Issues with the measurands in meteorology and climatology

Andrea Merlone

CCT WG Environment chair
WMO ET Measurement Uncertainty chair
WMO GCW Best Practice Permafrost team co-chair
GCOS – GSRN SG5 chair
ISTI Co-Chair
CCT TG Air temperature co-chair

Air Temperature

Air Temperature is the most measured variable

Air Temperature is the most measured variable

In:

- Our houses and buildings
- In refrigerators and furnaces
- In any laboratory
- In Industry
- In the atmosphere
- …

For:

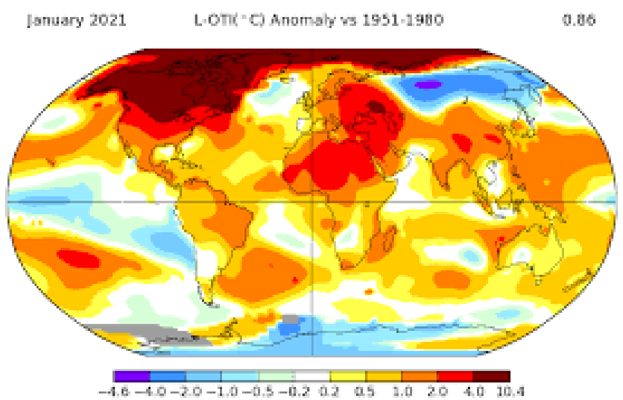
- Precision dimensional and mass measurements
- Indoor climatization
- Refrigerating processes
- Controlling processes

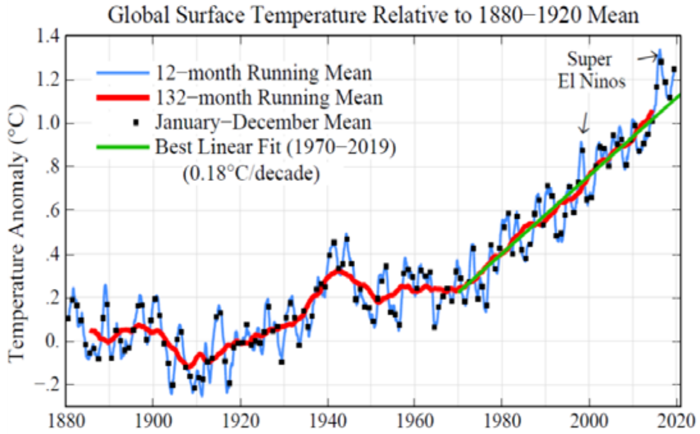
…

Air Temperature is the most measured variable

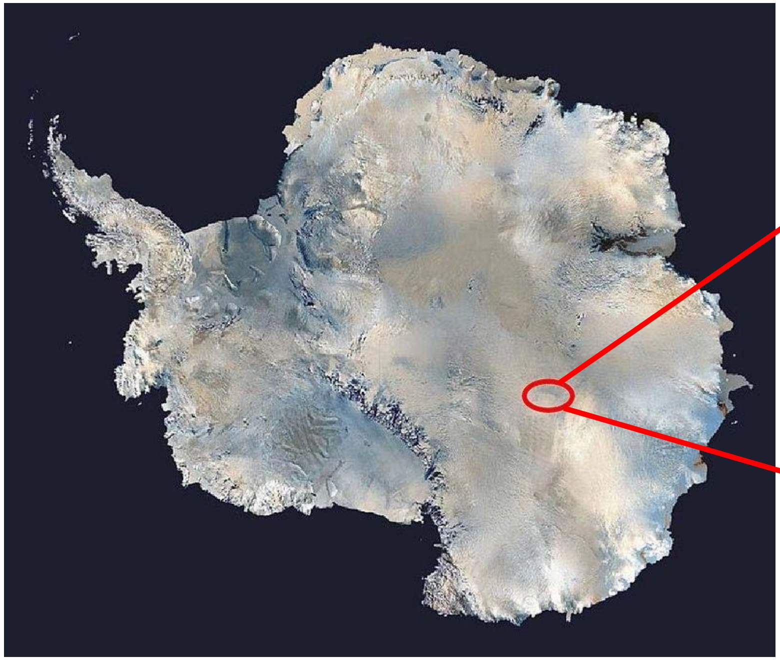
In Meteorology and Cliamatology,

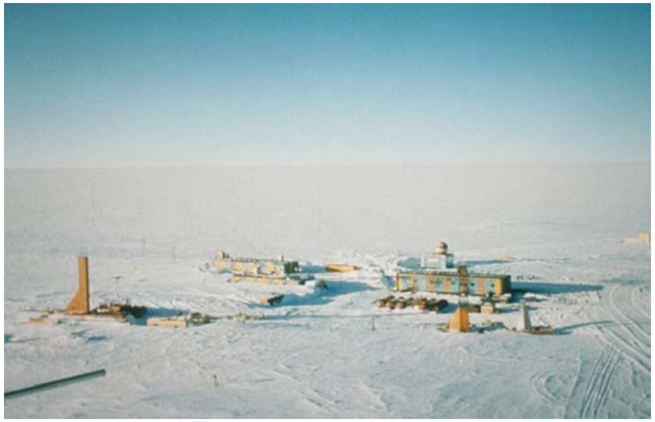
where it is the fundamental variable to understand calimate change and variability.





