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Traceability of Ground Based Air Temperature Measurements: a Case Study on the Meteorological Observatory of Moncalieri (Italy)

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Abstract

The robustness and reliability of any climatic assessment, especially those analysing climate variability and change, depends crucially on the soundness of data and uncertainty associated with measurements. The metrological traceability to national standards of the measurements involved in climate change is a milestone to address this need.

This work describes the first attempt to define a fully traceable procedure for the calibration of air temperature sensors in a special chamber manufactured for this purpose. The facility, a prototype was used for this activity, was designed to calibrate automatic weather stations (AWSs) by comparison with embedded reference standards traceable to temperature and pressure primary standards as maintained in a National Institute of Metrology.

An application example of calibration process is described for the temperature sensor working in the Meteorological Observatory of Moncalieri (Italy) of the Società Meteorologica Italiana where a continuous climate record has been kept since 1865 (www.nimbus.it/moncalieri/moncalieri.asp). As result, the data of the historical data series have now associated calibration uncertainties as contributions from instrument capabilities, resolutions and calibration procedure adopted.

Finally, the possibility to improve climatic considerations applying calibration data correction has been analyzed.

We report on the in-situ calibration campaign and the resulting differences between the corrected and uncorrected data for the most important quantities considered in the climate analysis: maximum, minimum, mean temperature.

Keywords: Air Temperature, Calibration Facility, Calibration Uncertainty, Climate Change Analysis, Historical Temperature Data Series, Metrology for Meteorology and Climate, Traceability.

1 Introduction

Over the last years great efforts have been devoted to the study of climate change in order to understand the phenomena and predict the consequences [1]. Robustness of any climate consideration strongly depends on the availability of reliable data (homogeneous or homogenised climate time-series) and on the uncertainty associated with measurements, among other issues. To improve the quality of data collection and their worldwide compatibility the adoption of a metrological measurement perspective is encouraged. A defined traceability to SI standards of measurements involved in climate studies and meteorological observations could be a pillar starting point.

The recognition of this need has lead in 2010 the World Meteorological Organization (WMO) and the Bureau International des Poids et Mesures (BIPM) to start a cooperation (WMO-BIPM Workshop: “Measurement Challenges for Global Observation Systems for Climate Change Monitoring: Traceability, Stability and Uncertainty”, Geneva, March 2010) that was formalized with the signature by WMO of the CIPM (International Committee for Weights and Measures) Mutual Recognition Arrangement (MRA). In this direction goes also the CCT (Consultative Committee for Thermometry) Recommendation to CIPM [2] that encourages a strong cooperation between National Metrological Institutes (NMIs) and meteorological organizations to work for traceable climate data over long temporal terms and wide spatial scales based on best practice metrology.

To study the climate variability and change, long climate time-series of proven quality and homogeneity are needed. In particular, temperature is a key climatic element. To understand the climate variability and changes, it is essential to know the surface temperature evolution – from month to month, up to decade to decade. Long term temperature time-series provide this vital information. From these records, trends in the climate system over long time periods can be discerned [3]. The century-long air temperature records are not only essential to study the trend and the changes on the mean but also fundamental to assess changes on the data distribution (e.g number of warmer nights and / or days, frost or icy days, periodicity and intensity of heatwaves), due to the enormous impact of the extremes on the socio-ecosystems.

Temperature has been widely measured from about the mid-19th century onwards, and long historical records nowadays exist. However, these climate time-series sometimes are not of adequate quality due to the presence of inhomogeneities and, therefore, they are not reliable for supporting any climate-related considerations and analysis nor for the generation of climate products [4, 5] or the delivery of timely and robust climate services, as being highly recommended in the Report of the High-Level Taskforce for the Global Framework for Climate Services [6]. It is well known that century-long air temperature records and also shorter time-series often contain variations that are not only due to the weather or climate forcing but

also to non-climatic factors, such as the introduction of new instrumentation, relocation of weather stations, changes in exposure of instruments or in observing practices, modification of the environment surrounding the meteorological stations, etc. [7]. WMO defined a homogeneous series as one in which the variations are produced only by variations in climate [8]. To deal with this issue, since the 1950s, many statistical homogenisation procedures have been developed for the detection and adjustment of these inhomogeneities. The approaches of these techniques are quite different and depend on the climate element, the temporal resolution of the observations (annual, monthly, daily, sub-daily), the availability of the metadata and the type of method (for absolute homogenisation methods the statistical test is applied separately to each station, for relative methods a reference station is compared with the station to be homogenized). Some of these procedures were analyzed under the Action Cost HOME "Advances in homogenisation methods of climate series: an integrated approach" [9]. Under the Action Cost HOME, the performances of currently available relative monthly homogenisation methods were tested through benchmarking, being ACMANT, Craddock, MASH, PRODIGE and USHCN the methods that best performed [9]. From them a consensus method was developed: HOMER [10]. With regard to adjustments at the daily scale, some of the currently available methods are HOM [11], SPLIDHOM [12] and the Trewin's method, although there are other simple techniques, based on the interpolation of monthly correction factor into the daily scale [13].

