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1 Executive Summary

Introduction

An Essential Climate Variable (ECV) is a physical, chemical or biological variable that critically contributes to the characterisation of the Earth's climate. ECVs include water vapour in the atmosphere, surface and deep sea temperature, ocean salinity, air temperature, precipitation and soil moisture. Prior to this project, long-term, high-quality observations of these variables did not exist, yet they are vital as society becomes increasingly affected by climate change.

This project investigated the performance of sensors used to monitor climate variables under different conditions and produced new measurement methods, techniques and standards, including a significant contribution to the accuracy, calibration, and traceability to the International System of Units of the meteorological measurements of temperature and humidity, both in static and dynamic conditions. The results will improve the monitoring of essential climate variables, which will benefit European industries such as agriculture, energy, and transport, and reduce the threat to public health.

The Problem

Long-term, high-quality, and uninterrupted observations of the atmosphere, land, and ocean are vital for all countries, as their economies and societies are increasingly affected by climate variability and change. High-quality and comparable observations are possible only if the measurements of the climate variables are traceable to the SI with reliably associated uncertainties. The need for complete traceability and reliable uncertainty calculation of the climate variables was already identified by the climatologists and addressed to the metrologists. For instance, a challenge for the humidity sensors is the changes, of a factor of more than 10000, of water content in the atmosphere. Reliable measurements require sensitive and fast responding sensors to quantify such dynamic changes. Radiosondes (small weather stations coupled with a radio transmitter, carried into the atmosphere by a weather balloon) needed to be improved and validated, to cover the real working conditions. To monitor decadal changes of the ocean heat-content and -flow, a comprehensive study was necessary of the effect of the main quantities of influence on sea-thermometers and salinometers. Laboratory intercomparisons were not yet able to evaluate the in-field behaviour of thermometers and humidity sensors and to define calibration procedures and methods to evaluate the measurement and calibration uncertainties. Calibration and measurement standards for precipitation and soil moisture were not yet sufficiently developed to cope with the differences between laboratory setups and field conditions.

The Solution

We set out to solve these problems by investigating the performance of temperature and humidity sensors in the laboratory and real working conditions. References, test facilities, and on-site experiments were developed. The project realised novel instruments, procedures, and methodologies such as a non-contact thermo-hygrometer and a spectrometer for the measurement of fast transients of temperature and humidity in the air; a facility for determining the temperature and pressure effects on salinometers; a pressure vessel for evaluating high-pressure effects on deep-sea thermometers. New sensors based on optical fibres, for seawater temperature measurements, were developed and tested in real conditions. The influence of albedo, rain, buildings, roads and trees on the air temperature measurements were measured onsite and analysed. The influence of solar radiation on air temperature measurements was also numerically investigated. On-site calibrations in high mountains and polar areas were carried out. Thermometers were characterised as regards to dynamics, hysteresis, and repeatability after thermal and mechanical shocks. The project also promoted an interlaboratory comparison of the European meteorological agencies, now even extended to Asia, and events to facilitate the interaction of metrologists, meteorologists, and climatologists, to constantly exchange information, and to establish permanent collaborations and reciprocal memberships in expert teams.

Impact

The project reported at international conferences and several papers were submitted to peer-reviewed scientific journals. Under the strong support of this project, the International Conference on "Metrology for Meteorology and Climate" was created and it is now recognised worldwide as a reference event. During the project, stakeholders and environmental agencies were trained on the reliability and calibration of temperature and humidity measurements. GRUAN, WMO CIMO, WMO CCl, and ISTI were continuously updated on the project results by teleconferences and participation of staff from MeteoMet to their respective expert teams. A laboratory intercomparison was organised in Region VI of WMO and participated by 17 Institutions and was extended to Asia regions, well beyond the project objectives. The WMO expert team on instrument intercomparisons accepted to submit a proposal for a comparison of thermometers and radiation shields to the CIMO management group to be included in future WMO comparisons. World leading manufacturers – such as Rotronic, Vaisala, NKE Instrumentation, Sea-Bird Electronics – are using the project calibrations and tests to improve their instruments. The project provided inputs to a number of documentary standards: i) Sustained Performance Classification for Surface Observing Stations on Land 1/6 Draft 2014 Rev 2017, ii) CIMO ET-A1-A2/Doc.8.1 – Guidelines on combining information from composite observing systems, iii) CIMO ET-Standard, Sustained Performance Classification for Surface Observing Stations on Land 1/6 24/06/2014, and iv) ISO/DIS 80000-5 Quantities and units - Part 5: Thermodynamics.

The calibration procedures, the assessment of the measurement uncertainties, and new instrumentation for hygrometry and sea measurements are expected to have a long-term impact on the reliability of climate trend evaluations. The numerical simulation of radiative heat transfer was used to design a chamber for calibration of air temperature sensors for the EMPIR project 15RPT03 HUMEA “Expansion of European research capabilities in humidity measurement” of the 2015 Research Potential call. Members of the project consortium, who are now members of WMO CIMO expert teams, are promoting a number of activities that follow on from the work of the project including a proposal for a comparison of thermometers and radiation shields and an interlaboratory comparision procedure and protocol in the field of termperature, humidity and pressure in Asia and Australia WMO regions II and V in collaboration with Region VI (Europe).

2 Project context, rationale, and objectives

"The demand for information on climate has never been greater than today. Long-term, high-quality and uninterrupted observations of the atmosphere, land, and ocean are vital for all countries, as their economies and societies become increasingly affected by climate variability and change" [1]. High-quality observations are not possible if they are not based on a sustained traceability to SI and a reliable uncertainty evaluation of the measurements of the Essential Climate Variables (ECV) defined by GCOS[1].

The preceding EMRP project, ENV07 MeteoMet, covered a limited number of needs for traceability and calibration in meteorology. On the basis of the results and experience achieved in the preceding project, this MeteoMet2 project aimed at: the improvement of the calibration procedures of meteorological sensors, the evaluation of the measurement uncertainties, the optimisation of the previously developed measurement devices and of their in-field use, the investigations of sensor characteristics to produce climate data of higher quality, the extension of the atmospheric Essential Climate Variables (ECVs) to soil moisture and some of the oceanic ones. The ECVs considered in this project are water vapour in upper-air and surface atmosphere, surface and deep-sea temperature and salinity, air temperature, precipitation, albedo, permafrost temperature and soil moisture.

Water vapour, amongst the upper-air ECVs, is a challenging quantity to be measured. Reliable measurements require sensitive sensors with fast response time, operating in a large dynamic range and bandwidth.
Temperature and salinity play an important role in the monitoring of oceans. High-quality instruments exist or are being developed. However, a comprehensive study of the effect of the main quantities of influence on thermometers and salinometers is needed, in order to determine the needed corrections.

As regards as air temperature, the estimation of the measurement uncertainty needs the knowledge of the measurement system, starting from its intrinsic behaviour, the influence of the place where the measurements are performed, and the influence of meteorological parameters such as albedo and precipitation.

The values of the air temperature measured by Automatic Weather Stations depend strongly on rain and sun radiation reflected by the ground; in particular, in snow covered areas. Due to a lack of satisfactory calibration standards for precipitation, the meteorological community requests studies on traceability and uncertainty calculation.

Soil moisture measurements are essential to understanding the interchange of water vapour between land and air, which interchange affects meteorology, earth observation, hydrology, agriculture, and management of flood risk. However, the accuracy of soil moisture measurements is low, because it is affected by the soil structure and interferences. Additionally, traceable calibrations are not yet good enough to solve these problems.

This project was structured in three objectives covering the observations of air, sea, and land.

Air

Water vapour is the most important greenhouse gas in the upper-air atmosphere and a key component for several physical and chemical processes. Therefore, air humidity (expressed in terms of volume concentration of water) is a key parameter to be measured. A big measurement challenge is the wide dynamic range of the water content in the atmosphere, which varies by a factor of more than 10 000. Furthermore, the atmosphere humidity changes continuously and quickly. Therefore, reliable measurements require sensitive sensors having a fast response time and a wide dynamic range. A GRUAN guide states: *Changes in water vapour in the UT/LS exert a greater radiative forcing than changes elsewhere. Standard radiosonde humidity sensors have generally a very poor response at the low temperatures (<-50 °C), pressures, and water vapour concentrations of the UT/LS. Although there has been significant progress*

since 2003, no operational radiosonde can be expected to measure with sufficient accuracy in the lower stratosphere for climatological purposes[1].
Radiosondes are fundamental measurement tools to detect atmospheric quantities in the upper atmosphere. Facilities for calibration at low temperature and pressure are needed and must be compared to develop a procedure miming as close as possible the environmental conditions encountered during the ascent flight.

The water vapour equation has a significant influence on the uncertainty of water vapour measurement. This equation is the base of the calculation of the vapour pressure and other humidity related quantities. To perform accurate water vapour measurements (mole fraction) in the atmosphere (especially where the water vapour fraction is at the level of some part per million), it is needed to reduce the uncertainty of the water vapour formulation in the temperature range from –80 °C to 100 °C to improve the primary standards for airborne measurements.

Measurements of fast-changing upper air ECVs (temperature and water vapour) are very challenging and the response time of the conventional sensors is too low to follow the rapid transients. To overcome this problem, the development and characterisation of sensors capable of sensing fast changing ECVs is needed.

The calibration of humidity sensors and the reliable analysis of data recorded during the measurement require the knowledge of the enhancement factor. It corrects the non-ideal behaviour of water vapour in the air (the saturation vapour pressure of water in a gas mixture is not the same as in pure water). Therefore, there is a need to measure the enhancement factors and to investigate its influence on ECV measurements.

Sea

The oceans have a central role in the climate system, because of their capacity to store, transport, and exchange heat with the atmosphere. Their warming accounts for approximately 90% of the warming of the Earth during the last 6 decades[2]. The GCOS/GOOS[3] plan for the global observing climate- system assumes[4] that global ocean observations will come from the composite surface and sub-surface ocean observing networks, based on satellite and *in situ* measurements and providing global monitoring of certain ECVs. In this global model, seawater temperature and salinity are oceanic ECVs to be measured and compared on a wide scale, by a large number of networks operating both at the ocean surface and depth.

Salinity. An accurate evaluation of the ocean's role in heat transport and in climate change requires the measurement of absolute salinity; in particular, it requires the traceability of salinity measurements over decades. Instruments based on seawater refractive-index measurement are being developed and have shown to be potentially able to provide high-accuracy measurements. To progress the development and to perform an accurate metrological characterisation, it is necessary to study of the effect of water pressure and temperature on these refractive-index salinometers. To increase the capability of measuring absolute salinity, a facility for determining temperature and pressure effects on a novel generation of salinometers – carrying out absolute measurements via the seawater refraction-index – was realised and characterised. This is a step improvement of the capability of measuring seawater salinity, as well as of the databases used to extract the salinity value from the measurements of the refractive index (at a given wavelength), temperature, and pressure.

Deep-sea sensors. The target uncertainty set by the World Ocean Circulation Experiment (WOCE) Hydrographic Program (WHP) on ocean temperature measurements is 2 mK. Since recent studies[5] reported

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[1] The GCOS Reference Upper-Air Network (GRUAN) GUIDE. GCOS-171, Version 1.1.0.3, March 2013, WIGOS Technical Report No. 2013-03
[2] J. A. Church et al, Revisiting the Earth's sea level and energy budgets from 1961 to 2008, Geophysical Research Letters, 2011; Volume 38, Issue 18; DOI: 10.1029/2011GL048794
[3] GOOS: The Global Ocean Observing System, http://www.ioc-goos.org/
[4] G. Needler, N. Smith, A. Villwock, The action plan for GOOS/GCOS and sustained observations for Clivar. Proceedings of the International Conference on the Ocean Observing System for Climate, Volume 1.OceanObs -99, 18-22 October 1999, San Raphael, France
[5] M. Fukasawa et al, Bottom water warming in the North Pacific Ocean, Nature 427, 825-827; 2004 doi:10.1038/nature02337

an increase of 5 mK per decade of the temperature of deep ocean water in the North Pacific Ocean, such an uncertainty level is necessary to ensure the traceability of long-term sea temperature measurements. However, deep-ocean *in situ* temperature measurements suffer from large uncertainties, because of the effect of water pressure on the thermometers (pressures up to 60 MPa cause deviations of several millikelvin). In addition, since the most widespread deep-ocean thermometers are thermistors, there is a need for a metrological validation of the temperature-resistance linearisation, especially on high-grade deep-sea reference thermometers.