The lowest natural temperature ever directly recorded at ground level on Earth is **–89.2 °C** at the Soviet Vostok Station in Antarctica on July 21, 1983 by ground measurements at 3900 m of altitude. (Satelllites observation recorded -94.7 °C in August 2010





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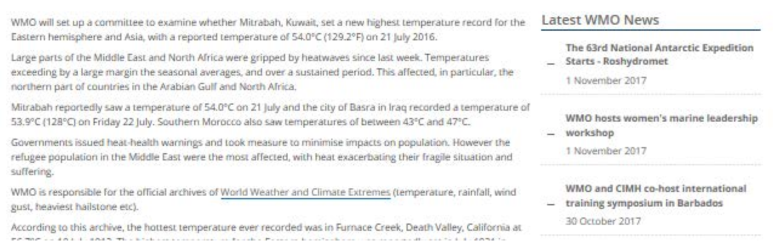
WMO Formally requests to validate two temperature records, being the third value ever recorded and the highest in Asia

2016 Mitribah - Kuwait 54 °C
2017 Turbat - Pakistan 54 °C

Study and research on conditions, heat wave, instruments, uncertainties

WMO examines reported record temperature of 54°C in Kuwait, Iraq



WMO will set up a committee to examine whether Mitrabah, Kuwait, set a new highest temperature record for the Eastern hemisphere and Asia, with a reported temperature of 54.0°C (129.2°F) on 21 July 2016.

Large parts of the Middle East and North Africa were gripped by heatwaves since last week. Temperatures exceeding by a large margin the seasonal averages, and over a sustained period. This affected, in particular, the northern part of countries in the Arabian Gulf and North Africa.

Mitrabah reportedly saw a temperature of 54.0°C on 21 July and the city of Basra in Iraq recorded a temperature of 53.9°C (128°C) on Friday 22 July. Southern Morocco also saw temperatures of between 43°C and 47°C.

Governments issued heat-health warnings and took measure to minimise impacts on population. However the refugee population in the Middle East were the most affected, with heat exacerbating their fragile situation and suffering.

WMO is responsible for the official archives of World Weather and Climate Extremes (temperature, rainfall, wind gust, heaviest hailstone etc).

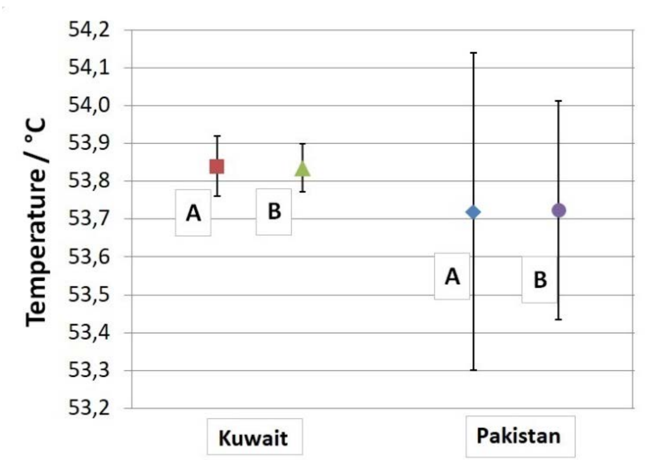
According to this archive, the hottest temperature ever recorded was in Furnace Creek, Death Valley, California at

Latest WMO News

- The 63rd National Antarctic Expedition Starts - Roshydromet
  1 November 2017
- WMO hosts women's marine leadership workshop
  1 November 2017
- WMO and CIMH co-host international training symposium in Barbados
  30 October 2017

Results

	Corrected Value (°C)	Uncertainty (°C)
Kuwait calibration (A)	53.87	±0.080
Kuwait comparison (B)	53.84	±0.064
Pakistan calibration (A)	53.72	±0.40
Pakistan comparison (B)	53.72	±0.29



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RESEARCH ARTICLE

International Journal of Climatology

Temperature extreme records: World Meteorological Organization metrological and meteorological evaluation of the 54.0°C observations in Mitribah, Kuwait and Turbat, Pakistan in 2016/2017

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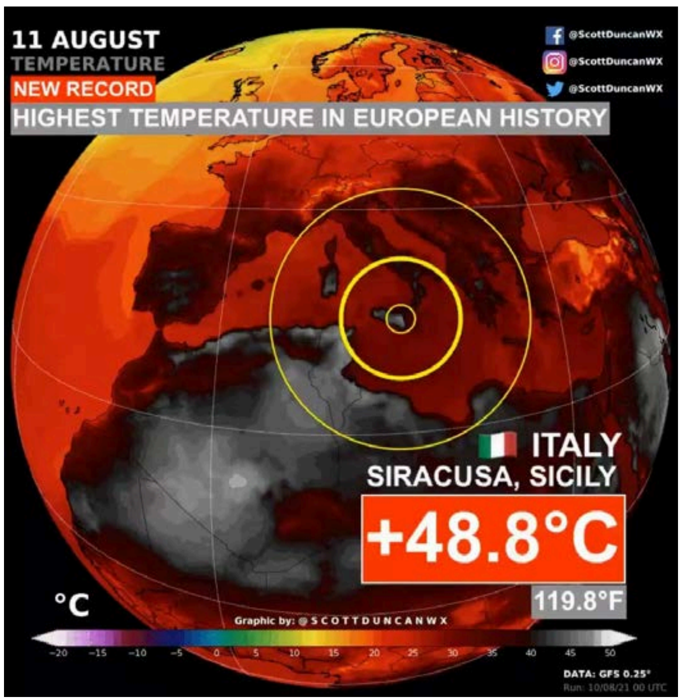
New temperature extreme under investigation: 48,8 °C on 11 August 2021 - Sicily

WMO Committee formed in late 2021

Data and evaluation started in February 2022



But…

But…

There’s not a definition of air temperature

But…

There's not a definition of air temperature

There's not a unique and complete uncertainty budget for its measurement results

But…

There’s not a definition of air temperature

There’s not a unique and complete uncertainty budget for its measurement results

There’s no normative on calibration of thermometers in air

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Atmospheric air temperature measurements:

can we evaluate a complete uncertainty budget?

