Ph.D. Florence Magnin
Laboratoire EDYTEM
Université de Savoie
F-73376 Le Bourget du Lac cedex
@ florence.magnin@univ-savoie.fr

8th December 2014

Author's response to reviewers' reports #2

Paper title: Thermal characteristics of permafrost in the steep alpine rock walls of the Aiguille du Midi (Mont Blanc Massif, 3842 m a.s.l.)

Authors: F. Magnin, P. Deline, L. Ravanel, J. Noetzli, P. Pogliotti

Dear Handling Editor: Dr. Tingjun Zhang,

We performed the required changes: we replaced "variability" and "change" by "difference" were we only considered a difference between two years, and we replaced south and north "faces" by "facing slopes". We hope that our paper now satisfies the required standards for a publication in The Cryosphere.

Best regards.

Florence Magnin, on behalf of all the co-authors.

Major concerns:

Latent heat:

The dampening of active layer thickness by latent heat consumption is postulated in the revised version as one of the main new findings (abstract, discussion, conclusions 10). This effect is well known in arctic ice-rich soils but I could not see the empirical evidence (zero curtain, isothermal profil) for this effect being relevant in the present data from steep bedrock.

Authors' reply:

Evidences are indeed not clearly presented in a plot and are not as obvious as in arctic soils. So we restricted this part and mentioned it as a future research direction.

Language:

Regarding terms and language the manuscript still needs improvement. Often I had to read the sentences twice to understand. The sentences could be expressed simpler and straighter to the point. There are several mistakes in grammar and style. Terms and adjectives may be used more accurate. Some of them are mentioned in the Detailed comments. The manuscript clearly needs a second revision regarding the language.

Authors' reply:

For this version, we paid a translator.

Non-conductive heat transfer (former section 6.3):

I think to simply erase this content from the manuscript is a petty. I don't agree that doing an analysis as suggested would go beyond the scope of the paper. Making a profile plot of several points in time of BH_N is a minor effort and would allow seeing (qualitatively; see below) where the fracture acts as a heat sink/source and where it simply causes a step in the temperature profile. (The other suggestion with a heat conduction scheme is a larger effort, I agree)

Authors' reply:

Thank you for explaining your thoughts and for providing an example. What we defined as beyond the scope was the heat conduction scheme. Concerning the profile, we totally agree that this is minor effort, and thanks to your explanation, we better understand your expectations. So, we proposed an additional figure to show and discuss the fracture effect following your proposition. This gives more weight to our observations on the fracture and completes the section 6.3. After this revision, the fracture observations have more importance than latent heat hypothesis.

Interannual variability

A large part of the discussion on "Snow cover and micro-meteorological influence" is focused on the interannual variability. Tree (of ten) conclusions are made on the interannual variability of the MAGST. Given the small evidence presented (without reference to an illustrative figure) to support of these conclusions this strong focus is not justified.

Authors' reply:

All the points that are discussed are at least visible in Figure 4. Taking into account this comment, we restricted the discussions lines in section 5.3. and gathered our main findings in a single conclusion.

I still have problems with the use oft the term "interannual variability": The difference

of 2 years is generalized as interannual variability. Accordingly I can not understand the following answer from the authors to the first review and I don't see how the concerns where considered in the revision:
Reviewer #2: „The term interannual variability of the surface offset needs some explanation for not being confused with interannual variability of the MAGST or MAGT. Interannual variability (or changes) alone is not sufficient in this context. The difference of the means of 2 years should not be called interannual variability. And, can a variability be negative?
Authors' reply: This is true that some explanations would be relevant. In the revised version, interannual variability of SO will be used for data description section (5.1), but in the discussion section (5.3), we explain the meaning of the change in SO in terms of change in MAGST: "On the north face, the higher ASOs at snow-covered sensors (BH_N) compared to at snow-free sensors (N1 and N2) show that the thermo-insulation of snow significantly increases the MAGST. On the south face, the lower ASOs at snow covered sensors (BH_S and S3) compared to snow free conditions (S1 and S2) indicates a lowering of MAGST due to snow." We agree that the means of 2 years should not be called interannual variability. However, in the submitted version, interannual variability is only described and discussed with annual surface offsets that are not averaged, and concerning the seasonal surface offsets (that are averaged over several seasons) we only describe the spatial pattern.

To make clear what I meant: To compute an interannual variability it needs more than two values (SO or MAGST of more than two years).
<u>*Authors' reply:*</u>
Ok, so we better understood what you meant. We paid attention to do not use interannual variability for description of change from year-to-year, and we used "interannual changes" instead.

The spatial pattern of interannual SO variability that you postulate on Line 332–350 are based on one single observation (2011 vs. 2012) according to Line 269–273. I agree with your reasoning, that the effect of insulation and reflection on south slopes COULD result in a reduced interannual variability but the presented examples (Line 269ff) do not clearly show this: E.g. why -0.3°C at E1 is considered as larger interannual variability (or better "difference") whereas +0.3°C at S3 is taken as example for a small variability?
<u>*Authors' reply:*</u>
The paragraph presents different observations: 1. Snow covered sensors on shaded aspect have greater changes that snow covered sensors on sunny aspect, and the different ranges of changes are illustrated through the comparison of S3 with BH_E and BH_N.
2. Snow covered sensors have opposite change/trend (positive versus negative) than snow free sensors: E1 is here presented to illustrate this opposite change as it has a negative trend, but it is not presented as having a large change!
Possibly, this confusion comes from the language and we paid attention with our translator to make all this section clear.

Why interannual variability of the MAGST appears in the conclusions whereas the results and discussion where mainly on the interannual variability of the SO? This two things are not quite the same because of the variations in MAAT. I don not see this being considered in the text.

Authors' reply:

We use SO to discuss surface temperature. We use ASO to discuss MAGST. Interannual changes of MAGST appear in the conclusions because they are discussed in the manuscript (lines 317 to 323; 339ff of the revised version #1), and the discussion section (5.3) is introduced with the key concepts for interpretation of SO in terms of surface temperature changes (line 296ff).

Also, this is true that MAAT variations have to be taken into consideration before any discussion of changes in ASO. This is why we compare sensors based on the same years of records: e.g. we compare BH_E and BH_N to S3 by using the same years of records for all these sensors (2011 and 2012), because their respective SOs were calculated with the same MAAT, so the changes in MAAT do not influence the different changes in SO from one sensor to another. If we would have compared sensors with different years of record (e.g. compare data of S3 in 2008-2009 and BH_S in 2011-2012), the changes in MAAT between these years would have impacted the results and we would not be able to interpret the part of the change due to changes in MAAT.

Please rephrase Lines 269-277 to clearly express the relevant differences and give a comprehensive overview of the "interannual differences" in a figure to demonstrate an empirical evidence for the spatial pattern that you describe. Otherwise restrict this "hypothesis" to a minimum and avoid to state it as empirical finding of the study in three different conclusions.

Authors reply:

Every pattern described in this paragraph is visible in Figure 4, that was designed to enhance the spatial pattern with the 360° axis. Also, as this is visible in Figure 4, and that the text you refer to only describes the data we have, we do not make any hypothesis, but only data description. But to satisfy this remark, we reformulated and restricted this paragraph, and then, verified the english language with our translator.

Detailed comments:

Line 23: "Analysis …" Why plural?

Authors' reply:

Sorry, but we did not understand what you meant. "Analysis" is singular. Analyses is plural. So why plural? It was singular in the abstract. After this second revision, we used plural. If your question was "why not plural", now it is.

Line 24: ",some of them …" rephrase; "them"?, what of the following is demonstrated the first time?

Authors' reply:

We rephrased.

Line 29ff: reference of second part of the sentence is unclear.

Authors' reply:

We rephrased most of the abstract sentences to make sure that it is a correct english, perfectly understandable and that we clear explain our findings.

Line 30: inhibit? not delay or reduce

Authors reply:

We replaced "inhibit" by "reduce".

Line 30ff: Consider general comment on "Latent heat"!

Authors reply:
We did, consider our answer to general comment.

Line 76: These scientific goals overlap with the research questions below. Avoid repetition (The precise research questions addressed here are most relevant). Just mention point tree as additional point and why this article may be relevant for it (describtion of installation and data quality).
Authors reply:
This is important to us to present the goal of our installations. We restricted our presentation of goal (i) and (ii). The goal (iii) makes the transitions with the paper content description.

Line 89–93: Style/grammar: Rephrase questions
Authors reply:
We corrected these questions with our translator.

Line 89 / 92: These two questions could be merged into one.
Authors' reply:
Done.

Line 121: Shift to acknowledgements.
Authors reply:
The authors deeply thought about this demand, but we definitely think that our collaboration and program are better placed in the site description as we do not have any one to acknowledge in these collaborations for this article and that the current work is not supported any more by any of these programs.

Line 205: This local snow accumulation will influence the profiles because
the deeper part is influenced by the surrounding snow-free rock.
How much?
Authors reply:
We had trouble to understand this question but we guess that "because" meant "in spite of". At this level of the article, in the installation description, we are not able to define how much the snow could influence the bedrock temperature at depth, and this question is thus discussed in regard of the data in section 6.3.

Line 230: This is still confusing compared with the statement on Line 218.
The gap is longer but only a part is within the respective year, right?
Authors' reply:
Sorry for this confusion, we reworked the text to make it clear with our translator (in yellow).

Line 231: Why you "felt" so if the effect on the annual mean was so small (see line 228)?
Authors' reply:
The term "felt" is not appropriated. This "feeling" is actually an advice personally communicated from PERMOS people (including some of the co-authors) that usually don't fill gaps > 1.5 months. Then, our gaps >1.5 months are actually interruptions of several months (e.g. S2 in 2008 has 6 months' gap), so we didn't performed any further tests on such long gaps. Anyway, we rephrased the sentence and explained that these choice was based on the standards of the PERMOS network and were personally communicated.

Line 242: "ASO" is a pleonasm if SO is defined such as on Line 235
Authors reply:
True. So we avoided the repetition in the revised version.

Line 266: At S2 the autumn SSO is larger!
Authors reply:
This may be a confusion, if you look at Figure 4, spring SSO is larger at S2.

Line 294: grammar: "micro-meteorological influences"
Authors reply:
Done.

Line 321ff: (i) is not a cooling effect compared with snow-free rock (but a reduced warming effect compared with thick snow cover). Next sentences need to be adapted accordingly.
Authors reply:
According to us, it is shown as a cooling effect because it is colder than the other sensors in same aspect but in snow free conditions. But, taking into account your point of view, this formulation is also conceivable so we followed your comment.

Line 329: Where is this zero-cutain effect visible? Neither in autumn 2010 nor 2011.
Authors reply:
As described by Hanson and Hoelzle, the zero-curtain-effect is partly ascribed to the effect of melting snow. So, what we see at the surface of BH_S (April 2012), BN_N (July 2011) and S3 (April-May 2012), visible in Figure 5, that we describe as a period of constant temperatures close to 0°C in section 5.2, is what we interpret at zero-curtain-effect in section 5.3, based on literature.

Line 337: grammar: "from one aspect"
Authors reply:
Done.

Line 341: style: "poorly"?
Authors reply:
We rephrased.

Line 363: style: "max. ALT occurred in…"; for BH_S it is problematic to make such a statement due to the missing data
Authors reply:
We reformulated in order to avoid confusions.

Line 389: I can not see how Table 3 supports this statement! MAAT and MART show different evolutions.
Authors reply:
We added an example to show how Table 3 support the fact that T(z) profiles follow MAAT signal.

Line 395–398: Rephrase sentence!
Authors reply:
According to our translator, the sentence was perfectly clear, but it made some minor correction (e.g. turned "deep" into "depth".

Line 405: temperature gradient can not be correct "–0.2°C/m" ?
Authors reply:
True!! It is been corrected: -0.02°C.m^{-1}

Line 423ff: "In bedrock…": Sentence contradicts content below! "any specific thickening…": no thickening? Be precise which study states what!
Authors reply:
We rephrased to avoid such confusions.