Land

To generate high-quality data, an accurate uncertainty budget is needed. Land-based ECVs, such as air temperature, water vapour, precipitation, albedo, permafrost temperature, and soil moisture, need consistent evaluations of the measurement uncertainty via a detailed knowledge of the measurement systems, their operation, influence quantities, and environmental effects.

Precipitation and sun radiation are the main influencing factors of the air temperature measurements. Up to now, they were not metrologically evaluated. The air temperature measured by the automatic weather stations (AWS) depends on the indirect sun reflexion by the ground, mainly in snow-covered areas. "*Environmental conditions of a site may generate measurement errors exceeding the tolerances envisaged for instruments […]. It is often environmental conditions that distort results, influencing their representativeness*."[6] Therefore, to make the generation of high-quality data possible, an accurate uncertainty budget is needed.

Reflected radiation from snow. Traceable measurements are necessary to assess the influence of the albedo and the associated uncertainty.

Siting uncertainty. In-field measurement campaigns are necessary to study different influence-factors: asphalt roads, trees and buildings to improve the siting classification as defined by the CIMO-XV/Doc. 4 CIMO Guide n. 8 and sustained performance classification.

Air temperature sensors. "*The primary quality factor of a measurement is the set of intrinsic parameters of the instrument used*"[7], that is, response time, self-heating, etc., properties that are also highlighted in the ISO 17714:2007 standard. In the ISO Guide, a practical method is given for the determination of the response time of shielded air-temperature sensors, but no guideline is given to evaluate the determination uncertainty, nor are given procedures to evaluate other intrinsic characteristics.

Air humidity sensors. The amount of water vapour in the air changes continuously. Reliable measurements of on-site humidity require sensitive sensors with a fast response time, which are able to quantify these fast changes. Traceable spectroscopic methods like TDLAS and CRDS have a potential for a use as reference standards, because of their stability, fast response time, and low measurement uncertainty. A dynamic calibration procedure to test fast-response sensors must be developed, to provide traceability and comparability in worldwide measured meteorological data.

Air humidity. Traceability of humidity data needs to be improved by the dynamic calibration of hygrometers with a reliable uncertainty calculation. Studies are needed to develop a calibration procedure including response time, hysteresis, and behaviour under fast humidity changes (not considered in the present calibration protocols).

Soil moisture. Soil moisture measurements are essential to understanding the water vapour interchange between land and air (heat and mass transfer). These exchanges are relevant to meteorology, earth observation, hydrology, agriculture, and management of flood risk. However, the accuracy of soil measurement is poor and it is affected by soil structure and interferences. Furthermore, traceable calibration methods are not yet well developed.

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[6] CIMO Secretary-General, CIMO-XV/Doc. 4: Instruments and methods of observation for surface measurements; surface observation technology (opag-surface) September 2010, Helsinki, Finland

[7] Report of the First Session of CIMO Expert team on Stadardisation.
http://www.wmo.int/pages/prog/www/IMOP/reports/2012/Final-Report_ET-Stand-1.pdf

Interlaboratory comparison protocol. The measurement traceability requires the calibration of the measurement instruments, usually performed by the calibration laboratories of the Regional Instrument Centres (RICs) whose Terms of Reference establishes "*the RICs must participate in, or organise interlaboratory comparisons of standard calibration instruments and methods*". However, there is a lack of laboratory intercomparisons, which are powerful tools to bring into light the discrepancies, if any, between the calibration laboratories of National Meteorological or Hydrological Services (NMHS). It is necessary that these calibrations are identified and taken into account, in such way that the meteorological measurements taken in different places are made compatible.

The WMO/CIMO notices the "*importance of instrument intercomparison as a tool to improve the data traceability and the uncertainty calculation and to improve operational and maintenance procedures*". The guidelines for drafting updated editions of the CIMO guide (2008) recommend that "*the new version of CIMO Guide should describe or reference well-documented comparisons or evaluation of instruments*". However, there is no specific protocol for the comparisons and the relevant uncertainty evaluation.

Terrestrial variables. GCOS reported: "*Measurement and reporting standards are emerging, but further work is needed to prepare and publish definitive reporting standards. Upscaling techniques for research sites and permafrost networks, initially on upgraded reference sites, are required to complement active layer and thermal observing networks with monitoring of active geological processes*". In addition, permafrost temperature and albedo are included in the minimum group of terrestrial variables that are required to detect climate change in the *GCOS/*GTOS plan for terrestrial climate-related observations.

Permafrost is a relevant parameter because "*thermal conditions within permafrost at high altitudes are closely linked to changes in atmospheric and surface conditions. Due to the important memory and filter function as well as the long timescales involved with heat conduction in the virtually impermeable ground, a recent warming of near-surface temperatures in permafrost constitutes a key signal of climate change impact with foreseeable long-term effects*"[8]. In addition, permafrost temperature and thickness are key components for validating hydroclimatic models, land surface models, and climatic change models.

The boreholes drilled in the permafrost need to be equipped with thermal probes to permanently measure the temperature at different depths. The probes are generally PT 100 and/or PT 1000 with a required accuracy of 0.1 °C for near-surface temperatures and from 0.05 °C to 0.1 °C for the temperature profiles. In particular, measurement accuracy is necessary for the neighbourhood of 0 °C, to evaluate thermal-cycles' occurrence and frequency. However, there are few or none measurement procedures or investigations reporting a detailed uncertainty budget. Therefore, it is necessary to establish best practices for sensor calibration, measurement methods, and the evaluation of the calibration and measurement uncertainties. This can be achieved by a laboratory facility to perform a comparison of the different methods used to measure the permafrost temperature.

To address the above challenges, the following objectives were set for this project:

1. <u>Air</u>

To improve the accuracy and traceability of humidity and temperature measurements in air

- Development of metrological procedures to calibrate radiosondes under atmospheric conditions including reduced pressures and temperatures.
- Measurement of humidity enhancement factors under atmospheric conditions.
- Development of spectroscopic techniques as standards for traceable humidity measurements and on-site references.
- Development of a traceable humidity source capable to provide on-site calibration to airborne instruments.
- Development of a reference instrument for the measurement of fast transients of temperature and humidity in free space.

[8] Global Climate Observing System: GCOS/GTOS Plan for terrestrial climate-related observations, Version 2.0. GCOS-32, WMO/TD-No.796, UNEP/DEIA/TR97-7

- Development of traceable humidity sensors based on microwave resonators with low response time and small size.

2. Sea

To improve the accuracy and traceability of temperature measurements in oceans

- Development of facilities to study the pressure dependence of deep-sea thermometers and to establish validated pressure-correction models.
- To perform a thermodynamic calibration of deep-sea thermometers, to analyse the temperature-resistance linearisation models, to define the uncertainties or to propose improved models.
- Development of temperature sensors distributed along optical fibres by means of Bragg-gratings to improve the traceability of sea-surface and sea-profile temperature measurements and to monitor temperature drifts of the thermometers in underwater observatories.

To improve the accuracy and traceability of salinity measurements in oceans

- Development of a facility for determining temperature and pressure effects on salinometers based on the measurement of the seawater refraction index and to characterise them metrologically.

3. Land

To improve the accuracy and traceability of temperature and humidity measurements in ground level measurements

- Analysis of the siting influence on air temperature measurements in terms of uncertainty components.
- Determination of the influence of rain and snow albedo on air temperature measurements.
- To evaluate the intrinsic behaviour of thermometers and humidity sensors plus radiation shields to define calibration procedures and methods to evaluate the measurement and calibration uncertainties with the aim of improving ISO Guide 17714:2007.
- To ensure consistency and coherence of meteorological measurements carried out in different places.
- Development of procedures for traceable dynamic calibrations and uncertainty calculation of hygrometers used to measure the humidity near the Earth surface.
- Development of a humidity generator capable of fast step changes to study the response of air-humidity sensors to fast humidity changes.
- To identify the needs of traceability and uncertainty calculation of soil moisture measurements and to carry out initial experimental trials of the relevant procedures.
- Analysis of drift of weather-station hygrometers and its impact on uncertainty applicable to meteorological humidity datasets.

3 Research results

3.1 Air

The project advanced detection techniques for the in-situ monitoring and quantification of ECVs in the upper atmosphere. Calibration facilities and procedures were developed in the relevant ranges and also for the extreme ECV values. Traceability was established and the instruments' contribution to the measurement uncertainty was evaluated, together with robust thermodynamic investigations of the thermal aspects of the measurements.

Objective 1: Calibration of radiosondes under atmospheric conditions

Radiosondes provide a method to measure the vertical humidity profile in the troposphere and lower stratosphere, which is vital for weather forecasts and climate change monitoring. Specific challenges include i) insolation, ii) wetting of the sensors, and iii) slow drying of the sensors.

The project developed calibration facilities for water-vapour radiosondes in the [0.03, 1.5] μmol/mol interval. The pressure and temperature lower limits are 10 hPa and –95 °C. These limits allow the conditions met during the ascent in the troposphere and lower stratosphere to be simulated. The mixing ratio uncertainty is better than 2% (better than 0.5% in elected ranges). This facility is the first example of a primary standard able to work at pressures well below the ambient one (down to 10 hPa) and in a wide frost-point temperature range (–20 °C to –95 °C). It is thus capable to provide traceability in real upper-air conditions.

To improve the quality of upper-air humidity data, the GCOS specified a challenging uncertainty requirement for the humidity measurements (2% in the water vapour mixing ratio). The traceability to the SI is an essential requirement to achieve this targeted uncertainty. To enable SI-traceable calibrations at the upper-air environmental conditions, a new humidity calibration facility was developed by the Centre for Metrology VTT at the VTT Technical Research Centre of Finland. In this facility, a humidity radiosonde probe can be calibrated at air temperature from –80 °C to 20 °C, dew/frost-point temperature from –90 °C to 10 °C and absolute air pressure from atmospheric pressure down to 10 hPa corresponding to an altitude of approximately 30 km. It has been necessary to reduce stabilisation time in the measurement chamber to enable an acceptable calibration duration. This was achieved by an appropriate design of the measurement chamber and by applying flow mixing in a two-saturator humidity control setup, as illustrated in Fig. 1. The apparatus was fully characterised at a surface pressure level and the uncertainty analysis showed that the targeted uncertainty is achieved.

A highly accurate humidity calibration facility was also realised at INRIM (see Fig. 2), where a humidity probe can be calibrated at varying air temperature between –50 °C and +20 °C, frost point temperature between –95 °C and –20 °C, and pressure between 200 hPa and 1100 hPa. The apparatus was fully characterised down to –75 °C and down to 200 hPa, achieving an uncertainty in humidity measurements of better than 0.5 %, thus meeting the target GCOS uncertainty. The characterisation below -75 °C in all the pressure range will be completed in the near future.