A thermometer measures the temperature of the air.

A thermometer measures the temperature of the air. ?

A thermometer measures the temperature of the air.
?
?

A (contact) thermometer gives an indication of its heat equilibrium at that time in that place under those conditions.

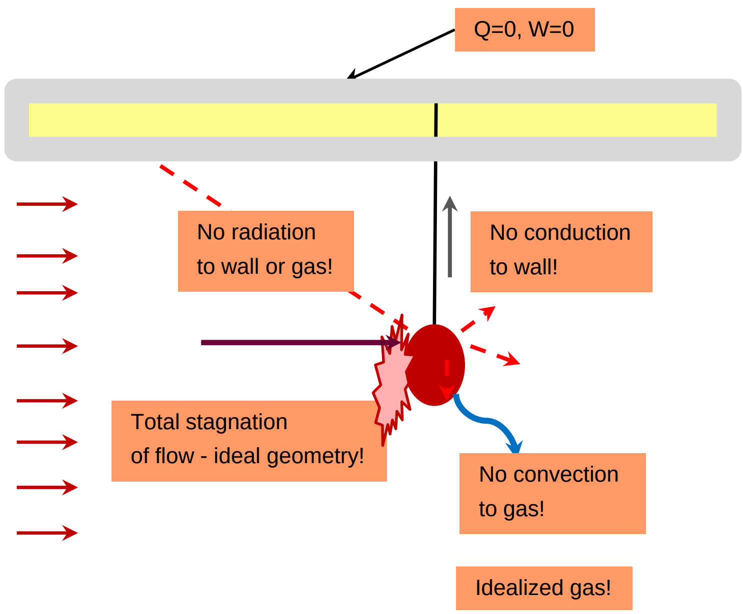
This equilibrium is influenced by:

- **Convection heat exchange**
  - Gas (wind) speed
  - Turbulent, laminar or mixed flow
  - Heat transfer coefficient
  - Convection surface area
  - Temperature gradients
- **Conduction heat exchange**
  - Coefficient of conductivity
  - Thickness of the conduction/insulation layers
  - Temperature gradients
- **Radiation heat exchange**
  - Emissivity coefficients
  - Reflectivity coefficients
  - Diathermy
  - Sub-surface conductivity (surface temperature)
  - Temperature difference
- **Phase change and heat sources**
  - Condensation/evaporation
  - Sublimation/melting
  - Heat sources in the thermometer body
- **Transient heat transfer**
  - Specific heat capacity of the thermometer
  - Mass of the thermometer
  - Initial temperature of the thermometer
  - Gas temperature dynamics (lag)

And…

- Probe is not adiabatic
  - Radiation exchange with surrounding
  - Convection between the probe and air
  - Conduction along probe stem
- Probe has imperfect geometry:
  - Partial stagnation
  - Stagnation different in laminar, turbulent or developing flow
- Flow is compressible at stagnation locations even at mainstream velocities less then 1/3 Mach
- Probe has finite mass – therefore time lag
- Probe has relatively large heat capacity vs. air
- Probe faces enclosures/surroundings with temperature:
  - different from gas
  - different from probe
- Probe indicates mean temperature (gas, probe body), not gas temperature.
- Difference of self-heating in air to that at calibration should be considered
- Real gas does not have one single total temperature

Ideal thermometer in ideal gas



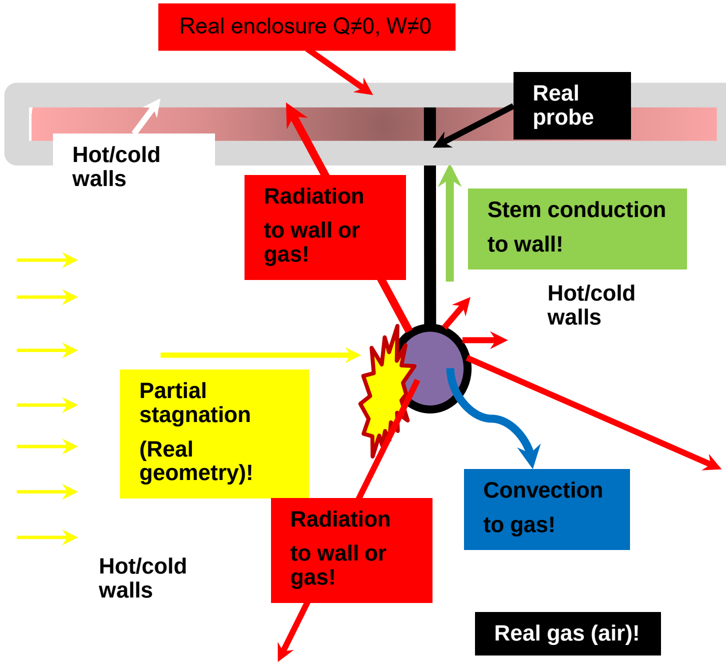
- **Idealized gas:**
  - **pv/T=konst,**
  - **Cp=konst**
  - **(resembles air at low pressures)**

