The MeteoMet2 project—highlights and results

THE METEOMET2 PROJECT – HIGHLIGHTS AND RESULTS

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Abstract

Launched in 2011 within the European Metrology Research Programme (EMRP) of EURAMET, the joint research project "MeteoMet – Metrology for Meteorology – is the largest EMRP consortium: National Metrology Institutes, universities, meteorological and climate agencies, research institutes, collaborators and manufacturers are working together, developing new metrological techniques, as well as improving already existing ones, for meteorological observations and climate records. The project focuses on: humidity in the upper and surface atmosphere, air temperature, surface and deep-sea temperatures, soil moisture, salinity, permafrost temperature, precipitation and snow albedo effect on air temperature. All tasks are performed under rigorous metrological approach and include design and study of new sensors, new calibration facilities, investigation of sensors characteristics, improved techniques for measurements of Essential Climate Variables with uncertainty evaluation, traceability, laboratory proficiency and inclusion of field influencing parameters, long-lasting measurements, and campaigns in remote and extreme areas.

MeteoMet vision is to make a further step towards establishing full data comparability, coherency, consistency and long-term continuity, through a comprehensive evaluation of the measurement uncertainties for the quantities involved in the global climate observing systems and the derived observations. The improvement of quality of Essential Climate Variables records, through the inclusion of measurement uncertainty budgets, will also highlight possible strategies for the reduction of the uncertainty.

This contribution presents selected highlights of the MeteoMet project and reviews the main ongoing activities, tasks and deliverables, with a view to its possible future evolution and extended impact.

Keywords:

Metrology for meteorology and climatology, atmospheric air temperature, humidity and pressure measurements, sea temperature and salinity measurements, permafrost, weather station, interlaboratory comparison.

1 INTRODUCTION

1.1 BACKGROUND

Measurements are at the core of meteorology and climatology, but typically instruments and methods of observation in these fields have evolved – quite understandably – with extreme conservatism. Thus great value has been placed on the continuity of measurement series made using the same technique, despite questions being raised over the continued appropriateness of the measurement technique, and the availability of new techniques. Viewed from a metrological perspective, we can view this tension between conservatism and innovation as arising from a combination of two weaknesses in traditional meteorological practice.

Firstly, traditional meteorological techniques can fail to adequately characterise the measurand and thus, for example, a measurement of humidity using a wet-bulb thermometer can be strongly influenced by wind speed at the measurement station. Changing instruments or methods can result in the measurement with quite different susceptibility to other quantities, and thus introduce different error characteristics – known as an inhomogeneity – into a measurement series.

Secondly, there is often a reluctance to fully quantity the measurement uncertainty associated with a measurement. This is because the conditions of measurement are frequently so hostile that issues of conventional measurement traceability are considered of secondary importance. Additionally, measurements from around the world are rarely taken in ideal conditions with professional metrologists at hand.

Meteorologists and climatologists are well aware of these shortcomings and have developed sophisticated strategies for analysing measurement series containing inhomogeneities. Nonetheless, the situation is far from ideal.

It is in this context that the two pan-european projects were created with aim of improving meteorological best practice by the application of new concepts and technology applied with a metrological perspective.

As stated by GCOS, "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 possible only if they are based on a sustained traceability to the SI and with uncertainties associated to the measured ECVs.

1.2 METEOMET

MeteoMet – Metrology for Meteorology – is a Joint Research Project (JRP) of the *European Association of National Institutes of Metrology* (EURAMET). Its first phase began in 2011 [2, 3] and focussed on the traceability of a subset of Essential Climate Variables (ECVs) to the International System of Units (SI) with specified uncertainties. In 2014, the project began its second phase, *Meteomet* 2, extending the investigations to additional variables and contributions to uncertainty in field measurements. The aim is that quality improvement of the recorded ECV data will eventually lead to strategies for the reduction of the uncertainty.

The *MeteoMet* 1 and 2 projects involves 18 National Measurement Institutes (NMI) and 6 Designated Institutes (DI) from 20 European countries, 14 universities, 13 research centres, 14 manufacturers and private companies, and 22 hydro-meteorological agencies. It is through this combination of organisations and perspectives that the project aims to translate ideas in practical implementation in the field. The project key data since the first phase is summarized in the table1 of annex I, with the full list of *MeteoMet 1 and 2* partners (table 2).

The project is structured into three main areas of observation: Air, Sea and Land. These categorisations are really short-hand because many of the 'land' ECVs refer to measurements of the temperature and humidity of air, but specifically address measurements in meteorological stations.

In Section 2 below we outline the challenges identified in the project considered in each domain: Air (Section 2.1), Sea (Section 2.2) and Land (Section 2.3). Within each subsection we list the specific work packages which respond to the identified measurement challenges along with the lead institution taking part in the research. Because *MeteoMet* 2 is not due to finish until December 2017, as we write this paper, not all projects have been finished. However we consider it valuable to include details to convey the scope of the work being undertaken. In Section 3 we select seven work packages for further exposition, and In Section 4 we describe the anticipated impact of the project and prospects for further research.

2 TOPICS IN METEOMET 2

2.1 AIR: HUMIDITY AND TEMPERATURE MEASUREMENTS ABOVE GROUND LEVEL

Climate science could be alternatively described as the study of the dynamics and thermodynamics of water in the Earth's atmosphere. Yet measurements of water vapour in air are especially problematic. Ideal sensors would be able to cover a range of specific humidity (kg H_2O per kg dry air) covering a factor of more than 10^4 and would be fast-responding to quantify dynamic changes. However real sensors are highly non-ideal. Most significantly, they display significant hysteresis; they dry down considerably more slowly than they wet; and their response time is particularly poor when cold. These shortcomings combine to create significant measurement challenges for radiosondes which travel from the warm, wet troposphere to the cold dry stratosphere.

The MeteoMet consortium set the following scientific and technological objectives:

1. Development of metrological procedures to calibrate radiosondes under atmospheric conditions including reduced pressures and temperatures.
2. Measurement of the water vapour enhancement factors which cause deviation from calculated specific humidity in air compared to water vapour only calculations.
3. Development of new spectroscopic methodologies as standards for traceable humidity measurements and on-site references.
4. Development of a traceable humidity source capable to provide on-site calibration to airborne instruments.
5. Development of a reference instrument for the measurement of fast transients of temperature and humidity.
6. Development of traceable humidity sensors based on microwave resonators having short response time and small size.

In response to these identified aims, the following steps have been taken.

2.1.1 Calibration of radiosondes under atmospheric conditions.

The development of a calibration facility for water-vapour measurements in radiosondes in the range from 0.03 to 1.5 μmol/mol [4] was completed at VTT MIKES. The pressure and dew-point temperature limits were decreased down to 10 hPa (abs.) and -90 °C at VTT MIKES and 20 kPa and -95 °C at INRIM, respectively, to simulate the conditions met during the ascent in the troposphere and lower stratosphere. The water vapour amount fraction uncertainty is less than 2%.

2.1.2 Measurement of the enhancement factor under atmospheric conditions.

The CETIAT completed a literature review to identify pros and cons of different experimental set-ups. Since there are two measuring methods, a direct one, by measuring the second virial coefficient, and an indirect one, by measuring humidity, studies were carried out to identify the most synergic with other measurements. An apparatus has been designed, the assembly is in progress and a measurements campaign will follow.

2.1.3 Spectroscopic thing

What has been done about this?

2.1.4 On-site calibration of airborne instruments.

PTB has built a portable instrument for in situ calibration of airborne instruments with uncertainty in the (1-20) parts per million by volume (ppmv) interval. A mobile, compact, and robust water vapour generator, which uses water permeation through air-purged plastic tubing was developed and manufactured. By stabilising the gas flow and the bath temperature, a well-defined mixing ratio is achieved. Performance tests are ongoing.

2.1.5 Measurement of fast transients of temperature and humidity.

NPL upgraded an airborne combined acoustic thermometer and infrared hygrometer for measurement of fast transients during ascents through the atmosphere [5]. The instrument can make 30 independent readings per second with a resolution of 0.001 °C and uncertainty <0.1 °C, measurement of water vapour mixing ratios from 10000 ppmv (~10%) to $3 \cdot 10^4$ ppmv (corresponding to dew points from -43 °C to 38 °C at 10^5 Pa).

