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In situ calibration of meteorological sensor in Himalayan high mountain environment

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ABSTRACT: A dedicated facility for *in situ* calibration of weather stations has been installed in the Everest Pyramid Laboratory/Observatory at an altitude of 5050 m in the Khumbu Valley, on the Nepalese side of Mount Everest. This highest metrology laboratory in the world represents a fruitful collaboration between metrological and environmental sciences. The common goal is the improvement of data quality and the reliability of climate monitoring. High altitude extreme environmental observations are of high scientific relevancy, underlining the advantages of performing *in situ* instrument calibration to make measurements fully traceable to standards. In establishing such a laboratory in extreme conditions, the involved staff had to face several challenges: weight of the system components for the eventual transport by human porters, modification to 'off the shelf equipment', special procedures and optimization of power request, reduced room available, properties of fluids at high altitude and many more.

The work and the mission reported are tasks of the MeteoMet project, which are presented here together with the organizations involved. The calibration chamber, the calibration procedure and the results of the first calibration campaign are then presented with full uncertainty analysis.

The capabilities achieved, together with the trained staff and dedicated procedures, now allow calibration and checking of the instruments positioned all along the Khumbu Valley, up to the Everest South Col at 8000 m, more frequently, with less difficulties and with reduced loss of time. Future plans include the extension of the calibration capabilities to soil, ice, permafrost and lake water temperature sensors.

KEY WORDS Metrology for Meteorology; Everest Pyramid; climatic chamber; MeteoMet; temperature sensors calibration; pressure sensors calibration; uncertainty

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1. Introduction

In recent years, the need for a robust, traceable and comparable measurement in the meteorological and climate fields has led to growing collaborations between environmental and metrology sciences aiming to improve the quality of data and, as a consequence, the reliability of climate change statements. In 2010, the World Meteorological Organization (WMO) signed the Mutual Recognition Arrangement (MRA) of the CIPM (Comité International des Poids et Mesures – International Committee for Weights and Measures) during a joint workshop with the Bureau International des Poids et Mesures (BIPM) (WMO-BIPM, 2010). In the same year, the CCT (Comité Consultatif de Thermométrie – Consultative Committee for Thermometry) signed a Recommendation to CIPM to encourage metrology offices to enforce co-operation with environmental sciences (CCT, 2010). In 2011, the European Association of Metrology Institute (EURAMET) funded the 3-year project MeteoMet, Metrology for Meteorology, addressing the need for new, stable and comparable measurement standards protocols, sensors and calibration procedures and data fusion and uncertainty evaluation methods. This project is focused on the traceability of measurements involved in climate change: surface and upper air measurements of temperature, pressure, humidity, wind speed and direction, solar irradiance and reciprocal influences between these measurands.

The project is divided into four technical work packages (WP), delivering results on metrology for upper air measurement, new instruments for climate parameters, ground-based meteorological observations and historical data. A task of the WP on ground-based systems includes the construction of portable climatic chambers for *in situ* calibration of pressure, temperature and humidity sensors. The frequent use to compare the weather station with a calibrated reference one, keeping both of them close in the same place, for a determined period, cannot be intended as a calibration procedure. This is an in-field test to evaluate the possible pathological behaviour in the weather station leading to the maintenance or replacement of the sensors, and even some instrument failures cannot be seen, because the whole range of annual environmental variability is not covered. It is, moreover, not possible to calculate a calibration curve (Lopardo *et al.*, 2012) or obtain correct and complete information about the sensor's drift or the effect induced by other quantities of influence. A correct metrological approach requires a proper calibration of the instruments leading to the evaluation of the calibration curve and the associated uncertainty. This can be done by generating the complete variability of the quantity the sensor will meet when operating in the field and by comparing its reading with that of a traceable standard placed in the same controlled

