## General comment of Referee#1

**The manuscript Warming permafrost and active layer variability at Cime Bianche, Western Alps by Pogliotti et al. describes a record of measurement results of per- mafrost properties. In general, the methods are sound, and the manuscript is written in a clear and well-structured way. From a technical point of view, the manuscript is state-of-the-art. The presented data basis is a bit at the edge of what deserves to be published in The Cryosphere, and new effects or processes are not described. I nevertheless recommend it for publication subject to some revisions. I am of the opin- ion that such baseline studies deserve to be published in a journal like The Cryosphere since they provide well-documented in-situ observations which will be of high value for many years to come.**

*Dear Referee#1,*
*we are grateful for the positive consideration about the manuscript and the analysis. In the following we discuss the comments and how the manuscript was modified to take into account your suggestions. We are confident to have fully answered all questions and incorporated most of the recommendations in the revised paper.*
*All the modifications are reported in red in the revised manuscript. In the following, your comments are in bold while our response in italics.*
*Best regards,*
*Paolo Pogliotti and coauthors.*

## Major comments

**1.The authors basically only describe results from one single area. While they do put it in the context of other monitored areas in the Alps, the authors should describe in more detail why the results from Cime Bianche are relevant. If there are three similar installations on other mountains close by which behave similarly, the findings would definitely not warrant publication. Does this site fill a geographical gap within the Alps? Maybe a map with other borehole sites in Switzerland/France/Italy would be helpful. Is it meant to be a baseline study for a permanent permafrost observatory?**

*We agree with referee#1 that is important to highlight why the results of Cime Bianche are relevant and why they fill a geographical and knowledge gap in the Alps. For these reasons we added specific sentences on that. Modifications on the revised manuscript: P3.L9-14, P21.L8-9*

**2. The authors should check once again the English language. While it is generally good, there are a few sentence fragments and other minor errors.**

*We sent the manuscript to a mother tongue for checking the English. We are confident that the revised manuscript is improved.*

**3. Section 4.3 The authors should briefly discuss why the trends are only statistically significant below a certain depth. This most likely has to do with the stronger interannual variability of the ground temperatures above. However, they of course do not behave independently, but temperatures at deeper depth are influenced by a much longer period. Therefore, trends in the deep layers represent longer-term trends of the surface forcing, which, if present, can be secured statistically more easily.**

*Thanks for this comment. We added a sentence for explaining why the trends are not significant in the first meters. Modifications on the revised manuscript: P18.L17-20.*

### Minor comments

**4. P4038,l18: This sentence is unnecessary, this is also a result of this study. The information on permafrost in the area is published in this manuscript for the first time, so a reference to unpublished data is unnecessary.**

*The sentence has been removed.*

**5. P4044,l6: Reword the second part of this sentence.**

*This first sentence of section 3.1 has been simplified. Modifications on the revised manuscript: P11.L6-8.*

**6. P4053,l24: phenomenon**

*We corrected the typo. Modifications on the revised manuscript: P5.L9, P20.L17*

## General comments of Referee#2

**Both Data and Methods and Results are presented in an understandable way. The measured data are interesting and highly relevant for the research community - and relevant for the readers of The Cryosphere. However, and here is my main objections; several points from the interpretations and conclusions presented are well known from the existing literature. The presented analysis are quite simple and do not reach the level of most recent knowledge/understanding. The potential for new insight is large but not fully utilized.**

*Dear Referee#2,*
*we are grateful for the positive consideration about the manuscript and the analysis. We carefully considered your main concern testing some of your suggestions and deepening the analysis on GST and snow cover: two figures (fig.2 and fig.5) and one paragraph (sec. 2.4) were thus added to the revised manuscript. In the following we discuss your comments and how the manuscript was modified to take into account your suggestions. We are confident to have fully answered all questions and incorporated most of your recommendations in the revised paper.*
*All the modifications are reported in red in the revised manuscript. In the following, your comments are in bold while our responses are in italics.*
*Best regards,*
*Paolo Pogliotti and co-authors.*

## Major comments

**1. The authors present an extensive list of existing and relevant literature in their introduction and try to put their work in a theoretical context. However, the Introduction in its present form is too long and unfocused. It is not obvious from the first paragraphs what their main research question(s) is. Why is it interesting? The introduction should summarize the relevant literature so that the reader will understand why you were interested in the question(s) you asked. In my point of view two to four paragraphs should be enough.**

*We agree with referee#2 that introduction was too long and unfocused. Thus we deeply reworked the introduction highlighting the main research questions and removing not relevant parts. Modifications on the revised manuscript: from P3.L3 to P4.L20.*

**2. The site in general appears to be reasonably homogeneous, but (A) it should be both interesting and possible to do more in-depth analyses on how the timing and the duration of the snow cover influence your ground surface temperature data. In addition the influences of other variables than snow cover on ground surface and ground temperature variability should be analyzed. (B) I suggest that the authors make more sophisticated analyses to get new insights into e.g. how the spatial and temporal variability of ground surface temperatures are in relation to several of the climatic parameters they have measured at the site - such as air temperature, solar radiation and precipitation (in- fluencing e.g. soil humidity) when the ground is not snow covered. (C) And how does the inter-annual variability of both air temperature and snow cover influencing your observed warming trends?**

*2A. We want to thank referee#2 for this constructive comment: we added a new paragraph (2.4) and 2 new figures (Figures 2 and 5) to answer to the question: "how timing and the duration of the snow cover influence your ground surface temperature data". In particular we looked at the influence on MAGST of snow cover duration and air temperature when ground is snow-free. For doing this analysis, we had to work only on* snow-covered *nodes applying the method of Schmid et. al, 2012 to determine snow cover duration. Modifications on the revised manuscript: from P8.L16-23, from P11.L17 to P12.L2, P16.L1-4, P21.L16-17, Figure 2, Figure 5.*

*2B. We acknowledge that an in-depth analysis of how spatial and temporal variability of ground temperature relate to meteorological drivers would be relevant. We partially answered to this suggestion by analyzing the impact of mean air temperature during snow free days on MAGST (see figure 5 panel B in the revised manuscript). Unfortunately spatially distributed measures of the other suggested climatic parameters (i.e solar radiation and precipitation) were not available. Thus we limited our analysis on the effect of air temperature. Moreover a specific in depth analysis of the impact climatic variables on GST data was beyond the main scope of this paper.*

*2C. We thank the referee#2 for this question pinpointing that we did not clarify enough that warming trends detected are not affected by inter-annual variability because a seasonal detrending was applied before SS and MK. In order to better clarify this point we added a sentence in the discussion. Modifications on the revised manuscript: P18.L17-20.*

**3. The English need some smoothing and corrections.**

*We sent the manuscript to a mother tongue for checking the English. We are confident that the revised manuscript is improved.*

**Specific comments**

**4. Title The (sub)region/term Western Alps may not be clear for all readers from e.g. America. I suggest writing western European Alps.**

*The title has been changed in accordance with this suggestion.*

**5. Abstract L2, P4034, L2: Suggest to include Italian or the Italian side of the Western Alps, e.g. write: . . .permafrost at the Italian monitoring site Cime Bianche (3100 m a.s.l.),Western Alps.**

*The sentence has been changed in accordance with this suggestion. Modifications on the revised manuscript: P2.L3-L4.*

**6. P4034, L3: ground temperature observations. Modifications on the revised manuscript: P2.L4**

*We corrected the typo.*

**7. P4034, L5-8: You write: The analysis aims to quantify. . .(iii) the warming trend of deep permafrost temperatures. Since this paper is the first synthesis on the state and recent evolution of permafrost at Cime Bianche, warming or cooling of the permafrost is a result itself. In L16-17 you conclude that: The analysis of deep temperature time series reveals that permafrost is warming. . .**

**Thus suggest that you in L8-9 replace (iii) the warming trend of deep permafrost temperatures with (iii) recent (or present?) temperature trends in deep permafrost.**

*The sentence has been changed in accordance with this suggestion. Modifications on the revised manuscript: P2.L7*

**8. P4034, L11-13: Is the accuracy in your measurements so high that the use of one centimeter can be justified here? As far as I can see the spacing of the thermistors around the ALT in DP is two meters! The use of a simple interpolation between two thermistors having two meter spacing for the determination of ALT based on the 0- isotherm. introduce a quite large uncertainty.**

*We agree with referee#2 comment. See the answer to comment 10 for our detailed answer. Modifications on the revised manuscript: P2.L12.*

**9. (A) Data and Methods P4039, L5-6: Did you do any calibration of the thermistor chains before installation? As far as I know such thermistors have $\pm 0.1°$C accuracy without calibration. Some additional information about this would be useful here. (B) You also mention sensor noise at P4041, L12-13. The whole setup with datalogger and possible external noise sources etc. should be included when talking about absolute accuracy.**

*9A. The calibration of the thermistor chains was performed by the manufacturer few days before the installation. About the accuracy, the values cited are those we have on the technical documentation received by the manufacturer. Modifications on the revised manuscript: P6.L6-7.*

*9B. About sensor noise this is present on deep sensors where temperature changes are very small. The amplitude of such noise is $\pm 0.01° C$ that is the sensor resolution. We think that this is mainly an electrical noise related to the resolution of differential channels of datalogger (campblell CR800) used to read voltage values. This noise is smoothed with a running mean and we think that it does not affect our results. Modifications on the revised manuscript: P8.L7-9.*

**10. P4040, L20-26: Please give some additional information about accuracy of the ALT determination used here (cf. my point**

**above (P4034, L11-13)), in the light of especially the spacing of your thermistors and their accuracy.**

*We thank the referee for this comment. We analyzed the uncertainty of ALT estimation by propagating the error associated to temperature measurements. This analysis was run on daily mean temperature data. For each day we first identified the two nodes encompassing the ALT. We then generated 500 random temperatures for these two nodes and linearly interpolated between them to calculate ALT. Standard deviation of the resulting 500 ALT values was used as an the actual ALT uncertainty for that particular day. The same was done for all days. Noise was generated according to three different amplitudes,* $\pm 0.01$*,* $\pm 0.02$ *and* $\pm 0.05°C$ *which are respectively the resolution, the relative accuracy and the absolute accuracy of the sensors. As expected the uncertainty increases with the increases of noise. The results are reported in the figure 1 (end of this document). Considering the worst case, that is assuming a noise of* $\pm 0.05°$*, the uncertainty of the ALT estimation is* $7.5 \pm 1\,cm$*. As a consequence, in the revised manuscript, we rounded to the first decimal all the ALT values and added a sentence. Modifications on the revised manuscript: P7.L21-23.*

**11. P4046, L18-21: did you compare this tendency with climatic data, e.g. air temperature and snow cover? Variable snow cover may be responsible for some of the inter-annual variability observed in the upper permafrost layers, but also for the observed warming trend at greater depths.**

