Metrological approach for permafrost temperature measurements

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This is a non-peer reviewed preprint of a manuscript submitted to Permafrost and Periglacial Processes

Abstract

Permafrost degradation is a growing direct impact of climate change. Detecting permafrost reductions, in terms of its extension, deepening of the active layer and rise of the base 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 5, 10 and 100 m deep with different characteristics, equipped with thermometric chains for a total of 36 temperature sensors (thermistors type). The raw collected data shows an active layer 8-9 m thick, and a degradation of the 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 calibrations campaigns were carried out aimed to understand the reliability of the measurements in progress. By repeated calibrations, two key results have been achieved: the profiles have been corrected for biases and the re-calibration allowed to distinguish the effective change of permafrost temperatures along the years, from possible drifts of the sensors, which can be of the same order of magnitude of the investigated thermal change. The reduction of permafrost starting from 2012 at a depth of ~60 m has been confirmed, with a rate of 0.042 ± 0.005 °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 in 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.

Keywords: permafrost monitoring, metrology, sensor calibration, reference site, calibration uncertainty

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 considered to be an increasing hazard in alpine environments (Gruber et al. 2004; Gruber & 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 (Harden et al. 2012; Schuur et al. 2015; Colombo et al. 2019) also through release of trapped gases in high latitude areas. In fact, 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 depth of the active layer is known to be progressively deepening in various parts of the cryosphere (Desyatkin et al. 2021; Li et al. 2022; Xu & Wu 2021).

The Global Cryosphere Watch (GCW), the World Meteorological Organization (WMO) program supporting all key cryospheric in-situ 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, such as temperature, depth and active layer thickness, 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 in the evaluation of permafrost temperature profiles become fundamental aspects for achieving more reliable knowledge on the evolution of this component of the cryosphere, especially for observations from different stations taking parts in networks.

In order to reach the objectives of organizing analyses and assessments of the cryosphere to support science, 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 are planned to be included as a chapter in the new WMO "Guide to Instruments and Methods of Observations", known as the GIMO or guide No. 8. Permafrost has also been identified as one of the cryospheric indicators of global climate change within the framework of the Global Climate Observing System (GCOS 2003) with associated Essential climate Variables (ECVs), which have also been refined in 2022, where a key ECV and product is now defined as the "permafrost temperature" (instead of the previous and ambiguous "thermal state", 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*"(WMO 2016).

In the framework of EURAMET project MeteoMet and follow-on actions (Merlone et al. 2015; Merlone et al. 2018), on-site calibration campaigns were planned in 2017, 2018 and 2020, under a cooperation between the Italian Institute of Metrological Research (*Istituto Nazionale di Ricerca Metrologica*, INRiM) and the Piedmont Regional Agency for Environmental Protection (*Agenzia Regionale Protezione Ambiente*, ARPA Piemonte), for the permafrost temperature sensors chains hosted in the western Italian Alps. Multiple objectives were included in the studies: dedicated calibration campaigns for temperature sensors and sensors chains have been planned, including selection of transportable devices and travelling standards, to achieve target uncertainties on site; definition and on-site testing of best practice for calibration and measurements for the permafrost temperature sensors; evaluation of sensors drift and stability; validation of temperature profiles in permafrost boreholes. The overall achievement of the experimental activities is in terms of improved 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.

2. Instruments and Methods

2.1 Permafrost monitoring station of the Sommeiller Pass

While Russian researchers and prospectors began investigating Arctic permafrost since the end of 19th century (Yachevskiy 1889; Anisimov & Reneva 2006), and the first systematic study published in English of perennially frozen ground was prompted by strategic considerations in World War II regarding the construction of roads and pipelines in Alaska (Osterkamp & Burn 2003), 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. in 2012, generic studies on single permafrost sites are only marginally older (Haeberli 1992), usually hint at the poor knowledge of their state and evolution especially compared to glaciers (Haeberli & Beniston 1998), and often are performed from the point of view of biology (Frey et al. 2016; Luláková et al. 2019), or chemistry (Harden et al. 2012; Colombo et al. 2018). Notable exceptions are localized in the Swiss Alps, where permafrost has been monitored since at least the 70s (Gartner-Roer et al. 2022), or sporadically even before (see Haeberli et al. 2011 for a review).

