Thermal Diffusivity Variability in Alpine Permafrost Rock Walls

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Abstract

Permafrost degradation has been hypothesized as being one of the main causes of rockfalls and rock wall instability in the recent past in high mountain areas. Ongoing rock wall permafrost evolution remains poorly understood because of the lack of systematic measurements; models are often validated and driven by few existing instrumented sites. In rock wall subsurface temperature modeling, thermal diffusivity (κ) is one of the main parameters to be considered. In this study, thermal diffusivity data series were inferred from rock temperature data in order to understand their annual variation, their distribution in different temperature ranges, and their relation to atmospheric conditions. A harmonic analysis was performed to define amplitude and phase of the daily temperature waves at different depths by means of a least square minimizing optimization procedure. The analysis conducted shows that changes in κ values are influenced by different factors such as depth, season, rock temperature, aspect, and snowfall.

Keywords: rock wall temperature; thermal diffusivity.

Introduction

Steep bedrock slopes in high mountain areas are subjected to permafrost action. During the very hot summer of 2003, many rockfalls occurred in the European Alps, and sometimes massive ice was visible in the exposed detachment zone (Gruber et al. 2004b). These observations suggest that permafrost degradation may be one of the main causes of rock wall instability observed in recent years in high mountain areas (Dramis et al. 1995, Noetzli et al. 2003, Gruber et al. 2004a).

Thawing and degradation of rock wall permafrost is very fast if compared to permafrost in gentle morphology because of the lesser amount of ice content and the absence of a debris insulation layer (Gruber et al. 2004b); moreover, steep bedrock morphologies are abundant in many cold mountain regions and contain a significant proportion of permafrost (Gruber & Haeberli 2007).

Present and future global warming (IPCC 2007) will likely lead to a significant increase in frequency and intensity of rockfall events caused by variations in rock wall thermal regimes (Davies et al. 2001). Consequently, its degradation is spatially a widespread problem (Gruber & Haeblerli 2007) which causes an increment in risks for people and infrastructures in high mountain areas (Harris et al. 2001).

In order to obtain a better understanding of rockfall trigger mechanisms and processes linking slopes warming and their local destabilization, an increase in knowledge on rock wall temperature regimes and their evolution is very important (Gruber & Haeberli 2007). Quantitative understanding and models of surface temperature distribution within steep rock faces in complex topography exist and have been validated with near-surface measurements (Gruber & Hoelzle 2001, Gruber 2005). However, many questions about active layer and sub-surface rock wall permafrost evolution remains poorly understood because of the lack of deeper systematic measurements and models.

In purely diffusive and stationary state models, thermal diffusivity is considered the only petrophysical parameter of importance (Yershov 1998), and in permafrost modeling, it is often considered as constant. Nevertheless, the continuous variability of water content linked to environmental conditions (Saas 2005), together with the latent heat effect associated with thawing and freezing (Mottaghy & Rath 2006), may cause great variability in thermal diffusivity in the active layer. These mechanisms may affect deeper temperature regimes and cause a probable “thermal offset” (Gruber & Haeblerli 2007) between the rock surface and the top of permafrost.

The main purpose of this work is to evaluate the annual course of thermal diffusivity on some alpine permafrost rock walls and its variability related to environmental conditions. Using rock wall temperature data series measured at different depths of the active layer, a harmonic analysis was used to define amplitude and phase of daily temperature waves by means of a least square minimization procedure. Optimized amplitude values at each depth were used to obtain hourly
data of rock thermal diffusivity $\kappa$. These data series were analysed in order to understand their annual variation, their distribution in different temperature ranges, and their relation to atmospheric conditions inferred from in situ meteorological collected data.

**Research Strategy**

*Field measurements*

All data series were collected within the international project PERMAdataROC started in March 2006, during which several measurement sites were equipped on high steep slopes in six different areas in the western European Alps. For this study, two of the six areas were selected because they are characterized by long data series and by a higher number of measured variables. One is the SW ridge of the Matterhorn, and the other is the peak of the Aiguille du Midi in the Mont Blanc massif (Fig. 1).