2.1.6 Microwave Hygrometry

CNAM realized a prototype of a fast airborne microwave hygrometer (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 few to 10^5 ppmv, and the uncertainty of measurement is approximately 1 ppmv. A comparison with a CETIAT calibrated chilled-mirror hygrometer showed that it could be an alternative standard for humidity measurements. However the measurement time is still too long about 100 seconds, primarily because a long sampling tube was used. A second generation has been made and the assembly of the full system is in progress

2.2 SEA: TEMPERATURE AND SALINITY MEASUREMENTS IN OCEANS

Two of the key oceanic ECVs, for monitoring and understanding decadal changes in heat content and heat transport, are temperature and salinity. A comprehensive study of the characteristics of the associated measurement instruments and the effect of the main quantities of influence on thermometers and salinometers is needed, in order to reduce measurement uncertainty. The scientific and technological objectives at the outset of the course:

1. Development of facilities to study the pressure dependence of deep-sea thermometers and to establish validated pressure-correction models.
2. To perform a thermodynamic calibration of deep-sea thermometers, to analyse the temperature-resistance models, to estimate the uncertainties or to propose improved models.
3. Development of distributed temperature sensors based on optical fibre Bragg-gratings to improve the traceability of sea-surface and sea-profile temperature measurements and to monitor temperature drifts of the thermometers used in underwater observatories.
4. Development of a facility for determining temperature and pressure effects on salinometers based on the measurement of seawater refraction index, and their metrological characterization.

2.2.1 Pressure dependence of deep-sea thermometers.

VSL realised a comparison block and carried out measurements on deep-sea thermometers using a high-pressure chamber available at NIOZ (Royal Netherlands Institute for Sea Research). The pressure dependence of Sea-Bird Electronics thermistors (the biggest manufacturer and supplier of oceanographic thermometers) was measured at 500 bar (-0.30 mK / 100 bar) confirms the values observed in the sea (from -0.17 to -0.33 mK / 100 bar) and the proper operation of the facility. A pressure of 100 bar corresponds to a depth of approximately 1000 metres.

2.2.2 Thermodynamic calibration of deep-sea thermometers.

The CNAM modified an acoustic gas thermometer and the associated calorimeter to integrate and to calibrate deep ocean thermometers from -5 °C to 35 °C within an uncertainty below 0.5 °C.

2.2.3 Ocean temperature sensors based on optical fibre Bragg gratings.

CEM, CSIC and UPC designed and assembled fibre Bragg-grating sensors to measure profile and near-surface sea temperatures. The onsite experiment was designed as well as the fibre Bragg-grating sensors were designed, assembled, tested and calibrated to be used as thermometers. These thermometers were integrated into the submarine observatory (OBSEA) – connected to the coast of Vilanova i la Geltrú (Barcelona, Spain) and placed at a depth of 20 meters.

This project is described further in the 'Highlights' Section 3.3

2.2.4 Test and calibration facility for refractive-index salinometers.

To make accurate, in-situ measurements, CNAM and SHOM are creating a test and calibration facility for determining temperature and pressure effects on a novel generation of salinometers allowing absolute salinity assessment – based on the refractive index of seawater. Such a facility will be used for investigating the impact of parameters such as temperature and pressure on the optical sensor, or temperature on the laser wavelength drift.

This project is described further in the 'Highlights' Section 3.4

2.3 LAND: TEMPERATURE AND HUMIDITY MEASUREMENTS IN GROUND LEVEL MEASUREMENTS

Ground-based ECVs have been historically recorded for meteorological purposes and the records now form one of the primary tools for evaluating decadal and longer climate trends. New techniques are being developed to improve data quality and comparability between measurement stations in space and time. A key focus for *Meteomet* has been the ability to make coherent of measurement uncertainty including the effects of the intrinsic sensor behaviour, and parameters of influence, including siting and thermometer screens.

An objective of the intrinsic and dynamic behaviour study of the air temperature sensors is to improve the ISO Guide 17714:2007 (Meteorology -- Air temperature measurements -- Test methods for comparing the performance of thermometer shields/screens and defining important characteristics), by defining calibration procedures and evaluating uncertainties through a better sensor characterisation. This will be achieved by means of different facilities, including the special wind tunnel with temperature and pressure control designed and developed by INRiM during the first three years of the project. CEM determined the self-heating effect and hysteresis effect of a selection of thermometers with different designs, covering Pt100 alone, as well as pt100 embedded in T& RH sensors. The analysis of self-heating effect were also performed at several temperatures and with the thermometers surrounded by different mediums. This project is described further in the 'Highlights' Section 3.5 and 3.5.

Regarding ECV's explicitly in the land rather than just above it, permafrost temperature is classified as a parameter to investigate climate changes but, today, few measurement procedures report a fully-detailed uncertainty budget. Similarly, calibration and measurements standards for precipitation and soil moisture are not yet developed to cope with the differences between laboratory setups and field conditions.

In response to these challenges the consortium set the following scientific and technological objectives:

1. Analysis of the siting influence on air temperature measurements in terms of uncertainty components.
2. Determination of the influence of rain and albedo on air temperature measurements.
3. 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.
4. To ensure consistency and coherence of meteorological measurements carried out in different places.
5. Development of procedures for traceable dynamic calibrations and uncertainty calculation of hygrometers used to measure the humidity near the Earth surface.
6. Development of a high-bandwidth humidity generator to study the response of air-humidity sensors to fast humidity changes.
7. To identify the needs of traceability and uncertainty calculation of soil moisture measurements and to carry out initial experimental trials of the relevant procedures.
8. Indications of consistent measurement uncertainties in meteorological humidity data sheets.

2.3.1 Thermometer Screens

SMD is modelling the temperature measurement inside a radiation shield. The KNMI made a 3-year in-field experiment with 10 different radiation shields and supplied the data needed to validate the model.

2.3.2 Effect of obstacles on meteorological sites

INRIM defined a protocol to study the influence of obstacles on surface-based air temperature measurements that received positive feedback by the WMO Expert Team on In-situ Operational Technologies. Three experiments are underway: in Italy, an experiment is running to evaluate the road influence; in the Czech Republic, for tree influence; in Spain, for buildings influence.

2.3.3 Effect of rain on temperature measurements

DTI is assessing the influence of rain on temperature measurements; the relevant experimental set-up is already operational.

2.3.4 Albedo of Thermometer Screens

BEV identified a mountain site to investigate the effect of albedo on temperature measurement and made it operational. Five pairs of shielded temperature sensors, with both naturally aspirated and mechanically ventilated shields, are used to ensure a representative group of devices. All logging issues were solved and tests were performed to evaluate the "zero" difference between each pair, as well as the corrections necessary and the relevant uncertainties. The measurements are in progress.

As a source of correction and uncertainty in air temperature records, the effect due to the aging of solar shields for atmospheric ground based sensors was evaluated [6].

2.3.5 Inter laboratory comparison

UL defined a protocol for the Inter-Laboratory Comparison (ILC) of temperature, humidity, and pressure internal standards of calibration laboratories of the National Meteorological and Hydrological Services (NMHS) [7]. The WMO made the protocol as an official document of its Commission for Instruments and Methods of Observations. Two loops of the ILC were organised, with 19 National hydro-meteorological agencies participating [8]. It is expected that the ILC will be extended also to other WMO regions outside Europe.

2.3.6 In situ calibration

Transportable facilities were studied and manufactured for the calibration of weather sensors on site. This calibration chamber, called *Earth Dynamics Investigation Experiment* 1 (EDIE1), is capable of simultaneous and independent control of pressure and temperature, The facility is also designed to allow the control in humidity, therefore completing the characterization of the whole AWS pressure–temperature–humidity modulus. [9], One of the greatest benefits of this facility is the reduced dimensions that makes it transportable for *in situ* calibration campaigns, also in remote areas [10].

2.3.7 Historical records

Historical temperature records for climate trend evaluations have also been a subject of the project: studies were made on the effect of change in instrumental methodologies on daily minimum and maximum recorded values, showing non-negligible and non-unique effects [11]; direct calibration of historical sensors without interrupting the series were made on site of centennial stations [12].

