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Metrological approach for permafrost temperature measurements

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ABSTRACT

Permafrost degradation is a growing direct impact of climate change. Detecting permafrost shrinkage, in terms of extension, depth reduction and active layer shift is fundamental to capture the magnitude of trends and address actions and warnings. Temperature profiles in permafrost allow direct understanding of the status of the frozen ground layer and its evolution in time. The Sommeiller Pass permafrost monitoring station, at about 3000 m of elevation, is the key site of the regional network installed in 2009 during the European Project "PermaNET" in the Piedmont Alps (NW Italy). The station consists of three vertical boreholes with different characteristics, equipped with a total of 36 thermistors distributed in three different chains. The collected raw data shows a degradation of the permafrost base at approximately 60 m of depth since 2014, corresponding to about 0.03 °C/yr. In order to verify and better quantify this potential degradation, three *on-site* sensor calibration campaigns were carried out to understand the reliability of these measurements. By repeating calibrations in different years, two key results have been achieved: the profiles have been corrected for errors and the re-calibration allowed to distinguish the effective change of permafrost temperatures during the years, from possible drifts of the sensors, which can be of the same order of magnitude of the investigated thermal change. The warming of permafrost base at a depth of ~ 60 m has been confirmed, with a rate of $(4.2 \pm 0.5)\bullet 10^{-2}$ °C/yr. This paper reports the implementation and installation of the on-site metrology laboratory, the dedicated calibration procedure adopted, the calibration results and the resulting adjusted data, profiles and their evolution with time. It is intended as a further contribution to the ongoing studies and definition of best practices, to improve data traceability and comparability, as prescribed by the World Meteorological Organization Global Cryosphere Watch programme.

1. Introduction

Together with sea ice, snow and glaciers, permafrost is a key component of the cryosphere through its influence on energy exchanges, hydrological processes, natural hazards, carbon dioxide and methane emission and the global climate system (Riseborough et al., 2008). The thawing of permafrost leading to the destabilization of rocks and mountain slopes is an increasing hazard in alpine environments (Gruber et al., 2004; Gruber and Haeberli, 2007; Krautblatter et al., 2013). Moreover, its degradation is seen as a major challenge in the current discussion of global warming (Stocker et al., 2013), due to the possible effects on climate (Colombo et al., 2019; Harden et al., 2012; Schuur et al., 2015) also through release of trapped gases in high latitude areas. Actually, as a consequence of global warming trends, ground temperature near the depth of Zero Annual Amplitude (ZAA) increased globally by 0.29 ± 0.12 °C during the decade between 2007 and 2016 (Biskaborn et al., 2019), while the active layer is known to be progressively deepening in various parts of the cryosphere (Desyatkin et al., 2021; Li et al., 2022; Xu and Wu, 2021).

European Alps permafrost studies are a rather recent field: the first map of the permafrost distribution in the Alps was published by Boeckli et al. (2012), but generic studies on single permafrost sites are only marginally older (Haeberli, 1992), and usually hint at the poor knowledge of their state and evolution especially compared to glaciers (Haeberli and Beniston, 1998). Notable exceptions are localized in the Swiss Alps, where permafrost has been monitored since at least the 1970s (Gartner-Roer et al., 2022) or, sporadically, even before (see Haeberli et al., 2011 for a review).

Correspondingly, knowledge on permafrost in the Italian Western Alps was rather poor up until the first years of the 21st century and

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limited to a few localized rock glacier studies in the Maritime Alps (Ribolini and Fabre, 2006). In 2006 ARPA Piemonte, Piedmont Regional Agency for Environmental Protection, in collaboration with the University of Insubria, started a regional study to improve knowledge on relations among alpine permafrost and climate change, natural hazards and water resources. These activities increased during the European project "PermaNET – Long-term monitoring network",[1] with the establishment of five new permafrost monitoring stations in the Piedmont Alps, from 2500 m to more than 3000 m of elevation, including the Sommeiller Pass station. Since 2009, the activity on permafrost monitoring has become an institutional service by ARPA Piemonte, allowing proper site maintenance and research activities on the permafrost and periglacial environment in Piedmont Alps (Paro and Guglielmin, 2013).

The Global Cryosphere Watch (GCW), the World Meteorological Organization (WMO) program supporting all key cryospheric on-site and remote sensing observations, has deep interest in implementing a metrological approach in such observations and analyses. A specific expert team was formed in 2020, tasked to draft best practice for permafrost measurements including optimized methods to establish metrological traceability, through dedicated calibrations and evaluation of uncertainties. Accurate measurements of the permafrost properties, calibration of instruments and sensors, improved data quality are fundamental to achieve more reliable knowledge on the evolution of this component of the cryosphere, especially for observations from different stations taking part in networks.

