PERMAFROST AND PERIGLACIAL PROCESSES
Permafrost and Periglac. Process. **15**: 299–307 (2004)
Published online in Wiley InterScience (www.interscience.wiley.com). DOI: 10.1002/ppp.501

Rock-wall Temperatures in the Alps: Modelling their Topographic Distribution and Regional Differences

Stephan Gruber, Martin Hoelzle and Wilfried Haeberli*

Department of Geography, Glaciology and Geomorphodynamics Group, University of Zurich, Switzerland

ABSTRACT

Rising temperatures or the complete thaw of permafrost in rock walls can affect their stability. Present as well as projected future atmospheric warming results in permafrost degradation and, as a consequence, makes knowledge of the spatial distribution and the temporal evolution of rock temperatures important. Rock-face near-surface temperatures have been measured over one year at 14 locations between 2500 and 4500 m a.s.l. in the Alps. Different slope aspects have been included in order to capture the maximum spatial differentiation of rock temperatures. These data were used to further develop and verify an energy-balance model that simulates daily surface temperatures over complex topography. Based on a 21-year (1982–2002) run of this model, spatial patterns of rock-face temperatures in the Swiss Alps are presented and discussed. This model provides a basis for the re-analysis of past rock-fall events with respect to permafrost degradation as well as for the simulation of future trends of rock temperatures. Furthermore, the spatial patterns of rock-wall temperatures provide a quantitative insight into the topography-related mechanisms affecting permafrost distribution in Alpine areas without local influence from snow cover or an active layer with a complex thermal offset. Copyright © 2004 John Wiley & Sons, Ltd.

KEY WORDS: rock temperatures; rock faces; Alps; mountain permafrost; energy balance; slope instability; rock fall

INTRODUCTION

Warming and thawing of permafrost can affect the stability of perennially frozen rock walls (Gruber *et al.*, 2004; Haeberli and Beniston, 1998). The thaw of ice-filled rock joints can open them to groundwater migration, raising water pressures (Haeberli *et al.*, 1997), and thus reduce the effective normal stresses. Davies *et al.* (2001) have shown that even the warming of ice in rock joints can result in reduced stability. Slopes that are stable when several degrees below freezing or when ice free could be destabilized in the temperature range between −1.5 and 0°C.

The transfer of these findings to the natural environment (cf. Nötzli *et al.*, 2003) requires knowledge about the spatial distribution of rock-wall temperatures and their evolution over time. Understanding and modelling of the processes that determine rock-face temperatures will also provide a means of assessing ranges of probable sub-surface temperatures caused by climate forcing and would provide a basis for assessing the impact of climatic change on rock-wall stability.

In comparison with debris-covered slopes, rock faces react quickly to climate change. This is due to the absence of a block layer (Harris, 1996; Harris and Pedersen, 1998; Mittaz *et al.*, 2000; Hoelzle *et al.*, 2001) and corresponding direct coupling of surface

* Correspondence to: Stephan Gruber, Department of Geography, Glaciology and Geomorphodynamics Group, University of Zurich, Winterthurerstrasse 190, CH 8057, Switzerland. E-mail: stgruber@geo.unizh.ch

Received 6 January 2004
Revised 29 June 2004
Accepted 29 June 2004

and sub-surface conditions, combined with a low water content and a small transfer of latent heat during melt.

This rapid reaction together with the effect of destabilization make rock fall due to permafrost degradation a likely and well perceivable impact of climate change in the near future (Gruber *et al.*, 2004). The influence that permafrost degradation in rock walls may have on human infrastructure and safety may be comparable to that of debris flows due to melt of perennially frozen debris slopes. Traditionally however, research on mountain permafrost has focussed almost exclusively on debris-covered slopes.

Although a wealth of rock-temperature measurements is available (see Gruber *et al.*, 2003, for a summary), only limited information on their spatial distribution can be extracted from them. Between the summers of 2001 and 2002 a measurement campaign (Gruber *et al.*, 2003) was carried out in order to investigate the spatial distribution and temporal evolution of near-surface temperatures in steep alpine rock faces.