- **System boundaries:**
  - **no heat is transfered**
  - **no work is transfered**

- **Ideal thermometer**
  - **Adiabatic:**
    - **no radiation**
    - **no convection**
    - **no conduction**
  - **Ideal geometry:**
    - **total stagnation of directed kinetic energy**

In real gas + real thermometer

The Dynamic Correction Factor (real gas + real probe)



Enter dynamic correction factor (K) which accounts for:

- impact effects,
- viscosity and thermal conductivity effects and
- diabatic probe effects (stem conduction & radiation)

$$T_p = T_s + KT_v$$

T_p = probe temperature (equilibrium temperature, real gas and real probe)

K - dynamic correction factor

$$K = \frac{T_P - T_s}{T_t - T_s}$$

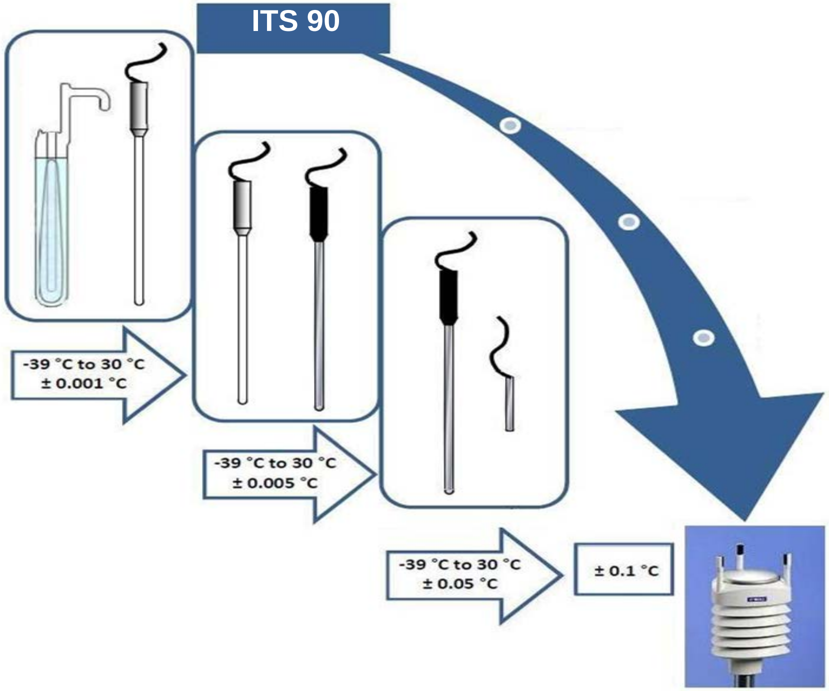
Moreover…

A (contact) thermometer is calibrated in (as close as possible) adiabatic conditions.

A (contact) thermometer is calibrated in (as close as possible) adiabatic conditions.

But then a thermometer for atmospheric air temperature measurement is used in non-adiabatic conditions

Traceability


ITS 90
-39 °C to 30 °C
± 0.001 °C
-39 °C to 30 °C
± 0.005 °C
-39 °C to 30 °C
± 0.05 °C
± 0.1 °C

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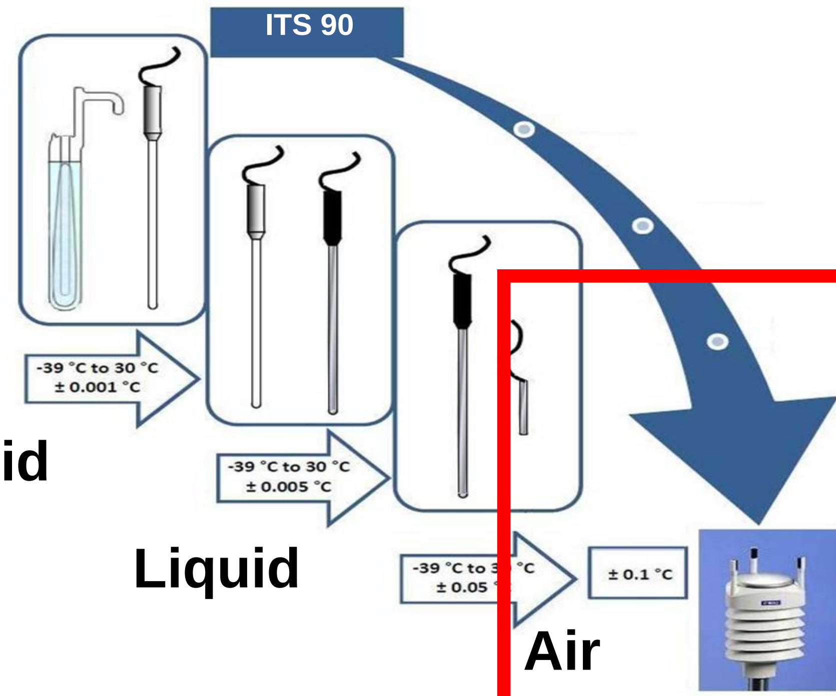
A further technical issue…



Liquid

Liquid

Liquid

Air

Air

Traceability ?