To organize scientific analyses of the cryosphere to support decision-making and environmental policy, GCW lists the need to "*Enhance the quality of observational data by improving observing standards and best practices for the measurement of essential cryospheric variables. This includes developing measurement guidelines and best practices; engaging in, and supporting, intercomparison of products, formulating a set of best practices for product intercomparisons*", as stated in the expression of interest sent to the European Association of National Metrology Institutes (EURAMET) Task Group Environment in November 2017. Best practices in cryosphere observations have been recently included as a chapter in the new WMO "Guide to Instruments and Methods of Observations", known as the GIMO guide #8. Permafrost has also been identified as one of the cryospheric indicators of global climate change within the Global Climate Observing System (GCOS, 2003) with its associated Essential Climate Variables (ECVs), whose definitions have been recently refined (GCOS, 2022). The need for metrological traceability and adoption of standard methods was also expressed by GCOS: "*Measurement and reporting standards are emerging, but further work is needed to prepare and publish definitive reporting standards*" (GCOS, 2016).

In the framework of EURAMET project MeteoMet and follow-on actions (Merlone et al., 2018; Merlone et al., 2015), three on-site calibration campaigns (2017, 2018, 2020) were planned and performed by the Italian Institute of Metrological Research (*Istituto Nazionale di Ricerca Metrologica*, INRiM) and ARPA Piemonte, for the permafrost temperature sensors chains managed by the latter and hosted at the Sommeiller Pass in NW Alps. Beyond the on-site temperature sensors calibration per se, this study was conceived with several other objectives, such as the definition and testing of calibration and measurement best practices; evaluation of sensors drift and stability; validation of temperature profiles in the boreholes. These experimental activities improve scientific and technical knowledge on establishing traceability, by means of calibration and uncertainty evaluation, to permafrost temperature profiles, their evolution in time and comparability of data from different stations and networks.

The paper is organized as follows: Section 2 will describe the Sommeiller Pass permafrost monitoring station, its scientific rationale, the calibration campaigns and the instrumental apparatus; Section 3 will present the results in terms of calibration correction and uncertainty, their effect on the borehole temperature profile and an evaluation of thermometer drift, along with a brief discussion; Section 4 will feature the conclusions drawn from the experiment.

2. Instruments and methods

2.1. Permafrost monitoring station at the Sommeiller Pass

The Sommeiller permafrost monitoring station is the key site of the regional network, located at about 3000 m a.s.l. in upper Susa Valley (NW Italy) and became fully operational in 2011. The station is defined as "key site" by ARPA Piemonte which manages it (Paro et al., 2018), because it is the only 100-m deep borehole, in contrast with the other sites which are only 30-m deep, which allows for more sophisticated analyses, not only for permafrost characteristics and evolution, but also for paleoclimatic estimates.[2]

The station features three boreholes, respectively 5, 10 and 100 m deep, vertically drilled in the bedrock, a few meters apart, equipped with thermistors chains (Campbell Scientific model 107, encapsulated in an epoxy-filled aluminium housing). The 5 m borehole is equipped with two sensors placed directly in the uncasing borehole filled with cuttings. The 10 m and 100 m boreholes are equipped with 12 and 22 sensors respectively, each placed in a Ø 50 mm HDPE tube. The 100 m borehole is equipped with a metal casing for the first 10 m, with head buried under about 70 cm of debris. Data is collected by a CR1000 Campbell Scientific datalogger and manually downloaded at least once a year.

In addition, a weather station equipped with a thermo-hygrometer, a nivometer and a radiometer has been installed in the same site. Since 2009, geoelectric and Bottom Temperature of the Snow (BTS) surveys have been also carried out in the site.

Until 2013, using raw data, permafrost was detected from −10 m all the way down to the bottom of the deepest hole at 100 m, with a temperature gradient from the base of the AL evaluable as ~ 2 mK/m, which includes a ~ 25 m plateau and a ~ 6 mK/m rise below 40 m. Since 2014, a positive temperature transition (~ 0.15 °C) has occurred at about 60 m of depth indicating a degradation of the permafrost base (Fig. 1). In order to verify this variation (grown to ~ 0.25 °C in 2016), sensor calibration became necessary to understand the reliability of the observed warming.

These values seem compatible to those described in literature: for instance, according to Dobiński (2020), "the active layer is thin in the High Arctic and becomes thicker farther south", and the thickest AL can reach over 20 m of depth. Li et al. (2022) and Luo et al. (2016) concur that "the ALT varied from approximately 30 cm in the Arctic and circumpolar regions to greater than 10 m in the midlatitude mountainous permafrost zone during 1990–2015". Regarding the temperature gradient, Harris et al. (2003) presented the results of measurements in the Alps which ranged from 0.005 °C/m at Schilthorn to 0.018 °C/m at Stockhorn (both in Switzerland).