2.3.8 Agro-meteorology

Metrology applied to agro-meteorology was also developed, in terms of evaluating the effect of the calibration's uncertainty inclusion on the meteorological measurements used as input values on epidemiological forecasting models [13]. Moreover, weather monitoring instruments installed on hill and mountain agricultural sites are often forced into non-ideal positioning due to slopes, tree proximity and other obstacles that primarily affect relative humidity, temperature, and solar radiation. The enclosure of the instrument positioning contribution in forecasting models affected positively the disease prediction [14].

2.3.9 Mars Simulator

A special facility, called "Mars simulator" at Aarhus University was accurately characterised operating in "Earth conditions" for testing weather sensors [15].

2.3.10 Dynamic calibrations of hygrometers.

A new water vapour generator was delivered to PTB and was integrated into the calibration facility. A climatic chamber reaching low temperatures (typically -60 °C) is operational at CETIAT. In collaboration with LMD, satisfactory response time measurements were made with the LMD hygrometer and also with a chilled mirror instrument.

2.3.11 Precipitation and soil moisture.

UniGe and associated Research Excellent Grant 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, major contributions of the type B uncertainty in the calibration of TBRGs have been quantified [16].

2.3.12 Soil Moisture Measurements

TUBITAK realized a soil moisture measurement set-up based on a gravimetric method and composed by a moisture analyser, a high precision balance, a desiccator, and an oven supplemented with a rotary pump. The NPL performed a survey on the measurements (about100 respondents) and the needs of calibrations. The online survey is left open so that more responses can be collected. The INRIM completed a literature search on soil moisture measurements and calibration methods, focus on agriculture and traceability requirements. It turned out there are a number of issues with the calibration, i.e. the soil used for calibration that may not represent the characteristics of the soil to be measured by the technique being calibrated. The calibration is also affected by some other factors such as soil temperature, barometric pressure, salts and air gaps in soil as well as the bulk density of the soil.

2.3.13 Soil Moisture questionnaire

The soil moisture questionnaire was designed to address the applications of soil moisture measurements, techniques, calibration methods (classical gravimetric method and remote sensing techniques). 25 questions have been prepared, 23 of which were technical. The questions were divided into five macro areas: Application; Measurement; Calibration; Classical gravimetric method; and Remote sensing techniques. Potential participants for the questionnaire were identified from numerous sources. The answers to the questionnaire were automatically sent to NPL and the survey results have been reported separately. In conjunction with VSL, INRiM contributed in circulating the questionnaire to over 350 contacts. MIKES, involved with steering the planning and realising the survey, is using the outcomes to improve the traceability of soil moisture sensors. NPL collected the Met Office, the United Kingdom’s national weather service, datasets of weather station hygrometer calibrations from 2012 to 2014 and added it to the initial subset of already analysed data for estimates of the drift.

2.4 CRYOSPHERE

Its main characteristics, like the temperature of permafrost, glaciers and rock glaciers, snow, ice, water, land and air are now under increasing observation. Field measurements of temperature are a key investigation for these cryosphere constituents, in Alpine and Arctic environment. Metrological traceability of measurements in such areas, of difficult access and where instruments are exposed to extreme environmental conditions, is a fundamental aspect of data comparability in space and time, to accurately capture trends. The project included challenging missions and activities at high altitude in Himalaya and in the Arctic [17, 18].

3 SELECTED HIGHLIGHTS.

3.1 SI TRACEABLE HUMIDITY CALIBRATIONS FOR RADIOSONDES

Radiosondes provide an economical method to profile humidity in the troposphere and lower stratosphere, an activity which is vital for weather forecasts and climate change monitoring.

- Specify problems:
  - insolation
  - wetting of sensors
  - Slow drying of sensors

To improve the quality of upper-air humidity data, the GCOS specified a challenging uncertainty requirement for humidity measurements (2 % in the water vapour mixing ratio) [19]. Traceability to the SI is an essential requirement for achieving the target uncertainty. To enable SI-traceable humidity calibrations of radiosondes at upper-air equivalent conditions, a new humidity calibration facility has been developed by the Centre for Metrology MIKES at the VTT Technical Research Centre of Finland. In this facility, a humidity probe of a radiosonde 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 ranges from atmospheric pressure down to 10 hPa corresponding to an altitude of approximately 30 km.

One target of the system development was to reduce stabilisation time in the measurement chamber to enable feasible calibration times. This was achieved by an appropriate measurement chamber design [20] and by applying flow mixing in a two-saturator humidity control setup [4, 21] illustrated in figure 1.

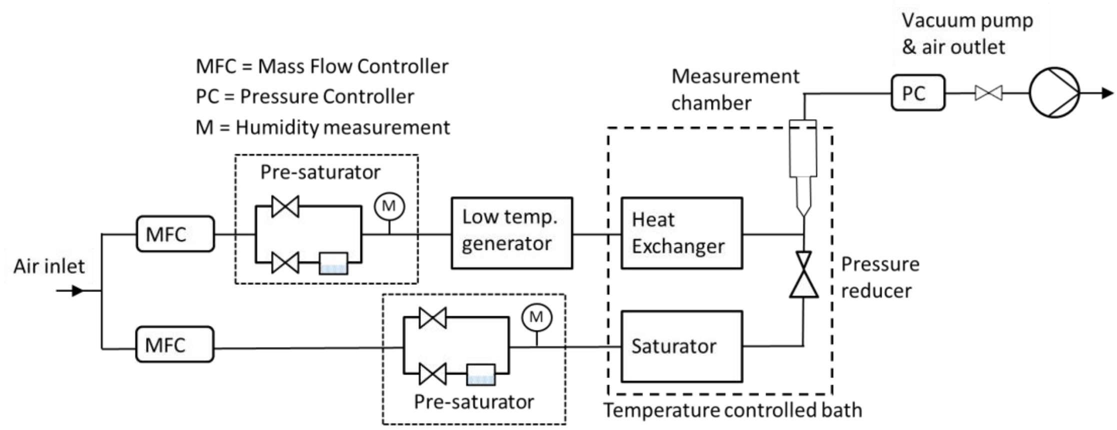

Figure 1. Schematic diagram of the facility developed by VTT MIKES for humidity calibrations of radiosondes.

The apparatus was fully characterised at surface pressure level and the uncertainty analysis showed that the target uncertainty of 2 % is achieved with this system. The characterisation will be completed with a comparison to be carried out with the recently commissioned INRIM standard frost point generator at sub-atmospheric pressure in the near future.

3.2 A CORRECTION FOR THE TEMPERATURE HISTORICAL SERIES

Daily temperature-time series, spanning over 300 years have been created in particular locations and these records have allowed for the creation of climate system models of the Earth, which are used to define the long-term temperature trends and are employed for the calibration of proxies used for temperature prediction further back in time.

Prior to the 1850s, the number of continuously operated observation stations declines considerably and the creation of reliable datasets is therefore difficult. A new international temperature scale was introduced in 1927, which was truly internationally, accepted and used. The scale evolution did not stop at this point and as knowledge of thermodynamic temperature improved, a series of practical temperature scales were introduced. However such changes introduces a small bias in long-term temperature records, which is mostly overlooked in meteorological literature. Therefore, the determination of the scale correction from 1927 to the present day is relevant when trying to estimate historical temperature trends.

The difference in temperature scales that causes the problem in historical data analysis originates from the variety of interpolating instruments, scales temperature range, fixed points and mathematical equations used to define the instruments output relation to temperature change. The net results is small, with changes in the range -20 °C to +20 °C being less than ±0.02 °C, which is typical of the calibration uncertainty of meteorological thermometers. However, the result will show up as a bias when large numbers of thermometers are averaged. A software tool [22] was developed during the first phase (2011-2014) of MeteoMet allows old temperature data series to be converted into ITS-90 values for a more robust comparability.

