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The Thermal Regime of the Active Layer at the Murtèl Rock Glacier Based on Data from 2002

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ABSTRACT

Active layer temperatures are presented from a rock glacier in the Swiss Alps. The data represent a full year (2002) covering parts of two very different winters. Winter/spring 2002 was very cold and dry; fall 2002 was characterized by an unusual amount of snow. Active layer temperatures are examined together with climate data and are used to discuss the processes which control the thermal regime of an active layer on a slope of a bouldery rock glacier surface. The development of the snow cover as well as the snow depth are shown to be essential, but the non-linear heating of the bouldery material with increasing air temperatures and the micro-topography of the rock glacier surface are also shown to have an influence on the thermal regime of the active layer. Furthermore, it is shown that the advective air movement within the blocky deposit has much less influence on the thermal regime than the vertical displacement of air masses. This is contradicts earlier literature on the subject. Copyright © 2004 John Wiley & Sons, Ltd.

KEY WORDS: active layer; blocky material; thermal regime; Swiss Alps

INTRODUCTION

During the last decade, work has focused on the better understanding of the thermal regime in the active layer. In general, fieldwork has been carried out in areas dominated by fine-grained material in the arctic or sub-arctic regions (see, e.g., Hinkel and Outcalt, 1994; Zhang *et al.*, 1997; Humlum, 1998; Kane *et al.*, 2001) while relatively few studies have been done on the response of ground temperature in or beneath blocky material (see, e.g., Humlum, 1997; Herz *et al.*, 2003). The blocky material acts as a filter between the surface energy balance and the permafrost. The medium, consisting of large boulders with open voids, complicates understanding and modelling of heat transfer from the surface because of its heterogeneity as the interconnected system of cavities gives rise to a complex pattern of air circulation, which is still not fully understood. Furthermore, the discontinuous alpine permafrost is naturally found in areas where the surface energy balance is often strongly influenced by local conditions such as slope and aspect, causing a complex microclimate.

The main objective of the present paper is to investigate the temperature regime of the coarse surface layer of a high alpine rock glacier. By presenting temperature data from the active layer over one full year from 1 January to 31 December 2002 together with climate data, it is intended to discuss the processes in the uppermost part of the active layer and their influence on the state of the thermal regime over the year. The discussion is based on the observations and represents typical processes for high alpine rock glaciers. The data set covers two cold periods, the beginning and the end of 2002, but the two winter

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periods are very different. The first period represent an unusually cold winter, where the snow arrives late and is sparse compared with earlier years. The second period is characterized by an unusually large amount of snow early in the fall. The year 2002 is, therefore, ideal for an investigation of the snow's influence on air exchange within the active layer as it exhibits very different winter conditions.

Permafrost and active layer are thermally defined systems and therefore dependent on the energy balance and the heat exchange at the ground surface. Therefore, the snow cover thickness and duration and the characteristics of the surface material and matrix are important for the processes.

THERMAL PROCESSES IN THE ACTIVE LAYER ON SLOPES COMPRISING COARSE BOULDERS—A HISTORICAL OVERVIEW

Not much work has been published on thermal processes within the bouldery active layer. The 'Balch effect' (Balch, 1990) is based on the idea of a simple replacement of warm air with cold air within the blocky material due to the density difference between the two air masses.

In 1996, Wakonigg summed up the sparse data from the Alps that showed much cooler ground temperature in the talus than would be expected from the mean annual air temperature (MAAT). Wakonigg (1996) suggested the 'chimney effect' on blocky slopes where, in winter, warmer air in the blocks tends to be displaced by denser cold air that enters wherever there are holes in the snow cover. The warm air moves through the voids and escapes to the atmosphere through holes in the upper part of the slope. The absence of snow cover during the summer period would cause cold air, trapped between the blocks, to sink down slope and escape into the atmosphere at the bottom of the deposit, permitting warmer air to replace it. Several studies have used this theory to explain unusually cold temperatures below the lower discontinuous permafrost limit (Sawada *et al.*, 2002; Delaloye *et al.*, 2003; Gude *et al.*, 2003; Kneisel, 2003). Several studies have furthermore investigated the snow–ground interaction on rock glaciers (Keller and Gubler, 1993; Hoelzle *et al.*, 1999; Bernhard *et al.*, 1998; Ishikawa, 2003; Ling and Zhang, 2003), which has added to a much better understanding of these wintertime processes.

Humlum (1997) suggested that exposure to high wind speeds and the surface texture (roughness) could lead to forced ventilation (in the blocky active layer) in such a way that the blocky surface of the rock glacier acts as a filter when very little or no snow cover is on the ground to protect the frozen core.