*We did not compare temperature trend with short term variations of air temperature and snow data. We are aware that the observed warming trend could be the results of both long term warming and short term inter-annual variability. But given that i) due to a lack of long term observations, it is not possible to disentangle the contribution of both long and short term components ii) the impact of climate data was not the main focus of this paper, we preferred to focus on the quantification of the warming trend and the estimation of related uncertainties. Moreover, as previously underlined in the answer number 2C, the seasonal detrending applied before the trend calculation has the specific purpose of removing these short-term fluctuations .*

**12. P4046, L27-28: during some warmer years or under/after a longer warm period the warming rate will always be higher near**

**the upper permafrost layers than in the deeper part. Thus, please rewrite this sentence.**

*We thank the referee for this comment. We rewrote this sentence. Modifications on the revised manuscript: P13.L26-27*

**13. P4047, L5-6: I cannot see that your results supports that permafrost is "degrading". The term "Permafrost degradation" is normally expressed as a thickening of the active layer, a lowering of the permafrost table, a rising of the permafrost base, or a reduction in the areal extent or the complete disappearance of permafrost. Thus I suggest to better write: . . .that permafrost at Cime Bianche is warming and that significant positive warming rates are reported at all depths.**

*We thank the referee for this comment. We rewrote this sentence. Modifications on the revised manuscript: P14.L2-4.*

**14. P4054, L26 to P4055 L8: this is also reported from several other studies, which are included by the authors in their reference list (see my general comments).**

*Looking at alpine literature, this is one of the first studies systematically analyzing and quantifying the small-scale spatial and inter-annual variability of both GST and ALT. The estimation of uncertainties is rarely reported in permafrost studies and we think it is fundamental for comparisons between sites. Moreover Cime Bianche site provides new data from the southern side of the Alps, a poorly represented region at European Alps level.*

**15. P4055 L11-12: I cannot see that your results supports that permafrost is degrading (see my previous point. And observed warming rate exponentially decreasing with depth is the normal case, and should not be a surprise.**

*We thank the referee for this comment. We rewrote this sentence. Modifications on the revised manuscript: P21.L26-27*

**16. Table 2, P4066: ZAA with two decimals can it be justified? Here the spacing of the thermistors is one meter (see my previous points).**

*The procedure of uncertainty estimation used for ALT has been replicated for ZAA (see reply to comment 10 for details). The results obtained for ZAA are very similar to those obtained for ALT. As a consequence, in the revised manuscript, all the ZAA values have been rounded to the first decimal. Modifications on the revised manuscript: P31.Tab.2*

**17. Figure 5, P4071: Especially the minimum profiles are not very smooth. How do you explain this, in the light of the apparently high accuracy of your measurements? Is it real and may be due to lithological contrasts, or variable ice-and water content and/or latent heat effects? Or is it due to non-calibrated thermistors (cf. my point at P4039)?**

*Since thermistors were calibrated few days before field installation, we are quite confident that instrumental issues are not responsible for unsmoothed temperature profiles. Weathering or bedrock fracturations and variable ice-water contents may both determine the observed behavior. Data in our possess does not allow to elucidate the reason of this pattern. However this pattern is not particularly uncommon in mountain permafrost (see PERMOS, 2013").*

## Figures

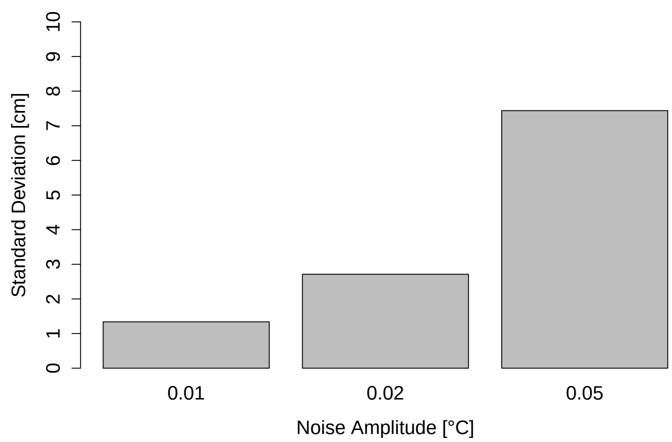


Figure 1: Uncertainty of ALT estimation as a function of simulated sensor noise.

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# Warming permafrost and active layer variability at Cime Bianche, Western European Alps

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## Abstract

The objective of this paper is to provide a first synthesis on the state and recent evolution of permafrost at the monitoring site of Cime Bianche (3100 m a.s.l.), Italian side of the Western Alps. The analysis is based on seven years of ground ~~temperatures~~ temperature observations in two boreholes and seven surface points. The analysis aims to quantify the spatial and temporal variability of ground surface ~~temperatures~~ temperature in relation to snow cover, the small scale spatial variability of the active layer thickness and ~~the warming trends on deep permafrosttemperatures~~current temperature trends in deep permafrost.

Results show that the heterogeneity of snow cover thickness, both in space and time, is the main factor controlling ground surface temperatures and leads to a mean range of spatial variability ($2.5 \pm 0.15\,^{\circ}\mathrm{C}$) which far exceeds the mean range of observed inter-annual variability ($1.6 \pm 0.12\,^{\circ}\mathrm{C}$). The active layer thickness measured in two boreholes at a distance of 30 m~~apart~~, shows a mean difference of ~~$2.03 \pm 0.15$~~$2.0 \pm 0.1$ m with the active layer of one borehole consistently ~~lower~~deeper. As revealed by temperature analysis and geophysical soundings, such a difference is mainly driven by the ice/water content in the sub-surface and not by the snow cover regimes. The analysis of deep temperature time series reveals that permafrost is warming. The detected ~~linear~~ trends are statistically significant starting from a depth below 8 m ~~, span the range~~ with warming rates between 0.1–0.01 $^{\circ}\mathrm{C}\,\mathrm{year}^{-1}$~~and decrease exponentially with depth~~.

~~Our findings are discussed in the context of the existing literature.~~

## 1 Introduction

~~Permafrost degradation can induce severe feedbacks on the climate system and directly on society, the first most importantly by greenhouse gas release in sedimentary lowlands (???) and the latter by hazards from changing slope stability in densely populated mountain areas (Stoffel et al., 2014; Allen and Huggel, 2013; Haeberli, 2013; Fischer et al., 2012, 2013) or by damaging infrastructures lying on ice-rich permafrost layers or high-mountain summits (Bommer et al., 2010; Springman and Arenson, 2008) . Because of this sensitivity, permafrost~~

~~has been defined as an important cryospheric indicator of global climate change (e.g., Harris and Haeberli, 2001) .~~

The study of permafrost in mountain regions has become relevant in view of ongoing climate changes ~~(Etzelmüller, 2013; Harris et al., 2009; Gruber and Haeberli, 2007; Gruber, 2004)~~ (Stoffel et al., 2014 Although permafrost warming and increasing active layer thickness has been observed worldwide (Harris, 2003; Smith et al., 2010; Romanovsky et al., 2010; Wu and Zhang, 2008; Christiansen et al., 2010; Guglielmin and Cannone, 2012; Guglielmin et al., 2014a), in mountain areas the ~~complex topography, the~~ complexity of topography, ground surface type, ~~the snow cover , the~~ snow cover distribution, subsurface hydrology and geology strongly influence the thermal regime of mountain permafrost (Gruber and Haeberli, 2009) altering the response to changing environmental conditions.

~~In the Alps~~ For monitoring the huge spatial variability of mountain permafrost, a number of ~~permafrost monitoring sites exists~~ monitoring sites has been established through the Alps during the last years (e.g., Cremonese et al., 2011). At present the ~~long-term observation~~ collection of temperatures in boreholes provides the best direct evidence of permafrost state and evolution. ~~Moreover~~ Nevertheless the combination of geophysical methods and thermal monitoring ~~approaches, such as electrical resistivity tomography (ERT) and boreholes temperature, have been shown to be~~ is particularly suitable for ~~permafrost~~ long-term monitoring ~~(e.g., Hilbich et al., 2008; Haeberli et al., 2010; PERMOS, 2013) .~~

~~The long-term monitoring~~ of mountain permafrost because it provides crucial informations on ground ice/water content and structure (e.g., Hilbich et al., 2008; Haeberli et al., 2010; PERMOS, 2013) . The site of Cime Bianche has been designed with the main objective of monitoring the spatial variability of mountain permafrost. Moreover Cime Bianche site is a permanent observatory in the southern side of the European Alps, a region where permafrost observations are more sparse and younger compared to the northern side (e.g., Cremonese et al., 2011) , and where significant climatological differences occurs (e.g., Frei and Schär , 1998; Evans and Cox , 2005) .




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At Cime Bianche, the spatial variability of ~~ground surface temperature and related spatial variability on differing types of land covers is also crucial because of its direct~~ ground surface temperature (GST) is measured because it has crucial implications on the initialization, calibration and validation of numerical models (e.g., Guglielmin et al., 2003; Noetzli and Gruber, 2009; Hipp et al., 2014) ~~. Snow cover exerts an important influence on the ground thermal regime based on differing~~ and it is often used as a proxy of permafrost occurrence. One of the main challenges in the study of GST variability is the quantification of the thermal effect of snow cover given the influence that it can have on thermal regime trough different processes (Zhang, 2005; Luetschg et al., 2008; Guglielmin et al., 2014b). ~~In mountain environment, on gently inclined slopes, it~~ On gentle slopes, snow cover mostly causes a net increase of mean annual ground temperature due to ~~its~~ the insulating effect during winter, but timing ~~and thickness of first snow cover, the mean snow cover thickness as well as the timing of~~ of onset and melt-out, duration, thickness and interaction with ground surface characteristics strongly control the local magnitude of this effect ~~(Hoelzle et al., 2003; Brenning et al., 2005; Pogliotti, 2010) . In addition to the snow cover also the characteristics of the ground surface (e.g. bedrock, debris, grain size) have a major influence on both near-surface and sub-surface temperatures as well as on downward heat propagation (?Gubler et al., 2011; Rödder and Kneisel, 2012; Schneider et al., 2012)~~ (Hoelzle et al., 2003; Brenni Although a number of studies focused on snow-GST interaction exists (e.g., Zhang, 2005, for a review) , little is known on its spatial and temporal variability especially over complex alpine terrains.

~~The active layer of mountain permafrost~~ Beside the GST, also the active layer thickness (ALT) is measured at Cime Bianche. The World Meteorological Organization recognizes permafrost and active layer as one of the Essential Climate Variables selected for quantifying the impacts of climate change (e.g., Harris and Haeberli, 2001) . In the Alps, the active layer is of particular interest because ~~of its influence on~~ it directly affects slope processes (e.g., Fischer et al., 2012) and ~~infrastructure stability (e.g., Bommer et al., 2010) . Active layer development is mainly controlled by~~ infrastructures stability (e.g., Bommer et al., 2010; Springman and Arenson, 2008) . The active layer dynamics are controlled by a number of variables such as air temperature, solar radiation, topography, ground surface characteristics, ground ice/water content and by ~~the~~ timing, distribution and physical characteristics of the snow cover (Zhang, 2005; Luetschg et al., 2008; Scherler et al., 2010; Wollschläger et al., 2010; Zenklusen Mutter and Phillips, 2012). As a ~~consequence it displays both~~ consequence the active layer thickness (ALT) has an high spatial and temporal variability (Anisimov et al., 2002; Wright et al., 2009) ~~. In the Swiss Alps , the thickness of the active layer typically varies between 0.5 and 8depth (Gruber and Haeberli, 2009; PERMOS, 2009, 2013) .~~ which in the Alps may occur at very small scale.