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environment. In the frame of the MeteoMet task 3.5, climatic chambers based on this principle and specially developed for laboratory (Piccato e*t al*., 2014) and *in situ* calibration of weather stations (Lopardo *et al.*, 2014) were studied, designed and built. In the context of a Research Excellence Grant, advancement in these systems was made, which was coded as EDIE2. The chamber was specifically designed for calibration of weather stations and instruments operating at high altitude, and to be hoisted in the Pyramid at an altitude of 5050 m. The whole system had to be designed in order to be separated into parts weighing <30 kg each, for the eventual transport by human porters; the thermostat had to be modified to allow the pumps to work in such an altitude; the insulating material had to be expanded because of the air bubbles inside, causing the need to readapt the insulation layer; the phase transition curves of the alcohol-based mixture forced the adoption of special care; the low power available in the Pyramid necessitated special procedures and optimization of power request by all the involved apparatuses and the reduced room available also imposed special design in the system configuration.

After its construction and characterization, this calibration chamber was installed in September 2013 in the Ev-K2-CNR committee Pyramid-Observatory in the Khumbu Valley on the Nepalese side of Mount Everest.

The Ev-K2-CNR is an Italian nonprofit association high-mountain-oriented research agency, operating mainly in the Himalayas. High mountain environmental measurements are fundamental in climate change monitoring since the absence of human impact gives time stability and reliability in climatic observations. Environmental observations in high altitude areas allow the acquisition of unique and fundamental information about the background conditions of the environment, also facilitating the study of the role played by natural or anthropic processes in perturbing such a pristine habitat. In 2008, the 78th UN General Assembly plenary meeting on sustainable mountain development (UN, A/Res/62/196, 2008) recognized that 'mountains provide indications of global climate change […] and stresses the need to undertake actions to minimize the negative effects of these phenomena' and encouraged the governments to collaborate with the scientific community to improve knowledge on mountain climate and on the effects of its change on local communities.

To promote high altitude measurement, the Ev-K2-CNR committee launched the SHARE project (Stations at High Altitude for Research on the Environment), http://www.share.evk2cnr.org, which aims to produce high-quality and long-lasting data series; the collaboration with MeteoMet is essential here to improve the metrological quality of the data acquired in the Khumbu Valley (Nepal).

The Ev-K2-CNR is best known for its Pyramid Laboratory/Observatory located at an altitude of 5050 m in the Khumbu Valley (Nepal) at the base of Mount Everest, which was built in 1990 in collaboration with the Nepal Academy of Science and Technology (NAST) and several sponsors. The Pyramid has a completely self-sufficient renewable energy supply and satellite telecommunications systems. The location is remote, accessible only after 6 days of trekking and acclimatization; helicopter flights are often available for delivering equipment but are not guaranteed and the nearest landing field is half an hour on foot from the Pyramid; thus, the great importance of the traditional Himalayan human porters in the management of the Laboratory is clear.

This condition imposed special design and construction features to the climatic chamber presented here, since it had to be transported by the Sherpas for 3 days along the high mountain track.

The Ev-K2-CNR, in the context of the SHARE project, installed eight weather stations in the Khumbu valley: two at Pyramid (5050 and 5079 m a.s.l.), one in Lukla (2800 m a.s.l.), one in Namche Bazar (3560 m a.s.l.), one in Pheriche (4200 m a.s.l.), one at Kala Patthar (5600 m a.s.l.), one at Changri Nup (5700 m a.s.l.) and one at Everest South Col (8000 m a.s.l.). The automatic weather stations (AWSs) of Lukla, Namche, Pheriche and Pyramid provide data with a 60 min time resolution: air temperature, atmospheric pressure, relative humidity, wind speed and direction, precipitation and solar radiation are measured there. The Pyramid and Lukla AWSs are equipped with two sensors for the determination of soil thermal flux, snow level, soil moisture, up and down short wave and long wave solar radiation.

The station in the plain over the Pyramid (5079 m a.s.l.) is part of the United Nations Environment Programme (UNEP) Project ABC (http://www.unep.org/pdf/ABCSummaryFinal.pdf) and all the stations installed in Nepal are Reference Stations in the CEOP (Coordinated Energy and Water Cycle Observations Project) (http://www.ceop.net/) project under the WMO's World Climate Research Programme (WCRP) – Global Energy and Water cycle Experiment (GEWEX) initiative (http://www.gewex.org/projects-ghp.html).