Harris and Pedersen (1998) summarized the various theories that had been suggested to explain unusually large differences in ground temperatures in coarse blocky material. Besides the 'chimney effect' and the 'Balch effect', they include summertime evaporation and sublimation of water/ice in the blocky deposit. They furthermore suggested a fourth theory, 'the continuous exchange of air with the atmosphere', as an extension of the 'chimney effect' in areas lacking a continuous snow cover in winter. This idea is basically an extension of the 'Balch effect' in areas without a continuous snow cover in winter, leading to fast temperature changes in the active layer. None of the above mentioned theories have ever been directly measured but are all based on a comparison of ground temperatures and climate data.

THE MURTÈL ROCK GLACIER AND ITS ENVIRONMENT

The Murtèl rock glacier is one of the best investigated rock glaciers in the Alps (Hoelzle *et al.*, 2002) and is situated in the Upper Engadine valley in the SE part of the Swiss Alps at 46° 26′N 9° 49′E (Figure 1). The climate is mainly influenced by SW air masses with mean annual precipitation of 800 mm in the valley and 1000–2000 mm in the periglacial areas. The area in general is classified as slightly continental (Schwarb *et al.*, 2000).

The rock glacier originates from the scree slope and the perennial snow patches at the foot of the steep rock faces of the Chastelets ridge at approximately 2800 m a.s.l. and has its steep front at 2620 m a.s.l. It has an area of 0.4 km^2 and is oriented towards the NW. The measurement site is at 2670 m a.s.l., and is indicated with a white square in Figure 1. As the altitude of the mean annual 0°C isothermal of the area is close to 2200 m a.s.l. (Hoelzle *et al.*, 2002), the rock glacier is located near the lower limit of the discontinuous alpine permafrost. In 2002, the minimum air temperature registered at the Murtèl rock glacier was −20°C and the maximum 16.1°C, an air temperature amplitude of more than 18°C. The rock glacier is active and the surface velocity varies from 5 $\mathrm{cm\ a}^{-1}$ to 15 $\mathrm{cm\ a}^{-1}$ (Kääb *et al.*, 1998). This has resulted in a compressive flow within the lower part of the rock glacier slope. Ogive-like transverse ridges exist with height differences of several metres between top and bottom. This velocity is probably related to an average slope of 10° (Kääb *et al.*, 1998) and to relatively warm ice. The core of the Murtèl rock glacier contains extensive