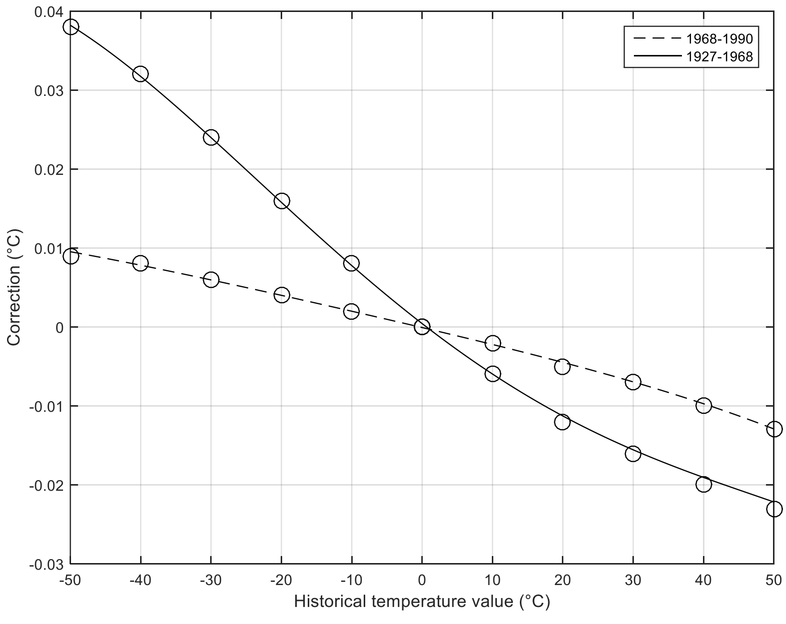

Figure 2. Corrections are necessary to adjust historical temperature data in order to be consistent with the modern temperature scale. The circles indicate the tabulated points from the BIPM documents describing the transforms from old scales to newer scales.

3.3 EXPERIMENTAL SEA TEMPERATURE MEASUREMENTS BY DISTRIBUTED TEMPERATURE SENSORS

A new technique to perform traceable temperature measurements in seawater was designed, it is being studied, developed and is being test in the field by CEM, CSIC and UPC [23]. Two different designs were used to avoid the corrosive environment of seawater.

The thermometers consist of several Fibre Bragg Gratings (FBGs) located at different points along an optical fibre. One fibre has 4 points of measurement and the other one has 11 points of measurement (figure 4). The FBGs are written on single mode optical fibre SM-ITU652 coated with acrylate. The fiber is inside a ¼” x 0.35 wall thickness 316L stainless steel tube and the final encapsulation is done with a layer of polypropylene/PEEK with resistance to seawater.

Sea water temperature profile and the sea surface temperature will be in the submarine observatory (www.obsea.es) (figure 3) and the devices examined for drift over lifetime of exposure.

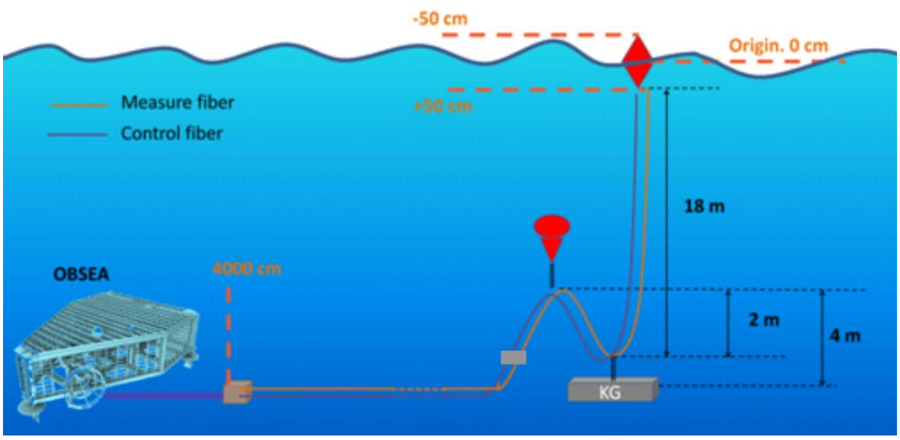

Figure 3. Design of the on-site experiment

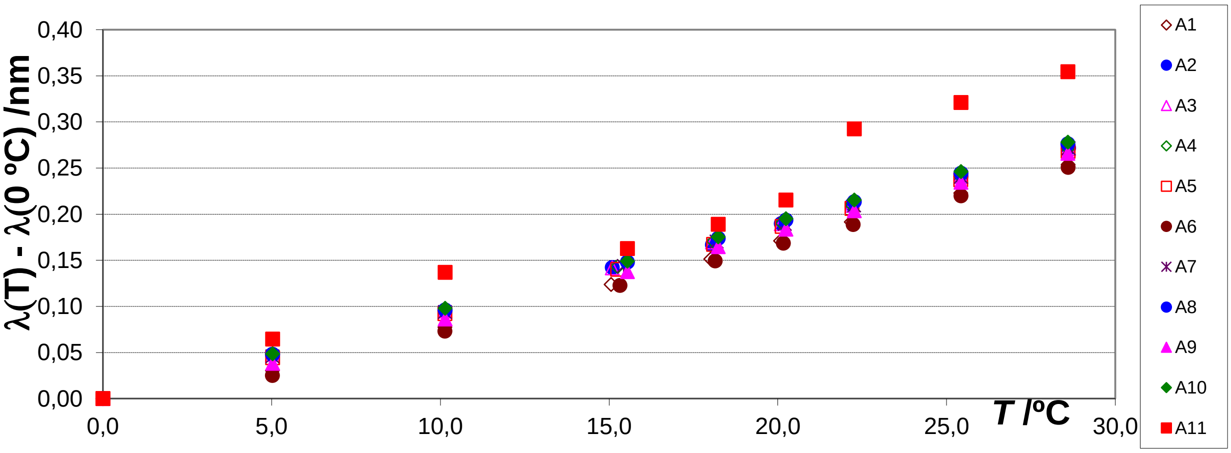

Figure 4. Calibration of the wavelength shift versus temperature performed at CEM of the optical fiber with 11 points of temperature measurement.

3.4 CALIBRATION OF CONDUCTIVITY, TEMPERATURE AND DEPTH SENSORS

CEM calibrated the temperature sensor located in submarine devices for the measurement of salinity, temperature and depth (Conductivity, Temperature and Depth, CTDs), specifically, SeaBird Electronics models 16plus and 37SMP (with dimensions, 808 x 136 x 103 mm and 564 x 103 x 67 mm, respectively). These instruments are currently in use in the OBSEA submarine observatory and because of their size, a large calibration bath was designed, assembled and characterized by CEM. The bath shows a stability and uniformity of 35 mK in the calibration range of the CTD's: (0-30) ºC

A calibration procedure has been developed with a complete calibration uncertainty model where each of the components is analysed (table1).

Table.1. CTD's uncertainty calculation

Uncertainty component description	Quantity	Unit	Uncertainty	Probability distribution	Divisor	Sensitivity coefficient	Standard deviation
	x_i					c_i	$u(x_i)$ °C
	Measuring system of the laboratory						
Resistance bridge calibration	L_p	≅ │	1.00E-06	Rectangular	√3	R_s/sp	1.48E-04
Drift of the resistance bridge	≅ L	≅ │	6.10E-06	Rectangular	√3	R_s/sp	9.03E-04
Reference Resistor calibration	R_s	≅	2.80E-04	Normal	2	L_{ref}/sp	7.18E-04
Drift reference Resistor	≅R_{sd}	≅	1.00E-04	Rectangular	√3	L_{ref}/sp	2.96E-04
Calibration of Reference thermometers	≅t_c	ºC	0,002 2	Normal	≅	1	1.00E-03
Drift of Reference thermometers	≅t_d	ºC	0.002	Rectangular	√3	1	1.15E-03
Temperature bath Stability	≅t_e	ºC	0.002	Rectangular	√3	1	1.15E-03
Temperature bath Uniformity	≅t_u	ºC	0.001	Rectangular	√3	1	5.77E-04
	Characteristics of the CTDs						
Resolution of CTD	t_i	ºC	0.005	Rectangular	√3	1	0.0029
			Combined uncertainty		ºC		0.004
			Expanded uncertainty		ºC	k = 2	0.008

3.5 SELF-HEATING EFFECT OF METEOROLOGICAL TEMPERATURE SENSORS

Self-heating of resistance sensors is an important issue to be considered among the uncertainty budget components of air temperature measurements. The influence of sensor self-heating is usually determined in calibration laboratories under fixed conditions of temperature, humidity and air speed, but these conditions are highly variable when the thermometer is performing measurements on site and under real environmental conditions. Besides, sometimes the resistance thermometers are used with different measuring currents than were used in their calibrations.