BIPM - CCT Strategy Document for Rolling Programme Development for 2018 to 2027

Achievements 2013-2017	Future Scan 2018-2022	Future Scan 2023-2027
Environment		
The RECOMMENDATION T3 (2010) to the CIPM entitled *"On climate and meteorological observations measurements"* is the basis for establishing long terms collaboration with the scientific community involved in research on climate and environmental monitoring and motivates specific projects and actions from the NMIs being increasingly diffused worldwide.	• The relationships with key world and international Institutions such as WMO, GCOS, and IAPWS will be sustained to provide channels for impact in the work of the WG ENV. • CCT recommends NMIs to create Metrology Networks to become reference institutions for the interacting and collaborating with the stakeholders and to preserve, improve and disseminate the experience achieved in thermal metrology for climate and environment. • CCT WG ENV members to continue to contribute as experts in WMO, GCOS task team.	CCT recommends NMIs to include in their vision documents all possible actions within the expertise of the thermal metrology community contributing to improve measurement quality and knowledge on observation and monitoring of the environment and climate
The "Metrology for Meteorology and Climate" – MMC Conference series and associated workshops and satellite events • were fully participated in and endorsed by CCT WG ENV members • represent world top level events for increasing the collaboration between thermal metrologists and the stakeholder communities.	• Data comparability: Include as reliable as possible uncertainty analysis in historical data; study and assess traceability. • Spatial and temporal comparability: Systematic evaluation of environmental and instrumental influences on measurement results; complete knowledge on measured quantity. • Temperature measurements: Improved measurement techniques, calibration procedures and develop, supervise and harmonise guides. • Water content measurements (air and soil): Develop suitable measurement techniques and guides. • Impact: CCT members continue to organize events, meetings, workshops, conferences and training to discuss and plan common activities with the climate and environmental communities.	• **Air temperature measurements** still present open issues in identifying the components of the uncertainties budget and in their evaluation. The evaluation of the uncertainty in atmospheric air temperature measurements, both at ground level ar in upper atmosphere, together with a fully documented traceability, is the fundamental condition to achieve data comparability within and among observing networks, in space and time and fo the validation of different techniques. • WG Environment to initiate studies and publication on this subject. • In a long-term vision, it is expected that the joint work of metrologists and the user community will improve the knowledge on this key measurement fo atmospheric studies and climate monitoring.
	The planned creation of a GCOS Surface Reference Network (GSRN) of observing stations on land[6] will require a continuous support from the thermal metrology community, being temperature and humidity of air and soil key observables.	• CCT WG ENV, together with operational meteoro-logists, climatologists and metrologists, to contribute with studies and activities to GCOS for the definition of the key aspects of GSRN in terms of station features, data characteristics and target uncertainties. • Provide roadmap to address needs of data quality arising from possible new climate evolution scenarios.

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A T M

Air Temperature Metrology

A T M

Air Temperature Metrology

EURAMET P1459

Started in 2018

(2016 Euramet TC-T workshop on air temperature)

24 EU NMIs/DIs

Coordinator: Andrea Merlone INRiM

EURAMET Project Form:
Progress and Final Report

EURAMET

Document: G-OPS-FRM-010 Version: 3.0
Approved: MSM 2019-02-21

1 **Title of project**
Air Temperature Metrology - ATM

2 **Report** X progress report ☐ final report	3 **Status of the project** X in progress ☐ ongoing ☐ completed ☐ concluded	4 **Registration No:** 1459

5 **Subject Field** T - Temperature T - Temperature

6 **Type of collaboration** Cooperation in Research

6A **In the case of a comparison**
Registered as Key comparison (KC) or Supplementary Comparison (SC) in the KCDB:
☐ no ☐ yes If yes: No. of KC/SC: °°°°°

7 **Progress/Final Report**
Progress

After a launch meeting during the TC-T in Borås (SE) in 24 May 2018, the project started with presentation of the two main tasks: the research intercomparison and the preparation of the guide on calibration of thermometers in air. At the meeting the activities preliminary to task 1 have been planned and during the year the advances have been the following:
a) The comparison has been defined and will be performed within the limits of near surface atmospheric air temperature, from -80 °C to +60 °C in two different ranges:
Range A: -80 °C to 60 °C
Range B: -40 °C to 60 °C
Participants choosed one of the two ranges considering that a condition for joining the pilot comparison is for all participants to have the capability to cover the whole temperature range for the selected option.

- Two sub tasks were created.

Sub Task 1.1 Liquid – air comparison of calibration results (to be confirmed)
Sub Task 1.2 INRiM – IMBiH bilateral comparison

A task 0 was added, for collecting thermometers
A task 3 was added to describe impact activities

b) the advisory board (AB) members have been identified and the AB group made operative. the first task has been the discussion and drafting of the ILC protocol.
c) The protocol has been completed and is now ready for discussion and approval by all participants at the project kick off meeting in Torino, TC-T April 7 2019. At that date the ILC will start. It prescribes the technical and data analysis features for the ILC, together with loop dates.
d) an excell file with different sheets has been prepared to collect ILC data
e) after presenting the project to manufacturers, a representative number of thermometers has been collected in groups of three identical (each one for taking part in one loop in parallel).