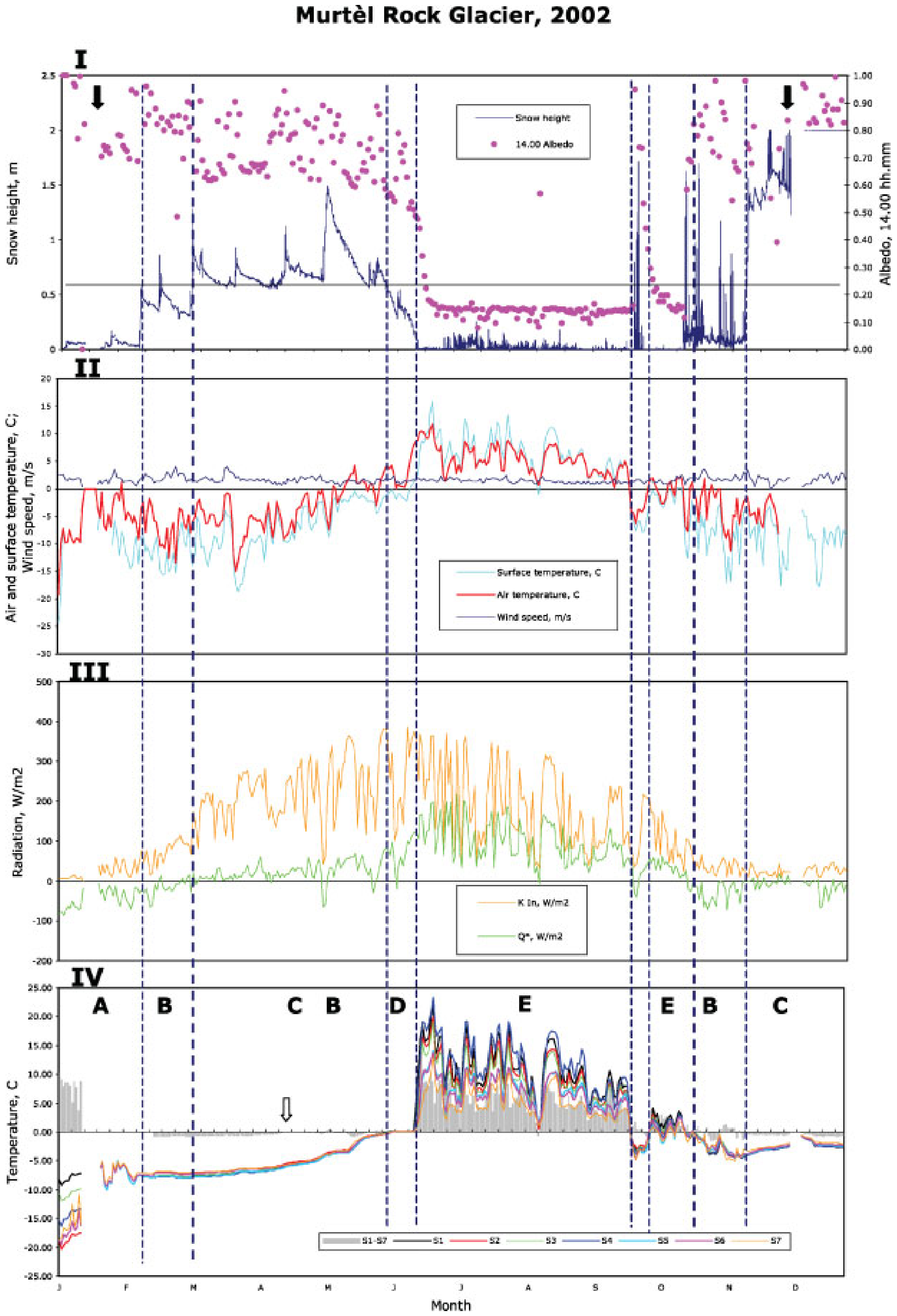

Plate 1 Climate data and active layer temperature from 2002. (I) Snow depth and albedo; (II) wind speed, air and surface temperature; (III) short wave incoming, net and long wave outgoing radiation; (IV) temperatures of the seven thermistors S1–S7. The year is divided into five main periods: (A) active layer cooling before the onset of a lasting snow cover, (B) shallow snow cover which allows a connection between the temperature of the atmosphere and the active layer and negative active layer temperatures, (C) lasting snow cover with no connection between atmosphere and active layer, (D) zero curtain, and (E) above zero active layer temperatures. The two black arrows show periods of missing data; the white arrow indicates the onset of melt.

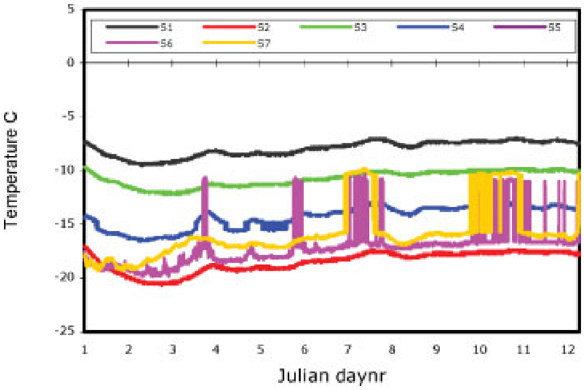

Plate 2 The temperatures measured in the active layer during the first 12 days of January 2002. The two thermistors which measure the air temperature in the cavities react strongly while the thermistors drilled into the rock react in a much more attenuated way, but they still do react.

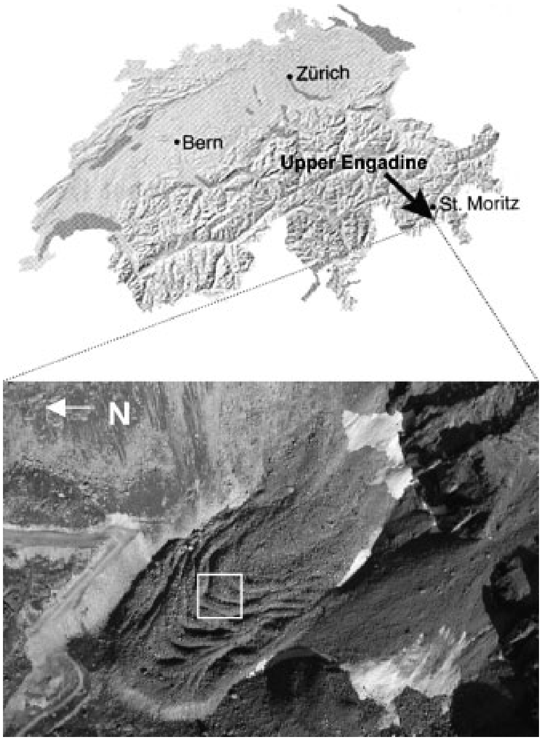

Figure 1 The Murtèl rock glacier is situated in the SE part of Switzerland. The lower part of the headwall of the Chastelets ridge is seen in the upper right corner of the picture and the white square indicates the active layer monitoring site. The rock glacier is approximately 200 m wide. Photo: C. Rothenbuehler.