Compared to the ~~deeper thermal regime, which reacts to long-term changes in climate the active layer~~ active layer which responds more to ~~short-term~~ short–term variations like seasonal snow and air temperature conditions~~(Beltrami, 2002) .~~

~~The~~ , the deeper thermal regime of permafrost reacts to long–term changes in climate (Beltrami, 2002) . The deep permafrost temperature regime ~~(at depths of 10 to 200) is a~~ is a sensitive indicator of the ~~decade-to-century climatic variability and long-term changes in~~ long-term climate variability and changes of the surface energy balance ~~. This is because the range of inter-annual temperature variations decrease significantly with depth, while decadal and longer time-scale variations penetrate to greater depths into permafrost with less attenuation. As a result the signal-to-noise ratio (i.e. long term variation vs. inter-annual variability) increases rapidly with depth and the ground acts as a natural low-pass filter of the climate signal (Romanovsky et al., 2002) . However, due to the rough topography and its influence on sub-surface thermal regime, the geothermal profiles in mountain permafrost are disturbed and their interpretation can be problematic (Gruber et al., 2004) . In addition, most of the Alpine permafrost temperature series cover time periods shorter than 20since the longest borehole temperature series in the Alps started in the Murtl–Corvatsch rock glacier in the late 1980s (Harris, 2003) . Therefore appropriate statistical models to analyze trends of decadal or even shorter time series are needed in order to extract the maximum information from such short time series (Bence, 1995; Helsel and Hirsch, 1992) . Although these time series do not yet allow~~

~~long-term trend analyses, they allow first assessments on the thermal state of the permafrost and its development over the past decade (Zenklusen Mutter et al., 2010) .~~

~~Within this context, the monitoring site of Cime Bianche, on the Italian side of the Western Alps, has been designed for the long-term monitoring of permafrost and ground surface temperatures. The~~ (Romanovsky et al., 2002) and trend analysis of temperature time-series allows to detect signals of past and ongoing changes of permafrost (e.g., Isaksen et al., 2001) .

The overall objective of this paper is to provide a first synthesis on the state and recent evolution of permafrost ~~related variables, focusing on: (~~at Cime Bianche. In particular we present i) the spatial and temporal variability of ~~ground surface temperatures in relation to snow cover , (~~GST and its relation with snow cover ii) the small scale (~~20–40) spatial variability of the active layer thickness and (~~30m) ALT differences and iii) the warming trend of deep permafrost ~~temperatures~~temperature.

## 2 Data and methods

### 2.1 Site description

The Cime Bianche monitoring site ~~(CB)~~ is located in the western Alps at the head of the Valtournenche Valley (Valle d'Aosta, Italia, $45°55'$ N–$7°41'$ E) on the Italian side of the Matterhorn, at 3100 m a.s.l. (Fig. 1). The site is located on a small plateau slightly westward degrading characterized by terraccettes, convexities and depressions that result in a high spatial variability of snow cover thickness during winter.

The bedrock lithology is homogeneous, mainly consisting of garnetiferous micaschists and calcschists belonging to the upper part of the Zermatt–Saas ophiolite complex (Dal Piaz, 1992). The bedrock surface is highly weathered and fractured, locally resulting in a cover of coarse-debris deposits with a thickness ranging from few centimeters to a couple of meters. The presence of small landforms like gelifluction lobes (between 0.6 to almost 5 m in length) and sorted polygons of fine material (with diameters ranging between 0.6 to 3.4 m) suggests the ~~potential~~ presence of permafrost and cryotic ~~phenomena~~phenomenon.

The climate of the area is slightly continental. The long-term mean annual precipitation is reported to be about 1000 $\mathrm{mm\,year^{-1}}$ for the period 1931–1996 (Mercalli and Cat Berro, 2003) while the in-situ records show a mean of 1200 $\mathrm{mm\,year^{-1}}$ for the period 2010–2013. The mean annual air temperature (MAAT) is about $-3.2\,^{\circ}\mathrm{C}$ (mean 1951–2011). Mean monthly air temperatures are positive from June to September while February and July are respectively the coldest and the warmest months. The site is very windy and mainly influenced by NE–NW air masses. The wind action strongly contributes to the high spatial variability of snow cover thickness.

Permafrost research in the area started in the late 1990s (Guglielmin and Vannuzzo, 1995) with repeated campaigns of BTS (Bottom Temperature of Snow) measures and glaciological observations showing that the monitoring site was probably ice-covered during the climax of the Little Ice Age. In 2003, as a preliminary investigations for site selection, the potential permafrost occurrence in the area was assessed using results from BTS, VES (Vertical Electrical Soundings) and ERT (Electrical Resistivity Tomography) and the application of numerical models like Permakart (Keller, 1992) and Permaclim (Guglielmin et al., 2003). ~~Results of this preliminary analysis (unpublished) revealed that the area is characterized by the presence of discontinuous permafrost.~~

## 2.2 Instrumentation

The site instrumentation started in 2005 and has been progressively upgraded during the following years. The current setting is nearly unchanged since August 2008 and consists of: two boreholes, a spatial grid of ground surface temperatures measures and one automatic weather station.

### 2.2.1 Boreholes

A deep (DP) and a shallow (SH) borehole, reaching a depth of 41 and 6 m respectively, located at a distance of about 30 m ~~apart~~ (Fig. 1), have been drilled in 2004 with core-destruction method. Both boreholes are 127 mm in diameter with a 60 mm sealed PVC pipe for sensor housing. The boreholes are equipped with thermistor chains based on resistors type YSI 44031 (resolution

0.01 °C, absolute accuracy ±0.05 °C and relative accuracy ±0.02 °C). Both chains have been calibrated by the manufacturer few days before installation. Sensors depths in meters from the surface are 0.02, 0.3, 0.6, 1, 1.6, 2, 2.3, 2.6, 3, 3.3, 3.6, 4, 4.6, 5.9 for SH and 0.02, 0.3, 0.6, 1, 1.6, 2, 2.6, 3, 3.6, 4, 6, 8, 10, 12, 14, 15, 16, 17, 18, 20, 25, 30, 35, 40, 41 for DP. In each borehole, the shallower sensors (0.02 and 0.3 m) are cabled on two independent chains and are used to measure the ground surface temperature (GST) outside the PVC tube in order to avoid the thermal disturbance of the casing. Temperatures are sampled every 10 min and recorded by a Campbell Scientific CR800 datalogger. The system is equipped with a GPRS module for daily remote data transmission.

### 2.2.2 Ground surface temperature grid (GSTgrid)

A small grid (40 m × 10 m) is used for monitoring the spatial variability of GST (Ground Surface Temperature). The grid consists of 5 nodes, 4 at the corners and 1 in the center (Fig. 1). Each node is equipped with 2 platinum resistors PT1000 (resolution 0.01 °C, accuracy ±0.05 °C) buried in the ground at depths of 0.02 and 0.3 m (according to Guglielmin, 2006). Ground temperatures are recorded hourly by a Geoprecision D-Log12 datalogger.

For the analysis, also ~~the~~ GST measured at the two boreholes ~~are~~ is included, thus data from 7 nodes are ~~overall considered~~used for the analysis. Ground surface at each node is mainly characterized by coarse-debris with a fine matrix of coarse-sand and fine-gravel. At each node, the sensors are placed in the matrix thus local ground conditions are nearly homogeneous between all nodes. In contrast, snow cover ~~conditions~~ depth and duration sharply differ across the grid nodes. ~~Based~~ For this reason, based on field observations and temperature time series analysis (Schmid et al., 2012) the ~~set~~ dataset is divided in *snow-free* and *snow-covered* nodes. The first group includes 3 nodes characterized by shallow or intermittent winter snow cover while the latter group includes 4 nodes that clearly show a long lasting deep snow cover ~~with a damping of~~ damping temperature oscillations during winter (Fig. 1).

### 2.2.3 Automatic weather station

An automatic weather station (AWS) is installed just above the borehole SH since 2006. Air temperature and relative humidity, atmospheric pressure, wind speed and direction, incoming and outgoing short- and long-wave solar radiation and snow depth are recorded every 10 min by a Campbell Scientific CR3000 datalogger. The system is equipped with a GPRS module for the daily remote data transmission. Since September 2011 a second snow depth sensor has been installed in the surroundings of the DP borehole. Finally solid and liquid precipitations are measured since January 2009 by an OTT Pluvio$^2$ system.

## 2.3 Data analysis

This section reports a short description of the ~~criteria applied for the calculation of the synthesis parameters used~~ methods used for the calculations of synthesis parameters considered in this study.

MAGT is the mean annual ground temperature at a specific depth (m) (e.g. $\mathrm{MAGT}_{10}$).

MAGST is the mean annual ground surface temperature. ~~It is calculated with the sensors at 0.02or 0.3of depth (specified each time).~~

ALT is the active layer thickness defined as the maximum depth (m) reached by the 0 °C isotherm at the end of the warm season. It is calculated considering the maximum daily temperature at each sensor depth and interpolating between the deepest sensor with positive value and the sensor beneath. The maximum of the resulting vector and the corresponding day are named ALT and ALTday respectively. Such procedure is applied on the warmest period ~~(in depth)~~ of the year, here fixed from 1 August to 30 November. Considering the absolute accuracy of temperature sensors (±0.05 °C) the uncertainty of ALT estimation has been quantified at $0.075 \pm 0.01$ m. For this reason all ALT values are rounded to decimeters.

TTOP is the MAGT at the top of the permafrost table (Smith and Riseborough, 1996). It is calculated by interpolation of the MAGT at depth of the ALT that is considering the first sensors ~~just above and the first just~~ above and below the ALT.

THO is the thermal offset within the active layer and is computed as TTOP-MAGST (Burn and Smith, 1988).

ZAA is the depth beneath which there is almost no annual fluctuation in ground temperature, nominally smaller than $0.1\,^{\circ}\mathrm{C}$ (van Everdingen, 2005). The annual fluctuation (AF) is calculated at each sensor depth as the difference between annual maximum and annual minimum of the mean daily temperatures. The ZAA is calculated by interpolation between the deepest sensor with AF greater than $0.1\,^{\circ}\mathrm{C}$ and the sensor beneath. ~~On deep nodes time series (below 8), a moving average~~When necessary, a moving average, with a window of 360 days, is applied on ~~hourly data before the~~ deep nodes data (below $8\,\mathrm{m}$) before daily aggregation to remove ~~the electrical sensor's noise(sometimes present~~electrical noise. ($\pm 0.01\,^{\circ}\mathrm{C}$).