Correspondingly, knowledge on permafrost in the Piedmont Alps was rather poor up until the first years of the 21st century, and limited to a few localized rock glacier studies in the Maritime Alps (Ribolini & Fabre 2006). In 2006, ARPA Piemonte, in collaboration with the University of Insubria, started a regional study aimed 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 of ARPA Piemonte, allowing the maintenance and implementation of the study and monitoring of the permafrost and periglacial environment in Piedmont Alps (Paro & Guglielmin 2011).

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 operative in 2011. The station consists of three boreholes, respectively 5, 10 and 100 m deep, vertically drilled in the bedrock, a few meters apart, equipped with thermistors chains (Pt107 Campbell Scientific). 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, placed in both cases 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 are collected by a CR1000 Campbell Scientific datalogger and manually downloaded once a year at least.

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

Permafrost conditions were present all along the observed 100 m of depth until 2013. Since 2014, a positive temperature transition (~0.15 °C) has occurred at about 60 m of depth indicating a degradation of the permafrost base (Figure 1). In order to verify this variation (about 0.25 °C from 2012 to 2016), sensor calibration became strictly necessary to understand the reliability of the observed warming.

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

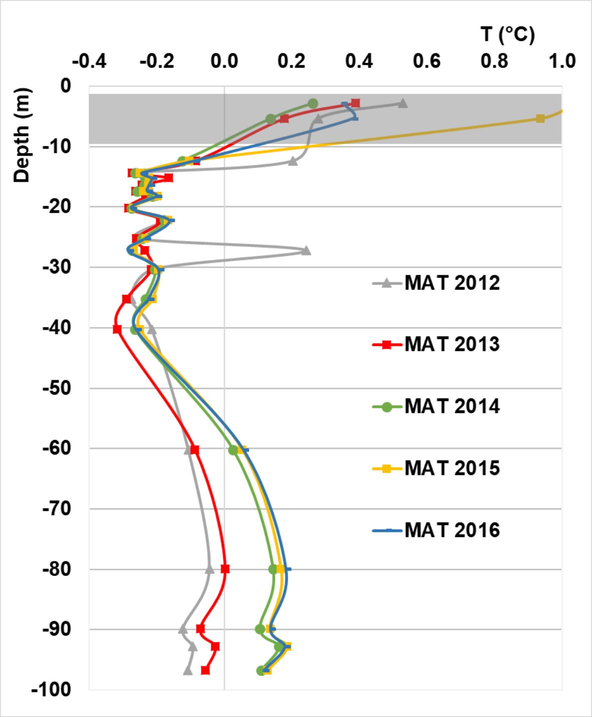

Figure 1. Permafrost profile temperatures measured at different depths along the years, before the starting of the calibration campaigns. Shown in grey is the active layer. MAT = Mean Annual Temperature

2.1 Temperature measurements at the Sommeiller Pass station

Three on-site calibration campaigns at the Sommeiller Pass station have been carried in summer seasons of 2017, 2018 and 2020. Multiple reasons motivated these campaigns, opposed to the usual laboratory characterization and calibration.

Several factors indirectly or directly affect both temperature measurements and sensors' calibration differently in the field with respect to the laboratory: the of use of the logger in place at that temperature and environmental conditions, instead than in stable and controlled laboratory; the use of the same cables, connections, and multiplexing scheme makes the reading under calibration identical to those recorded during measurements; environmental conditions are the same as those the whole equipment is operating (high solar radiation, cold wind, low temperature etc.). All these aspects make the calibration curve more representative of the measuring process and the calibration uncertainty becomes in this case the largest contribution to the overall measurement uncertainty, reducing most of the other factors to negligible contributions. This point is the key in understanding the overall measurement uncertainty: as a matter of fact, the calibration part 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 an easy process, 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.