CEM are evaluating the correction of the self-heating effect of some meteorological sensors by applying different currents to two of the four Pt100 wires usually used in meteorological and climate measurements. The self-heating effect is being analysed with the thermometer immersed in different isothermal enclosures, fixed points, and a stirred liquid bath and climatic chamber. The influence of temperature on self-heating effect is being also studied, as well as the influence of the radiation shield.

As examples of the self-heating evaluation that is being performed at CEM, figures 5 shows that the dependence of self-heating effect with the surrounding medium increasing with the current applied to the sensor . Notice that in air a current of 3 mA introduces an error of almost 0.1 °C when compared with a 1 mA measuring current.

figure 6 and figure 7 show the negligible effect of the radiation shield on the self-heating correction. CMI evaluated the self-heating effect under different wind speeds, determined in the wind tunnel (figure 12).

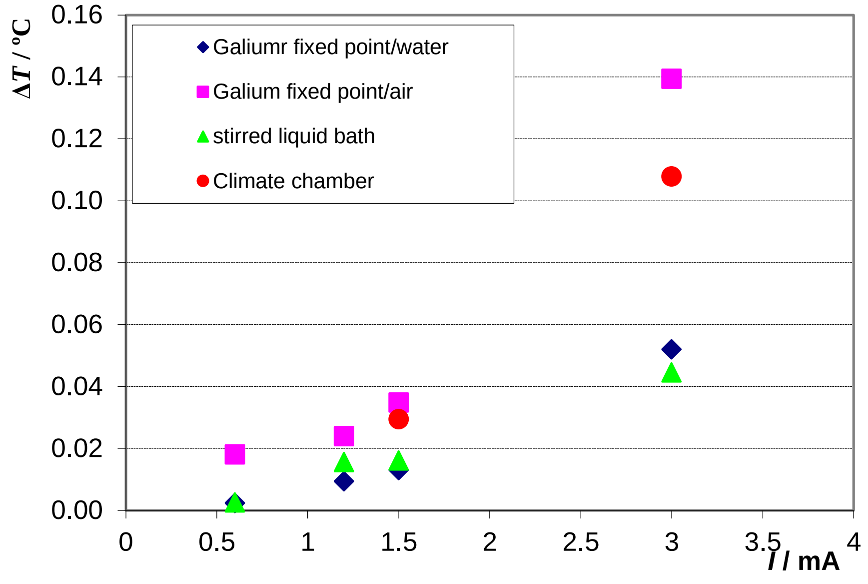

Figure 5. Self-heating effect in a Pt100 in different isothermal enclosures at 30 ºC

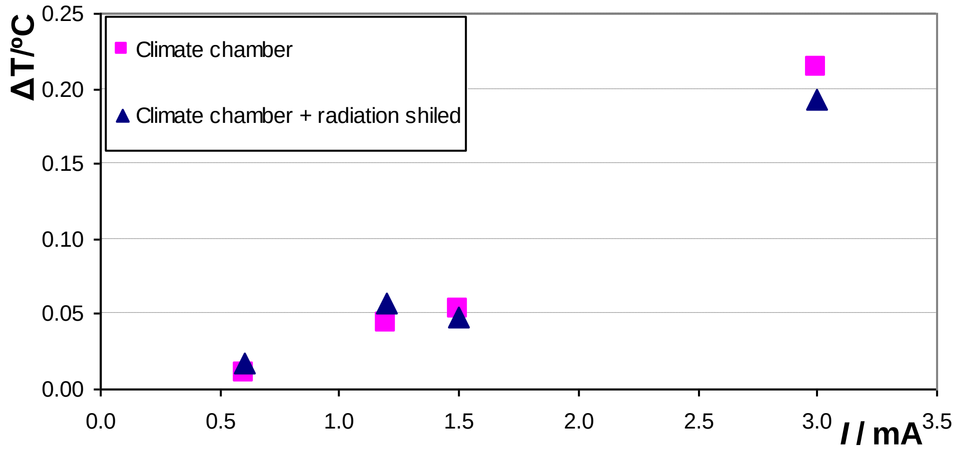

Figure 6. Influence of the radiation shield on self-heating effect in a Pt100

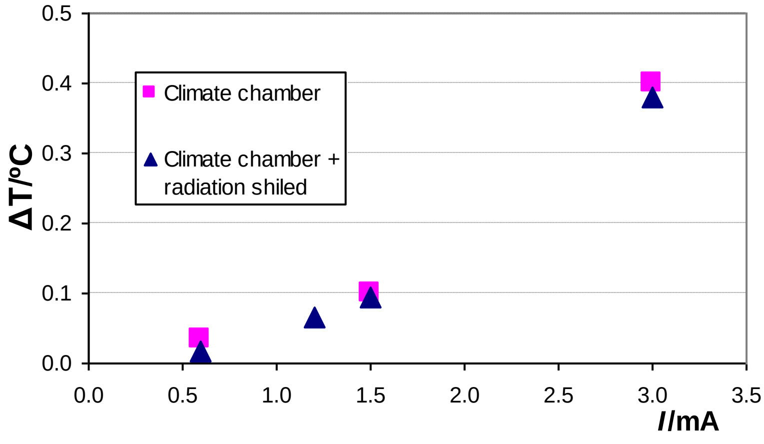

Figure 7. Influence of the radiation shield on self-heating effect in a Pt100 inside a T&RH

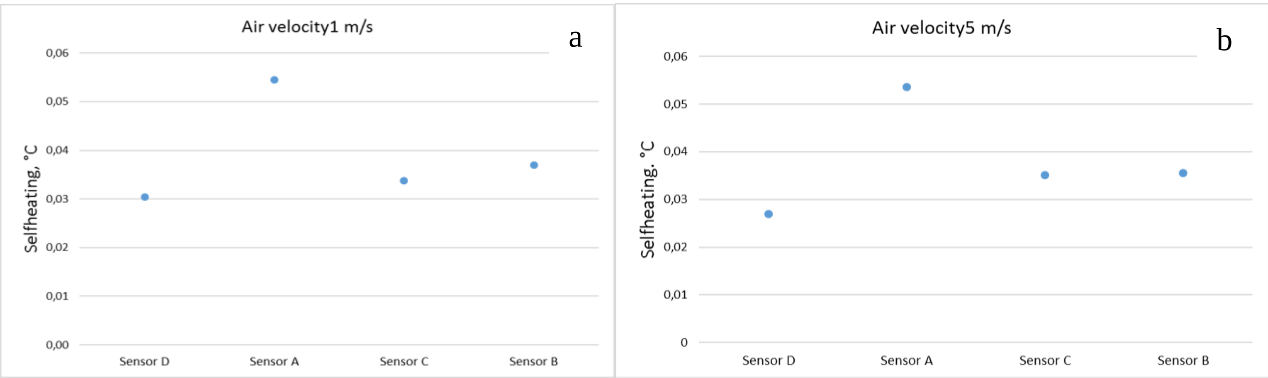

Figure 8. Self-heating effect under different wind speeds; at 1 ms^{-1} (a) and 5 ms^{-1}(b)

3.6 Evaluation of the hysteresis effect of some meteorological thermometers

Rapid changes of air temperature are usual in real weather conditions but such changes could cause hysteresis in resistance thermometers used for onsite air temperature measurements. In order to have a more reliable knowledge about the uncertainty of air temperature measurements, the hysteresis effect was studied at CEM.

Thermometers were exposed to a heating and cooling cycle between 10 °C and 50 °C and then two methods to evaluate the hysteresis effect in automatic weather stations have been tested.

In the first method (Figure 13 results were assessed after exposure at several intermediate temperatures. In the second method the ice point was re-measured after the exposure of the thermometers at extreme conditions of temperature.