In each area the measured variables are: rock wall temperature at depths of 3, 30, and 55 cm; air temperature and relative humidity (10 cm from the rock surface); and solar radiation, wind speed, and wind direction, measured by means of an automatic weather station (MAWS), installed on the rock wall with sensors parallel to the rock surface (Table 1).

Measurements started in November 2005 at the Matterhorn site, and at the end of December 2006 at the Aiguille du Midi site. For this study, a total of eight data series were used; data series characteristics are shown in Table 2.

In order to identify snow events, daily albedo values were calculated from radiation data, and a snow index ($S_i$) was defined as the ratio between daily and mean albedo: snow index values greater than 1.25 are caused by snow events. Since some problems in snow index definition may occur, mainly in winter due to snow deposition on MAWS’s sensors during snowfalls events, sonic anemometer, air temperature, and humidity data series were also used as further confirmation of snow events.

**Thermal diffusivity evaluation**

Rock temperature data were used for thermal diffusivity evaluation. Signal detrending using running-mean was performed on rock temperature data series in order to remove low frequency oscillations as seasonal and annual ones. Assuming that temperature variation at any depth is sinusoidal, the thermal diffusivity of rock, $\kappa$ (m$^2$ s$^{-1}$), can be calculated with the following equation (1) (Matsuoka 1993):

$$\kappa = \frac{\pi}{P} \left[ \ln \left( \frac{A_1}{A_2} \right) \right]^2$$

where $P$ is the period of one complete harmonic oscillation (24 hours) given in seconds, $A_1$ and $A_2$ are the amplitude of temperature waves ($^\circ$C) at depth $Z_1$ (i.e., 0.03 m) and $Z_2$ (i.e., 0.3 m).

A harmonic analysis of rock temperature data was performed to define amplitude $A_1$ and $A_2$ of daily temperature waves at different depths using the following equation which describes a general harmonic oscillation:

$$T_{(z,t)} = A_{(z)} \sin(\omega t + \phi)$$

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**Table 1. Instrumentation**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Instrument</th>
<th>Log. interval</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rock temp.</td>
<td>Geoprecision - M-Log 6</td>
<td>60 min</td>
</tr>
<tr>
<td>Air temp. &amp; hum.</td>
<td>Geoprecision - M-Log 5</td>
<td>60 min</td>
</tr>
<tr>
<td>Radiation</td>
<td>Kipp&amp;Zonen - CNR-1</td>
<td>10 min</td>
</tr>
<tr>
<td>Wind</td>
<td>Vaisala - WMT50</td>
<td>10 min</td>
</tr>
</tbody>
</table>

**Table 2. Data series characteristics**

<table>
<thead>
<tr>
<th>Site</th>
<th>Series name</th>
<th>Aspect (m a.s.l.)</th>
<th>Elevation (m)</th>
<th>Length (days)</th>
<th>Season</th>
<th>Mean rock temp. (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>-55cm</td>
<td>-30cm</td>
<td>-3cm</td>
</tr>
<tr>
<td>Matterhorn</td>
<td>CCS_Tr</td>
<td>N158-90</td>
<td>3820</td>
<td>126</td>
<td>sum</td>
<td>3.12 3.70 4.14</td>
</tr>
<tr>
<td></td>
<td>CCS_Ta</td>
<td>N158-90</td>
<td>3820</td>
<td>126</td>
<td>sum</td>
<td></td>
</tr>
<tr>
<td></td>
<td>CCS_Rad</td>
<td>N158-90</td>
<td>3820</td>
<td>370</td>
<td>sum</td>
<td></td>
</tr>
<tr>
<td></td>
<td>CHEM_Tr</td>
<td>N180-90</td>
<td>3750</td>
<td>744</td>
<td>win-sum</td>
<td>0.58 0.90 1.28</td>
</tr>
<tr>
<td>Aig. du Midi</td>
<td>ADMS_Tr</td>
<td>N160-85</td>
<td>3820</td>
<td>209</td>
<td>win-sum</td>
<td>0.56 0.98 1.05</td>
</tr>
<tr>
<td></td>
<td>ADMN_Tr</td>
<td>N335-80</td>
<td>3825</td>
<td>209</td>
<td>win-sum</td>
<td>-7.20 -7.16 -7.03</td>
</tr>
<tr>
<td></td>
<td>ADMS_Ta</td>
<td>N160-85</td>
<td>3820</td>
<td>209</td>
<td>win-sum</td>
<td></td>
</tr>
<tr>
<td></td>
<td>ADMS_Rad</td>
<td>N160-85</td>
<td>3820</td>
<td>209</td>
<td>win-sum</td>
<td></td>
</tr>
</tbody>
</table>

