Ground penetrating radar (GPR), Gravimetry

In addition, the permafrost temperatures in the Murtél borehole show a peculiarity at a depth of 52 m, where a thin seasonal talik exists caused by ground water flow (Haeberli et al. 1998a, Vonder Muhl 1992).

Slope indicator measurements were performed in the 1987 borehole as well as in the more recently drilled holes, which are some 20 m upslope to the 1987 drill site. Arenson et al. (2001) and Vonder Muhl et al. (2001) describe the measurements within these holes. Measured borehole deformation reveals steady-state creep within the upper 30 m of the rock glacier, where an ice-supersaturated layer exists. According to the borehole deformation measurements and photogrammetrical analyses, the surface velocity at the drill site is about 6 cm a⁻¹. The main part (c. 4 cm a⁻¹) takes place at a depth of 28–30 m, i.e. within the transition zone between the two main permafrost layers with the upper (supersaturated) layer obviously undergoing steady-state creep and overriding the non-deforming (structured) lower layer (Wagner 1992). The slope indicator measurements could be performed until 1994. Vertical deformation mainly occurs between 25 and 30 m depth: the layer immediately above the shear horizon is being shortened by roughly 1 cm a⁻¹. The inclination of the flow vectors resulting from the horizontal and vertical displacements is about 10° to 15° and, hence, is closely comparable to the surface inclination of the compressing flow part of the rock glacier. Wagner (1992) tried to model this type of borehole deformation using a power-type flow law, which seemed to fit the observed

deformation best. New results from borehole observations in other rock glaciers (Arenson et al. 2001, Arenson & Springman 2000, Hoelzle et al. 1998) indicate that the ice/rock mixtures contain pronounced heterogeneities and cause important variability in apparent viscosity. The assumption of linear vertical strain rates and constant volume appears to be inappropriate, a fact, which has important impacts on rock-glacier modelling approaches. Despite the fact that the internal structures are different at three investigated sites (Murtél, Muragl and Pontresina-Schafberg) within the Upper Engadin, similar phenomena can be observed. Rock glaciers have distinct shear zones where horizontal and vertical differential movements are concentrated. In addition, a reduction in volume can be caused by compressive flow due to the presence of air voids within the permafrost body. The flow velocity depends on the temperature, the slope of the rock glacier and on the composition of the ground. Within degrading permafrost, the ice content decreases, the creep velocity increases and the shear zone moves closer to the surface where seasonal temperature changes. The presence of liquid water might also influence the deformation. Obviously, common to all borehole observations in rock glaciers is the existence of a shear zone at variable depths, where normally more than 70% of the deformation takes place. Below this zone a stiff layer can be found consisting of hard bedrock and/or only partly ice-saturated coarse blocks. These findings lead to a general model of the evolution of rock glaciers, which are described by Haeberli (1985) and Haeberli et al. (1998a).

The physico-chemical properties have been investigated in several studies (cf. Haeberli 1990). C¹⁴-dating of organic material found in one of the cores confirmed the earlier assumption that the rock glacier formed during a time period of several thousands of years (Haeberli et al. 1998b). This finding is consistent with age estimates from photogrammetrically determined flow fields (Kaab et al. 1998); it implies that the formation of the rock glaciers started around the onset of the Holocene, when the area of Corvatsch–Furtschellas became totally deglaciated. The understanding

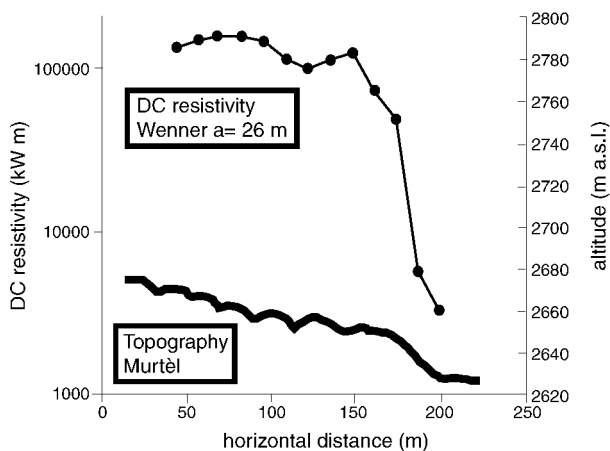


Fig. 3. DC resistivity measurements at Murtél–Corvatsch rock glacier. Mapping across the rock glacier: resistivity values decrease by about one order of magnitude at the permafrost free terrain in the forefield for the rock glacier (a is the distance between the current electrodes).