This paper presents the results of this campaign as well as modelling results that extend the knowledge so gained beyond the measured years and locations. In particular this paper presents new results on

1. the distribution of rock-wall temperatures in the Alps
2. the inter-annual variability of temperatures
3. the processes that govern rock-face temperatures
4. process-based models of rock temperatures as a tool for research and engineering.

BACKGROUND AND STRATEGY

Rock Temperatures

Several researchers report rock surface or near-surface temperature measurements (e.g. Coutard and Francou, 1989; Hall, 1997; Matsuoka et al, 1997; Wegmann, 1998; Matsuoka and Sakai, 1999; Hall and André, 2001; Lewkowicz, 2001) but the question of their spatial distribution on a regional scale and in differing topographic conditions remains largely open. It is obvious that in rugged topography air temperature alone is a poor surrogate for rock surface temperatures. Net short-wave radiation is likely to be the major controlling factor causing the lateral variation of several degrees Celsius that can be deduced from previous research (Gruber *et al.*, 2003). Data recorded during Antarctic/Arctic winters by Hall (1997) and Lewkowicz (2001) demonstrate that, in the absence of solar radiation, rock-surface temperatures follow air temperature closely. Snow cover and mixed-media active layers are largely absent from near-vertical rock walls, making them a rather straightforward system characterized mainly by the influence of air temperature and short-wave solar radiation.

Temperature Variations with Time

The surface temperature in rock faces is subject to fluctuations over various time intervals: short term (e.g. moving clouds), diurnal (day–night cycles), annual (changing seasons) and inter-annual. The inter-annual variability in mean annual air temperature (MAAT) is of the order of 2–3°C for Swiss mountain stations and global radiation has fluctuated by about $\pm 5\%$ in recent decades (based on Aschwanden *et al.*, 1996). The combination of the two fluctuations can lead to an expected compound inter-annual signal having a range of up to 5°C. These signals are progressively dampened by heat diffusion with increasing depth in the rock.

Modelling Rock Temperatures

Rock faces are a comparatively straightforward system to model using energy-balance approaches such as PERMEBAL (Stocker-Mittaz *et al.*, 2002). The main sources of error are probably the extrapolation or parametrization of atmospheric variables in extreme topography and terrain geometry.

Hoelzle and Haeberli (1995) and Gruber and Hoelzle (2001) demonstrate successful statistical modelling of a ground temperature proxy that is subject to noise induced by snow cover and a mixed-media active layer. The absence of these sources of error makes statistical parametrization of rock-wall temperatures more likely to be successful than that on debris-covered slopes in more gentle terrain.

Research Strategy

A general distribution pattern of rock temperatures cannot be deduced from one or only a few years of measurements because rock temperatures are subject to large inter-annual fluctuations. Furthermore, the research goal is to relate the thermal response of rock surfaces to climatic change. Therefore, in this study, one year of measurements is used to improve and validate a process-based model of rock-face temperatures. This model is then used to simulate time series of rock temperatures over 21 years in order to deduce spatial patterns and temporal fluctuations.

The results from the process-based 21-year model experiment are then available as a basis for a statistical model (not presented in this article) relating rock-wall permafrost distribution to simple variables such as slope/aspect/elevation or MAAT and potential direct short-wave radiation. In this way PERMEBAL experiments forced with a simulated future climate can be applied to a larger area and evaluated in a larger spatial context in future studies.

It has been demonstrated that rock-face temperatures mainly vary in response to air temperature (influenced by elevation) and short-wave radiation (influenced by slope aspect). The sampling strategy of the measurement campaign was therefore designed to include both factors.

MEASUREMENTS OF NEAR-SURFACE TEMPERATURES

In summer and autumn 2001, 21 data loggers were installed at elevations between 2000 and 4500 m a.s.l. Loggers were placed in the following areas: Gornergrat/Stockhorn, Monte Rosa and Kleinmatterhorn/Gandegg close to Zermatt, Birg/Schilthorn and Jungfraujoch in the Bernese Alps and Corvatsch/Furtschellas close to St. Moritz. For the recording of realistic daily surface temperatures, thermistors were placed at a depth of 10 cm, avoiding the difficult and error-prone direct measurement of rapidly fluctuating surface temperatures. Temperatures were logged every 2 hours. All measurement sites were roughly vertical and several metres above flat ground to ensure snow-free conditions. The research methodology and equipment is described in more detail by Gruber *et al.* (2003). 14 loggers yielded complete one-year time series from 15 October 2001 to 14 October 2002 upon recovery in autumn 2002. Table 1 summarizes their locations and site characteristics. Some of the time series were missing 1–5 days of the one-year interval and were completed by multiple regression analysis based on the three most correlated loggers in order to generate a consistent database of daily average temperatures for further processing. The temperature measured at the depth of 10 cm is considered a valid representation of the surface temperature on the basis of daily averages.