All the ~~synthesis~~ parameters listed above, with the exception of ALT, are computed considering as reference period the hydrological year (beginning 1 October). All the analysis are performed with the free statistical software R (R Core Team, 2014). When appropriate, the variability of the results is expressed in terms of standard error ($\mathrm{se} = \mathrm{sd}/\sqrt{n}$ where se is standard error, sd is standard deviation and $n$ is the sample size).

## 2.4 Snow cover duration and snow-free days

In order to investigate the effect of snow cover duration and air temperature on MAGST the method of Schmid et al. (2012) is applied on *snow-covered* nodes, considering only the sensors at $0.02\,\mathrm{m}$. This method allows to extract, directly from ground temperature measures, the date of snow onset (OD) and the date of snow melt (MD) for each hydrological year. From OD and MD, it is possible to calculate (i) the duration of snow cover (SD, Fig. 2) as the number of days between OD and MD, and (ii) the number of snow-free days as the sum of remaining days of autumn and summer. The latter period is used as reference for calculating the mean annual air temperature of snow-free days (MAATsf, Fig. 2).

## 2.5 Trend analysis

In order to look for linear trends that might reflect warming, two non-parametric methods are applied to boreholes temperatures: Mann–Kendall test (MK) (Mann, 1945; Kendall, 1948) and Sen's slope estimator (SS) (Sen, 1968). These methods are commonly used to assess trends and related significance levels in hydro-meteorological time series such as water quality, stream flow, temperature and precipitation (e.g., Gocic and Trajkovic, 2013; Kousari et al., 2013). The reason for using non-parametric statistical tests is that they are more suitable for non-normally distributed data and are not sensitive to outliers or abrupt changes.

The procedure chosen includes (i) a pre-whiten of the data for removing the lag-1 autocorrelation components as recommended by von Storch and Navarra (1999) (see also Hamed, 2009 and Bence, 1995 ), (ii) fitting of the trend's slope with SS and (iii) testing of trend ~~'s~~ significance level ($p$ value) with MK. Such a procedure is implemented in the R-package zyp (Bronaugh et al., 2013).

Given the short climatological time-span of the ~~given borehole 's~~ borehole observations, a seasonal detrending is recommended, as suggested by Helsel and Hirsch (1992), for better discerning the long-term linear trend over time. Thus a seasonal decomposition based on loess smoother (Cleveland, 1979; Cleveland et al., 1990) is applied on the monthly aggregated time series of each borehole before applying SS and MK (Fig. 3). Such a seasonal detrending method is implemented by the R-function *stl* (R Core Team, 2014).

## 2.6 Geophysics

At the end of the summer 2013, two geophysical surveys ~~took place at the Cime Bianche~~ have been realized with the objective to assess the composition of the subsurface. A first explorative geoelectric (ERT) profile was performed on 16 August 2013, and on 9 October 2013 the ERT measurement was repeated in combination with one refraction seismic tomography (RST) along the same line (see Fig. 1). Combining refraction seismic and ERT measurements enables to unambiguously identify the subsurface materials in the ground. Due to very different specific resistivities, ERT is best suited to differentiate between ice and water whereas the distinction between air and ice can more easily be accomplished by RST, because of large contrasts between their respective $p$ wave velocities.

### 2.6.1 Electrical Resistivity Tomography (ERT)

A 94 $\mathrm{m}$ long electrode array composed of 48 electrodes with 2 $\mathrm{m}$ spacing was installed along a straight line less than two meters far from the two boreholes (Fig. 1). Current was injected using varying electrode pairs, and the resulting potential differences were automatically measured by a Syscal (Iris Instruments) for each quadrupole possible with the Wenner–Schlumberger configuration (529 measurements, 23 depth levels). The electrode locations were marked with spray paint and a number of electrodes were left on site to facilitate further measurements.

The measured apparent resistivity datasets were then inverted using the RES2DINV software (Geotomosoft, 2014) with the following set-up. A robust inversion constraint was applied to avoid unrealistic smoothing of the calculated specific resistivities. Additionally the depth of the model layers was increased by a factor 1.5 and an extended model was used to match the model grid of the corresponding seismic inversion. Note, that for geometric reasons, the two lower corners of the resulting tomograms have very low sensitivity to the obtained data and should not be over-interpreted. Finally, a time-lapse inversion scheme was applied to the two ERT data sets yielding the percentage of resistivity change from the first measurements to the second. Here, an unconstraint inversion was chosen, meaning that the ERT measurements were inverted independently.

### 2.6.2 Refraction Seismic Tomography (RST)

The measurements were conducted using a Geode seismometer (Geometrics) and 24 geophones placed with 4 $\mathrm{m}$ spacing. A seismic signal was generated in-between every second geophone pair by repeatedly hitting a steel plate with a sledge hammer. To improve the signal-to-noise ratio the signal was stacked at least 15 times at each location. Two additional offset shot points were measured (3 $\mathrm{m}$ before the first geophone and 6 $\mathrm{m}$ beyond the last one) in order to maximize the spatial resolution and match the ERT profile length and depth of investigation.

The first arrivals of the seismic $p$ wave were manually picked for each seismogram using the software REFLEXW (Sandmeier, 2014). A Simultaneous Iterative Reconstruction Technique (SIRT) algorithm was then used to reconstruct a 2-D tomogram of $p$ wave velocity distribution based on the obtained travel times. Starting from a synthetic model the travel times are calculated and compared to the measured ones. The model is then updated iteratively by minimizing the residuals between measured and calculated travel times.

## 3 Results

### 3.1 Ground surface temperatures

Figure 4 shows MAGST at 2 and 30 cm ~~of depth for each hydrological year calculated~~ on the seven GST nodes. ~~The analysis of the GST dataset shows a mean range of the spatial variability of $2.5 \pm 0.15\,^{\circ}\mathrm{C}$ versus a mean range of the inter-annual variability of $1.6 \pm 0.12\,^{\circ}\mathrm{C}$.~~ Some years (e.g. 2009, 2011, 2013) show a ~~-~~MAGST spatial variability~~that can be~~, evaluated as the range of MAGST measured in all nodes, greater than $3\,^{\circ}\mathrm{C}$, ~~far exceeding the observed mean~~ which clearly exceeds the inter-annual variability.

~~The time series analysis of snow-covered nodes (Schmid et al., 2012) reveals that the mean duration of the insulating snow cover is about 270~~In general, considering all 7 years, we observed that mean spatial variability ($2.5 \pm 0.15\,^{\circ}\mathrm{C}$) is greater than mean inter-annual variability ($1.6 \pm 0.12\,^{\circ}\mathrm{C}$). The results are similar at both depth. The difference between MAGST measured at 2 ~~while on snow-free nodes such effect is only sporadic or absent (not shown).~~ cm and 30 cm is, on average, $0.4 \pm 0.11\,^{\circ}\mathrm{C}$ with deeper sensors usually warmer than the shallower ones. On average the thermal offset due to snow cover is about $1.5 \pm 0.17\,^{\circ}\mathrm{C}$ with ~~snow covered nodes usually warmer than snow-free~~ *snow-covered* nodes being warmer than *snow-free* nodes. These observations confirm that the warming and cooling effects of respectively a thick and thin snow cover (Zhang, 2005; Pogliotti, 2010) can coexist over short distances ($< 50\,\mathrm{m}$) and lead to high spatial variability of the GST.

The ~~results are similar at both depth. The difference between MAGST measured at 2~~duration of snow (SD) on *snow-covered* nodes is on average $270 \pm 6$ days with a mean range of spatial variability of 28 ~~and 30~~days, and a mean range of inter-annual variability of 48 ~~is, on average, $0.4 \pm 0.11\,^{\circ}$C with deeper sensors usually warmer than the shallower ones~~days. To disentangle the influence of snow and air temperature on surface temperature in *snow-covered* nodes, we tested the relationship between MAGST and mean annual air temperature (MAAT), mean air temperature during snow-free days (MAATsf) and SD. We found no significant correlation between MAGST and MAAT. Figure 5 shows the scatterplot between SD (A), MAATsf (B) and MAGST: MAGST is significantly correlated to both SD ($p < 0.05$) and MAATsf ($p < 0.001$) with the latter explaining the higher portion of variance ($R^2 = 0.39$). Being computed on snow-free days, MAATsf is mainly controlled by air temperature but partially also by the duration of snow cover, therefore integrating the relative contribution of both components (snow duration and air temperature) on MAGST.

### 3.2 Active layer

Table 1 summarizes the active layer ~~variables~~ parameters observed in the two boreholes. Since August 2008 data are available at both SH and DP boreholes hence results of ALT can be compared over 6 years while MAGST, TTOP and THO over 5 years (shaded rows in Table 1). Missing values (column %NA) in both boreholes are lower than 4 % in all years.

ALT is the ~~variable~~ parameter showing the greater difference between the two boreholes with a mean of ~~2.75~~2.7 $\pm$ ~~0.35~~0.3 m in SH and ~~4.78~~4.7 $\pm$ ~~0.26~~0.2 m in DP. The mean inter-annual difference of ALT between the two boreholes is ~~2.03~~2.0 $\pm$ ~~0.12~~0.1 m while the mean absolute inter-annual variability of ALT at borehole level is ~~1~~1.0 $\pm$ ~~0.13~~0.1 m. In both boreholes the maximum ALT has been recorded in 2012 while the minimum in 2010. ALT-Day is normally anticipated in DP (except 2013) with differences ranging from few days (e.g. 2009) to more than 3 weeks (e.g. 2012). The MAGST is on average slightly lower in SH which normally shows a thinner winter snow cover compared to DP (Fig. 6). The TTOP values are very similar, around $-0.9\,^{\circ}$C. The THO is negative in both boreholes (except 2013) with a mean value of about $-0.5\,^{\circ}$C in DP and $-0.3\,^{\circ}$C in SH.

The values of Table 1 show that all the active layer ~~variables~~ parameters are very similar between the two boreholes with the only exception of ALT which in DP is nearly double than in SH. To better understand the causes of this difference, the daily mean temperatures at selected depths within the active layer of both boreholes and the corresponding snow cover thickness are compared in Fig. 6. Despite a consistently thinner snow depth is recorded on SH compared to DP (mean difference $\sim 41 \pm 14\,\mathrm{cm}$ during the winter seasons 2012 and 2013), the duration of the insulating snow cover is similar ($250 \pm 16\,\mathrm{days}$ for SH vs. $254 \pm 17\,\mathrm{days}$ for DP) and effectively does not determine a ~~big~~ large difference in MAGST (Table 1). Consequently the snow cover regimes ~~above the two~~ of the 2 boreholes can be considered equivalent~~and snow probably plays a major role for the inter-annual variability of ALT while the observed spatial differences must be explained otherwise~~.