In general, these methods not consider type B uncertainties and so the climatic studies are usually presented only with type A uncertainties. The evaluation and inclusion of a type B measurement uncertainty could result in an improvement in data analysis. Since now, few are the attempts to give a complete uncertainty budget for the measurements performed using weather stations, or other temperature sensors. Data with associated uncertainty could help to consider various data sets in a different manner and so to better weight their contribution in regional and global analysis.

In temperature data series, amongst many complicating factors causing systematic effects to be identified and adjusted, thermometer calibration is a relevant aspect often neglected. In the past and even in recent years, routine thermometer calibration procedures were not usually adopted and standard procedures are sometimes not defined or missing. Today the most used in situ "calibration" approach consists in setting up a travelling "reference" sensor of high quality which is installed for some days (at least 20) in the proximity of operative sensors, and an inter-comparison trial is carried out. If the difference between data recorded by the two sensors are within a defined and accepted value, that takes into account the specification of the sensors, its drift, ageing, damages, etc., then the operative sensor is kept working, otherwise it is removed and substituted. This intercomparison exercise has not to be considered a "calibration" process of the meteorological sensor but instead a check allowing the identification of possible malfunctioning of specific

sensors. This procedure is therefore affected by some limitations [14]. Firstly, the sensors are tested only within a limit range of values (determined by the actual weather variability during the inter-comparison), and possible non-linear effects above or below the observed values cannot be evaluated. Secondly, due to the very complex topography, possible effects of the different positioning between the sensor and the “reference” sensor cannot be completely quantified. On the other side, the proximity of the two sensors can create artifacts in the readings. Moreover, the evaluation of the mutual influence between parameters (temperature, wind, pressure, humidity, solar wind) is not achievable. Then, it is not possible to calculate a calibration function to directly refer the sensor readings to well-defined standards. A robust metrological traceability is therefore missing when such a procedure is adopted.

In this context at the Italian Metrological Institute (INRiM) a dedicated calibration chamber for meteorological automatic weather stations (AWS) and sensors was implemented. The facility allows the calibration against pressure and temperature sensor traceable to national standards in a full range of atmospheric variability and its reduced dimensions make it transportable for in situ calibrations campaigns. This calibration chamber, representing a real “travelling standard”, directly links the measurements carried out in field to SI standards as maintained in an NMI.

This work presents the first attempt to give traceability to temperature measurements recorded in an ancient meteorological observatory. The sensor was calibrated in situ in the developed calibration facility and a full calibration budget was calculated.

In section 2 an overview about the historical meteorological observatory is given. In section 3 the calibration facility, the calibration procedure and uncertainty evaluation method is illustrated. The section 4 is dedicated to data analysis with a focus on the impact on temperature series of the calibration process from a climatological point of view. Finally the conclusions are drawn in section 5.

2 The Observatory of Moncalieri

The Meteorological Observatory of the Real Collegio Carlo Alberto located in Moncalieri (Italy) ($44^{\circ} 59' 52''$ N/ $7^{\circ} 41' 43''$ E at 260 m asl) was founded in 1859. In 1865 temperature values started to be recorded, creating the still active and unbroken data series that is maintained by Società Meteorologica Italiana (www.nimbus.it/moncalieri/moncalieri.asp).

After a period of less reliable measures between 1960's and 1980's, in 1990 meteorological recordings were improved in a new wooden “Stevenson” screen (figure 1) sited on the balcony of a little tower on the main building (20 m high, NW exposure). In time, the screen has hold different types of temperature sensors until

the current working sensor a SIAP SM 3840 installed in 2001. The sensor was subjected only to the manufacturer initial calibration process.

The reason for this siting has to be found in the close connection, established in the past, between the study of the climate and the astronomy. In fact, the observatories founded in XIX century usually covered a double function: meteorological and astronomic observations were carried on simultaneously, with instruments on the top of building (towers, terraces etc).

Temperatures recorded here are in average 2 °C higher than that measured in the vicinity by rural stations [15] but, in spite of this, the series is relevant from a historical point of view. Its length makes it a valuable tool for evaluating climate change at this local scale.

3 Experimental Apparatus and Calibration Procedure

3.1 Calibration Chamber

The calibration of the sensor in use at Meteorological Observatory of Moncalieri was performed by means of a prototype of portable climatic chamber manufactured at INRiM in the framework of task 3.5 of the project “Meteomet” [www.meteomet.org], founded by the European Metrology Research Project (EMRP). Goal of this task is the manufacturing of a portable climatic chamber which allows the in situ calibration of AWS pressure, temperature, and humidity sensors. These parameters will be generated simultaneously and independently to investigate the mutual influence between them, such as the temperature influence on pressure sensor response or humidity influence on temperature measurement. The prototype (named EDIE-0) used for the calibration of the sensor working in the Moncalieri Observatory was manufactured in July 2012 as a test bench, to underline the main challenges planning to design the final climatic chamber. EDIE-0 allows only the simultaneous control of temperature and pressure. It is made of two concentric steel cylinders between which there is a volume filled with alcohol. This bath is temperature controlled by means of a copper coil rolled around the inner cylinder and connected with a thermostat which pumps alcohol in the duct, avoiding any mixing with the bath fluid. The inner cylinder (the test chamber), is closed on the top by a Plexiglas cover hosting the pressure line and electrical contacts. A scheme of the chamber is reported in figure 2.

