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Rock temperature variability in high-altitude rockfall-prone areas

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Abstract

In a context of cryosphere degradation caused by climate warming, rock temperature is one of the main driving factors of rockfalls that occur on high-elevation mountain slopes. In order to improve the knowledge of this critical relationship, it is necessary to: i) increase measurement capability of rock temperature and its variability in different lithological and slope/aspect conditions; ii) increase local scale studies; iii) increase the quality and the comparability of the observational data. This paper shows an example of metrological characterization of sensors used for rock temperature measurement in mountain regions aiming at establishing, traceability and evaluating measurement uncertainty. Under such approach, data and results from temperature measurements carried out in the Bessanese high-elevation experimental site (Western European Alps) are illustrated. The procedures for the calibration and field characterization of sensors allow to measure temperature in different locations, depths and lithotypes within 0.10 °C of overall uncertainty. The main results are: i) Metrological traceability is fundamental to assess data quality and establish comparability among different measurements; ii) There are strong differences between air temperature and near-surface rock temperature; iii) There are significant differences of rock temperature acquired in different aspect conditions. Solar radiation, slope/aspect conditions and lithotype, seem to be the main driving factors of rock temperature.

1. Introduction

In a context of a climate change that affects mountain cryosphere, landscapes are evolving and new hazards are emerging. Changes in mean and extreme air temperature and precipitation values are, in fact, important preparatory and triggering factors for slope instability in the mountain cryosphere (Haeberli and Whiteman, 2015; Allen et al. 2017; Patton et al., 2019; Deline et al., 2022). In particular, several processes relate temperature fluctuations to slope instability: glacier recession due to climate warming may cause stress change in slopes and rock weathering (Deline et al. 2015), while glacier fluctuations can result in rock damage (Grämiger et al. 2018); frost weathering (Thapa et al. 2017) and thermo-mechanical stresses due to temperature fluctuations induce crack opening or widening (Draebing and Krautblatter 2019); permafrost degradation reduces rock strength (Fischer et al. 2012; Krautblatter et al. 2013); diurnal and seasonal freeze/thaw cycles and, more in general, cycles of thermal expansion/contraction weaken rock slopes, predisposing them to failure (Gunzburger et al. 2005; Jia et al. 2015; Collins and Stock 2016; Matsuoka, 2019). Finally, several recent studies pointed out the role of the snow cover in controlling ground temperature and, consequently, thermal processes taking place in rock slopes (Magnin et al. 2015; Draebing et al. 2017). In the last decades, an increase in natural instability processes affecting high-elevation mountain slopes has been documented and linked to climate warming (Fischer et al. 2012a; Allen et al. 2013; Mourey et al. 2019). In particular, a growing number of rockfalls has been reported (Ravanel et al. 2017; Paranunzio et al. 2019a; Paranunzio et al. 2019b; Chiarle et al. 2021; Guerini et al. 2021; Nigrelli et al. 2021c). This trend can be ascribed to the cryosphere (including permafrost) degradation caused by air and rock temperature increase (Harris et al. 2009; Chiarle et al. 2015; Nigrelli et al. 2018; Hock et al. 2019; Bajni et al. 2021; Nigrelli et al. 2021b).

From a thermodynamic point of view, a complete modelling and understanding of heat transfer processes, associated temperature values and gradients in rocks exposed to radiative, convective, conductive and condensation forcings is highly complex. At the air-rock interface there are thermal exchanges by irradiation, convection, condensation and evaporation, while inside the solid rock thermal exchanges occur only by conduction. Moreover, the thermal regime of the rock surface is very complex because is highly dependent on short- and longwave radiation, albedo, surface roughness, snow and vegetation cover and its distribution/variability in time and space (Haberkorn et al. 2015).

Although temperature data at the air-rock interface is fundamental, currently there are no data loggers capable of measuring and storing on-site the temperature data acquired at the air-rock interface for long periods of time (more than one year) and with a level of accuracy needed for improving knowledge on instability and rockfalls.

In order to better understand the effects of climate warming on slope instability, in a context of cryosphere degradation, it would be necessary to have long-lasting, homogeneous rock temperature datasets, distributed throughout the Alps, to be analyzed in relation to the main geomorphological and meteorological parameters. However, this is difficult to do because:

1. Long time series of rock temperature data, acquired in the mountain cryosphere of the Alps are rare;
2. Where available, rock temperature data are often acquired by means of sensors and acquisition chains, for which measurement uncertainty is not always known and instrument traceability is often undocumented;
3. Weather stations located in the mountain cryosphere of the Alps (specifically above 2500 m a.s.l.) are scarce.

Despite these problems, during the last 20 years several studies on rock temperature have been carried out in the Alps (Gruber et al. 2004; Gunzburger et al. 2005; Gunzburger et al. 2011; Hasler et al. 2011; Moor et al. 2011; Magnin et al. 2017; Weber et al. 2017; Draebing et al. 2019; Weber et al. 2019; Viani et al. 2020; Gasc-Barbier et al. 2021). These studies highlight the importance of local studies in high-elevation experimental sites (Matsuoka 2019; Musacchio et al. 2021). The local scale approach through the availability of instrumented experimental areas allows to obtain precious information on relations between climate variability and thermal conditions of geological materials, necessary to better understand processes driving slope instability in the cryolithosphere (van Everdingen 1998). However, to take a step forward, two fundamental objectives need to be pursued, to improve data comparability in time and space: a constant check of data quality through the entire acquisition chain, and the standardization of measurement techniques and methods. These issues are clearly highlighted in Humlun et al. (2004), which however does not yet indicate the need to evaluate the uncertainty of measurements and the traceability of instruments. In summary, the key questions related to this research field are the following:

1. How to increase rock temperature knowledge in the mountain cryosphere?
2. How to increase quality and comparability of rock temperature data?

On such basis, the aims of this work are:

1. To propose a measurement method which includes a robust metrological approach delivering measurement uncertainty evaluation and improved data quality through documented traceability and comparability;
2. To apply the proposed measurement approach to a high-elevation experimental site, in order to assess rock temperature, its variability and the relation with the main geomorphological and meteorological parameters;
3. To promote to the international scientific community the need for shared and standardized procedures, and the importance of local scale studies through the realization of instrumented experimental areas in the mountain cryosphere.

In this study, we illustrate the results coming from our high-elevation experimental site, during two years of measurements in the framework of the RiST2 Project.

