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Thermal characteristics of mid-latitude high-alpine rockwalls at the Aiguille du Midi (3842 m a.s.l., Mont Blanc massif)

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Introduction

Permafrost degradation has been recently recognized as an essential triggering factor of rock falls/avalanches in high mountains areas. As permafrost in steep rockwalls is presumed highly sensitive to climate forcing, the ongoing global warming would likely impact their frequency and magnitude in the near future. Nevertheless, links between climate, permafrost degradation and rock instabilities are not quantitatively defined and remain misunderstood.

In densely populated areas such as European Alps, risk assessment and geotechnical responses are requiring fundamental understanding of the processes involved. A monitoring network has recently been developed throughout the Alpine range with a growing number of instrumented sites. But because of the difficulty of these *in situ* measurements in harsh and remote areas, statistical and numerical models are important tools to map permafrost distribution and to investigate thermal processes. Located on the French side of the Mont Blanc massif (western European Alps), high-elevated steep rockwalls of the Aiguille du Midi (AdM) have been the first site of such context to be instrumented with 10-m-deep boreholes. This study focuses on the first results of the measurements. It aims to characterize the permafrost at the site, and to discuss the main parameters in relation with our observations.

Site and monitoring system

The Aiguille du Midi area

With its three granitic peaks located on the NW side of the Mont Blanc massif (N45°52'-E6°53'), the AdM has been chosen as a study site for several reasons. First, with its high elevation and with a mean annual air temperatures (MAAT) close to -7.8°C (2007-2011), permafrost occurrence was extremely likely. Then, its topographical settings with varying aspect and slope are representative of the Mont Blanc rockwalls. Some of them have besides displayed a recent and remarkable rockfall activity such as the north side of the Aiguilles de Chamonix which includes the AdM [Ravel & Deline, 2010]. Finally, a cable-car leads to the AdM (half a million of tourists per year), where abseiling is possible for equipment installation, maintenance and data collection.

Instrumentation and monitoring

Two EU-funded projects *PERMAdataROC* (2006-2008) and *PermaNET* (2008-2011) have supported the equipment of the AdM.

Since 2005, a high-resolution DEM of the outer and inner (galleries) rockwalls of the AdM has been realized using terrestrial laser scanning. Between 2007 and 2010, automatic weather stations on the north and south faces of the Piton

Central have recorded air temperature near the rock surface, wind speed and direction, short and long incoming, and outgoing solar radiations. Météo France is also recording air temperature and wind speed and direction at the top of the Piton Central since 2007.

Rock temperatures are monitored by ARPA VdA and University of Zurich since 2005 with near-surface sensors (from 3 to 55 cm; Geoprecision M-Log6, resolution: 0.01°C, accuracy: $\pm 0.05^\circ\text{C}$) on all aspects, and by EDYTEM Lab with 10-m-long chains of 15 thermistors (Stump YSI 44031; resolution: 0.1°C, accuracy: $\pm 0.1^\circ\text{C}$) installed into three boreholes on the NW, NE and SE faces (Table 1) since December 2009 (April 2010 for the NE borehole).

Table 1. The three 10-m-deep boreholes of the AdM

Borehole Code	Elevation (m a.s.l.)	Aspect (°)	Slope angle (°)	MART* (10 m-2011)
ADMNW	3738	345	90	-4.7
ADMSE	3745	135	55	-1.45
ADMNE	3753	50	65	-3.85

*MART: mean annual rock temperature

Five geophysical surveys (Electrical Resistivity Tomography) have also been carried out with the University of Bonn.

Thermal characteristics of the site

Scattered rock temperature data highlight the strong variability of thermal conditions on spatial and on temporal scales.

Spatially, Fig. 1 is displaying the different temperature profiles: NW subsurface temperature is roughly 4 to 5°C colder than the SE one. This difference decreases with depth, and is close to 3°C at 10 m deep. However, the NW profile at around 2.5 m deep is locally distorted and globally cooled. This corresponds to a rock discontinuity pointed out during the drilling.

Temporally, Fig. 1 also shows varying thermal conditions from one year to another at a same location. 2010 was the coldest recorded year since 2007 (MAAT: -9.1°C), and 2011 the warmest one (-6.7°C). SE and NW changing profiles from 2010 to 2011 are in agreement with this climatic parameter. Mean annual temperature was positive at the SE borehole up to 1.4 m deep in 2011, whereas it remained negative during 2010. Active Layer Thicknesses (ALT) on the SE face in 2011 was exceeding the 2010 one for nearly 3 m, reaching up 7.9 m deep in October. A slighter thickening of the active layer has also been observed on the NW borehole: in 2011, the rock thawed on 2.3 m, which is 0.5 m deeper than the previous year.