Line 433: Daily SO! This is new data that is not shown anywhere! This makes this paragraph not retractable. What is the main message and where can we see that?
Authors reply:
This is true that it is not visible here. This would have involved a specific figure that would have required a long description and introduction of other dataset non presented here (precipitations). We restricted this part of the argumentation, as this is a project for future research, and we rather proposed the effect of summer snow fall as an hypothesis to validate with further investigations to understand the here presented anomaly (reduction of ALT in only one borehole).

Line 442: where can we see the "isothermal conditions"? Compare comment Line 329.
Authors' reply:
In Figure 6, so we added reference to this figure in the revised version and we extended the sentence to make it clearer.

Line 449: grammar: "temperatures"
Authors' reply:
Done.

Line 450: grammar: "smoother"
Authors' reply:
Done

Line 454: Style: What means "usually greater"? Better: "According to a modelling study…"
Authors' reply:
We modified following this proposition.

Line 456ff: I can not see an empirical evidence for the reasoning presented.
Latter refreezing with larger ALT is a simple result of heat conduction. The freezing in figure 6 BH_S looks quite linear. Detailed data is not presented.
Authors' reply:
Similarly to the detailed comment on line 433, we restricted this part of the argumentation as this is not a major issue and that will be part of our future research directions.

Line 472: Logic: "MAAT changes up to 10m depth"?
Authors' reply:
We modified the sentence to avoid such confusion.

Line 473–476: Interesting! Where this is shown?

<u>Authors' reply:</u>
The pattern described (warming above the fracture an cooling below compared to the previous year) is visible in Figure 7, and the coherence of the upper layer with MAAT signal is visible in Table 3. We referred to these figure and table in the second revision.

Line 483: Inflection in the range of measurement error?
<u>Authors' reply:</u>
Yes, so we removed that sentence.

Line 496 and 503: Style: "deep temperatures"? Borehole temperatures?
<u>Authors' reply:</u>
Yes, we replaced with "borehole temperatures"

Line 568: Correct typographical inconsistences.
<u>Authors' reply:</u>
We reviewed all the bibliography.

Line 600: Gruber AND Haeberli.
<u>Authors' reply:</u>
Done.

Line 757: "depth" instead of "deep",
<u>Authors' reply:</u>
We didn't find where this was referring to, but we corrected our figure captions with our translator in Figure 4 and 5.

Line 761: "depth" instead of "deep", AT is missing in caption
<u>Authors' reply:</u>
We didn't find where this was referring to, but we corrected our figure captions with our translator in Figure 4 and 5.

Thermal characteristics of permafrost in the steep alpine rock walls of the Aiguille du Midi (Mont Blanc Massif, 3842 m a.s.l)

F. Magnin[1], P. Deline[1], L. Ravanel[1], J. Noetzli[2], P. Pogliotti[3]

[1]{EDYTEM Lab, Université de Savoie, CNRS, Le Bourget-du-Lac, France}

[2]{Glaciology and Geomorphodynamics Group, Department of Geography, University of Zurich, Zurich, Switzerland}

[3]{ARPA Valle d'Aosta, Saint-Christophe, Italy}

Correspondence to:

F. Magnin (florence.magnin@univ-savoie.fr)

P. Deline (philip.deline@univ-savoie.fr)

L. Ravanel (ludovic.ravanel@univ-savoie.fr)

J. Noetzli (jeannette.noetzli@geo.uzh.ch)

P. Pogliotti (paolo.pogliotti@gmail.com)

Abstract

Permafrost and related thermo-hydro-mechanical processes are thought to influence high alpine rock wall stability, but a lack of field measurements means that the characteristics and processes of rock wall permafrost are poorly understood. To help remedy this situation, in 2005 work began to install a monitoring system at the Aiguille du Midi (3842 m a.s.l). This paper presents temperature records from nine surface sensors (eight years of records) and three 10-m-deep boreholes (four years of records), installed at locations with different surface and bedrock characteristics. ~~Analysis~~ In line with ~~of the temperature data confirms~~ previous studies, ~~,~~ our temperature data analyses showed that~~some of them being demonstrated empirically for the first time~~: micro-meteorology controls the surface temperature, active layer thicknesses are directly related to aspect and ranged from <2 m to nearly 6 m~~, warm and cold permafrost (about –1.5°C to –4.5°C at 10-m-depth) coexists within the Aiguille du Midi, resulting in high lateral heat fluxes~~, and that thin accumulations of snow and open fractures are cooling factors. Thermal profiles empirically demonstrated the coexistence within a single rock peak of warm and cold permafrost (about –1.5°C to –4.5°C at 10-m-depth) and the resulting lateral heat fluxes.~~Some observations extent~~ Our results also extended ~~existing~~current knowledge of the effect of snow, in that~~is extended~~ we found similar -thermo-insulation effects as reported for gentle mountain areas. Thick snow warms shaded areas,~~ that globally cools the rock surface,~~ and may reduce~~s~~ active layer refreezing in winter and delay~~s~~ its thawing in summer. However, thick snow thermo-insulation has little effect compared to the high albedo of snow which leads to cooler conditions at the rock surface in areas exposed to the sun.~~ Latent heat consumption due to interstitial water phase changes in bedrock discontinuities possibly dampens the active layer and permafrost changes~~ A consistent inflection in the thermal profiles reflected the cooling effect of an open fracture in the bedrock, which appeared to act as a thermal cutoff in the sub-surface thermal regime. Our field data are the first to be obtained from an Alpine permafrost site where borehole temperatures are below –4°C, and represent a first step towards the development of strategies to investigate poorly known aspects in steep bedrock permafrost such as the effects of snow cover and fractures.

1 Introduction

The last few decades have seen an increase in rockfall activity from steep, high-altitude rock walls in the Mont Blanc Massif (Western European Alps) (Ravanel and Deline, 2010; Deline et al., 2012). Several studies of recent rock avalanches and rockfalls in mid-latitude alpine ranges have ascribed such increases to climate-related permafrost degradation (Deline, 2001; Gruber et al., 2004a; Huggel et al., 2005; Fischer et al., 2006; Huggel et al., 2008; Allen et al., 2009; Ravanel et al., 2010, 2012; Deline et al., 2011). Rockfall magnitude and frequency are thought to be linked to the timing and depth of permafrost degradation, which can range from a seasonal deepening of the active layer to long-term, deep-seated warming in response to a climate signal (Gruber and Haeberli, 2007). Local warming of cold permafrost may be induced by advection and the related erosion of cleft ice (Hasler et al., 2011b), which can lead to unexpected bedrock failures. As Krautblatter et al. (2011) noted, before being able to predict permafrost-related hazards, it is necessary to develop a better understanding of the thermo-hydro-mechanical processes involved, which means collecting rock temperature measurements and developing modeling strategies.

Measurement strategies and numerical experiments have been used to investigate the thermal conditions and characteristics of near-vertical and virtually snow-free alpine rock walls that are directly coupled with the atmosphere (Gruber et al., 2003; 2004b, Noetzli et al., 2007). These studies have shown the domination of topographical controls on steep bedrock permafrost distribution, with a typical surface temperature difference of 7-8°C between south and north--facing slopeses, the possible coexistence of warm and cold permafrost in a single rock mass, and lateral heat fluxes within the rock mass inducing near-vertical isotherms. Hasler et al. (2011a) suggested that, both thin accumulations of snow on micro-reliefs and cleft ventilation may cause deviations of 1°C (shady faces) to 3°C (sunny faces) compared with the smooth, snow-free rock wall model test cases. The thermal influence of snow on steep rock faces has been addressed *via* numerical experiments (Pogliotti, 2011), which have shown that the effect of snow is highly variable and depends on topography, and the depth and timing of the accumulation. However, few empirical data are available to evaluate numerical experiments. Recent advances in the study of steep alpine rock walls have helped to build bridges between what is known about the general characteristics of permafrost and processes related to the microtopography and internal structure of rock masses, which may be significant in their short-term evolution and in permafrost distribution. However, a much larger corpus of field observations and monitoring data for a variety of bedrock conditions is needed to develop, calibrate, and evaluate reliable models.

As part of our research into geomorphic activity in the Mont Blanc Massif, in 2005 we started a long-term permafrost-monitoring program at the Aiguille du Midi (AdM), currently the highest instrumented bedrock permafrost site in the European Alps (3842 m a.s.l). This monitoring program was designed to ~~meet three scientific goals:~~

characterize ~~the surface temperature of high-alpine steep rock walls;~~and

determine the thermal state of the permafrost and ~~analyze the variability of~~ active layer~~and deep temperature;~~, and to

collect temperature data under variable snow-cover and structural conditions that could be used to calibrate and validate high-resolution numerical experiments on permafrost thermal processes.

In this paper we ~~paper addresses goals (i) and (ii). It~~ describe the monitoring program at the AdM, and present temperature data from nine surface mini-loggers and three 10-meter-deep boreholes. Due to the morphology of the AdM, the monitoring network is concentrated in a very small area; however the data obtained allowed us to address the following questions:

- How much ~~is~~ of the surface temperature variability over this small area is due to topography ~~in a so small area~~and snow cover?

~~- How much can be the thermal effect of snow cover on surface temperature in steep rock walls?~~

- How much ~~is~~ of the variability ~~of~~ in the active layer is due to the topography ~~in~~ of the steep rock walls?

- What are the thermal effects of snow and fractures on sub-surface temperatures at the AdM?

We used eight years of surface records and four years of borehole to analyze seasonal and annual variations in temperature patterns, in the active layer, and in the permafrost thermal regime. We discuss our results in the light of previous research and provide new empirical evidence for the effects of snow and fractures on permafrost in steep rock walls.

2 Study site

The AdM lies on the NW side of the Mont Blanc Massif (Fig. 1). Its summit (45.88° N, 6.89°E) consists of three granite peaks (Piton Nord, Piton Central, and Piton Sud) and culminates at 3842 m a.s.l. The steep and partly glaciated north and west--facing slopeses of the AdM tower more than 1000 m above the Glacier des Pélerins and Glacier des Bossons, while its south-–facing slopee rises just 250 m above the Glacier du Géant (i.e., the accumulation zone of the Mer de Glace). This part of the Mont Blanc Massif is formed by an inclusion-rich, porphyritic granite and is bounded by a wide shear zone. A main, N 40°E fault network intersected by a secondary network determines the distribution of the main granite spurs and gullies (Leloup et al., 2005). The highest parts of the peak tend to be steep, contain few large fractures, and, in places, are characterized by vertical foliation bands and small fissures. The lower parts are less steep and more fractured. In the present paper we use the abbreviation AdM to refer only to the upper section of the Piton Central, between 3740 and 3842 m a.s.l. where most of the instruments are installed. A tourist cable car runs from Chamonix to the Piton Nord. Galleries and an elevator allow visitors to gain the viewing platform on top of the Piton Central, from where there is a 360° panorama of the Mont Blanc Massif.

We chose the AdM as a monitoring site for the following scientific and logistical reasons: (i) permafrost is extremely likely due to the AdM's high altitude and the presence of cold-based hanging glaciers on its north-–facing slopee; (ii) the morphology of the peak offers a range of aspects, slope angles, and fracture densities that are representative of many other rock walls in the massif; (iii) the easy access by cable-car from Chamonix and the availability of services (e.g., electricity) at the summit station. Monitoring equipment was installed as part of the *PERMAdataROC* (2006–2008) and *PermaNET* (2008–2011) projects, funded by the European Union and run jointly by EDYTEM Lab (France), ARPA VdA (Italy), and the Universities of Zurich (Switzerland), Bonn, and Munich (Germany). As such, it complements other rock wall observation sites, for example, those within the Swiss Permafrost Monitoring Network (PERMOS).