From figure 13 and figure 14, it can be deduced that the evaluation of the hysteresis effect in similar methods, taking more time the evaluation of hysteresis by means the complete cycle.

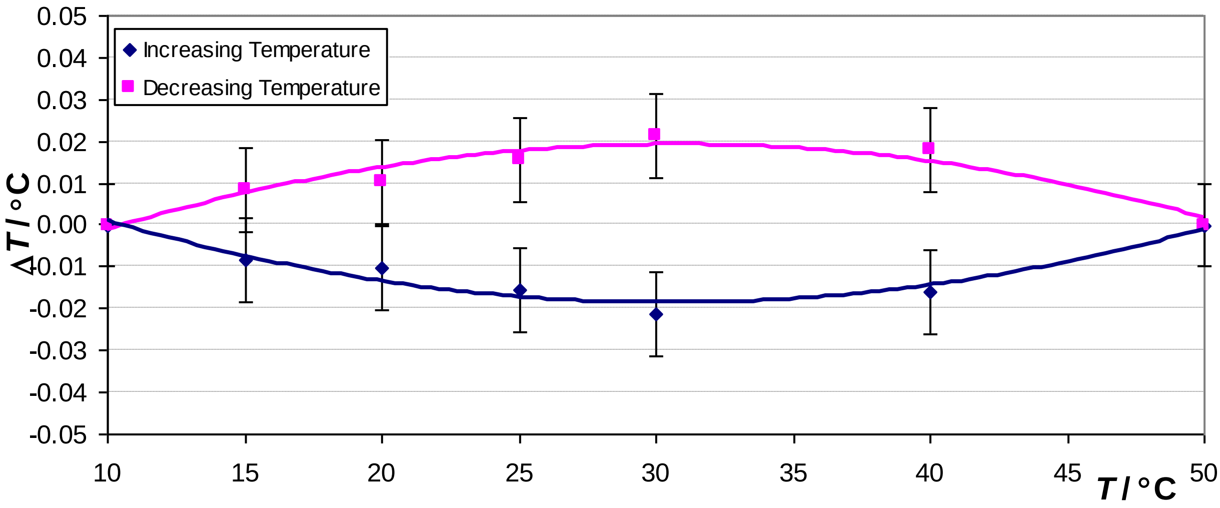

Figure 9. Hysteresis effect of a Pt100 measured in a stirred liquid bath. Complete cycle (10-50) ºC.

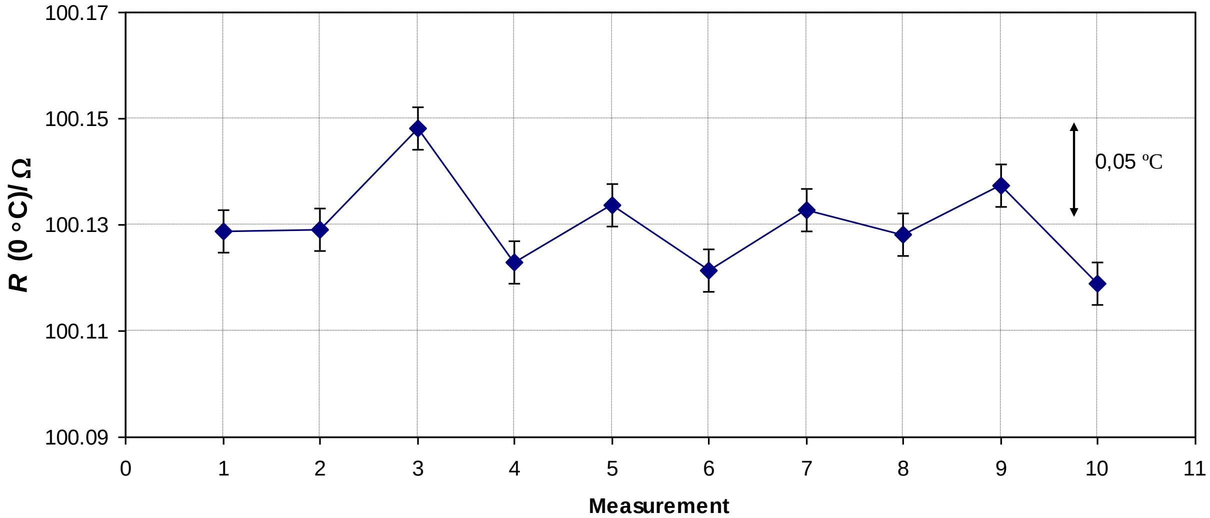

Figure 10. Hysteresis effect of a Pt100 measured in an ice bath, after exposure to extreme temperatures (-60 ºCand 50 ºC)

3.7 PERMAFROST SENSOR DYNAMIC

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 the information difficult to evaluate in metrological terms. From the nature of these measurements, the changes during every day and so knowing the dynamic response of the sensor is relevant to complete the uncertainty budget. Sensor dynamic gives the user valuable information, which can significantly affect the decision on frequency of recording. Overestimating or underestimating the recording times can affect temperature measurements in such a way that the daily maximum and minimum values most likely be unrecorded.

So far, four types of sensors have been 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 better represent the measurement conditions in the permafrost boreholes. The introduction of sensors to a temperature shock began after their indicated temperature was stable for a minimum of 10 min. After the placement into the positive temperature environment the equilibrium time was measured together with the behaviour of the sensors temperature output. To ensure the validity of the sensor behaviour a minimum of five runs were performed. The temperature conditions were as well monitored by a calibrated reference PRT (Platinum Resistance Thermometer). The thermal shock was also conducted in a reversed order to see if there is any difference in their response time. A typical dynamic test result can be seen in figure 15. In this graph we can see how fast the sensor will achieve equilibrium and the typical curve of sensors temperature output. In general a steeper curve is preferred, meaning a shorter equilibrium time. This predetermines the sensor for more dynamic measurements as well as for slower changing temperature processes.

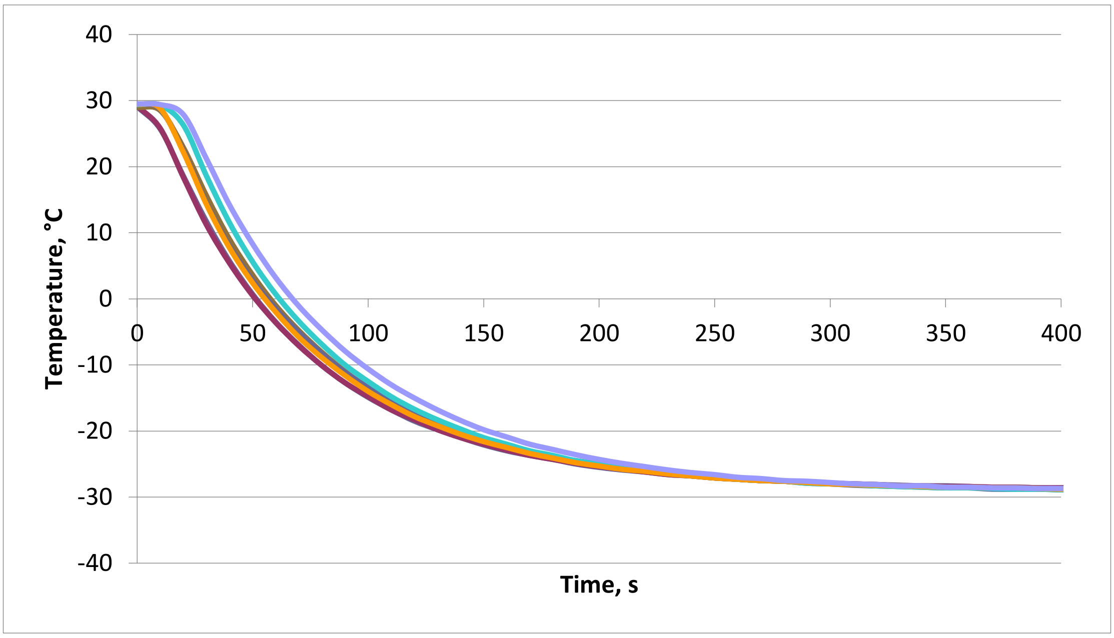

Figure 15. Repeated permafrost sensors (marked - M) reaction to a thermal shocks generated by a rapid temperature drop from +30 °C to -30 °C. According to the sampling frequency used by the involved datalogger, this curve can be used to include the sensors response time in the uncertainty budget

The measurements are still on-going and their results are intended to determine an uncertainty budget component into the permafrost measurements originating from this sensor property and help to create a best practice document to help the end users to determine a specific permafrost sensor dynamic.

