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The MeteoMet project – Metrology for Meteorology: challenges and results

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5 JV Justervesenet, Kjelle, Norway

6 UL-FE/LMK Univerza v Ljubljani, Ljubljana, Slovenia

7 PTB Physikalisch-Technische Bundesanstalt, Braunschweig, Germany

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9 CEM Centro Español de Metrología, Tres Cantos, Madrid, Spain

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15 MIKES Mittateknikan Keskus, Espoo, Finland

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Abstract: Aiming to ensure the metrological traceability to the International System of Units (SI) through national standards in meteorological observations and climate data, the joint research project “MeteoMet - Metrology for Meteorology” was funded by European Metrology Research Program (EMRP). The 3-years project started in 2011 and involved 18 European National Metrological Institutes (NMIs), 3 universities as unfunded partners and 35 collaborating stakeholders including national meteorology organisations, research institutes, universities, associations and instrument companies.

The major challenge of the project was the propagation of a metrological measurement perspective to meteorological and climate observations, in order to better meet the expressed requirement of reliable data and robust datasets over large scale and long term.

The project covered several aspects from upper air to ground based measurements. It included development and testing of novel instrumentation as well as improved calibration procedures and facilities, in-situ practical calibrations, instrument intercomparison under real dynamic conditions and best practice dissemination. Historical temperature data series validation with respect to measurement uncertainties and a methodology for recalculation of the values were included.

A valuable outcome has been the establishment of a long lasting cooperation between metrologists and climatology and meteorology communities. The NMIs involved in this project have jointly worked in order to address the needs expressed by meteorological data users, opening up new perspectives for both research fields.

Key words: Metrology, Calibration, Earth surface observations, Historical temperature data series, Joint Research Project, MeteoMet, Traceability, Upper air.

1 Introduction

In the last decades climate change became a crucial issue (IPCC, 2007, 2014; Blunde and Arndt, 2012) because of its ecological, environmental, economic and political implications. Reliable assessments of climate change depend crucially on data quality, but measurements of Essential Climate Variables (ECVs), as defined by the Global Climate Observing System (GCOS) (2003; 2004), are still often expressed without uncertainty and clear traceability statement. Nowadays the scientific community is moving to fill this gap: the World Meteorological Organization (WMO) signed the Mutual Recognition Arrangement (MRA) of the Comité International des Poids et Mesures (CIPM) during a workshop with the Bureau International des Poids et Mesures (BIPM) (WMO-BIPM, 2010). The two international associations recognised the need of improving meteo-climatic measurements and opened a common discussion about the collaboration as well as effective actions to be undertaken by National Metrology Institutes (NMIs).

In line with these requirements the project MeteoMet – Metrology for Meteorology - was launched in 2011 by 18 European NMIs. The project has considered several variables involved in meteorological observations from upper air to ground based measurements: temperature, pressure, humidity, wind speed and direction, solar irradiance (Merlone *et al.*, 2012).

Fully characterised calibration procedures, with complete uncertainty evaluations were provided, through laboratory and in field calibration campaigns, sensors characterisations, laboratory and field comparisons, development of new instruments.

This paper presents first an overview of the MeteoMet project context, then reports the most noticeable scientific progresses and finally discusses the impact of metrological and meteorological cooperation. The activities described are focused on key highlights achieved during the project.

2 Project context, rationale and objectives.

Recent decades have seen notable changes in the global and European climate, together with an increased desire to both monitor climate change and reduce the impact of human activity on the climate. The need to improve data has been expressed by different climate data users such as climatologists, economists and politicians (IPCC, 2007, 2014; Blunde and Arndt, 2012; GCOS, 2003; 2004).

To address these requirements and enable the development of a sustained integrated monitoring and observation system for Europe this project responded to some principal needs:

2.1 *Climate measurements calibration uncertainty evaluation*

Although standard operating procedures and data quality objectives are in place for some measurements, extensions to a wider range of applications and parameters and improvements of existing procedures are necessary. Routine calibration procedures are generally not adopted for most of the measurements but are necessary to maintain a high level of confidence in the quality of the data.

2.2 *Improving humidity sensors and calibration methods*

The humidity of air in terms of the volume concentration of water is a key parameter to be measured for understanding the climate processes all over the world. A big challenge for humidity sensors of every type is the wide dynamic range of more than a factor 10 000 of water content in the atmosphere.

Errors in upper-air observations due to the effect of solar radiation on temperature measurements and the uncertainty of saturation water vapour data are issues that require detailed study. Better instruments with smaller calibration uncertainties are required by the meteorological community.

2.3 *Calibration of reference radiosondes*

In 2007, the Global Climate Observing System (GCOS) of the WMO laid out the need for a GCOS Global Reference Upper-Air Network, or GRUAN. Current upper air measurements networks do not meet the accuracy and detail of observations needed to specify climate variability and changes above the Earth's surface (WMO, 2010). To meet GRUAN's requirements for the reliability of humidity measurements, improved traceable calibration methods are needed. GRUAN specifies the target relative uncertainties in the stratosphere of 2% in terms of the mixing ratio. A key factor in achieving the required reliability of data is the traceability of radiosonde sensor measurements through appropriate calibration. However, humidity calibrations in conditions equivalent to Upper Troposphere and Lower Stratosphere (UT/LS) with conventional systems are very time consuming and not suitable in this context.

2.4 Calibration of automatic weather stations

Weather stations sensors need to be constantly calibrated to improve the reliability of measurements. Accurate methods for in-situ calibrations of weather stations, including those operating in extreme conditions, are required. Input from NMIs in defining procedures, developing capabilities, calibration standards and traceability chains can improve data quality.

2.5 Robustness of the historical temperature measurement data

Historical data series often lack clear statements on the measurement techniques, sensors, calibration uncertainty, and traceability to standards and temperature scales, making it difficult to assess the reliability of the data and to compare the data of the different periods.

3 Results delivered

3.1 Wind speed measurements, calibration and uncertainty evaluation

3.1.1 Development of a method for establishing traceability for wind speed measurements

With a novel laser based anemometer (LIDAR) on-site wind speed measurements at 10 m and 50 m were performed in different terrains and related to simultaneously measured data of an ultrasonic anemometer 10 m above ground. The ultrasonic anemometer of the type Vaisala WTM 700 has previously been calibrated according to international standards in different wind tunnels ().

