IL NUOVO CIMENTO **47 C** (2024) 309
DOI 10.1393/ncc/i2024-24309-3

Communications: SIF Congress 2023

The metrology-meteorology cooperation on thermodynamic environmental issues

G. Coppa, C. Musacchio and A. Merlone

Istituto Nazionale di Ricerca Metrologica, INRiM - Strada delle Cacce, 91, 10135, Torino, Italy

received 17 January 2024

Summary. — Environmental measurements represent a phenomenal societal and scientific challenge of ever-growing importance in the light of the ongoing and future climate variability. Thermal quantities (temperature of air, sea, snow and soil, humidity, permafrost depth) are key among the Essential Climate Variable (ECVs) as defined by the WMO Global Climate Observing System in these areas. In order to accurately capture climatic trends and enable early detection, metrological rigor in terms of sensor calibration and uncertainty budget evaluation are of paramount importance. For this reason, the metrology and meteo/climatological communities have started a decade-long ongoing cooperation through the mutual recognition accords between the WMO and BIPM. This cooperation led to the exchange of representatives in WGs, the co-hosting of a series of joint workshops ("Metrology for Climate Action"), and a general strict cooperation, through the development of new measurement techniques and instruments; the understanding of uncertainty components both for laboratory calibration and for field conditions; the accurate evaluation of quantities of influence; and the development of guidelines, best practices and recommendations.

1. – Introduction

Metrology and meteorology, as full-fledged, independent sciences, share a very similar date of birth: while the former was formally established in 1875 when the *Convention du Métre* was signed in Paris —which later gave birth to the *Bureau International des Poids et Mesures* (BIPM), the current governing body of worldwide metrology— the latter was established in 1873 when the creation of the International Meteorological Organization (IMO), precursor of the World Meteorological Organization (WMO), was agreed upon in Vienna.

Despite this, metrology and meteorology have reciprocally recognized the importance of common visions only relatively recently. In 2010, a Mutual Recognition Agreement (MRA) between the two bodies was signed in Geneva, and since then the cooperation grew ever stronger [1].

This communication will report on the ties between BIPM and WMO, the joint initiatives and the cooperation in thermodynamic measurements for the environment. A focus on air temperature definition and measurement uncertainty, which in the last few years has carved out a very central place for itself, is presented here.

2. – Metrological issues

Air temperature is a fundamental Essential Climate Variable as defined by GCOS (Global Climate Observing System). However, air temperature suffers from a series of important issues that jeopardize its metrological traceability and the possibility to evaluate a complete uncertainty budget, hence its comparability among different networks, epochs, methodologies [2].

As a matter of fact, there is currently neither consensus nor standardized practice for the calibration of temperature sensors in air. Metrological procedures envisage an uninterrupted chain of calibrations by comparison in a liquid stirred bath, which constitute a very different environment from the one in which the sensors will be set to operate (the air). This leads to a break in the metrological traceability chain which is difficult to mend (fig. 1).

Moreover, a sensor that measures the temperature of air is subject to a plethora of influences due to other environmental quantities, such as solar radiation, wind speed, condensation/evaporation/icing, surface albedo, precipitation and others. These so-called quantities of influence (quantities that are not the measurand but affect the result of the measurement) affect both the measurand and the sensors itself in ways which are difficult to fully disentangle.

Lastly, there is not even a consensus metrological definition of "air temperature", so a future guideline on thermometer calibration in air will have to take into account the rigorous definition of the measurand which is not a trivial issue. Quantities of influence like pressure, solar radiation, wind will have to be considered when calibrating sensors and possibly adjusted in order to match as close as possible the environmental conditions in which the sensors will be employed.

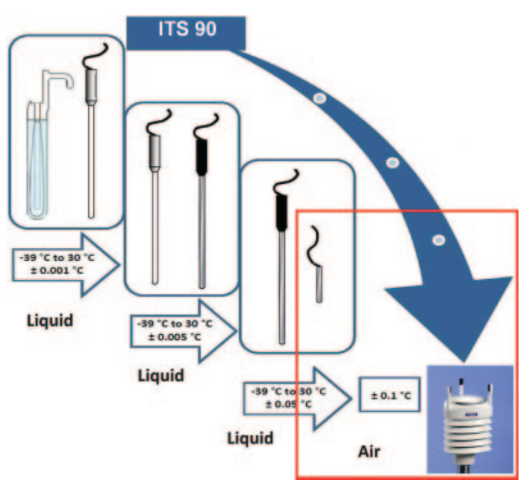

Fig. 1. – Schematics of a temperature calibration traceability chain. Primary sensors calibrated at the fixed points of the ITS-90 are used to calibrate lesser-quality sensors, in cascading comparison inside a liquid bath. The chain is severed at the liquid-air calibration step.

One of the largest cooperation programs between the meteorological and metrological communities, which addressed some of these problems and others, was the MeteoMet initiative.

3. – The cooperation

3˙1. *MeteoMet: Metrology for Meteorology.* – In 2011, the first EMRP project "MeteoMet - Metrology for Meteorology" [3], led by INRiM, was funded by the European Association of National Metrology Institutes (EURAMET). Beyond its scientific achievements, it gave birth to a worldwide consortium of metrology institutes, universities, research centres, hydro-meteorological services and instrument makers with the common goal of improving measurement techniques and uncertainty evaluation in environmental measurements. It was later followed by its second installment, "MeteoMet 2 - Metrology for Essential Climate Variables" [4], which tackled some important issues such as the quantification of errors (and their uncertainty) in near-surface temperatures measurements due to roads, buildings, trees [5, 6], the evaluation of uncertainty due to solar radiation reflected by snow [7,8], the calibration and measurement uncertainty evaluation of temperature sensors for permafrost [9, 10], radiosondes [11], applications in polar [12] and high-mountain environments [13, 14].