4 CONCLUSIONS AND PROSPECTS

4.1 CONCLUSIONS

4.2 FURTHER WORK

The MeteoMet2 project here reported is funded by EURAMET until October 2017. Among the numerous activities, some key studies and researches are planned to be continued by NMIs in collaboration with the key stakeholders, also beyond the official lifetime of the JRP. In particular, the studies on the full evaluation of field measurement uncertainties will be continued for cryosphere observations and extreme environmental conditions, such as high Alps and the Arctic. Measurements of ECVs in the Arctic are performed under numerous research initiatives, stations and groups, generating an increasing amount of data, recorded by a multitude of instruments and installations. For example, cryosphere systems like permafrost are very sensitive to the exchange of energy between soil and atmosphere. Homogenised and traceable procedures of measurement are desirable and needed in order to produce comparable data. International efforts are lead in this direction by the Global Terrestrial Network for Permafrost, which collects permafrost temperature and active layer data around the world (mainly in the Arctic region) revealing an exceptional warming trend in the last decades.

When a global analysis of the climate trend needs to be delivered from separate studies, the comparability of the individual datasets is of primary importance. Full documented traceability with inclusion of calibration and measurement uncertainties is frequently missing, due to the logistic difficulties in the shipment of instruments. The evaluation of measurement uncertainties is also a challenging aspect, and standard calibration procedures, available from calibration services, do not fully represent real measurement conditions. In the 2015 Arctic Circle Assembly and the 2015 NySMAC[a] meeting, the contribution from the metrology community in addressing such issues was identified to be of urgent importance, and an action towards the creation of a metrological infrastructure was included as a priority in the Flagship Programme on Atmospheric Research.

The proposed research extends the underpinning metrology developed during the MeteoMet EMRP projects, which included an "Arctic Metrology Campaign", performed in 2014 in Ny-Ålesund [18], where special calibration devices were transported to the Arctic base and involved in the calibration of sensors installed in the Climate Change Tower and another used as a pre-launch ground check of GRUAN-contributing balloon sondes. The benefit of having calibration devices available on site was acknowledged by the research community in Ny-Ålesund, with the proposal of starting a collaboration towards the realisation of a permanent calibration laboratory on Svalbard [24]. As a main impact of the MeteoMet JRPs, the organisation of a series of events have been undertaken, such

[a]Ny-Ålesund Science Managers Committee (NySMAC) was established to enhance cooperation and coordination among researchers and research activities in Ny-Ålesund – Svalbard.

as the first Arctic Metrology workshop in 2015 and the session on Metrology in Arctic Environment, supported by EURAMET and BIPM at the 2016 Arctic Circle Assembly.

The proposal was drafted to:

- Address the current performance limits and improve measurement strategies in terrestrial (i.e. non-satellite) ECV measurement capabilities in climate-sensitive regions (Arctic and Alpine environments).
- Establish a permanent Arctic Metrology Facility in a polar research station, to directly link metrological traceability to on site environmental measurements, with the implementation of dedicated devices, specific calibration procedures, and uncertainty evaluations including quantities of influence. This should be carried out in close cooperation with the interdisciplinary research community at the Ny-Ålesund international Arctic research facility.
- Optimise and integrate the combined measurement capabilities by developing the metrology tools to enable robust comparison between different measurements of the same geophysical parameters including the effect of temporal and spatial co-location differences. Equivalent tools also developed for the combination of different data sources to provide a best estimate of the atmospheric and cryosphere state together with the combined uncertainty estimate.
- Implement an Alpine open-air laboratory, for testing, comparing and evaluating instrumental performances and for adopting metrology techniques to evaluate field measurement uncertainties under the harsh environmental conditions experienced across the three key climate regions.

Following an open discussion within the climatology community, the MeteoMet consortium intends to contribute in the study and definition of reference-grade ground-based observing stations, in terms of instruments capabilities, procedure to establish full documented traceability and target uncertainty.

Ground-based stations continue to play a key role in the measurement of ECVs for the generation of data series, to detect long-term climate evolution. To reach full reliability and comparability in different places and different times, measured records need documented traceability to the SI and uncertainty evaluations. These metrological aspects are fundamental when measurement sites and stations are designed to provide reference-grade data. A proposed study addresses the theoretical and experimental evaluation of target uncertainty, measurements methodology, instruments characteristics, and observing site requirements for reference climate ground-based observing sites.

The establishment of the metrological requirements for air temperature and precipitation reference surface-based observing systems will allow improvements in the monitoring accuracy of local meteorology and climate change. It will also imply the possibility of performing stronger validation and realistic quantification of the climate models, climate change and climate predictions in a global view, as well as their use for other scientific studies related to the understanding of Earth's evolution. It will be also a very useful tool for the validation of space-based measurements.

The philosophy behind the definition of the metrological requirements for a reference-level surface observing system could also be used for other purposes, other variables, and/or in other networks, including where the data quality requirements are not as stringent, such as urban areas and agricultural sites. When top-level requirements are defined, downgrading the specification can lead to a better classification of sites, thus improving the current siting classifications under a cost-efficient approach. Adapting these requirements to applications that could work with larger uncertainties of measurement, reduced calibration and maintenance frequency, could address observational requirements for a wide range of application areas across all WMO and WMO-sponsored Programmes, as well as products and services from the NMHS.

Key improvements of this proposal with respect to the state-of-the-art can be summarized as it follows:

- a unique definition of reference-grade climate records, in terms of required measurement uncertainty, measurement method and instrument characteristics, including documented traceability to SI;
- highest quality installations, as reference observing stations in distributed networks;
- improvement in site classification and sustained performances classification guides;
- a contribution in the renewal process for historical and centennial stations;
- a preliminary contribution for the definition of reference urban and agricultural stations;
- a contribution in future actions, towards the creation of a European global climate reference network.

At the time of the submission of this article, the mentioned actions are being considered, to establish continuity in this fruitful collaboration between the metrology and meteorology/climatology communities. The creation of Joint Research Units and Joint Research Laboratories is also being discussed within MeteoMet partners. Such distributed centres aim at becoming references for delivering high-quality research and services for potential stakeholders needing to deliver more robust data. Fields like agro-meteorology, precipitation, geology, weather forecasting and early warning services, climate research institutions and universities are all expressing interest. Needs range from defining calibration procedures in field, also according to ISO 17025:2005, to certification of weather records also for legal aspects in insurance issues linked to agricultural production, to traceable and comparable data, quality and comparability of network stations under cost effective parameters, and more. Such joint initiative are being drafted by project partner and collaborators, to create consortia where all participating partners can contribute in developing specific areas of metrology to support those needs and deliver calibration services and dedicated procedures. This process will also try to avoid duplication and make well-identified distributed centres as references for data quality.

The proposed studies combine the expertise achieved in traditional fields of metrology into new interdisciplinary and multidisciplinary strategies.

The general vision of this project and the associated initiatives is to establish permanent liaisons between the involved communities, for better environmental and climate knowledge and benefit to the present and future generations of operators and scientists. It will also imply the possibility of performing stronger validation and realistic quantification of the climate models, climate change and climate predictions in a global view, as well as their use for other scientific studies related to the understanding of Earth's evolution and most importantly contributing to Earth's survival.

4.3 Impact

World leading manufacturers – such as Rotronic and Vaisala – will use the calibrations and tests performed within the framework of the MeteoMet project to improve their instruments. The GCOS Reference Upper-Air Network (GRUAN), WMO CIMO, WMO CCl[b], and ISTI[c] have been kept regularly updated on the project results by teleconferences. Hydro-meteorological agencies and local environmental services – such as, the MeteoSwiss (Payerne research site), UK MetOffice, ARSO (Slovenia), ARPA (Piemonte, Val d'Aosta - Italy), Società Meteorologica Italiana (Italy), and European Meteorological Society – have been updated on the project results by dedicated meetings.