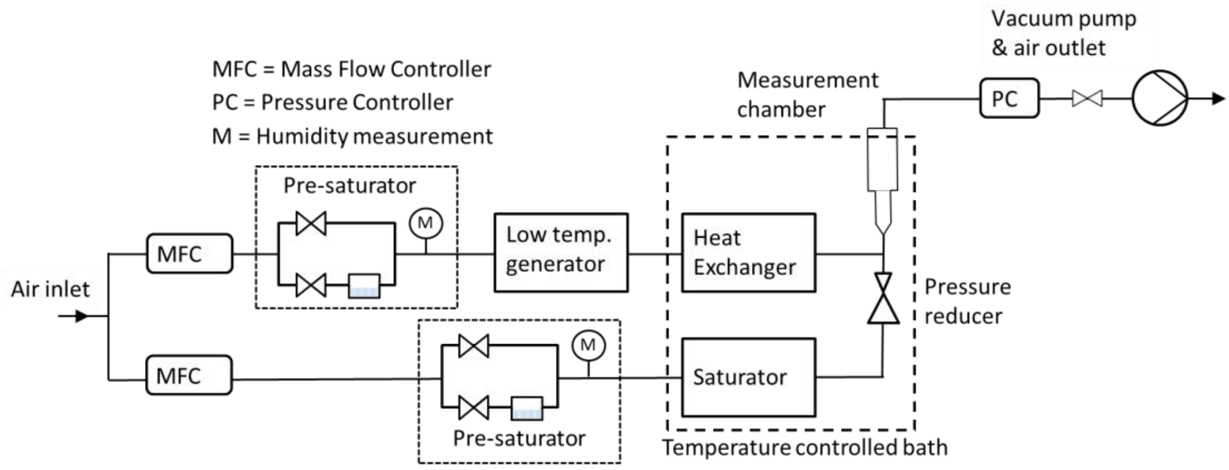


Figure 1. *Schematic diagram of the facility developed by VTT for the humidity calibrations of radiosondes.*

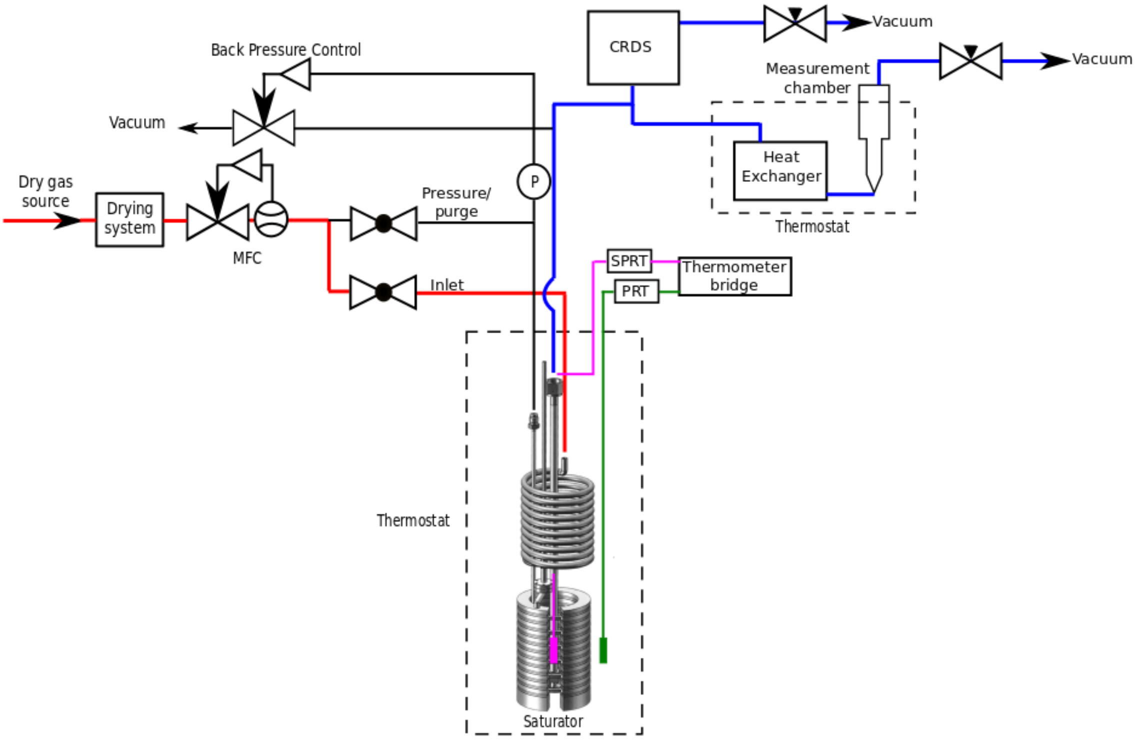


__Figure 2__. Schematic diagram of the facility developed by INRIM for the humidity calibrations of radiosondes.

Objective 2: Measurement of the enhancement factor under atmospheric conditions
The project measured the enhancement factor under atmospheric conditions. For this purpose, the project developed a humid-air generator which is capable of reproducing the atmospheric conditions from the troposphere to the tropopause, i.e., pressures from 101325 Pa to 40000 Pa and humidities from 300 ppmv to 1 ppmv. The mixing ratio of water in air is based on the evaporation/dilution principle.

CETIAT completed a literature review to identify pros and cons of different experimental set-ups to measure the enhancement factor. Two methods are generally used: i) the direct measurement of the second virial coefficient and ii) the indirect measurement of the humidity. Studies were carried out to identify the method that is most synergic with other measurements. The indirect method was chosen and a measurement facility was designed. It mixes dry air and evaporated water at a well-controlled flow rate and operates at low humidity and low pressure. The measurement is based on a single saturation isotherm. It uses a single-pass constant-flow dew-point generator and/or a mixing generator dry air and evaporated water at a controlled flow rate. The dew point temperature range is from –60 °C to 10 °C, the pressure range is from 400 hPa to 1000 hPa.

Objective 3: On-site calibration of airborne instruments.
The project realised: i) a portable instrument for on-site calibration of airborne instruments with uncertainty in the [1, 20] ppmv interval; ii) a mobile, compact, and robust water vapour generator, which uses water permeation through air-purged plastic tubing, was developed and manufactured; iii) a calibration facility for airborne upper air reference instruments capable of the following uncertainties: frost point temperature, in the range [–95, –20] °C, from 0.06 °C to 0.03 °C; water vapour amount fraction, in the [30, 1] mmol/mol range, from 1.2% to 0.6%.

INRIM developed a calibration facility for airborne upper air reference instruments. Functionality was tested in the frost point temperature range from –95 °C to –20 °C and pressures from 200 hPa to 1100 hPa. A preliminary computed fluid dynamics analysis was used to validate the saturator design and pinpoint the actual temperature and pressure ranges and flow control rate. The system is accommodated in a high-stability calibration cryostat, where a coil heat-exchanger is stacked over the ice saturator unit to enhance the heat transfer mechanism of the dry gas and to improve the gas saturation along the sublimation line. The uncertainty of the generated water mole fraction and frost point temperature were evaluated. The uncertainties (combined uncertainty, k=2) are frost point temperature, in the range [–95, –20] °C, from 0.06 °C to 0.03 °C; water vapour amount fraction, in the [30, 1] mmol/mol range, from 1.2% to 0.6%.

Objective 4: Measurement of fast transients of temperature and humidity.
NPL completed a fast-responding version of a non-contact thermometer and hygrometer (NCTAH), for response-time testing of temperature and humidity sensors. Signal sampling (30 Hz) and processing (including cross corrections of temperature and humidity values in real time) of temperature and humidity are fully integrated into the instrument. The instrument has been demonstrated in the temperature range from −40 °C to 40 °C and dew point range of −43 °C to 38 °C, including comparisons against conventional (slower-responding) instruments. It is capable of 2 Hz bandwidth, 0.01 °C resolution, 0.1 °C uncertainty, measurement of water vapour mixing ratios from 100 ppmv to 3E4 ppmv (corresponding to dew points from −42 °C to 24 °C at 1E5 Pa).

Objective 5: Development of spectroscopic techniques as standards for traceable humidity measurements and on-site references.
The project realised a fast direct tuneable diode laser absorption spectrometer (dTDLAS). It combines scanning units with retro-reflective mirrors. dTDLAS was identified as metrologically sound ground reference. H_2O-permeation through the plastic tube was studied for what concerns: material optimisation, H_2O concentration, tube dimensions, temperature, ageing, and accelerated averaging. Besides covering a measurement area of (0.8 x 0.8) m^2, it achieves measurement rates of 2.5 Hz. It is capable of error less than 6 % of the absolute concentration and 1.1 ppmv m^{-1} $Hz^{-1/2}$ length and bandwidth normalised detection limit.

Objective 6: Development of traceable humidity sensors based on microwave resonators with low response time and small size.
The project realised a prototype of a fast airborne microwave hygrometer (volume 200 cm^3) operating from –50 °C to 10 °C (frost point temperature) and from –20 °C to 20 °C (dew point temperature). The measurement range is from 3 ppmv to 10^5 ppmv and the uncertainty of measurement is close to 1 ppmv. However, the measurement time is about 100 seconds, which is considered too long for the purpose, primarily because a long sampling tube was used.
A second prototype was realised (volume 30 cm^3) operating from –50 °C to 10 °C (frost point temperature) and from –20 °C to 20 °C (dew point temperature). The measurement range is from 3 ppmv to 105 ppmv, the uncertainty is close to 1 ppmv. Both microwave hygrometers were compared with a CETIAT calibrated chilled-mirror hygrometer; the results showed that it might be an alternative standard for humidity measurements (see Fig. 3).

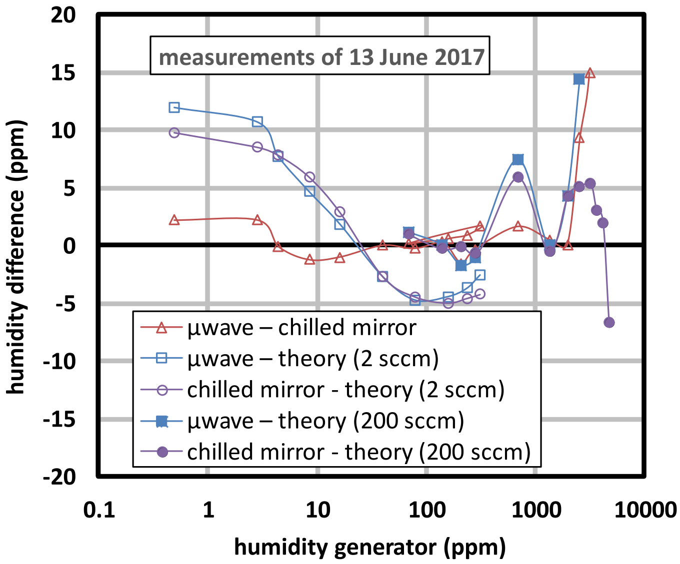


***Figure 3**. Comparison between the uncalibrated microwave hygrometer developed at CNAM and a calibrated chilled mirror hygrometer supplied by CETIAT (µwave – chilled mirror). sccm = standard cubic centimeters. The picture shows also comparisons of the microwave hygrometer and the chilled mirror with theoretical predictions.*

3.2 Sea

The project developed new tools to reduce the measurement uncertainty on oceanic temperature and salinity, employed in thermodynamic models to determine the heat flux carried by seawater and the consequent effects on the climate. This project studied i) the temperature-resistance linearisation by calibrating the sensors at several thermodynamic temperatures and ii) the pressure dependence of the most widespread deep-sea thermometer. These studies improved the quality and the traceability of deep-ocean temperature measurements and contributed to the reduction of the measurement uncertainties.

Objective 7: Pressure dependence of deep-sea thermometers

The project realised a facility to compare deep-sea thermometers in a high-pressure chamber available at NIOZ (Royal Netherlands Institute for Sea Research). The measured pressure dependence of Sea-Bird Electronics thermistors (the biggest manufacturer and supplier of oceanographic thermometers) at 500 bar (–0.30 mK / 100 bar) confirmed the values observed in the sea (from –0.17 to –0.33 mK / 100 bar) and the proper operation of the facility. A 100 bar pressure corresponds to a depth of approximately 1000 meters.

Objective 8: Thermodynamic calibration of deep-sea thermometers

The CNAM modified an acoustic gas thermometer and the associated calorimeter, in order to integrate and calibrate the deep ocean thermometers from –5 °C to 35 °C, within a calibration uncertainty below 0.5 mK. Previously, the best achievable calibration uncertainties on high-grade deep ocean thermometers were close to 2 mK. They might be further reduced to meet the target overall uncertainty of 2 mK in deep ocean temperature measurements, required by the World Ocean Circulation Experiment (WOCE) Hydrographic Program[9]. Measurements are currently in progress at CNAM to evaluate the suitability of the most common high-grade deep ocean thermometers for such reduced uncertainty.