SIMULATING THE SURFACE ENERGY-BALANCE

The model PERMEBAL (Stocker-Mittaz *et al.*, 2002) has been extended and adapted for the simulation of rock temperatures in rugged topography. The model uses daily meteorological time series of air temperature, vapour pressure, air pressure, precipitation, wind speed, wind direction and global radiation from the operational Swiss meteorological network as input data. Based on these data, atmospheric variables are extrapolated over complex topography and the surface energy balance is simulated.

In the context of this article, only the one-dimensional version of the model that simulates one individual point is used. A two-dimensional version that calculates temperatures based on arrays representing the investigation area has also been developed.

Two different approaches are employed.

1. PEB: surface-only calculation, where the ground heat flux is set to a fixed value (5.0 W m^{-2}) and the surface temperature is calculated based on long-wave emitted radiation as the sum of all calculated fluxes.

Table 1 Location and site characteristics of the 14 data loggers that recorded one-year time series.

ID No.	Location	Elevation [m]	Aspect [°]	Slope [°]	MAGST [°C]
70576	Klein Matterhorn	3850	170 (S)	86	−2.5
70611	Gandegg	3020	188 (S)	72	6.4
70623	Riffelhorn	2600	230 (SW)	77	5.5
70625	Klein Matterhorn	3845	50 (NE)	71	−2.9
70678	Eismeer	3150	100 (E)	87	1.5
70748	Jungfrau Ostgrat	3655	145 (NE)	70	1.2
96474	Mönchsgrat/Sphinx	3464	288 (W)	72	−4.1
109329	Schilthorn/Birg	2680	200 (S)	103	5.9
109381	Signalkuppe	4545	180 (S)	67	−4.5
109441	Corvatsch—Top	3290	15 (N)	62	−2.8
109478	Corvatsch—Mittel	2750	23 (N)	84	1.0
109482	Signalkuppe	4545	109 (E)	90	−5.4
109489	Schilthorn/Birg	2690	197 (S)	80	6.2
326947	Eigerwand	2860	325 (NW)	90	−0.4

2. PEB_HC: calculation with a ground heat-conduction scheme, where the ground heat flux is derived as the sum of all calculated fluxes. It serves as the upper boundary condition in a heat-conduction scheme.

The ground heat conduction is solved in a finite-difference Crank–Nicholson scheme. Latent heat is included as apparent heat capacity between -0.5 and 0.0°C assuming no movement of water.

For the calculation of the turbulent heat fluxes and emitted long-wave radiation (for PEB_HC), the surface temperature needs to be estimated. The models iterate part of the energy balance in order to converge the initial temperature estimate and the final result. For PEB the assumed and calculated surface temperature is iterated. For PEB_HC the estimated surface temperature and the temperature of the surface node of the heat conduction scheme are iterated. During a one-year run, only occasionally one or two days do not converge to better than 0.3°C within 30 iterations. Testing the model in several runs for all measured locations revealed that the surface roughness length $z_0 = 50$ mm that had been used in earlier versions of PERMEBAL was too high. A value of $z_0 = 0.3$ mm is assumed in this study. This lies well within the published range of 0.05–10 mm for soil, sand or snow (see, e.g., Oke, 1987).

MODEL VERIFICATION

All 14 locations with measured time series were simulated using both PERMEBAL approaches. Both approaches were tested in order to relate the benefit from the higher accuracy of the heat-conduction version (PEB_HC) to the much larger computational effort required.