The objective of the SHARE project is to deliver, especially in developing countries, long-lasting quality data series on climate trends and global warming, allowing mitigation policy based on reliable assessments to be established. The activities carried out in collaboration with the Istituto Nazionale di Ricerca Metrologica (INRiM) are intended to guarantee metrological quality to temperature and pressure data recorded by these AWSs, allowing the periodic calibration by means of a special climatic chamber installed in the Pyramid Laboratory that is able to generate different temperatures and pressures covering the whole range of local environmental variability and making possible the evaluation of a correction curve applicable to all the measurements. Furthermore, the definition of specific procedures for the periodic calibration of the instrument enforces a long-lasting homogeneity and robustness of data series.

The Pyramid Laboratory that is already the headquarters of the whole Khumbu Valley network also now became the calibration centre for all these instruments, being the highest metrology laboratory in the world. Figure 1 shows the Everest Pyramid and the staff from the different institutions involved, at the end of the activities mentioned here.

2. A new facility for calibration in extreme environment

Atmospheric measurements, by means of ground-based weather stations, are frequently lacking in a robust and documented traceability: less information is provided on data quality, calibration procedures and uncertainties, and more often, the manufacturer assessments are considered satisfactory, even in the longer term. The current procedure, to check the measurement by comparison against reference high-quality instruments, is a non-metrological approach and can be overcome only by the introduction of systematic periodic calibrations that guarantee expressed traceability and uncertainty. The first prototype of the portable climatic chamber, coded EDIE0 (Earth Dynamic Investigation Experiment 0), was designed in 2010 at the INRiM, aiming to promote this *modus operandi*; giving it appeal; allowing *in situ* calibration of temperature, pressure and humidity sensors; and evaluating their mutual influences. In 2012, a more defined system coded as EDIE1 was designed; one of the key aspects of this chamber

Figure 1. Picture taken at the successful completion of the mission in September 2013 is presented: EV-K2-CNR, Nepal Academy of Science and Technology, Istituto Nazionale di Ricerca Metrologica and C3 staff in front of the Everest Pyramid Observatory-Laboratory (view on the Lobuche glacier on the back), Khumbu Valley, Nepalese side of the Mount Everest.

was the calibration by comparison of sensors in air and not in liquid. The experience acquired with this chamber, together with the collaboration with the Ev-K2 CNR committee on measurement in extreme environment, highlighted the need for a new portable climatic chamber, specifically designed to address high altitude challenges. A key point of this new facility design is weight reduction, because a period of at least 3 days of human transport is highly likely required to reach the pyramid, besides a mass reduction to allow faster thermal stability to save energy in this remote laboratory. This new chamber, coded EDIE2, allows the calibration of temperature and pressure sensors and their mutual influence, especially the influence of temperature on barometers, by means of simultaneous control of temperature and pressure. The chamber is formed by two concentric cylinders, the inner one is made up of copper and is equipped with a copper coil on the whole surface. Copper was used to speed up the thermal stability and exchange. The temperature is controlled by means of an external thermostat that pumps fluid through a pipeline welded to the copper wall. The fluid used in the thermostat is alcohol at a temperature <5 °C and water and glycol for higher temperatures. This copper chamber is hoisted in a bigger, sealed, steel chamber that allows pressure control, which is done by means of a hand pump connected through a valve to the chamber. A duplex layer of Armaflex® wraps the whole chamber, as insulation from the external room.

Before shipment in Nepal, the climatic chamber had been fully characterized at the INRiM laboratories: stabilization time, thermal uniformity and stability had been observed and recorded at all temperatures at which the calibrations will be performed. The experimental set-up for the characterization procedure, shown in Figure 2, includes four pt100 thermometers: one is placed at about 7 cm below the cover, one in the central zone, one about 15 cm over the bottom and one at half the height near the external wall; in this way, the whole inner thermal gradient was evaluated.