2. Study area and measurement design

The temperature monitoring site (TMS) considered for this study is located in the Bessanese high-elevation experimental basin in the Northwestern Italian Alps (Lat. 45°17’52” N, Lon. 7°8’35” E, Figure 1). The Bessanese experimental basin is an open-air laboratory, instrumented since 2016 for studying the relationships between climate forcing and geomorphological dynamics, in particular slope instabilities, in a context of climate warming. This site was chosen because of the variety of geomorphological features and processes that can be found in the area. Regarding slope instability, nine recent main rockfall events have been identified in the study area. The earliest documented event dates back to 1956 and produced a “large” rockfall deposit on the glacier front, located at that time upstream of the glacial lake at 2581 m a.s.l. The second one, reported in 1958, was described as a “recurring fall of blocks” from the incisions in the Bessanese rockwall. The six most recent events were reported by the Gastaldi Hut keeper. Lastly, on August 23, 2019 at 12:51 (CEST) a rockfall detached from the top of the NE rockwall of the basin. The main features of this experimental site and a detailed study of rockfalls occurred in this area are described in Viani et al. (2020). The lithotype of the TMS is an outcrop of calc-schists. In this site, three rock-faces with different orientation (N-E, S-E, S-W) were chosen: respectively TMS1, TMS2 and TMS3. In each of these sites, three instruments for temperature measurement and recording (sensors with embedded data loggers) were inserted in the rock, horizontally and in three different drills, about 10 cm apart from each other, respectively at 10 cm (also identified as near-surface rock temperature, NSRT), 30 cm and 50 cm depth (Table 1).

In this experimental configuration the N-W exposure is missing due to the geological and topographical conditions of the site. This TMS is ideal to carry out continuous monitoring in the calc-schists, a common lithotype in the western alpine sector.

Air temperature and other meteorological data were provided by an automatic weather station (AWS) installed by ARPA Piemonte in 1988. The AWS is located about 130 m away from the TMS, at an elevation of 2659 m a.s.l. and its sensors are positioned 6 m above the ground level. Since 2018, the AWS also acquires total incident and reflected solar radiation (Nigrelli et al. 2021a). The Bessanese experimental basin is part of the Dynamic Ecological Information Management System – Site and dataset registry (https://deims.org).

3. Measurement approach

The methodology we propose here consists in an innovative approach integrated by the use of advanced technologies. The main aim of our approach is to achieve a fully documented measurement traceability. In fact, in cryosphere studies, a fully documented metrological traceability of measurements is frequently missing but it is fundamental for data comparability in space and in time (Merlone et al. 2015; Musacchio et al. 2021).

This is obtained in two specific steps:

1. Selection of high-quality instruments and sensors, considering the condition of use, the possibility to store data for long periods, the possibility to be calibrated several times;
2. Definition of specific calibration methodologies and procedures; sensors calibration with associated calibration curve and uncertainty, including characterization "on-site", also for evaluate further components of the overall measurement uncertainty (not limited to the calibration uncertainty).

For this study, we used MadgeTech MicroTemp Data Loggers (MT). This choice was made because these MTs are miniaturized (length 66 mm, diameter 18 mm, weight 14 g), waterproof, self-contained temperature data loggers that can be easily inserted into rock and other geological materials, such as coarse and fine debris, soil, ice, water. They can measure and store data for more than one year, since they have user-replaceable batteries, and work in the temperature range [-40; +80] °C, with a resolution of 0.1 °C. Differently from other disposable sensors, MTs can be routinely calibrated and their measurements made traceable to SI standards. Based on our experience, these MTs offer an excellent compromise between ease of use in extreme conditions, cost and data quality.

The proposed measurement approach consists in the following four steps:

Step 1. Laboratory calibration of the MTs.

This calibration is necessary to: a) establish full traceability, b) correct for instrumental errors, c) determine the calibration uncertainty, a key component of the overall measurement uncertainty, before and after the on-site deployment. The calibrations have been performed at the Italian National Metrology Institute (Istituto Nazionale di Ricerca Metrologica, INRiM), by comparison against a reference standard thermometer traceable to national reference fixed points. The calibration was performed by comparison in a characterized liquid bath, in the range [-20; 40] °C, a Fluke 1594A high-accuracy readout bridge was used for reading the reference PT100 thermometer. The calibration uncertainty was evaluated taking into account all components such as the MT resolution, the bath stability and uniformity and the reference thermometer uncertainty.

All procedures here adopted are in agreement with the Guide to the Expression of Uncertainty in Measurement (GUM), No. 100:2008, while the terminology here used is aligned with the International Vocabulary of Metrology (VIM), No. 200:2012).

Step 2. Evaluation of measurement uncertainty.

The calibration procedure explained in Step 1 was expressly designed to minimize the differences with the measurement environment in which the sensors are exposed. The measurement procedure adopted in this work, including tests, characterization and calibration results, allowed us to draft a tentative measurement uncertainty budget (Table 2). In the table, all the considered contributions to uncertainty are present: due to calibration of the devices, their resolution, the mathematical fitting of the calibration curve (which was found to be negligible) and their field comparability. The latter term includes a comparison among the MT sensors made in a real-world situation, to assess the behavior of the instruments when subject to the same environmental factors, not unlike what was done by Coppa et al. (2021) for AWS. This procedure, briefly reported as well by Viani et al. (2020), allowed us to evaluate this contribution, which is by far the largest contributor to the overall uncertainty. Using this approach, more acquisition time, and more sophisticated statistical techniques, in principle this contribution can be reduced to few hundreds of a degree Celsius while, in general, in the environmental research field, uncertainty is normally declared at around 0.1 °C (if any), rarely with complete traceability documentation.

Step 3. Rock temperature monitoring.

Considering that the bibliographic analysis did not point out clear standardized practices in relation to depth configurations, we chose to position the MTs at three different depths in the rock (10, 30 and 50 cm, Table 1). The MTs have been preventively smeared with white silicone grease to maximize the contact with the rock, thus improving the thermal conductivity (Figure 2). This mimics the conditions met in liquid bath during calibration, thus making the calibration curve and associated uncertainty more representative of the measurement conditions. Data acquisitions of the nine MTs started on 20 July 2018 and ended on 5 August 2020, without missing data. Rock temperatures were logged every 30 min: MTs acquisitions were synchronized with the AWS acquisitions, in order to make a correct time comparison. Hours are expressed in Central European Summer Time (CEST).

Step 4. Data analysis.