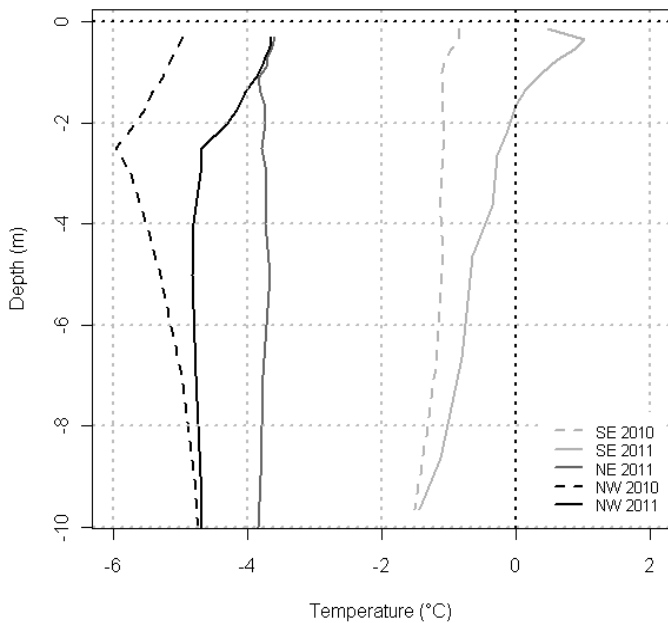


Figure 1. Mean annual temperature profiles at the SE, NW (2010 and 2011), and NE (2011) boreholes.

The NE face is not responding in the same way to the 2011 warm period: its ALT is 0.3 m thinner than in 2010 (3 m deep in 2010). This phenomenon underlines the complexity of thermal behavior of the rock faces controlled by interacting parameters.

Discussion

By comparing boreholes measurements with air temperature data and models outputs, we obtained a qualitative understanding of the interaction of the parameters responsible for observed features.

The warmer profiles in 2011 are illustrating the strong sensitivity of rock faces to climatic signal. Nevertheless, the changing ALT with aspect and time reveal how topography affects the intensity of the signal. Firstly, topography controls the amount of incoming direct radiations. That would explain the temperature and ALT differences in the most exposed to radiation (SE) and shadowed (NW) faces. This phenomenon is also displayed by the recorded maximum temperatures: the 30-cm-deep sensor reached a maximum temperature at least twice warmer on SE than on NW faces: 17.8°C and 8°C in 2011, respectively.

Secondly, the particular response of the NE ALT to the warm summer of 2011 would be induced by a thin snow cover which is partly under topographical control. Indeed, the face is prone to relatively thin snow accumulation, and summer snowfalls could have isolated or cooled the face. The NW near-vertical rockwall, where snow accumulation is only possible on small terraces, is directly controlled by air temperature. The SE face is mainly controlled by direct radiation, and the snow could have melted rapidly. Also, simulated profiles extracted from a 2D numerical model [temperature fields of an horizontal slice of the Piton Central, Noetzli et al., 2011] are

warmer than the observed ones. That suggests a cooling factor likely due to global effect of snow cover. This assumption is strengthened by studies on steep faces showing that thin snow accumulations on complex morphologies can lead to this effect [Pogliotti, 2011].

The distorted NW profile highlights the complexity in the heat transfer processes introduced by rock discontinuities. Heat fluxes calculations indicate a varying impact of the fracture: air ventilation is potentially responsible for cold conditions and remains the most important pattern [Hasler et al. 2011], but heat is temporarily brought during summer, perhaps because of water circulation. This non-linear profile indicates that conductivity is not the unique heat transfer way as it is often assumed in massive rock. It is locally interacting with convective transfers (air ventilation) and heat advection (water circulation).

Conclusion and outlooks

The two years of recorded rock temperatures bring out the characteristics of permafrost in steep rockwalls. Variability of thermal regimes is resulting of interacting parameters. Primarily, the atmosphere-rock interface is controlled by imbrications between climatic and topographical factors which regulate the amount of energy received by rockwalls. For heat transfer, even if thermal conductivity is dominant, lithological settings locally involve air ventilation and heat advection which can affect the global thermal regime. These observations provide a conceptual basis for future model development. A quantitative approach will be further required for parameterization of the simulation including snow cover effect and heat transfer interactions. Measured data on distribution, characteristics and evolution of the snow cover during the winter 2011-12 will be available for the TICOP and will support this quantitative analysis. By using potentialities of these field measurements, 3D models of the AdM site simulating steady-state and transient temperature field will be built in the near future.

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