Figure 2 The surface of the Murtèl rock glacier consists of boulders varying in size from 0.4 m to several metres. The block at the front is almost 2.5 m wide. The meteorological station can be seen in the middle of the picture. Photo: S. Hanson.

amounts of nearly pure ice in the upper 10–20 m, where the volumetric ice content is 80–90% (Haeberli and Beniston, 1998; Arenson and Springman, 2000; Arenson *et al.*, 2002). The frozen material continues into the bedrock at nearly 50 m depth and the active layer reaches depths of 2–4 m in summer (Vonder Mühll and Haeberli, 1990). The surface consists of granite boulders (mainly of the granodiorite type) and wide-open pore spaces (Figure 2). For this reason rain and percolating melt water quickly disappear and the surface is generally dry. The orientation of the rock glacier towards the NW, the altitude, the shade of the Chastelets ridge and the high local scale surface roughness create a near surface wind field and surface energy balance that are typical boundary conditions for discontinuous alpine permafrost.

INSTRUMENTATION

In 1999, thermistors were placed in the uppermost 90 cm of the active layer at the Murtèl rock glacier. The aim was to compare local climate data directly with changes in the temperature of the active layer. This would allow a better understanding of the important processes that determine the upper boundary conditions. Seven thermistors (YSI 55008) were placed in the active layer, each having a resolution of 0.5°C and an error of less than ±0.2°C. Thermistors S1–S5 were drilled 5 cm into the boulders while S6 and S7 were left hanging in cavities between the boulders measuring the air temperatures (Figure 3). Temperatures are registered every minute and logged as a 5 min mean. All thermistors were calibrated before their placement in 1999 and are annually, indirectly calibrated by the zero curtain in spring.

A microclimate station was installed at the Murtèl rock glacier in 1997 (Mittaz *et al.*, 2000). Air temperature, wind speed and wind direction, humidity, in- and outgoing long wave radiation, in- and outgoing short wave radiation and snow depth are registered every 10 minutes and logged every half hour as a 30 minute mean. The thermistors in the active layer were installed less than 1 m from the climate station. Snow depth is measured with a sonic ranger (SR50). The uneven, blocky surface can disturb the instrument in such a way that a snow depth is registered even though there is no snow on the ground. Comparing snow depth data with albedo measurements compensates for this error. Periods without data (indicated by a black arrow in Plate 1) are normally due to lighting.