Thermal stabilization took about 5 h, the worst uniformity had been measured at the farthest temperature from the ambient: at −25 °C, there is a variation of 3 mK cm^{-1} in the lower zone, 2 mK cm^{-1} in the highest zone and a radial variation of 2 mK cm^{-1} at half height, the colder point is the centre in this case; short-term thermal stability is under 5 mK at every temperature. The characterization results are useful to choose the best part of the chamber to place the sensors in calibration, the lower part in this case.

The chamber, in its final shape, is provided with two reference pt100 thermometers read by a datalogger Fluke 1524, this being the whole measurement chain calibrated in the INRiM laboratories with expanded calibration uncertainty of 20 mK in the final data. During the calibration use, beside the sensors under calibration and the reference thermometer, an additional pt100 thermometer is left at a different height inside the chamber to evaluate the thermal gradients that are induced by the presence of the sensors in calibration and not detectable during the characterization.

The reference sensor for pressure calibration is an Additel 681, also calibrated at the INRiM with calibration expanded uncertainty of 15 Pa.

At the end of July 2013, all the equipment for setting the high altitude metrology laboratory was ready to be shipped. Finally, in an effort to reduce the weight and volume of the carriage, the whole system was packed in three boxes: the chamber (30 kg), the thermostat (30 kg) and a cartoon box with the instruments, the wires and the pressure line (<15 kg).

3. September 2013: the INRiM mission in Nepal and installation

The INRiM mission in Nepal to install the calibration laboratory in the Pyramid laboratories took place in September 2013 and lasted about 2 weeks. On the first day in Nepal, 10 September, a workshop on Metrology for Meteorology was held at the NAST head office. The day after, the team left for Lukla (at an altitude of 2800 m), which is the starting point for the trekking to the Pyramid. The scientific equipment were meanwhile transported by a helicopter to Syangboche airport (3750 m, over Namche Bazar). Helicopter transport was not available further since the monsoon was not yet over: the equipment delivery to the Pyramid was then made by Sherpa porters (Figure 3). On 16 September, the whole team and the instruments reached the Pyramid.

The room selected to house the laboratory was originally designed to be the Pyramid wooden sauna, small and without windows; the most thermal stable room in the structure, but never used for this purpose due to power-saving procedures. Unpacking and installation started immediately, and the following morning, the chamber was ready, with all the auxiliary equipment working, and the technical training to the local staff started (Figure 4).

Low pressure and consequent low air density continually affected the experiment, in some aspects not all of which were identified before reaching the altitude. This caused a partial change in the work plan and in the characterization results. Air thermal conductivity was reduced, decreasing the efficiency of the whole thermostatic system, and the entire stabilization process took much more time than in the first tests (10 h). Low pressures also cause a swelling and bubbling in the external insulating layer that in any case does not affect the chamber insulation. The low atmospheric pressure of approximately 50 kPa at the Pyramid altitude changes the vapour/pressure curve of fluids, causing early evaporation that, when using alcohol-based thermostat fluids, required reduction in the range to lower temperature, to avoid danger in the excessive evaporation rate. This limited the maximum value achievable without changing the fluid and required special mixtures to be created by adding glycol, antifreeze, to distilled water to reach the net temperature range, taking care not to overheat the thermostat pumps when the fluid density increases at lower temperatures.