However, the particular characteristics of Sommeiller pass borehole, in terms of geology, geomorphology, climatology and location of the site in comparison with other European sites, as well as the thermal characteristics of the permafrost geomaterial, are the subject of two further papers which are currently in progress.

2.2. On-site calibrations

Several factors directly or indirectly affect both temperature measurements and sensors' calibration differently in the field with respect to the laboratory. Environmental conditions can condition the performance of the datalogger; cables, connectors, and multiplexing schemes

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[1] PermaNET 2011. Permafrost Long-term Monitoring Network, Synthesis Report. http://www.permanet-alpinespace.eu/home.html

[2] ARPA Piemonte. Il permafrost nelle Alpi Piemontesi – Sito del Colle del Sommeiller. https://www.arpa.piemonte.it/media/3242 (in Italian).

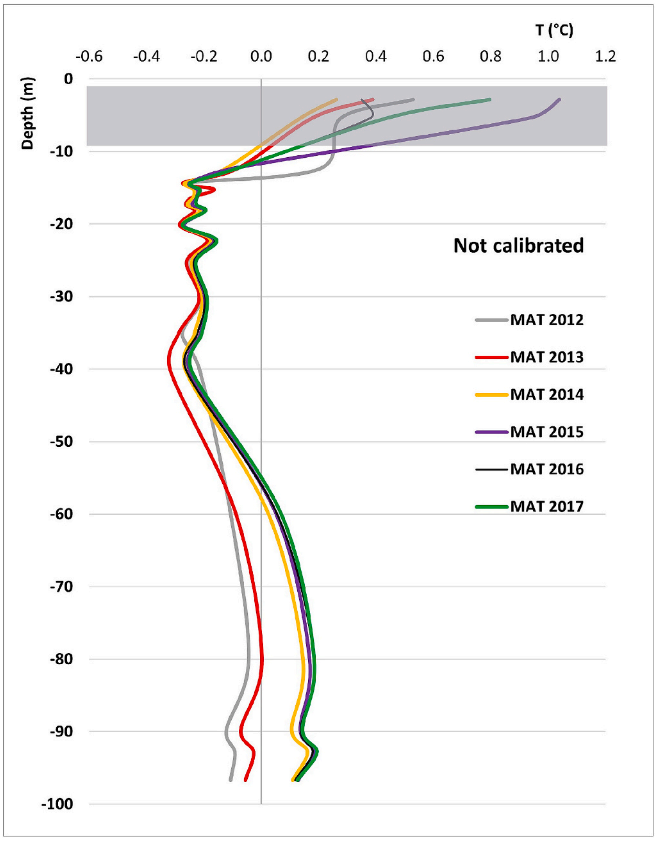

Fig. 1. Permafrost profile temperatures measured in different years, before the start of the calibration campaigns (raw data). Shown in grey is the active layer. MAT = Mean Annual Temperature.

are used under the same conditions they usually work, as well as the sensors themselves. All these aspects make the calibration curve more representative of the measuring process and the calibration uncertainty becomes the largest contribution to the overall measurement uncertainty, reducing most of the other factors to negligible contributions. As a matter of fact, the calibration uncertainty sometimes is considered as the total measurement uncertainty, despite being just a component of the overall budget. By performing on-site calibration in almost identical conditions to the measurement ones, the calibration uncertainty becomes the major if not almost total contribution to the overall measurement uncertainty.

Moreover, removing a chain of sensors from a borehole, bringing it to the laboratory and restoring them in place is not always easy or feasible, especially in remote and hard-to-reach areas; transportation itself can cause shocks to the sensors, thus changing their response curve, as evaluated during the calibration.

Temperature sensors and, more in general, sensors that have been exposed for prolonged periods of time to harsh environmental conditions, are known to exhibit slight modifications in their physical properties that can also change their measurements – or *drift* (Bell et al., 2017; Musacchio et al., 2015). In laboratory conditions, thermistor drift can be evaluated to be as low as few mK per year or even lower (Lawton and Patterson, 2002); however, thermistors in permafrost boreholes are subject to much more stress and can exhibit larger drifts (Widmer et al., 2023), which are difficult to evaluate given the long periods of time necessary to detect them (Batir et al., 2017) and are sometimes only evaluable in certain conditions given the lack of references (Luethi and Phillips, 2016). Sensor drift is mainly caused by oxidation due to ageing and imperfect insulation. It can be caused as well by thermal or mechanical shocks (Kowal et al., 2020), all of which can act on the resistor and change its electrical resistance, which is proportional to the temperature measured. A change in electrical properties of the resistor can therefore mimic a change in temperature, even when this is not happening.