For close-by measurement positions of both systems in flat terrain the deviation of the mean values over one hour were < 1% (Figure 1). The results show that comparison measurements with the new laser based wind LIDAR can be used for on-site calibrations provided that the wind conditions for the reference and test location are consistent.

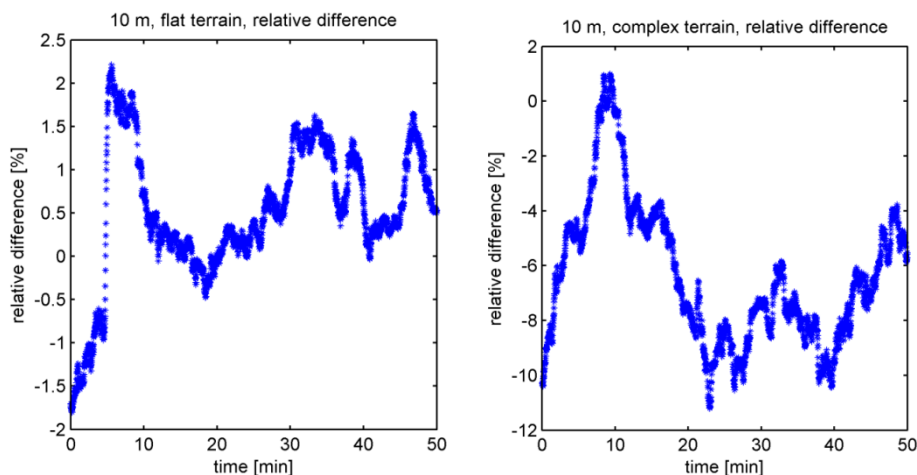


Figure 1: Relative difference between the wind speed data of the calibrated Vaisala ultrasonic anemometer and the laser based PTB-Lidar; the measurement data were detected simultaneously at the same measurement height, 10 m above ground with measurement positions 1 m close each other.

3.2 Improving humidity sensors and calibration methods

Water vapour is the most important atmospheric greenhouse gas, which causes a major feedback to global warming and other changes in the climate system. The knowledge of physical properties, distribution and climate induced changes of water vapour is especially important in the UT/LS, where vapour plays a critical role in atmospheric radiative balance, cirrus cloud formation, and photochemistry. Accurate understanding of the water cycle is frequently limited by the uncertainties in current water measurements, particularly in the 2 to 100 ppmV concentration range. Furthermore, reduction of the uncertainty of the water vapour formulation in the temperature range between -80 °C and +100 °C is needed for the improvement of humidity .

3.2.1 A traceable TDLAS hygrometer

Tunable diode laser absorption spectroscopy (TDLAS) has proved in the past to be a highly interesting technique for sensitive, selective and fast water detection, in particular for environmental sciences, which has also favourably

performed in a recent large scale sensor intercomparison (Fahey *et al.*, 2014). Here TDLAS hygrometers have been developed e.g. for airborne platforms or to better study the exchange processes between plants, soil and the atmosphere (Seidel *et al.*, 2012, 2014; Buchholz *et al.*, 2014a; Hunsmann *et al.*, 2008). Within MeteoMet a new, absolute, wide dynamic range TDLAS hygrometer was developed using specially designed single pass and multipass gas cells. This instrument was operated using a distributed-feedback (DFB) tunable diode laser emitting at 1.4 μm , which can relatively easily be replaced by a 2.7 μm laser to enhance the sensitivity depending on the intended amount fraction measurements range (Nwaboh *et al.*, 2014a). The MeteoMet hygrometer was operated in a sealed housing purged with dry air or nitrogen in order to minimize parasitic light absorption (Buchholz and Ebert *et al.*, 2014) by water vapour outside the optical cells. Spectroscopic amount fraction measurements were performed and analysed in a similar manner as reported earlier. The TDLAS sensor is operating as an absolute system, which has sufficient absolute accuracy and long term stability to be operated without the need for frequent calibration by means of reference gases from i.e. humidity generators (Nwaboh *et al.*, 2013; Buchholz *et al.*, 2014b). The traceability of the TDLAS H_2O amount fraction results to the International System of Units (SI) is addressed by appropriate spectral line data for the used water transition (Werhahn *et al.*, 2014; Pogány *et al.*, 2013), i.e. collisional spectral broadening coefficients and transition line strength, as well as by the traceably measured gas properties (gas pressure and temperature), and the optical interaction path length (Nwaboh *et al.*, 2014b) independently determined beforehand. The MeteoMet TDLAS hygrometer's absolute performance was validated via comparison with the German national humidity standards. For this absolute measurement scheme employed to the TDLAS hygrometer, H_2O line data have been measured (see 3.2.3). Figure 2 (upper panel) depicts the comparison of the TDLAS hygrometer at the lower concentration range of 1-350 ppm with respect to the national primary humidity standard, which uses a coulometric humidity generation principle (Mackrodt, 2012).

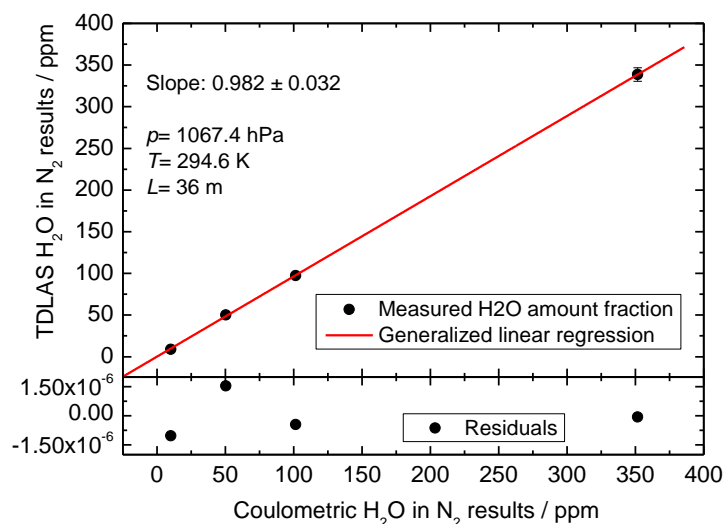


Figure 2: Comparison of TDLAS versus coulometric H_2O in N_2 amount fraction results

TDLAS H_2O -in- N_2 results are compared to the coulometric H_2O -in- N_2 amount fractions. The slope value in Figure 2 is close to 1, showing an excellent absolute agreement between the TDLAS and coulometric results, as well as a good linearity. Residuals from the linear fit are shown in the bottom of Figure 2.

