Final Publishable JRP Summary for ENV07 MeteoMet Metrology for pressure, temperature, humidity and airspeed in the atmosphere

Overview

The effects of climate change are expected to be widespread and substantial, and robust climate data and models are needed to predict and mitigate their social and economic impacts. This project reduced the measurement uncertainties of essential climate variables by developing methods to trace and calibrate measurements to their underlying SI unit definitions. These techniques will be used to increase the accuracy of climate measurements, supporting the development of improved climate models.

Need for the project

Climate change threatens ecosystems, economies, and the quality of life in Europe and the rest of the world*. Its effects are likely to be as complex as they are damaging – accurate and reliable climate modelling is needed to understand and mitigate the effects of climate change.

The effectiveness of climate modelling depends upon the quality of the data upon which the models are founded – "*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*"[#]. To ensure climate data continues to be consistent and of high-quality, standard global protocols are needed for improved temperature, humidity, pressure and airspeed measurements, traceable to measurement standards.

Specifically, before this project: improved calibration methods were needed to reduce the uncertainties of air temperature and airspeed measurements. Measuring humidity is important but challenging, due partly to the wide disparity in atmosphere water content in different locations, and improved primary techniques were needed for more accurate humidity measurement. Once established, calibration methods were then needed to validate field measurements against the improved primary standards. Weather stations distributed throughout the world operate in a wide range of environmental conditions, which effect their measurements in different ways. In-situ calibration methods were needed for weather stations to correct for interference from environmental conditions. Sources of measurement uncertainty in historical temperature data also needed to be identified, to assess their accuracy and to allow for consistent comparisons across datasets.

* *IPCC Climate Change 2014 Synthesis Report Summary for Policymakers.*

[#] *http://www.gcos-science.org/*

Scientific and technical objectives

The overall goal of this project is to reduce measurement uncertainties of both historic and future climate measurements. To achieve this, objectives 1 to 6 focussed on developing methods to calibrate temperature, airspeed and humidity measurement instruments. Objectives 7 to 10 developed calibration methods for automatic weather stations. Objective 11 focussed on understanding and minimising the sources of measurement uncertainty in historic temperature datasets.

Traceability for air temperature and wind speed measurements

1. Development of accurate laboratory calibration facilities and procedures for air temperature sensors
2. Development of a method for establishing traceability for wind speed measurements

Improving humidity sensors and calibration methods

3. Realisation of traceable, self-calibrating tunable diode laser (TDLAS) hygrometers
4. Intercomparison of airborne field humidity sensors of different types (Aquavit 2 campaign)
5. Generation of new data to improve the water vapour formulae
6. Novel methods and instruments for atmospheric humidity measurement

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Calibration of automatic weather stations (AWSs)
7. Proposal for AWSs calibration methods
8. Evaluation of AWS degradation due to solar radiation effect and ageing
9. Development of facilities for laboratory and in situ calibration of AWSs
10. Development of protocols for software validation of AWSs

Robustness of the historical temperature measurement data
11. Investigation of uncertainties sources in historical temperature data

Results

Traceability for air temperature and wind speed measurements

1. Development of accurate laboratory calibration facilities and procedures for air temperature sensors
Reducing the level of uncertainty in temperature measurements helps to improve the accuracy of climate forecasts. Uncertainty of measurement depends on the uncertainty of calibration, so more accurate temperature calibration methods will produce more accurate temperature measurements.
This objective was achieved by developing a facility for calibrating air temperature sensors (thermometers and automatic weather stations). The facility is a transportable chamber, available at INRiM, the Italian National Measurement Institute, and can be used to calibrate sensors both in the laboratory and at external stations. This facility allows measurement uncertainty to be reduced from 0.08 °C to the level of less than 0.05 °C (within a temperature range between -20 °C to +50 °C), through reducing the contribution of calibration uncertainty to overall measurement uncertainty.

2. Development of a method for establishing traceability for wind speed measurements
Airspeed is one of the most difficult climate parameters to evaluate, as weather conditions, such as ice and rain, can cause measurement instruments (anemometers) to drift, becoming progressively less accurate over time. Novel methods were needed for field calibration of anemometers on weather stations.
On-site calibration methods were developed and validated for a range of anemometers, including the newly developed LIDAR (Laser Imaging Detection and Ranging) anemometer, and sonic and ultrasonic anemometers. The effects of various weather conditions were studied and defined, to allow for their correction during calibration. Finally, the anemometer blockage effect was fully characterized (the aerodynamic effect the anemometers themselves have on wind measurements), to account for its influence on airspeed measurements and to provide a more reliable calibration, suited to the conditions under which the sensors will be used.