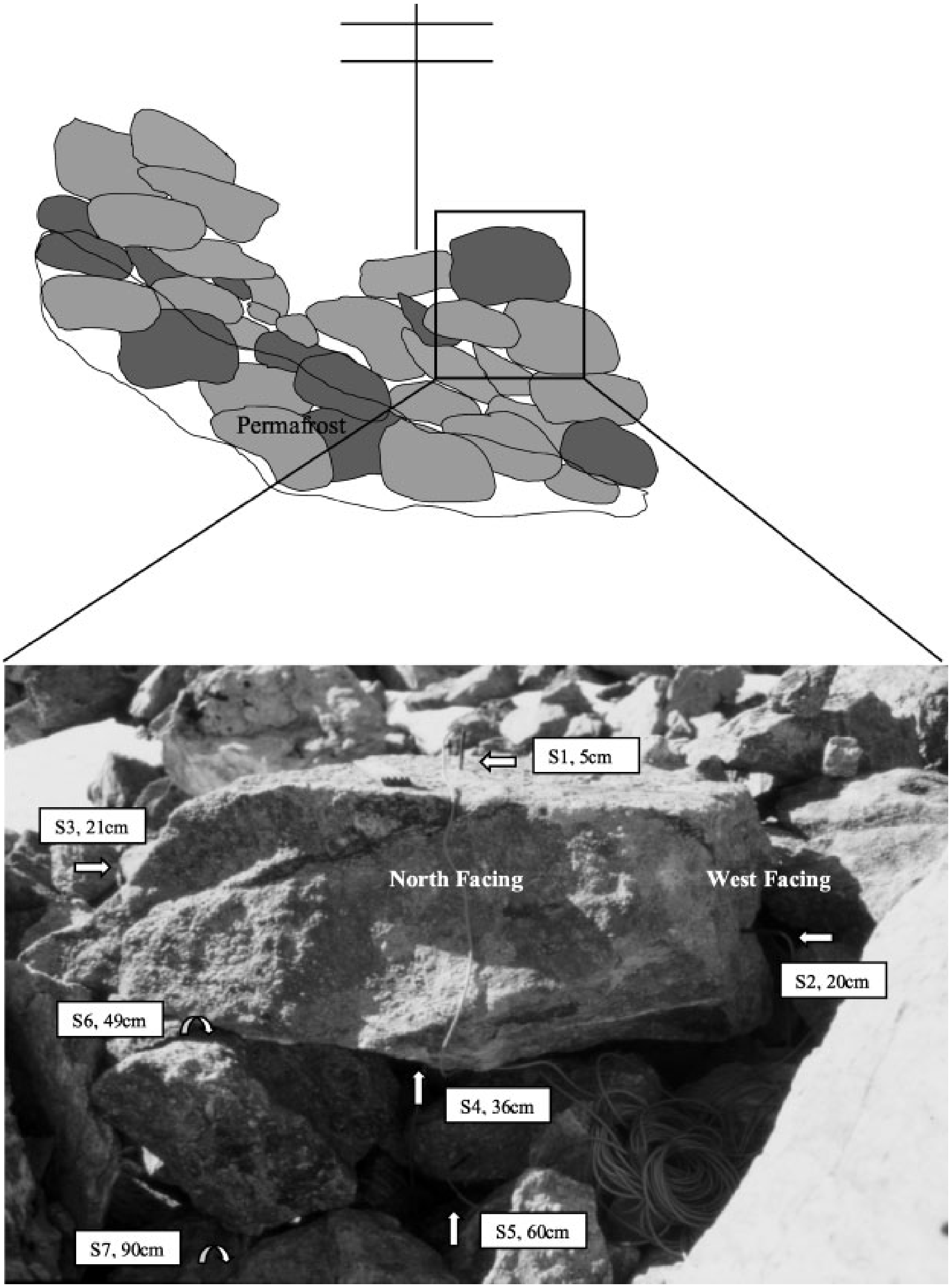

Figure 3 The thermistors installed in the uppermost levels of the active layer at the Murtèl rock glacier. S1–S5 were drilled 5 cm into the blocks while S6 and S7 were left hanging in the cavities and cannot be seen in this picture. The folding rule on top of the block is for scale. Photo: S. Hanson.

RESULTS

The climate data together with the ground temperatures in the active layer during the year 2002 are presented as daily mean values in Plate 1. The quantitative analysis is performed on the originally stored data described above.

Plate 1(I) displays snow depth together with the albedo calculated from the measured incoming and outgoing short wave radiation at 2 pm local time. Observations by the snow and albedo sensors indicate a shallow snow cover present on the ground during the first 39 days of 2002. The surface is snow free during the summer period from mid-June to mid-September. An exception is 11 August; an isolated, short-term snowfall results in the recording of an exceptionally high snow depth. This is probably the result of the snow in the air blurring the true surface.

The winter 2002/2003 is quite unusual because of the large amount of snow. After 5 December the SR50 is buried in snow and it can only be stated that there is more than 2 m of snow. Nearby snow pit measurements showed a snow depth of 3–4 m as compared with a normal maximum snow depth of 1.5 m.

Plate 1(II) presents wind speed, air temperature and surface temperature calculated from long wave outgoing radiation. The maximum wind speed measured is $9.4\,\mathrm{m\,s^{-1}}$, which is surprisingly low for this open landscape. The explanation is probably to be found in the fact that the prevailing wind direction in the area is from the SW and that the Chastelets ridge, with its half-moon shape, protects the Murtèl rock glacier from the wind.

The MAAT for 2002 cannot be calculated as the amount of snow in mid-November buried the thermometer, but it is known from former years to be close to −1.8°C at the measuring site. When snow is on the ground, surface temperatures are lower than those on exposed boulder surfaces because of the snow's much higher albedo. This causes a decrease in absorbed incoming short wave radiation. The outgoing long wave radiation increases due to the higher emissivity of snow. The emissivity of a snow surface varies from 0.96 to 0.99 with an average of about 0.98 (Zhang *et al.*, 2001), while debris in the investigated area has an emissivity of 0.8 (Keller and Gubler, 1993). This higher emissivity of snow leads to an increase of outgoing long wave radiation and, therefore, to a cooling of the surface. In the same way, the low albedo and emissivity of debris cause the bare surface to absorb more short wave radiation and to lower the emitted energy so that the surface heats up. This is evident in Plate 1(IV), where the surface temperature increases when the snow disappears and falls as soon as snow is present.

Plate 1(III) displays incoming short wave radiation and net radiation. The maximum incoming radiation is about $1230\,\mathrm{W\,m^{-2}}$ and is reached during the snowmelt period. However, as the snow melts and the albedo drops noticeably, a maximum net radiation is registered during the snow-free period of $787\,\mathrm{W\,m^{-2}}$. The influence of the shadow from the Chastelets ridge and its control on the radiation balance is very evident.

Plate 1(IV) illustrates the temperature regime of the active layer registered by the seven thermistors and the thermal gradient, calculated as the difference between S1 and S7 of the uppermost 90 cm of the active layer based on daily means. A large temperature gradient illustrates a poor connection between the surface and the interior of the active layer. A positive temperature gradient exemplifies the fact that the interior is colder than the upper boundary of the active layer.