The main weak point of this prototype is the temperature gradient along the vertical axis of the chamber. This is due to the thermal contact between the Plexiglas cover and the room. Such thermal inhomogeneity, of the order of about 0.03 °C/cm (larger value) in the measurement zone, is a non negligible source of calibration uncertainty. The solution of this flaw is the most meaningful target for the final calibration chamber.

The instrumental set up for calibrations consists of:

- a standard thermometer SPRT25 Ω calibrated at fixed points of ITS-90 scale (H₂O - In and Hg - H₂O- Ga, temperature range: -38.8 °C ÷ 156.6 °C)
- a thermocouple copper-constantan for the evaluation of temperature gradient in the measurement zone;
- an external barometer DPI740 Druck, calibrated against INRiM primary standard, connect to the inner vessel through a pressure line

3.2 Description of the Calibration Procedure

During the calibration process, a second AWS was used to take measurements in order to preserve the continuity of the series. This weather station was a Vaisala WXT520 calibrated using the same facility and procedure described below. Aiming to compare the data acquired by the two different instruments some days of paired measurements were performed both before and after the calibration period. In these days, the sensors were installed in the same conditions: both in the wooden screen and quite close together, but far enough to avoid any mutual heating.

The temperature sensor, to be calibrated, was removed from the screen and placed in the climatic chamber at the same height of the reference thermometer in order to reduce the temperature gradient contribute to uncertainty. However, there is an indetermination on the sensor position of about 4 cm, corresponding to a temperature uncertainty of 0.14 °C, because the sensor is surrounded by traspiring not see-through material making it impossible a better determination of its position inside its probe.

The temperature sensor and its ADC converter found place in the chamber and were connected to the datalogger, which instead remained at its usual position inside the metrological observatory office; in this way the whole measurement chain was calibrated in its working condition.

The calibration curve was obtained from six points of temperature (about -20 °C, -10 °C, 0 °C, 15 °C, 30 °C, 40 °C), covering the whole meteorological variability of Moncalieri.

The calibration function evaluated is a function $T=f(T_{\text{READ}})$ where T_{READ} is the temperature recorded by the sensor in calibration. $T=f(T_{\text{READ}})= T_{\text{READ}}+\Delta T$ was obtained computing $\Delta T=T_C-T_{\text{READ}}$ for every temperature and fitting $\Delta T= f(T_{\text{READ}})$ with a second order polynomial curve which represents the correction to add to the recorded values (figure 3). T_C is the temperature measured by the reference thermometer. The collected values for T_C , T_{READ} , and their differences are reported in table 1.

The obtained calibration function is:

$$T=T_{\text{READ}}+aT_{\text{READ}}^2 + bT_{\text{READ}} +c \quad (1)$$

with $a=-0.000255$, $b=0.023347$, and $c=-0.685355$.

The pressure sensor calibration was carried out from seven points of pressure (910 hPa, 930 hPa, 950 hPa, 970 hPa, 990 hPa, 1010 hPa, 1030 hPa), at room temperature in order to check the correct operation of the sensor. The barometer is hosted in the datalogger case located inside the observatory tower and no investigation about the temperature dependence of the pressure sensor reading has therefore been performed.

3.3 Uncertainty Estimation

Estimating the calibration uncertainty requires the composition of every source of uncertainty in the calibration process. In this case we considered:

- Resolution of the sensor in calibration: 0.029 °C.

This value is the uncertainty estimated supposing a rectangular distribution for the resolution uncertainty.

- Thermal inhomogeneity in the chamber: 0.14 °C.

This is the maximum value evaluated for each calibration temperature.

- Uncertainty of the reference thermometer: 0.01 °C.
- Interpolation uncertainty: 0.14 °C.

This value is defined through the differences between each measured value (T_{READ}) and calculated (T_i) by calibration curve in Eq. 1:

$$u_{int.} = \sqrt{\frac{\sum_i (T_{READ,i.} - T_{t,i.})^2}{d}}$$

$d=4$ are the degrees of freedom [16].

The global uncertainty budget is the quadratic sum of all these contributes, multiplied for the coverage factor $K=2$ in order to express the uncertainty with a confidence level of 95%. The expanded calibration uncertainty is 0.33 °C. This value is considered constant for all the calibration values defined in the temperature range.

4 Data Analysis

In this section, the impact on the data series of the application of the calibration curve is considered. The aim is to establish in which manner the not calibration of the instruments influences the results and climate considerations.

The differences between corrected and uncorrected data for the period from 23 June 2012 to 31 May 2013 have been evaluated from a climatological point of view. The quantities considered are: daily minimum (T_n), maximum (T_x) and mean (T_m) temperatures.

Figure 4 reports the daily winter (December 2012 and January 2013) and summer (July 2012 and August 2013) data of the maximum (fig. 4 a and b) and minimum (fig. 4 c and d) temperature. The data corrected and uncorrected by calibration curve are shown to underline the magnitude of differences. The daily data was computed from the hourly maximum and minimum temperature.

Table 2 summarizes the mean values of T_x , T_n , and T_m calculated over one year of observations for corrected and uncorrected data. The calibration uncertainty is also reported for the corrected data.

The histograms in figure 5 show the frequency density of the differences between corrected and uncorrected data for T_x , T_n , and T_m .