The local-scale variability of rock temperature and its relation with the main geomorphological and meteorological parameters were processed and plotted. The on-site daily maximum rock temperature gradient (or lapse rate, DTLR)

of calc-schist rock was calculated. For our analyses, we considered the maximum values for calculating DTLR, because this is one of the main driving factors of rockfalls that occur at high elevation. The DTLR is an important parameter that is used for the calculation of the thermal conductivity of materials, through the application of Fourier's law (Schön et al. 2015). The formula applied to calculate DTLR is: $\Delta T/\Delta x$ (°C/cm), where ΔT is the difference of daily maximum rock temperature acquired by two MTs of the same monitoring site, and Δx is the difference between two depths, in our cases is set to 20 cm (10 cm vs 30 cm and 30 cm vs 50 cm).
The zero-curtain state is characterized by a constant temperature close to 0 °C due to the snow cover (thermal insulation) and due to the latent heat released in the melting snow pack (Hasler et al. 2011; Kellerer-Pirklbauer 2017; Viani et al. 2020). In this study, the zero-curtain periods were determined for days with near-surface rock temperature between [-0.2; +0.2] °C, a range similar to that applied in Gubler et al. (2011). The zero-curtain periods were not included in the calculation of DTLR. Furthermore, the main physical properties of the calc-schists (color, bulk density and specific heat capacity) were determined in laboratory on rock samples of about 10-15 cm^3 of volume. The rock samples were collected in the TMS, taking the samples from the surface of the rock outcrop. Rock color was determined both in wet and dry conditions, by using the Munsell Rock Color Chart. Density (ρ) is defined as the quotient of mass m (sample of about 5 g) and volume V of a material ($\rho = m/V$). In this work, the bulk density was calculated, i.e. the mean density of the considered rock volume, including pores. Bulk density (g/cm^3) was calculated by means of pycnometers (Schön et al. 2015). Finally, the specific heat capacity (c_p) is defined as the ratio of the heat input Q to the product of the mass m (sample of about 50 g) and the resulting temperature increase ΔT, where the subscript p indicates specific heat capacity at constant pressure: $c_p = Q/(m*\Delta T)$. The specific heat capacity (in J/kg K) was calculated by using a Dewar vessel calorimeter (Schön et al. 2015). Temperature in the calorimeter was measured by using a copper-constantan thermocouple (measurement accuracy 0.2 %) and it was recorded each 1 s by means of a data logger.

4. Results

Table 3 synthetizes rock and air temperature acquired for the entire period of measurement. Regarding rock temperatures, the highest value was recorded by MT Q62110 (TMS3, 10 cm depth): 40.8 °C at 18:00 hours of the 28/06/2019 with nearby air temperature of 18.5 °C, and difference between rock and air temperature of 22.3 °C. The lowest value was recorded by MT Q61213 (TMS1, 10 cm depth): -7.5 °C from 3:00 hours to 4:30 hours of the 14/11/2019 (air temperature -10.3 °C, ΔT between rock and air temperature -2.8 °C). Regarding air temperatures, the highest value observed is 19.9 °C (16:00 hours of the 25/06/2019, when the maximum rock temperature is 28.4 °C, observed by MT Q62110) and the lowest value is – 18.8 °C (6:30 hours of the 26/03/2020, when the minimum rock temperature is 0.50 °C, measured by MT Q61213 under snow cover conditions).
Figure 3 shows rock and air temperature and snow depth trends during the entire observation period. The trends observed for rock temperature are similar, but several differences in the quantitative values have been found in relation to the different depths of data loggers and to the different aspect of the three measuring sites. In this figure, particular evident is the zero-curtain period. The transition to the zero curtain is more gradual at TMS1 (facing N-NE) than at TMS2 and TMS3 (facing SE and SW, respectively). Snowfalls of just 20 cm were sufficient to substantially decouple rock and air temperature at this site, both in autumn 2018 and in 2019, while in the other two sites rock temperature remained substantially aligned with that of the air. However, the final onset of the zero-curtain period is almost synchronous for the three stations, coinciding with the first snowfall reaching a thickness of at least one meter. On the contrary, the zero-curtain period ends earlier and more gradually at the TMS2 and TMS3 sites, when the snow pack at AWS is still almost 2 m thick. At the TMS1 site, on the other hand, the zero-curtain period ends almost 2 months later, when the snow depth at AWS drops to about 80 cm. Figure 3 also highlights the limited number of diurnal freeze-thaw cycles in the rock, which usually occur in autumn: in fact, when the rock is finally out of the zero-curtain, air temperature tends to remain above 0 °C. This result is in agreement with the findings of Viani et al. (2020) in other rock temperature measuring sites in the Bessanese experimental basin. In addition, only the most surficial MTs experience freeze/thaw cycles.
Strong differences between air temperature and NSRT (MT at 10 cm depth) are visible in Figure 3. During Summer, the minimum daily air temperature is above 0 °C for several consecutive days: this may cause ground ice melting at a growing depth in rock slopes and permafrost degradation, predisposing slope to failure (Gruber et al., 2004; Viani et al., 2020). Figure 4 shows an example of rock and air temperature trends in TMS3, during four consecutive days (from 1 to 4 September 2019) and their relation with the global and reflected solar radiation. In the night-time, rocks cool down and, the following morning, before sunrise, the NSRT is sometimes higher than the air temperature by a few degrees, due to the thermal inertia of the rock mass with respect to air. An example of this process is shown in Figure 4: during sunny days, high values of ΔT between air and rock temperature were found (see 3 and 4 September 2019). When direct solar radiation is absent, e. g. during cloudy days (see 1 and 2 September 2019),

differences are minor but still significant. The NSRT is higher than air temperature, due to major radiation absorption, transferred into available heat content, here detected as temperature increase. Even if ΔT between air and rock decreases with increasing rock depth, it never becomes zero.
In Figure 5 the descriptive statistics of the two DTLRs calculated for each TMS, using the three different depths (10 cm vs 30 cm and 30 cm vs 50 cm) are reported. In TMS1 the linear correlation between the two DTLRs is: y = 0,5022x - 0,0121 (R^2 = 0,83; n=262); in TMS2 the linear correlation is: y = 0,3021x - 0,0188 (R^2 = 0,86; n=365); in TMS3 the linear correlation is: y = 0,3205x - 0,0305 (R^2 = 0,88; n=391). DTLR shows a clear variability between temperatures acquired in each measurement site (TMS1, TMS2 and TMS3), especially between the shallower MTs, as reported in Figure 5.

5. Discussion

The work here presented is based on an innovative and robust methodology that involves improved understanding of the whole measurement process: from the sensor calibration and characterization, to the measurement procedure and complete uncertainty analysis. This process allowed more robust understanding of the local scale relationships among rock temperature, geomorphological features and meteorological parameters through a spatiotemporal comparability of data. In this discussion, particular relevance is given to the rock temperature variability, which is a key driving factor of slope instability. In relation to the results illustrated in the previous paragraph, the key results are as follows:

1. Metrological traceability is fundamental in data acquisition to achieve comparability and to accurately capture trends;
2. Strong differences exist between air and rock temperature, in particular NSRT;
3. Significant differences exist between temperatures acquired in each measurement site (TMS1, TMS2 and TMS3), with particular reference to NSRT;
4. DTLR shows a clear variability between temperatures acquired in each measurement site (TMS1, TMS2 and TMS3), especially between the shallower MTs;
5. Long periods of zero-curtain;
6. Only a few freeze-thaw cycles occur in the NSRT, with respect to the air temperature.