The available dataset covers the 2012 to 2017, for 32 of 34 sensors in boreholes 10 and 100 m deep, while the 2 sensors in the 5 m deep borehole were activated in summer 2017.

2.2 Test calibration campaign (2017)

In the first on-site campaign, carried out in August 2017, two reference temperature sensors (RS) – Platinum Resistance Thermometers, Pt100, 5615-6-Fluke), along with a thermostatic bath (Thermo Scientific Enco Haake G50 - AC200), a high-accuracy resistance bridge for readout (1594A – Fluke), two power generators and a light shelter were brought to the site (Figure 2). Due to space and time constraints, only thirteen out of the 36 total temperature sensors (coded PS) were selected for calibration. Each PS consists of a thermistor encapsulated in an epoxy-filled aluminium housing.

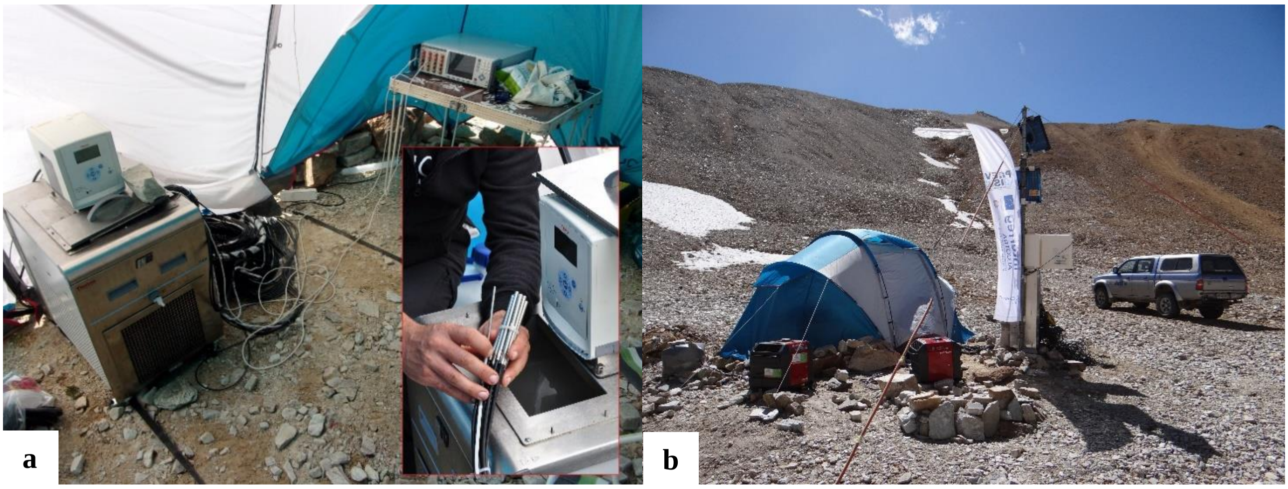

Figure 2. The mobile calibration facility at Sommeiller Pass during the 2017 campaign. a) Inside the shelter: thermostatic bath and high-accuracy readout bridge, grouped permafrost sensors chain with reference sensors. b) Outside: 100 m permafrost borehole, shelter and power generators.

The thirteen PS used for the measurement of permafrost temperature were extracted from the boreholes of 100 m and 10 m and grouped with the two PRT used as reference sensors, coded NS01 and NS03. These two RS were in turn calibrated at INRiM laboratories in liquid bath (INRiM internal procedure, Calibration and Measurement Capabilities PT-T.2.2-01, Key Comparison Database), by comparison against a 25 Ω Standard Platinum Resistance Thermometer (SPRT) calibrated at the mercury, water, gallium and indium fixed points of the International Temperature Scale ITS-90. The grouped sensors, PSs and the two RSs, were inserted in the thermostat bath. In order to maximize the calibration accuracy in the temperature range most important for permafrost studies and minimize the interpolation uncertainties, five temperature points close to the freezing point of water were decided to be -7 °C, -3 °C, 0 °C, +3 °C, +7 °C. The 0 °C point was measured twice to check for stability-hysteresis as normally done in calibration procedures.