With regard to mean T_x (evaluated on 1 year), the difference is in average -0.37 °C (see table 2) and this value is slightly larger than the calibration uncertainty (0.33 °C). In case of daily values of T_x , 46.20% of the measures are within calibration expanded uncertainty.

The application of the calibration function has an impact greater if we consider T_m and T_n data. In fact, only the 26.32% of the daily T_m measures are within the calibration expanded uncertainty and the mean difference evaluated on 1 year is $-0.43\text{ }^{\circ}\text{C}$ (see table 2)

Considering the minimum temperatures (T_n), the rate of daily uncorrected data within calibration uncertainty falls to the 16.67% and the mean difference, calculated on 1 year of observations, is $-0.5\text{ }^{\circ}\text{C}$ (see table 2).

In general, the major differences between corrected and not corrected data are recorded in winter seasons when lower temperatures occur and this effect is principally evident for minimum temperatures (see fig. 4). This particular behaviour is due to the specific calibration curve evaluated, which associates higher corrections for lower temperature.

5 Conclusions

This work illustrates the first example of air temperature historical data series traceable to SI standards. Since 2012, the data recorded in the historical meteorological observatory of Moncalieri have been corrected with the calibration function and the associated calibration uncertainty. This result has been achieved through a calibration facility manufactured at INRiM and dedicated to metrological sensors. The thermometer working in the observatory was calibrated in situ following a dedicated procedure and involving a travelling standard. Working in situ allowed reducing the calibration time and so minimizing the data loss, a fundamental aspect for the quality of a long series. In fact the datalogger (not easily transportable) was kept in its usual position and it was used to record the sensor response. In this manner, the whole measurement chain was calibrated reducing a further uncertainty contribution due to the datalogger, the ADC conversion and the software elaboration.

After the calibration, data were recorded for 1 year in order to analyze a large set of atmospheric conditions. During this time both uncorrected and corrected, with calibration curve, data were archived in order to analyze the impact of the calibration process on the data series. The differences between corrected and uncorrected data were evaluated with respect to most important quantities employed in the climate analysis: maximum, minimum, mean temperature.

This analysis indicates that the application of the calibration function to correct data, in the case of Moncalieri series, influences the climatological analysis. Significant differences, outside the calibration uncertainty, between corrected and uncorrected data are evaluated ($\Delta T_n = -0.5\text{ }^{\circ}\text{C}$, $\Delta T_x = -0.37\text{ }^{\circ}\text{C}$, $\Delta T_m = -0.43\text{ }^{\circ}\text{C}$ averaged on the whole observation period). Moreover, a not negligible number of observations are outside this threshold value. The differences are more noticeable in winter seasons and this effect can have an important impact on temperature time-series, especially on the long series made by

measurements carried out with different instruments. The not application of the calibration curve could bring to increase the differences between the instruments.

The calibration or not of the sensor is particular important when the data are used to make comparison on data recorded in different meteorological sites or in the evaluation on time of trends.

These results demonstrate that working with uncalibrated sensors introduces a not negligible artificial bias influencing climate analysis. The application of suitable calibration procedures could avoid or minimize this problem. The traceability of the century-long temperature series, as proposed in this work, could lead to increase confidence and improve assessment in detecting and predicting climate change.

The use of calibrated sensor to generate temperature data represents a fruitful example of direct cooperation between metrological and meteorological/climatological communities as supported by the European joint research project MeteoMet. This cooperation will add value at these different research fields.

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Table 1: Calibration results. T_C is the temperature measured by the reference thermometer, T_{READ} is the temperature recorded by sensor in calibration and ΔT is their differences.

T_C (°C)	T_{READ} (°C)	$\Delta T = T_C - T_{\text{READ}}$ (°C)
-0.39	0.2	-0.59
14.92	15.3	-0.38
30.24	30.5	-0.26
39.96	40.1	-0.14
-19.14	-18	-1.14
-10.45	-9.4	-1.05

Table 2: Summary of mean maximum (T_x), minimum (T_n), and mean (T_m) temperature recorded applying calibration curve compared with the raw data (uncorrected). The means on the whole experimental period (among 1 year) were calculated from daily values. ΔT is the difference between temperature corrected with the calibration curve and uncorrected.

	T _x mean (°C)	T _n mean (°C)	T _m mean (°C)	calibration uncertainty (°C)
corrected	18.38	8.82	13.60	0.33
uncorrected	18.75	9.32	14.03	
ΔT	-0.37	-0.5	-0.43	

Figure Captions

Fig. 1 A view of the Historical Observatory of Moncalieri. A red circle points out the sensor screen.

Fig. 2 A scheme of the prototype calibration chamber carried out at INRiM and used for the meteorological sensor calibration.

Fig. 3 Correction curve for the calibrated temperature sensor. T_{READ} is the temperature recorded by the sensor in calibration and ΔT the difference between the reference and the sensor in calibration.

Fig. 4 The daily winter (December 2012 and January 2013) and summer (July 2012 and August 2013) data of the maximum (a,c) and minimum (b,d) temperature. Corrected and uncorrected by calibration curve data are shown.

Fig. 5 Frequency density of the daily differences between corrected and uncorrected data (from June 2012 to May 2013) for T_x (a), T_n (b), and T_m (c).