Point 1). Metrological traceability of measurements is a fundamental requirement to achieve data comparability and a fundamental aspect to accurately capture trends. Improved and dedicated calibration procedures, uncertainty evaluation of field measurements results is being carried out under a direct collaboration between metrologists and scientists operating in instrumented experimental areas in the cryosphere. Field measurements of temperature are a key investigation for cryosphere studies, in high mountain regions and Arctic environments. Among the numerous Essential Climate Variables (ECVs), defined by the Global Climate Observing System (GCOS) recommended terrestrial measurements include quantities of interest in cryosphere studies also under a co-siting vision with the proposal of a Global Climate Reference Network (Thorne et al. 2018). The WMO's Global Cryosphere Watch (GCW) has deep interest in implementing metrology and metrological approach. Result of interest for GCW have already been delivered by European Metrology Research Programme Joint Research Projects such as MeteoMet (Merlone et al. 2012; Merlone et al. 2015). The activities on the improvement of the data quality for permafrost measurements, the discussion opened by the series of “Arctic Metrology workshops”, the calibration campaign in high mountain regions and the proposal for a dedicated metrology infrastructure for polar research are all valuable examples. Such direct collaboration with the metrology community brings proved benefits and progresses in the quality of data recorded by the multitude of network and stations of GCW and more in general on studies on the cryosphere.
It is under such framework, that the work here presented addresses the needs of the GCW as an example of documented traceability and best practice for calibration and measurement uncertainty.

Point 2). Strong differences exist between air and rock temperature, in particular NSRT. These differences have been reported in some papers that compared air temperature with NSRT, such as in Haberkorn et al. (2016), Viani et al. (2020). Our study confirms that there is a low linear correlation between daily maximum air temperature and daily maximum NSRT (zero-curtain days excluded, see Point 5) below. Linear correlation coefficient (R^2) for the three pairwise comparisons are 0.37 (with 262 days), 0.52 (365 days) and 0.46 (391 days), respectively for TMS1, TMS2 and TMS3. These results must be taken into serious consideration when analyzing the thermal conditions associated with the triggering of slope instability. In fact, simply taking into account air temperature trend can lead to a significant underestimation of rock mass temperature, during the summer or even all year round, in particular in case of vertical rock walls, where snow cannot accumulate and solar radiation reaches the rock surface all year round.

Point 3). Significant differences between temperatures acquired in each measurement site (TMS1, TMS2 and TMS3). These differences are clearly visible in Figures 3 and 5, and are particularly marked for NSRTs. NSRT is mainly influenced by rock-face slope/aspect and by the thermal characteristics of the specific lithotype, as found also by other authors (Gruber et al., 2004; Matsuoka 2008; Fischer et al., 2012b; Viani et al. 2020). Differences in solar radiation and in the timing and thickness of the snow cover are also important (Haberkorn et al. 2015; Haberkorn et al. 2016). Data in Table 3 highlight this point, in particular MT Q62110 in TMS3. This MT is inserted in a rock-face that is oriented 225 ° N, with a slope angle of 45°. This optimal positioning, in relation to the absorption of solar radiation, is evident in the curve of temperature growth in Figure 4. In this figure, after sunrise, temperature acquired by MT Q62110 (10 cm depth), rises rapidly, well above that of the air, and also while this latter remains almost stable, until the angle of incidence of the sun decreases. The same trend is displayed by the other MTs in rock, with different timing and absolute values, in relation to the different slope/aspect conditions of the rock-face.
In Figure 4 is clearly visible the time shift among the peak values of the global solar radiation and the rock temperature at 10 cm, 30 cm and 50 cm depth, especially during sunny days. The time shift is due to thermal diffusivity and it is specific for each lithotype. Thermal diffusivity is a measure of penetration of temperature changes into a material; it controls the time-dependent temperature distribution (Schön 2015). At seasonal time-scale, thermal variation can affect rock up to 6 m depth, as other authors have found (Magnin et al. 2015; Gasc-Barbier et al. 2021; Haberkorn et al. 2021). An in-depth, stronger effect linked to thermal diffusivity occurs in fractured rocks, where air and water can transfer surficial rock temperatures at depth faster than a compact rock. However, it should not be forgotten that rocks are strongly anisotropic. In relation to this, several on-site measurement points and several years of measurements are required, as also reported in Keller-Pirklbauer (2017). These results confirm that, over a period of several days with stable meteorological conditions, seasonal fluctuations are not perceptible, and temperatures vary almost periodically with a 1-day period, as reported in Gunzburger et al. (2011). In the Cryosphere-Climate laboratory of the CNR-IRPI of Torino, the determination of the thermal properties of the different types of rock that are predominant in the Alps is underway, in order to provide the input parameters needed to develop accurate and exportable heat transfer models of rocks prone to failure in the Alps.

Point 4). The data relating to the thermal gradient (or lapse rate) of the rocks, provide one of the most important parameters useful to the definition for the heat transfer models in rock. Due to the different physical, chemical and mineralogical characteristics of the different types of rocks, these data must be acquired for each lithotype. As reported above, the lithotype of the three TMSs is an outcrop of calc-schist and the DTLRs of this lithotype are summarized in Figures 5. In this figure, differences in the DTLR values are clearly visible. The most evident differences are observed in the calculated values for TMS1-a (0.18 °C/cm), TMS2-a (0.25 °C/cm) and TMS3-a (0.39 °C/cm). These values indicate that a compact calc-schist rock exposed to SE heats up twice as much as the same rock exposed to the NE. The differences observed for the extreme values (the whiskers of the box plot) are even larger for the different aspects of the rock mass. The results of our study confirm that daily temperature fluctuations are less pronounced for rock faces exposed towards N, than for those exposed towards S, reaching the highest values for SW exposures. As a result, south-facing rock slopes are particularly exposed to cycles of thermal expansion/contraction, even if temperature remains above 0 °C (Collins and Stock 2016), which can cause the progressive degradation of rock properties. On this regard, Nagai et al. (2013), for example, found that southwest-facing slopes supply the largest quantity of debris mantle on glaciers in the Bhutanese Himalaya. On the contrary, North-facing slopes are more sensitive to seasonal temperature fluctuations and in general to climate warming, since their temperature depends on air temperature more than on solar radiation, as it happens for South-facing slopes. In fact, North-facing slopes are the source of many rock falls occurred in recent decades (Viani et al., 2020).
The values calculated for TMS1-b (0.08 °C/cm), TMS2-b (0.06 °C/cm) and TMS3-b (0.09 °C/cm), are very close, suggesting that thermal diffusivity, at the daily scale, in a compact calc-schist rock, rapidly decreases with depth.