In the verification run, only elevation, aspect and slope were adjusted to each logger site and the closest driving meteo station selected. Because measurements of surface and subsurface properties were not available parameters were set to one fixed value for all sites in order to prevent fitting of the result. The driving stations were Corvatsch (3315 m a.s.l.), Jungfraujoch (3580 m a.s.l.) and Zermatt (1638 m a.s.l.) (data source MeteoSwiss). Surface characteristics of rock were set to albedo = 0.2, emissivity = 0.96 and roughness length = 0.3 mm. The atmospheric lapse rate is taken as $-0.006\,\mathrm{K\,m^{-1}}$. For the heat-conduction scheme, the volumetric heat capacity of rock is assumed to be $1.8 \times 10^6\,\mathrm{J\,m^{-3}\,K^{-1}}$ and the thermal conductivity $2.2\,\mathrm{W\,K^{-1}\,m^{-1}}$ based on published values (Cermák and Rybach, 1982). A water content of 1% has been assumed. Due to strong topographic (Kohl, 1999) and transient (Harris *et al.*, 2003) effects it is not known whether the geothermal heat flux in complex topography is positive or negative. It is therefore assumed to be zero at the lower boundary of the heat-conduction scheme. The depth discretization is linear with a spacing of 10 cm and 150 elements. The second node is therefore located at a depth of 10 cm, like the measured temperatures.

Graphs for two neighbouring locations are provided to illustrate model performance (PEB_HC). PEB generally performs similarly to PEB_HC but has slightly stronger deviations. The locations represent two extreme cases in close proximity and roughly the same elevation: the north face of the Eiger with almost no direct radiation and a south-facing wall at Birg. Figure 1 shows a scatter plot of measured versus modelled temperature, Figure 2 plots measured and

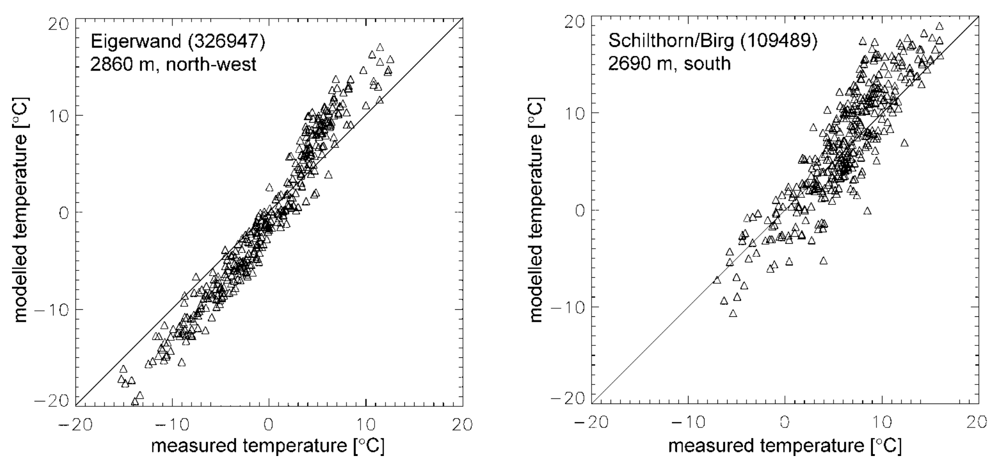

Figure 1 Measured versus modelled (PEB_HC) daily average near-surface (10 cm) temperatures [°C].