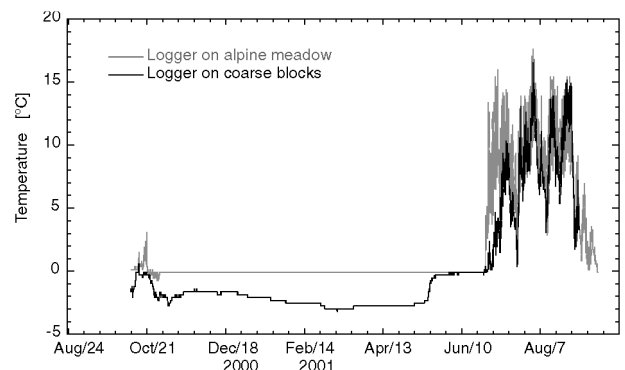


Fig. 4. Selected ground temperature measurements in the area around the rock glacier Murtél in the long-term monitoring project PERMOS (Permafrost Monitoring of Switzerland of Swiss Glaciological Commission). The measurements show the clear temperature difference between measurements in different surface materials. The winter 2000/2001 was characterized by several early huge autumn snow falls.

of the ice-forming processes, however, remains strongly limited.

Surface velocity measurements

In addition to the deformation measurements within the boreholes, photogrammetric surveys have been performed by Barsch & Hell (1975), Kaab (1998), Kaab et al. (1998) and Kaab & Vollmer (2000). The results show that the whole perennially frozen body was creeping over the period 1987 to 1996, with horizontal velocities in the range 5 cm a^{-1} to 15 cm a^{-1} . The temporal changes in surface elevation for the same period are about -5 cm a^{-1} . In its upper part, the rock glacier exhibits a flow regime with longitudinal extension, whereas in the lower part a longitudinal compression zone follows mainly influenced by the flatter topography. The compressive zone is characterised by ogive-like ridges and furrows.

Geophysical investigations

Several geophysical surveys – refraction seismics, DC resistivity soundings, ground penetrating radar (GPR), gravimetry and various electro-magnetic (EM) methods – have provided data for modelling subsurface structures, and these models were validated against the borehole information (Hauck et al. 2001; Lehmann et al. 1998; Vonder Muhl 1993; Vonder Muhl & Klingel 1994). The main objectives are to determine: (a) the thickness of the active layer and its shape around the strongly pronounced micro-topography of furrows and ridges; (b) the depth of a so-called shear horizon, which forms the base of the creeping part of the permafrost; and, (c) the depth of the bedrock which outcrops at the front of the rock glacier.

In unconsolidated debris containing permafrost, DC resistivity and seismic refraction soundings are the best methods for investigating the permafrost table. Both methods show abrupt changes of either resistivity or velocity at the permafrost table. The use of small spacing between the geophones and electrodes allows a suitable high resolution. The change of physical properties at the shear horizon in the rock glacier and at the bedrock is characterised by density and impedance contrasts and, therefore, gravimetry and GPR are the most promising approaches.

Refraction seismics were performed in October 1990, when thickness of the active layer was greatest and hence corresponds to the position of the permafrost table. Explosives were used as the seismic source. The shape of the permafrost table underneath the markedly pronounced furrows and ridges on the rock glacier surface was of particular interest (Vonder Muhl 1993). Seismic velocities in the top layer, which consists of coarse boulders, varied over a large range (700 m s^{-1} to $1,000 \text{ m s}^{-1}$). The refractor below with typical velocities between $3,400 \text{ m s}^{-1}$ and $3,700 \text{ m s}^{-1}$ is continuous and represents the ice-rich permafrost layer. Results of the survey line oriented in the rock glacier flow direction indicate that the permafrost table is 2 m deep on average: beneath the furrows the permafrost table was very shallow, sometimes even at the surface (0–

1 m), while the depth increased beneath each ridge. Hence, the permafrost table smoothes the marked micro-relief.