To align the procedure to the usual laboratory ones, the 5 selected temperature points were performed in sequence, from the lowest, -7 °C to the highest, with the repetition of the 0 °C point at the end to check for stability and hysteresis. Data is considered valid for inclusion in the statistical analysis associated to each calibration point, when the bath temperature, read by the two reference thermometers is found stable within ±0.02 °C for a period of one hour, after the transient occurred at each temperature step. This procedure was repeated at each point.

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 better 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 re-inserted 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.

2.3 On-site sensors calibration activities (2018 and 2020)

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

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 change also their measurements – or *drift* (Bell et al. 2017; Musacchio et al. 2015). This drift is often evaluable as few hundredths of a °C (Kowal et al. 2020), comparable with the signal coming from climate change-related thermal phenomena, like the permafrost thawing (Biskaborn et al. 2019; Haberkorn et al. 2021). For this reason, meteorological sensors are required to be calibrated frequently – possibly annually – to evaluate this drift and disentangle this component from real measurand changes.

For the 2018 and 2020 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 changed (PP15R-40-A12E Polyscience, USA) equipped with a wider reservoir and cover that allowed the insertion of a larger number of sensors (Figure 3a). Moreover, thanks to the lower power requirements, the use of a single generator was sufficient, therefore reducing costs and weight of the equipment.

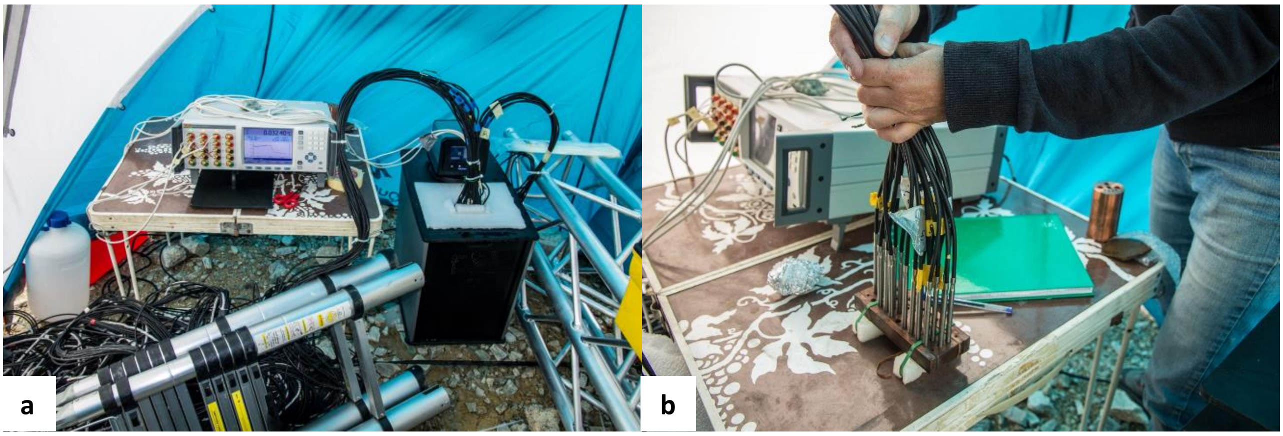

Figure 3. The calibration apparatus in its final configuration (a), and a closeup of the copper comparator block with all the reference sensors and the devices under test (DUTs) inserted (b), during the 2018 campaign.

A dedicated copper comparator block (Figure 3b) was designed, manufactured and characterized at INRiM laboratories, allowing the insertion of the 32 permafrost temperature sensors plus the three PRT reference sensors (Merlone et al. 2020).