A comparison of the TDLAS results to other humidity standards (not shown) throughout the full range of 1-18000 ppm resulted to a slope of 0.9932 ± 0.0088 , again indicating an excellent compatibility between absolute TDLAS results and the humidity standard values, also for the full range, even though the TDLAS sensor response was never calibrated and the TDLAS response is solely based on absolute knowledge of p , T , length as well as H_2O spectral data.

3.2.2 Improvements of molecular spectral line data at 1.4 μm

An independent, specially designed TDLAS setup was employed to measure the H_2O self-broadening coefficient (γ_{self}) and its temperature dependence (n_{self}) at 1.4 μm . The setup contained a DFB diode laser emitting at 1.4 μm and an adaptable, short gas cell with variable path length (2 - 50 mm). The variable path length (VPL) cell is designed such that both the laser light output port and the detector (an InGaAs photodiode) are located inside the gas cell, i.e. inside the measurement gas. This design suppresses light absorption by parasitic water outside the gas cell, which is important for a high absolute accuracy (Nwaboh *et al.*, 2013, 2014a). The light from the laser to the gas cell is coupled

via a single mode fibre. For a highly homogenous water vapour temperature inside the VPL gas cell, we immersed the VPL cell in a water bath. The temperature of the water bath was varied to determine the temperature dependence of the spectral properties. The spectroscopic broadening coefficient data were analysed similar as reported previously. The air broadening coefficient (γ_{air}) and its temperature dependence (n_{air}) for the probed H₂O line at 1.4 μm were determined with relative uncertainties of 1.6 % and 2.7 % respectively. As shown in Table 1, a slight improvement has been achieved for the uncertainty of γ_{air} while an improvement by a factor of 7 has been reached for that of n_{air} . The relative combined uncertainties of γ_{self} and n_{self} were 2.8 % and 1.4 %, respectively. Compared to data taken from the HITRAN2012 data base (www.hitran.com), an improvement by a factor of 4 has been achieved for γ_{self} as shown in Table 1. No previous value of n_{self} was reported in the HITRAN data base. The traceability of these broadening coefficient results to the SI was addressed via the traceability of the measured input parameters, i.e. traceable gas pressure and temperature values. The water vapour pressure and temperature were measured with sensors calibrated against the respective PTB standards.

Table 1: Improvements of H₂O broadening coefficients and temperature dependence at 1.4 μm

Coefficient	Relative combined uncertainty (HITRAN2012)	Relative combined uncertainty (this work)	Improvement factor
γ_{self}	10 %	2.8 %	4x
γ_{air}	2 %	1.6 %	1.3x
n_{self}	-	2.4 %	-
n_{air}	20 %	2.7 %	7x

The line strength value of the H₂O line at 1.4 μm has also been determined. In order to perform the spectroscopic line strength measurements, the VPL gas cell was replaced by a 20 cm single pass gas cell whose path length is traceable to the SI. Also, here, the water vapour gas pressure and temperatures were measured with sensors calibrated against the respective PTB standards. The analysis of measured line strength data was done according to (Pogány *et al.*, 2013; Nwaboh *et al.* 2014a). The relative combined uncertainty of the line strength value derived here is 1.72 %. Compared to the 10 % uncertainty reported by HITRAN for the H₂O line at 1.4 μm , an improvement by a factor of about 6 has been achieved for the results reported in this work.

3.2.3 Intercomparison of airborne field humidity sensors of different types (Aquavit 2 campaign).

One of the most comprehensive inter-comparison campaigns for airborne hygrometers, termed *AquaVIT* (AV), took place in 2007 at the Aerosol Interaction and Dynamics in the Atmosphere (AIDA) chamber available at the Karlsruhe Institute of Technology (KIT) in Germany. AIDA is a unique, highly stabilized, 84 m³ aluminium vessel, which can be precisely controlled over a pressure range of 1 to 10⁵ Pa (± 1 hPa) and a temperature range of 183 K to 313 K (± 0.3 K). This range of conditions allows for simulating atmospheric cloud processes in UT/LS on relevant time scales. The possibility of rapid and large pressure variations (e.g 1000 hPa to 700 hPa in 2 min) e.g. at ice or water saturated conditions allows controlled formation of ice, mixed-phase or liquid water clouds. One significant metrological deficit of AV was that no traceable reference instrument participated in inter-comparison experiments, therefore no direct link to the national metrological water scales and hence no link to the SI could be established. Consequently a second inter-comparison, *AquaVIT2* (AV2), was organized in April 2013, which, also provided a traceable link to the international humidity scale. This AV2 campaign was organised together with MeteoMet, by an international organizing committee, and again located at KIT/AIDA. 17 groups from 5 different countries participated in AV2 with 32 atmospheric hygrometry instruments and 6 calibration/validation/reference systems. The AV2 inter-comparison was divided in two parallel comparisons: 1) AV2-A was a simultaneous comparison of all instruments (including sampling and in situ instruments) over a broad range of conditions characteristic for the UT/LS using AIDA; 2) AV2-B (Smorgon, 2014) was a sequential, metrological comparison of selected hygrometers and their reference calibration infrastructure by means of a traceable chilled mirror hygrometer and a commercial two pressure generator acting as a highly stable source of water vapour by PTB. Both AV2-A and AV2-B comparison experiments were performed on a blind basis, the data delivery was agreed by all participants and the data analysis and data-sets were assigned to two independent referee teams. This inter-comparison gave for the first time calibration data to the participants from the atmospheric community on a metrological basis. This is an added value to the measurements taken in the tropospheric and stratospheric region.

3.2.4 Water vapour formula improvement

Static measurement principle experiments of both temperature and pressure were carried out in the MeteoMet project in order to improve the calibration of the instruments used for accurate water vapour mole fraction measurements in the atmosphere. The temperature is measured with capsule-type standard platinum resistance thermometers (CSPRTs) calibrated at the ITS-90 fixed points (Preston-Thomas, 1990), while the pressure is measured by a set of capacitive diaphragm-type pressure gauges with increasing full scale to cover the whole range of vapour pressure from 10^{-1} Pa to 105 Pa. Two different devices were used to detect and quantify corrections related to possible systematic effects, and to define their impact on the final uncertainty budget. Investigation of the saturation vapour pressure along the sublimation line have been performed by INRIM, in the temperature range from the triple point of water down to 60 °C.