Point 5). The entire time-series of measurements highlights the impact of snow cover on rock temperature (Figure 3). The thermal insulation properties of snow are well known (Barry, 2008; Harris et al., 2009; Barry, 2011; Ming-ko, 2012). This is the so-called zero-curtain effect. When data loggers are under snow cover, they are thermally insulated from the atmosphere and consequently their temperature is close to 0 °C, decoupling them from air temperature trend. This situation confirms the marked role of the snow cover, in our case from a thickness of about 15-20 cm, as also other authors reveal (Haberkorn et al., 2015). Since the height of the holes in the rock faces selected for this study are 100 cm and 130 cm, when the mean snow depth during winter and spring can be higher than 250 cm, and the slope range of the three TMSs is from 45° to 50°, MTSs are under the insulating effect of the snow from late autumn to late spring. This situation considerably reduces the number of useful measures; however, also in this case, the rock face exposure is a relevant factor, significantly reducing snow cover duration, and thus the zero-curtain period, for the SE-SW aspects.

Point 6). Field monitoring in the World has highlighted the roles of diurnal and annual frost cycles in controlling the timing and magnitude of frost weathering (Matsuoka et al. 2008; Draebing et al. 2017; Draebing et al. 2019). The weathering by freeze-thaw cycles is an important process that occur in the rock slopes of the Alps. However, in our study, only a few freeze-thaw cycles in rock were identified. The main causes are three: a) the relatively low altitude of the measurement site (<3000 m a.s.l.); b) the presence of snow cover for a long period each year (from late Autumn to late Spring), precisely in the months in which the air temperature undergoes most of the oscillations above and below 0 °C and could thus causes freeze-thaw cycles and the so-called thermal stress weathering, as some authors have found (Draebing et al. 2019). These affect rock, debris, ice and water temperature (Fischer et al. 2012a; Fischer et al. 2012b; Weber et al. 2017). In these seasons, when snow cover is absent from near-vertical rock slopes, NSRT can be higher than near-surface air temperature and can be some degrees above 0 °C: this is due to strong short-wave solar radiation; c) the non-vertical conditions of the rock slope at the TMSs, and the limited height of TMSs from the ground (max. 130 cm). These are significant limiting factors, because do not allow the rock slope to be without snow cover and therefore to be directly irradiated by the sun.
Considered that near-vertical rock slopes are also the most prone to instability, and that some of the largest slope failures occurred in recent years in permafrost alpine areas happened from Autumn to Spring (Paranunzio et al. 2018; Paranunzio et al. 2019a), the knowledge of the actual thermal condition of rock slopes during these seasons is crucial for understanding processes leading to failure (Gruber et al., 2004; Weber et al. 2017). In order to solve this problem, it would be necessary to set up a measuring site at a higher altitude than the current one, but this would entail greater logistical difficulties.

Summing up we conclude that, in order of importance, solar radiation ans slope/aspect conditions seem to be the main driving factors of rock temperature variation at short time-scales (daily to seasonal). We believe that the lithotype is also one of the main driving factors of rock temperature variation at short time-scales. As regards this aspect, specific studies are currently underway. It is important to underline that a more in-depth comparison between the results reported in this work and the results reported in the bibliography is difficult, due to the significant differences between the applied methodologies and the different sensor types used.
Regarding the crucial parameter of temperature, however, the reference datum is air temperature, as it is usually the only available. However, this study highlights the strong difference between air and rock temperature and the time shift that exists between their peak values. This means that, even with all the limitations/exceptions of the case, estimating rock temperature on the basis of the air temperature alone can lead to a significant underestimation of the former, and therefore to an incorrect interpretation of the mechanisms associated with geomorphological dynamics/slope instability. This could explain, e.g., rockfalls occurred at high altitudes in Winter, when air temperature is well below 0 °C, difficult to interpret if only air temperature is considered (Schnepfleitner et al. 2018). It is evident that solar radiation is critical in this regard, both in terms of cloudiness/seasonality, and with regard to slope and aspect of rock masses, as other authors mentioned above have also reported.
As already mentioned, the lithological composition of rock masses also plays a role in the thermal behavior of mountain slopes: new data acquisitions in the laboratory and in the field, specific for each lithotype involved in rockfall are necessary. The methodological approach used for this work, ensuring comparability of results and definition of measure uncertainties, is the most appropriate to investigate also these aspects.

6. Conclusions

This paper shows one example of the application of procedures aimed at the metrological characterization of sensors used for the measurement of temperature in mountain cryosphere. The main novelty is a rigorous application of metrological principles to establish traceability and fully evaluate measurement uncertainty for this specific application and linked studies on cryosphere degradation. The case study in an instrumented experimental area, the Bessanese glacial basin, is the first field application. Data and results from two years of measurements have been reported. This case study can be considered a preliminary approach for new and more modern research methods regarding temperature studies in glacial and periglacial areas, with a focus on temperature as a driving factor of slope instability.
Answering the two key questions reported in the introduction, we conclude that:

1) How to increase rock temperature knowledge in the alpine cryosphere?
Rock temperature knowledge in the alpine cryosphere can be increased by extending and comparing the instrumented experimental areas; rock blocks and outcrops can be used as analogous of rock slopes, when these latter are difficult and/or dangerous to reach. This solution can be the right compromise to new data, while keeping low cost and risks associated with this type of investigation. These instrumented experimental areas could become authentic reference sites, in which to collect data, but also to develop new methodological approaches and to test and compare different and evolving instruments and technologies. Furthermore, rock temperature knowledge in the alpine cryosphere can be increased by using sensors and metrological approaches that take favor of a fully traceability of measurements.

2) How to increase the quality and the comparability of the data?
It is possible to increase the quality of the data using local scale approaches, applying shared and standardized methodologies, using sensors and acquisition chains with known measurement uncertainty. In a long-term vision, setting up an experimental site designed according to the results of the analysis on top quality-reference grade measurements represents a preliminary example towards a network of reference sites at large regional or future global scale. During the last twenty years, several projects in the cryosphere have been implemented, several working groups have been activated, led by the most important government agencies or associations in the world, for example the Global Cryospheric Watch of the World Meteorological Organization (WMO-GCW), the National Snow and Ice Data Center (NSIDC), the International Permafrost Association (IPA), the International Association of Cryospheric Sciences (IACS). During these twenty years many instrumented experimental areas in the cryosphere have been equipped, following independent approaches and different solution. This results in a low level of data comparability, very different technical methods adopted, total absence of measurement guidelines or discussed dedicated calibration procedure. Full understanding and evaluation of measurement uncertainty is not present in literature, and rarely reported results include at least instrumental uncertainty evaluation. This situation is well known by WMO-GCW, which in 2020 formed specific working groups tasked to define standards and best practice for observations and measurements of parameters of the cryosphere: snow, permafrost and glaciers. The final goal is to extend the WMO guide No.8 to the cryospheric observations. The approach here proposed can be intended as a local scale case study in order to stimulate the international scientific community towards the adoption of shared and standardized procedures. When general principles will be formally adopted, a reference network can originate in harmonized and comparable way, for generating long term measurement records.