Data from the monitoring equipment on the AdM was completed by data from ARPA VdA's weather stations, which measured air temperature and relative humidity, incoming and outgoing shortwave and longwave solar radiation, wind speed, and wind direction on the south and north--facing slopeses between 2006 and 2010. Electrical Resistivity Tomography (ERT) and Induced Polarization (IP) have been measured since 2008 in conjunction with the

Universities of Bonn and Munich. High-resolution (cm-scale) triangulated irregular networks (TIN) of rock walls and galleries of the AdM were obtained from terrestrial laser scanning. In July 2012, six crack-meters equipped with wireless sensors were installed in major fractures in the Piton Central and Piton Nord in order to complement existing studies of cleft dilatations and shearing movements in rock wall permafrost, to check the stability of the AdM and to test an early warning system. Finally, two GPR surveys were performed along vertical transects in 2013 and 2014. Not all of these data were used in the present study but they will contribute to future research.

3 Data collection methods

3.1 Rock temperature monitoring

The present study was based on rock surface temperatures taken at the top of the AdM (between 3815 and 3825 m a.s.l.; Fig. 2) since 2005 by a network of mini-loggers (GeoPrecision PT1000 sensors, accuracy ±0.1°C) installed by the University of Zurich and ARPA VdA. Two loggers were installed in snow free locations on each face of the AdM (Table 1). The south-facing slopee has an additional logger (S3) installed just above a small ledge on which snow accumulates in winter, covering the logger. The loggers record the temperature every hour at depths of 0.03, 0.30, and 0.55 m, in line with the method described by Gruber et al. (2003).

In September 2009, three boreholes were drilled in the lower section of the Piton Central, at between 3738 and 3753 m a.s.l.

In order to minimize possible thermal disturbances caused by air ventilation in the galleries and heating from staff rooms, the boreholes were drilled several tens of meters below the galleries running through the AdM. The criteria used to decide the exact location of each borehole were the aspect, fracturing, roughness, and angle of the rock wall (Fig. 2). Each borehole was drilled perpendicular to the rock surface and to a depth of 11 meters. Borehole depths were constrained by the drilling equipment and the funding available. The boreholes on the northeast (BH_E) and south- (BH_S) facing (BH_S) slopeses were drilled in fractured rock walls that slope at 65° and 55°, respectively. Even on rock walls at these angles, snow can accumulate on the micro-reliefs in the face. The borehole on the northwest-facing slopee

(BH_N) was drilled in a vertical, unfractured wall. The only place that snow can accumulate on this wall is on small ledges such as the one above which BH_N was drilled.

The boreholes were drilled between September 14th and September 27th, 2009 by a team of five people (two mountain guides, plus three members of the EDYTEM Lab) who had to contend with very variable weather and challenging logistics. For each borehole it was necessary to: (i) install a safety line for the workers, (ii) set up a rope system to carry the equipment from the galleries to the drill site, (iii) install a work platform for the three drillers, (iv) anchor a base on which to fix a rack way, (v) drill the hole using a 380-V Weka Diamond-Core DK 22 electric drill, (vi) insert into the hole a polyethylene PE100 tube (outer diameter: 40 mm; inner diameter: 29 mm) sealed at its bottom, and (vii) remove the work platform. In addition to the difficult environment and harsh weather, the drilling work was complicated by the heterogeneity and hardness of the granite, which took a heavy toll on the equipment (11 diamond heads worn out or broken, a dozen steel tubes damaged, and a motor broken). At first we tried to drill 46-mm-diameter boreholes but we had to increase the diameter to 66 mm so we could use a more robust pipe string. Cooling required 1 to 3 m^3 of water per day, which was carried up from Chamonix in 1-m^3-tanks via the cable car. Space between the drill hole and the casing was not filled.

The three boreholes were fitted with 10-m-long Stump thermistor chains, each with 15-nodes (YSI 44031 sensors, accuracy ±0.1°C) arranged along a 6-mm fiberglass rod. Following calibration at 0°C in an ice-water basin, the sensors were inserted in BH_S and BH_N in December 2009 and in BH_E in April 2010 (Fig. 3). In order to prevent heat convection, each sensor was separated from the others on the chain by insulating foam. The boreholes were closed at the top, but the chains can be removed to check for thermistor drift. Rock temperatures at depths between 0.3 and 10 m are recorded every three hours (Table 1). Because BH_S is shallower than 10 m, the thermistor chain protrudes from the rock surface by 36 cm. Temperature comparisons between BH_S and BH_N/BH_E were carried out at the closest equivalent depths (*e.g.*, temperatures at a depth of 2.64 m in BH_S were compared with temperatures at a depth of 2.5 m in BH_E and BH_N).

3.2 Air temperature and snow cover measurements

In order to aid interpretation of the rock temperature data, we collated air temperature data (AT, Table 1) collected by Météo France at a station 3 m above the top of the Piton Central

(3845 m a.s.l.) since 2007. Data prior to 2007 (1989–2006) are very fragmented due to insufficient equipment maintenance and are not used in this study.

Two automatic cameras have taken six pictures per day of the south and northeast borehole sites since January 2012. In addition, five graduated stakes were placed around each borehole in order to evaluate the spatial variability of snow accumulation from the photographs. Visual analysis of the photos taken during the winters of 2012 and 2013 showed a thick spatially homogeneous snow cover (>1m), which lasted until late spring at BH_S, and a thin (<0.5 m) spatially variable snow cover at the BH_E, where the rock face is much steeper and more complex (Table 1). Snow accumulations at BH_N and S3 were estimated from field observations. Accumulations of snow at BH_N were restricted to the relatively large ledge above which the borehole is drilled. This snow patch was over 1-m-thick for most of the year. S3 is also frequently covered by >0.5 m of snow, which accumulates during winter and spring on the small ledge above the sensor. Snow depth is more variable at S3 than at BH_N because the intense solar radiation at S3 leads to more frequent melting.

4 Dataset preparation

The borehole time series were all continuous except for short periods for BH_S, as this logger was removed from September 2012 to January 2013 and from October 2013 to January 2014 to prevent it being damaged by engineering work close to the borehole. Gaps in the 0.3-m temperature and AT time series were filled in so we could calculate seasonal and annual means (cf. Table 2). First, we calculated daily means from rock temperature time series for days with complete records. Then, we filled short gaps (<5 days) by linear interpolation between the nearest available data points for the same depth. Longer gaps (up to 1.5 month) were filled by replacing missing data with the average value for the 30 days before and 30 days after the gap (cf. Hasler et al., 2011a). To fill the longest gaps for E1, N1, S1, and W1 (from December 4th, 2007 to February 7th, 2008) we used a third approach that involved applying a linear regression equation, fitted using data from each pair of loggers (e.g., E2 and E1) and records for the missing periods (*i.e.*, December-February) from groups of years with complete records (2006–2007 and 2008–2009). Correlation coefficients for the equations ranged from 0.89 (S1 and S2) to 0.94 (E1 and E2). We tested this approach by simulating corresponding gap periods in the years with complete data and then filling these gaps using the regression equations. Differences between the annual means obtained using this method and the annual means calculated from the complete data set were in the range 0.01-0.15°C and can be considered negligible. Our calculations of seasonal means did not include data obtained using the 30-day average or linear regression methods. The longest gap we filled in any one year was <1.5 months, in line with standard practice for the PERMOS network (personal communication).We did not fill gaps longer than 1.5 month per year because we felt that the resulting data would not be reliable enough to give realistic annual means.

5 Rock surface temperature

Smith and Riseborough (2002) defined Surface Offset (SO) as the difference between local Mean Annual aAir tTemperature (MAAT) and Mean Annual gGround sSurface tTemperature. (MAGST). SO is a parameter in the TTOP model (Temperature at the Top of Permafrost, Smith and Riseborough, 1996), originally developed to define the functional relation between air and ground temperatures in polar lowlands and later applied to high-latitude mountainous terrain (Juliussen and Humlum, 2007). SO can be used to quantify the overall effect of ground cover and ground surface parameters on the surface energy balance.

We calculated annual SOs (ASO), using Mean Aannual Air Temperature (MAAT)means and Mean Annual Ground Surface Temperature (MAGST),, and seasonal SOs (SSO) using from seasonal means for winter of rock surface and air temperature of the season for winter (December to February), spring (from March to May), summer (from June to August), and fall (from September to November), using time series measured at depths of 0.3-m (boreholes and E2, S2, W2, N2) and 0.1-m (E1, S1, W1, N1) - points we considered representative of surface conditions. We applied a standard lapse rate of 0.006°C.m^{-1} to air temperatures in order to balance the elevation difference between the Météo France station and the sensors. Figure 4 shows ASOs for all the complete years (Fig. 4A), SSOs for snow-free sensors for the available seasons (Fig. 4B), and SSOs for snow-covered sensors for the available seasons (Fig. 4C). We also analyzed daily temperature records for the snow covered sensors and air temperature trends as part of our investigation of the effect of snow cover on snow temperatures (Fig. 5).

5.1 Surface Offset patterns

Maximum and minimum ASOs were 9.3°C at S1 in 2011, and 1.3°C at N1 in 2009 (Fig. 4A). These are typical values for the Alps (PERMOS, 2013). On the south-–facing slopee, the snow-covered sensors gave lower values than the snow-free sensors. For example, the ASOs for S3 were between 0.1°C (2010) and 1.4°C (2011) lower than the ASOs for S1. Conversely, on the north side, the snow-covered sensor gave higher ASOs than the snow-free sensors. On a seasonal timescale, the maximum SSOs occurred in summer for the snow-free sensors (Fig. 4B), except for the sensors on the south-facing slope (S1 and S2), where the maximum SSOs occurred in spring, with values >10°C. The lowest SSOs were recorded in winter, and ranged from approximately 8°C on the south-facing slope to <1°C on the north-facing slope (N1 and N2). SSO patterns for the snow-covered sensors (Fig. 4C) were opposite to those for the snow-free sensors, except for BH_E. At BH_N and BH_S, SSOs were largest in winter (4.1°C and 9.5°C, respectively) and lowest in summer. At S3, the largest SSO was in the fall. Fall SSOs were also relatively high at BH_N and BH_S. In contrast to SSOs at other snow-covered sensors, SSOs at BH_E followed a similar pattern to that recorded at the snow-free sensors, in that SSO values were directly related to insolation duration.

From 2011 to 2012, the changes in ASO at snow-covered and shady sensors such as BH_E and BH_N were greater (+1.1°C) than they were at the snow-covered and south-facing sensors (only +0.3°C at S3). Conversely to the snow-covered sensors, the ASO decreased at the snow-free sensors from 2011 to 2012, with, for example, values of -1°C at S2 and -0.3°C at E1. The maximum and minimum ASOs for the different snow-free sensors varied with aspect, with, for example, maximum ASOs in 2008 at W1 and W2, but in 2011 at S1 and S2.

5.2 Daily temperatures at snow-covered sensors

Daily temperature curves for the snow-covered sensors are smoothed compared to air temperature oscillation during cold periods (Fig. 5). The S3 and BH_S temperature curves were strongly smoothed from mid-November 2010 to January (BH_S) or April 2011 (gap for S3), and from early December 2011 to mid-May 2012. Both sensors recorded a period of almost constant 0°C conditions from April to mid-May 2012. The temperature curve for BH_N was strongly smoothed until the summer, with a similar constant 0°C period for three weeks in July 2011. Although the BH_E temperature curve from late September to February-March was mostly smoother than daily air temperature curve, the two curves were more closely coupled than they were at the other sensors, as the oscillations in temperatures at BH_E were in-synch with major changes in AT, such as the large drop in temperature in December 2012. From September 2010 to March 2011 and from November 2011 to February 2012, the temperatures recorded at BH_E were lower than those recorded at BH_N.

5.3 Snow cover and micro-meteorological influences

Normally on steep, snow-free bedrock in the high mountains, the MAGST is higher than MAAT, mainly because of direct solar radiation (Gruber et al. 2004b) but also due to a contribution from reflected solar radiation from large, bright glacier surfaces below measurement points (PERMOS, 2013). In the European Alps, the ASO can be up to 10°C on south-facing rock walls, whereas the maximum ASO values recorded on steep rock walls in Norway are only 3°C, as there is less direct solar radiation at higher latitudes (Hipp et al., 2014). In New Zealand, at similar latitude to the Alps, Allen et al. (2009) reported a maximum ASO value of 6.7°C. This lower value is probably the result of reduced direct solar radiation due to the influence of the oceanic climate and related frequent cloud cover. Most of the surface sensors used in the above studies were installed in snow-free conditions in order to test energy balance models (Gruber et al., 2004b) or for statistical fitting (Allen et al., 2009, Boeckli et al., 2012). At the AdM, the ASO patterns of snow-covered sensors at snow-covered sensors differed from those at snow-free sensors, mainly due to decoupling from atmospheric conditions during the winter season and the lower surface albedo of the snow-free sensors.