Abbreviations: Tr: rock temperature; Ta: air temperature and relative humidity; Rad: solar radiation.

Lithology: Matterhorn, gneiss; Aiguille du Midi, granite.
Table 3. Mean values and standard deviations of $\kappa$ data series at Cheminée site (Matterhorn).

<table>
<thead>
<tr>
<th>Depth interval (cm)</th>
<th>Entire series $\kappa$ mean $10^4$ (m$^2$s$^{-1}$)</th>
<th>Entire series standard deviation $10^4$ (m$^2$s$^{-1}$)</th>
<th>Warm Period $\kappa$ mean $10^4$ (m$^2$s$^{-1}$)</th>
<th>Warm Period standard deviation $10^4$ (m$^2$s$^{-1}$)</th>
<th>Cold Period $\kappa$ mean $10^4$ (m$^2$s$^{-1}$)</th>
<th>Cold Period standard deviation $10^4$ (m$^2$s$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3 - 30</td>
<td>2.401 $10^4$</td>
<td>0.175 $10^4$</td>
<td>2.505 $10^4$</td>
<td>0.189 $10^4$</td>
<td>2.298 $10^4$</td>
<td>0.065 $10^4$</td>
</tr>
<tr>
<td>30 - 55</td>
<td>1.524 $10^4$</td>
<td>0.041 $10^4$</td>
<td>1.517 $10^4$</td>
<td>0.029 $10^4$</td>
<td>1.530 $10^4$</td>
<td>0.050 $10^4$</td>
</tr>
<tr>
<td>3 - 55</td>
<td>1.898 $10^4$</td>
<td>0.072 $10^4$</td>
<td>1.932 $10^4$</td>
<td>0.071 $10^4$</td>
<td>1.865 $10^4$</td>
<td>0.048 $10^4$</td>
</tr>
</tbody>
</table>

Warm period: summary of all springs and summers; cold period: summary of all autumns and winters.

Figure 2. Annual course of computed thermal diffusivity at the Cheminée site (Matterhorn) smoothed over 15 days.

where $\omega$ is the angular frequency of the oscillation (i.e., for daily cycles $\omega=\left(2\pi/24\right)$ h$^{-1}$), $A(z)$ is the amplitude of temperature oscillation at depth $z$, and $\Phi$ is the phase angle.

A least-square minimization procedure was applied using equation 2 in order to obtain estimates of unknown parameters $A(z)$ and $\Phi$. $A(z)$ is the parameter chosen for thermal diffusivity evaluation. Amplitude values at different depths were used in equation 1 to obtain hourly data of rock thermal diffusivity $\kappa$. As rock temperature data at three different depths were available, three different couples of amplitude data series were used: 3−30cm, 30−55cm, and 3−55cm. The fitting procedure was computed on every series using a three-day running-window, moving with an hourly step. The standard error of computed thermal diffusivity values was evaluated using a bootstrap resampling technique. In the bootstrap procedure, the original dataset is randomly resampled N times (in this study N=500); in this way, for each hourly step, 500 synthetic thermal diffusivity datasets were generated. Instead, as described in Efron and Tibshirani (1993), the standard deviation of the distribution of these 500 values is a good measure of the parameter’s standard error. The parameter standard error was used as an indicator of the reliability of amplitude values. Finally, the resulting thermal diffusivity data series was smoothed with a median filter of three hour’s width, to avoid rapid fluctuations.