This drift is often evaluable as few hundredths of a °C, comparable with the signal coming from climate change-related thermal phenomena, like the permafrost thawing (Haberkorn et al., 2021). For this reason, and in order to prevent that drift could be mistaken for climate change signal (Kenner et al., 2017), environmental thermometers are required to be calibrated frequently – possibly annually – to evaluate this drift and disentangle this component from real measurand changes (Noetzli et al., 2021).

For these reasons, several on-site calibrations were deemed necessary, and a dedicated transportable calibration system was developed at INRiM (Merlone et al., 2020) and used for the three campaigns at the Sommeiller Pass station.

2.3. *Test calibration campaign (2017)*

For the first on-site campaign, carried out in August 2017, two reference temperature sensors (Pt100, 5615–6-Fluke, labelled RS henceforth), a thermostatic bath (Thermo Scientific Enco Haake G50 – AC200), a high-accuracy resistance bridge for readout (Fluke 1594A), two power generators and a light shelter were brought to the site (Fig. 2). Due to space and time constraints, only 13 out of the 36 total temperature sensors (coded PS) were selected for calibration.

The PS were extracted from the boreholes of 100 m and 10 m and grouped with the two RS used as reference sensors, coded NS01 and NS03. These two RS were already calibrated at INRiM laboratories in a liquid bath (INRiM internal procedure, CMC PT-T.2.2–01, Key Comparison Database), by comparison against a 25 Ω Standard Platinum Resistance Thermometer calibrated at the fixed points of the ITS-90. The grouped sensors were then inserted in the thermostatic bath, filled with pure alcohol as a medium. In order to maximize the calibration accuracy in the permafrost temperature range and minimize the interpolation uncertainties, five temperature points close to the freezing point of water were chosen as calibration points (−7 °C, −3 °C, 0 °C, +3 °C, +7 °C). The 0 °C point was repeated to check for hysteresis as usually done in calibration procedures.

After the given temperature point reached the requested stability, data was recorded for 30 min, at one-minute recording/storing frequency. Within this recorded interval, a sub-range of 10 min with best stability was selected and used to compare the readings of each PS sensors differences from the weighted average reference temperature given by the RS sensors.

The calibration required two days of measurements at the end of which the “calibration camp” was dismantled and the PS chains reinserted in the boreholes. The whole procedure required three days: half day to setup the on-site calibration laboratory, two days of calibration activity and about a half-day to dismantle the systems.

2.4. *Calibration campaigns (2018 and 2020)*

Following the experience acquired in 2017, a second calibration campaign was carried out in August 2018, and a third in August 2020.

For these activities, the same reference temperature sensors and high-accuracy readout bridge used in the previous campaign were employed. A third reference sensor was added (coded NS02) while the thermostatic bath was replaced by another (Polyscience PP15R-40-A12E) equipped with a wider reservoir that allowed the insertion of a larger number of sensors (Fig. 3a). Moreover, thanks to the lower power requirements, the use of a single generator was sufficient, therefore reducing costs and weight of the equipment.

A dedicated copper comparator block (Fig. 3b) was designed, manufactured and characterized at INRiM laboratories, allowing the insertion of the 32 permafrost temperature sensors plus the three PRT reference sensors.

Fig. 2. The mobile calibration facility at Sommeiller Pass during the 2017 campaign. a) Inside the shelter: thermostatic bath and high-accuracy readout bridge, grouped permafrost sensors chain with reference sensors. b) Outside: 100 m permafrost borehole, shelter and power generators.