For these reasons we hypothesize that ALT difference may be related to a greater ice/water content in SH compared to DP. This is ~~also~~ revealed by the geophysical survey (see Sect. 3.4 and Fig. 9) and can be inferred by temperature at greater depth. At $1.6\,\mathrm{m}$ (red lines, Fig. 6) a pronounced zero-curtain effect can be observed in SH (dashed lines) twice per year, (i) from snow melt to mid-summer and (ii) from the snow onset to mid-winter, while a similar behavior is missing in DP. The occurrence of the zero-curtain reflects a large consumption of energy, both for ice melting during summer and water freezing during winter resulting in lower temperatures of SH. Deeper down, the summer heat wave in SH is further delayed if compared to DP: at $3\,\mathrm{m}$ in SH (dashed blue lines) the zero-curtain effect is almost continuous from late-summer to early-winter (e.g. in 2010 and 2011) and it is not possible to see a breaking point between melting and freezing processes. Such a behavior is totally missing in DP. It is also interesting to observe that freezing zero-curtain ends nearly contemporary at 1.6 and $3\,\mathrm{m}$ and is followed by a rapid temperature drop.

In conclusion, the ALT at Cime Bianche shows a pronounced spatial variability probably caused by the variability of ice/water content in the sub-surface and associated energy consumption resulting from freezing and melting processes.

### 3.3 Permafrost temperature and warming trend

Due to the small depth reached by the borehole SH, the analysis of ~~deep temperature and~~ permafrost temperature is limited to the borehole DP. Looking at temperature profiles with depth (Fig. 7), the permafrost layer at Cime Bianche has a thickness greater than 40 m and a mean temperature of about $-1.2\,^{\circ}\mathrm{C}$. The ZAA varies across years and during the observation period ranged from a minimum of 14.2 m in 2011 to a maximum of 16.2 m in 2013 (Table 2). During the observed years, both minimum (solid lines) and maximum (dashed lines) temperature profiles (deeper than ~~8~~6 m) tend to progressively shift toward warmer temperatures (Fig. 7). The only exceptions are represented by the 2011 ~~'s~~ maximum and the 2009 ~~'s~~ minimum, the latter only above 10 m of depth.

The observed temperature shift is also quantitatively supported by the trend analysis~~performed on deeper sensors (range 8–41of depth, Fig. 8)~~. The analysis ~~has been~~ was conducted at all depths~~within both boreholes but only trends~~ , but only deeper temperatures (below 8 m~~have shown to be significant~~ ) show significant trends (Kendall's $p$ value ~~of the time series~~ $< 0.01$)~~hence only DP borehole is shown~~. Figure 8 reveals that a pronounced warming rate ~~is present at all depths although it exponentially decrease with depth, varying from around~~ ranging from $0.1\,^{\circ}\mathrm{C\,year^{-1}}$ at 8 m to $0.007\,^{\circ}\mathrm{C\,year^{-1}}$ at 41 m can be observed. The upper boundaries of the confidence intervals (CI) are systematically unbalanced toward higher values and the lower boundaries are always above zero. This means that, at all depths, the statistical distribution of all possible fitted trends is ~~asymmetric towards greater values and also that negative significant trend have never been fitted by the model.~~

~~Based on the trend analysis, is possible to conclude~~ positively skewed. Based on these analysis, it is concluded that permafrost at Cime Bianche is ~~degrading with a warming rate decreasing with depth~~warming because significant positive warming rates are reported below 8 meter.

### 3.4 Geophysics

Figure 9 shows the final distribution of specific resistivity for the two ERT measurements, the percentage of change in the model resistivity between the two time steps and the $p$ wave velocity distribution over the same subsection. Additionally, the surface characteristics and a detailed analysis of the geophysical properties at the two borehole locations (SH and DP, Fig. 10) are included in the analysis.

The overall characteristics of both ERT profiles are very similar (Fig. 9a and b) and can be divided into three main zones: a low resistive layer directly below the surface varying between 2.5 $\mathrm{m}$ thickness at the top of the slope to 7 $\mathrm{m}$ thickness at the bottom, respectively, two high resistive areas with values exceeding $20\,000\,\Omega\,\mathrm{m}$ located below the superficial layer (from the start of the subsection to the superficial borehole, 0–34 $\mathrm{m}$ and between 40–52 $\mathrm{m}$) and a less high resistive area on the lower part of the profile below 5 $\mathrm{m}$ depth.

Comparing the two ERT data sets (cf. also the time-lapse image in Fig. 9c), one can observe a clear increase of the uppermost low resistive layer between August and October which is coherent with a thickening of the active layer observed in the borehole temperature during this period. Another main difference between the two measurements is the apparition of two low resistive zones at 34 $\mathrm{m}$ and 60 $\mathrm{m}$ visible down to 10 $\mathrm{m}$ and 15 $\mathrm{m}$ depth, respectively. These areas can also be seen in the ERT tomogram from August, but much less developed and limited to a few meters. In addition, the very high resistive area located in the upper part of the profile is much smaller and displaced of about 5 $\mathrm{m}$ towards the lower part of the profile in the second measurement.

These changes are clearly visible in blue (increase) and red (decrease) colors in Fig. 9c. As said before the two datasets were inverted independently within the time-lapse scheme. A constrained inversion (results not shown here) would yield very similar overall distribution of resistivity changes the only difference being a much smaller range of values. The large area of resistivity increase located just above the superficial borehole location and reaching down to the bottom of the profile corresponds to the displacement of the high resistive area observed in the ERT tomograms.

The RST tomogram exhibits much less lateral variations than the ERT results (see Fig. 9d), pointing to the influence of liquid water in the ERT results. One can clearly see a relatively slow layer with velocities between 300 and $1500\,\mathrm{m\,s^{-1}}$ (red and dark red colors) just below the surface with varying thickness between 3 and $5\,\mathrm{m}$. This layer is thickest in the vicinity of the shallow borehole (SH) and thinnest at DP ($64\,\mathrm{m}$). Below this first layer the velocities increase steadily until reaching the maximum (around $6400\,\mathrm{m\,s^{-1}}$). The rate of velocity increase is strongest around $40\,\mathrm{m}$ and there is a clear distinction between the upper part of the profile (until $45\,\mathrm{m}$) and the lower one. At depth the high velocity zone is present in the upper part and not in the lower part of the profile. Conversely the velocities at the surface are much higher in the lower part (especially around DP) than in the upper part.

Both geophysical profiles show clear differences in the subsurface properties at the boreholes locations. To relate in detail the results yielded by the geophysics and the measured temperature, the vertical distribution of specific resistivity, seismic velocity and ground temperature at SH and DP are shown in Fig. 10.

## 4 Discussion

### 4.1 Ground surface temperatures

In this study both the inter-annual and the spatial variability of MAGST within a restricted area have been analyzed and compared: the results show that, at Cime Bianche, the mean range of spatial variability ($2.5\pm0.15\,^{\circ}\mathrm{C}$) far exceeds the mean range of observed inter-annual variability ($1.6\pm0.12\,^{\circ}\mathrm{C}$). Given the comparatively homogeneous characteristics of the ground surface at the sensors ~~'~~ locations, such a variability is essentially caused by the heterogeneity of the snow cover thickness both in space (effect of wind redistribution and micro-morphology) and time (effect of variable weather conditions and precipitations). In particular the combination of snow cover duration and air temperature during the snow-free period are the main factors controlling MAGST values. This is true not only for *snow-free* nodes but also for nodes experiencing long-lasting (270 days) yet highly variable (28 days) snow cover.

The thermal effect of snow cover on ground surface temperature has been extensively analyzed (e.g., Goodrich, 1982; Keller and Gubler, 1993; Zhang, 2005; Luetschg et al., 2008). In recent years, with the advances of mini-loggers technology, the number of field experiments aimed at the characterization of the spatial variability of GST has grown. Recently Gubler et al. (2011) observed a spatial variability of more than $2.5\,°\mathrm{C}$ within a number of square homogeneous areas of $10\,\mathrm{m} \times 10\,\mathrm{m}$. In Norway, Isaksen et al. (2011) report that MAGST varied by $1.5$–$3.0\,°\mathrm{C}$ over distances of 30–100 m in a region characterized by mountain permafrost. Rödder and Kneisel (2012) observed ranges exceeding $4.3\,°\mathrm{C}$ between adjacent loggers ($< 50\,\mathrm{m}$), although this values include inhomogeneities of surface characteristics. Similar results were obtained by Gisnås et al. (2014) who observed a variability of the MAGST of up to $6\,°\mathrm{C}$ within heterogeneous areas of $0.5\,\mathrm{km}^2$.

The inter-annual variability of MAGST caused by snow is also well known and documented by a number of studies (Romanovsky et al., 2003; Hoelzle et al., 2003; Karunaratne and Burn, 2004; Brenning et al., 2005; Etzelmüller, 2007; Ødegård and Isaksen, 2008; Schneider et al., 2012) but rarely has been explicitly analyzed and quantified. An exception in the Alps is represented by Hoelzle et al. (2003) who reported an inter-annual variability of $\pm 2.7\,°\mathrm{C}$ measured during two seasons on 8 mini-loggers with ~~differing~~ different surface characteristics in the Murtèl–Corvatsch area. Our results thus report a more robust quantification of the mean inter-annual GST variability ($1.6 \pm 0.12\,°\mathrm{C}$), based on a longer time series (7 years).

The obtained results are very similar at both measurement ~~depth~~depths. Given such a small difference and the agreement of temperature fluctuations between 2 and 30 cm, it is arguable that to describe the spatial variability of GST and run long-term GST observations, measures at two or more depth are not needed.

## 4.2 Active layer

In this study both ~~thaw depth~~ ALT and temperature fluctuations within the active layer of two adjacent boreholes have been compared. Such experimental design provides direct evidence of the small-scale spatial variability of the ALT and ~~allow to compare~~ allows to evaluate the effect of ~~snow cover and~~ ice/water content on sub-surface ~~temperatures~~temperature.

From 2009 to 2013 the ALT at Cime Bianche varied within ~~2~~ 2.0 and 5.5 m with a mean inter-annual variability of ~~$1 \pm 0.13$~~$1.0 \pm 0.1$ m. These ranges ~~of thaw depth~~ and the observed inter-annual variability of ALT are comparable to those recorded in other alpine sites ~~(PERMOS, 2013) and the same is true for the observed inter-annual variability (Anisimov et al., 2002; Christiansen, 2004; Schneider et al., 2012; Smith et al., 2010)~~ (Anisimov et al the Swiss Alps, the thickness of the active layer typically varies between 0.5 and 8 m depth (Gruber and Haeberli, 2009; PERMOS, 2009, ?) .