Results and Discussion

Annual course of thermal diffusivity

In order to show the annual variations in thermal diffusivity at each depth, the longer available data series (CHEM) is considered in Figure 2. Table 3 shows mean values of $\kappa$ and standard errors of the whole data series and for cold (autumn plus winter) and warm (spring plus summer) periods.

The first 30 cm of rock show a mean value of about $2.4\times10^4$ m$^2$s$^{-1}$ and great annual variability, with values generally below the mean during the cold season, and above the mean during the warm season. This observed variability decreases with depth: oscillations of deeper thermal conductivity data series are strongly reduced, and the seasonal behaviour underlined for the shallower rock layer cannot be seen. These differences are probably due to the different variability in water content during the year: greater in the first centimetres of rock and lesser at depth. Moreover, mean $\kappa$ values of 30−55cm depth interval are significantly reduced, probably because of the different degree of saturation in comparison to the shallower rock layer.

To gain an understanding of the reliability of the diffusivity values presented, laboratory measurements of thermal conductivity were performed on gneiss samples collected at the Matterhorn study site. The results give a mean value of thermal conductivity equal to 2.7 Wm$^{-1}$K$^{-1}$. Using a mean tabled value of volumetric heat capacity for granitic rock equal to $1.75\times10^6$ Jm$^{-3}$K$^{-1}$ (Yershov 1998), the resulting value of thermal diffusivity is $1.54\times10^4$ m$^2$s$^{-1}$, a value which is very similar to the mean of the whole series calculated for the 30−55cm depth interval ($1.52\times10^4$ m$^2$s$^{-1}$).

These results seem to suggest that significant differences in thermal diffusivity values can be obtained by considering the first centimetres rather than the deeper rock layers. This matter should be taken into account when thermal diffusivity values are applied to heat conduction models for the projection in depth of rock wall temperature.

Distribution of $\kappa$ values in different rock temperature ranges

Figure 3 show the distribution of 3−55cm thermal diffusivity values above and below 0°C both at the north and south Aiguille du Midi sites.

The 30 cm depth data series was used as the rock temperature reference at each site. In the period considered, on the northern site only 10% of rock temperature data were
above 0°C, whereas in the south, this proportion was around 50%. Moreover, minimum north and south values were -17.97°C and -14.06°C respectively, while the maxima were 3.97°C and 16.4°C, respectively.

The histograms in Figure 3 show the effect of rock wall aspect and different conditions on thermal diffusivity. Regarding aspect, the northern site showed values lower than the southern one and less dispersed around the mean. Lower values suggest that northern exposures may be more saturated than southern exposures, as indicated in previous studies (Saas 2005). On both aspects, \( \kappa \) values are generally greater below 0°C; this is probably due to the substitution of water by ice in the pore space and fractures of frozen rock (Williams & Smith 1989).

Thermal diffusivity variations caused by snow events and rock wall temperature

Evaluation of the effect of snow events on thermal diffusivity was conducted by choosing some meaningful summer and winter events in the Matterhorn and Aiguille du Midi data series. Using a smoothed (24-hour) thermal diffusivity normalized deviation index \( \kappa_{di} \) (defined as \( \kappa / \kappa_{mean} \)), the temporal evolution of the CCS and ADM thermal diffusivity data series was analysed, considering 3–55cm depths.

In the CCS data series, an intense summer snow event (2nd half of August 2006) was considered. As shown in Figure 4, when the snow index increases, \( \kappa_{di} \) decreases (maximum reduction of about 40% of the mean value) and vice-versa: as the \( S_i \) starts decreasing \( \kappa_{di} \) rises closer to the mean value. During snowy days, shallower rock (-3 cm) temperature crosses above and below 0°C several times, while the deeper one (-55 cm) is closer to zero. In such a condition, phase changes may occur in the active layer: thus the consumption and release of latent heat due to thawing and freezing of percolating water cause the variation in apparent heat capacity. This variation affects \( \kappa \) which is inversely proportional to apparent heat capacity (Mottaghy & Rath 2006). The decrease in thermal diffusivity shown in Figure 4a during snow events is probably linked to water phase changes.