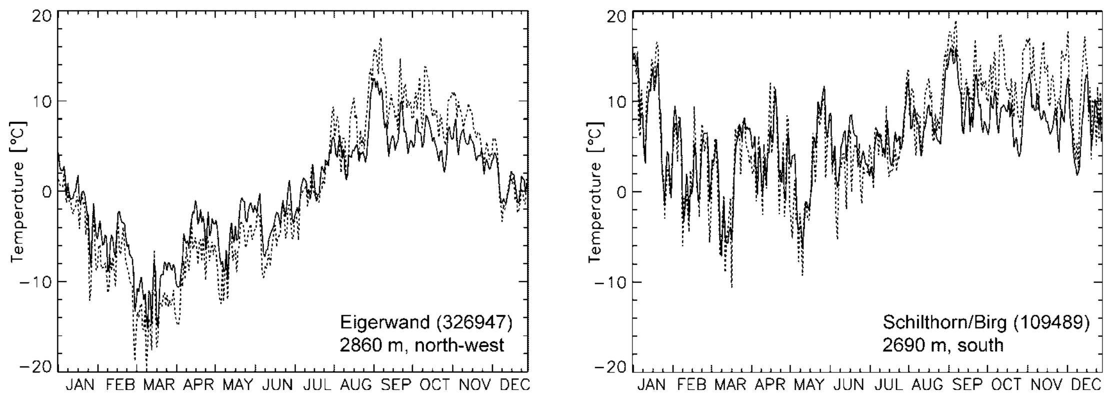

Figure 2 Measured (solid line) and modelled (PEB_HC, dashed line) mean daily near-surface (10 cm) temperatures at two locations.

modelled time series together and Figure 3 displays the difference between the two. Generally, mean annual temperatures and the temperature fluctuations are represented well. The south-facing site has a much greater variability because it receives a strong signal of short-wave radiation in addition to the long-wave signal related to air temperature. The amplitude of the day-to-day noise (Figure 3) on the north-facing rock wall is in the order of 2.5°C and about twice this amount on the south-facing slope. This is likely to be an effect of the parametrization of short-wave radiation and its spatial variability. The development of convective clouds, for instance, reduces surface temperatures through shading of direct radiation and is spatially and temporally highly variable. Additionally, an annual sinusoidal signal with an amplitude of about 2.5°C in the difference (measured PEB_HC) can be observed in Figure 3. At present, it is uncertain whether this is mainly related to the parametrization of long-wave radiation, turbulent fluxes, ground heat flux and subsurface thermal conditions or albedo and short-wave terrain-reflected radiation.

Table 2 summarizes the results of the model verification. It compares the daily measured values to the model runs using PEB and PEB_HC. A comparison with extrapolated air temperature is added in order to provide an intuitive reference against which to judge the accuracy achieved. From Table 2 and Figures 1–4, it is evident that temperature variability as well as model uncertainty are greater in locations with a high input in solar radiation.

The overall simulation of rock-wall temperatures with a mean coefficient of determination of 0.88 and a mean absolute difference in the mean annual ground surface temperature of 1.2°C is considered very encouraging. It should be kept in mind that surface temperatures accumulate the errors in the extrapolation and parametrization of all other variables and fluxes. The following sources contribute errors to the values discussed above:

- extrapolation over large distances (horizontal up to 14 km, vertical up to 2900 m)
- extrapolation in extreme terrain geometries

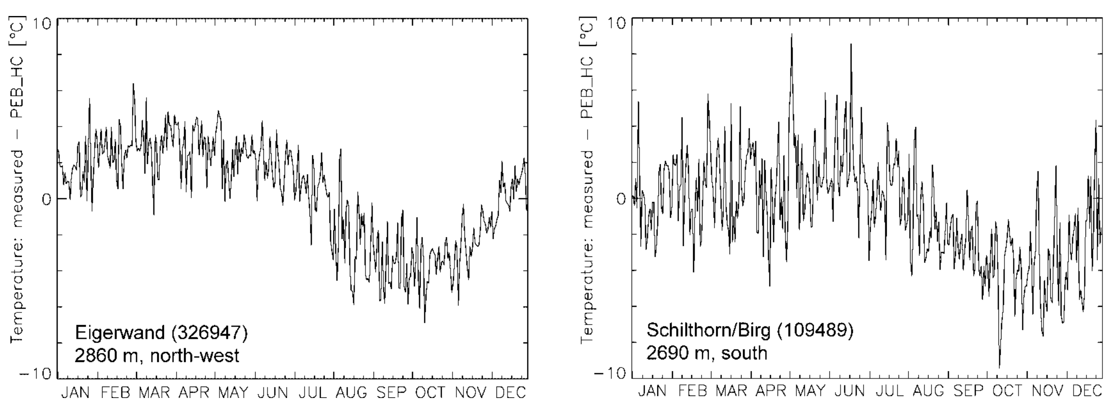

Figure 3 Residuals (measured–modelled) of daily average near-surface (10 cm) temperatures simulated using PEB_HC.