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www.euramet.org

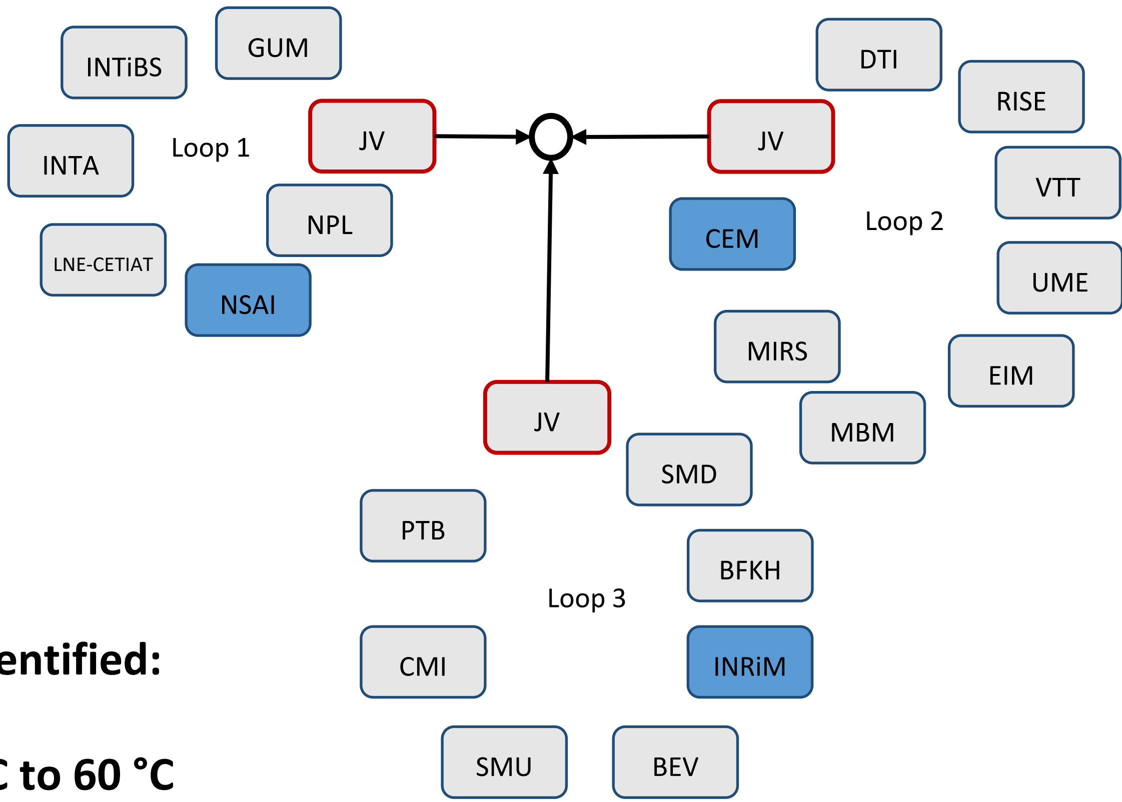
Air Temperature Metrology – ATM

ATM
Air Temperature Metrology

Two main tasks:

1. Perform a pilot study in the form of interlaboratory comparisons, to explore issues around calibration in air of temperature sensors ;

2. Feed into a guidance document the findings from the pilot study. (main objective)



Two ranges identified:

Range A: -80 °C to 60 °C
Range B: -40 °C to 60 °C

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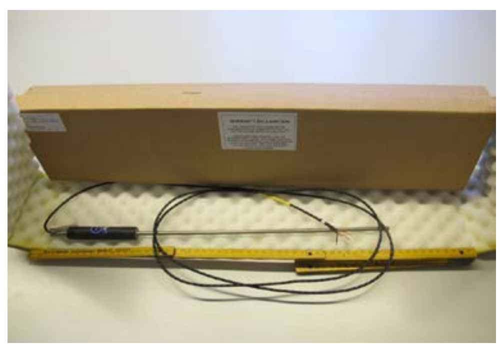
Different sensor for representative applications



In 2021 the ILC was concluded.

Next steps:

ILC data analysis

Extension of the ILC to other RMOs (within BIPM TG Air coordination)

Guide preparation

CCT Task Group on Air temperature «TG Air»

Chair: Åge Andreas Falsen Olsen (JV)
Co-Chair: Andrea Merlone (INRiM)

SG1: To work towards and propose a practical definition of air temperature (S. Bell – NPL)

SG2: To work towards and propose how to evaluate the uncertainty contributions in air temperature measurements (D. Zvizdic – FSB)