The differences in ASOs between snow-covered and snow-free sensors on similar aspects show that snow has a substantial effect on the annual energy balance. According to empirical and numerical studies (Hanson and Hoelzle, 2004; Luetschg et al., 2008), snow cover must be at least 0.6-0.8-m-thick to insulate the rock surface from the air temperature, but snow cover on steep rock walls is usually thinner than this insulating threshold (Gruber and Haeberli, 2009). The differences between BH_N and BH_E in terms of ASOs and SSOs can probably be ascribed to variations in mean snow cover thickness (Table 1), and demonstrate that the insulating effect of snow can occur locally also in steep rock walls. On the north~~- face~~facing slope, ASOs were higher at snow-covered sensors (BH_N) than at snow-free sensors (N1 and N2), showing that thermo-insulation by snow significantly increases the MAGST. On the south~~- face~~facing slope, ASOs were lower at the snow-covered sensors (BH_S and S3) than at the snow-free sensors (S1 and S2), indicating that snow lowers the MAGST. This reduced warming effect could result from the combination of (i) thin snow cover with negligible thermo-insulation, (ii) a higher surface albedo, (iii) and melt energy consumption (Harris and Corte, 1992; Pogliotti, 2011). The latter two factors seem to be prevalent at the AdM because snow cover on the south-~~-~~facing slope~~e~~ is often greater than 1-m-thick during winter (sect 3.2) leading to a marked smoothing of daily temperature oscillations (Fig. 5). These results extend previous studies on thin snow accumulations (Hasler et al. 2011a). The importance of this reduced warming effect on sunny faces is probably reinforced by the fact that snow is present for much of the year at such altitudes, as suggested by (i) the high fall SSOs (early snow accumulation) for snow-covered sensors, (ii) their low summer SSOs, and (iii) by the nearly-constant temperature close to 0°C in late summer (Fig. 5). This constant 0°C temperature may reflect the zero-curtain effect, which results in the snow melting and retards the thawing of the active layer, as has been described for snow-covered gentle mountain slopes (e.g. Hanson and Hoelzle, 2004; Gubler et al., 2011).

~~Different~~ Various interannual ~~changes~~ differences were recorded at snow-covered and snow-free sensors. The PERMOS study (2013) has reported analogous ~~differences~~ variability in interannual ~~variability~~ differences between rock walls and gentle snow-covered terrain. Interannual ~~changes~~ differences at the snow-free sensors were mainly related to differences in insolation due to cloud cover. It may be that ~~differences~~ variability in interannual ~~changes~~ differences from one aspect to another are also due to variations in cloud formation from year-to-year. Energy balance models have shown that convective cloud formation can cause differences in the spatial distribution of MAGST over a single rock peak (Noetzli et al., 2007). ~~The difference in the spatial distribution of MAGST over a same rock peak due to the effect of convective cloud formations was already shown by energy balance models (Noetzli et al., 2007), but the evolution of these differences through time with the micro-meteorological control was poorly explored.~~ On shady faces, the effect of solar radiation control is greatly reduced and snow cover may be the most important factor affecting interannual ~~changes~~differences. Consequently, the temperature at a snow-covered sensor can increase from one year to the next if snow insulation from the atmospheric temperature increases, while the temperature at a snow-free sensor may drop due to reduced insolation. In the case of sun-exposed and snow-covered sensors, such as S3, the balance between warming and cooling effects leads to smaller interannual ASO ~~changes~~ differences than at sensors in shadier locations, where temperature are mostly controlled by the warming effect of snow insulation. Thus, the influence of snow cover on the surface temperature of high-altitude rock walls is a due to a combination of topography, snow depth, and micro-meteorology.

6 Borehole records

Four years of data from the three boreholes allowed us to describe daily temperature patterns (Fig. 6), mean annual Temperature-Depth (T(z)) profiles, and annual temperature envelopes (*i.e.*, the maximum and minimum daily temperatures at each depth in 2011; Fig. 7). We focused on the active layer and the permafrost thermal regime, paying special attention to thermal effects related to snow cover and bedrock structure. We discuss their possible influence on the active layer and bedrock thermal regime.

6.1 Active layer

Active Layer Thickness (ALT) varied with aspect, with means of ca. 3 m at BH_E, 5.5 m at BH_S, and 2.2 m at BH_N (Fig. 6). Interannual variability during the monitoring period was ca. 0.7 m for each borehole (Table 3). Maximum ALTs occurred in 2012 at BH_N (2.5 m deep~~), ~~) and in 2013 at BH_E (3.4 m deep). ~~, and in 2011 for BH_S (5.9 m deep; however, there are no relevant data for 2012).~~ At BH_S, data are missing for 2012 and 2013, but 2010 and 2011 data show a maximum ALT in 2011 of 5.9 m.

The length of the thawing period, marked by continuous positive temperatures at the uppermost thermistor, also varied according to aspect. It was longest at BH_S, starting in June (April in 2011), but with isolated thawing days already in March (e.g., in 2012). In general, the surface at BH_S refroze in October, but total refreezing of the active layer did not occur until December in 2010 and 2011. The 2011–2012 freezing period was particularly mild and short (3–4 months) at BH_S. This pattern was not as marked at BH_E, which even recorded its lowest surface temperature in 2011–2012. BH_N had the longest freezing periods because temperatures in the rock sub-surface remained positive only from June to October. In 2011, thawing did not start until August. BH_E had the most balanced thawing and freezing periods (ca. 6 months each).

The timing of maximum ALT depended on aspect and year (Table 3). In 2010 and 2011, maximum ALT occurred earliest at BH_E, even though the active layer was thicker at BH_E than at BH_N. In 2012 and 2013, BH_N was the first site to reach maximum ALT. In 2010, maximum ALT at BH_S occurred very late, three months after BH_E. Although the BH_S active layer had mostly thawed by mid-July, thawing continued steadily until the end of

October. Maximum ALT always occurred later at BH_S than at the other boreholes, but the lowering of the 0°C isotherm was more linear.

6.2 Thermal regime

Annual Temperature-Depth T(z) profiles (Fig. 7A) revealed different thermal regimes. The AdM's Piton Central has both warm (ca. –1.5°C at BH_S) and cold (ca. –4.5°C at BH_N) permafrost (Table 3). Interannual changes were not similar in every borehole. In BH_N and BH_E, the changes over 2010-2013 generally followed the changes in MAAT all along the T(z) profiles. For example, the T(z) profiles show considerable warming from 2010 to 2011 in response to the 2.3°C rise in MAAT (Table 3). The BH_N T(z) profile in 2011 was significantly warmer than in other years for depths up to 2.5 m; however it was colder than 2012 for depths greater than 3 m and colder than 2013 for depths greater than 7 m. In BH_S, the mean annual T(z) profile for 2011 showed remarkably high temperature near the surface with positive temperatures up to a depth of 1 m. Temperatures were higher than in 2010 for the shallowest 6 m of the profile but slightly lower than in 2010 below this depth.

The zero annual amplitude depth is >10 m for every borehole (Fig. 7B), which is consistent with other bedrock sites in the European Alps (PERMOS, 2007). In 2011, the largest amplitudes in daily temperature (peak to peak) at the surface (>20°C) and at 10 m depth (1.6°C) were at BH_E, and the smallest surface (15.5°C) and 10-m (1.0°C) amplitudes were at BH_N and BH_S, respectively. In line with the surface pattern, the minimum T(z) profile from the surface to 1.4-m depth was warmer at BH_N than at the sunnier BH_E (Fig. 7B).

The minimum and mean annual T(z) profiles for BH_N contain two distinct sections separated by an inflection at ca. 2.5 m deep (Fig. 7A). This coincides with an 8–10 cm-wide cleft encountered at this depth during the drilling operation. The temperature gradient is negative (–0.39°C m^{-1}) from the surface to the cleft, and then positive from the cleft to 10-m-deep (from 0.16°C m^{-1} to nearly isothermal). The mean annual profiles for BH_E are almost linear and have a temperature gradient of ca. –0.02°C m^{-1}. Small inflections in the profiles (e.g., at 1.1 m, 2.5 m, and 7 m depth) occur every year. In the case of BH_S, the upper parts of the annual T(z) profiles for 2010 and 2011 differ greatly, with an almost linear temperature gradient of –0.07°C m^{-1} in 2010, and a much steeper overall temperature gradient of -2.26°C m^{-1} in 2011.

6.3 Snow cover and bedrock discontinuity controls

The coexistence of warm and cold permafrost, and the opposite temperature gradients at BH_S and BH_N, probably due to lateral heat fluxes, are in accordance with the results of numerical simulations (Noetzli et al. 2007).

In terms of the permafrost thermal regime, the values recorded at BH_N were below -4°C, which is a value typical for high latitude monitoring sites, such as those in Svalbard (Noetzli et al., 2014a), and the warmest boreholes of the continuous permafrost zone in Alaska (Romanovsky et al., 2014).

The spatial and temporal variability of ALT is consistent with values reported for Swiss boreholes in bedrock (PERMOS, 2013). For example, the thickness and timing of the ALT in BH_E are similar to those recorded at the Matterhorn-Hörnligrat site (3295 m a.s.l, vertical borehole on a crest), with values ranging from 2.89 to 3.66 m between 2008 and 2010, and with maximum ALT occurring between early September and early October. Early studies considered that ~~I~~in bedrock slopes, changes in ALT ~~seem~~ are strongly controlled by summer air temperature, as indicated by the ALT at Schilthorn (2909 m a.s.l) which was twice as thick as usual (from 4-5 m to > 8 m) ~~. D~~during the hot summer of 2003 ~~for instance, the ALT at Schilthorn (2909 m a.s.l) has been deepened by twice~~, while there was no unusual increase in the ALT under the debris-covered slopes, such as Les Gentianes moraine and the Arolla scree slopes, located in the same area and at similar altitude (PERMOS, 2013).

The different patterns of ALT variability at the three AdM boreholes (Table 3) suggest that the air temperature is not the only controlling factor. ~~The thinning of BH_E active layer in 2011 in contrast with other two boreholes may be ascribed to the cooling effect of a summer snow fall, but the cameras and snow probes were not installed yet (sect. 3.2) to check this hypothesis. However, a significant drop in daily SO at BH_E occurred just after three precipitation episodes (in August, the 26th, and in September, the 3rd-4th and 16th-19th), which supports this hypothesis but is hardly visible on a plot. These events occurred just before BH_N maximum ALT in 2011 (Table 3). Daily SO generally decreased at BH_S just after the precipitation events, and then, rapidly increased. The snow fall would have rapidly melted and shortened its cooling effect compared to the more shaded BH_E. BH_N rather showed a general increase of its daily SO, which possibly reflects a thermo-insulating effect.~~

The relatively mild and short 2011–2012 freezing period at BH_S may have been due to snow insulation, as suggested by the subsequent period of constant temperature from the surface to a depth of 3 m (Fig. 6). This isothermal period coincided with , which may reflect the zero-curtain effect observed at the surface temperature from April to mid-May 2012 (see sections 5.2 and 5.3, Fig. 5). As reported by Hoelzle et al., (1999), thick, long lasting snow cover reduces both freezing of the active layer by insulating it from low temperatures and thawing of the active layer by late snow melting. Such an effect on the active layer freeze-thaw cycles has been reported by studies in gentle mountain terrains, but has not been observed in steep bedrock permafrost (Gruber et al. 2004a). A comparison of temperature variations at BH_E and BH_N clearly shows the effect of snow insulation (Fig. 5). Most notably, winter surface temperatures are always warmer and smoother at BH_N than at BH_E (Fig. 5) and at depth (Fig. 7B). Snow appears to have a warming effect at depths of up to 1.4 m. In terms of ALT, the different trends between BH_E and BH_N during the period 2011-2013 (Table 3) may be due to the effect of long-lasting snow cover at BH_N modifying its response to the climate signal. Conversely, the reduced ALT at BH_E in 2011, in contrast with BH_S and BH_N, may be the result of variations in the effect of summer snow fall on these different faces. Unfortunately, the cameras and snow stakes that would have allowed us to check this hypothesis were not installed in 2012 (sect. 3.2). Further studies are needed to verify this hypothesis.