The degree of connection between the air temperature and the thermal regime of the active layer over the year can be classified by five main categories (A–E). The definition of these five categories is based on the correlation between the active layer temperatures and the air temperature together with the registered snow depth and therefore reflects the main heat transfer processes between the atmosphere and the active layer. Some of the categories are repeated several times over the year, resulting in nine periods during the year 2002.

A. Active Layer Cooling Before the Onset of a Lasting Snow Cover

Period A in Plate 1 is characterized by a lack of continuous snow cover and daily mean active layer temperatures below the melting point. A lack of a continuous snow cover enables a direct coupling of air and active layer temperatures (Harris and Pedersen, 1998). The low air temperatures just around New Year 2001 strongly influence S2, S6 and S7. Both air and active layer temperatures drop to approximately −20°C. In the first hours of the year 2002 the air temperature raises by approximately 13°C while a thin snow cover settles on the surface of the rock glacier. The snow cover is so thin that the system is still open and the exchange of air masses is directly dependent on density differences or on mechanical forces such as wind pumping. The warmer atmospheric air is now not able to penetrate into the active layer despite an exceptionally strong positive thermal gradient. While the air temperature settles to around −10°C for a period of 2 weeks, the lower thermistors show a delay of more than 10 days. In this period the lower three thermistors register high frequency temperature fluctuations, which are strongest in the thermistors measuring the air temperature between the blocks (thermistors S6 and S7). The upper four thermistors show weaker signals with a delay (Plate 2).

By the end of period A, a much stronger correlation between air temperature and the temperature recorded by thermistor S7 exists ($R^2 = 0.7$). The R^2 value is, in this case, an expression for the dependency of the temperature variations in the active layer on the temperature variations of the air.

B. Shallow Snow Cover, Which Allows Connection Between Atmosphere and Active Layer in Addition to Negative Active Layer Temperatures

The winter 2001/2002 is cold as well as dry and a distinct snow cover does not develop before 6 February 2002. A shallow snow cover of less than 0.6 m covers the Murtèl rock glacier. The snow attenuates the correlation between the active layer temperatures and the air temperature ($R^2 \sim 0.4$), but as long as the snow cover is less than 0.6 m the main pattern of the air temperature is reflected in small, synchronized short term variations in the temperature throughout the active layer. The correlation between air temperature and active layer temperature is negative and the gradient within the active layer has a mean value during the period of $-0.87°\text{C m}^{-1}$.

Period B in autumn 2002 is much warmer than the first one described above and is interrupted by Period E with above freezing temperatures. Altogether, the system cools for 34 days before a thick snow cover closes off the connection to the atmosphere. This period is characterized by heavy snowfalls and is followed by melting periods and air temperatures around the freezing point. Short term variations in active layer temperatures are proof that a connection to the atmosphere exists through funnels in the snow cover. This results in an almost instantaneous, but damped, warming and cooling of the blocky deposit in response to changes in the air temperature. A weak correlation between air temperatures and thermistor S7 temperature ($R^2 = 0.5$) is observed but no negative correlation, as in spring 2002, is found. Short wave radiation is still strong enough to warm up the surface and to create a positive gradient that warms up the active layer during periods of positive air temperature, although the active layer itself remains below freezing point.

C. Lasting Snow Cover With No Connection Between the Atmosphere and the Active Layer

Period C in Plate 1 starts on 3 March and is characterized by a thick, lasting snow cover of more than 0.6 m depth that inhibits the connection between the active layer and the atmosphere, so that the air temperature has no more influence on active layer temperatures ($R^2 = 0.01$).

The snow pack starts to melt on 12 April (white arrow in Plate 1), the first day on which snow-surface temperatures reach the melting point. The snow pack increases in density due to metamorphism, which in turn results in a decreasing thermal resistance and, hence, an increase in thermal conductivity. Despite this fact, snow depth further increases due to continuous new snowfall. On 29 April, the thermal gradient shifts to positive, indicating that heat transfer from the snow pack overrules the influence of the active layer temperatures from below. Rapidly rising active layer temperatures on 17 May indicate refreezing of melt water percolating into the active layer and release of latent heat.

In autumn 2002 a thick snow cover develops on 13 November, 111 days earlier than in the previous winter. The mean active layer temperature is −2.4°C, almost 5°C warmer than in spring 2002.

D. Zero Curtain

Period D is characterized by a period where melting of the superimposed ice layer keeps the active layer at the freezing point even though the MAAT is approximately 3°C during a 14 day long period in spring 2002.

E. Active Layer Temperatures Above Zero

As soon as surface melting is completed (15 June) the temperatures of the active layer rise immediately. The lower part of the active layer warms up more slowly than the upper part but all thermistors reach maximum temperature during the same day. Over the next 100 days, the gradient in the active layer is strongly positive except for one day during mid-summer, 11 August, where a thin layer of snow causes a reverse thermal gradient. The warm Period E is interrupted by a 9 day cooling period with snowfall and a strong correlation between active layer and air temperatures before the snow finally settles on 16 October.