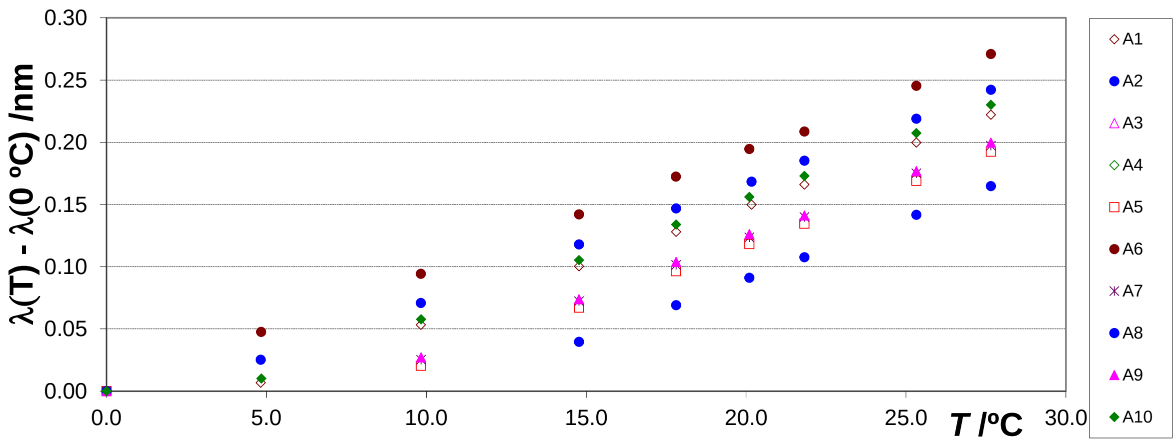
[9] World Climate Research Programme (WCRP), Scientific plan for the World Ocean Circulation Experiment, WMO/TD-No. 122, July 1986. https://www.nodc.noaa.gov/woce/wdiu/wocedocs/sciplan/sciplan.pdf

Objective 9: Test and calibration facility for refractive-index salinometers

To make accurate, in-situ, and absolute salinity-measurements, the European projects NAOS (Novel Argo Ocean Observing System, a Copernicus project to consolidate and improve the French contribution to the international Argo observing system and to prepare the next scientific challenges for in-situ monitoring of the world ocean) and NOSATS developed an absolute salinometer based on the refractive index of seawater. The project characterised this instrument metrologically as a necessary aid to its commercial deployment.

Objective 10: Distributed temperature sensors based on optical fibre Bragg gratings

To improve the traceability of the sea-surface and sea-profile temperature measurements, optical fibres based on Bragg grating were designed, realised, tested, and characterised as distributed temperature sensors by CEM, CSIC and UPC. They consist of several Bragg gratings recorded along the optical fibres (single mode SM-ITU652 coated with acrylate). One fibre had 3 measurement points, the other one has 10. To protect the fibres from the corrosive environment of seawater, the fibres are placed inside a ¼" x 0.35 mm wall thickness, 316L stainless steel tube. The final encapsulation was done with a layer of polypropylene/PEEK with resistance to seawater. The fibres were optically tested and calibrated as thermometers. Due to their dimensions, a large calibration bath was designed, assembled, and characterised. The bath shows a stability and uniformity of 35 mK in the calibration range. A calibration procedure was developed with a complete calibration uncertainty model. The calibration result of one assembled fibre optic is shown in Fig. 4, where a linear increase of wavelength with temperature is displayed for each one of the Fibre gratings. The optical fibres were deployed in the OBSEA underwater observatory (Vilanova i la Geltrú, Barcelona, Spain), where the seawater temperature profile and the surface temperature were measured (Fig. 5) and monitored during 3 months. The results showed that the fibre Bragg gratings are suitable to measure the sea temperature, but they must be improved to reduce the measurement uncertainties.



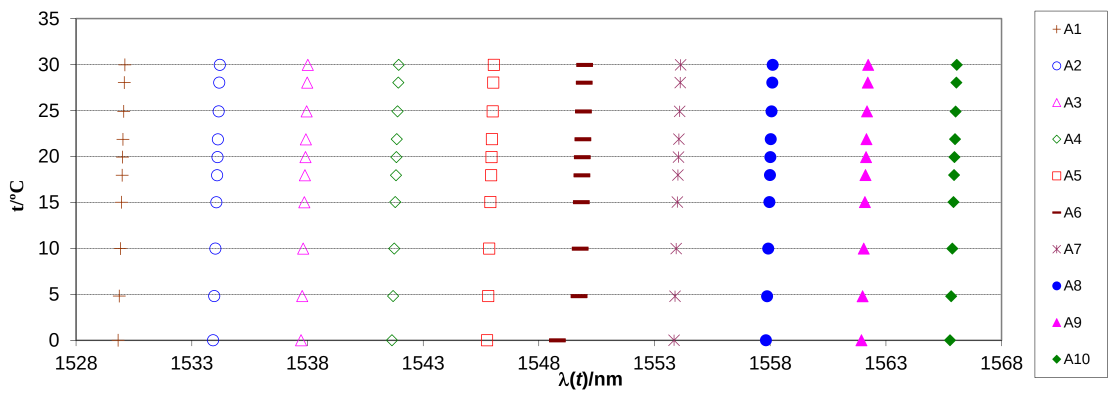


Figure 4. *Calibration results of the fibre Bragg grating calibrated as a thermometer.*

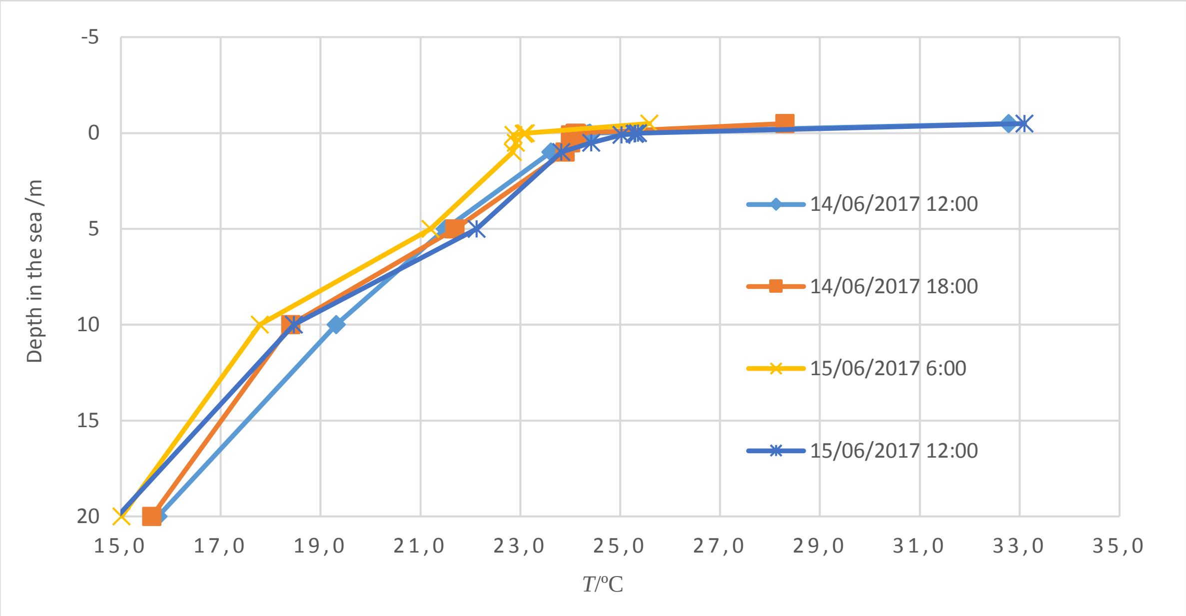


Figure 5. *Seawater profile and sea surface temperature measured by optical fibers*

3.3 Land

Since "*Environmental conditions of a site may generate measurement errors exceeding the tolerances envisaged for instruments […]. It is often environmental conditions that distort results, influencing their representativeness*"[10], moving from the uncertainty contributions studied in the EMRP ENV07 project MeteoMet, the project MeteoMet2 deeply studied the intrinsic characteristics of the sensors and the effect of the influence factors, like the siting and reflected sun radiation and rain.

The project provided traceable procedures for sensor calibration, sensor characterisation, and measurements of some terrestrial (albedo, permafrost and soil moisture) and surface (air temperature, water vapour and precipitation) ECVs defined by GCOS, with a consistent, realistic and reliable uncertainty calculation.

Objective 11: Influence of siting, radiation shield, rain, and albedo on air temperature and humidity measurements

Starting with the study of the intrinsic behaviour of the thermometers, self-heating, hysteresis, and response time of a set of thermometers used for meteorological and climate applications were evaluated. The effect of the self-heating in resistance thermometers was found to be from 0.04 ºC to 0.4 ºC (depending on the thermometer design and environmental conditions), for electrical currents of 1 mA and 3 mA, respectively, and with the thermometer surrounded by air. The effect of hysteresis was 0.02 ºC to 0.04 ºC, depending on the thermometer design, in the temperature interval 10 - 50 °C.

Two methods were applied in the study of the hysteresis. In the first one, the thermometers were exposed to a temperature cycle ranging from 10 ºC to 50 ºC (Fig. 6). Readings were taken at several intermediate temperatures. In the second, the thermometers were checked at the ice melting point of water after exposure to 10 ºC and 50 ºC. For each extreme temperature, measurements were performed 5 times (Fig. 6). From Figs. 6 and 7, it can be deduced that the results have similar values.

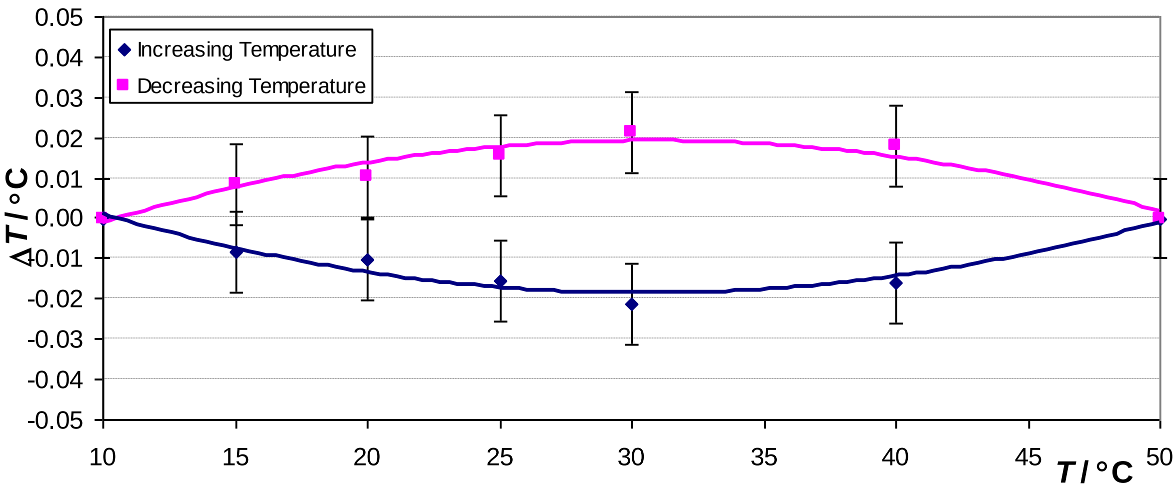


Figure 6. *Hysteresis of a Pt100 measured in a stirred liquid bath. Complete cycle (10 ºC and 50 °C).*

[10] CIMO Secretary-General, CIMO-XV/Doc. 4: Instruments and methods of observation for surface measurements; surface observation technology (opag-surface) September 2010, Helsinki, Finland

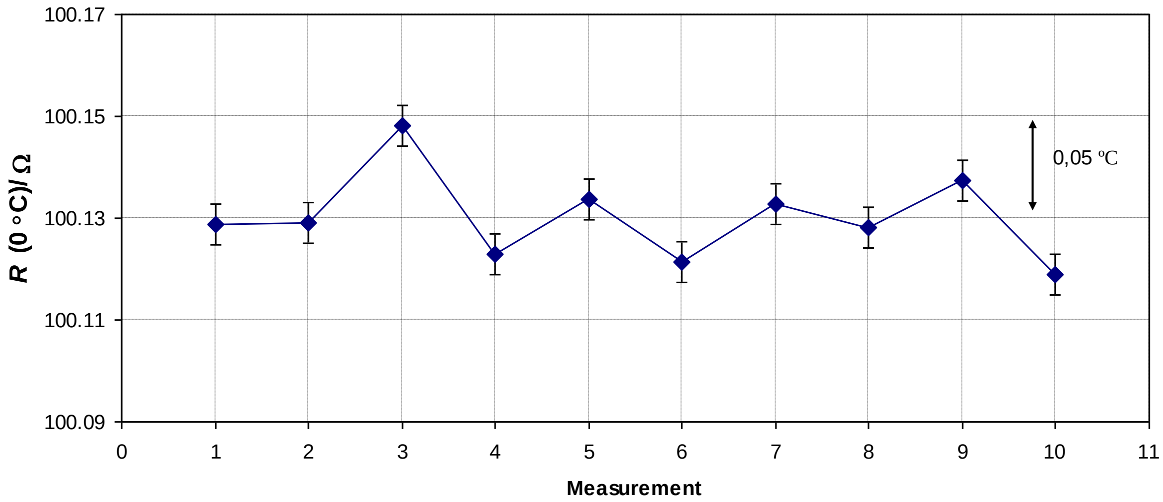


Figure 7. *Hysteresis of a Pt100 measured in an ice bath, after exposure to extreme temperatures (–60 ºC and 50 ºC)*

The World Meteorological Organisation-Commission for Instruments and Methods of Observations (WMO-CIMO) Guide 8 establishes a classification to determine the small-scale representativeness of the ground-based observation sites. This classification associates a discrete uncertainty to the temperature measurements carried out in sites where exposure rules are not fully met. The project quantified the uncertainty associated with some of the site influences: closeness to trees, buildings, and asphalt roads. INRiM defined a protocol to study the influence of such obstacles on surface-based air temperature measurements that received positive feedback from the WMO Expert Team on In-situ Operational Technologies. Three in-field experiments were carried out. In Italy, an experiment evaluated the influence of roads; in the Czech Republic the influence of trees; in Spain, that of buildings. The experiments were based on identical setup and measurement protocols; the temperature was measured close to the obstacles and in seven measuring points up to 100 m of distance in the open field (see Fig. 7). The results provided to the WMO CIMO Expert team inputs to revise the prescriptions of the CIMO guide.