According to a modelling study, the interannual variability of ALT is greater on sun-exposed faces, as they respond as much to change in air temperature as to changes in solar radiation (Gruber et al. 2004a). However, our data did not conform to this prediction, as the change in ALT at BH_S was similar to the ALTs at the shadier BH_E and BH_N. Furthermore, BH_S experienced the smallest interannual changes at 10-m-depth, and the shape of its T(z) profiles between 2010 and 2011 did not follow the trend of the MAAT signal at depths between 6 and 10 m. This may be due to the consumption of latent heat. In fact, previous studies have attributed the delaying and dampening effect of latent heat consumption to the thermal response of bedrock permafrost (Kukkonen et Safanda, 2001; Wegmann et al. 1998, Noetzli et al. 2007). Field observations during drilling revealed the presence of wet-detritic materials in the fractures in BH_S, suggesting that latent heat may be consumed by phase changes between interstitial water and ice during phase-change. This may explain this incoherence. Moreover, the active layer of BH_S shows late refreezing, especially in its deepest layers that can refreeze a few months after the surface (sect. 6.2, Fig. 6), which is also coherent with

~~latent heat effects. This assumption is supported by previous studies explaining the delaying and dampening effect of latent heat consumption on the thermal response of bedrock permafrost (Kukkonen et Safanda, 2001; Wegmann et al. 1998, Noetzli et al. 2007). BH_S patterns would demonstrate that this process may also be visible at short time scale in steep rock walls. The cooling from 2010 to 2011 of its mean annual T(z) profile from 6 to 10 m-depth which is inconsistent with the MAAT change (Fig. 7, Table 3) also supports this assumption as this likely results of a dampened and delayed response. The probable control of latent heat~~ Evidence for latent heat consumption ~~in~~ at BH_S is supported by the temperatures in the borehole, which are around the values required for phase-change processes. Snow accumulation and melting on the south~~-~~-facing slope~~e~~ are an obvious source of water to supply bedrock discontinuities.

Interannual changes at ~~Such possible latent heat controls are not visible at~~ BH_E and BH_N followed variations in ~~which interannual changes are coherent with~~ MAAT all along their profiles (except for BH_N in 2011) suggesting that latent heat consumption did not occur ~~changes up to 10 m-depth, except for BH_N in 2011~~ (Fig. 7A). From 2010 to 2011 t~~T~~he BH_N T(z) profile ~~The significant~~ warmed significantly above the cold inflection~~-~~. This ~~in coherence with~~ followed_MAAT ~~change from 2010 to 2011~~(Table 3), but the colder conditions below the inflection ~~has no~~ were not in accordance ~~coherence~~ with the climate signal. Hence, the fracture seems to act as a thermal cutoff between the surface layer and the deep bedrock. The sharp inflection in the profiles at the fracture depth, which is especially prominent in the mean and minimum annual T(z) profiles, indicates that the fracture locally cools the rock. Mean annual temperature is even lower at depth of 2.5 m than it is at the surface, which, as explained above, is probably insulated by the snow cover. Seasonal temperature profiles for BH_N (Fig. 8) show a relatively large difference between the temperature gradient above and below the fracture depth during winter (Dec. to Feb.) and a much smaller difference during summer (June to Aug.). In winter, the temperature gradient above the fracture depth was quite low (between 0.5 and 0.9°C m^{-1} between 0.3 and 2.5 m, depending on the year), but much higher at greater depth (between 5.1 and 6°C m^{-1} between 2.5 and 3 m, 6.3°C m^{-1} between 3 and 4 m, and >4°C.m^{-1} down to 7 m). In summer the difference in temperature gradients was much less marked, although there was still a substantial change in temperature gradient at the fracture depth. The mean gradient stepped up from between -1.4°C and -2°C m^{-1} between 0.3 to 2-m-depth, to between ~~the fracture depth with a step in the~~ -2.3 to -5.1°C m^{-1} between 2 and 2.5-m-depth. The temperature gradient remained relatively high (> 2.4°C.m^{-1} except in 2010) up to 4-m-depth, and then progressively decreased. These observations suggest that the fracture provokes a heat sink, with greater downward propagation in winter, and a more localized effect in summer. This cooling effect may be due to air ventilating through the open fracture, a process that has been shown to have an important cooling effect on steep rock wall permafrost (Hasler et al. 2011a). In our study this cooling effect was greater when the air temperature was low. Nevertheless, despite this this cooling effect, water percolation can occur along the fracture and heat advection could locally warm the rock (Hasler et al. 2011b). However, the temperature data for BH_N do not provide any evidence for this. ~~The small inflections visible in~~ The temperature profile for BH_E ~~at several depths every year (sect. 6.2) are also possibly induced by bedrock discontinuities, but they have a negligible impact on~~ is generally linear indicating that conduction is the dominant heat transfer process (Williams and Smith, 1989). ~~The fracture width is probably the critical factor controlling the magnitude of the perturbation.~~ Thus, active layer thickness and timing and permafrost temperatures at the AdM are controlled by a number of factors that interact with each other, including snow cover, latent heat consumption (which delays and dampens short-term responses to climate signals), and cooling effect due to air ventilation within open fractures.

7 Conclusion

The high altitude, morphology, and accessibility of AdM make it an exceptional site for investigating permafrost in steep rock walls. A monitoring network installed on the AdM to investigate the thermal effects of topography, snow cover and fractures on permafrost provided eight years of rock surface temperature and four years of borehole temperature data. The results of our analyses of this new dataset supported the findings of previous field studies and a number of numerical experiments:

- The thermal characteristics of the AdM's rock walls are typical of steep bedrock permafrost. The spatial variability of surface temperature, active layer thickness and timing, and the permafrost thermal regime are mainly controlled by topography.

- Borehole temperature data confirm the characteristics of the sub-surface thermal regime predicted by numerical experiments, in particular the coexistence within a single rock peak of warm and cold permafrost, which generates lateral heat fluxes from warm to cold faces.

- MAGST ~~are not uniform at all aspects~~around a single rock peak is controlled by micro-meterological parameters (variable cloud formation from year-to-year) when the rock face is ~~in~~ snow free~~conditions~~, and by local accumulations where there is snow on the face. Snow-free areas and snow-covered areas can show opposite trends. ~~This may be ascribed to variable cloud formation from year-to-year.~~

- ~~Interannual change of snow-covered sensors may be opposite to snow free sensors as the snow can increase the MAGST due to higher thermo-insulation (more precipitations) meanwhile MAGST at snow free sensors can decrease because of reduced solar radiation and lower air temperature.~~

- Surface temperature data confirm that thin (not-insulating) snow cover can lower the ~~MAGST~~ surface temperature ~~because of a~~ due to the low snow surface albedo~~strong reduction of surface albedo~~.

~~1. Open fractures have a strong, localized cooling effect possibly resulting from air ventilation within the fracture.~~

Our results also extended ~~Observations~~ the results ~~from~~ of previous studies ~~are extended and new characteristics are highlighted~~:

- Sensors with thick snow cover showed evidence of a similar thermo-insulation effect to that found on gentle mountain slopes, with smoothing of daily temperatures in winter, a melting period marked by constant surface temperature of around 0°C, reduced freezing of the active layer in winter, and delayed thawing of the active layer in summer.

- Thick snow accumulations warm MAGST of shady areas and increases interannual differences compared with sunny areas which are cooled by snow blocking solar radiation, and where interannual differences are reduced by the balance between the opposite effects of thermo-insulation and strong albedo.

- ~~the cool the MAGST of sun-exposed sensors. On south faces, a thick (insulating) snow cover may cool the MAGST because of a prevailing effect of increased surface albedo and latent heat consumption. On north faces, thermo-insulation can dominate and snow can warm MAGST similarly to gentle mountain slopes.~~

- ~~The interannual changes of MAGST in snow covered areas are greater on shaded aspects than on sunny faces because the latter combines the controls of solar radiation and snow.~~

- ~~The effects of snow cover on ALT in steep rock walls follow the same rules of gentle morphologies. In particular: (i) a thick (insulating) snow cover may reduce cooling during winter leading to a thickening of ALT; (ii) a long-lasting (early summer) snow cover may reduce summer warming leading to a thinning of ALT.~~

~~Such a contrasting effects may coexist or not both in space (e.g. aspects) and time (e.g. season).~~

- Open fractures have a strong, localized cooling effect, possibly due to air ventilation within the fracture. This cooling effect is greater in winter and the heat sink mainly affects the 3-4 m below the fracture.

~~1. Latent heat due to phase change processes of interstitial water in bedrock fractures can dampen active layer and permafrost interannual changes in steep bedrock.~~

8. Further developments

The thermal characteristics of the AdM illustrate the complexity of the processes controlling the thermal regime of shallow layers in rock wall permafrost. Modelling these processes represents a major challenge but the data presented here provide a step towards achieving this goal. Studies into the controlling effect of snow cover are needed in order to determine the impact of thick accumulations and summer snow fall on ALT and permafrost changes. The current research project has already collected a large amount of data, including picture showing the evolution of the south and northeast~~-~~facing slopes~~es~~ of the AdM, snow-stake measurements, and borehole records. Further analyses of these data would help improve understanding of rock fall activity. Research into latent heat consumption in compact bedrock may also provide insight into ALT thickness and timing on some snow-covered rock walls, and into permafrost evolution over short-time scales. The BH_N fracture could be used to investigate non-conductive heat transfers, for example by developing a heat conduction scheme. Ground-penetrating radar measurements of the northwest~~-~~fac~~e~~ing slope, including BH_N, offer a detailed picture of the bedrock discontinuities and provide useful additional data for developing a heat flow model integrating bedrock structure. The combined use of crack-meters, air temperature measurements, and borehole data provides a promising avenue for developing understanding of the thermal and mechanical factors affecting rock wall instabilities.

The dataset presented here was used for evaluation of statistical and numerical models designed to map the distribution of permafrost in the Mont Blanc Massif (Magnin et al., 2014) and to predict the distribution and evolution of the temperature field at the AdM over the next century (Noetzli et al., 2014b). The statistical model will be used to determine bedrock temperatures and the related permafrost thermal regime at rock fall locations in order to analyze the relationship between bedrock temperature and rock failures.

Acknowledgements: We would like to thank S. Gruber, U. Morra di Cella, E. Cremonese, and E. Malet, for their help with equipment installation and data acquisition at the Aiguille du Midi. The Chamonix *Compagnie des Guides* provided invaluable assistance with the drilling operations. We would also like to thank the *Compagnie du Mont Blanc* (especially E. Desvaux) for allowing access to the site, and Météo France for providing air temperature data. Thank you to A. Hasler and anonymous reviewer for their useful comments and recommendations. The english text was corrected by P. Henderson. This work was supported by the Region Rhône-Alpes (*CIBLE* program).

References

Allen, S. K., Gruber, S., and Owens, I. F.: Exploring steep bedrock permafrost and its relationship with recent slope failures in the Southern Alps of New Zealand, Permafrost Periglac., 20, 345–356, doi:10.1002/ppp.658, 2009.

Boeckli, L., Brenning, A., Gruber, S., and Noetzli, J. Permafrost distribution in the European Alps: calculation and evaluation of an index map and summary statistics. The Cryosphere Discuss., 6, 849–891, doi:10.5194/tcd-6-849-2012, 2012.

Deline, P.: Recent Brenva rock avalanches (Valley of Aosta): new chapter in an old story? Supplementi di Geografia Fisica e Dinamica Quaternaria, 5, 55–63, 2001.