The five temperature points selected were closer to the freezing point of water with respect the previous campaign: -5 °C, -3 °C, 0 °C, 3 °C, 5 °C; this guarantees an improvement of the interpolation uncertainty.

The calibration campaign of 2020 was similar: the only difference was in the calibration points which were the same as in the 2017 test 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 the most satisfactory, as the uncertainties in the calibration were higher than anticipated (Figure 4a) and sometimes not even easily determinable. The largest problem was identified in the setup of the DUTs inside the calibration bath: being in close contact with one another, the comparator 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.

3.1 Calibration curves and drift evaluation

Shown in Figure 4a, b and c (related to 2017, 2018 and 2020 calibration campaign, respectively) are the calculated calibration curves t_{calc} (for sensor PS9 only, as an example) obtained through a second order polynomial fit on the differences between the readings of the reference sensors (t_c) and the sensor in calibration (t_{PSx}).

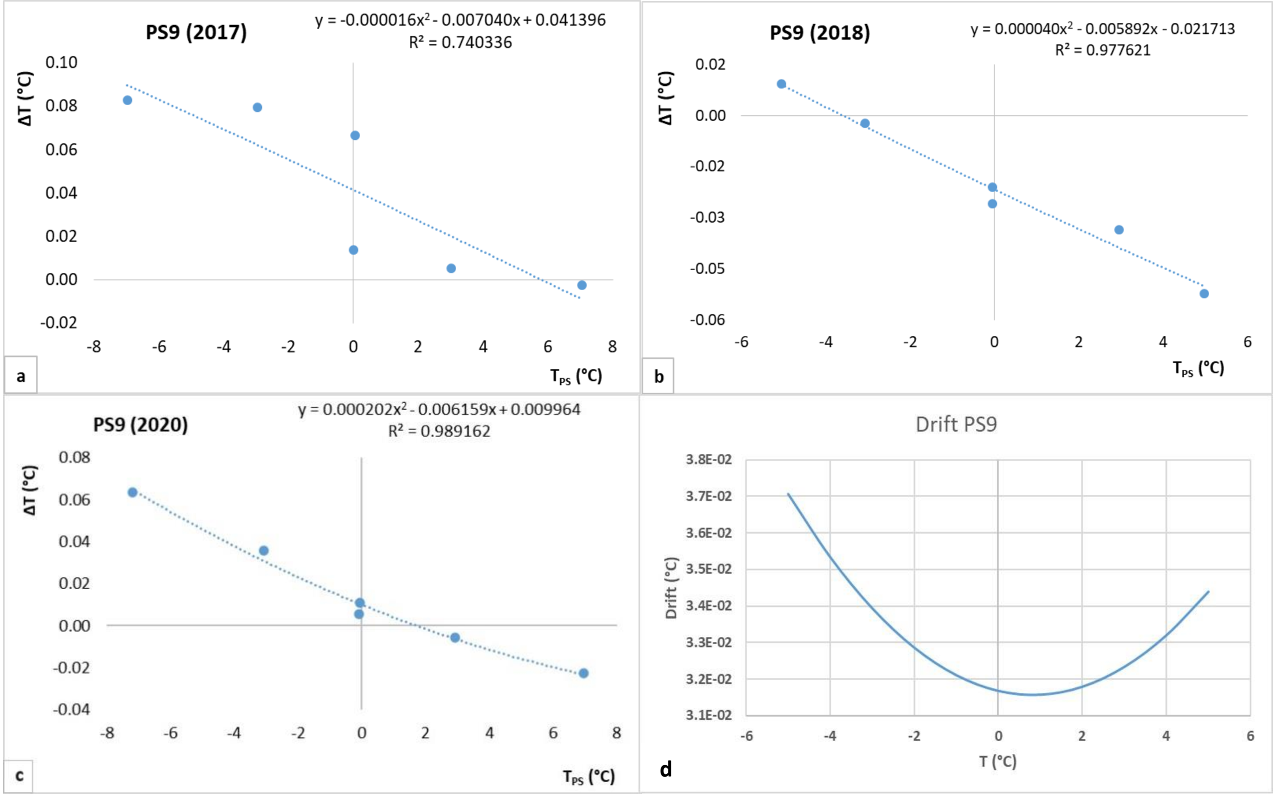

Figure 4. Calibration curves related to 2017 (a), 2018 (b) and 2020 (c) calibration campaign for the sensor PS9, obtained through a polynomial fit on the temperature differences between the readings of the sensors in calibration and the reference sensors. Subfigure (d) shows the drift function of PS9, evaluated as differences between the calibration function of 2020 and 2018.

Figure 4a 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.

Figure 4b and c show the calibrations of 2018 and 2020, with much better fits, reproducibility and hysteresis. The differences the two calibrations still show are due to the sensor drift, evaluated in Figure 4d as 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 ~ $3.2 \cdot 10^{-2}$ °C during this 2-years period, corresponding to $1.6 \cdot 10^{-2}$ °C/yr. The other sensors show similar values of annual drift, between $2 \cdot 10^{-2}$ and $1 \cdot 10^{-3}$ °C/yr, while one sensor showed a drift of $6 \cdot 10^{-2}$ °C/yr, spy of a possible mechanical or electrical problem.

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

3.2 Calibration correction effect on measured permafrost temperature profile

Data provided by ARPA were recorded every hour 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 and the averages.

From the new elaborations with data gathered from calibrated sensors, the 6-year record of permafrost temperatures from the 100 m deep Sommeiller Pass boreholes show a warming trend. It was noted that the active layer and the ZAA are approximately 10-11 m thick and about 12-13 m deep, respectively (Figure 5).