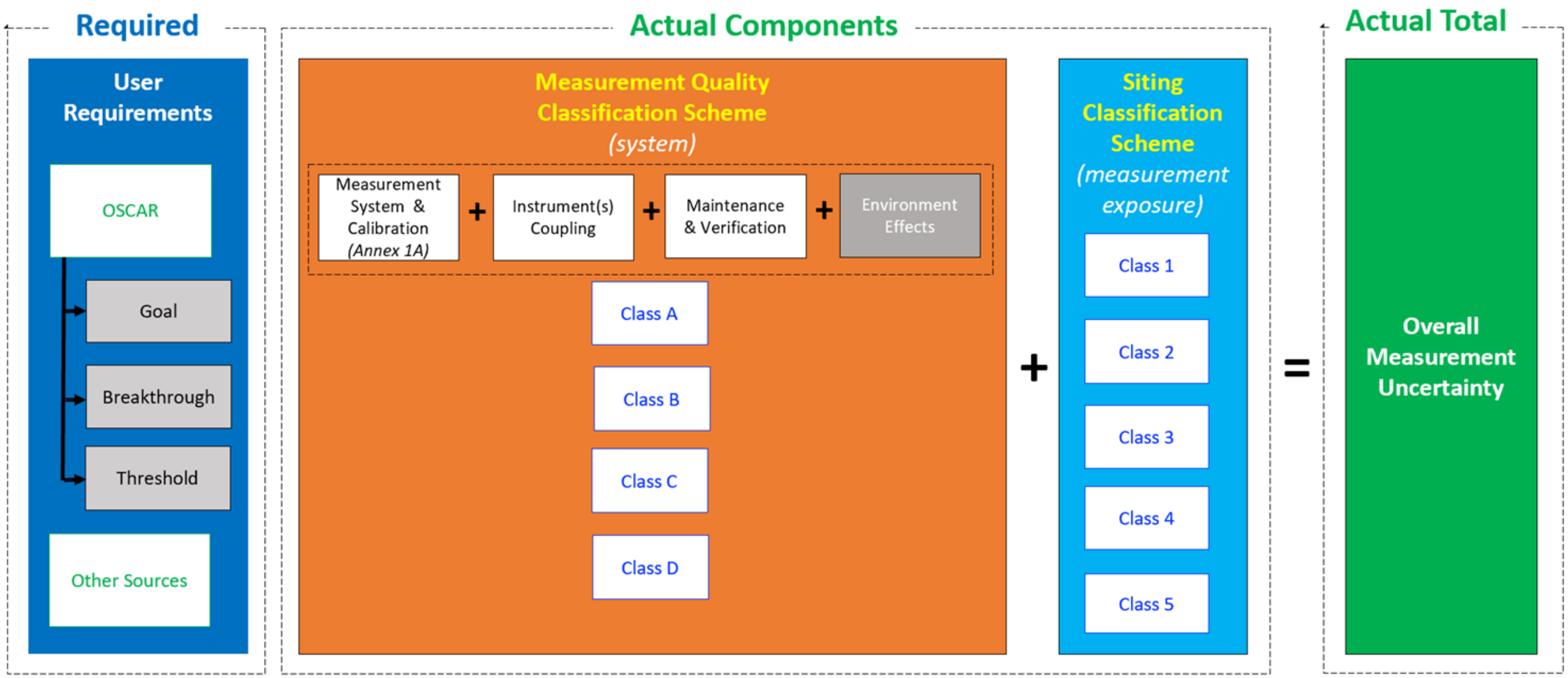
SG3: To develop guidelines for the calibration of thermometers in air (Y-G. Kim – Kriss)

Membership finalized. Kickoff meeting 13 December 2021
Work started in SG3 with the preparation of a questionnaire

World Meteorological Organization

MEASUREMENT QUALITY CLASSIFICATIONS
FOR SURFACE OBSERVING STATIONS ON LAND

INFCOM-1/Doc. 4.2(4)



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Measurement Quality Classification Scheme *(system)*

Measurement System & Calibration *(Annex 1A)* + Instrument(s) Coupling + Maintenance & Verification + Environment Effects

- Construction quality,
- Resolution,
- Instrument and logger calibration,
- Linearity,
- Hysteresis,
- Time constant,
- Drift with temperature,
- Sampling method,
- Sampling frequency,
- Processing algorithm,
- Digitization and rounding,
- Response time.

Class A

Class B

Class C

Class D

No problems*: Calibration certificates with complete expanded uncertainty uncertainty normally available

(* *almost*)

+

Siting Classification Scheme *(measurement exposure)*

Class 1

Class 2

Class 3

Class 4

Class 5

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Measurement Quality Classification Scheme *(system)*

Measurement System & Calibration *(Annex 1A)* + Instrument(s) Coupling + Maintenance & Verification + Environment Effects

Class A

Class B

Class C

Class D

- Radiation screen,
- Static pressure head,
- Rain gauge fence screen.

Only minor issues. Solved by

Manufacturer/technical specifications,

Intercomparisons

User's studies

+

Siting Classification Scheme *(measurement exposure)*

Class 1

Class 2

Class 3

Class 4

Class 5

Measurement Quality Classification Scheme *(system)*

Measurement System & Calibration *(Annex 1A)* + Instrument(s) Coupling + Maintenance & Verification + Environment Effects

- Frequency of maintenance,
- Instrument and system drift with time,
- Instrument and system aging,
- Instrument and system faults (that affect data but do not cause failure),
- Cleanliness of instrument and site.

Class A

Class B

Class C

Class D

Minor issues.
Solved by:
Evaluating drift in time
Calibration uncertainty
Maintenance procedures