Climate change is significantly modifying the cryosphere and one of the most evident consequences is the increase of natural instability processes, and of related hazards and risks. In order to improve knowledge on hazards and risks in the cryosphere, a rapid progress in such research activities is needed. To achieve this, it is necessary to combine efforts by applying standardized methodologies, increasing data acquisition and sharing results within and among different communities.

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References

Allen S, Frey H, Huggel C, et al. (2017) Assessment of Glacier and Permafrost Hazards in Mountain Regions – Technical Guidance Document. GAPHAZ, Zurich, Switzerland/Lima, Peru

Allen S, Huggel C (2013) Extremely warm temperatures as a potential cause of recent high mountain rockfall. Global and Planetary Change 107: 59–69. https://doi.org/10.1016/j.gloplacha.2013.04.007

Bajni G, Camera C, Apuani T (2021) Deciphering meteorological influencing factors for Alpine rockfalls: a case study in Aosta Valley. Landslides 18: 3279–3298. https://doi.org/10.1007/s10346-021-01697-3

Barry R (2008) Mountain weather and climate. 3rd edn. Cambridge University Press, New York

Barry R, Gan TY (2011) The Global Cryosphere. Past, Present and Future. Cambridge University Press, New York

Boeckli L, Brenning A, Gruber S, Noetzli J (2012) Permafrost distribution in the European Alps: calculation and evaluation of an index map and summary statistics. The Cryosphere 6: 807–820. https://doi.org/10.5194/tc-6-807-2012

Chiarle M, Coviello V, Arattano M, Silvestri P, Nigrelli G (2015). High elevation rock falls and their climatic control: a case study in the Conca di Cervinia (NW Italian Alps). In Engineering Geology for Society and Territory-Volume 1 (pp. 439-442). Springer, Cham. https://doi.org/10.1007/978-3-319-09300-0_84

Chiarle M, Geertsema M, Mortara G, Clague J (2021) Relations between climate change and mass movement: Perspectives from the Canadian Cordillera and the European Alps. Global and Planetary Change 202: 103499 https://doi.org/10.1016/j.gloplacha.2021.103499

Collins B, Stock G (2016) Rockfall triggering by cyclic thermal stressing of exfoliation fractures. Nature Geoscience 9: 395-400. https://doi.org/10.1038/ngeo2686

Coppa G, Quarello A, Steeneveld GJ, Jandric N, Merlone A (2021) Metrological evaluation of the effect of the presence of a road on near-surface air temperatures. International Journal of Climatology 41(6): 3705-3724. https://doi.org/10.1002/joc.7044

Deline, P., Hewitt, K., Shugar, D., & Reznichenko, N. (2022). Rock avalanches onto glaciers. In Landslide hazards, risks, and disasters (pp. 269-333). Elsevier.

Draebing D, Krautblatter M, Hoffmann T (2017) Thermo-cryogenic controls of fracture kinematics in permafrost rockwalls. Geophysical Research Letters 44. https://doi.org/10.1002/2016GL072050

Draebing D, Krautblatter M (2019) The Efficacy of Frost Weathering Processes in Alpine Rockwalls. Geophysical Research Letters 46. https://doi.org/10.1029/2019GL081981

Fischer L, Huggel C, Kääb A, Haeberli W (2012a) Slope failures and erosion rates on a glacierized high-mountain face under climatic changes. Earth Surface Processes and Landforms 30: 836-846. https://doi.org/10.1002/esp.3355

Fischer L, Purves RS, Huggel C, Noetzli J, Haeberli W (2012b) On the influence of topographic, geological and cryospheric factors on rock avalanches and rockfalls in high-mountain areas. Natural Hazards and Earth System Science 12: 241-254. https://doi.org/10.5194/nhess-12-241-2012

French HM (2018) The Periglacial Environment. 4th edn. John Wiley & Sons Ltd, Chichester

Gasc-Barbier M, Merrien-Soukatchoff V, Virely D (2021) The role of natural thermal cycles on a limestone cliff mechanical behavior. Engineering Geology 293: 106293. https://doi.org/10.1016/j.enggeo.2021.106293

Gruber S, Hoelzle M, Haeberli W (2004) Rock-wall temperatures in the Alps: modelling their topographic distribution and regional differences. Permafrost and Periglacial Processes 15: 299-307. http://dx.doi.org/10.1002/ppp.501

Gubler S, Fiddes J, Keller M, Gruber S (2011) Scale-dependent measurement and analysis of ground surface temperature variability in alpine terrain. The Cryosphere 5: 431-443. https://doi.org/10.5194/tc-5-431-2011

Guerini M, Giardino M, Paranunzio R, Nigrelli G, Turconi L, Luino F., Chiarle M (2021) Slope failures at high elevation in the Italian Alps in the period 2000-2020. Pangaea Data Publisher for Earth & Environmental Science. https://doi.pangaea.de/10.1594/PANGAEA.931824

Gunzburger Y, Merrien-Soukatchoff V, Guglielmi Y (2005) Influence of daily surface temperature fluctuations on rock slope stability: case study of the Rochers de Valabres slope (France). International Journal of Rock Mechanics & Mining Sciences 42: 331–349. https://doi.org/10.1016/j.ijrmms.2004.11.003

Gunzburger Y, Merrien-Soukatchoff V (2011) Near-surface temperatures and heat balance of bare outcrops exposed to solar radiation. Earth Surface Processes and Landforms 36: 1577-1589. https://doi.org/10.1002/esp.2167

Haberkorn A, Hoelzle M, Philips M, Kenner R (2015) Snow as a driving factor of rock surface temperatures in steep rough rock walls. Cold Regions Science and Technology 118: 64-75. https://doi.org/10.1016/j.coldregions.2015.06.013

Haberkorn A, Kenner R, Noetzli J, Phillips M (2021) Changes in Ground Temperature and Dynamics in Mountain Permafrost in the Swiss Alps. Frontiers in Earth Science, 9. https://doi.org/10.3389/feart.2021.626686

Haberkorn A, Phillips M, Kenner R, Rhyner H, Bavay M, Galos SP, Hoelze M (2016) Thermal regime of rock and its relation to snow cover in steep alpine rock walls: Gemsstock, central Swiss Alps. Geografiska Annaler 97 (3) 579-597. https://doi.org/10.1111/geoa.12101

Haeberli W, Whiteman C (2015) Chapter 1 - Snow and Ice-Related Hazards, Risks, and Disasters: A General Framework. In Snow and Ice-Related Hazards, Risks, and Disasters. Hazards and Disasters Series. Elsevier. https://doi.org/10.1016/B978-0-12-394849-6.00001-9

Harris C, Arenson L, Christiansen H, et al. (2009) Permafrost and climate in Europe: Monitoring and modelling thermal, geomorphological and geotechnical responses. Earth Science Review 92 (3-4): 117-171. https://doi.org/10.1016/j.earscirev.2008.12.002

Hartmeyer I, Delleske R, Keuschnig M, Krautblatter M, Lang A, Schrott L, Otto JC (2020) Current glacier recession causes significant rockfall increase: the immediate paraglacial response of deglaciating cirque walls. Earth Surface Dynamics 8: 729–751. https://doi.org/10.5194/esurf-8-729-2020

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

Hock R, Rasul G, Adler C, Cáceres B, Gruber S, Hirabayashi Y, Jackson M, Kääb A, Kang S, Kutuzov S, Milner A, Molau U, Morin S, Orlove B, Steltzer H (2019) High Mountain Areas. In: IPCC Special Report on the Ocean and Cryosphere in a Changing Climate [H.-O. Pörtner, D.C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegría, M. Nicolai, A. Okem, J. Petzold, B. Rama, N.M. Weyer (eds.)]. In press.