The first device developed at the CETIAT in cooperation with CNAM was conceived to realize a static measurement of pressure and temperature of a pure water sample in a copper cell, placed inside a closed, temperature-controlled thermostat (Mokdad *et al.*, 2012). The covered temperature range was comprised between 193.15 K and 373.15 K, corresponding to saturation vapour pressure from 0.1 Pa to 105 Pa for the pure water. The vapour pressure was measured by three absolute capacitance manometers (type MKS), with a full-scale pressure of 1 Torr, 100 Torr, and 1000 Torr with an external thermalization. The measurement of the equilibrium temperature was made with Goodrich CSPRTs, calibrated by CNAM at the highest degree of accuracy.

The second device developed at MG/GUM consisted of the following components: a calibration bath, in which stainless steel experimental cell was immersed; one pressure transducer (capacitive diaphragm) to measure the vapour pressure; a platinum resistance thermometer (PRT) to measure the sample temperature; a turbomolecular pump to maintain a high level of vacuum inside the system. Pump, experimental cell and manometer were connected by means of ultra-high vacuum fittings. The pressure gauge was a differential manometer, with one side kept at a very low pressure and the other connected to the experimental cell.

INRIM device was composed of: a calibration bath, in which a Pyrex sample cell was immersed; a PRT to measure the sample temperature; a turbomolecular pump to maintain a high level of vacuum inside the system; two capacitive diaphragm pressure gauges to measure the vapour pressure. The sample cell was cylindrically shaped with a terminating bulb. The bulb was filled partially with about 1 ml of distilled water, taken from a commercial ultra-pure water source. The aim was to increase the probability to keep water at a super-cooled state at temperatures well below 273.15 K.

Water vapour pressure measurements realized in this project were compared to the reference equation determined by Wexler (1976), adapted to the International Temperature Scale of 1990 by Sonntag (1990). The plots in Figure 3 show relative differences between experimental data and Wexler's equation modified by Sonntag.

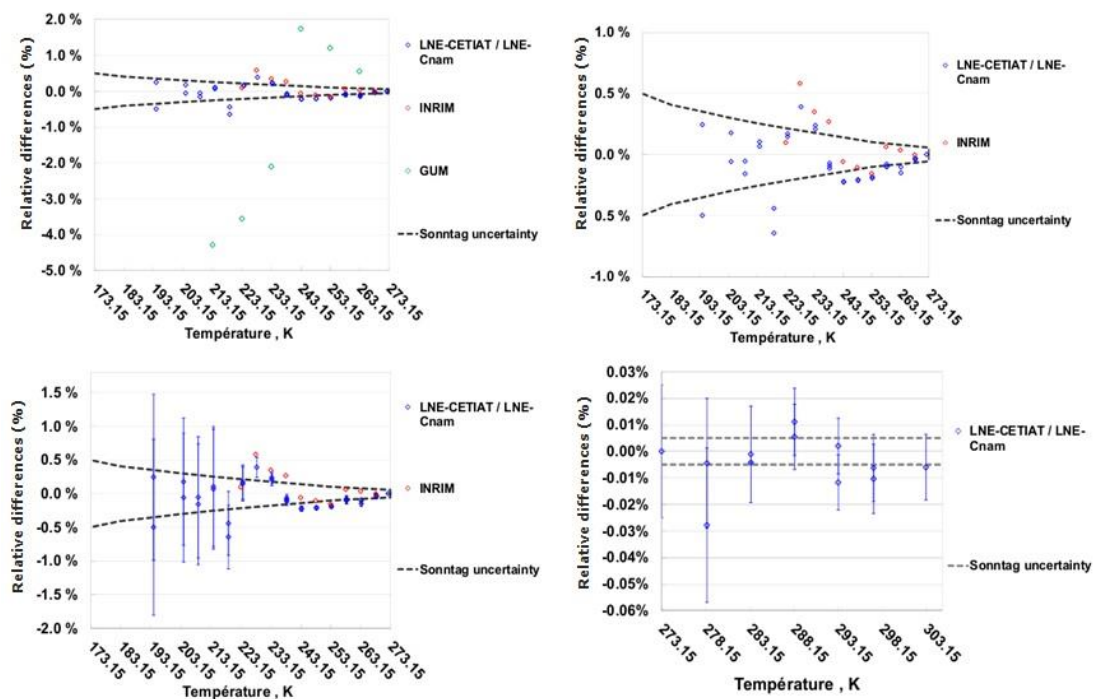


Figure 3: Relative differences between experimental data measured in this JRP and reference Wexler's equation modified by Sonntag.

3.2.5 Novel methods and instruments for atmospheric humidity measurement.

In these tasks the focus was the development of new sensors to improve measurements of temperature, humidity and pressure in the lower and upper atmosphere and reduce calibration uncertainty. The developments concerned are: an acoustic thermometer, a free-space non-contact multi sensor and novel methods for GPS and Galileo-based measurements.

A) The recent advances in theoretical modelling of the microwave field inside a quasi-spherical cavity (Mehl, 2009), especially related to the development of quasi-spherical acoustic gas thermometers, were exploited to develop a new generation of compact, robust and high-sensitivity hygrometers based on microwave quasi-spherical resonant cavities, with target relative measurement uncertainties at the level of 1 ppmv.

The differential microwave hygrometer (DMWH) measures the polarizability change in a moist gas with respect to the same gas devoid of humidity. The change is proportional to the shift of resonance frequencies in a microwave resonator filled with moist gas, with respect to another nearly identical resonator filled by the same dry gas. Differential measurements remove any dependence from gas pressure and temperature. This technique also offers the possibility to check if water condenses on the inner surface of the sphere, by measuring selected TE and TM microwave modes

Two generations of differential microwave hygrometers were realized. The first was built with two copper quasi-spherical resonators that were used for the Boltzmann constant determination experiment, namely BCU1 and TCU1. The second generation was built to overcome the problems of poor thermal stability of the first one, and to reduce the overall size. The resonators BCU1 and TCU1 had an inner volume of 523.6 cm³ but two different masses; conversely the volume of the spheres of the second hygrometer generation was about 65.6 cm³ and they were realized both with the same mass. Depending on the different dimensions of these spheres, two different experimental setups were developed. Figure 4 shows the second generation hygrometers and their associated experimental setup.

A test humidity generator was developed, it is composed of two gas lines, able to produce moisture content between 100 ppmv and 1×10^4 ppmv. Gas lines were equipped with two cold traps, to additionally determine water concentration with a gravimetric method and validate the measurements performed with microwave hygrometers. A dedicated system for microwave signal generation and measurement was developed and characterized. It uses a robust and rapid frequency-locking technique, based on a modified version of the Drever-Pound-Hall technique (Drever *et al.*, 1983), and is able to follow sudden changes of the frequency in only few seconds.

