Abstract

Climate change is one of the defining challenges of the 21st century. The ability to detect, attribute, and project changes in the Earth's climate system depends critically on the availability of long-term, high-quality observational records of essential climate variables. Many climate datasets are derived from networks originally designed for operational weather forecasting rather than for the precise detection of long-term trends. Consequently, they often lack the traceability, redundancy, and systematic uncertainty evaluation that are hallmarks of metrology.

The application of metrological principles to atmospheric measurements is not an easy task: a complete evaluation of their uncertainty budget represents a challenge, especially due to the complex environmental thermodynamic interactions involved at the Earth's surface. This is particularly true for air temperature, which is the key quantity in evaluating global warming compared to preindustrial times. Past EURAMET-funded projects, MeteoMet and MeteoMet 2, addressed some key aspects of air temperature measurements by performing experiments aimed at improving our knowledge of the corresponding uncertainty budget. Despite the effort, fundamental difficulties are still met in evaluating the many thermodynamic contributions to the total uncertainty, from the laboratory calibration to the environmental effects in the field.

In addition to air temperature, other quantities used to study the state of the climate need metrological standardization. Turbulent fluxes have long been studied to understand the interaction between the atmosphere and the ground, but also to determine the health of ecological systems (e.g. forests, croplands, grasslands) and their response to climate change. The eddy covariance technique has emerged in the last four decades as the most popular method to measure turbulent fluxes, mainly thanks to the technological progress that has permitted its implementation. Despite the establishment of continental-scale networks and infrastructure, implementing the

eddy covariance methodology following standardized procedures and instruments, a rigorous metrological assessment of the technique is still missing, as proven by the absence of a stated measurement uncertainty along with the flux estimates.

Recent works highlighted that another variable, not related to atmospheric physics, started to be affected by the air temperature anomaly: the air/rock temperature in caves. Correctly measuring this variable is crucial for monitoring the underground climate, known to be stable and little influenced by the external conditions. The main metrological challenge concerns the harsh conditions in which a measurement system must operate, requiring periodic verification to ensure the SI traceability chain is not broken by sensor drifts or failures of the acquisition device.

This dissertation seeks to demonstrate how a rigorous application of metrology can enhance the quality and robustness of weather and climate observations, but also to propose new methodologies for quantifying currently unknown uncertainty components. The research specifically focused on improving the quality of three key variables: air temperature, CO_2 turbulent flux, and temperature in subterranean environments (caves), through a series of dedicated laboratory and on-field experiments. The main objectives of this project were:

- To define climate reference data and prototype a Climatological Reference Station.
- To improve the measurement uncertainty budget of air temperature, focusing on three uncertainty sources: datalogger contribution, influence of rain and different exposure due to installation's height;
- To develop a comprehensive framework for evaluating the measurement uncertainty of CO_2 turbulent fluxes by propagating the uncertainties associated with the models' input quantities;
- To demonstrate the feasibility of on-site thermometer verification in caves and promote a cost-effective, easily transportable experimental setup for this purpose.

Collectively, this research demonstrates that the application of metrology is not confined to laboratory settings but can be systematically applied across the full spectrum of climate monitoring to transform observational data into defensible, SI-traceable datasets, which are essential for informing high-stakes decision-making in global climate mitigation and adaptation strategies.