Deline, P., Alberto, W., Broccolato, M., Hungr, O., Noetzli, J., Ravanel, L., and Tamburini, A.: The December 2008 Crammont rock avalanche, Mont Blanc massif area, Italy, Nat. Hazard Earth Sys., 11, 3307–3318, 2011.

Deline, P., Gardent, M., Magnin F., and Ravanel, L.: The morphodynamics of the Mont Blanc massif in a changing cryosphere: a comprehensive review, Geogr. Ann. A, 94(2), 265–283, 2012.

Fischer, L., Kääb, A., Huggel, C., and Noetzli, J.: Geology, glacier changes, permafrost and related slope instabilities in a high-mountain rock wall: Monte Rosa east face, Italian Alps, Nat. Hazard Earth Sys., 6, 761–772, 2006.

Gruber, S. and Haeberli, W.: Permafrost in steep bedrock slopes and its temperature related destabilization following climate change, J. Geophys. Res-Earth., 112, F02S13, doi:10.1029/2006JF000547, 2007.

Gruber S. and Haeberli W.: Mountain permafrost, in: Permafrost soils, Margesin R, Springer, 16, 33-44, 2009.

Gruber, S., Peter, M., Hoelzle, M., Woodhatch, I., and Haeberli. W.: Surface temperatures in steep alpine rock faces: a strategy for regional-scale measurement and modelling, in: Proceedings of the 8th International Conference on Permafrost, L. Arenson, Zürich, 325-330, 2003.

Gruber, S., Hoelzle, M., and Haeberli, W.: Permafrost thaw and destabilization of Alpine rock walls in the hot summer of 2003, Geophys. Res. Lett., 31, L13504, doi:10.1029/2004GL0250051, 2004a.

Gruber, S., Hoelzle, M., and Haeberli, W.: Rock-wall temperatures in the Alps: modelling their topographic distribution and regional differences, Permafrost Periglac., 15, 299–307, doi: 10.1002/ppp.501, 2004b.

Gubler, S., Fiddes, J., Keller, M., and Gruber, S.: Scale-dependent measurement and analysis of ground surface temperature variability in alpine terrain, The Cryosphere, 5, 431–443, 2011.

Hanson, S. and Hoelzle, M.: The thermal regime of the active layer at the Murtèl rock glacier based on data from 2002. Permafrost Periglac., 15, 273–282, doi: 10.1002/ppp.499, 2004.

Harris, S. and Corte, A.: Interactions and relations between mountain permafrost, glaciers,snow and water, Permafrost Periglac., 3, 103–110, 1992.

Hasler, A., Gruber, S., and Haeberli, W.: Temperature variability and offset in steep alpine rock and ice faces, The Cryosphere, 5, 977–988, doi:10.5194/tc-5-977-2011, 2011a.

Hasler, A., Gruber, S., Font, M., and Dubois, A.: Advective heat transport in frozen rock clefts - conceptual model, laboratory experiments and numerical simulation. Permafrost Periglac., 22, 378–349, doi: 10.1002/ppp.737, 2011b.

Hipp, T., Etzelmüller, B. and Westermann, S.: Permafrost in Alpine Rock Faces from Jotunheimen and Hurrungane, Southern Norway. Permafrost Periglac., 25: 1–13. doi: 10.1002/ppp.1799, 2014.

Hoelzle, M., Wegmann, M., and Krummenacher, B.: Miniature temperature dataloggers for mapping and monitoring of permafrost in high mountain areas: first experience from the Swiss Alps. Permafrost Periglac., 10: 113–124. doi: 10.1002/(SICI)1099-1530(199904/06)10:2<113::AID-PPP317>3.0.CO;2-A, 1999.

Huggel, C., Caplan-Auerbach, J., and Wessels, R.: Recent extreme avalanches triggered by climate change, EOS, Transactions American Geophysical Union, 89, 469–470, 2008.

Huggel, C., Zgraggen-Oswald, S., Haeberli, W., Kääb, A., Polkvoj, A., Galushkin, I., and Evans, S.G.: The 2002 rock/ice avalanche at Kolka/Karmadon, Russian Caucasus: assessment of extraordinary avalanche formation and mobility, and application of Quick- Bird satellite imagery, Nat. Hazard Earth Sys., 5, 173–187, doi:10.5194/nhess-5-173-2005, 2005.

Krautblatter, M., Huggel, C., Deline, P., and Hasler, A.: Research Perspectives on Unstable High-alpine Bedrock Permafrost: Measurement, Modelling and Process Understanding. Permafrost Periglac., 23, 80–88, DOI: 10.1002/ppp.740 2011.

Juliussen, H. and Humlum, O.: Towards a TTOP ground temperature model for mountainous terrain in central-eastern Norway. Permafrost Periglac., 18, 161–184, doi: 10.1002/ppp.586, 2007.

Kukkonen, I. T. and J. Safanda.: Numerical modelling of permafrost in bedrock in northern Fennoscandia during the Holocene, Global Planet. Change, 29, 259– 273, 2001.

Leloup, P. H., Arnaud, N., Sobel, E. R., and Lacassin, R.: Alpine thermal and structural evolution of the highest external crystalline massif: The Mont Blanc. Tectonics, 24, TC4002, doi: 10.1029/2004TC001676, 2005.

Le Roy, M.: Reconstitution des fluctuations glaciaires holocènes dans les Alpes occidentales, Thèse de Doctorat de Géographie, Université de Savoie, Le Bourget du Lac, 344 pp, 2012.

Luetschg, M., Lehning, M., and Haeberli, W.: A sensitivity study of factors influencing warm/thin permafrost in the Swiss Alps, J. Glaciol., 54, 696–704, 2008.

Magnin, F., Brenning, A., Bodin, X., Deline, P., Ravanel, L.: Statistical modelling of rock wall permafrost distribution: application to the Mont Blanc massif, Géomorphologie, Manuscript submitted.

Noetzli, J., Gruber, S., Kohl, T., Salzmann, N., and Haeberli, W.: Three-dimensional distribution and evolution of permafrost temperatures in idealized high-mountain topography, J. Geophys. Res-Earth, 112, F02S13, doi:10.1029/2006JF000545, 2007.

Noetzli, J., Christiansen, H. H., Guglielmin, M., Romanovsky, V. E., Shiklomanov, N. I., Smith, A.L., and Zhao, L.: Permafrost thermal state, in: State of the Climate in 2013, Bull. Amer. Meteor. Soc., 95, 2014a.

Noetzli, J., Ravanel L., and Deline P.: Combining measurements and modelling to describe the permafrost conditions at the Aiguille du Midi (3842 m asl, Mont Blanc Massif). The Cryosphere, in preparation.

PERMOS: Permafrost in Switzerland 2002/2003 and 2003/2004, in: Vonder Mühll, D. (eds.), Glaciological Report (Permafrost) No. 4/5 of the Cryospheric Commission of the Swiss Academy of Sciences, Zürich, 121 pp, 2007.

PERMOS: Permafrost in Switzerland 2008/2009 and 2009/2010, in: Noetzli, J. (eds.), Glaciological Report (Permafrost) No. 10/11 of the Cryospheric Commission of the Swiss Academy of Sciences, Zürich, 95 pp, 2013.

Pogliotti, P.: Influence of Snow Cover on MAGST over Complex Morphologies in Mountain Permafrost Regions. PhD thesis, Turin, Italy, Università degli Studi di Torino, 79 pp, 2011.

Ravanel, L. and Deline P.: Climate influence on rockfalls in high-Alpine steep rock walls: the north side of the Aiguilles de Chamonix (Mont Blanc massif) since the end of the 'Little Ice Age', The Holocene, 21, 357–365, doi: 10.1177/0959683610374887, 2010.

Ravanel, L., Allignol, F., Deline, P., Gruber, S., and Ravello, M.: Rock falls in the Mont Blanc Massif in 2007 and 2008, Landslides, 7, 493–501, 2010.

Ravanel, L., Deline, P., Lambiel, C., and Vincent C.: Intability of a high Alpine rock ridge: the lower Arête des Cosmiques, Mont Blanc massif, France, Geogr. Ann. A, 95, 51–66, doi: 10.1111/geoa.12000, 2012.

Romanovsky, V. E., Smith, S. L., Christiansen, H. H., Shiklomanov, N. I., Streletskiy, G. A., Drozdov, D. S., Malkova, G. V., Oberman, N. G., Kholodov, A. L., and Marchenko, S. S.: [Terrestrial permafrost, in: State of the Climate in 2013, Bull. Amer. Meteor. Soc., 95, S139–S141, 2014.

Smith, M. W. and Riseborough, D. W.: Permafrost monitoring and detection of climate change. Permafrost Periglac., 7, 301–309, doi: 10.1002/(SICI)1099-1530(199610)7:4<301::AID-PPP231>3.0.CO;2-R, 1996.

Smith, M. W. and Riseborough, D. W.: Climate and the limits of permafrost: a zonal analysis. Permafrost Periglac., 13, 1–15, doi: 10.1002/ppp.410, 2002.

Williams, P. J. and Smith, M. W.: The frozen earth, Studies in polar research, Cambridge University Press, Cambridge, 306 pp., 1989.

Tables

Site Code	Elevation [m a.s.l]	Aspect [°]	Slope [°]	Sensor depths [m]	Estimated snow accumulation [m]
BH_S	3753	135	55	0.14, 0.34, 0.74, 1.04, 1.34, 1.64, 2.14, 2.64, 3.64, 4.64, 6.64, 8.64, 9.64	> 0.8
BH_N	3738	345	90	0.3, 0.5, 0.7, 0.9, 1.1, 1.4, 1.7, 2, 2.5, 3, 4, 5, 7, 9, 10	> 1.0
BH_E	3745	50	65	0.3, 0.5, 0.7, 0.9, 1.1, 1.4, 1.7, 2, 2.5, 3, 4, 5, 7, 9, 10	< 0.6
W1	3825	270	80	0.1	0
S1	3820	140	74	0.1	0
N1	3820	354	84	0.1	0
E1	3823	124	60	0.1	0
N2	3820	334	80	0.03, 0.1, 0.3, 0.55	0
E2	3820	118	60	0.03, 0.1, 0.3, 0.55	0
S2	3815	160	85	0.03, 0.1, 0.3, 0.55	0
W2	3825	270	85	0.03, 0.1, 0.3, 0.55	0
S3	3820	158	70	0.03, 0.1, 0.3, 0.55	0.5 to 1.0
AT	3845	0	0		0

Table 1. Instrument positions.

BH: borehole thermistor chains, ~~x~~X1 and ~~x2~~X2: rock surface temperature loggers, AT: air temperature. Estimated snow accumulation: from automatic cameras and probes for BH_S and BH_E (winter 2012 and 2013), from field observation for S3 and BH_N.

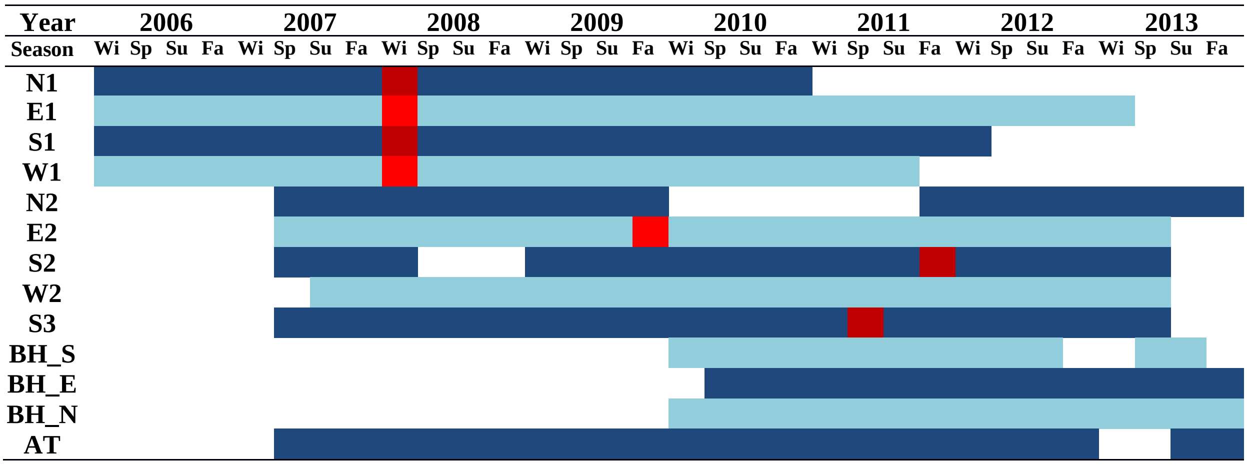

Table 2. Data availability after gap filling.