The project International Conference on "Metrology for Meteorology and climate" (MMC), launched by MeteoMet in 2014 [25] is now recognized worldwide as a reference event in this interdisciplinary field. The MMC-2016 was held in conjunction with WMO CIMO Technical Conference (TECO) for a full week of presentations, satellite meetings and presence at the Meteorological Technology World Expo in Madrid. The MMC-2019 is already planned together with Tempmeko and Tempbeijing, in Beijing, China.

The project results are moreover expected to contribute to the improvement of:

- ISO 17714:2007 and CCT[d] Task Group for Guides on Thermometry (CCT-TG-GoTh) and Working Group for Humidity (WG-Hu);
- ISO/TS 17892-1:2004 and ISO 11271:2002 on Soil moisture;
- CIMO-XV/Doc. 4 and CIMO Expert team on standardisation documents on siting uncertainty;
- European Earth Observation Programme "Copernicus"[e];
- PermaNET network[f].

4.4 Acknowledgments

This work is being developed within the frame of the European Metrology Research Program (EMRP) joint research project ENV07 and ENV58 "METEOMET". The EMRP is jointly funded by the EMRP participating countries within EURAMET and the European Union.

[b]Commission for Climatology
[c] International Surface Temperature Initiative
[d]*Comité Consultatif de Thermométrie* (Consultative Committee for Thermometry)
[e]http://www.copernicus.eu/
[f]http://www.permanet-alpinespace.eu/home.html

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Annex 1. MeteoMet summary data, partners and collaborators

Table 1. MeteoMet summary data

JRP start date and duration:	1 October 2011, 36 + 36 months
Budget: Number of planned deliverables Total person month equivalent (including grants)	> 11 M€ 350 Approx. 1000
JRP-Coordinator:	Dr Andrea Merlone, INRIM
JRP website address	http://www.meteomet.org

Table 2. MeteoMet Partners and Granted Institutions

Acronyms	Name	Nationality
Funded Partners		
INRIM	Istituto Nazionale di Ricerca Metrologica (acting as JRP-Coordinator for the JRP-Consortium)	Italy
BEV/PTP	Physikalisch-Technischer Pruefdienst des Bundesamt fuer Eich- und Vermessungswesen	Austria
CEM	Centro Espanol de Metrologia	Spain
CETIAT	Centre Technique des Industries Aerauliques et Thermiques	France
CMI	Cesky Metrologicky Institut Brno	Czech Republic
CNAM	Conservatoire National des Arts et Metiers	France
CSIC	Agencia Estatal Consejo Superior de Investigaciones Cientificas	Spain
DTI	Teknologisk Institut Denmark	Denmark
GUM/MG	Ministerstwo Gospodarki	Poland
IMBiH	Institut za mjeriteljstvo Bosne i Hercegovine	Bosnia and Herzegovina
INTA	Instituto Nacional de Tecnica Aeroespacial	Spain

INTiBS	Institut Niskich Temperatur i Badan Strukturalnych	Poland
JV	Justervesenet	Norway
MIKES/VTT	Mittatekniikan Keskus/ Teknologian tutkimuskeskus	Finland
NPL	National Physical Laboratory	United Kingdom
PTB	Physikalisch-Technische Bundesanstalt	Germany
SMD	Federale Overheidsdienst Economie, KMO, Middenstand en Energie	Belgium
SMU,	Slovensky Metrologicky Ustav	Slovakia
SP	SP Sveriges Tekniska Forskningsinstitut AB	Sweden
TUBITAK/UME	Türkiye Bilimsel ve Teknolojik Araştirma Kurumu/Ulusal Metroloji Enstitusu	Turkey
UL	Univerza v Ljubljani	Slovenia
VSL	Van Swinden Laboratorium B.V.	Netherlands
Unfunded Partners		
Chalmers	Chalmers tekniska hoegskola AB	Sweden
SHOM	Service hydrographique et océanographique de la Marine	France
UWr	Uniwersytet Wrocławski	Poland
Research Excellent Grant/ Research Mobility Grant		
REG(AU)	Aahrus Universitet,	Denmark
REG(C3)	Universitat Rovira i Virgili, Centre for Climate Change	Spain
REG(EV-K2 CNR)	EV-K2 Consiglio Nazionale delle Ricerche	Italy
REG(IMAMOTER-CNR)	Istituto per le Machine Agricole e MOvimento TERra – Consiglio Nazionale delle Ricerche	Italy

REG(KIT)	Karlsruhe Institut für Technologie	Germany
REG(UniGe)	Università degli Studi di Genova	Italy
REG(UniNa2)	Seconda Università degli Studi di Napoli	Italy
REG(UPC)	Universitat Politècnica de Catalunya	Spain
RMG(FSB)	Fakultet Strojarstva I Brodogradnje	Croatia
RMG(INBiH)	Institut za mjeriteljstvo Bosne i Hercegovine	Bosnia and Herzegovina
RMG(INTiBS)	Institut Niskich Temperatur i Badan Strukturalnych	Poland
RMG(MBM)	Montenegrin Bureau of Metrology	Montenegro
RMG(SMU)	Slovensky Metrologicky Ustav	Slovakia

In different ways, along the lifetime of the project, since 2011, are or have been involved as collaborators in MeteoMet:

Private companies:

3a Srl, Bodeker-Scientific, CAE, Cal Power, Climate Consulting S.r.l., Grafinta Sociedad Anonima, Lombard & Marozzini, Lufft, Meteomodem, Michell Italia S.r.l., Rotronic, TRUEBNER Instruments, Vaisala Oyj, NKE Instrumentations.

Hydro-meteorological and environmental agencies and Organizations:

Agencia Estatal de Meterorologia (AEMET), Alfred-Wegener-Institut (AWI), Agenzia Regionale per la Prevenzione e l'Ambiente(ARPA) Lombardia; Piemonte; Sardegna; Valle d'Aosta, NOAA's National Climatic Data Center, Czech Hydrometeorological Institute, Danish Meteorological Institute - Department of Geosciences, DHI-Water Environment, Environmental Agency of the republic of Slovenia (ARSO), Federal Civil Aviation Department - Federal Hydrometeorological Institute of Bosnia and Herzegovina (FHMZ), Finnish Meteorological Institute (FMI), Japan Meteorological Agency (JMA), Met. Office Research Unit, Meteo Swiss, Météo France National, Royal Meteorological Institute of Belgium, Royal Netherlands Institute for Sea Research (NIOZ), Royal Netherlands Meteorological Institute (KNMI), Scientific Committee on Oceanic Research (SCOR), Sistemas de Monitorización Medio Ambiental, S.L.U., Società Meteorologica Italiana (SMI), Swedish Meteorological and Hydrological Institute (SMHI), Turkish State Meteorological Service (TSMS), World Meteorological Organization (WMO).

Research Institutes, networks and Initiatives:

Cooperative Institute for Climate and Satellites – NC, Extreme Energy Events Project Centro Studi e Ricerche "E. Fermi", GCOS Reference Upper Air Network, Hochschule Bonn-Rhein-Sieg -

Internationales Zentrum für Nachhaltige Entwicklung - Institut für Umweltphysik, Instituto Nacional de Tecnologìa Industrial, International Association for the Physical Sciences of the Ocean (IAPSO), International Association for the Properties of Water and Steam (IAPWS), International Surface Temperatures Initiative, Consiglio Nazionale delle Ricerche (Istituto di Ricerca per la Protezione Idrogeologica – IRPI; Istituto di Scienze dell'Atmosfera e del Clima – ISAC; Istituto per le Macchine Agricole e Movimento Terra – IMAMOTER, Istituto di Metodologie per l'Analisi Ambientale – IMAA) , Istituto Superiore per la Protezione e la Ricerca Ambientale (ISPRA), Joint Committee on the Properties of Seawater, Laboratorio de Calibración de Sensores Meteorológicos - Osservatorio Meteo Duomo

Universities:

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