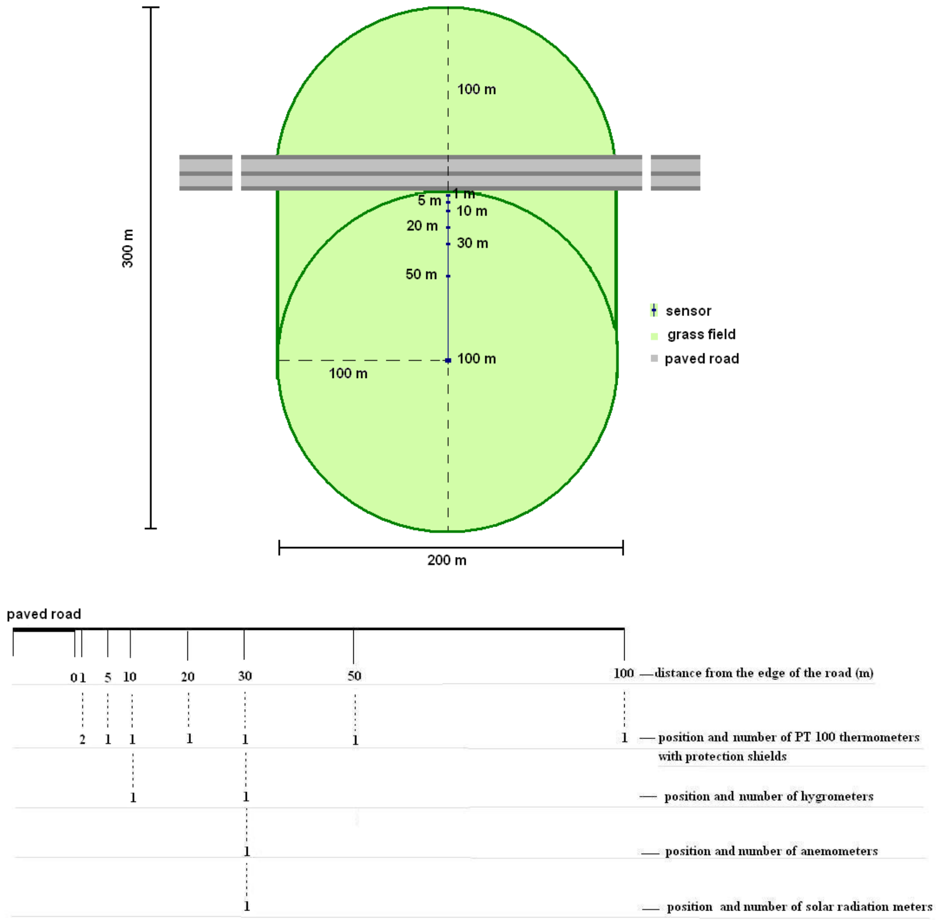


Figure 8. *Setup of the three experiments carried to evaluate the influence of obstacles in the vicinity of automatic weather stations.*

Operators of weather stations, in presence of snow below the measuring area, normally observe a rise in the temperature readings during sunny days. A part of this phenomenon is the warming of the air due to the heat diffused by the reflected radiation, the albedo from the snow-covered surface. This is not the subject of this study since it is a part of the meteorological measurand. Another component, the overheating of the sensor by the radiation reflected from the snow-covered surface, is not part of the measurand. This effect is strongly dependent on the geometry and characteristics of the shield and sensor and can affect the measurement up to more than a degree Celsius. INRiM and BEV identified a mountain site where to investigate this effect. Five pairs of shielded temperature sensors, with both naturally aspirated and mechanically ventilated, were used to ensure a representative group of devices. Tests were performed to evaluate the "zero" difference between each pair, as well as the necessary corrections and the relevant uncertainties. The results confirm the validity of the methodologies for the correction calculation.

a

b

Figure 9. *A field experiment to evaluate the effect of reflected radiation from the snow-covered surface on near-surface air temperature measurements. a) Field setup with both positions above the snow, b) snow removed from above one of the two identical instrument setups.*

On-site comparisons of solar shields by parallel observations of six pairs of instruments exposed and not-exposed to snow albedo showed a maximum temperature difference between couples of identical instruments of 3 °C; the uncertainty of the temperature differences, evaluated in field conditions, is 0.3 °C (k=2). The contribution of the snow albedo to the uncertainty of near ground air temperature measurements was estimated to be 1.73 °C (k=2). These results led to recommendations addressed to the end users and to manufacturers of atmospheric temperature sensors.

The thermometers used for meteorological measurements are normally housed in solar shields to avoid direct sun radiation. Besides the direct solar radiation, other effects can cause deviations of the measurement results from the air temperature. While the effect due to the ageing of the solar shields and the associated decrease of the reflecting properties of the white painting was investigated in the previous project MeteoMet1, this project quantified the effects of rain, in order to include the relevant component in the uncertainty budget of the temperature measurement.

The standard ISO 17714:2007, recommends test methods for characterising thermometers together their radiation shield. The rainfall is recognised in this documentary standard as an "Influence factors". It says: "*Another effect is that the temperature of the precipitation is that the temperature of the precipitation is generally lower than the temperature of the air…This can suddenly cool the screen at a different rate than the air (up to 5 K in 5 min)"*. The project brought contributions to improve this guide, submitted them to WMO expert team for further discussion and submission to the ISO. It developed procedures to determine the response time, self-heating, and hysteresis of air temperature sensors and the influence of the associated solar-radiation shields on these determinations. A physical model was developed to derive deriving corrections (with the associated uncertainties) for existing shielded sensor and to update these corrections with the changes of the shield plus sensor configuration. The project studied the measurement error due to the overcooling of the thermometer screen due to the lower rain drop temperature with respect to the air temperature. This effect was assessed by an experiment generating raindrops at a known temperature in a volume with air temperature accurately measured.

Tap-water was cooled to a constant temperature by means of a plate heat-exchanger connected to a brine cooling system. The water temperature, between 6 °C and 14 °C and stable within ±1 K, was monitored using a Pt500 sensor. The flow rate was controlled by a manual control valve regulating the water supply pressure and checked with a flowmeter. The accumulated volume was measured with a mechanical flow meter. For practical reasons, the setup was built in a tarpaulin-covered outdoor shaft; therefore, the air temperature was not controlled. As the meteorological thermometers of different design were tested one at a time, measurements were made relative to reliable reference sensors. Four aspirated reference thermometers (designed and constructed at Danish Technological Institute) were positioned beside the device under test for measuring the true air temperature. The reference sensors were protected from being exposed directly to the rain.

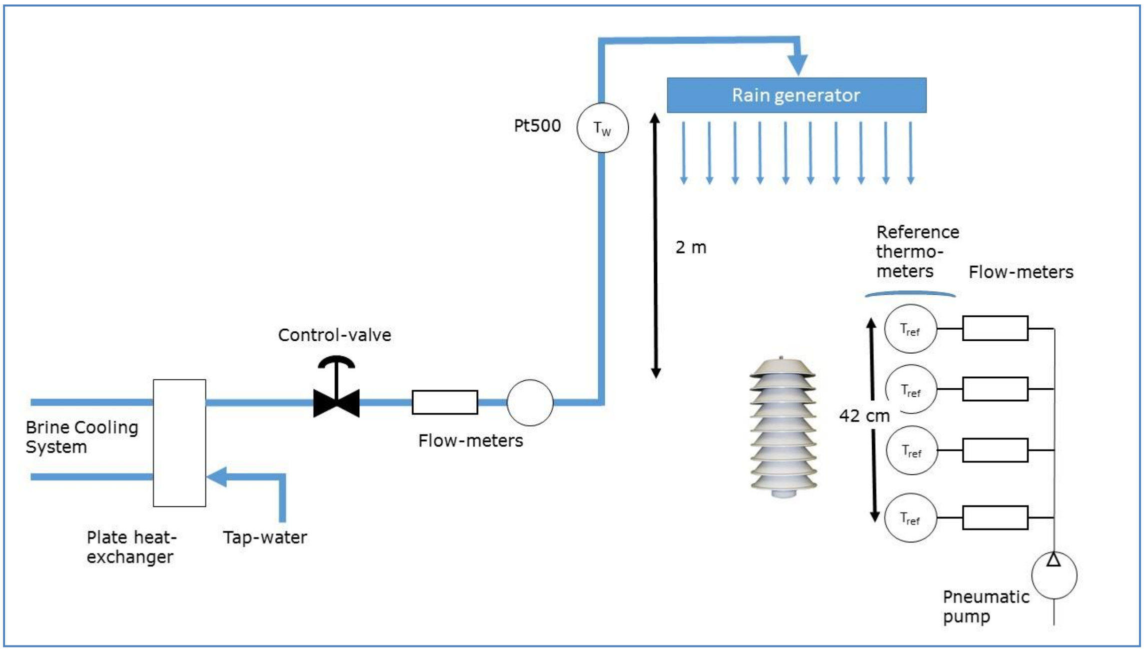


Figure 10. *Schematics of the set-up testing meteorological air-thermometers under the influence of rain.*

The experiment based on the creation of a rain simulation facility under temperature controlled conditions showed that the cold raindrops overcool the thermometer shields up to values well above the calibration uncertainty of the thermometers. Moreover, it was observed that the effect lasts for hours after the rain ends. Several tests were performed. They showed that, especially for naturally ventilated thermometers, the errors due to rainfall can be unacceptably large and the time before the thermometer is again in equilibrium might be very long. For the artificially ventilated air thermometers, the errors observed are less significant. The error and time constant depends on the difference between the rain and air temperatures and, in a lesser degree, on the rain intensity. Applying a correction is therefore not practical. Instead, standardised tests can be made to qualify the device with regards rainfall errors as a function of the rain intensity and temperature and how fast it recovers.

SMD modelled numerically the heat transfer inside and outside a radiation screen and the temperature measurement inside the radiation shield. Based on the model, the collaboration with RMG researcher from FSB allowed going further than initial objective. Combining numerically the heat and flow transfer and taking all the radiation modes shown in Fig. 11 into account was not possible till now due computer power limits. FSB researcher developed unique numerical approaches in order to overcome these limitations while keeping a true screen geometry into account (see the temperature simulation inside a Stevenson screen in Fig. 5). The numerical model allows changing the following input parameters: surrounding air (temperature and velocity), sun (irradiance and position), meteorological screen (design, materials and painting properties; emissivity and absorptivity), thermometer (design, material properties and position), and ground surface (temperature and properties; emissivity and absorptivity). The model has proven to be suitable for a detailed analysis of the influence of above parameters on the air temperature measurements. The error obtained for extreme conditions of low wind speed and high solar irradiation is in very good agreement with an assessment performed through experimental in-field comparisons of screens. Quantifying the errors is a step towards calculating real in-field measurement uncertainties. An example is given in table 1 for the case of a Stevenson screen, where the influence of painting condition, grass type, ground and air temperature, sun position, and sensor material are investigated in order to calculate a worst-case combined uncertainty in low wind and maximum sun conditions.