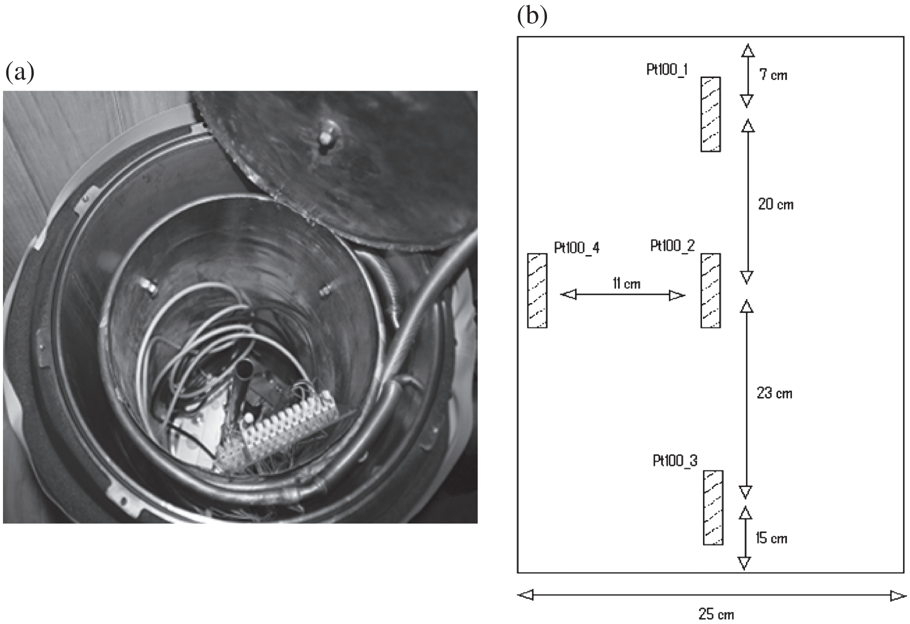

Figure 2. (a) Picture of the inner part of the chamber during the characterization procedure. (b) Scheme of the sensor positions inside the portable climatic chamber, during the characterization procedure.

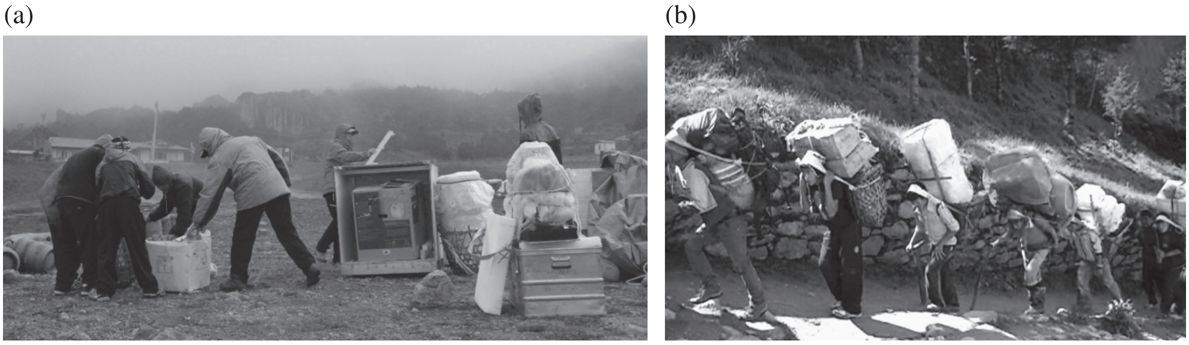

Figure 3. (a) On a rainy day, picking up the whole instrumentation left almost 'abandoned' by the last helicopter transport in Syangboche 'airport' (3750 m, over Namche Bazar). (b) Sherpa porters start the journey from Namche to the Pyramid (5050 m) carrying all the equipment by shoulders.

4. Calibration campaign at 5050 m of altitude

4.1. Temperature calibration

The first sensors calibrated in the new metrological laboratory were those usually used by the Ev-K2-CNR committee as reference: a Vaisala HMP155 thermohygrometer and a PTB 330 barometer. The associated datalogger was also placed inside the chamber during the calibration in order to reproduce the actual in-field work condition, thus evaluating the possible temperature and pressure effects on the reading system. The temperature calibration curve is obtained by comparing the reading from Vaisala and those from the reference standard INRiM sensor T1 over the temperature range typical of Himalayan environment (−35, −20, 0, 5, 15, 25 °C). To guarantee that the sensors are at the most similar temperature, they were fixed at the same height on the bracket; the second temperature probe T2 was used to check the vertical temperature gradient being positioned at a different and measured height inside the chamber. The function to be evaluated is $T(T_V)$ where T_V is the uncorrected reading from the probe under test and T is the value corrected with the calibration curve. Using a second-order polynomial interpolation, the co-efficients of the curve $T = aT_v{}^2 + bT_V + c$ are: $a = -0.000093\,°C^{-1}$; $b = 0.9917$; $c = 0.134\,°C$, the amplitude of this correction is reported in Figure 5.