Table 2 Summary of the success of modelling daily surface temperatures. C_ refers to the coefficient of determination between the measured data and the model run. D_ refers to the mean annual difference between measured data and the model run. C_/D_AIR compares measured data with extrapolated air temperature. The means in the last line are mean coefficients of determination and mean absolute differences.

ID No.	C_PEB	D_PEB	C_PEB_HC	D_PEB_HC	C_AIR	D_AIR
70576	0.85	0.4	0.87	−0.1	0.85	6.4
70611	0.90	3.4	0.93	2.7	0.87	10.4
70623	0.87	0.6	0.88	0.2	0.89	7.0
70625	0.94	1.4	0.96	1.5	0.92	6.1
70678	0.79	0.0	0.87	−0.4	0.70	5.7
70748	0.82	0.8	0.88	−0.6	0.72	8.4
96474	0.88	−3.4	0.93	−3.8	0.83	1.9
109329	0.66	2.0	0.72	2.1	0.55	7.3
109381	0.70	1.1	0.73	−0.1	0.68	8.6
109441	0.93	−1.7	0.95	−0.9	0.82	1.9
109478	0.93	0.3	0.94	1.7	0.81	2.5
109482	0.84	2.4	0.86	2.0	0.87	7.7
109489	0.72	0.1	0.78	−0.7	0.62	7.6
326947	0.91	−0.6	0.95	0.3	0.80	2.1
Mean:	0.84	1.3	0.88	1.2	0.78	6.0

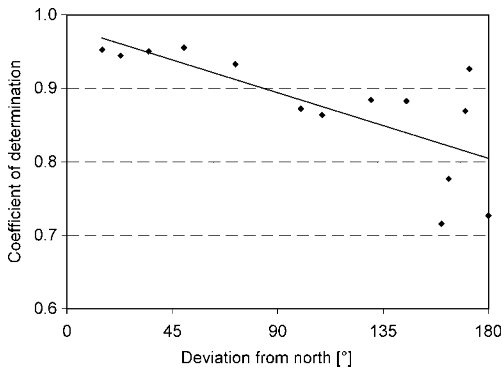

Figure 4 The coefficient of determination between the measured time series and that modelled using PEB_HC as a function of the deviation from north. This indicates the result of the growing influence of solar radiation on rock temperature.

- measurement errors at the meteorological stations
- deviation of the assumed and real surface and subsurface characteristics
- measurement errors in the rock-wall temperatures and the measurement of local aspect/slope
- limitations of the validity and completeness of the energy-balance model used.

As the actual energy balance in the measured rock face is not complicated by snow or coarse blocky layers but situated in terrain with extreme relief, this model evaluation is expected to reveal the maximum expected total error due to extrapolation of meteorologic variables and energy fluxes for more gentle, debris-covered surfaces.

The successful simulation of temperatures over a wide range of air temperature and radiation regimes establishes the validity of the model in the Alps. It is expected to yield results of equal reliability for other years using measured past time series of the Swiss meteorological network.

SPATIAL DISTRIBUTION OF SURFACE TEMPERATURES

One year of near-surface rock-temperature data is not sufficient to deduce permafrost distribution because of the large inter-annual fluctuations of air temperatures and global radiation. Therefore, rock-wall surface temperatures are modelled for the period 1982–2002 based on existing meteorological data from the stations Corvatsch and Jungfraujoch (data source: MeteoSwiss). As the Zermatt station is situated in a valley bottom and subject to corresponding local climatological effects it is not considered a valuable data source for this analysis. Corvatsch represents central-Alpine conditions with high radiation budgets and little clouding, whereas the data from Jungfraujoch is typical for the northern Alps, having comparably little direct solar irradiation and frequent clouding. For both areas, slopes of 50°, 70° and 90° steepness are modelled. Calculations are performed every 500 m at elevations between 2000 and 5000 m