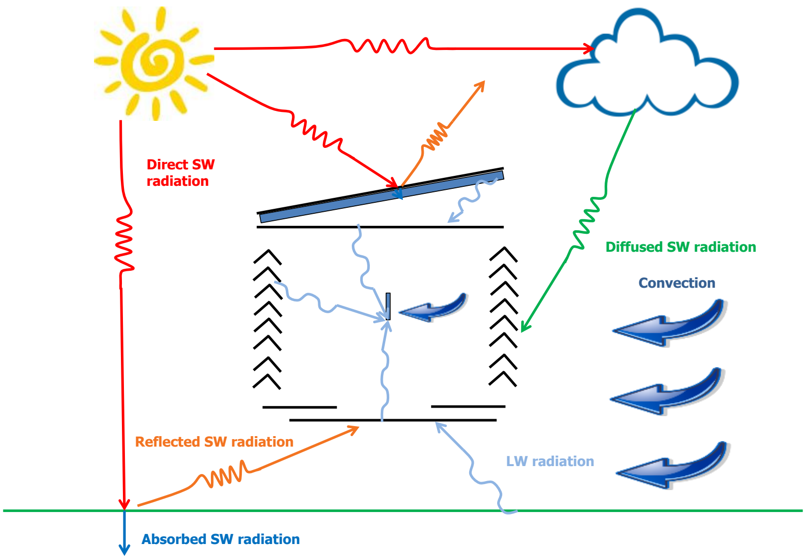


***Figure 11**. Heat transfer modes involved in modelling the measured temperature inside a meteorological screen.*

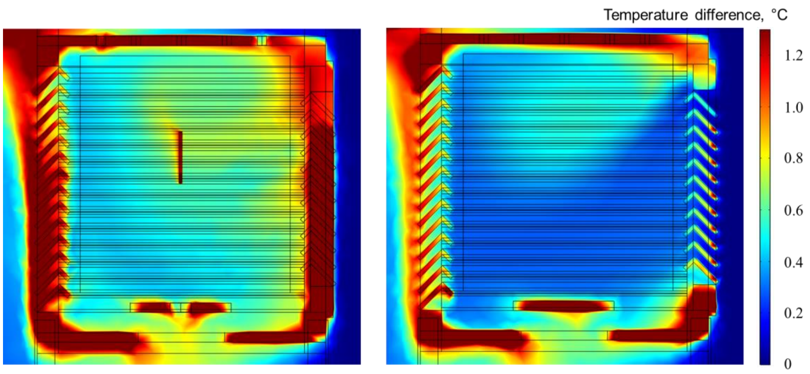


***Figure 12.** Numerical simulation of the temperature difference between the air inside a Stevenson radiation shield and the surrounding air. Left: the plane through the thermometer (behind the door frame). Right: the plane located 250 mm to the left of the thermometer (behind the door louvres).*

Table 1. Uncertainty contributions related to ambient parameters at low wind speed (1 m/s and high solar irradiation 1000 W/m^2)

Factor	Parameter	Range of parameter	Range of difference Tsensor-Tair °C	Uncertainty °C
Grass	Absorptivity	0.7 – 0.84	0.62	0.36
Paint	Absorptivity	0.2 – 0.45	0.09	0.05
Ground temperature	Temperature	10 – 20 °C	0.28	0.16
Air temperature	Temperature	10 – 20 °C	0.27	0.16
Sensor material	Copper, steel		0.24	0.14
Sun position	Hour	12:00 – 19:00	0.34	0.20
			Combined uncertainty	**0.49**

CEM elaborated a feasibility study about a future comparison of thermometers and radiation shields. This feasibility study was submitted to the WMO-CIMO expert team on instrument intercomparisons and it will be submitted to CIMO-MG for its inclusion as the future activity of CIMO. The comparison of thermometers and radiation shields would imply laboratory tests and on-site measurements and it will allow the development of transfer functions between different systems to measure air temperature, giving very valuable information to Climate community.

The effect of the snow albedo on near ground air-temperature measurements was investigated both theoretically and experimentally. On-site comparisons of solar shields by parallel observations of six pairs of instruments exposed and not exposed to the snow albedo showed a maximum temperature difference between pairs of identical thermometers of 3 °C; the uncertainty of the temperature differences, in field conditions, is 0.3 °C (k=2). The contribution of the snow albedo to the uncertainty of near ground air-temperature measurements was estimated to be 1.73 °C (k=2). These results led to recommendations addressed to the end users and manufacturers of the temperature sensors.

The project investigated the self-heating, hysteresis, and response time of thermometers. Self-heating takes values from 0.04 ºC to 0.4 ºC (depending on the thermometer design and environmental conditions), for electrical currents of 1 mA and 3 mA, respectively, and with the thermometer surrounded by air. As regards the hysteresis, it takes values from 0.02 ºC to 0.04 ºC, depending on the thermometer design, in the temperature interval [10, 50] °C.

Aiming at developing methods and procedures to ensure that automatic weather stations report data comparable and traceable to the SI, a protocol and a procedure for the interlaboratory comparison of in-field calibration laboratories of the National Meteorological and Hydrological Services (NMHS) of temperature, humidity, and pressure sensors was developed. Actually, the project went beyond the expected deliverable by running a full intercomparison campaign in WMO Region VI (Europe), extended to regions II (Asia) and V (South-West Pacific). In Europe, the intercomparison was participated by 17 laboratories, in two loops. The WMO made the protocol an official document of its CIMO. Next, an inter-laboratory comparison with two loops was organised, with 17 National meteorological agencies participating in the European Regional Associations (RA-VI). As regards temperature, out of 270 submitted results, three laboratories had 5 results with $|E\text{n}| > 1$. As regards relative humidity, out of 117 submitted results, only one laboratory had 5 results with $|E\text{n}| > 1$. As regards pressure, out of 784 submitted results, only three laboratories had results with $|E\text{n}| > 1$. It was recommended that all the laboratories with unsatisfactory results check their procedures for any potential systematic error, the traceability of their references and the uncertainty budget. Some of the uncertainties of the participating laboratories were on the level of the best national metrology laboratories. It is expected that the ILC will be extended also to other WMO regions outside Europe. First expressed interest was from RA-II and RA-V (Japan, Australia, Philippines, China).

Objective 12: Development of a humidity generator capable of fast steps to study the response of air-humidity sensors to fast humidity changes

Past studies barely investigated the dynamic response of hygrometers. Often, the manufacturers give an indication of the response time of the sensing element itself for a given temperature level. The response time at 63 %rh, or sometimes at 90 %rh, represents the time required to reach 63%, or 90%, of the final humidity value, in steady-state regime. In order to investigate the response time of hygrometers, CETIAT has developed a facility composed by a source of humid air, a source of dry air, a divider plate, and a testing chamber placed in a climatic chamber reaching low temperature (–60 °C), see Figs. 13 and 14. The divider plate is equipped with high-speed valves allowing a switch from one humidity to another in few hundreds of milliseconds. The climatic chamber enables a user to perform measurements at different temperatures. Two hygrometers, with and without shields, were tested with a chilled mirror instrument, an impedance hygrometer based on silicon oxide. PTB and CETIAT integrated an infrared cell, developed by PTB, and a test chamber, developed by CETIAT, and placed a highly accurate and high-speed reference instrument, e.g., based on Tunable Diode Laser Absorption Spectroscopy, as close as possible to the device under test. The spectrometer maximum sampling rate is 7 ms at water vapour concentrations from 500 ppmV to 5000 ppmV. Depending on the device under test, its distance from the spectrometers grid of laser beams is adjustable from 1 cm to 5 cm.

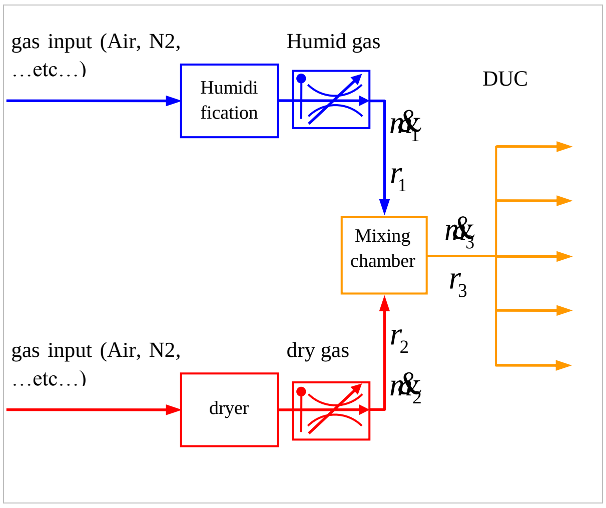


Figure 13. *Schematic drawing of humid air generator based on dilution principle*

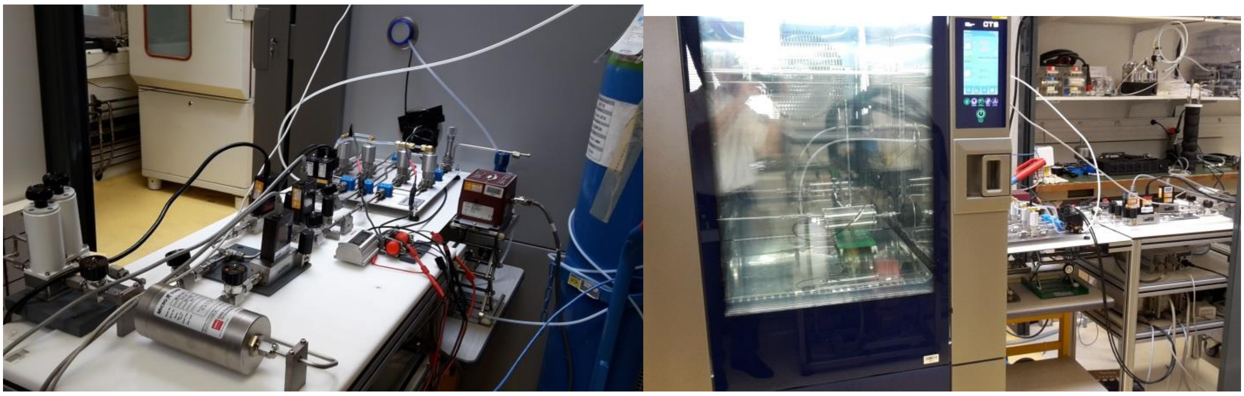


Figure 14. *Overview of the facility. From the left to the right, humid air generator, divider plate, climatic chamber with testing chamber*

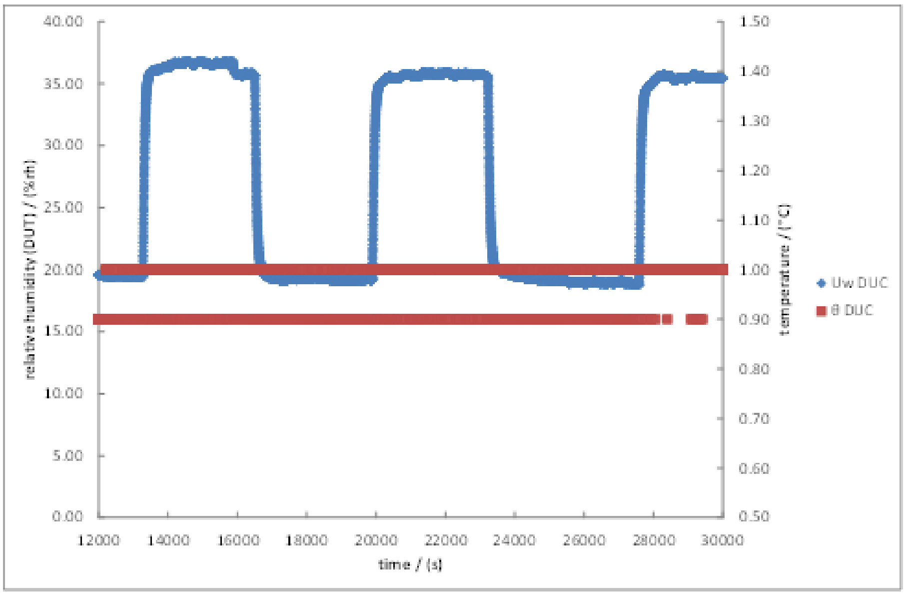


Figure 15. *Measured values of humidity and temperature.*

As shown in Fig. 8, the humidity steps are recorded together with temperature with a 1 Hz sampling frequency. The changes of humidity do not affect temperature stability, which remains within 0.1 °C. Thanks to the position transducer, it is possible to detect the time at which valves have commuted, that is, the time at which humidity has changed from one level to another.