At low water-vapour concentration of few parts per million in volume, the differential microwave hygrometer was able to measure a water concentration step of 100 ppmv, followed by a step of about 6000 ppmv and then followed by a step of 200 ppmv. At high water-vapour concentration, the hygrometer was able to measure the moisture evolutions of the laboratory during more than ten hours and with a better time response than a commercial high-quality hygrometer.

In this work, the following objectives were attained:

1. demonstrate the potential of the apparatus to perform an absolute measurement of moisture in air;
2. show the ability of detecting traces of liquid on the inner resonator surface;
3. demonstrate the robustness of the detection method, since frequencies can potentially remain locked indefinitely;
4. show that, by reducing the size of the resonators, the quality of the signal was improved: this opens the way to further volume reductions.



Figure 4: second generation of microwave hygrometers and their assembly

B) A novel, rapid, non-contact air-temperature sensing system has been designed and a prototype instrument constructed (Figure 5a) It is configured so as to be suitable for conventional (ground-based) meteorological use, and for stratospheric deployment. The device is designed to be mounted together with a TDLAS trace moisture instrument so that both temperature and humidity can be measured in the same open-cell space.

The thermometer uses measurement of speed of sound, by acoustic interferometry between a pair of acoustic reflectors, to make non-contact measurement of air temperature. Combination of this with TDLAS humidity measurement enables the necessary correction to be applied for the presence of water vapour. The non-contact nature of the measurement has the advantage of minimal perturbation of the measured condition by the instrument. The near-instantaneous sensing of both humidity and temperature allows rapid changes to be measured. Initial tests in a climatic chamber have shown that the thermometer works in a temperature range from $-40\text{ }^{\circ}\text{C}$ to $+40\text{ }^{\circ}\text{C}$, agreeing with a reference thermometer to within $0.1\text{ }^{\circ}\text{C}$ across this range (Figure 5b), after a single-point calibration at $20\text{ }^{\circ}\text{C}$. Very preliminary experiments varying other conditions show that the thermometer is able to operate at reduced pressure down to 50 hPa, and is insensitive to wind at speed of about 1 m s^{-1} , and to wetting of reflectors.

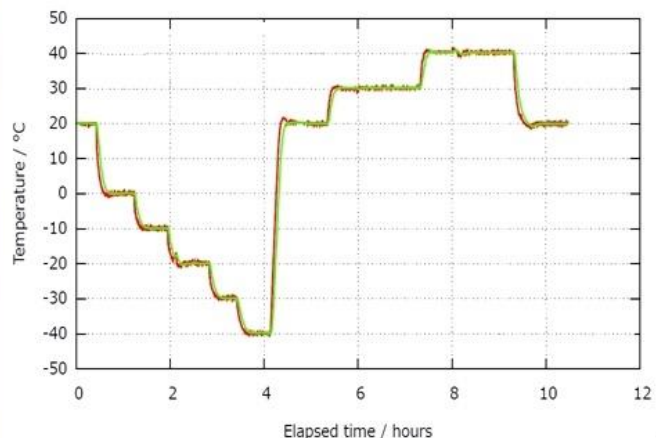


Figure 5: a) Acoustic free-space thermometer positioned inside a climatic chamber; b) Acoustic measurements (red line) in the range -40 °C to +40 °C, compared with measurements using a calibrated PRT (green line) shown for comparison. The starting points at time 0 correspond to the calibration point at 20 °C.

C) Global Navigation Satellite Systems (GNSS) signals such as GPS and Galileo can be used for measuring the atmospheric water vapour. With a ground-based approach, permanently installed GNSS receivers are used. In the case of GNSS receivers on-board satellites, vertical profiles of atmospheric temperature, pressure, and water vapour can be determined. In the project new models describing GNSS electromagnetic signals were developed and implemented., to determine tailor-made strategies for measuring atmospheric water vapour.

Using ground-based GNSS receiver networks it is possible to determine the Integrated Water Vapour (IWV) in the atmosphere, from an observed fractional phase φ :

$$\varphi = \rho/\lambda + N + f(\delta t^s + \delta t^r) + \ell_o + \ell_i + \ell_t + \mu + \varepsilon$$

where λ is the signal wavelength, ρ is the calculated geometrical distance between receiver and satellite, N is the integer number of cycles (ambiguity parameter) and f the signal frequency. δt^s and δt^r represent satellite and receiver clock errors respectively, ℓ_o is the signal error due to errors in the reported satellite orbital model, ℓ_t is the signal delay in the low atmosphere, ℓ_i is the signal delay in the ionosphere, μ is signal multipath, and ε is receiver measurement noise.

The effects identified that are of importance when estimating water vapour from GNSS signals are briefly summarized in the following list:

1. *Reference Frames*: the choice of reference frames shall be consistent between all satellite systems used and receiver antenna locations;
2. *Satellite Phase Patterns*: it is recommended to use satellites with phase centre models from the IGS based on estimation from several years' long time series;
3. *Ionosphere*: unmodelled ionospheric effects of higher order are not a significant error source that needs to be taken care of;
4. *Multipath*: Absorbent material below and just adjacent to the antenna can affect the estimated amount of water vapour at the percentage level. Careful documentation of changes in the environment of the antenna is essential.

Concerning satellite-based measurements, GNSS occultation measurements are considered a powerful tool for detecting climate trends (Steiner *et al.*, 2001). They are obtained by deploying GNSS receivers onboard Low Earth Orbit satellites, to observe the Doppler shift of the received signal phase and infer the vertical profile of the refractive index, in order to estimate temperature, pressure, and water vapour amount in the atmosphere.

The main uncertainty sources identified in satellite-based measurements are:

1. *Assumption of horizontal Stratification*: it is an important error source in the troposphere. The effect is are most pronounced below 7 km heights;
2. *Atmospheric Multipath*: strong gradients in refractive index are caused mainly by water vapour variations, may cause interference of signals.
3. *Separation of bending angle into pressure, temperature, and humidity*: from the Doppler shift, the bending angle of the signal path can be calculated, to infer a refractive index profile. The refractive index can be modelled as: $N = k_1 \cdot (p-e) / T + k_2 \cdot e / T + k_3 \cdot e / T^2$, where p is the atmospheric pressure, e is the partial pressure of the water vapour, T is the temperature, k_1 to k_3 are constants. At lower altitudes, the separation of bending angle into pressure, temperature, and humidity may cause errors.