Wi: December, January, February; **S**p: March, April, May; **Su**: June, July, August; **Fa**: September, October, November.

Red sections indicate where gaps <1.5 month per year have been filled in order to calculate annual means but seasonal means were not calculated for the seasons in question. The time series interrupted with white gap areas indicate that annual mean is not computed for the concerned year.

Year	BH_E			BH_S			BH_N			MAAT
	ALT [m]	**Max. ALT [dd.mm]**	**$MART_{10m}$ [°C]**	**ALT [m]**	**Max. ALT [dd.mm]**	**$MART_{10m}$ [°C]**	**ALT [m]**	**Max. ALT [dd.mm]**	**$MART_{10m}$ [°C]**	
2010	3.1	27.07	-	5.2	23.10	-1.4	1.8	28.08	-4.7	-9
2011	2.7	30.08	-3.8	5.9	22.10	-1.5	2.3	18.09	-4.6	-6.7
2012	3.3	26.08	-3.6	-	-	-	2.5	26.08	-4.3	-7.7
2013	3.4	08.09	-3.6	5.8	30.09	-	2.2	25.08	-4.5	-

Table 3. Borehole and air temperature records.

ALT: Active Layer Thickness

$MART_{10m}$: Mean Annual Rock Temperature at 10-m depth

MAAT: Mean Annual Air Temperature

Figures

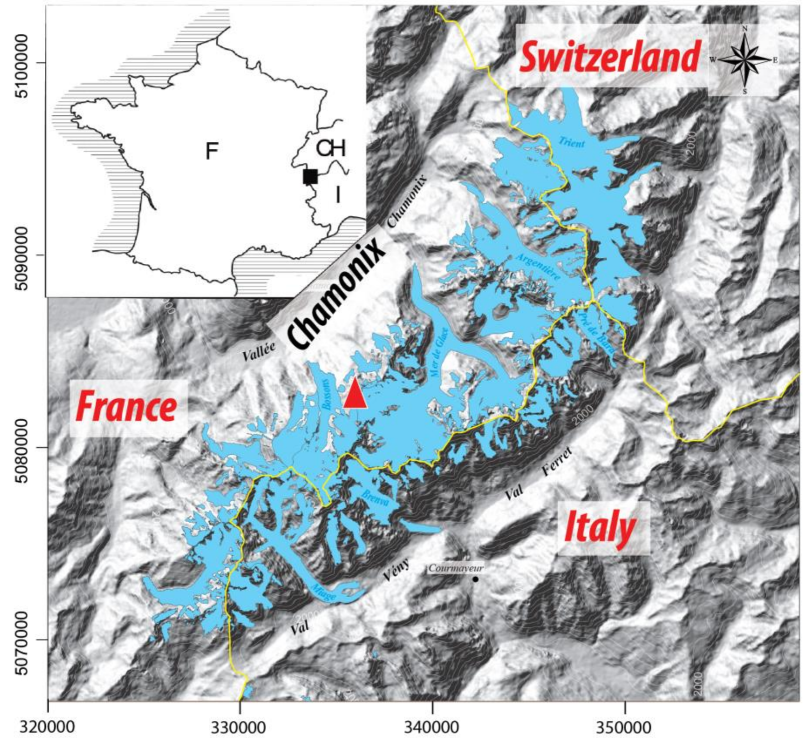

Figure 1. Location of the Mont Blanc Massif and the Aiguille du Midi (red triangle) (modified from Le Roy, 2012).

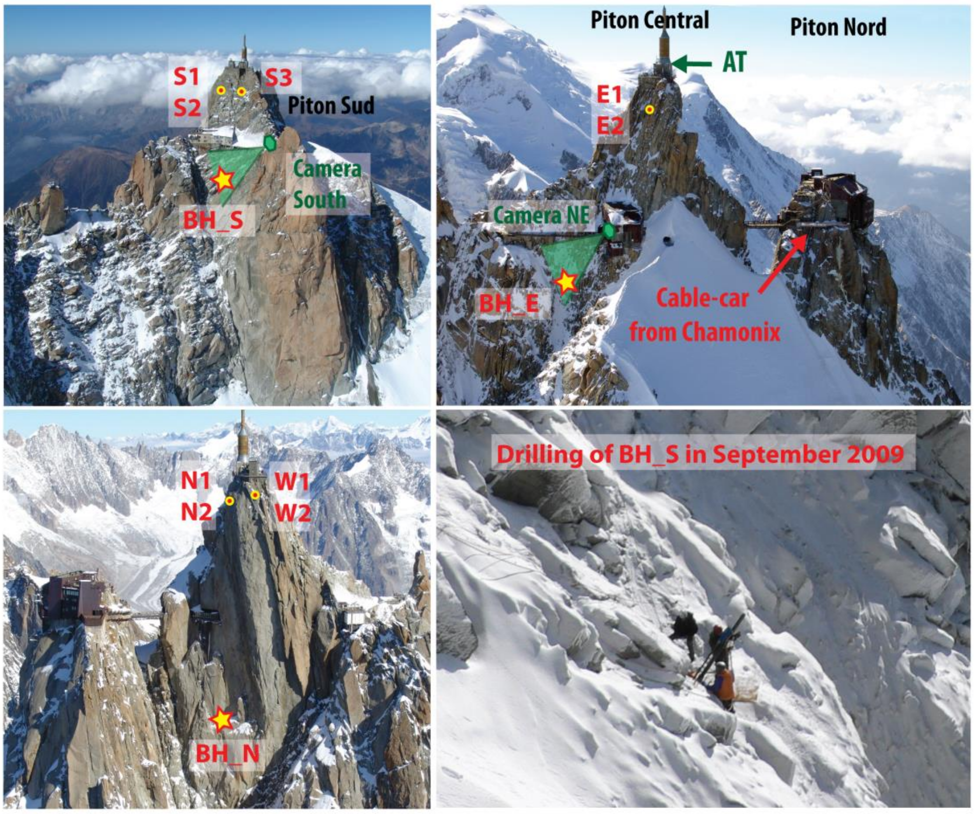

Figure 2. The Aiguille du Midi with snow camera, air temperature, ~~RST~~rock surface temperature, and ~~BH~~ borehole logger locations.
Pictures: S. Gruber (top left and right, bottom left); P. Deline (bottom right).

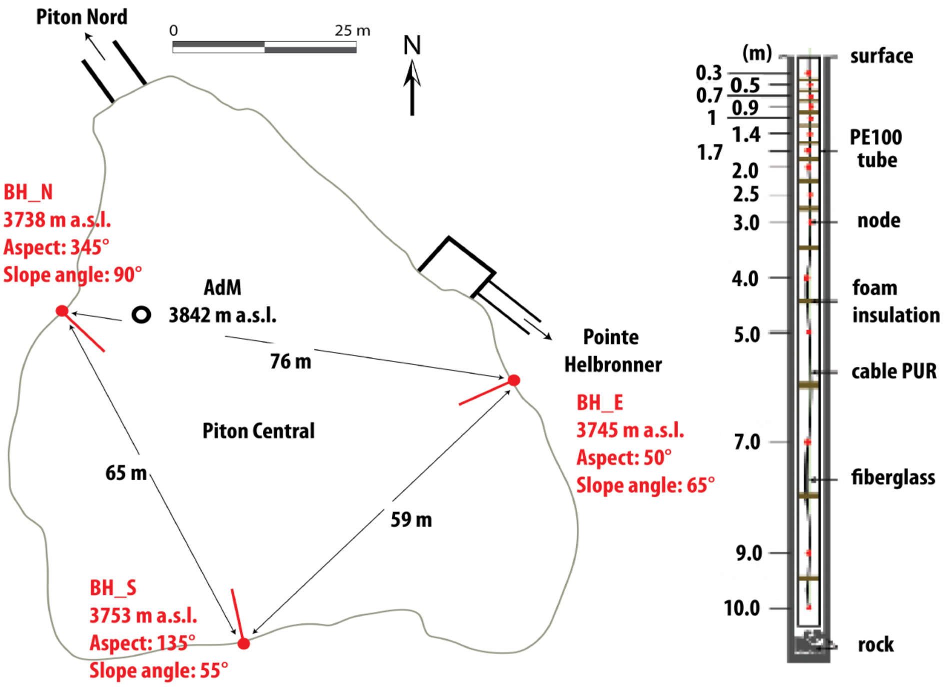

Figure 3. Borehole positions and components.

Left: Horizontal cross-section through the AdM's Piton Central. Borehole positions are marked in red.

Right: 10-m-long, 15-node thermistor chain installed in the boreholes.

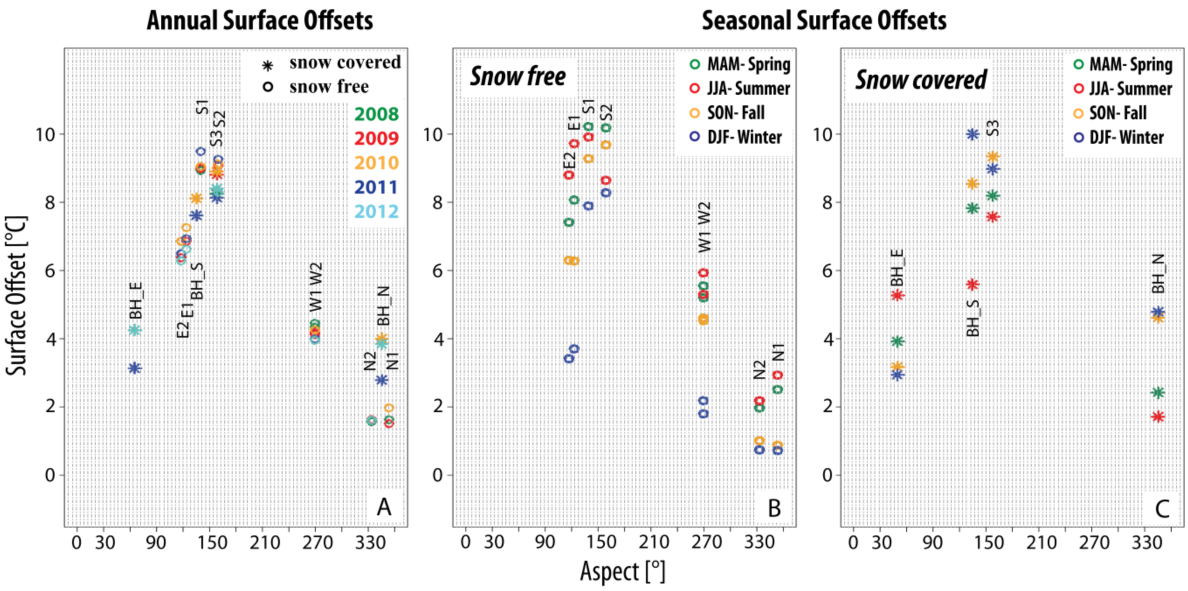

Figure 4. Annual and Seasonal Surface Offsets calculated from sensors at 0.3-m depth. ASOs are shown for all the available years. SSOs are the mean values for the available seasons for each logger listed in Table 2.