ALT in the borehole SH is systematically lower than in DP (mean difference ~~$2.03 \pm 0.15$~~$2.0 \pm 0.1$ m) even though all the active layer parameters (MAGST, TTOP, THO see Table 1) are very similar between the two boreholes. On one side such a similarity suggests that snow cover regimes above the two boreholes are nearly equivalent thus snow probably plays a major role ~~just for~~ only on the inter-annual variability of ALT. On the other side the pronounced spatial variability of ALT is probably caused by the variability of ice/water content in the sub-surface and associated variation of energy consumption resulting from freezing and melting processes. Probably snowmelt and meltwater infiltration along preferential discontinuities (a borehole acts a discontinuity itself) is different between SH and DP. Hilbich et al. (2008) observed at Schilthorn (Swiss Alps) a similar situation between two boreholes 15 m apart, ascribing the lower ALT of one borehole to the higher moisture contents (and related freezing) caused by preferential water flow paths from the surrounding slopes. Schneider et al. (2012) analyzed the thermal regime of four adjacent boreholes drilled on differing material (coarse debris, fine debris and bedrock) at Murtèl–Corvatsch (Swiss Alps) and recognized meltwater and ice content as the main responsible for the observed ALT spatial variability.

The different amount of available water in the active layer of the two boreholes is also reflected by the occurrence of the zero-curtain in the borehole SH and its absence in the borehole DP. In the upper part of the active layer a pronounced zero-curtain can be observed two times per year, (i) from snow melt to mid-summer (spring zero-curtain) and (ii) from the snow onset to mid-winter (autumn zero-curtain). Recently Zenklusen Mutter and Phillips (2012) deeply analyzed similar behaviors on a sample of 10 boreholes in Switzerland observing that, on average, the duration of the spring zero-curtain is usually shorter than the autumn one and is strongly dependent on snow depth at the end of the winter. At Cime Bianche, in the deeper part of the active layer such a distinction between spring and autumn zero-curtain is not always possible. As observed also by Rist and Phillips (2005) it may happen that, below a certain depth, the ground temperature does not become positive because the energy from the summer heat wave is not sufficient to melt all ice before the onset of the subsequent winter season. This continuous zero-curtain is more probable when ~~an~~ a higher amount of meltwater is available (Scherler et al., 2010; Kane et al., 2001) and can occur at ~~differing~~ different depth from year to year strongly influencing the resulting ALT.

### 4.3 Permafrost temperature and warming trend

In order to look for trends that might reflect warming, two non-parametric methods ~~have been~~ were applied to boreholes temperatures time series. The detected linear trends are statistically significant (Kendall's $p$ value $< 0.01$) only at depth below 8 m~~and~~. Probably, in the first meters, the seasonal and inter-annual variability of temperatures is so strong that significant trends are not detectable, despite a seasonal detrending has been applied for removing such high-frequency oscillations (see also section 2.5). The detected trends span the range 0.1–0.01 $^{\circ}\mathrm{C\,year}^{-1}$ ~~decreasing exponentially with depth. The latter evidence suggests~~ suggesting that at Cime Bianche ~~the~~ permafrost is warming~~from surface~~.

As discussed also by Zenklusen Mutter et al. (2010), the detection of trends on time series covering a short time-span needs caution and adoption of specific criteria. Moreover the estimation of uncertainties and significance levels ~~are~~ is also fundamental to facilitate the comparisons of trends between differing sites and for reproducing trend ~~'s~~ detection methods on others datasets.

Permafrost warming trends have been observed worldwide, both at high ~~latitudes~~ latitude (Harris, 2003; Osterkamp, 2005; Smith et al., 2005; Osterkamp, 2007; Isaksen et al., 2007; Farbrot et al., 2013; Jonsell et al., 2013) and at lower ~~latitudes~~ latitude in high mountain (Vonder Mühll, 2001; Harris, 2003; Gruber, 2004; Wu and Zhang, 2008; Phillips and Mutter, 2009; Zenklusen Mutter et al., 2010; PERMOS, 2013; Haeberli, 2013).

Recently in the Alps Zenklusen Mutter et al. (2010) detected ~~linear trends applying generalized least-square methods~~ trends on daily temperature time series of two boreholes in the Muot da Barba Peider ridge (Eastern Swiss Alps). For the deep frozen bedrock between 8 and 17.5 m a general warming trend was found, with significant ($p$ value $< 0.05$) values ranging respectively from 0.042 to 0.025 °C year$^{-1}$. At Cime Bianche a similar range of warming rate ~~exists~~ was found between 16 and 20 m. The substantial difference between the two sites is that the Swiss boreholes are drilled at the top of a NW-oriented ridge with a mean slope of 38° thus with a strong 3-D thermal effect induced by topography (Noetzli et al., 2007). In the mountains of Scandinavia Isaksen et al. (2007) reports ~~linear~~ warming trends between 20 and 60 m of depth ranging from about 0.05 to 0.005 °C year$^{-1}$ respectively over three sites, while Isaksen et al. (2011) found an increase in mean ground temperature between 6 and 9 m of depth at two sites, with rates ranging from about 0.015 to 0.095 °C year$^{-1}$. Recently at Tarfala mountain station (Sweden) Jonsell et al. (2013) found ~~linear~~ trends over 11 years (2001–2011) ranging from 0.047 to 0.002 °C year$^{-1}$ between 20 and 100 m of depth respectively.

The absolute values of warming rates are difficult to compare because of ~~differing~~ different site characteristics, ~~differing~~ geographical regions and ~~differing~~ methods used for trend ~~'s~~ detection. Nevertheless, some similitudes exist between our and the above mentioned case studies: (i) trends are difficult to detect at shallower depth because of the higher seasonal variability of temperatures (ii) warming trends are mainly significant below 8–10 m of depth, (iii) warming trends exponentially decrease with depth, (iv) there is no evidence of negative (cooling) trends at any depth in recent literature.

### 4.4 Geophysics

Given the relatively high resistivity and $P$ wave velocities along the profiles, the presence of permafrost observed in the borehole data is confirmed by the geophysics over the whole profile length (Fig. 9). Moreover a clear discrepancy between the upper part of the profile, where SH is located, and the lower one with borehole DP can be seen in both, the ERT and the RST data.

At DP the $P$ wave velocities indicates the presence of weathered bedrock close to the surface whereas at SH a layer of coarse-debris deposits in the uppermost 5 m is confirmed by very low

$P$ wave velocities. Conversely, $P$ wave velocities at depth are higher for SH ($\sim 6000\,\mathrm{m\,s^{-1}}$) than for DP ($\sim 5000\,\mathrm{m\,s^{-1}}$, see also Fig. 10). This difference, also seen in the resistivity data (around $17\,000\,\Omega\,\mathrm{m}$ at SH and $13\,000\,\Omega\,\mathrm{m}$ at DP), would indicate that a larger ice content is present in the upslope part of the profile than in the lower part. This is in good agreement with the spatial variation of ALT highlighted in Sect. 3.2 and the zero curtain phase observed only at SH (see Fig. 6).

The low resistivity and low velocity layer near the surface, which thickness increases visibly between August and October in the ERT data, is considered to be the active layer. Figure 10 compares the vertical distribution of specific electrical resistivity, $P$ wave velocity and temperature for both boreholes and dates. On the first glance, there seems to be a mismatch between resistivity and temperature regarding ALT for SH. However, in SH borehole temperatures in August show constant values at the freezing point between 1 and $3\,\mathrm{m}$ depth (between 2 and $4\,\mathrm{m}$ in October), the deeper level being the depth of the sharply increasing resistivity values. As resistivity is sensitive to the liquid water content its values will not increase significantly before most of this liquid water has been frozen, coinciding with a temperature increase to values below the freezing point (e.g., Hauck, 2002). Due to the higher water/ice content in SH, this ~~phenomena~~ phenomenon ($\sim$ vertical zero-curtain) is only seen in SH and not in DP.

In addition, considering the $P$ wave velocities ($500\,\mathrm{m\,s^{-1}}$ at SH and $3000\,\mathrm{m\,s^{-1}}$ at DP), one can assume that the remaining discrepancies observed between geophysics and temperature data are due to very different surface and subsurface properties. The general description of the surface constitution (Fig. 9e) is already an indication of these differences: DP is located in-between two zones with big blocks (from pluri-decimetric to metric), whereas SH is located at the junction between medium size blocks (from pluri-centimetric to decimetric) mixed and non-mixed with soil. These differences in subsurface material are likely to cause the strong differences in $P$ wave velocities at the two borehole locations.

The two low resistive areas (34–40 m and 53–60 m) visible already in August and more pronounced on the second ERT profile in October are interpreted as preferential water flow path. Since the melt water cannot infiltrate through the two ice-rich (high resistive) bodies close by (at 20–33 and 40–52 m horizontal distance), it is forced to follow a preferential path in between. The lower infiltration area is constrained in the upper part by the ice rich zone and in the lower one by the presence of bedrock near the surface.

Finally the displacement of the high resistive area observed near SH (blue zone at depth on the time-lapse tomogram) is most likely an inversion artefact (overcompensation) due to the appearance of the low resistive area in the second ERT profile.

## 5 Conclusions

This paper presents a first synthesis on the thermal state and recent evolution of permafrost in the monitoring site of Cime Bianche one of the few permanent observatories on the southern side of the European Alps. The analysis ~~has been~~ focused on: the spatial and temporal variability of MAGST in relation to snow cover, the small scale (~~20–40~~30 m) spatial variability of ALT and the warming rate of deep permafrost temperatures.

~~The analysis of MAGST has been conducted considering seven years of monitoring on~~ Seven years of MAGST measured over 7 ~~sensors located in nearly homogeneous conditions in terms of both topographic and ground surface characteristics. Such experimental design~~ nodes allowed to quantify the thermal effect ~~essentially due to the~~ of snow cover variability~~alone~~. Results show that: (i) the ~~sensors characterized by~~ areas with shallow or intermittent winter snow cover are systematically colder than those with a long lasting ~~deep~~ insulating snow cover; (ii) the snow cover variability ~~alone can~~ leads to a spatial variability of MAGST greater than its inter-annual variability; (iii) on *snow-covered* nodes a combination of air temperature during the snow-free period and snow duration controls MAGST variability.

The analysis of ALT spatial variability ~~has been~~ was conducted within two adjacent boreholes considering 6 years of observations as well as by the analysis of ERT and seismic profiles. ~~The results~~ Results show that ALT at Cime Bianche has a pronounced spatial variability caused mainly by a different ice/water content in the sub-surface~~while the snow cover probably plays a role just in the inter-annual variability of ALT~~.

The geophysical analysis revealed very different surface and subsurface conditions between the 2 boreholes in terms of weathering and fracturation of bedrock. This is probably the cause of different ice content and water circulation paths.

The warming rates of ground temperatures ~~time series~~ below 8 m ~~of depth have been analyzed by two non-parametric methods~~ were analyzed considering 5 years of monthly data. The results show that permafrost at Cime Bianche is ~~degrading with a warming rate which is higher at~~ warming at significant rates below 8 m~~depth and exponentially decreasing with depth. Detected trends are similar to those observed recently in others boreholes both in the Alps and northern mountain environments. Moreover a review of the existing literature reveals a number of similitudes between our findings and the existing studies~~.