Fig.1

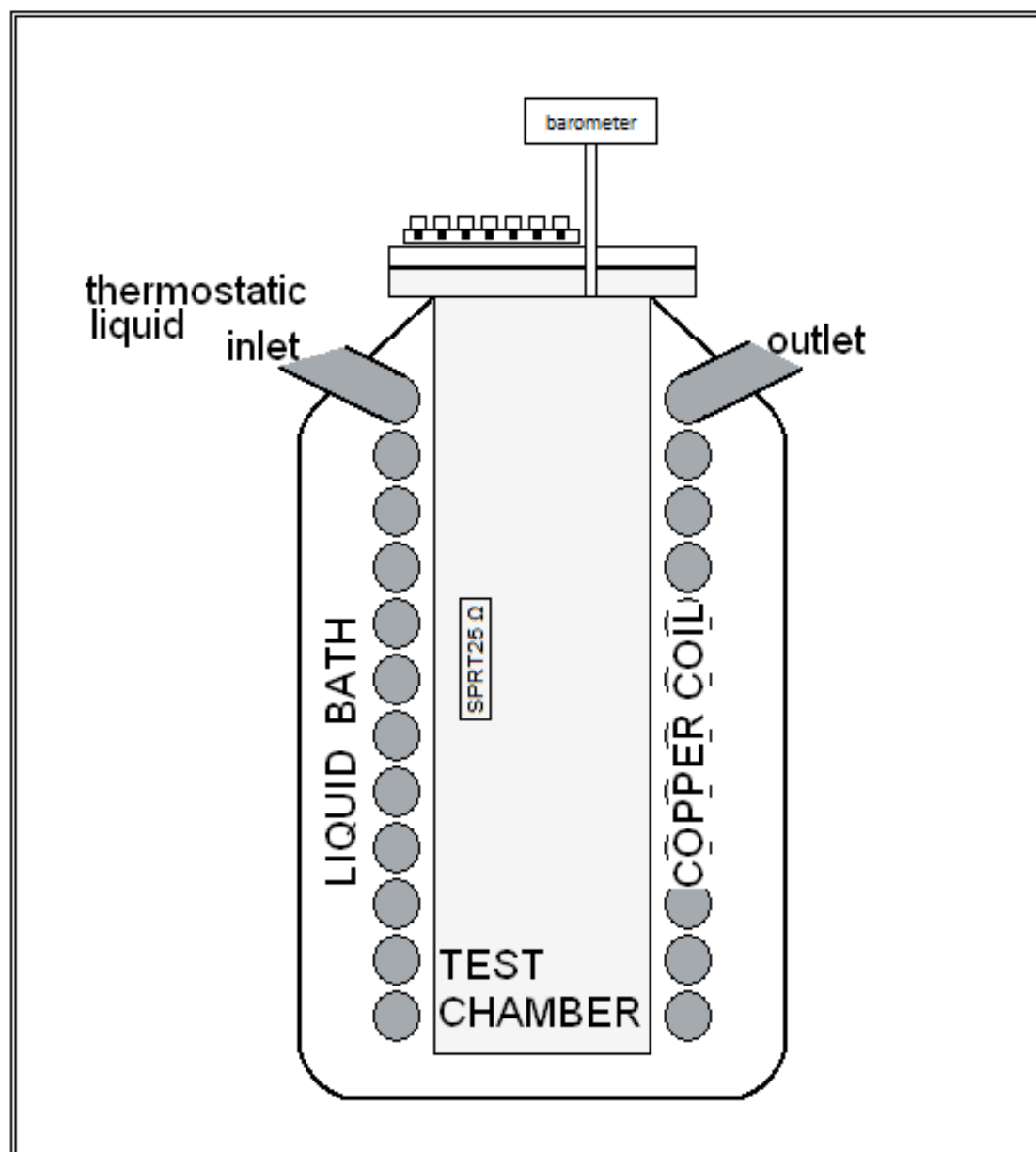


Fig.2