3.3 Calibration of reference radiosondes

Radiosondes are used to obtain upper air weather data needed for climate change studies and weather forecasts. Reference radiosondes are being developed to meet GRUAN accuracy requirements and they will be used at GRUAN sites stations (Sairanen *et al.*, 2014). The major challenge in developing a humidity calibration system for radiosondes is the time of stabilisation at air temperatures down to -80 °C: when approaching very low water vapour concentration in

air at low temperatures the effects of surface moisture on walls and dead spaces in tubing become significant and the time required to obtain equilibrium lengthens too much for practical calibration purposes.

To overcome this problem, MIKES has been designing and constructing a calibration system comprising two saturators and an optimised measurement chamber. These will enable a fast change from a stable humidity level to another one in the chamber. High limit of relative humidity is achieved by supplying air to the chamber solely from a saturator (HS) immersed with the measurement chamber in a thermostatic bath. Water condensation in the chamber is prevented by a slight pressure reduction at the saturator outlet. The minimum relative humidity (RH) is achieved by the other saturator (LS) located in a separate liquid bath or a getter drier. Dew-point temperatures below $-85\text{ }^{\circ}\text{C}$ are achieved by the pressure reduction (2-P) or diluting with dry air (2-F) in the LS outlet. In near future, a thermostatic bath enables reaching dew-point temperatures down to $-90\text{ }^{\circ}\text{C}$. As the air supply to the measurement chamber can be switched between the saturators or the supply air can be mixed from outlets of the two saturators, the dew-point temperature at the measurement chamber inlet can be changed quickly.

To find a chamber geometry ensuring fast humidity stabilisation, numerical simulations have been successfully performed using COMSOL® software. The simulations covered air flow, temperature and water vapour concentration in the chamber with different geometries. Based on the simulations, a stainless steel chamber was constructed. The effect of a step change in the inlet dew-point temperature was studied experimentally with a radiosonde and a cavity ring down spectroscopy (CRDS) humidity analyser using the new chamber and the chamber of the MIKES Relative Humidity Generator (MRHG) (Heinonen and Uusipaikka, 2005). The air temperature was $-70\text{ }^{\circ}\text{C}$ in these tests. Both simulations and experiments show significant improvement in the time of stabilisation in the new chamber compared to the MRHG chamber.

3.4 Calibration of automatic weather stations

3.4.1 Traceable protocols for ground-based measurements

In order to develop traceable protocols for temperature, humidity, and pressure ground-based measurements by automatic weather stations (AWSs) a review of the procedures, type of sensors, calibration practices was carried out.

A database (<https://meteomet.e-science.pl>) was prepared by which presents the state of art of weather stations in European countries. It collects the following data:

- a) weather station information: owner, location, type, amount, type of meteorological parameters observed;
- b) sensor employed: manufacturer, type, range of measured parameter, accuracy, ability to dismantling;
- c) measurement: frequency, method, software to register data;
- d) calibration: frequency, method;

The base contains data obtained from 20 countries. The database is a tool to serve the community of metrologists and meteorologists even after the end of the project. It is open to further complement the data and modifications. The database allows creating all kinds of statistics related to the data.

To define the best procedures for calibration of sensor employed in AWSs a group of different types of sensors, commonly used by the meteorological services, was selected. The sensors were tested in laboratory conditions at every $10\text{ }^{\circ}\text{C}$ between $-50\text{ }^{\circ}\text{C}$ and $+50\text{ }^{\circ}\text{C}$ to check stability, reproducibility and temperature characteristic. For the study a typical liquid thermostat bath with a cylindrical copper air chamber was used. The temperature measurements were carried out simultaneously. The temperature characteristics were not linear what confirms the need for calibration in more than two or three temperature points. The uncertainty budget for measurements was elaborated in accordance with the EA-4/02 document (2013). The contribution of individual components of the measurement uncertainty was analyzed. The investigation showed a good reproducibility of metrological parameter of the sensors used in meteorology for temperature measurements (Szmyrka-Grzebyk *et al.*, 2012).

A task was focus on the correlations between pressure, temperature and humidity in automatic weather stations and weather transmitters. Conventionally each parameter is calibrated separately for multiparameter instruments so possible correlations are not taken into account. An analysis of current calibration practices has been performed, as far as the correlations have been concerned. The work included analysis of information already available and experiments with a Vaisala WXT520 weather transmitter. The obtained results are here summarized

1. No specific correlation issues related to temperature sensors were found.
2. Significant temperature dependencies have been found for some barometers but correlations with relative humidity seem to be insignificant. Type test approach may be sufficient for including the dependences in the measurement uncertainty.

- Often, humidity sensors have significant temperature dependence that is not stable in time. Calibration scheme should at some extent cover the temperature dependence (depending the target uncertainty).

3.4.2 Solar radiation effect

In order to evaluate the effect due to solar radiation on climate measurements a new radiation shield model with forced ventilation was designed and constructed by SP during the project (Figure 6). Shields with different coatings (black and white, Figure 7) were tested in sun light in 2012. The measured temperature difference between black radiation shield and the white shield was in average 0.11 K. In addition, the measured temperature difference depended on the weather conditions: the difference increased with increased solar radiation. The wind speed seemed not to influence the measured temperature difference between the two shields.

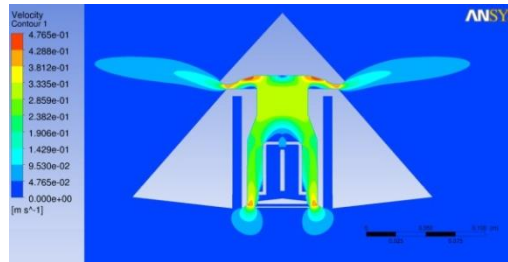


Figure 6 The results from the CFD-simulation performed with Fluent. The results shows that the air is leaving the radiation shield more or less straight out limiting the risk of having the same air circulating through the shield.