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**Table 1.** Synthesis parameters of active layers recorded in the two boreholes of Cime Bianche. Refer to Sect. 2.3 for acronyms.

| H.Y. | ALT [m] | | ALT [date] | | MAGST [°C] | | MAPT [°C] | | THOFF [°C] | | %NA | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | SH | DP | SH | DP | SH | DP | SH | DP | SH | DP | SH | DP |
| 2006 | ~~3.07~~ 3.1 | – | 11 Oct | – | – | – | – | – | – | – | – | – |
| 2007 | ~~2.45~~ 2.4 | – | 14 Oct | – | −0.34 | – | −0.78 | – | −0.44 | – | 0 | – |
| 2008 | 1.9 | ~~3.94~~ 3.9 | 27 Sep | 25 Sep | −2.13 | – | -1.82 | – | 0.31 | – | 4.38 | – |
| 2009 | ~~3.05~~ 3.0 | ~~4.93~~ 4.9 | 24 Oct | 20 Oct | −0.03 | 0.01 | −0.68 | −0.85 | −0.65 | −0.86 | 3.28 | 3.28 |
| 2010 | ~~1.87~~ 1.9 | ~~3.86~~ 3.8 | 18 Oct | 8 Oct | −1.11 | −1.16 | −1.19 | −1.28 | −0.08 | −0.12 | 1.37 | 1.37 |
| 2011 | 3.3 | ~~5.13~~ 5.1 | 8 Nov | 23 Oct | −0.47 | 0.13 | −1.1 | −1.01 | −0.63 | −1.14 | 0.27 | 0 |
| 2012 | ~~3.58~~ 3.6 | ~~5.42~~ 5.4 | 30 Oct | 4 Oct | −0.4 | −0.26 | −0.79 | −0.72 | −0.39 | −0.46 | 2.74 | 3.01 |
| 2013 | ~~1.96~~ 2.0 | 4.6 | 13 Oct | 13 Oct | −1.3 | −0.67 | −0.98 | −0.58 | 0.32 | 0.09 | 3.6 | 3.59 |
| Avg. 2009–2013 | ~~2.75~~2.7 ± ~~0.35~~ 0.3 | ~~4.78~~4.7 ± ~~0.26~~ 0.2 | 24 Oct | 13 Oct | −0.66 ± 0.23 | −0.39 ± 0.23 | −0.94 ± 0.09 | −0.88 ± 0.12 | −0.28 ± 0.18 | −0.49 ± 0.22 | 2.25 ± 0.62 | 2.25 ± 0.68 |

**Table 2.** Interpolated ZAA depths and corresponding mean temperatures in the borehole DP.

| H.Y. | ZAA ($\Delta T = 0.1\,°C$) | |
|---|---|---|
| | Depth [m] | Temp. [°C] |
| 2009 | ~~15.56~~ 15.5 | −1.34 |
| 2010 | ~~15.24~~ 15.2 | −1.25 |
| 2011 | ~~14.22~~ 14.2 | −1.29 |
| 2012 | ~~15.38~~ 15.3 | −1.24 |
| 2013 | ~~16.28~~ 16.2 | −1.21 |
| Avg. | ~~15.33~~ 15.3 | −1.26 |

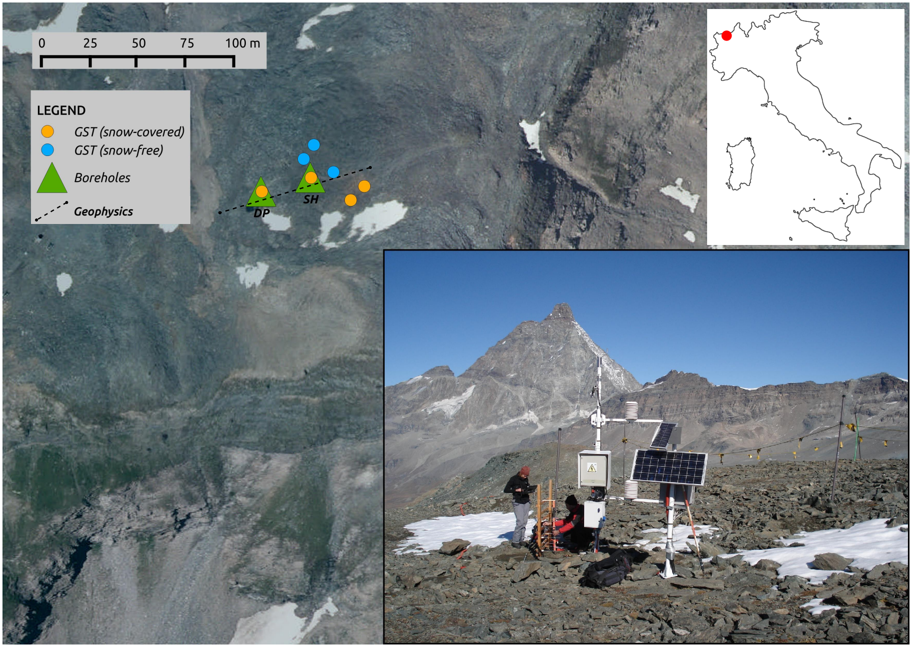


**Figure 1.** Overview of the Cime Bianche monitoring site.

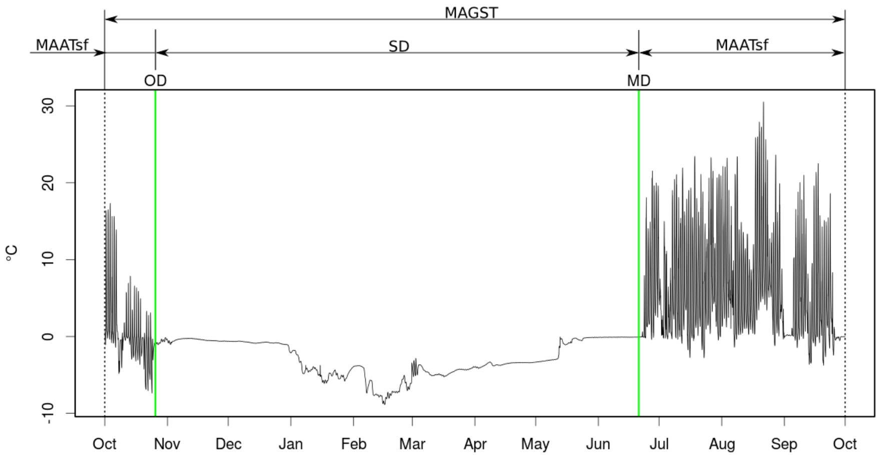


**Figure 2.** Example of detection of snow cover duration from GST time series with the method of Schmid et al. (2012) . OD: on-set date of snow. MD: melting date of snow. The periods used for the calculation of MAGST, SD and MAATsf are represented by the scheme on top.

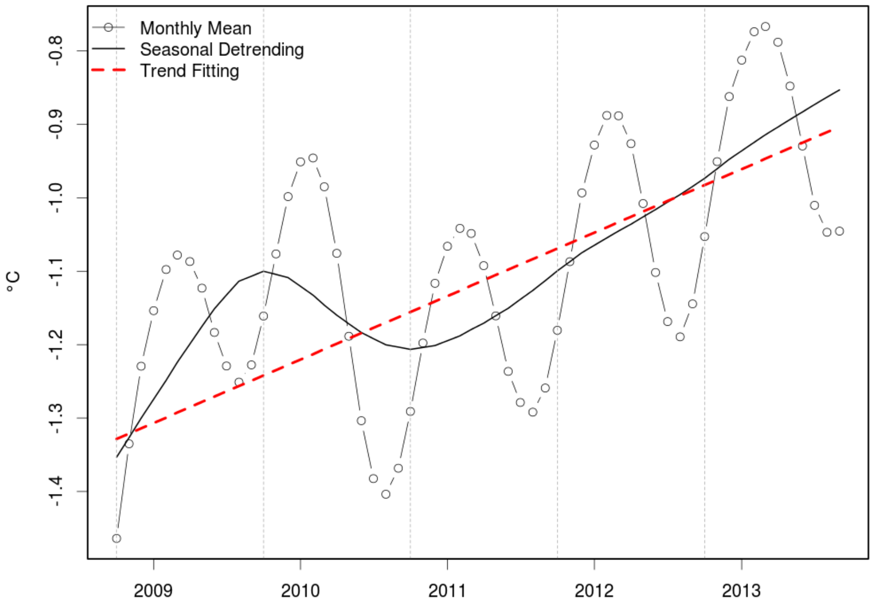


**Figure 3.** Methodological steps of trend analysis: (1) monthly aggregation, (2) seasonal detrending, (3) trend fitting. Vertical dashed lines represents the 1 October, materializing the limits of the hydrological years.

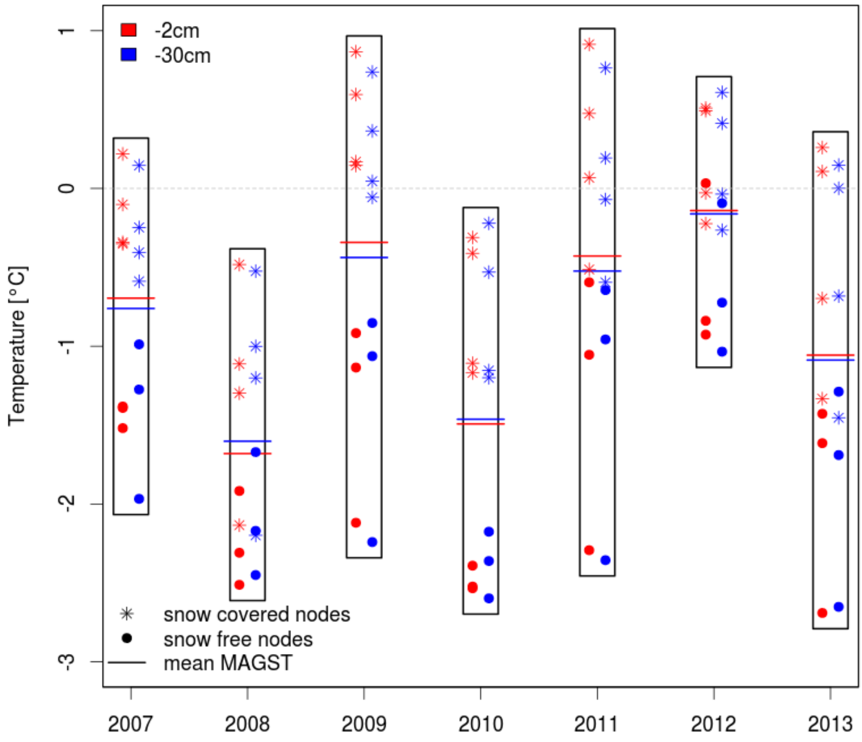
-2cm
-30cm
Temperature [°C]
1
0
-1
-2
-3
snow covered nodes
snow free nodes
mean MAGST
2007
2008
2009
2010
2011
2012
2013

**Figure 4.** Mean annual ground surface temperatures at 2 cm (red) and 30 cm (blue) of depth. Star symbols indicate ~~snow-covered~~ *snow-covered* nodes while bullets indicate ~~snow-free~~ *snow-free* nodes. The horizontal lines indicate the mean ~~of all~~ MAGST for each year and each depth. Black rectangles are used to highlight the min–max envelope for inter-annual comparison.