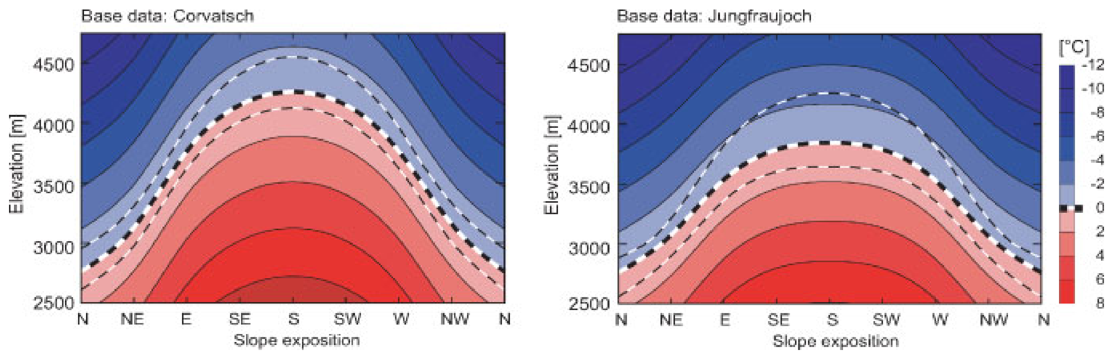

Plate 1 Mean simulated (PEB_HC) annual rock-wall surface temperature for 70° slope steepness and two locations, 1982–2002. The thick dashed line indicates the elevation of the mean 0°C isotherm during these 21 years. The thin dashed lines indicate the highest and lowest positions of the mean annual 0°C isotherm.

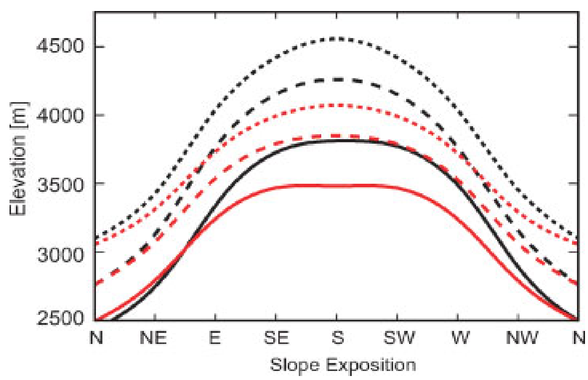

Plate 2 Mean elevation of the modelled (PEB_HC) 0°C isotherm for Corvatsch (black) and Jungfraujoch (red) and different slope angles: solid line, 90°; dashed line, 70°; dotted line, 50°.

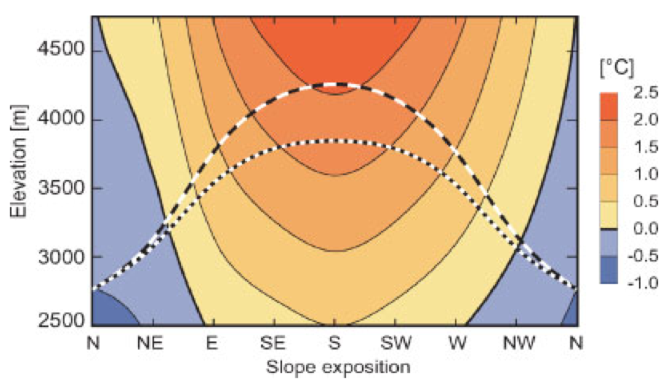

Plate 3 Difference in modelled (PEB_HC) mean annual surface temperature (1982–2002), Corvatsch–Jungfraujoch, for a slope angle of 70°. The dashed lines indicate the mean 0°C isotherm: long dashes, Corvatsch; short dashes, Jungfraujoch.

a.s.l. and for eight aspects (N, NE, E, . . . , NW). The same conditions as in the model verification were used. The depth discretization was 10 cm, having 200 nodes. The temperature profile at depth was initiated using the mean 1982 surface temperature followed by a two-year transient run with 1982 data before the 1982–2002 experiment to ensure realistic temperature distribution at depth.

Plate 1 shows the MAGT 1982–2002 for a slope steepness of 70°. The calculated temperatures have been averaged over the 21-year period and interpolated as a minimum curvature surface for better display. The thick dashed line indicates the elevation of the mean 0°C isotherm for the 21 years of this study. It approximates the limit of permafrost occurrence in rock walls as caused by the climatic conditions of that period. However, due to 20th century warming (Haeberli and Beniston, 1998; Beniston *et al.*, 1997; Diaz and Bradley, 1997) the actual lower limit of permafrost in rock walls is likely to be about 1.0°C or 150 m lower. This is due to possible remnants of inactive permafrost at greater depths within a rock face. Plate 2 shows the elevation of the modelled mean 0°C isotherm for both areas and other slope angles. Between slope angles of 90° and 50°, temperatures generally increase (and so the isotherm rises) with decreasing slope due to increased solar irradiation. The disturbance due to snow cover (Goodrich, 1982; Keller and Gubler, 1993; Zhang *et al.* 2001) that is not taken into account in this model increases at the same time, so the temperatures calculated for shallower slopes should be interpreted with care.