2D resistivity tomography was performed by a multi-electrode system (ABEM Lund) with 30 electrodes (5 m spacing) in a Wenner array. Sponges soaked with salt water were used to reduce the contact resistivity between the electrodes and the big boulders on the rock glacier surface. The measured apparent resistivities were inverted using the software package RES2DINV (Loke & Barker 1996). Because of the limited array length, the penetration depth was only some 15–20 m. From the model results, the difference between the ice-rich permafrost of the rock glacier and the permafrost-free terrain in front is seen clearly, with specific resistivity values of up to $1 \text{ M}\Omega \text{ m}$ for the ice-rich permafrost layer and values lower than $10 \text{ K}\Omega \text{ m}$ for the non-permafrost region in front of the rock glacier (see Fig. 3). The modelled permafrost layer is located at depths between 4 m (furrows) and 7 m (ridges). Note, however, that because of the coarse measurement grid (smallest electrode spacing 5 m), the resolution of the first few metres below the surface is poor (Hauck & Vonder Muhl 1999).

Gravimetry was carried out in the area of the Murtél-Corvatsch rock glacier, first to check the applicability of this method in Alpine permafrost, and second to deduce the lateral extent of both shear horizon and bedrock (Vonder Muhl & Klingel 1994). Measurements were corrected for latitude, elevation, topography of the surrounding terrain and Earth tide. This allowed inferences to be made concerning the density variation within the subsurface material. The gravity anomaly is given by the difference between the measured and the calculated gravity of the model.

In the present case, the creeping permafrost represents the disturbing body, which has a lower density than the bedrock because of the ice contained within it. The density structure of the rock glacier for modelling four different layers was derived from the γ - γ -log (density-log) of the borehole 2/1987. The thickness of the layers is greatest near the drill site, where the supersaturated permafrost (ice content more than 40% by volume, i.e. the volume of the voids) is about 25 m thick. The bedrock surface underneath the rock glacier is bowl-shaped and is obviously over-deepened. This clearly causes the compressing flow and hence the pronounced ground surface topography with marked ridges and furrows. Towards the upper end, the shear horizon and the bedrock ascend towards the valley.

GPR may be described as ‘echo sounding with EM waves’. An EM wave field generated at a transmitter antenna propagates through the medium of interest and is reflected or scattered from subsurface impedance contrasts. GPR has the potential of providing high-definition images of the shallow subsurface. GPR data were recorded across a permafrost-rich zone within the Murtél-Corvatsch rock glacier. The dataset was corrected for elevation (Lehmann et al. 1998, Vonder Muhl et al. 2001). Two strong reflection bands could be recognised, one from an internal shear zone and one from the bedrock surface. The internal shear zone separates an upper mobile permafrost layer from a lower stationary one. Depth estimation with georadar was verified with the nearby borehole. Depths of bedrock and shear horizon differ by less than a metre compared to the borehole and gravimetry.

An additional geophysical method is the BTS method (bottom temperature of the winter snow cover). This thermal method was successfully introduced by Haeberli (1973), and since then applied many times, especially in the Alps. In the Corvatsch–Furtschellas area, several BTS measurements were carried out (Hoelzle 1992) constituting an important database to test the permafrost distribution models in the same area (Hoelzle & Haeberli 1995, Hoelzle et al. 1993). Continuous BTS measurements with miniature temperature loggers (UTL-1) over the winter season at different sites helps to better understand and interpret BTS mapping results (Hoelzle et al. 1999). Combination of conventional BTS mapping with continuous BTS measurements is used today at several investigation sites in the Swiss permafrost monitoring project (PERMOS).