DISCUSSION AND INTERPRETATION

An overview of the correlation between active layer temperatures and air temperature for each of the nine periods under the five main categories (A–E) is presented in Table 1.

Table 1 Each period is shown with its correlation between mean daily air temperature and daily active layer temperatures for thermistors S4 and S7.

Period	Julian day No.	Sensor S4	Sensor S7
Period A	1–12	0.2	0.4
	27–36		0.7
Period B	37–61	−0.4	−0.4
	266–274	0.8	0.8
	292–316	0.1	0.2
Period C	62–118	0.0	0.0
	119–151	0.1	0.2
	317–365	0.1	0.0
Period D	151–165	0.0	0.0
Period E	166–265	0.5	0.5
	275–291	0.6	0.7

An Important Threshold of 0.6 m Snow Depth Controlling Ground Temperatures

The 0.6 m snow depth appears to be an important threshold in influencing the temperature gradients within the active layer at the Murtèl rock glacier. This value of 0.6 m depends strongly on the local surface characteristics (e.g. size of boulders), which are spatially highly variable in alpine environments. The whole system seems to close off when the snow depth exceeds 0.6 m on the Murtèl rock glacier and during the periods C and D no correlation exists between the active layer temperatures and the air temperature (Table 1). The cold subsurface flow of air concentrating on the surface of the permafrost table will force the relatively warmer air, still trapped in bouldery deposits, upwards to the surface. As soon as the thick snow cover has closed off the funnels and continuous snowfalls prevents the development of new ones, the warmer air becomes trapped within the ridges. In spring 2002 the cold air trapped beneath the snow pack continuously warmed up until the system reached the site-specific thermal gradient. The system would respond by cooling if the active layer temperatures were warmer than the site-specific equilibrium temperature.

The active layer stays below freezing even though the air temperature is above the freezing point for longer periods during the spring (Period C). The following zero curtain (Period D) prolongs this situation. For this reason the timing of the arrival and melting of the lasting thick snow cover is crucial. The timing of the melting of the snow pack is more predictable than the timing of the development of a thick snow pack. This is because melting is largely influenced by the site-specific shadow effect of the Chastelets ridge and its control of the local radiation balance.

The Continuous Exchange of Air with the Atmosphere

Periods A and B are periods where there is less than 0.6 m of snow. In most cases, the correlation between the daily mean air temperatures and the daily mean active layer temperature is pronounced. In general, a prevailing continuous exchange of air occurs as long as the snow cover is absent or less than 0.6 m. Instantaneous warming and cooling of the blocky deposit with a lack of continuous winter snow cover will take place only when the thermal conditions between the active layer and the atmosphere are favourable. A much more detailed discussion is needed as the system is very complex.

Vertical Displacement of Heat

The beginning of period A (Table 1, Period A, Julian days 1–12) is an example where the theory of ‘continuous exchange of air temperature’ does not apply. The micro-topography (furrows and ridges) plays a significant role in protecting the active layer from warming up. This is despite the fact that there is free passage of air because of a shallow snow cover of less than 0.08 m and a strong positive temperature gradient between the air and the active layer in this 12 day period. During the strong cooling of air temperatures around New Year, cold, denser air is trapped in the furrows on both sides of the ridge and isolates the interior of the ridge from the warmer atmospheric air (cf. Hoelzle *et al.*, 1999). The fast temperature change seen in Plate 2 may indicate rising ‘heat bubbles’. This period does not exhibit the negative correlation with air temperature observed during the periods of the ‘chimney effect’. Measured wind and air temperatures do not support wind-pumping processes. Furthermore, the radiation seems too weak to create the melting that could explain the temperature rise if a local release of energy were caused by refreezing. This suggests that the relatively warmer air must come from underneath, and, forced by the denser cold air, is rising towards the surface like bubbles. It is therefore probably not a product of horizontal advective energy transport but rather a function of vertical heat exchange. The result is a system that reacts very slowly to the changes of the air temperature in the atmosphere above.

The Chimney Effect

The chimney effect, where cold dense air displaces warmer air in between the blocks, is widely used to explain the cooling of the active layer on blocky slopes. The cold air is believed to enter the active layer by funnels in the snow at the top of the slope and glide downwards by gravity, forcing the lighter air upward toward the surface. This process is only observed once during 2002: Table 1, Period B, Julian days 37–61, shows a negative correlation between the colder atmospheric air and a temperature rise in the active layer underneath the snow. This process is active over a time span of 2 weeks and the gradient within the active layer has a mean value during the period of $-0.87^{\circ}\mathrm{C\,m^{-1}}$. The process stops as soon as the atmosphere heats up and becomes warmer than the active layer. This is the process that Wakonigg (1996) suggested as the 'chimney effect' and provides an explanation for the fact that the correlation between air and active layer temperature is as low as 0.4 for Period B as a whole. This tendency is not found during the continuously changing conditions in Period B in fall 2002. This important process, which effectively cools the active layer, only develops under certain critical conditions and it seems that a stable snow cover of less than 0.6 m and a well developed funnel system are needed.