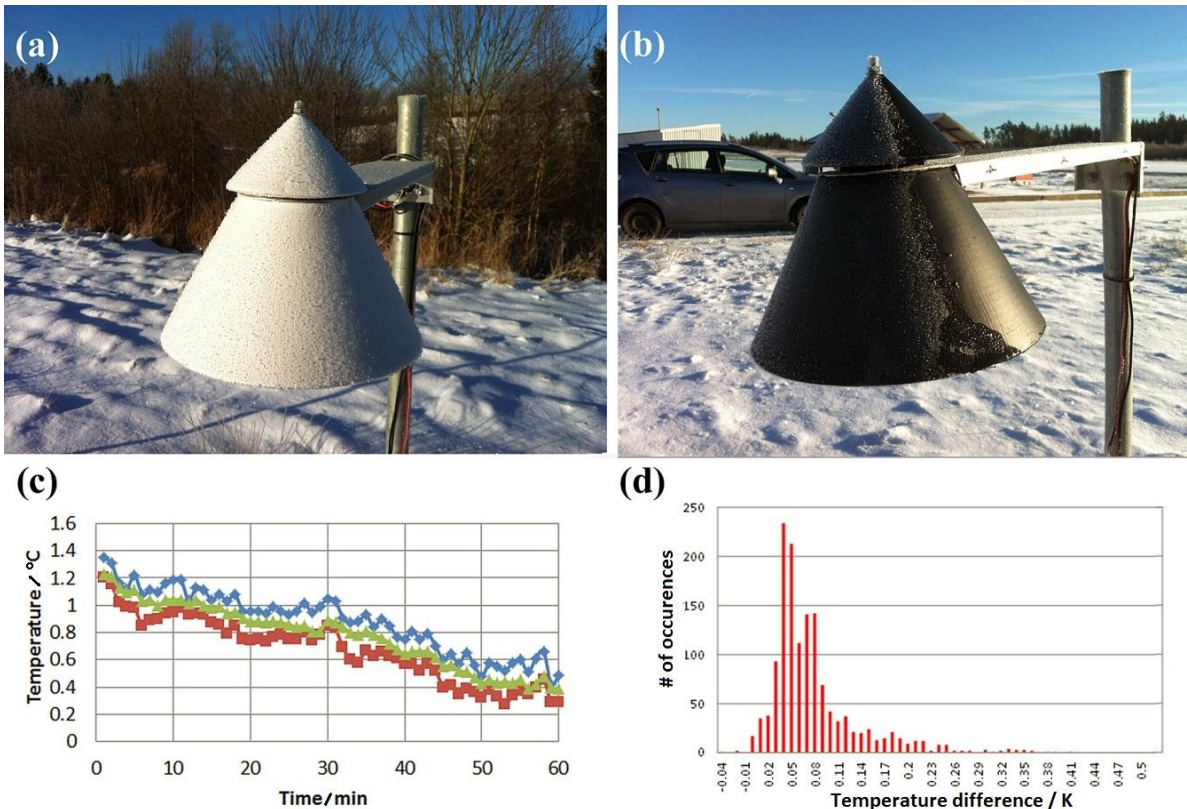


Figure 7 a) The custom solar screen in the white version with ice covering; b) In the black version of solar screen, ice is melted by absorption of solar radiation; c) temperature measured in the white (red line), the black (blue line) and a Stevenson shield (green line) d) number of time a temperature difference among the white and black shield has been recorded (occurrences) among the interval the differences are distributed.

A long-term investigation consisting of 4 reference shields and 6 other commonly used radiation shields has been performed in the project. Measurements have been done at two different locations, in Sweden by SP and in Spain by INTA. Three models of radiation shields were tested at both locations. For both measurement locations, the radiation shields designed by SP was used as a reference.

From the analyzed measurements in Sweden, from September 2013 to February 2014, in average the measured temperature differences varied from +0.14 K to -0.24 K. In 84 % to 94 % of all the measured temperatures the

differences was between -0.5 K to +0.5 K. All radiation shields except the SP White III (who had no active ventilation) measured in average a higher temperature than the reference radiation shield. At specific times the measured difference could be above 4.9 K.

From the analysed measurements in Spain, from November 2013, the measured temperature average differences varied from -0.04 K to -0.21 K. In 87 % to 99 % of all the measured temperatures the difference was between -0.5 K to +0.5 K. All radiation shields measured in average a higher temperature than the reference radiation shield. At specific times the measured difference could be above 2.3 K.

One objective was to propose a procedure for harmonizing the temperature measurement with different radiation shields. For this case the most interesting part to investigate are the commonly used radiation shields. It was concluded that in average over a period of time there were small differences for the different shields, it was not possible to set up robust correction models. Further work and data is needed for proposed harmonization model for measurement with different radiation shields.

3.4.3 Development of facilities for laboratory and in situ simultaneous calibration of temperature, humidity and pressure sensors in weather stations.

To obtain more accurate AWS calibration results a new in situ calibration system, named EDIE (Earth Dynamics Investigation Experiment), with simultaneous and independent control of pressure and temperature was developed (Lopardo *et al.*, 2014). The facility is equipped with reference sensors traceable to SI to guarantee documented calibration uncertainty. One of the big advantages of this apparatus is its reduced dimensions. The good compromise between the measuring test chamber (inner diameter 220 mm and volume of around 15 l) and external total dimensions (350 mm x 650 mm) makes it transportable for in-situ calibration campaigns holding the whole sensor and datalogger. In this manner, the whole measurement chain can be tested in working conditions to reduce further calibration uncertainty contributions. During the project, the EDIE calibration chamber was used for two calibration campaigns in extreme environmental conditions where difficulties to access delay or forbid periodic calibrations:

- in the Ev-K2-CNR Pyramid-laboratory in Khumbu Valley at 5050 m of altitude in the Nepalese side of mountain Everest. An ad-hoc calibration chamber, named EDIE2, have been manufactured. This chamber is similar to EDIE1 but can be split in light weight components to be delivered by human porters, Sherpas. On September 2013 the climatic chamber was installed in the Pyramid laboratory, and the calibration campaign of the AWS in use in the whole valley was carried out (Merlone *et al.*, 2014).
- in the Alfred Wegener Institute for Polar and Marine Research (AWI) Research Base in Ny-Ålesund, where a GRUAN station is hosted. In June 2014, the work has been devoted to the calibration of the pressure and temperature measuring instruments used as ground check for the radiosondes sensors just before launch (Musacchio *et al.*, 2014).

The EDIE chamber has been also used for the calibration of the air temperature and relative humidity sensors of the AWSs installed in an agricultural research site for agrometeorological studies. The outcomes data collected during 2012 and 2013 were used as a input values for the simulation of infections on grapevine, by employing an epidemiological forecasting model. The simulations with inclusion of measurement uncertainty foresee with better accuracy the period of infection and the moment to make treatments in the vineyard respect the simulation without inclusion of uncertainty, up to 7 days (Sanna *et al.*, 2014).