Energy flux measurements

Microclimatological studies in progress at Murtél–Corvatsch since 1997 provide data on heat and energy fluxes between the atmosphere and the active layer, and between the active layer and the underlying permafrost (Mittaz 1998, Mittaz et al. 2000a, 2000b, Mittaz et al. in press). The processes involved in the energy balance comprise the net exchange of radiation between the atmosphere and the earth surface, the transfer of sensible and latent heat by turbulent motion of the air, and conduction of heat into the ground. The nature of the earth surface and the relative abilities of the ground and the atmosphere to transport heat govern the exact partitioning between the components of the radiative and heat balances. In order to enhance the understanding of these energy exchange processes, a complete energy balance dataset has been obtained. These measurements help to identify the most important climatic and site-specific factors for determining local and regional permafrost distribution patterns (Hoelzle 1996).

Among all energy exchange processes, net radiation and snow cover appear to play the determining role for the existence of mountain permafrost: net radiation is negative during winter (minimum monthly value -66 Wm^{-2} in February 1997), but reaches monthly values as high as 143 Wm^{-2} in July 1998. During the snow-free period, typical albedo values of around 15% were measured. Snow cover insulates the ground from atmospheric conditions and strongly influences surface characteristics such as albedo, aerodynamic roughness length defined after (Oke 1987) and emissivity. Thus, ground heat flux remains small during winter (monthly values of around 1 Wm^{-2}), whereas heat transport during summer is higher (-8 Wm^{-2} in July 1998). Monthly values for turbulent heat exchange are within -20 Wm^{-2} and $+20 \text{ Wm}^{-2}$. Ground heat flux, latent melt energy (during the snowmelt season) and turbulent fluxes during summer all vary within the same order of magnitude but are much smaller than the radiation fluxes.

The sum of all measured components indicates a non-zero energy budget, with an average annual positive deviation of 19 Wm^{-2} in 1997. It is proposed that this overall imbalance of the energy exchange fluxes could be explained by unmeasured advective energy fluxes that occur within the

layer of large boulder and blocks at the top of the permafrost (Bernhard et al. 1998, Hoelzle et al. 1999, Keller & Gubler 1993, Mittaz et al. 2000a). The mean annual ground surface temperature was determined as the average of the 0.6 m borehole temperature during winter 1997 ($\pm 0.02^\circ\text{C}$), respectively the temperature at the ground surface as measured with miniature temperature loggers ($\pm 0.25^\circ\text{C}$) during winter 1997/1998 (Hoelzle et al. 1999). For the snow-free period, the surface temperature was calculated from longwave radiation measurements. To obtain more information on the processes taking place within the active layer, mean annual ground surface temperature and mean annual ground temperature were compared. The difference between these two temperatures is a key parameter for modelling permafrost/climate relationships (Hoelzle et al. 2001). The mean temperature difference between the surface and 1.6 m depth was around 16°C during all summers of 1997, 1998 and 1999, when the surface was much warmer than the underlying ground. During the winter months, it was less than 2°C only and negative. The large temperature difference during the summer months cannot only be explained through heat conduction from the surface towards depth or vice-versa, but probably originates from unmeasured advective heat fluxes within the blocky surface layer and corresponds to the observed non-zero energy budget (Hoelzle et al. 1999, 2001, Mittaz et al. 2000a). Figure 4 shows an example of mean annual ground temperature measurements carried out in the permafrost monitoring project PERMOS (Permafrost Monitoring of Switzerland). The two selected logger sites represent typical alpine locations. One place is on coarse debris and the second one on alpine meadows. The results presented here are typical for these surface materials, which show that the temperatures in winter in coarse blocks are several degrees colder than on alpine meadows.