The MeteoMet consortium expanded its activities in the following years by giving birth to a series of more focussed projects: the INCIPIT project gave the first systematization and uncertainty analysis of the so-called "non-catching" rain gauges [15,16], while project COAT proposed an inter-comparison of meteorological sensors and shields in a polar environment [17], and project CRS defined the protocols and the best practices for a future network of climatic reference stations [18].

The EURAMET project P1459 "ATM - Air Temperature Metrology" started in 2018 as a pilot study, in the form of an inter-laboratory comparison of techniques and instruments regarding the calibration of temperature sensors in air and the drafting of guidelines for their implementation. The project currently has been extended beyond Europe in order to involve and include the expertise of National Metrology Institutes in other continents as well.

Concurrently, in 2021 the Consultative Committee for Temperature (CCT) of BIPM launched a Task Group "Air Temperature" in order to work on a shared definition of air temperature, draft an as complete as possible uncertainty budget for temperature measurements in air, both from a theoretical and an experimental point of view, and write the guidelines relative to the best practices and future protocols for calibration of temperature sensors in air.

3˙2. *Exchange of expertise.* – Part of the cooperation between the meteorological and metrological communities consists in the reciprocal participation of experts in Working Groups, Expert Teams and Technical Committees.

For instance, metrologists sit in the WMO's Global Cryosphere Watch (GCW) Permafrost Best Practice Task Group, which drafted a document where all the guidelines regarding permafrost related measurement (permafrost temperature, active layer thickness, rock glacier velocity) are laid out in a comprehensive and metrologically rigorous way. Metrologists sit in GCOS Reference Upper Air Network (GRUAN) Working Group as well, in order to provide assistance in sensors management and uncertainty evaluation of upper air measurements by means of radiosondes. The future GCOS Surface Reference Network (GSRN), which is currently under development [19], will also feature metrologists; conversely, meteorologists and climatologists are active part in several metrology groups, such as the the CCT Task Group on Air Temperature.

This cooperation was further consolidated by the Arctic Metrology Workshops which established a collaboration between metrology and the Arctic meteo community, culminating in the creation of a metrology laboratory at the Italian scientific base in Ny-Ålesund, Svalbard [20], and by the series of WMO-BIPM co-hosted workshops, "Metrology for Climate Action", whose 2022 edition recommended the development of "methods to handle metrological traceability and uncertainty analysis when data is processed through complex processing chains", as is common for air temperature measurements. From the metrology side, the series of "Metrology for Meteorology and Climate" conferences, organized by INRiM under the MeteoMet consortium umbrella [21], was instrumental in bringing the metrological capabilities to the service of the meteo-climatic community, as well as the instrument producers and end users.

4. – Conclusions

With the ever growing need for accurate measurements in environmental sciences, the cooperation between the metrology and meteorology communities is of paramount importance to identify the current issues in measurements for the environment —especially air temperature.

This communication reported on the close ties that the two communities have built for the last 15 years, in the form of joint projects, conferences and workshops, exchange of expertise in working groups and task teams. Among others, the MeteoMet (`http://www.meteomet.org/`) initiative proposes an articulated platform of metrological research and services to help meteorologists and climatologists in their efforts at measuring climate change, and policymakers to have the best baseline for political decisions.

REFERENCES

[1] Merlone A., Musacchio C. and Bich W., *Nat. Phys.*, **19** (2023) 1518.
[2] Merlone A., Coppa G. and Musacchio C., *Nat. Phys.*, **20** (2024) 520.
[3] Merlone A. *et al.*, *Meteorol. Appl.*, **22** (2015) 820.
[4] Merlone A. *et al.*, *Meas. Sci. Technol.*, **29** (2018) 025802.
[5] Coppa G. *et al.*, *Int. J. Climatol.*, **41** (2021) 3705.
[6] Garcia Izquierdo C. *et al.*, *Atmosphere*, **15** (2024) 209.
[7] Musacchio C., Coppa G. and Merlone A., *Meteorol. Appl.*, **26** (2019) 161.
[8] Musacchio C. *et al.*, *Atmos. Meas. Tech.*, **14** (2021) 6195.
[9] Coppa G. *et al.*, submitted to *Cold Reg. Sci. Technol.*
[10] Merlone A. *et al.*, *Permafr. Periglac. Process.*, **31** (2020) 610.
[11] Rosoldi M. *et al.*, *Atmosphere*, **13** (2022) 773.
[12] Coppa G. *et al.*, to be published in *Arct. Sci.* (2024).
[13] Viani C. *et al.*, *J. Mt. Sci.*, **17** (2020) 2591.
[14] Nigrelli G. *et al.*, *J. Mt. Sci.*, **19** (2022) 798.
[15] Lanza L. *et al.*, *Meteorol. Appl.*, **28** (2021) e2002.
[16] Baire Q. *et al.*, *Sensors*, **22** (2022) 6413.
[17] Garcia Izquierdo C. *et al.*, *Atmosphere*, **15** (2024) 841.
[18] Merlone A. *et al.*, *Int. J. Climatol.*, **44** (2024) 1710.
[19] Thorne P. W. *et al.*, *Int. J. Climatol.*, **38** (2018) 2760.
[20] Musacchio C. *et al.*, *Rend. Fis. Acc. Lincei*, **27** (2016) 243.
[21] Merlone A., Musacchio C. and Sanna F., *Meteorol. Appl.*, **22** (2015) 817.