Table 1 shows the results obtained for one hygrometer, equipped with its own filter, set at two different temperatures. For each temperature, the measurements were repeated three times. The measurements seem more reproducible at a higher temperature than at lower temperature. Nevertheless, the scattering could be also related to the filter surrounding the device under test or to the detection of the steady-state value. The response time decreases when the surrounding temperature or the humidity is higher

Table 1. *Results obtained for one hygrometer set at two different temperature levels*

	Temperature -10 °C	Temperature 10 °C
$t_{90\%}$ (s) increasing humidity	324 333 353	148 158 158
$t_{90\%}$ (s) decreasing humidity	364 380 374	199 192 204

Objective 13: High mountains observations: permafrost and albedo

INRIM completed three in-situ calibration campaigns: two at the arctic research station in Ny-Ålesund (Svalbard) in May and September 2017 and one in a high mountain alpine site at 3000 m of altitude. The arctic activities involved the transportation and installation of a special chamber developed by the MeteoMet ENV07 project, a liquid thermostat, and travelling standards of pressure and temperature. These systems were installed in Ny-Ålesund, in cooperation with the ISAC-CNR. In May 2017, these systems were used for the calibration of the sensors installed in the “Climate Change Tower” and used to measure pressure and vertical temperature profiles from ground to 30 m. In September 2017, the system was involved in the calibration of soil and permafrost temperature sensors installed in Ny-Ålesund.

Figure 16. *Dismantling sensors at the Climate Change tower of ISAC-CNR in Ny-Ålesund*

Figure 17, *A calibration laboratory at 3000 m of altitude at the Sommeiller pass, for the calibration of permafrost sensors chains.*

In August 2017 the third on-site campaign was carried out, in cooperation with ARPA Piemonte. A "calibration camp" was installed at 3000 m altitude based on a liquid thermostat, an electric generator, travelling standards PT100, and a resistance bridge. The campaign involved the calibration of thermometers used to measure the temperature profiles in permafrost boreholes. A total of 14 sensors, inserted in two boreholes of 10 m and 100 m depth, were calibrated. Two reasons motivated the on-site campaign: the difficulties in the removal of the cables and data logging equipment and the need to keep the data logger in the same environmental conditions, to improve the representativeness of the calibration uncertainty with respect to the measurement uncertainty.

The dynamic temperature response of permafrost sensors from different manufacturers, types, and constructions is a matter of some interest. Permafrost temperature measurements are currently reported without associated uncertainties, making it difficult to evaluate this information in metrological terms. Therefore, knowing the dynamic response of the sensor is relevant to complete the uncertainty budget. Sensor dynamic gives to the user a valuable information, which affects the choice of the frequency of recording. Overestimating or underestimating the recording times can affect temperature measurements in such a way that the daily maximum and minimum values likely to be unrecorded.

Four types of sensors were tested in laboratory conditions. The dynamic response was tested by exposition to a shock temperature change from –30 °C to 30 °C and from 30 °C to –30 °C. The test was performed in air, with no ventilation, to represent the measurement conditions in the permafrost boreholes. The temperature shock was applied after their indicated temperature was stable for at least 10 min. Then, the equilibrium time was measured together with the behaviour of the sensors reading (a minimum of five runs were performed). The temperature conditions were monitored by a calibrated reference Pt resistance thermometer. The thermal shock was also applied in reverse, to see if there was any difference in the response time. Fig. 14 shows a typical result. It can be observed how fast the sensor achieves equilibrium and the typical curve of sensors output. In general, a steeper curve is preferred, meaning a short equilibrium time.

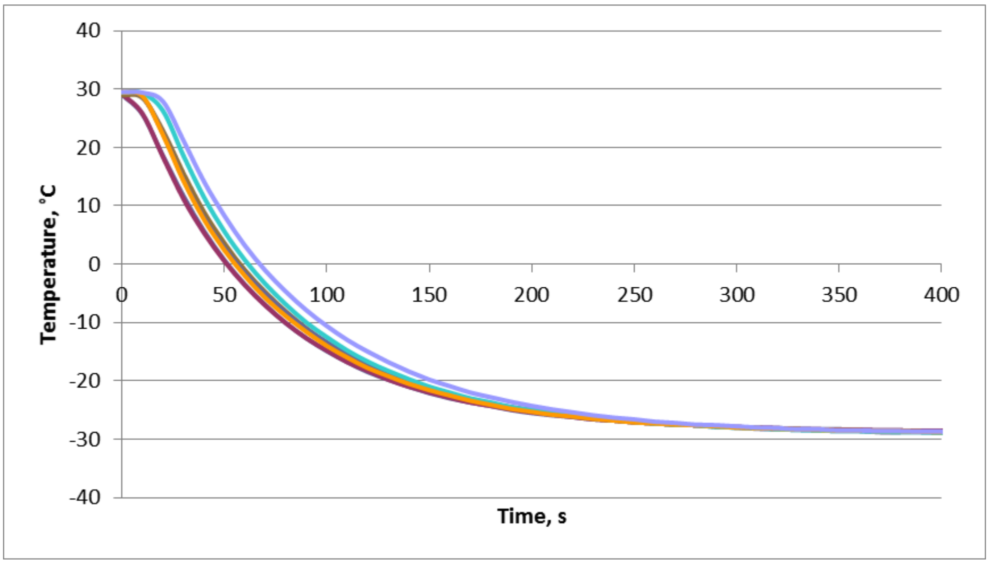


Figure 18. *Repeated permafrost sensors (marked - M) reaction to thermal shocks generated by a rapid temperature drop from 30 °C to –30 °C. This curve can be used to include the sensors response time in the uncertainty budget, by also taking the sampling frequency into account.*

Objective 14: Precipitation and metrological requirements for traceable measurements of soil moisture

UniGe analysed a typical calibration system for tipping-bucket rain gauges (TBRGs), using the gravimetric method, in accordance with the recommendations and requirements of both meteorology and metrology. As a result, there were identified two major contributions of the type B uncertainty in the calibration of TBRGs: the weighing system calibration (1.68 %) and resolution (0.74 %). Rounding off errors in the conversion from inches to millimetres were also observed. The 1 mm uncertainty of the measurement of the collector diameter results in a 0.58 % contribution to the calibration uncertainty.

The NPL performed a survey of the measurements and the needs of calibration of soil moisture measurements. The questionnaire addressed applications of soil moisture measurements, measurement techniques, and calibration methods (classical gravimetric method and remote sensing techniques). VTT was involved with steering the planning and realising the survey and used the outcomes to improve the traceability of soil moisture sensors. The survey is still open online and more answers can be collected. TUBITAK realised a soil moisture measurement set-up based on a gravimetric method and using a moisture analyser, a high precision balance, a desiccator, and an oven supplemented with a rotary pump. It turned out that there are a number of issues with the calibration: the soil used for calibration that may not represent the characteristics of the soil to be measured. The calibration is also affected by soil temperature, barometric pressure, salts and air gaps in the soil as well as the bulk density of the soil.

Objective 15: Analysis of drift of weather-station hygrometers and its impact on uncertainty applicable to meteorological humidity datasets.

The datasets of weather-station hygrometer calibrations from 2012 to 2014 of the United Kingdom's national weather service were analysed to make estimates of hygrometer drift and of the drift impact on bias and uncertainty of climate data. Sensors returned from use had typical drift (mean values) of up to +4 %rh, with a high scatter (standard deviation) of up to 4 %rh. This shows precautions are necessary when interpreting observations and estimating the associated uncertainty, particularly at high relative humidity.

4 Actual and potential impact

Dissemination and stakeholder engagement

The project was organised in such a way as to achieve an appropriate balance between the science and dissemination. Dissemination and impact were mainly achieved through the existing collaborations established during the lifetime of the previous project EMRP ENV07 MeteoMet, and new stakeholders were identified and co-opted in the lifetime of the project. The consortium has given 85 presentations at international conferences and has published 27 papers in peer-reviewed scientific journals. The project promoted, launched and organised the series of International Conferences on "Metrology for Meteorology and climate" (MMC-2014-2017-2019) which is now recognised worldwide as a reference event. The consortium carried out 13 upgrading and training classes (targeted to stakeholders and environmental agencies) on the humidity measurement and calibration, the reliability of humidity and moisture measurements, metrology for meteorology and climatology, general and thermal metrology for the environment, metrology for radiosondes of interest for the GRUAN and temperature measurement and calibration.

The meteorological community GRUAN, WMO CIMO[11], WMO CCl[12], and ISTI were regularly updated on the project results by direct involvement in research activities, by in-person meetings and teleconferences. The membership of the project coordinator and other project participants in WMO Expert Teams allowed the WMO to address the project work and to uptake the results:

The project representative delivered to the WMO CIMO expert team on *instrument intercomparisons* a proposal for a comparison of thermometers and radiation shields. This proposal is now under feasibility study and drafting to become a CIMO commission action for future comparisons.

The results of the siting and albedo experiments were presented and regularly reported by the project coordinator to the WMO CIMO expert team on *instrument intercomparisons*. The results of the siting experiments are being included in the revision of the CIMO guide. The project deliverables are also being used for the revision of the "Sustained Performance Classification for Surface Observing Stations on Land.

The problems of the measurement accuracy of the air temperature and a potential solution in terms of identification, evaluation, and the inclusion of the uncertainty contributions were reported to the WMO CIMO *operational metrology* expert team. An interlaboratory comparison was also designed by the project members UL and INRIM in collaboration with ARSO and this WMO expert team. The relevant protocol became an official WMO document.

The coordinator regularly reported the project advances to the WMO CCl expert panel on *observational issues*, with emphasis on the issues related to the inclusion of instrumental uncertainties in the historical temperature data series. Such focus on the instrument and achievable knowledge and uncertainty were the bases of a joint paper on the need to establish reference grade observing stations and networks for climatology. This supported the launch of the GCOS Surface Reference Network (GSRN).

[11]Commission for Instruments and Methods of Observation
[12]Commission for Climatology

The project coordinator was co-opted as a member of the GCOS *Surface Reference Network* task. This GCOS initiative was launched in 2017 among climatologists and meteorologists in the representation of different WMO Regions. The project coordinator is the only member of the metrology community. The group scope is to define (instrument installation, management, target uncertainty, and traceability) a future global world initiative aiming at the creation of a network purposely made to generate comparable and traceable climate records. The GSRN is expected to be a long-lasting network making robust climate observation for the future generations of climatologists.

The project outputs were reported regularly to the GRUAN by the two project members (INRIM and NPL). The project studies on the calibration of radiosondes were reported in the GRUAN Implementation plan. A training course was also organised. Work on a joint paper on the change from Vaisala RS91 to RS41 is being prepared with the GRUAN lead centre and a measurement campaign (not initially planned over the project lifetime) was carried out. This improved the harmonisation of the GRUAN series, by the inclusion of the instrument uncertainties, when the new radiosondes will replace the old ones.

MeteoMet2 members participate in two H2020 projects: Gaia-Clim (http://www.gaia-clim.eu/) and in ECMWF-Copernicus C3S 311a Lot3. In both, the MeteoMet2 results are used to assess the data traceability and uncertainty.

The International Surface Temperature Initiative (a collaboration between MeteoMet and the Società Meteorologica Italiana) delivered a case study for the inclusion of the uncertainty relevant to the replacement of old thermometers with new ones in the decennial historical series. A paper is being prepared on the parallel observations with old and modern instruments.

New services

World leading manufacturers – such as Rotronic, Vaisala, NKE Instrumentation, Sea Bird Electronics, Barani, Lombard & Marozzini, – have been using the project calibrations and tests to improve their instruments. The calibration procedures, the assessment of the measurement uncertainties, and new instrumentation for hygrometry and sea measurements are expected to have a long-term impact on the reliability of climate trend evaluations.