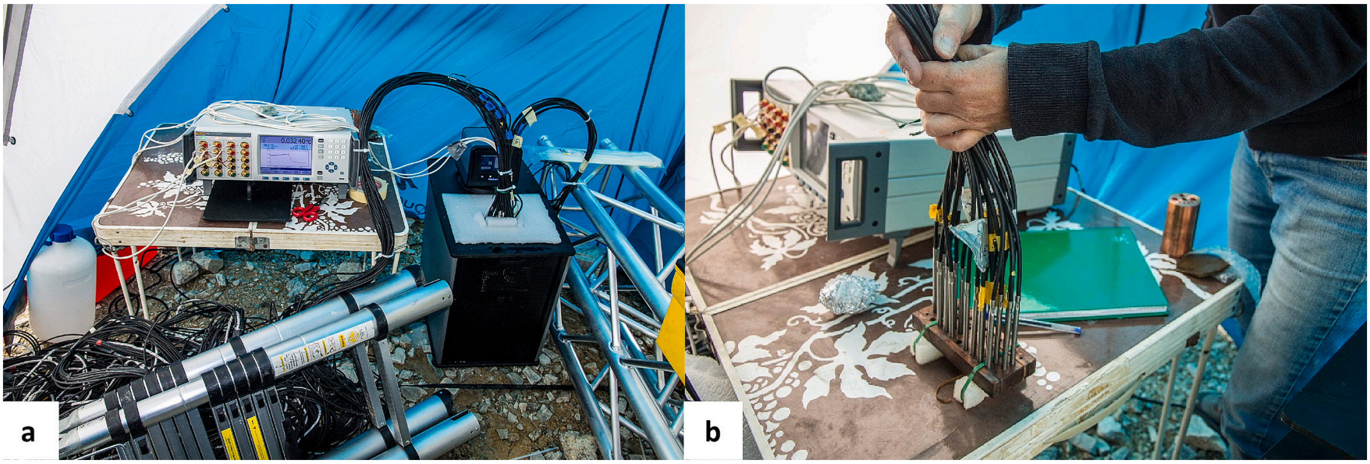

Fig. 3. The calibration apparatus in its final configuration (a), and a closeup of the copper comparator block with all the RS and the PS inserted (b), during the 2018 campaign.

3. Results and discussion

As already mentioned, the experimental calibration performed in 2017 has been considered as a test for the methods and the equipment. Unfortunately, it was evident that the setup was not satisfactory, as the calibration uncertainties were higher than anticipated (Fig. 5a) and sometimes not even easily determinable. The largest problem was identified in the PS setup inside the calibration bath: being in close contact with one another, the medium was not able to correctly enclose all of them and make the temperature uniform; moreover, the self-heating generated by each sensor was not correctly dissipated by the medium and affected the measurements of the nearby sensors, in a hard-to-determine way.

For this reason, the 2017 calibration was not considered for the determination of the sensor's drift.

During the calibrations described, no anomalous data have been recorded; in case they were, they would have been immediately recognized as spikes, given that calibrations are performed at constant temperature.

According to the data measured by ARPA Piemonte on-site weather station, air temperatures during the calibration campaigns of 2018 and 2020 ranged from 3 °C to 15 °C, much lower than in laboratories, so we also questioned the stability and the performance of the readout bridge exposed to such low environmental temperatures. For this reason, the bridge was tested in the lab against another identical unit.

The bridge was put inside a climatic chamber, set first at room temperature (~ 21 °C), then at temperatures similar to those recorded by the weather station on-site, while reading the output of two reference sensors inside a stirring bath set at the same temperature at which the calibrations were performed (3 °C). The second identical unit, kept outside of the climatic chamber at room temperature, was set to read two other reference sensors inside the same bath.

Fig. 4 shows the results of this experiment. Lines represent the readings of the four reference sensors by the two bridges, while the coloured background indicates the temperature at which the "chamber" bridge was exposed. In the yellow part of the plot, both bridges were exposed to room temperature, then the climatic chamber was set first at 8 °C, then at 3 °C, simulating the environmental conditions during on-site calibrations. The impressive stability of both bridges at all temperatures is evident, therefore we concluded that the environmental conditions did not contribute significantly to the acquisition system uncertainty budget.

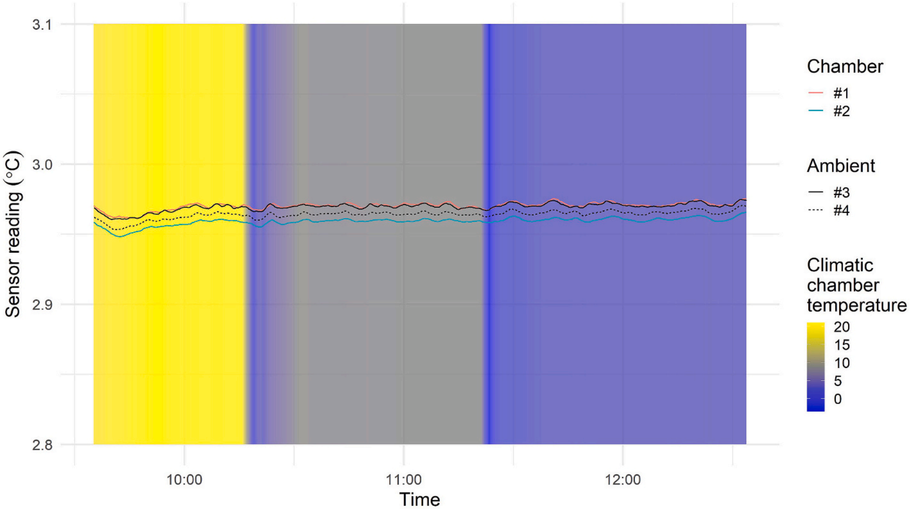

Fig. 4. Stability of the readout bridge at different ambient temperatures. Four sensors, kept at ~3 °C inside a calibration bath, are read in couples by two identical readout bridges, one kept constantly at room temperature ("Ambient"), the other kept inside a climatic chamber with varying temperature from room (yellow) to ~ 8 °C, to 3 °C. The four sensors measure the same temperature, with differences well within their calibration uncertainty, and their readings are not influenced by the temperatures at which the bridges are exposed. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

3.1. *Calibration curves and drift evaluation*

Shown in Fig. 5a, b and c (related to 2017, 2018 and 2020 calibration campaign, respectively) are the calculated calibration curves (for sensor PS9 only, as an example) obtained through a second order polynomial fit on the differences ΔT between the averaged readings of the reference sensors ($T_{\overline{RS}}$) and the sensor in calibration (T_{PS}).