Huggel, C, Clague JJ, Korup O (2012). Is climate change responsible for changing landslide activity in high mountains? Earth Surface Processes and Landforms, 37(1): 77-91. https://doi.org/10.1002/esp.2223

Humlun O, Matsuoka N. eds. (2004) A Handbook on Periglacial Field Methods. International Permafrost Association. https://ipa.arcticportal.org/publications/handbook accessed 17 May 2018

Huwald H, Higgins CW, Boldi MO, Bou-Zeid E, Lehning M, Parlange MB (2009) Albedo effect on radiative errors in air temperature measurements. Water Resources Research 45 (8): 1-13. https://doi.org/10.1029/2008WR007600

Kellerer-Pirklbauer A (2017) Potential weathering by freeze-thaw action in alpine rocks in the European Alps during a nine-year monitoring period. Geomorphology 296: 113-131 https://doi.org/10.1016/j.geomorph.2017.08.020

Knoflach B, Tussetschläger H, Sailer R, Meißl G, Stötter J (2021). High mountain rockfall dynamics: rockfall activity and runout assessment under the aspect of a changing cryosphere. Geografiska Annaler: Series A, Physical Geography, 103(1): 83-102. https://doi.org/10.1080/04353676.2020.1864947

Lucchesi S, Fioraso G, Bertotto S, Chiarle M (2014) Little Ice Age and contemporary glacier extent in the western and south-western Piedmont Alps (north-western Italy). Journal of Maps 10 (3): 409-423. https://doi.org/10.1080/17445647.2014.880226

Magnin F, Deline P, Ravanel L, Noetzli J, Pogliotti P (2015) Thermal characteristics of permafrost in the steep alpine rock walls of the Aiguille du Midi (Mont Blanc Massif, 3842 m a.s.l). The Cryosphere 9: 109–121. https://doi.org/10.5194/tc-9-109-2015

Magnin F, Yosnin JY, Ravanel L, Pergaud J, Pohl B, Deline P (2017) Modelling rock wall permafrost degradation in the Mont Blanc massif from the LIA to the end of the 21st century. The Cryosphere 11 (4): 1813-1834. https://doi.org/10.5194/tc-11-1813-2017

Matsuoka N (2019) A multi-method monitoring of timing, magnitude and origin of rockfall activity in the Japanese Alps. Geomorphology 336: 65–76. https://doi.org/10.1016/j.geomorph.2019.03.023

Matsuoka N, Murton J (2008) Frost Weathering: Recent Advances and Future Directions. Permafrost and Periglacial Processes 19: 195-210. https://doi.org/10.1002/ppp.620

Merlone A, Lopardo G, Antonsen I, et al. (2012) A new challenge for meteorological measurements: the “MeteoMet” project – metrology for meteorology. 9th International Symposium on Temperature. AIP Conf. Proc. 1552, 1030-1035

Merlone A, Lopardo G, Sanna F, et al. (2015) The MeteoMet project - metrology for meteorology: challenges and results. Meteorological Applicatios 22 (S1): 820–829. http://dx.doi.org/10.1002/met.1528

Ming-ko W (2015) Permafrost Hydrology. Springer-Verlag, Berlin Heidelberg

Moore J, Gischig V, Katterbach M, Loew S (2011) Air circulation in deep fractures and the temperature field of an alpine rock slope. Earth Surface Processes and Landforms 36: 1985-1996. http://dx.doi.org/10.1002/esp.2217

Mourey J, Marcuzzi M, Ravanel L, Pallandre F (2019) Effects of climate change on high Alpine mountain environments: Evolution of mountaineering routes in the Mont Blanc massif (Western Alps) over half a century. Arctic, Antarctic, and Alpine Research 51(1): 176-189. https://doi.org/10.1080/15230430.2019.1612216

Musacchio C, Coppa G, Merlone A (2018) An experimental method for evaluation of the snow albedo effect on near-surface air temperature measurements. Meteorological Application 26 (1): 161-170. https://doi.org/10.1002/met.1756

Musacchio C, Coppa G, Begeš G, Hofstätter-Mohler C, Massano L, Nigrelli G, Sanna F, Merlone A (2021) Effect of snow-covered ground albedo on the accuracy of air temperature measurements. Atmospheric Measurement Techniques 14: 6195–6212. https://doi.org/10.5194/amt-14-6195-2021

Nagai H, Fujita K, Nuimura T, et al. (2013) Southwest-facing slopes control the formation of debris-covered glaciers in the Bhutan Himalaya. The Cryosphere 7: 1303-1314. https://doi.org/10.5194/tc-7-1303-2013

Nelson FE, Outcalt SI (1987) A computational method for prediction and regionalization of permafrost. Arctic andAlpine Research 19 (3): 279-288. https://doi.org/10.1080/00040851.1987.12002602

Nigrelli G, Barbero S, Chiarle M (2021a) Solar radiation at the Bessanese high-elevation experimental site (Italy). Pangaea Data Publisher for Earth & Environmental Science. https://doi.pangaea.de/10.1594/PANGAEA.930679

Nigrelli G, Chiarle M (2021b) Evolution of temperature indices in the periglacial environment of the European Alps in the period 1990–2019. Journal of Mountain Science 18(11), 2842–2853. https://doi.org/10.1007/s11629-021-6889-x

Nigrelli G, Luino F, Turconi L, Mortara G., Guerini M, Paranunzio R, Giardino M, Chiarle M (2021c) Catasto delle frane di alta quota nelle Alpi italiane. http://geoclimalp.to.cnr.it/ILIA/index.html#6/45.019/9.382 Accessed on 23 june 2021

Nigrelli G, Fratianni S, Zampollo A, Turconi L, Chiarle M (2018) The altitudinal temperature lapse rates applied to high elevation rockfalls studies in the Western European Alps. Theoretical and Applied Climatology 131: 1479-1491. https://doi.org/10.1007/s00704-017-2066-0

Nigrelli G, Lucchesi S, Bertotto S, Fioraso G, Chiarle M (2015) Climate variability and Alpine glaciers evolution in Northwestern Italy from the Little Ice Age to the 2010s. Theoretical and Applied Climatology 122 (3): 595-608. https://doi.org/10.1007/s00704-014-1313-x