- INRIM and VTT characterised a reference radiosonde prototype for Vaisala (world leader in environmental and industrial measurement). These results will allow Vaisala to improve the product for humidity and temperature measurement;
- The snow albedo experiment made by BEV and INRIM provided recommendations on how to improve the instruments by delivering values to quantify the effect of backward radiation on systems made by Rotronic, Barani, CAE and Lombard & Marozzini;
- The study on sensor dynamics and self heating made by CMI, CEM, INRIM and SMU (REG) provided information on sensor performance to Vaisala, NKE, Rotronic and Luft.
- A facility to compare deep-sea thermometers in a high-pressure chamber was developed at the Royal Netherlands Institute of Sea Research (NIOZ). It was used to measure pressure dependence of Sea-Bird Electronics thermistors (the biggest manufacturer and supplier of oceanographic thermometers).
- NPL reduced the uncertainty of their UKAS calibration service in the meteorological temperature range -50 °C to +20 °C.
- NPL calibrated 12 specialised air-temperature sensors for aircraft use for customer Facility for Airborne Atmospheric Measurements.
- The University of Genova installed a calibration device for tipping-bucket rain gauges at Environmental Measurements Ltd (UK).
- The University of Genova developed a calibration device for tipping-bucket rain gauges at LSI Lastem srl (Italy): two prototypes have been delivered to the Hong Kong Observatory and to the EML UK company.
- INRIM calibrated sensors are used to continue recording for the historical temperature series at Regio Collegio di Moncalieri, part of the WMO recognised centennial stations.

- Staff from both INRIM and the Institute of Atmospheric Sciences and Climate (Italy) calibrated atmospheric and permafrost temperature sensors for environmental measurements in the Arctic, at the research town Ny-Ålesund.
- NPL built a fast responding version of the non-contact thermometer and hygrometer instrument (Objective 1) for response time testing of temperature and humidity sensors.
- The numerical simulation of radiative heat transfer was used to design a chamber for calibration of air temperature sensors for the EMPIR project 15RPT03 HUMEA "*Expansion of European research capabilities in humidity measurements*" of the 2015 Research Potential call.

Events

The project promoted, launched, and organised a series of international events on topics linked with the MeteoMet research, tasks, and deliverables.

Metrology for Meteorology and Climate – MMC. Originally born as a MeteoMet project (EMRP ENV07) workshop, this event was raised to an international level. The first edition in Brdo saw participation from all over Europe and the four continents and covered topics such as chemistry, oceanic observations, and climate. The second was organised jointly with the WMO CIMO Teco conference (Madrid 2016, the most important WMO world conference on instrumentation). The presence of the world meteorological technology expo gave a unique opportunity to present the metrology developed by MeteoMet (data quality, standards, calibration, measurement procedures) and allowed the collaboration between metrology and meteorology to take off. In 2017 MMC was organised as the special session on the "Metrology for Meteorology and Climate" (chaired by MeteoMet2 representatives) of the European Meteorological Society conference in Berlin. MMC will be repeated in 2018 in Budapest, while the MMC 2019 is planned in Chengdu, China, on June 2019 jointly with Tempmeko (the world leading conference on temperature and thermal measurements).

Arctic Metrology Workshops. The workshop series started in 2015 in Torino with about 50 participants and moved every year towards the North pole! In fact, in 2016, it moved to Oslo In association with the EURAMET GA and, in May 2017, to Ny-Ålesund (in association with the Arctic metrology MeteoMet2 campaign). The workshop grouped metrologists and researchers operating in the arctic stations in Ny-Ålesund and Svalbard, to plan the creation of a permanent common laboratory for calibration and studies on field measurements uncertainty in the arctic. The main impact is expected in the coming decades, in terms of improved comparability of the data recorded by the numerous research group from different nationalities, a direct involvement of the users in the calibration and uncertainty analysis, dedicated procedures and knowledge on the sensors used in such extreme environment.

Special breakout session at the Arctic Circle Assembly. The 2015 Arctic Circle Assembly (opened by French President François Hollande) brought together more than 2000 participants, including parliamentarians, ministries, ambassadors, researchers. There, MeteoMet2 organised a special breakout session on "Metrology for the environment in the Arctic" that attracted both scientific and diplomatic attention. It set the basis for the metrology collaboration in Ny-Ålesund and the following participation of metrologists at the Ny-Ålesund Science Managers Committee (NySMAC) meetings and the ongoing metrology activities in the Arctic.

High mountains workshop. The joint workshop on metrology for high mountains, organised by INRIM and BEV, established a new area of collaboration between the metrology community and the Global Cryosphere Watch station operators. It was participated by metrologists and researchers from different EU countries and set the basis for opening the discussion on standardised methods and instruments for the climate studies of thermal quantities in a high mountain environment.
The activities on site calibration of the permafrost temperature-sensors set for the first time a methodology and procedure to assess data quality the measurements. The results will be presented at the next European conference on permafrost (EUCOP 2018) and are expected to set the basis for reference grade procedures.

Contribution to standards

The project provided inputs to the following documentary standards:

- Sustained Performance Classification for Surface Observing Stations on Land 1/6 Draft 2014 Rev 2017

- CIMO ET-A1-A2/Doc.8.1 - Guidelines on combining information from composite observing systems
- CIMO ET-Standard, Sustained Performance Classification for Surface Observing Stations on Land 1/6 24/06/2014, and iv) ISO/DIS 80000-5 Quantities and units - Part 5: Thermodynamics.

Potential future impact

The calibration procedures, the assessment of the measurement uncertainties, and new instrumentation for hygrometry and sea measurements are expected to have a long-term impact on the reliability of climate trend evaluations.

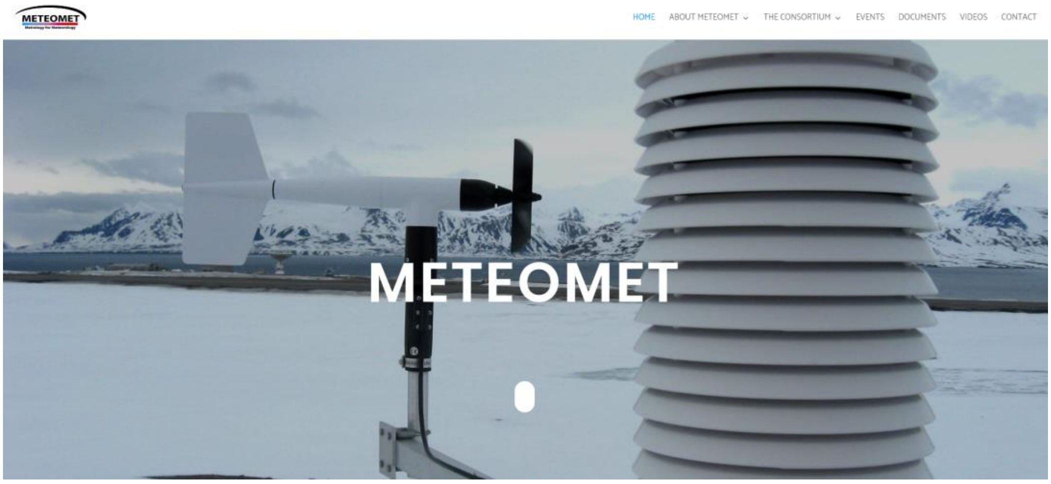
Members of the project consortium, who are now members of WMO CIMO expert teams, are promoting the following activities that follow on from the work of the project:

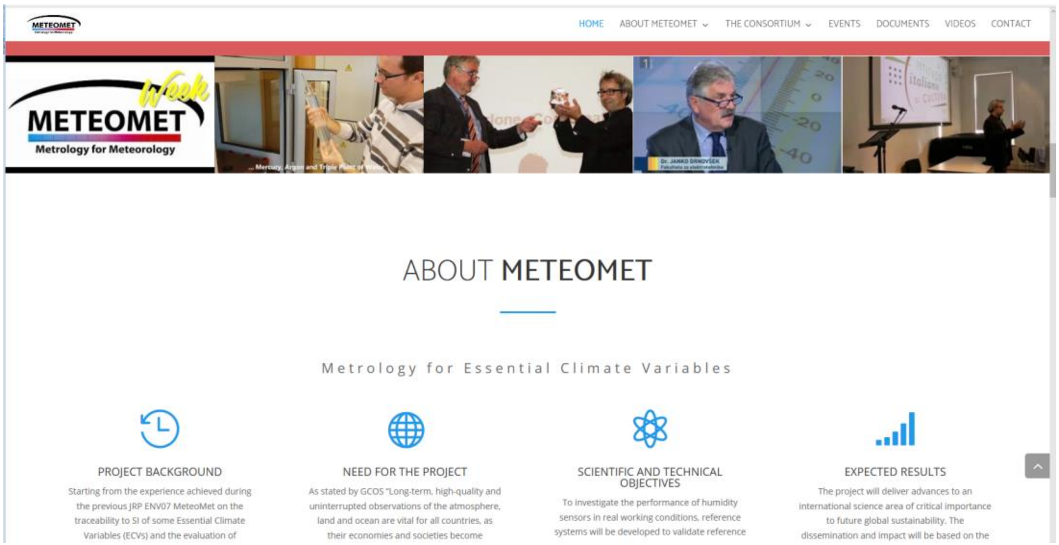
- A proposal is being discussed by the WMO CIMO A.3 *Expert team on Instrument intercomparisons*, about a comparison of thermometers and radiation shields as a future activity lasting 3 years: it will be submitted to the CIMO Session in October 2018 for inclusion in the future work plan (2018-2022).
- Interlaboratory comparison procedure and protocol in the field of temperature, humidity and pressure in Asia and Australia WMO regions II and V in collaboration with Region VI (Europe) (was agreed in March 2018 – Document: OBS-WIGOS/OBS- 06023/2018/OBS/OSD/RIC Inter-laboratory comparison for RICs in RA II and RA V, in collaboration with RA II&V)

Further information

Since the beginning, social media have been used by the project to communicate events and news. A website is available, where the main results, meetings, and events are reported. Presentations from the conferences, workshops, and meetings held during the project lifetime are downloadable in the public section "documents". A partners' restricted area shares work documents and deliverables.

MeteoMet website: www.meteomet.org

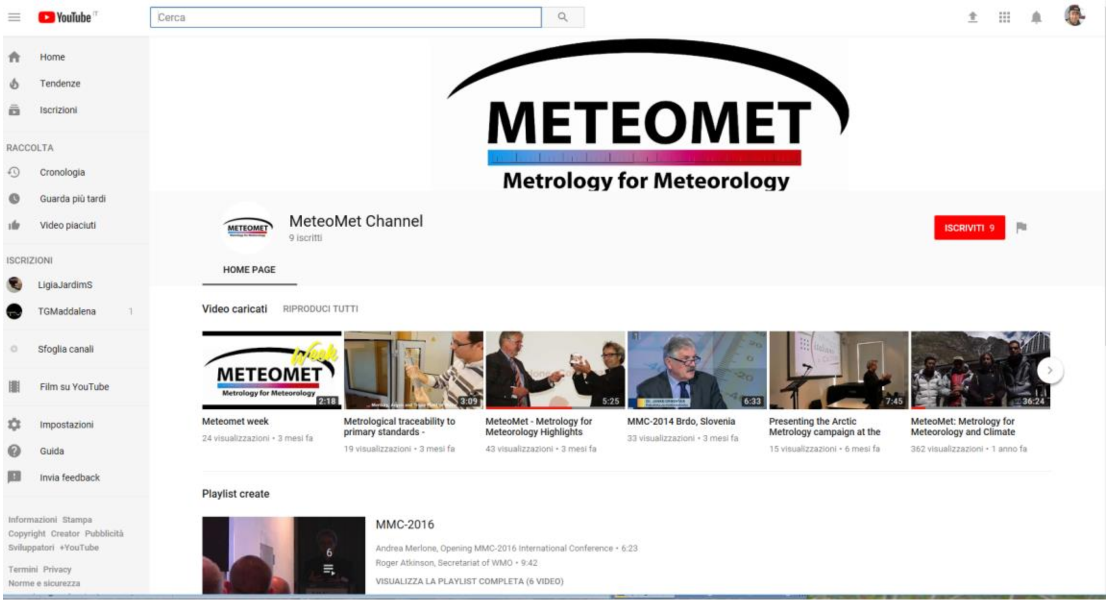




MeteoMet is active on Twitter with constant updates and news from the project and linked topics.
Twitter: https://twitter.com/meteomet

MeteoMet opened a youtube channel where the two MeteoMet documentaries are shown, together with conference videos and TV broadcast videos

MeteoMet Youtube channel: https://www.youtube.com/channel/UCO3gac4GoHX_7JsOqTMc2eQ



The project contributed to two documentaries:

WMO video on centennial stations (https://www.youtube.com/watch?v=c1PPrRBnuS8&t=169s)

GRUAN video documentary (https://www.youtube.com/watch?v=3y113Zz3y4U&t=373s)

5 Website address and contact details

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JRP website: https://www.meteomet.org/

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