Permafrost distribution modelling

Knowledge about permafrost distribution patterns is especially useful during the planning stages of hazard mitigation measures such as flood and avalanche protection work, or any other construction activity (Haeberli 1992, Ives & Bovis 1978, Keusen & Haeberli 1983, Phillips 2000, Wegmann & Keusen 1998). Therefore, various efforts have been made during recent years to develop and improve spatial modelling of mountain permafrost distribution. In particular, the Task Force on 'Mapping and Distribution Modelling of Mountain Permafrost' established by the International Permafrost Association (IPA) and the European PACE project brought considerable progress (Etzelmüller et al. 2001, Harris et al. 2001). Permafrost distribution models combine stochastic with deterministic elements and can be divided into two main types: regionally calibrated empirical-statistical models and more physically based process-oriented models (Etzelmüller et al. 2001, Hoelzle et al. 2001). Empirical-statistical models directly relate documented permafrost occurrences to topoclimatic factors (altitude, slope and aspect, mean air temperature, solar radiation) which can easily be measured or computed (e.g. Keller 1992, Keller et al. 1998). In the Corvatsch–Furtschellas area,

several of these model types were developed and applied during the past decade (Fig. 5) (Hoelzle 1996, Hoelzle & Haeblerli 1995, Hoelzle et al. 2001, Keller 1992). The complex energy exchange processes at the surface and within the active layer are not treated explicitly but rather as a grey box with topoclimatic factors being selected according to their relative influence in the energy balance equation. The model results are yes/no functions about the presence or absence of permafrost, primarily applicable to certain areas and assume steady-state conditions. Such models can be used in carefully and well-calibrated areas for palaeo-reconstructions and simple future simulations (Frauenfelder et al. 2001, Frauenfelder & Käab 2000, Hoelzle & Haeblerli 1995).

Model approaches allowing spatio-temporal extrapolations should be process-based. Such models focus on more detailed understanding of the energy fluxes between the atmosphere and the permafrost (Hoelzle et al. 2001, Marchenko 2001). They explicitly parameterise solar radiation, sensible heat, surface albedo, heat conduction. They are often complex and need a correspondingly large amount of precisely measured or computed data and are especially well suited for sensitivity studies with respect to interactions and feedback involved with climate-change scenarios. They enable surface temperatures to be computed and, hence,

thermal conditions at depth and transient effects to be estimated. In the PACE project, a process model was developed that is able to calculate surface temperatures (Hoelzle et al. 2001, Mittaz et al. 2000b, Mittaz et al. in press). Future steps will allow a coupling of the modelled surface temperatures with the ground temperatures by using the concept of 'thermal offset' (Burn & Smith 1988, Romanovsky & Osterkamp 1995).

Conclusions and perspectives

In the past 30 years, the Corvatsch–Furtschellas area has become a well-investigated high-mountain permafrost site. Several important conclusions can be drawn:

– borehole temperatures

- a trend of rapid warming by about 1°C/decade until 1994 was largely compensated by rapid cooling in 1994/1995 and 1995/1996 with warming up again afterwards
- snow conditions – especially in early winter – exert an important influence on ground temperatures
- documented ground thermal signals probably reflect conditions and evolutions characteristic of regional rather than local scales