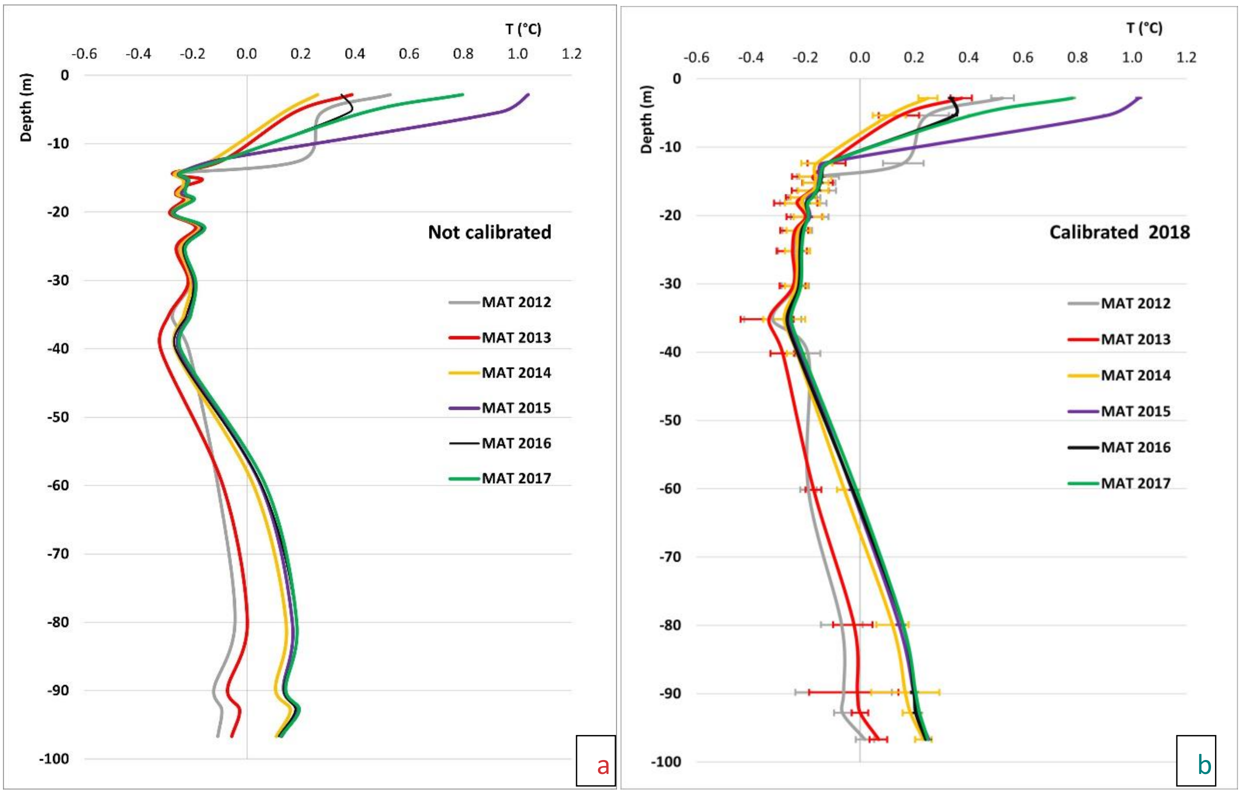

Figure 5. Temperature profiles from the 100-m-deep borehole. Data from (a) uncalibrated sensors and (b) sensors calibrated in 2018, where uncertainty bars represent calibration uncertainty plus the drift evaluated from 2018 and 2020 calibrations.

As it can be seen from the Figure, 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 the calibration plus the drift uncertainty for almost all sensors.

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.

Figure 6 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 0.056 ± 0.016 °C per year during 2012-2014 and a slower, steadier rate of 0.014 ± 0.016 °C/yr from 2014 to 2017. The overall rise, during the whole period, is evaluable as 0.042 ± 0.005 °C/yr.

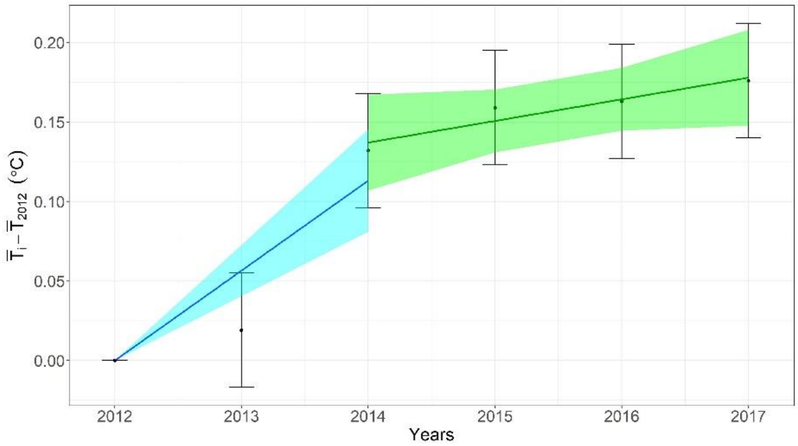

Figure 6. Temperature increase with respect to the 2012 value recorded by the sensor at 60 m. Each value represents the difference between average recordings between each year and the 2012 value, with measurement uncertainties as error bars and uncertainty bands due to the weighted fits.

4. Conclusions

This study showed the advantage of the collaboration between metrology and the community working in cryosphere observations. A need emerged 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. This work also allowed a better understanding of advantages and disadvantages of different measurement system adopted by different stations, in terms of possibility to calibrate, calibration and measurement uncertainties. Together with the experience achieved during the calibration campaign at the Sommeiller Pass, and the issues encountered during laboratory calibration of different typologies of thermometers, best practice procedures can now be adopted, and studies can be started towards definition of agreed reference calibration and measurement methods for designing 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.

5. Acknowledgements

This work was developed within the frame of the European Metrology Research Program (EMRP) joint research project ENV58 “METEOMET2”. The EMRP is jointly funded by the EMRP participating countries within EURAMET and the European Union.

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