A second facility (called EDDIE – Earth Dynamics Direct Investigation Experiment) has been realized in order to perform several laboratory tests on weather stations (Piccato *et al.* 2014). The facility consists in a closed tunnel that can generate independently and simultaneously the following environmental conditions: air pressure range from about 75 kPa to 110 kPa, air temperature range from about -40 °C to 40 °C and airspeed range from 0 m s⁻¹ to about 30 m s⁻¹. One of the relevant characteristics of EDDIE consists in the test chamber, which is equipped with a device (shield system) that will allow to evaluate the instrument behavior in a specific condition of temperature and pressure both in absence and in presence of wind.

3.5 Robustness of the historical temperature measurement data

3.5.1 Development of the calculation model for instrumental uncertainty evaluation of historical data and with respect to ITS-90.

The aim of this task has been the investigation of the sources of instrumental uncertainty in historical temperature data, include them into the uncertainty budget and possibly correct the input to the climate models. A table of uncertainty

contributions was created, based on knowledge achieved by the thermal metrology community on the instruments evolution, sensors characteristics (sensitivity, stability, resolution and measurements limits) and the calibration procedures and standards adopted along the years. The table, containing weighted values distributed along the years, from early 1900 up to today, formed the basis for the development of a novel software model, for the harmonisation of data under such a metrological approach.

A further computer program which implements the conversion of historical records to ITS-90 temperature values was developed and can now be downloaded (<http://surfacetemperatures.blogspot.no/2014/06/understanding-effects-of-changes-in.html>). It provides a quick and reliable conversion of temperature data from the ITS-27 through all the international temperature scales up to the current ITS-90. The program is implemented in visual basic. It is simple yet effective in design and can batch convert large amounts of temperature data from files.

3.5.2 Homogenisation approaches to develop historical temperature time-series.

A further task was dedicated to estimate the impact on historical temperature series of the changeover from conventional manual stations to AWS by means of harmonising and combining the statistical analysis based on exploiting the state-of-the-art in homogenisation methods, (Venema *et al.*, 2012) and the metrological procedures to account for Type A and Type B uncertainties. The systematic AWS' bias size and shape and its ad-hoc correction function has been estimated from parallel measurements at the experimental sites of a 1905 onwards long-standing series of the Ebro's Observatory in north-eastern Spain, and a second one in northern Italy, Castello Borello, which is operational since 2005 onwards. At both experimental sites, calibrated instruments were installed following a metrological strategy to account for the AWS bias and shorten, ideally to zero, the period required of parallel measurements, as well as producing a reference temperature series with a metrological assessment. It has been explored the performance and feasibility of the jointly application of the metrological and statistical approaches to account for the AWS bias by means of instruments calibrated against national standards and the estimation of the adjustments required to minimise such a bias from a climatological perspective. This scheme constitutes a first step to assess the feasibility of combining the instrumental uncertainties and those derived from the statistical adjustments calculated in future joint studies.

4 Impact

Since the start of the MeteoMet project, important efforts were devoted to setting up communication systems, engaging stakeholder and disseminating information at local and international level. The large consortium has offered a wide forum for discussing and proposing common procedures, new devices and research on novel instrumentation. The NMIs, operating at a national level, in cooperation with meteorological agencies and institutes have disseminated more efficiently and directly the results and best practices, with the awareness that reliable climate data is a geographically equally relevant matter. At worldwide level, active liaisons have been established with WMO, WMO Commission for Instruments and Methods of Observation (CIMO), WMO-GRUAN, International Surface Temperatures Initiative (ISTI), and the climatological community. Metrological contributions to ISTI are helping to develop this as a unique undertaking which will lead to open source global surface temperature data that can be traced back to original records in a way never before available.

The collaboration with GRUAN, as an initial activity, has brought to the revision of the GRUAN Manual and Guide with the adoption of the Guide to the Expression of Uncertainty in Measurement (GUM) (JCGM 100, 2008) as core guide for the evaluation of uncertainty and also for correct terminology. This represents a first step to bring a new level of metrology interaction to meteorological stakeholders. Having succeeded in enforcing such mutual benefit, the JRP coordinator was awarded the EURAMET "Impact prize" in 2013 with the following motivation: "*The MeteoMet project has achieved significant impact with the science undertaken within it, but also in bringing two scientific communities together to collaborate on problems that have far reaching implications for us all*" (EURAMET 2013).

5 Conclusions

Towards supporting documented and defined traceability to SI standards, this project represents a first step towards reliable measurements for meteorology and climate. The project ended on 30 September 2014 with a closing meeting held during the Metrology for Meteorology and Climate (MMC2014) conference in Brdo, Slovenia. More than one hundred deliverables provided by the project have been all in time with the protocol and grants schedules and regarded new calibration devices, novel instruments for humidity, temperature and pressure measurements, better definition of the water vapour formula, dedicated calibration chamber for radiosondes tests, remote sensing modelling for GNS

signals, historical temperature series, laboratory and in situ activities, field campaigns also in remote areas, a number of peer reviewed publications, organisation of workshops and conferences. Different expertises and techniques have been involved in a multidisciplinary effort: high level thermal metrology, hygrometry, acoustic physics, spectroscopy, thermodynamics, fluid dynamics and more. The consortium participating in the MeteoMet project has been the largest one ever grouped by an EMRP project. It was formed by funded NMIs partners, Research Excellence Granted institutions and researchers, the many collaborators offering an active part in dissemination activities, comparison and results discussion.

Based on the results and experience achieved, the proposal for an extension of MeteoMet project was submitted to EMRP and funded in 2014. The new project called MeteoMet2, "Metrology for essential climate variables" aims to extend to further objectives: from meteorological sensor calibration uncertainties to evaluation of measurement uncertainties, improvement of the previously developed devices and their use in field oriented activities, new investigations on sensor characteristics for the generation of higher quality climate data; extension of the atmospheric ECVs to include air, sea and land, sea surface temperature, salinity, sub-surface oceanic temperature, permafrost temperature, albedo, precipitation, soil moisture. The improvement of quality of ECVs recorded data through the inclusion of measurement uncertainty budget will bring to possible strategies for the reduction of the uncertainty. This is a general vision requiring step by step investigations focused on single aspects, defining a mission that even goes beyond the deliverables of these projects.

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