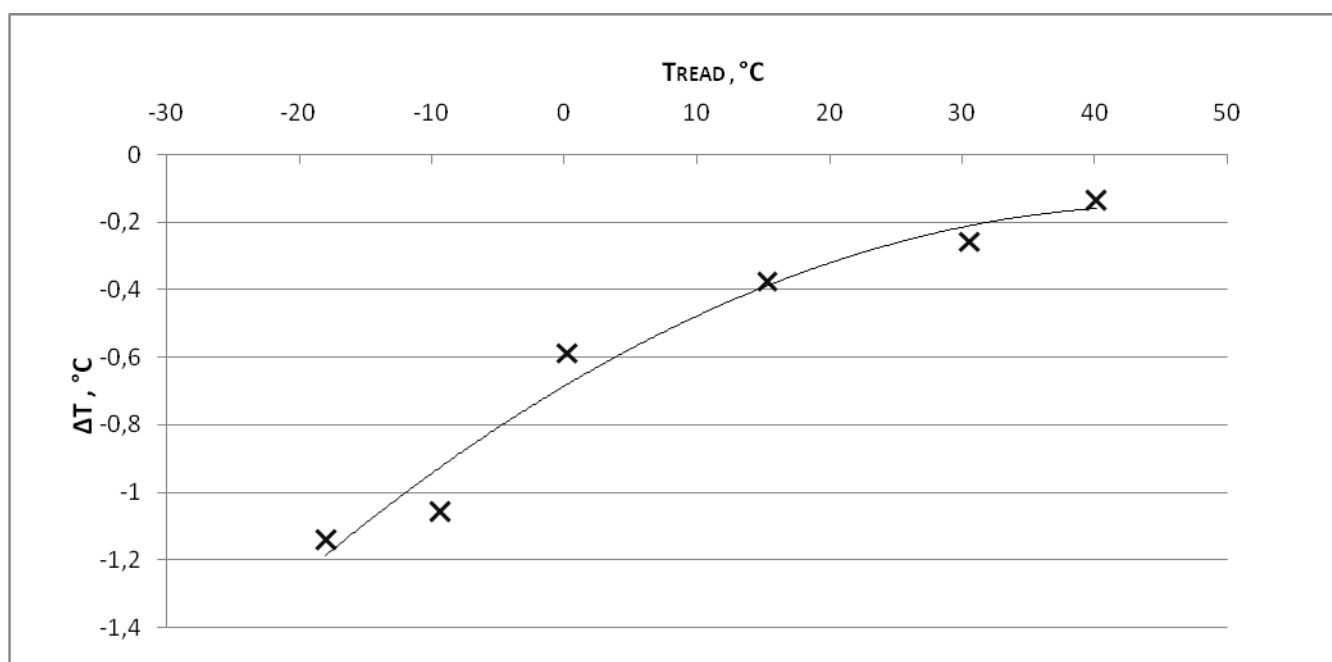
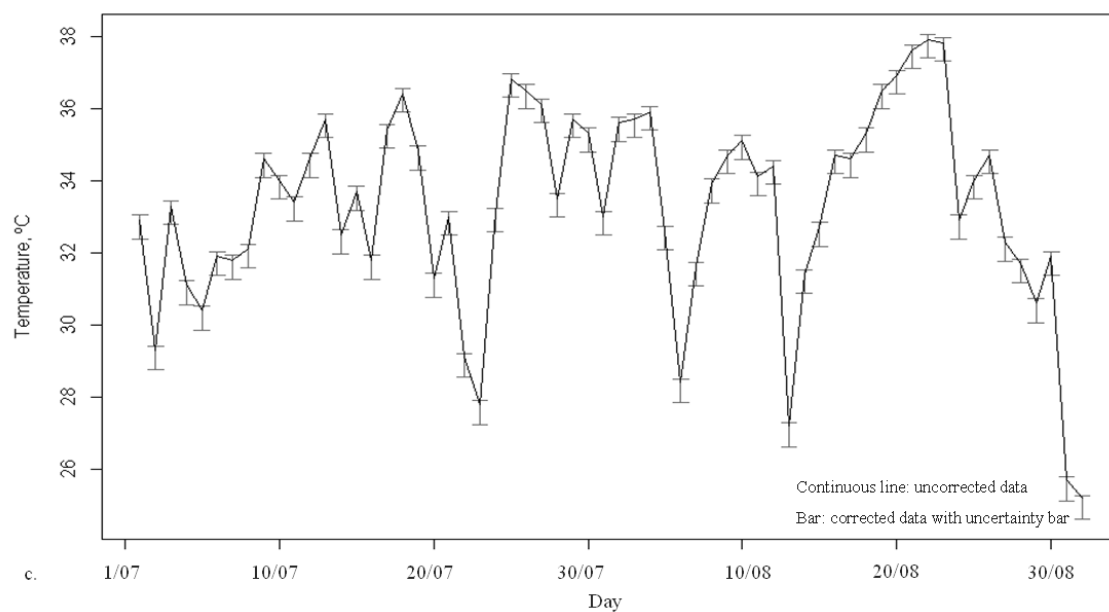