4.2. Uncertainty in temperature calibration

Aiming for an easy application of the calibration curve, a single value of uncertainty was associated to the whole range of its validity. This value is evaluated considering sources attributable to three main fields:

1. reference temperature uncertainty (contributions from the reference sensors and the chamber characteristics during the use in the Pyramid, such as the different thermal gradient);
2. uncertainty related to the sensor in calibration;
3. interpolation uncertainty.

Regarding the chamber, the worst value for the thermal homogeneity observed in the characterization phase was 0.12 °C of difference in 20 cm in the upper zone. The temperature probe T1 used as a reference had a calibration uncertainty of 20 mK; its short-term stability, evaluated in its calibration phase, was 5 mK; the maximum standard deviation on the whole sets of

Figure 4. Assembling the calibration chamber and the auxiliary equipment in the small room available at the Everest Pyramid.

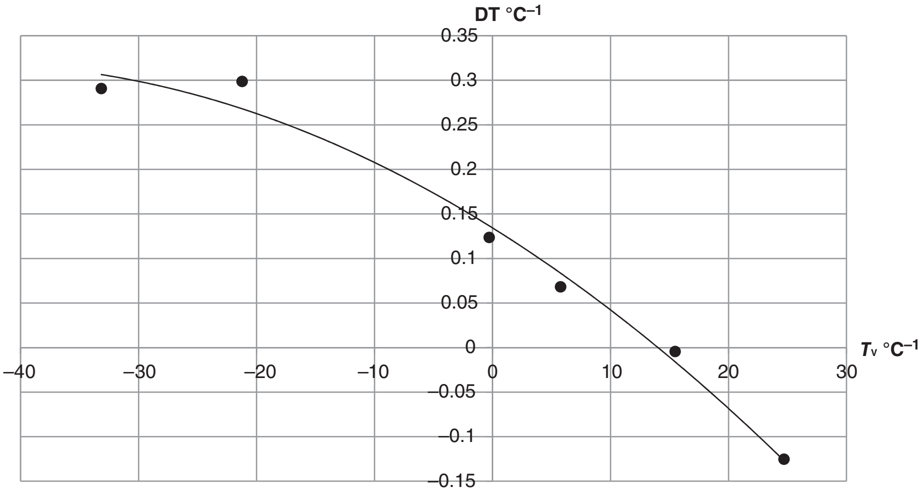

Figure 5. Calibration curve evaluated as correction function to be applied to the sensor readings as a function of the temperature.

measurement was 8.8 mK and the Fluke 512 resolution was 0.1 mΩ corresponding to 0.25 mK. The resolution of the Vaisala MP155 was 0.01 °C and the maximum standard deviation in the measurement sets was 0.007 °C. The last contribution to the final curve uncertainty is due to the interpolation process and was evaluated using residuals.

The temperature expanded uncertainty, in $k = 2$, results in 0.094 °C, as reported in the following table:

Uncertainty contribution	Standard uncertainty	Distribution	Sensibility	Contribution to standard uncertainty
Temperature reference				
Pt100 calibration unc.	0.02 °C	Gaussian	–	0.01 °C
Datalogger resolution	0.1 mΩ	Rectangular	O.4 Ω/°C	0.00014 °C
Short-term stability	0.005 °C			0.005 °C
Repeatability	0.0088 °C	Gaussian		0.0088 °C
Chamber uniformity	0.12 °C	Rectangular		0.038 °C
Sensor in calibration				
Resolution	0.01 °C	Rectangular	–	0.006 °C
Repeatability	0.007 °C	Gaussian		0.007 °C
Calibration curve				
Residual	0.021 °C	Gaussian		0.021 °C
Standard uncertainty				0.047 °C
Expanded uncertainty ($k = 2$)				0.094 °C