Fig. 5a clearly shows the problems that arose during the test calibration of 2017, with a bad R^2 on the fit, poor reproducibility shown by the very different values of the 0 °C points and in general large uncertainties.

Fig. 5b and c show the calibrations of 2018 and 2020, with much better fits, reproducibility and hysteresis. The differences between the two calibrations are due to the sensor drift, evaluated in Fig. 5d as

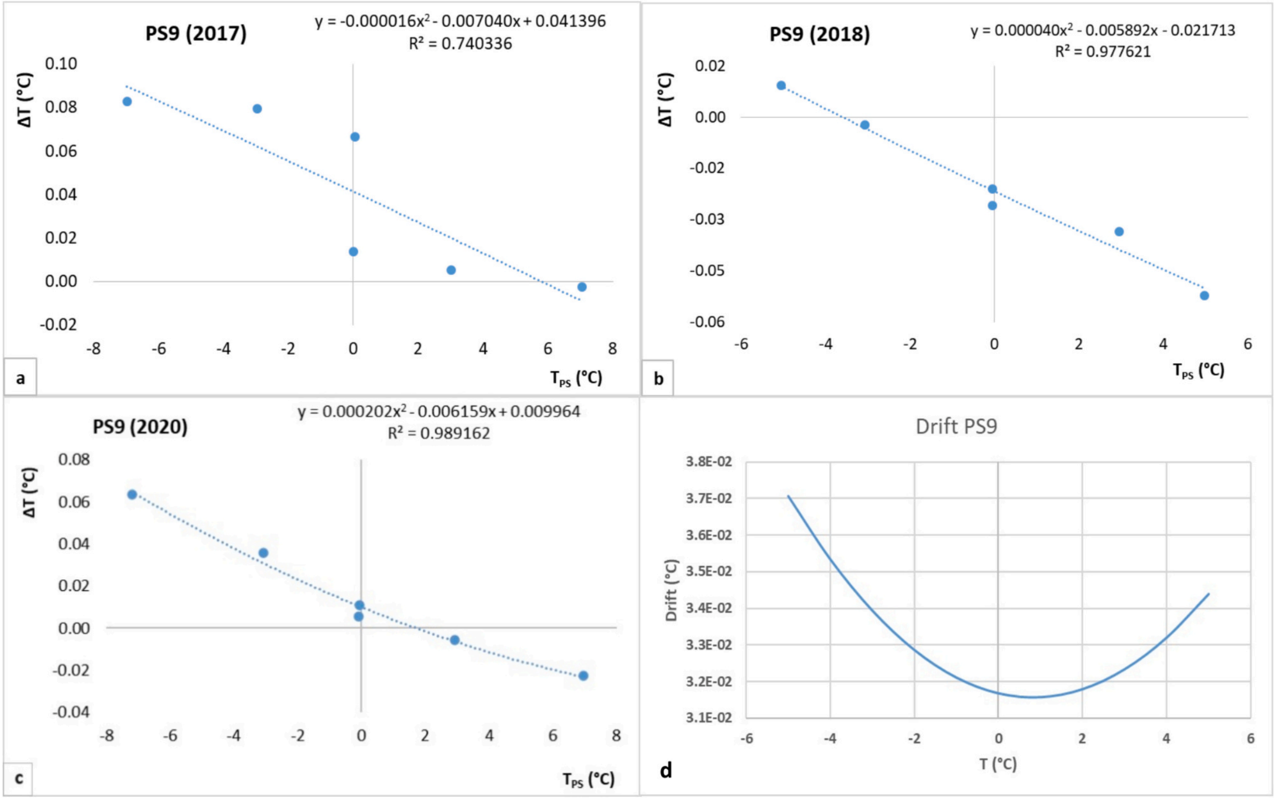

Fig. 5. Calibration curves relative to 2017 (a), 2018 (b) and 2020 (c) calibration campaign for the sensor PS9, obtained through a polynomial fit on the temperature differences between the averaged readings of the reference sensors and the sensors in calibration. Subfigure (d) shows the drift function of PS9, evaluated as differences between the calibration functions of 2020 and 2018.

polynomial differences between the calibration curves of 2020 and 2018. In this case, at the temperatures typical of the permafrost, the drift can be evaluated as $3.2\bullet10^{-2}$ °C during this 2-years period, corresponding to $1.6\bullet10^{-2}$ °C. The other sensors show similar values of annual drift, between $2\bullet10^{-2}$ and 10^{-3} °C/yr, while one sensor showed a larger drift of $6\bullet10^{-2}$ °C/yr, spy of a possible mechanical or electrical problem.