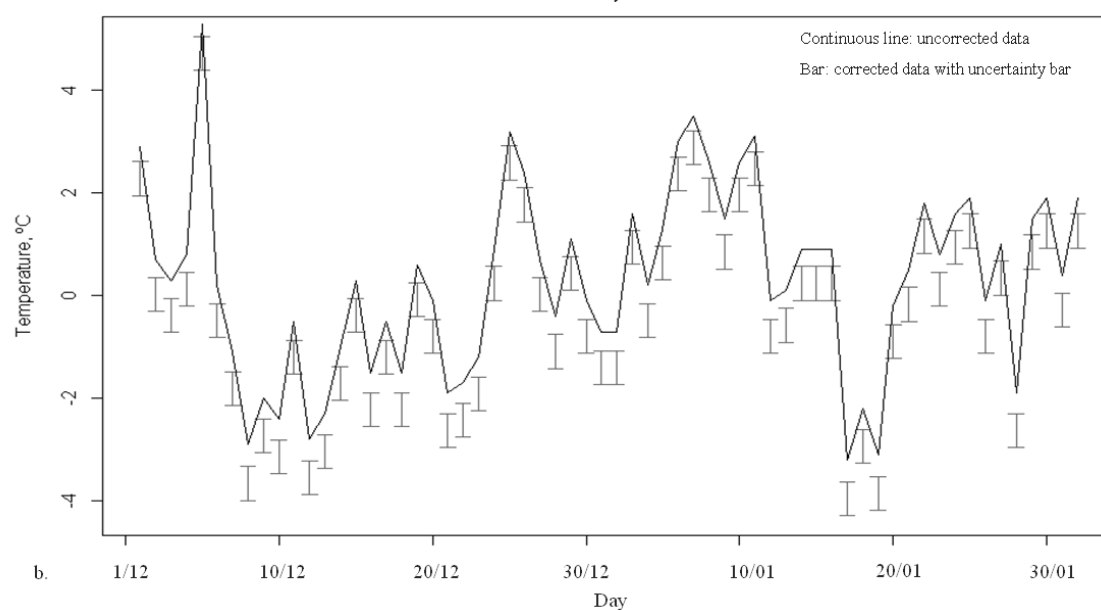
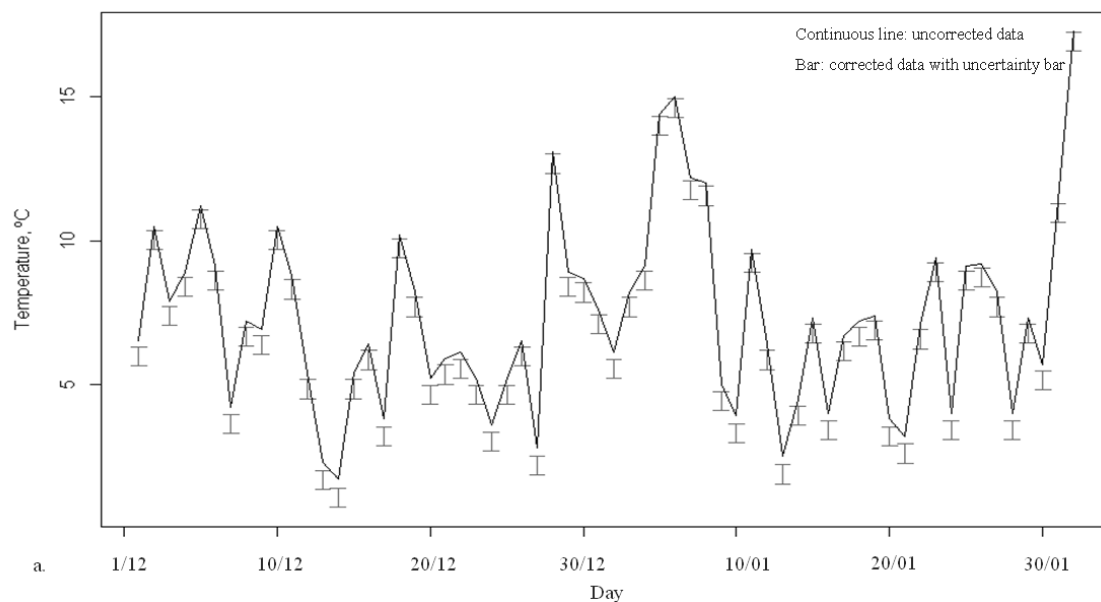