Improving humidity sensors and calibration methods

Humidity, the amount of moisture in air, is a key parameter for understanding a range of climate processes. But humidity measurement is challenging, as atmosphere water content can vary by a factor of over 10 000, so humidity sensors (hygrometers) need to be accurate over a large measurement range. One source of uncertainty in humidity measurement is the uncertainty associated with various parameters in the water vapour equation used in primary measurements. Reduction of this uncertainty, at temperatures between -80 °C to close to 100 °C, was needed to reduce primary humidity measurement uncertainty at national measurement institutes. Methods were then needed to calibrate a range of humidity sensors against the new, lower-uncertainty primary measurements. This objective was achieved by:

3. Realisation of traceable, self-calibrating tunable diode laser (TDLAS) hygrometers
New optical cells for TDLAS hygrometers were developed, and accurate and traceable measurements of the line parameters for the water absorption line were carried out.To simplify calibration procedures and to allow field calibration, a portable humidity standard was developed and realised. The new system will allow for the more accurate *in-situ* calibration of hygrometers, and traceability to primary measurement standards.

4. Intercomparison of airborne field humidity sensors of different types (Aquavit 2 campaign)
An inter-comparison campaign of airborne hygrometers, called AquaVIT2, was organized at the Aerosol Interaction and Dynamics in the Atmosphere chamber at the Karlsruhe Institute of Technology in Germany. The inter-comparison provided a traceable link to the international humidity scale for airborne hygrometers for the first time, improving the accuracy of the measurements made in the tropospheric and stratospheric regions.

5. Generation of new data to improve the water vapour formulae
New measurements were obtained from three different experiments of the saturation water vapour pressure, in equilibrium, in air over water and ice. These measurements were added to the available water vapour data, and allow subsequent measurements to be traced to measurement standards, and uncertainties to be evaluated according to best practice.

6. Novel methods and instruments for atmospheric humidity measurement
A range of new hygrometers were developed and validated, including: a new generation of compact and high-sensitivity hygrometers, based on microwave quasi-spherical resonant cavities, with target relative measurement uncertainties of less than 10^{-5}; and a free-space, non-contact, multi-parameter atmospheric measurement sensor, with techniques to enable rapid simultaneous measurements of temperature, pressure and relative humidity of the same air mass, whilst reducing the influence of the sensor itself on the measurements.
Reference radiosondes were developed to meet the accuracy requirements of GRUAN (Global climate observing system Reference Upper-Air Network). The radiosondes overcome the key challenge of making quick measurements at very low temperatures, and will be used at GRUAN reference weather stations around the world. The project also successfully developed and implemented models for the calculation of water vapour concentration and temperature measurements based on the signals from GNSS (Global Navigation Satellite Systems), such as GPS and Galileo (as these signals can be used for measuring atmospheric water vapour).

Calibration of automatic weather stations (AWSs)

Standardised methods are needed for the *in-situ* calibration of sensors on automatic weather stations operating in wide range of different weather and environmental conditions, to ensure data collected is accurate, uniform and comparable. The objective was achieved by:

7. Proposal for AWSs calibration methods
To develop traceable ground-based procedures for temperature, humidity, and pressure measurements by AWSs, a review of existing measurement processes, sensor types, maintenance procedures, and calibration practices was performed and collated in a database. This database was used to develop a better knowledge of sensor technical details, to identify and recommend optimum calibration methods.

8. Evaluation of AWS degradation due to solar radiation effect and ageing
To examine ways to minimise the effects of solar radiation on climate instruments, a long-term investigation was conducted to test the performance of radiation shields. A new type of radiation shield was developed for the project with forced ventilation, and was tested against four reference shields and six other commonly used shields, in Spain and in Sweden. Additionally, the effects of radiation shields on temperature sensors in extreme temperature and humidity conditions was investigated in a climate chamber. The results obtained were used to improve the design of optimal and standard radiation shields.

9. Development of facilities for laboratory and in situ calibration of AWSs
Facilities were developed for the initial calibration of AWSs in the laboratory before deployment in the field, and methods to re-calibrate AWSs once out in the field.
A laboratory calibration facility called EDDIE (Earth Dynamics Direct Investigation Experiment) was developed, consisting of a closed wind tunnel that can control air pressure, temperature, and wind. The environmental wind tunnel facility at the Mars Simulation Laboratory, Aarhus University, was modified to be used for testing, developing and calibrating meteorological sensors under a wide range of environmental conditions. The system is now operating at INRiM in a new, dedicated laboratory, and is already being used to test sensor responses and dynamics.