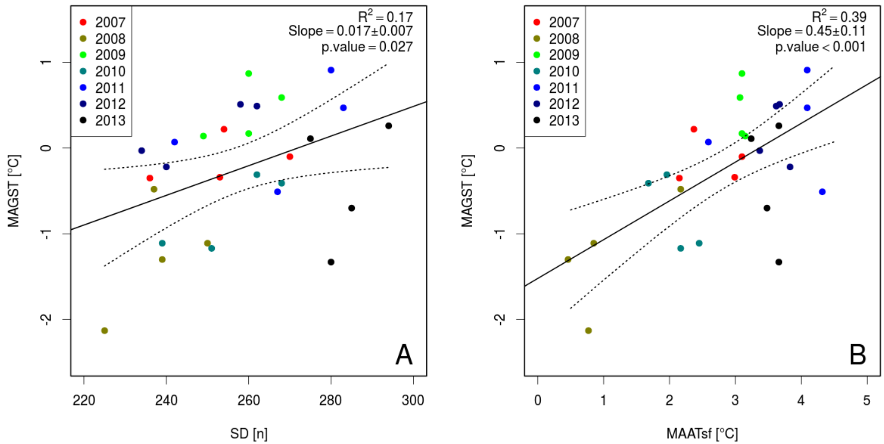


**Figure 5.** Scatterplots of SD (A) and MAATsf (B) against MAGST. The solid line represents the linear fit while the dotted lines are the confidence intervals. The metrics of the fitting are also reported.

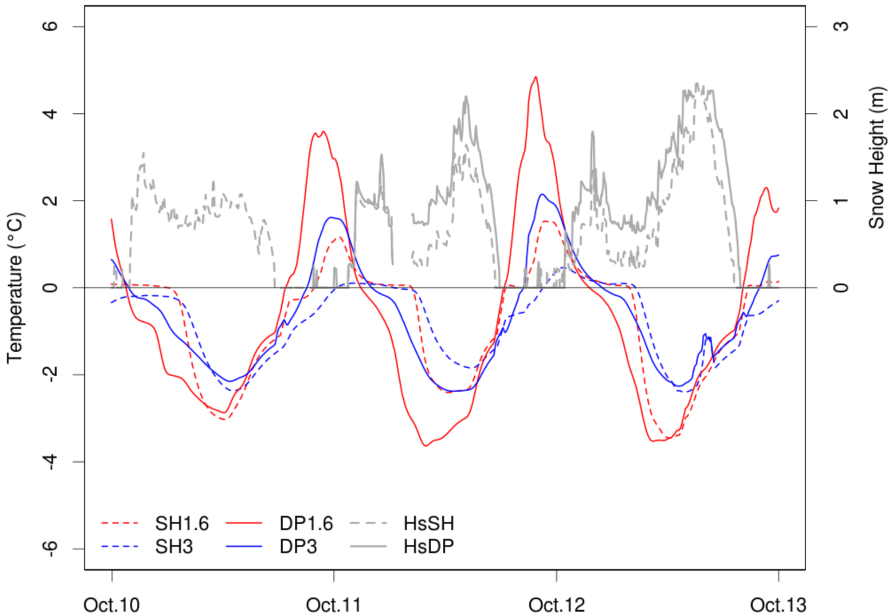


**Figure 6.** Fluctuations of snow cover thickness (Hs) and ground temperatures (daily mean) at selected depths in the active layers of Cime Bianche from 1 October 2010 to 30 September 2013. Lines type: dashed is for SH, solid is for DP. Colors: red is for shallower temperatures (1.6 m), blu is for deeper temperature (3 m), grey is for snow.

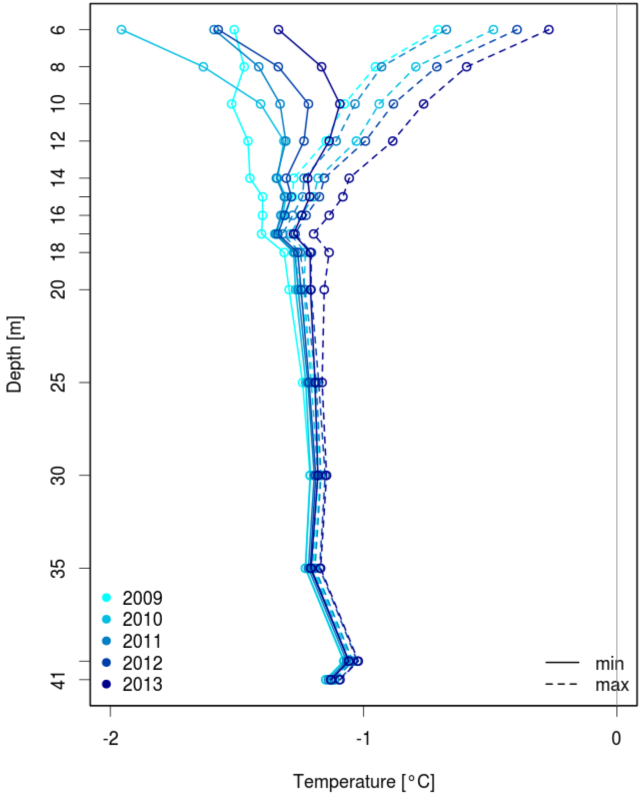


**Figure 7.** Minimum (solid lines) and maximum (dashed lines) temperature profiles in the borehole DP below 6m of depth.

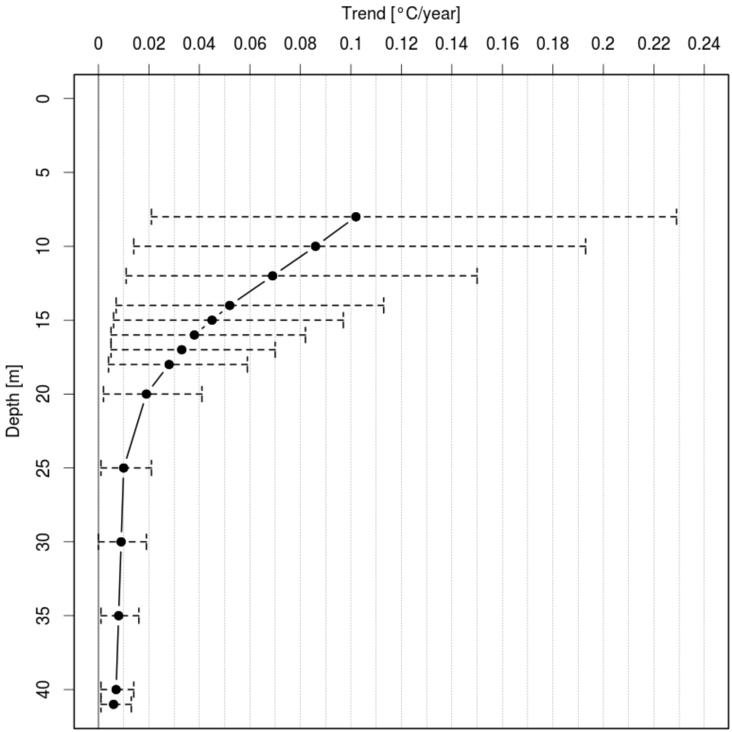


**Figure 8.** Warming rate below 8 m in the borehole DP as a function of depth. Black dots represent linear trends as $^{\circ}\mathrm{C\,year^{-1}}$. The uncertainty of trend values is represented by the dashed bars which indicate the lower and upper boundaries of the 95 % confidence interval (CI) of the fitting model (see Sect. 2.5 for details).

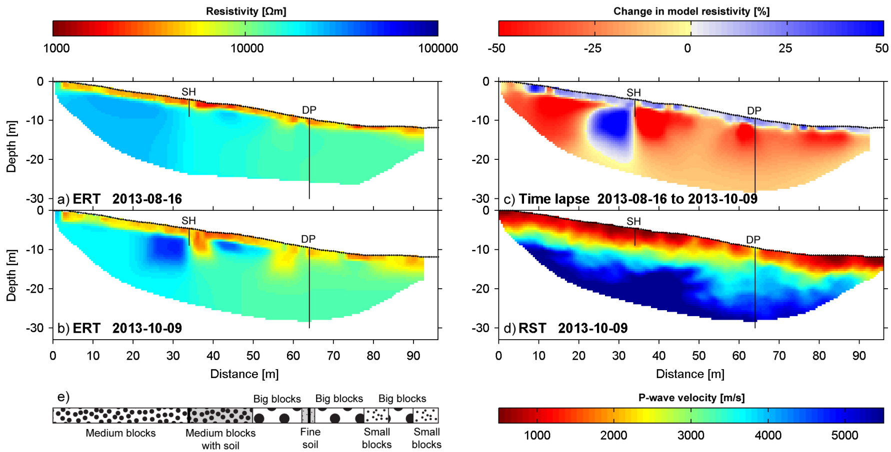


**Figure 9.** Tomograms of the specific resistivities for both ERT measurements: **(a)** 16 August 2013 and **(b)** 9 October 2013, **(c)** percentage change in model resistivity between the two dates and **(d)** seismic velocities. The location of SH and DP is figured with vertical black lines of respective length. A rough description of the surface aspect along the profile is also shown **(e)**.

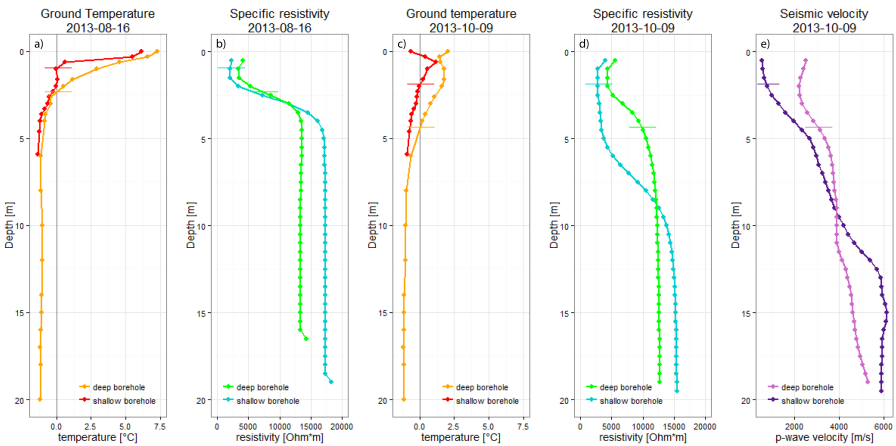


**Figure 10.** Vertical distribution of specific resistivity and $P$ wave velocity at the borehole locations extracted from the tomograms shown in Fig. 7 as well as borehole temperatures for the dates of the ERT and RST measurements. The horizontal lines represent the active layer thickness at the respective time periods.