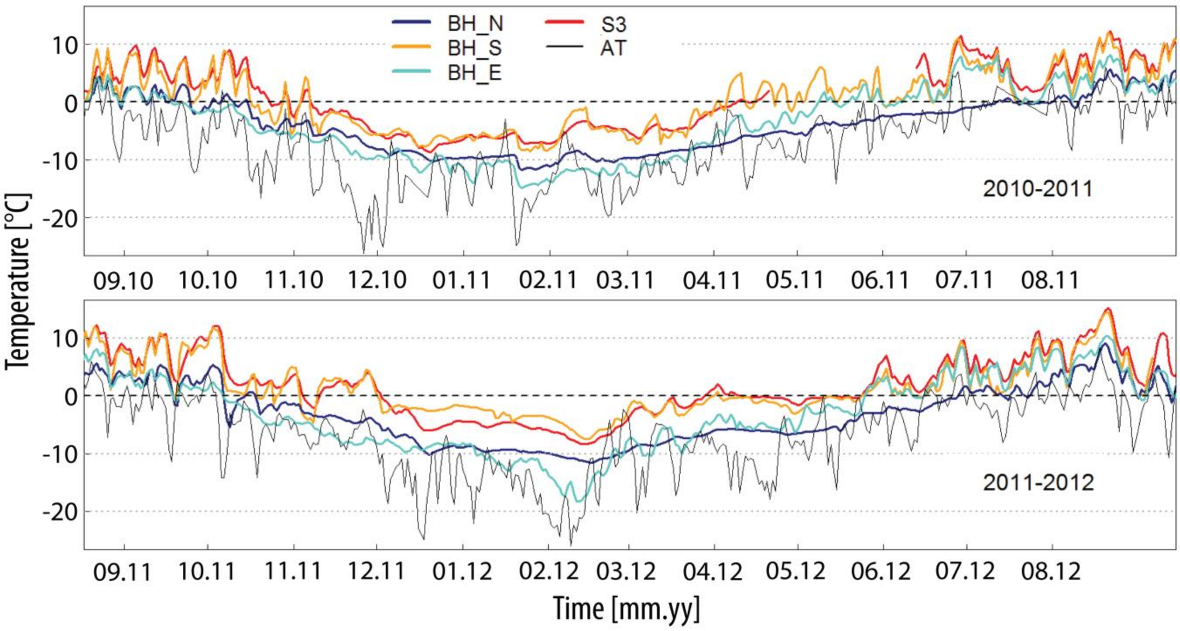

Figure 5. Daily temperature records at 0.3-m depth for snow-covered sensors for the 2010-2011 and 2011-2012 hydrological years.

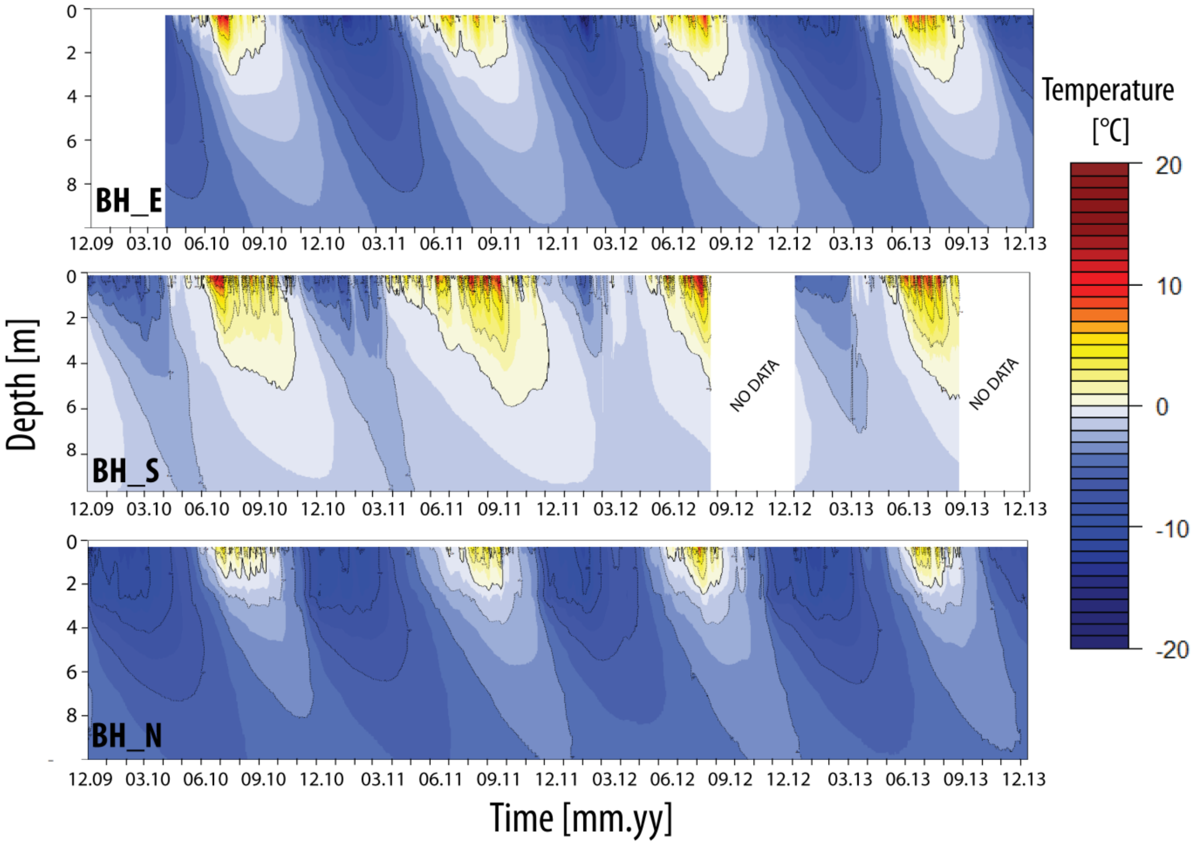

Figure 6. Daily temperature records in the AdM boreholes from December 2009 to December 2013.

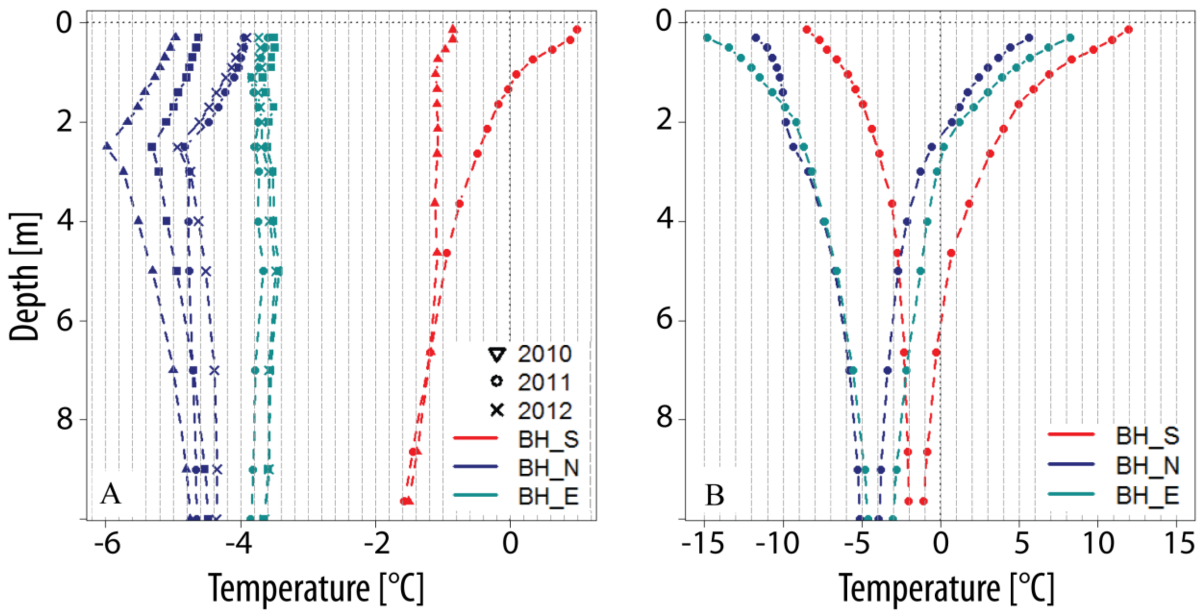

Figure 7. Mean T(z) profiles (A) and 2011 temperature envelopes (B) of the AdM boreholes.

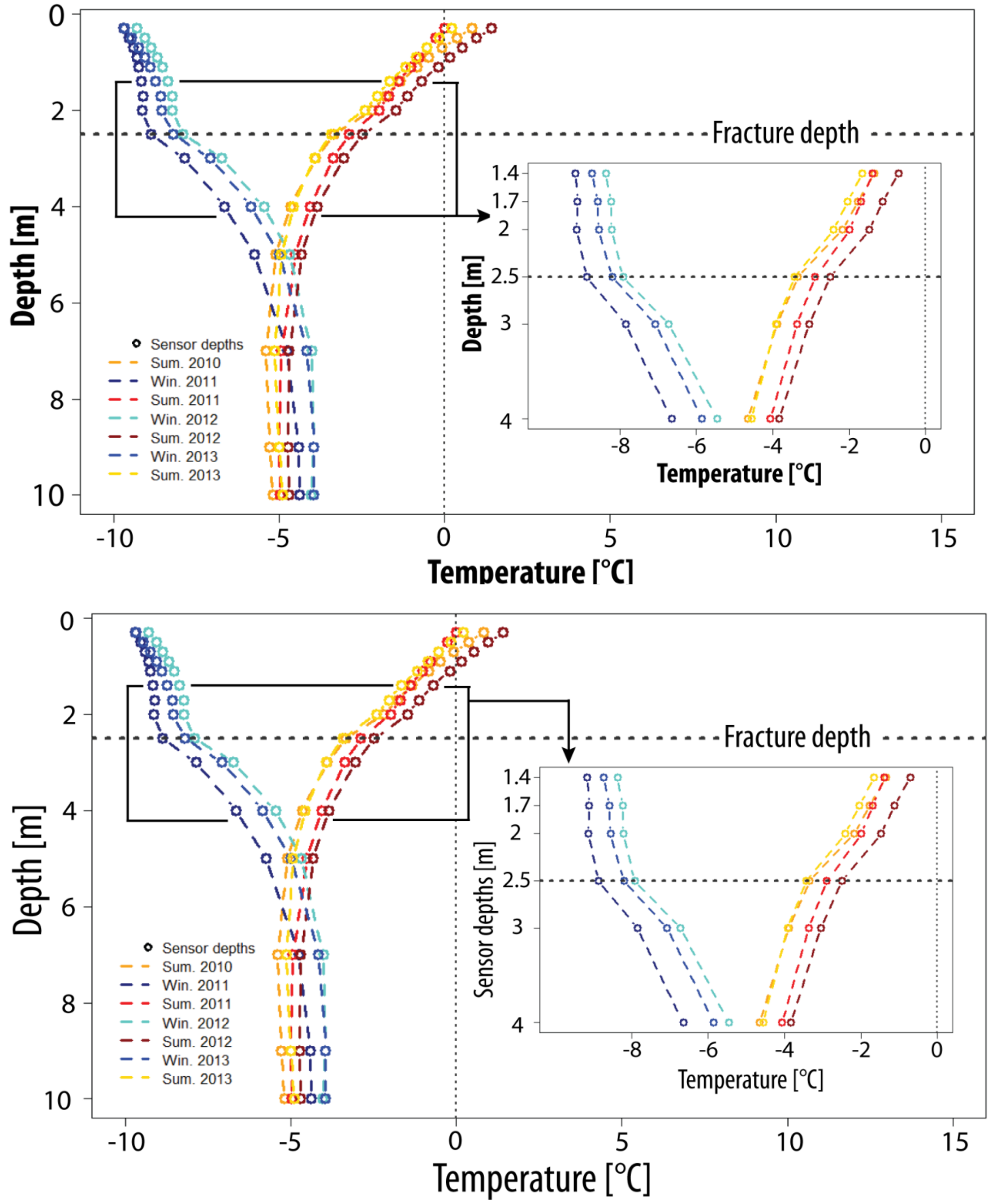

Figure 8. Seasonal T(z) profiles for winters (December to February) and summers (June to August) recorded in BH_N.