For the *in-situ* calibration of AWSs, an in-field calibration system was developed called EDIE (Earth Dynamics Investigation Experiment), which provides simultaneous and independent control of pressure, temperature, and humidity. This calibration apparatus is small and portable, suitable for installation in remote areas without easy access for vehicles, where periodic calibration is typically rare, if not impossible.
During the project, EDIE was used for two calibration campaigns in extreme environmental conditions; at the Ny-Ålesund research site, in the Arctic Region; and at the Ev-K2-CNR Pyramid-laboratory in the Khumbu Valley, at 5050 m of altitude in the Nepalese Himalaya. A calibration chamber was set up in the Pyramid laboratory to establish traceability of the measurements made at this climate change monitoring site. The device is now in permanent operation, and can be used to calibrate pressure and temperature sensors with direct traceability to measurement standards. The system used in Ny-Ålesund allowed the calibration of temperature and pressure sensors used for the pre-launch ground check of the radiosondes used by the GRUAN (GCOS Reference Upper Air Network) station operating in that location.
EDIE was also used to calibrate sensors installed in an agricultural research site operated by the Italian National Research Council (CNR) in the wine area of Monferrato – Piemonte, where wine production is the primary activity and studies on seasonal weather condition on the final product are vital. EDIE demonstrated the importance of reducing measurement uncertainty in climate observations, as the lower-uncertainty data that EDIE provided was used to refine a model that predicts the outbreak of grapevine infections from climate conditions. This work serves as a case-study that encapsulated the importance of the project, as the improved calibration methods resulted in a model that predicts outbreaks with greater accuracy, and allows the faster and more effective treatment of infections.

<u>10. Development of protocols for software validation of AWSs</u>
A questionnaire was distributed among European and non-European meteorological organisations to gather information on the key characteristics of software running on AWSs throughout the world. With the growing use of AWS data, software should be sufficiently user friendly, but also of sufficient quality to accurately record and manipulate measurements, as the software is used for quality control, can be a source of uncertainty, and can directly influence final results. Validation of AWS software is challenging though, as a range of different programming languages, operating systems, and hardware platforms are used. Results were analysed from 25 counties using a Quality function deployment tool (QFD), an established method used to transform responses into engineering characteristics. The QFD analysis revealed critical elements of AWS software needed to fulfil the requirements of users of AWS data. The results were published to ensure their broad dissemination and to inform future AWS software design.

Robustness of the historical temperature measurement data

<u>11. Investigation of uncertainties sources in historical temperature data</u>
Historical temperature datasets can lack clear descriptions of the measurement techniques used, the surrounding environmental conditions, their levels of uncertainty, and their traceability to primary standards – making it difficult to assess the accuracy and comparability of different sources. A further complication in historical data comes from the lack of a universal temperature scale before the 20th century, meaning that data was recorded in a variety of different units.
99 historical series were collected from climatologists in different nations, representing a substantial sample of data that have already been studied and harmonised using established statistical techniques. These series were also selected for the quality of their metadata, such as details on the measurement instrument used. Instrument sources of uncertainty were studied and evaluated by reviewing the most widely used temperature sensors and creating uncertainty budgets for each. A program was developed to convert different temperature scales within the datasets to degrees Celsius (available here), and to account for the historic changeover from manual temperature measurements to the use of automatic weather stations.

Actual and potential impact

<u>Dissemination of results</u>
To promote the uptake of the new calibration techniques and facilities, project results were shared broadly with scientific, meteorology, climate change and industrial communities. 29 papers have been published in international scientific journals (listed in the next section), and input has been provided for 6 measurement guides, being completed under the follow-on EURAMET project ENV58:MeteoMet2. 26 separate training sessions have been delivered, and presentations were made at over 90 events, including the 2014

Metrology for Meteorology and Climate workshop in Slovenia. The workshop was attended by a wide range of meteorology researchers and practitioners, and allowed project results to be shared with a broad section of the meteorology community.

Early impact on climate observatories and industry

The calibration service and the new traceable measurement procedures are being used by meteorological and climate organizations, such as SMI, Observatory of Ebro and Climate Consulting, to improve the accuracy of their observations, and their climate models and analysis.

The new instruments developed, and the comparison exercises involved in the project, were carried out in collaboration with a range of manufacturers, including Vaisala, CAE, MODEM, Luft, Rotronic, Thies, Setra, Seac, E+E. The results of this project are being used by these companies to develop the next generation of weather and climate measurement instruments.

Potential future impact

This project has spearheaded an increasing focus on the measurement of climate variables in the metrological community. Technical groups have been established in key metrology institutions, such as the CIPM Consultative Committee for Thermometry, and the EURAMET Technical Committee for Thermometry, putting climate and weather firmly on the agenda. In addition, nominees from the metrology community have been appointed by invitation to World Meteorological Organization (WMO) Expert teams. This provides a framework for long-term collaboration, and ensures metrology expertise is available to WMO decision-making groups, supporting the development of best practice meteorology and climate science. The achievements of MeteoMet will also be further developed in the follow-on MeteoMet2 project, where improved measurement techniques will be developed for a wider set of climate variables under a broader range of conditions.

Ultimately, by ensuring that climate measurements are traceable to their underlying SI unit definitions, measurement uncertainties in climate data will be reduced, and the accuracy of climate models can be improved. In the short-term, weather forecasts and weather warning systems can be made more exact, supporting a range of economic sectors including energy, transport, and agriculture. Over the longer-term, more accurate climate models are crucial to monitor and predicts the progress of climate change, and will help in the mitigation of its potentially severe social and economic effects.

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