Non-Linear Heating of the Active Layer with Air Temperature

A stronger correlation exists when the air temperature is below approximately 6°C and there is a lack of a continuous snow cover of more than 0.6 m. If the temperature above 6°C is neglected the correlation increases from 0.5 to 0.6 between the air temperature and thermistor S7. If the temperatures are lowered even more, as shown in Table 1, Period E, Julian days 275–291, and Period A, Julian days 27–36, the correlation increases even further. Delaloye *et al.* (2003) found similar evidence in a scree slope in the Jura Mountains, Switzerland. They showed that a direct correlation existed when the daily mean air temperature was below 7°C and found a negative correlation when temperatures were above this threshold. This negative correlation is not found at Murtèl. When the air temperature is above the threshold of 6°C at Murtèl, the active layer temperature has a strong correlation with the incoming short wave radiation. High temperatures generated by intense radiation during daytime create heat transfer by conduction, while low radiation caused by horizon-effects, at night time or during cold weather conditions, enables sensible heat transfer by the differences in density of the cold and warm air. For the system as a whole, there is dissimilarity in its response to cold or warm weather, where the system reacts rapidly to cooling by non-conductive processes and reacts slowly to warming by conduction.

Zero Curtain

The zero curtain is a result of phase change. If the material is fine, this phenomenon is known to delay the onset of frost in the ground during autumn. The release of latent heat of fusion acts to retard the penetration of the freezing front advancing from the surface downwards and from the base of the active layer upwards (see, e.g., Kane *et al.*, 2001). In coarse blocks this process occurs very seldom in autumn because of the lack of water in the system. Instead, several authors have reported an almost opposite process within snow-covered boulders in spring (Humlum, 1997; Ishikawa, 2003; Hoelzle, Haeberli, & Stocker-Mittaz, 2003), which is also found at the Murtèl rock glacier. As the melting front moves downward in the snow pack, melt water is released. This melt water reaches the cold subsurface air/boulders and creates a layer of superimposed ice, where it refreezes and releases energy as seen in Period C. The length of the zero curtain is dependent on the amount of superimposed ice created in the voids, which acts as an energy sink that has to be filled before a warming of the active layer can begin.

CONCLUSIONS AND PERSPECTIVE

Detailed monitoring of thermal conditions within the coarse, blocky active layers of permafrost in the Murtèl rock glacier (Eastern Swiss Alps) revealed the following facts.

- When there is a lack of continuous snow cover the temperature in the active layer is a result of a complex pattern of subsurface advective air currents and vertical replacement of air due to mechanical forces such as density differences and air pumping. The theory of the 'continuous exchange of air with the atmosphere' developed by Harris and Pedersen (1998) will only take place when the right conditions exist.
- Vertical processes dominate heat transfer between the active layer and the atmosphere. The 'chimney effect' often used in the literature to explain cooling of the active layer of rock glaciers turns out to be surprisingly unimportant at the Murtèl rock glacier.

- When the daily mean air temperature is above approximately 6°C, the correlation between active layer and air temperature becomes weak. In other words, there is no linear heating up of the active layer with air temperature. This effect protects the inner core of the permafrost against high mid-summer temperatures.
- The system as a whole reacts faster to non-conductive processes (typically cold weather) than to heat transfer by conduction alone (typically warm weather). This effect protects the system from strong heating.
- Wind pumping is shown to be not of importance for this rock glacier.
- A snow depth of 0.6 m acts as a threshold isolating the active layer thermally from the atmosphere. This threshold is local and depends on the roughness of the bouldery surface.
- Furrows formed by the compressive flow of the rock glacier have a thermally protective influence by preserving cold air that isolates the active layer from the warmer atmospheric air.
- The timing of the development of a snow cover thicker than 0.6 m will be the most important single factor controlling the thermal state of the active layer.

Future investigations will concentrate on the analysis of additional measurements. In addition, the modelling of heat flow in the ground based on a coupled atmosphere and a ground heat flux model will enable a better quantification and separation of the individual heat fluxes by using the developed categories, the 0.6 m snow depth limit and the 6°C threshold between conductive and non-conductive processes. Non-conductive processes will allow a first step towards a simple model approach of heat transfer in the bouldery active layer. The comparison of model results and measurements will lead to new insights into this most complex system.

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