To illustrate the differentiation between the two locations, Plate 3 displays the difference between Corvatsch mean temperatures and Jungfraujoch mean temperatures modelled for a slope angle of 70°. Generally, the differences increase from north to south because they are related to short-wave radiation. The increase from lower towards higher elevations is caused by the growing importance of short-wave over long-wave radiation. Short-wave incoming radiation increases with elevation whereas long-wave incoming radiation decreases due to lower air temperature, air pressure, vapour pressure and other factors. The location of both 0°C isotherms is plotted in Plate 3 to underscore the aspect dependence of radiation-based differences in permafrost distribution.

Thin dashed lines in Plate 1 refer to the uppermost and lowermost mean annual 0°C isotherm between 1982 and 2002. These lines therefore separate three zones for this time interval: the zone of active permafrost (AP-zone; MAGST < 0 for all years); a transitional zone (T-zone; MAGST < 0 for some years) and the zone of seasonal frost (SF-zone; MAGST > 0 for all years). The vertical spread of these lines indicates the large inter-annual fluctuation of the MAGST and thus supports the combined approach of measurement and modelling used in this study.

CONCLUSION AND OUTLOOK

A combination of systematic rock-face near-surface temperature measurements and an energy-balance model has been employed to investigate rock-surface temperatures in the Swiss Alps. Spatial distribution patterns of rock-surface temperatures as well as ranges of their temporal fluctuation during 21 years have been revealed. The suitability of the energy-balance modelling approach in PEMEBAL for the simulation of ground temperatures in rugged terrain has been demonstrated.

Recently, scientific and public interest in the impact of climate change on the stability of perennially frozen slopes has increased and, thus, robust information on rock temperatures is required. In the Alps, the hot summer of 2003 resulted in increased depths of thaw and markedly increased rock-fall activity, especially on slopes exposed towards the north (Gruber *et al.*, 2004). This project lays the required basis for re-analysis of these events and for simulation of future scenarios and hazard zones.

The retreat of glaciers and the melt of ice faces change the temperature (and possibly also the hydrological) regime of many steep mountain-sides at an increasing speed. The tools developed here can assist the combined, quantitative assessment of ice/rock faces under transient conditions.

Large rock slopes usually have a complex structure comprising different slope angles, and as a consequence varying degrees of snow and debris cover. The near-vertical situation investigated in this paper and a talus slope or rock glacier can be regarded as two end-members of a continuum that characterizes most alpine rock walls. Further investigations of the distribution debris and snow cover in steep slopes and their effect on sub-surface temperatures are needed in order to understand and simulate temperatures realistically.

In 2003, the Swiss Permafrost Monitoring Network (PERMOS) initiated monitoring of rock-face temperatures routinely following the approach of this research programme. This will provide an opportunity for re-evaluation and further development of the model presented.

Based on the model put forward in this article, a more straightforward statistical model of rock temperatures is currently being designed and applied.

Northern slopes have the most abundant permafrost, and, at the same time the least spatial differentiation in rock temperature. This provides the opportunity to model a large proportion of existing rock-wall permafrost in Switzerland with relatively low computational effort and to estimate its total area.

ACKNOWLEDGEMENTS

The authors are grateful for the support given by the International Foundation High Altitude Research Stations Jungfraujoch and Gornergrat (HFSJG), the Corvatschbahnen cable car, the Gornergrat-Monte Rosa-Bahnen, the Matterhornbahnen and Burgergemeinde Zermatt. This project was funded by the Swiss National Science Foundation grant 'Analysis and Spatial Modelling of Permafrost Distribution in Cold-Mountain Areas by Integration of Advanced Remote Sensing Technology'. Project numbers 246979 and 21-63678.

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