4.3. Pressure calibration

The pressure gauge PTB330 of Vaisala (Helsinky, Finland) calibration has been performed by comparison with the Additel 681 of Additel Corp. (Salt Lake City, UT) calibrated at the INRiM, acting as transfer standard for this campaign and being directly traceable to the Italian primary national standard. The two gauges are connected to the same pressurized volume, but they work at a different temperature and at a different height: the first is placed in the chamber, whereas the latter is at room temperature and is connected over the top of the chamber, outside it. While the PTB330 needed to be calibrated in operating conditions, thus at a different temperature, the traceability given by the Additel was guaranteed only if this sensor was used at room temperature, having been calibrated in the INRiM laboratory at 20 °C. The different height position was measured to be about 45 cm and was corrected taking into account the effect of the air column at each pressure. The comparison of readings was done at 450, 550, 650, 750, 850 hPa, this series of measures has been repeated twice, the first time increasing pressure, the second time decreasing pressure, to evaluate the hysteresis of the barometer. Moreover, aiming to evaluate the temperature effect, the entire test was repeated at −35, −10, 0, 10, 30 °C. All the points recorded were included in the calculation of the calibration curve, in the effect of the temperature on the pressure reading and in the evaluation of the uncertainty. The series acquired at 10 °C was much different from the other, so it was rejected

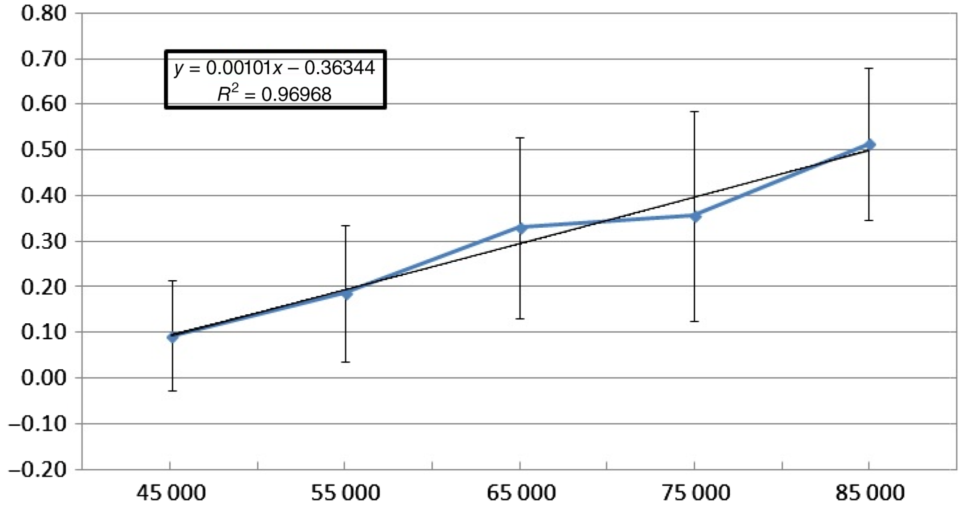

Figure 6. Pressure calibration points (x-axis) and differences between the readings of the sensor under calibration and the reference one (y-axis) with uncertainty bars and linear regression calculated as calibration curve.

during the post-processing of data: the gradient was not satisfactory and the instrument readings had much noise, with respect to the other calibration points and expectations. It is possible that this was caused by the unstable power supply from the general power plant: during the metrology campaign, the whole solar power system was subject to complete substitution and the generated electric power was frequently disturbed by the use of diesel generator.

The final result of calibration is the unique curve $P = P(P_R)$, where P_R is the pressure uncorrected as read from the device in calibration and P is the calibrated value. Hysteresis effects are included in the uncertainty budget; at each value of pressure, the single difference is evaluated averaging over all temperatures and up and down cycles. The temperature dependence of the pressure sensor response was evaluated to be non-negligible, but since its behaviour turned out not to be linear and of reduced amount, the decision taken was that not to apply a corrective factor $P(T)$, instead to consider the maximum deviation due to temperature as a further uncertainty component. This will allow more robust data declaration during the exposure of the pressure gauge to annual temperature seasonal cycles.