Not counting this outlier, these are typical drift values for resistors and thermistors even when not exposed to harsh environments (Kowal et al., 2020).

The drift has been here evaluated on the basis of only two calibrations, which may be deemed not enough for an accurate assessment. In laboratory conditions, thermistors (and RTDs in general) are known to exhibit very linear drifts (Kulkarni et al., 2015; Li et al., 2023), even though environmental sensors are subject to much more strain and stress, and therefore their drifts can vary in ways which are difficult to predict.

For this reasons, more on-site calibrations are envisaged, to refine and validate the present analysis.

3.2. *Calibration correction effect on measured permafrost temperature profile*

Data provided by ARPA was recorded hourly from January 2012 to December 2017. The daily and monthly averages were calculated. A quality data check was performed before applying the calibration curves. The outliers, the periods in which the sensor chain were in maintenance or those in which there were technical problems were eliminated from the analysis. For instance, some anomalous data have been identified in the temperature profiles, in particular with the sensor placed at −27 m (coded PS24). It showed erratic behaviour, especially in older measurements, therefore it has been excluded from the analysis altogether.

Data coming from calibrated sensors show that the 6-year record of permafrost temperatures from the 100-m deep Sommeiller Pass borehole show a warming trend. With respect to uncalibrated sensors data, the active layer ends at a depth of ~ 11 m (Fig. 6).

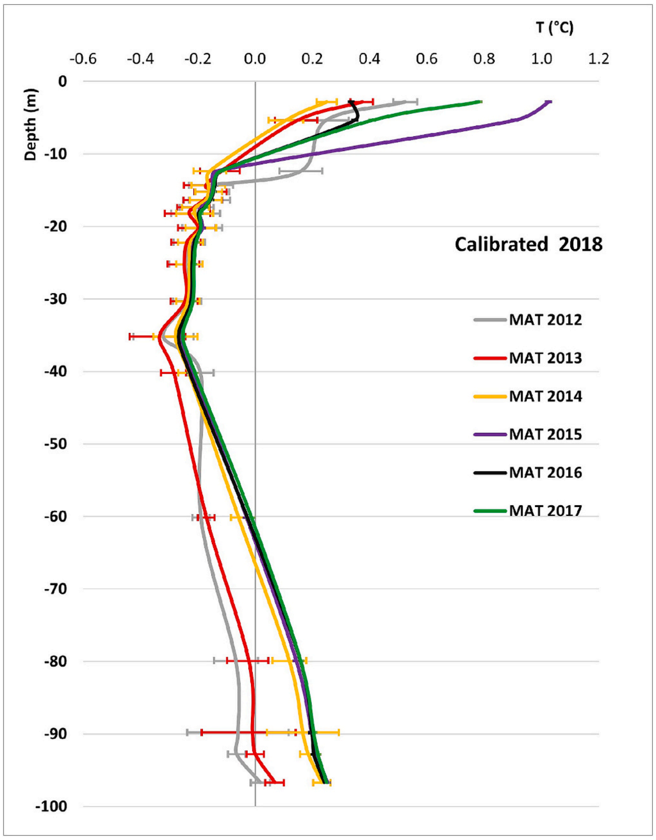

Fig. 6. Temperature profiles data using 2018 calibration. Uncertainty bars represent calibration uncertainty plus the drift evaluated from 2018 and 2020 calibrations.

As it can be seen by comparing to Fig. 1, the implementation of the 2018 calibration curves to the 2012–2017 profiles had the effect of pushing the permafrost degradation point downward from ~ 55 m to ~ 65 m, with the uncalibrated values generally overestimating temperatures at that depth by ~ 0.08 °C, larger than calibration plus drift uncertainties for almost all sensors. It must be noted, however, that for the majority of the other sensors, it is actually the vice versa (uncalibrated values indicate lower temperatures). This depends essentially on the way they are calibrated or characterized at the factory, and their history of measurements.

As far as the permafrost base is concerned, borehole thermal gradients may be influenced, among the major factors, by the regional geothermal heat flux (Harris et al., 2003). The calibrated profile at low depths (from −80 m) showed a more consistent curvature with the geothermal heat flux coming from the ground beneath the borehole, compared to the curvature shown by the uncalibrated profile. Calibrated values have the effect of steepening the gradient to ~ 4 mK/m from the AL base and ~ 7 mK/m from the end of the temperature plateau.