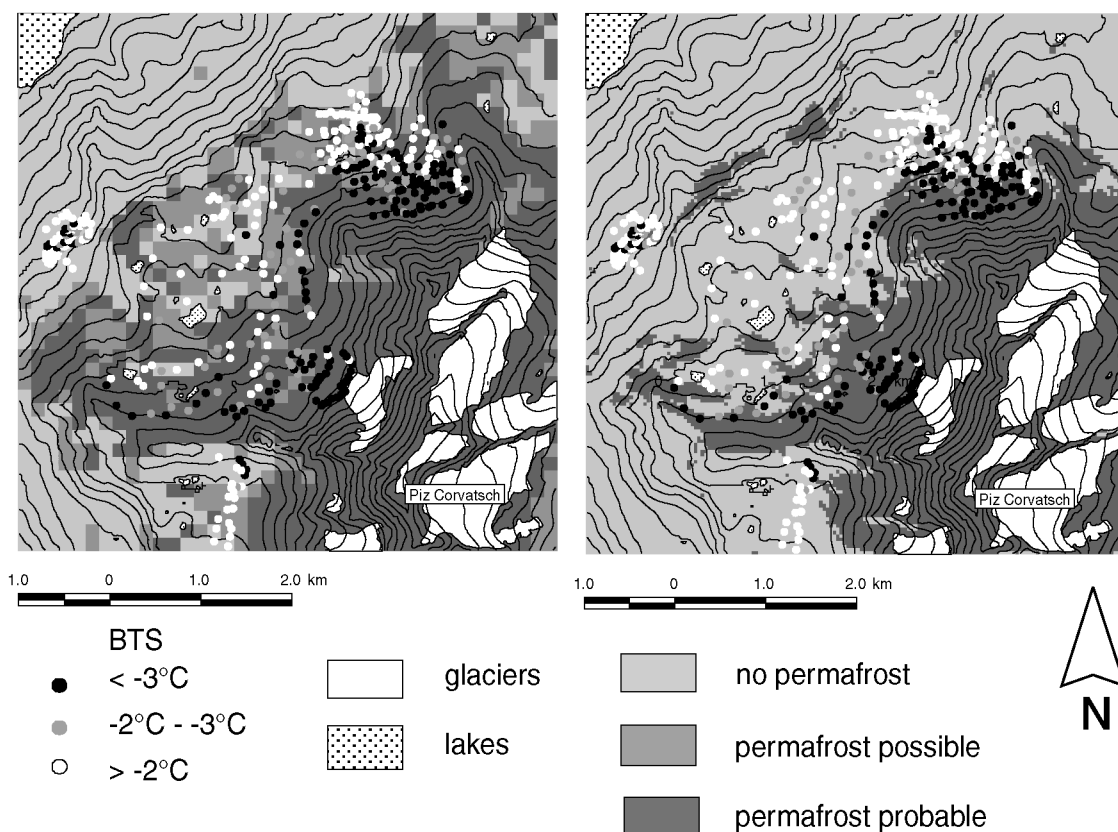


Fig. 5. Calculated permafrost distribution in the Corvatsch–Furtschellas area with the program PERMAKART (left figure, after Keller 1992) and with the program PERMAPAP (right figure, after Hoelzle & Haeblerli 1995). The points indicate BTS measurements (bottom temperature of winter snow).

– borehole deformation

- rock glaciers have distinct shear zones where horizontal and vertical differential movements are concentrated
- flow velocity depends on the temperature, the slope of the rock glacier and on the composition of the ground

– physico-chemical properties

- C^{14} -dating of organic material found in one of the Murtél cores and age estimates from photogrammetrically determined flow fields confirmed the earlier assumption that the rock glacier formed during a time period of several thousands of years

– photogrammetry

- the whole perennially frozen body is creeping with horizontal velocities in the range 5 cm a^{-1} to 15 cm a^{-1}

– geophysical soundings

- the permafrost table modelled from the DC resistivity tomography could be confirmed by several means: refraction seismic, borehole temperatures and observation in the field
- shape and depth of the shear horizon and the bedrock determined by gravimetry and GPR match very well
- combinations of (a) seismics with DC resistivity and (b) gravimetry with GPR, supplemented with information from a borehole, are regarded to be the most ideal

– energy balance measurements

- net radiation, snow cover and surface characteristics play the determining role for the existence of mountain permafrost
- energy balance measurements form the basis for model development and calibration

– permafrost distribution modelling

- several empirical-statistical models exist, which are well calibrated and tested
- process-based models are developed and applied successfully in the described area

Many questions concerning high-mountain permafrost could be answered during the past 30 years of intensive and systematic research. However, still many questions remain open, such as:

- the processes leading to ground ice formation in debris material of moraines or in scree slopes
- the processes of debris production in connection with permafrost in rock walls is at the beginning (Matsuoka, 1998)
- better determination of age structure of creeping permafrost
- geophysical data, especially resistivity measurements, could be used as proxy data for temperature evolution at different depth (Hauck 2001)
- monitoring of long-term active layer development as a response to climate change

- quantification and modelling of the energy fluxes in the active layer ('thermal offset') for different types of surface material
- coupling of atmosphere and ground thermal models
- determination of spatial estimates for permafrost thickness

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