The calibration curve obtained is linear (Figure 6):

$$P = a \times P_R + b; \quad a = 1.00101; \quad b = -0.36344 \text{ Pa}$$

4.4. Uncertainty in pressure calibration

In the case of pressure also, a single value of uncertainty was associated to the whole calibration range. The contributions due to the reference of pressure are the Additel probe calibration (15 Pa), its resolution (10 Pa) and the maximum dispersion of data acquired at a particular pressure value (113 Pa). The uncertainty source due to the sensor in calibration is its resolution (1 Pa) and as for the reference of temperature, the maximum value of measurements dispersion is at one pressure (117 Pa). The uncertainty associated with the air column pressure effect and correction is considered negligible, this being the height difference between the two sensors measured within few millimetres, corresponding to negligible values in pascal. Adding the additional contribution of 3 Pa due to the interpolation uncertainty, the final uncertainty of pressure calibration curve results to be 3.3 hPa with 95% of confidence ($k = 2$).

Uncertainty contribution	Standard uncertainty	Distribution	Contribution to standard uncertainty
Pressure reference			
Additel 681 calibration unc.	15 Pa	Gaussian	7.5 Pa
Additel resolution	10 Pa	Rectangular	6 Pa
Repeatability	392 Pa	Rectangular	113 Pa
Sensor in calibration			
Resolution	1 Pa	Rectangular	0.6 Pa
Repeatability	403 Pa	Rectangular	117 Pa
Calibration curve			
Residual	3 Pa	Gaussian	3 Pa
Standard uncertainty			163 Pa
Expanded uncertainty ($k = 2$)			326 Pa

5. Conclusion

The relevance of the work presented in this paper lies in providing traceability and metrological quality to mountain atmospheric data; this result was obtained during installation of the first *in situ* high altitude calibration laboratory (the Pyramid) hosting a dedicated chamber designed for the calibration of pressure and temperature instruments. Such instruments, operating in the surrounding environment, up to 8000 m of altitude, can be easily checked and calibrated without their shipment to manufacturers or accredited calibration laboratories. The traceability to national standard is guaranteed by pressure and temperature standards installed in the chamber and annually sent to the primary National Institute of Metrology for calibration. This process allows to reach a full long-term measurement traceability, reaching quality improvement, better homogenization and comparability of the data archives generated all over in such a relevant area. A complete analysis of any uncertainty source in the calibration process is reported here along with the total expanded uncertainty results satisfactory for this application.

This is the first case of a laboratory dedicated to provide metrological quality to a small but highly relevant network of high altitude sensors. The local staff had been trained on metrology fundamentals and are continuously in contact with the metrologists at the Istituto Nazionale di Ricerca Metrologica (INRiM) that remotely follows all the calibrations performed. The collaboration between the research community operating in the Pyramid and the metrology staff will continue, aiming at evaluating further uncertainty components also for the measurement process. Other instruments will be the subject of future improvement of the system, such as those temperature probes measuring permafrost, soil and water temperatures. This work represents a further advancement in the collaboration between metrology and meteorology that will bring valuable results, in terms of data quality and comparability, for the benefit of the future generations of climatologists.

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References

CCT. 2010. Recommendation to CIPM T3 (2010) on climate and meteorological observations measurements – Doc. CCT/10-09.

Lopardo G, Bellagarda S, Bertiglia F, Merlone A, Roggero G, Jandric N. 2014. A calibration chamber for automatic weather stations. *Presented at the Metrology for Meteorology and Climate Conference*, 15–18 September 2014, Brdo, Slovenia.

Lopardo G, Marengo D, Meda A, Merlone A, Moro F, Pennecchi FR, et al. 2012. Traceability and online publication of weather station measurements of temperature, pressure, and humidity. *Int. J. Thermophys.* **33**: 1633–1641, DOI: 10.1007/s10765-012-1175-3.

Piccato A, Spazzini PG, Bertiglia F, Merlone A. 2014. A facility for the evaluation of mutual influences of environmental quantities on weather station outputs. *Presented at the Metrology for Meteorology and Climate Conference*, 15–18 September 2014, Brdo, Slovenia.

WMO-BIPM. 2010. Measurements Challenges for Global Observation Systems for Climate Change Monitoring, 30 March 2010, Geneva, Switzerland.