Similar considerations can arise from the observations of thermal diffusivity data series at ADM northern and southern sites (Fig. 5). During the spring-summer period \( \kappa_{di} \) temporal evolution, and the magnitude of its variation during snow events, are similar to what is observed in CCS data series. The southern face shows thermal diffusivity reduction related to snow events starting from the end of March (Fig. 5c); the same behaviour is observed on the northern side (Fig. 5a) only at the end of spring, when rock temperature rises toward 0°C (Fig. 5b), suggesting a possible role played by rock temperature on water availability.

On the other hand, during winter, \( \kappa_{di} \) variations related to snow events show an opposite behaviour: a strong increase in \( \kappa_{di} \) is observed on both faces, with a general higher intensity on the northern one, where a doubling of thermal diffusivity value occurred.

On the southern face, a strong increase of \( \kappa_{di} \) values, comparable to those in the north, occurred at the end of February. During this event, the southern face rock temperature showed values of about -10°C at the depth of 55 cm: a value closer to annual minima and similar to northern face rock temperature in the same period (-13°C). This means that the thermal conditions of the south wall were very similar to those experienced by a northern wall, suggesting, once again, that rock temperature may influence thermal diffusivity variability. However, further investigations are needed in order to understand the reliability of these winter increases.

Figure 3. Distribution of thermal diffusivity values (3–55cm depth interval) below and above 0°C at ADM northern and southern sites.

Figure 4. Comparison between CCS thermal diffusivity deviation index, snow index, and rock temperature.
As outlined in Figure 5d, periods of strong rock wall warming can be followed by thermal diffusivity reductions: \(\kappa_{di}\) variations observed at the end of April on the ADM southern face may have been caused by the previous 10 days of rock temperature above 0°C.

This reduction is more likely related to this rock warming period, rather than to the snow event which occurred during the first days of May, when the \(\kappa_{di}\) reduction had already reached its maximum value. A similar situation can be observed at the end of May. Moreover, on the northern face, a late May \(\kappa_{di}\) reduction occurred when rock temperature was above 0°C (Fig. 5b).

These observations suggest that thermal diffusivity variability may be influenced both by snow events and rock temperature and their interactions. Summer \(\kappa_{di}\) reductions can be explained by an increase in water circulating in the rock heap resulting from snow melting, and from ice-filled discontinuities melting due to warming periods. Winter thermal diffusivity increases, which occur during snow events, appear to be related to cooling intensity rather than to water supply as discussed in Williams & Smith (1989).

**Conclusions and Outlook**

The analysis conducted in this study leads to the following conclusions:

The estimation of thermal diffusivity variability, from rock temperature data measured at different depths, is possible, and the applied methodology gives reliable values. Changes in thermal diffusivity values are influenced by different factors such as depth, season, rock temperature, aspect, and snowfall. Thermal diffusivity variability decreases with
depth, and its mean values in deeper layers are significantly reduced with respect to shallower ones. This should be taken into account when using heat conduction models on the whole rocky heap.

Mean northern $\kappa$ values are lower than southern ones: this difference may be related to the higher degree of saturation experienced by northern exposures. $\kappa$ values are greater below 0°C because of the substitution of water by ice in the pore space and fractures of frozen rock.

Reductions in thermal diffusivity related to snow events were observed both on southern and northern faces during warm periods and are probably linked to water phase changes. Winter thermal diffusivity increases, which occur during snow events, appear to be related to cooling intensity rather than to water supply. Thermal diffusivity variations seem to be related to rock temperature, as well: warming periods may result in strong reductions in $\kappa$ values, likely due to an increase in water circulating in the rock wall.

Such behaviours were observed on both monitoring sites: they, therefore, appear to be independent of system variables such as lithotype, degree of fracturing, and aspect.

In order to test the reliability of these first observations, it is necessary to wait for the results of the PERMAdataROC project: longer data series are needed in order to better understand the behaviour of thermal diffusivity variability.

A first application of computed thermal diffusivity values can be found in energy balance estimation. $\kappa$ values and rock temperature data at different depths allow calculation of heat conduction which, coupled with net radiation measurements, may allow estimation of the ratio of available energy dissipated through turbulent fluxes. This information may be useful in heat conduction modeling.

References