Paranunzio R, Chiarle M, Laio F, Nigrelli G, Turconi L, Luino F (2019a) New insights in the relation between climate and slope failures at high-elevation sites. Theoretical and Applied Climatology 137: 1765-1784. https://doi.org/10.1007/s00704-018-2673-4

Paranunzio R, Chiarle M, Laio F, Ntgrelli G, Turconi L, Luino F (2019b) Slope failures in high-mountain areas in the Alpine Region. Pangaea Data Publisher for Earth & Environmental Science. https://doi.pangaea.de/10.1594/PANGAEA.903761

Paranunzio R, Laio F, Chiarle M, Nigrelli G, Guzzetti F (2016) Climate anomalies associated to the occurrence of rockfalls at high-elevation in the Italian Alps. Natural Hazards and Earth System Science 16 (9): 2085–2106. https://doi.org/10.5194/nhess-16-2085-2016

Ravanel L, Magnin F, Deline P (2017) Impacts of the 2003 and 2015 summer heatwaves on permafrost-affected rock-walls in the Mont Blanc massif. Science of the Total Environment 609: 132–143. https://doi.org/10.1016/j.scitotenv.2017.07.055

Schnepfleitner H, Rode M, Sass O (2018) Validation of simulated temperature profiles at rock walls in the eastern alps (Dachstein). Permafrost and Periglacial Processes 29: 34–48. https://doi.org/10.1002/ppp.1962

Schön JH (2015) Physical Properties of Rocks. 2nd edn. Amsterdam: Elsevier

Thorne PW, Diamond HJ, Godison S, et al. (2018) Towards a global land surface climate fiducial reference measurements network. International Journal of Climatology 38: 2760-2774. https://doi.org/10.1002/joc.5458

van Everdingen RO ed. (1998) *Multi-language Glossary of Permafrost and related Ground-ice Terms. International Perma*frost Association. Revised 2005

Viani C, Chiarle M, Paranunzio R, Merlone A, Musacchio C, Coppa G, Nigrelli G (2020) An integrated approach to investigate climate-driven rockfall occurrence in high alpine slopes: the Bessanese glacial basin, Western Italian Alps. Journal of Mountain Science 17: 2591-2610. https://doi.org/10.1007/s11629-020-6216-y

Weber S, Beutet J, Faillettaz J, et al. (2017) Quantifying irreversible movement in steep, fractured bedrock permafrost on Matterhorn (CH). The Cryosphere 11: 567–583.

Weber S, Beutel J, Da Forno R, Geiger A, Gsell T, et al. (2019) A decade of detailed observations (2008–2018) in steep bedrock permafrost at the Matterhorn Hörnligrat (Zermatt, CH). Earth System Science Data, 11: 1203–1237. https://doi.org/10.5194/essd-11-1203-2019

Tables

Table 1. Main characteristics of the three rock-faces (TMS No.) and the nine MT data logger (ID No.) used in this study. AGL, height of the hole in the rock, above the ground level. * also identified as near surface rock temperature (NSRT)

TMS (No.)	Elevation (m a.s.l.)	Aspect (°N)	Slope (°)	Latitude (N)	Longitude (E)	ID (No.)	AGL (cm)	Depth (cm)
TMS1	2667	30	50	45.29758	7.14259	Q61213	100	10*
						Q62122	100	30
						Q61215	100	50
TMS2	2666	135	50	45.29702	7.14390	Q61212	130	10*
						Q62114	130	30
						Q62121	130	50
TMS3	2653	225	45	45.29711	7.14421	Q62110	100	10*
						Q62097	100	30
						Q61211	100	50

Table 2. Measurement uncertainty components: D, Distribution; N, Normal; R, Rectangular; U, Uncertainty

U component	Value (°C)	D	U (°C)
U calibration	0.027	N	0.027
Resolution	0.1	R	0.029
Calibration curve residuals	Negl.		0.000
Field comparability	0.1	R	0.029
Total U (K)			0.049
Total U (K=2)			0.098

Table 3. Rock (ID No.) and air (AWS) temperature observed during the two years of measurements, from 20 July 2018 to 5 August 2020 (Tmean, Tmin and Tmax are respectively mean, minimum and maximum temperature; Sd, standard deviation; * data loggers that have acquired near surface rock temperature)

ID (No.)	Tmean (°C)	Tmin (°C)	Tmax (°C)	Data (No.)	Sd (°C)
Q61213*	3.1	-7.5	27.2	35858	5.4
Q62122	3.0	-5.7	20.7	35858	5.4
Q61215	2.9	-4.3	17.2	35858	5.0
Q61212*	5.4	-2.7	33.0	35858	7.4
Q62114	5.2	-1.6	23.4	35858	6.4
Q62121	5.1	-1.8	20.5	35858	6.2
Q62110*	5.6	-5.0	40.8	35858	7.9
Q62097	5.5	-2.8	26.0	35858	6.2
Q61211	5.5	-1.8	20.5	35858	5.7
AWS	1.7	-18.8	19.9	35158	6.7

Figure captions

Figure 1 Map of the Bessanese high-elevation experimental site. TMS, temperature monitoring site; AWS, Automatic Weather Station (owner ARPA Piemonte); Webcam, on the right glacial moraine at 2775 m a.s.l. (https://bessanese.panomax.com/); Black arrows indicates the glacier terminus at specific years (Aerial photo by Franco Rogliardo, 7 September 2016, source Comitato Glaciologico Italiano)

Figure 2 Drilling operations at TMS1 (A) and insertion of the temperature data logger at 30 cm depth (B)

Figure 3 Rock temperature trend at different depths (10 cm, 30 cm and 50 cm) at the three rock-faces (TMS1, TMS2 and TMS3) and air temperature and snow depth trends (AWS) acquired during the entire observation period. The different aspect of the measuring sites is also indicated (black circle in the wind rose)

Figure 4 Trend of rock temperature at TMS3 at the three different depths (10, 30, 50 cm), and of air temperature (Tair), during four consecutive days of September 2019 (1-2 September, cloudy days; 3-4 September, sunny days) in relation to the global (Gsr) and reflected (Rsr) solar radiation. Weather conditions of these four days can be checked by consulting the image archive of the webcam positioned to monitor the Bessanese experimental basin, at an altitude of 2775 m a.s.l. (https://bessanese.panomax.com/)

Figure 5 Descriptive statistics of the daily temperature lapse rate (DTLR, °C/cm) calculated in TMS1, TMS2 and TMS3, considering the two different depths intervals: a, 10 cm vs 30 cm; b, 30 cm vs 50 cm. In each box, the median and the mean are marked (respectively horizontal line and cross), the box edge indicate the first quartile (bottom) and the third quartile (top), the whiskers indicate the minimum (bottom) and the maximum (top) value