Fig. 7 shows the differential temperature increase during the period 2013–2017 from calibrated profiles at the depth of 60 m, calculated as differences between each year and the 2012 baseline. The plot shows positive differences for each year, with a rate of $(5.6 \pm 1.6)\bullet10^{-2}$ °C per year during 2012–2014 and a slower, steadier rate of $(1.4 \pm 1.6)\bullet10^{-2}$ °C/yr from 2014 to 2017. The overall rise, during the whole period, is evaluable as $(4.2 \pm 0.5)\bullet10^{-2}$ °C/yr.

4. Conclusions

This study reports a multiple calibration campaign, carried out by INRiM between 2017 and 2020, for permafrost temperature sensors installed and managed by ARPA Piemonte on a 100-m deep borehole at the Sommeiller Pass, in NW Italian Alps. The in-situ calibrations have been performed using a portable system designed and developed by INRiM, and tested in 2017. The calibrations performed in 2018 and 2020 have been used to correct the measurements obtained from 2012 by the 20 temperature sensors installed at different depths in the 100-m borehole, and have been used also to compute the sensors' drift, i.e. the variation in response by the sensors, subject to the same temperature.

Most sensors exhibit deviations from the real temperature of the order of 0.1 °C or less, with maximum values at lower temperatures. Some of the sensors, however, showed deviations of ~ 0.3 °C at −7 °C, and around 0.15 °C at 0 °C. Drift of the sensors, computed as differences between the deviations calculated by the 2020 and 2018 calibrations, has been evaluated between $2\bullet10^{-2}$ and 10^{-3} °C/yr, similar to the signal generated by the general degradation of the permafrost caused by climate change. After the application of calibration curves to the past data the permafrost degradation is still present, however the permafrost degradation point has been pushed downward from ~ 55 m to ~ 65 m. At that point, uncalibrated sensor readings overestimate temperatures by ~ 0.08 °C, while other sensors generally underestimate real temperatures.

This study shows the added value that collaboration between metrology and the community working in cryosphere observations can bring to permafrost studies. A need to discuss and agree on common approaches, best practice and uncertainty evaluation on the numerous measurements made in glacial and periglacial areas, including methods to measure permafrost temperature profiles, had emerged. Together with the experience achieved during the calibration campaign at the Sommeiller Pass, and the issues encountered during laboratory

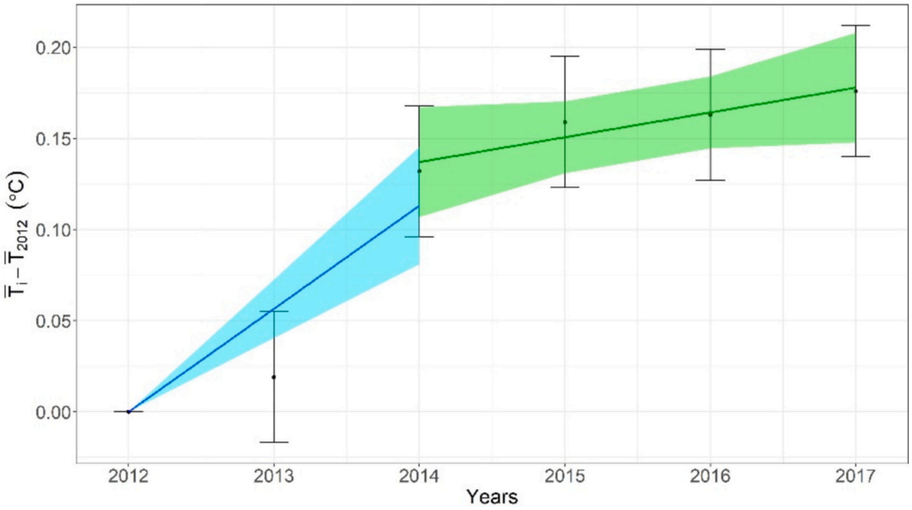

Fig. 7. Temperature increase with respect to the 2012 value recorded by the sensor at 60 m. Each value represents the difference between average recordings between each year and the 2012 value, with measurement uncertainties as error bars and uncertainty bands due to the weighted fits.

calibration of different typologies of thermometers, best practice procedures can now be adopted, and studies can be started towards the definition of reference calibration and measurement methods for reference sites. Documented traceability is the primary tool to improve data comparability within a single station, among stations taking part in a network and among networks. This initiative can be expanded to further agreed processes for calibration and uncertainty evaluation to also benefit the data quality achievable by the Cryonet stations network supervised by the Global Cryosphere Watch of the World Meteorological Organization.

CRediT authorship contribution statement

Graziano Coppa: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation. **Francesca Sanna:** Software, Methodology, Formal analysis. **Luca Paro:** Resources. **Chiara Musacchio:** Methodology, Investigation. **Andrea Merlone:** Visualization, Project administration, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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