Fig. 3



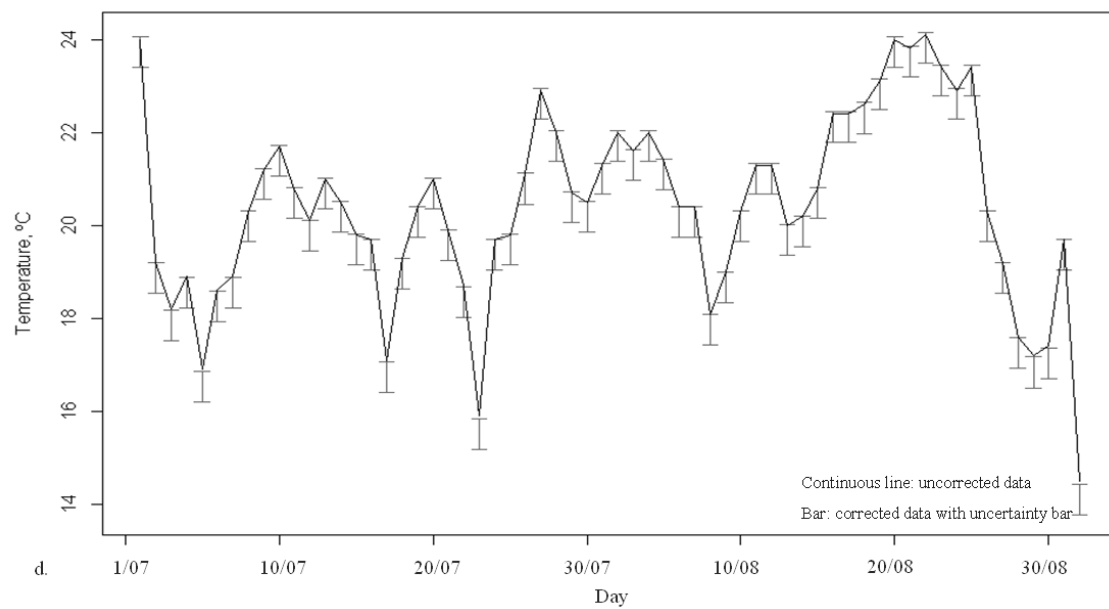


Fig. 4

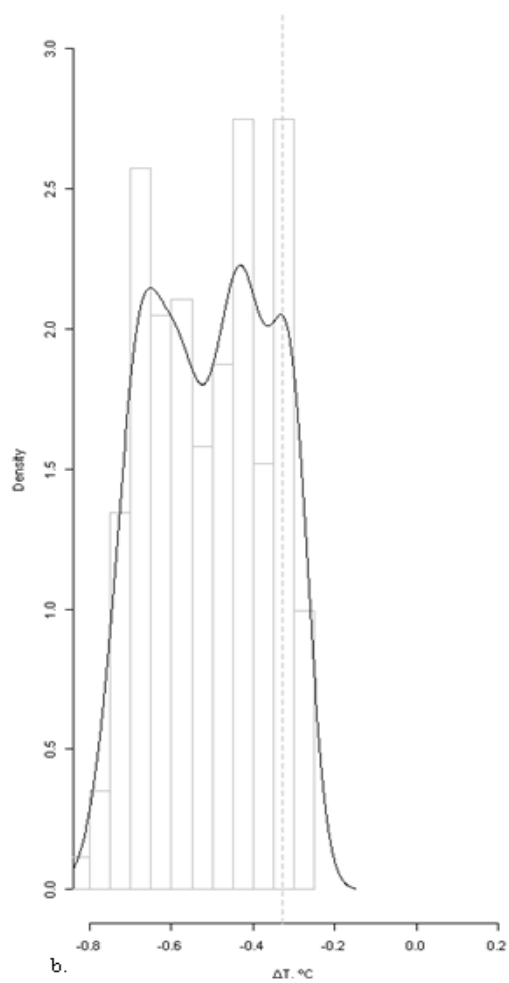
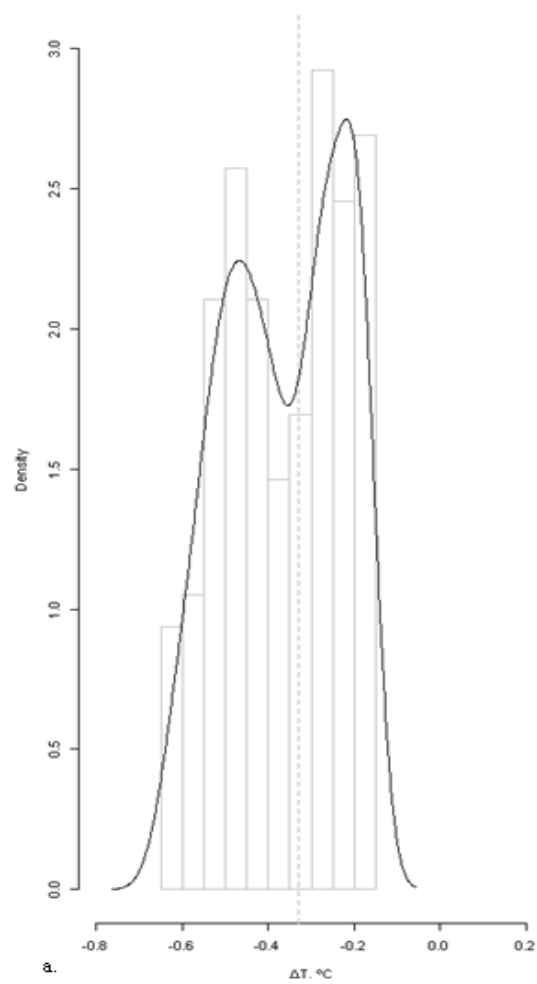
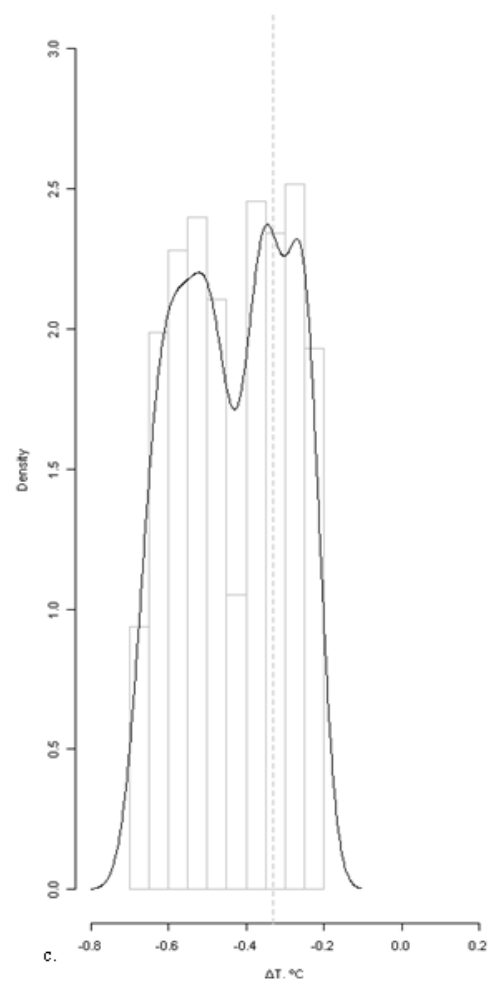


Fig. 5