\+

Siting Classification Scheme *(measurement exposure)*

Class 1

Class 2

Class 3

Class 4

Class 5

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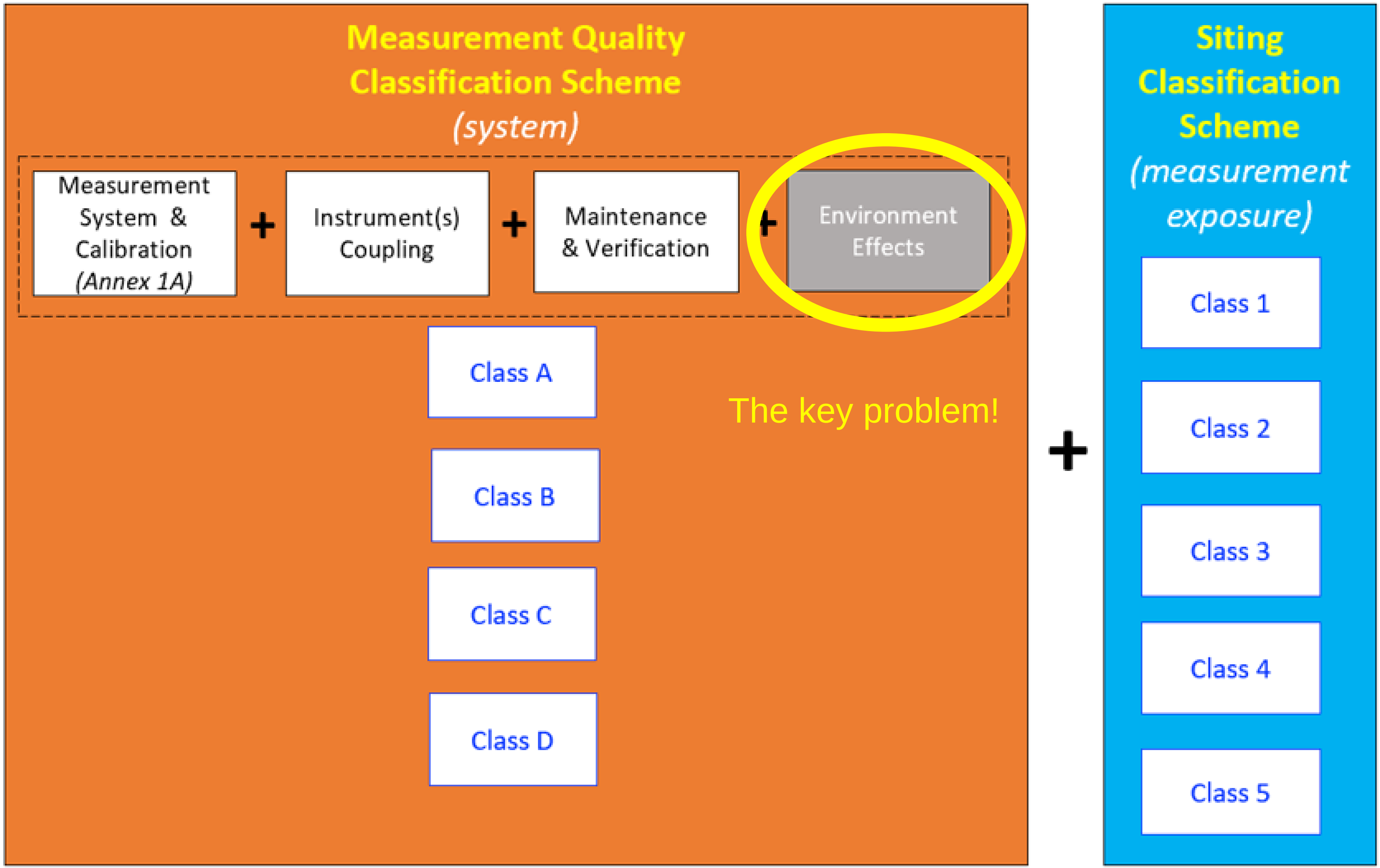

INFCOM-1/Doc. 4.2(4)

Environmental effects

(Associated Quantities of Influence)

- Sensor mechanical stress during transport and operation,
- Precipitation on screen,
- Wind effects on measurement,
- Condensation/evaporation on temperature instrument,
- Solar radiation effects on measurement.
- Clear definition of the measurand
- Albedo
- Height from the ground

Prescribed by Guides

Measurement models are given

Experiments are made on representative numbers and typologies of instruments

Results are published in literature

Values are included in prescriptions and guidance on uncertainty evaluation

Pros: values are available in guides as «given» uncertainty estimations
Wide applicability

Cons: Larger unceraintyless representative of the measured data

INFCOM-1/Doc. 4.2(4)

Environmental effects

(Associated Quantities of Influence)

- Sensor mechanical stress during transport and operation,
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- Solar radiation effects on measurement.
- Clear definition of the measurand
- Albedo
- Height from the ground

Evaluated by User

Measurement models are given (where possible)

Users evaluate some of the effects for their specific equipment

Results are published in literature

Values can be used by other users **only** for the same equipment and in similar conditions

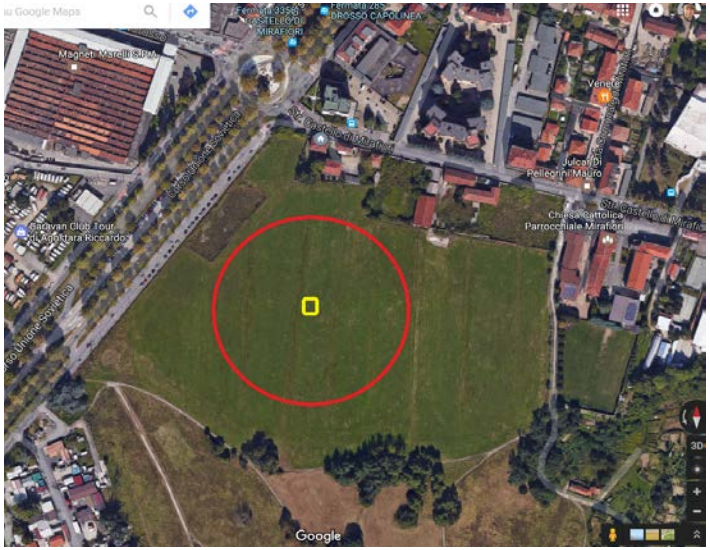
Pros:	better evaluation of uncertainty reduced uncertainty active role and contribution to science by direct users
Cons:	time and costs limited applications

The contribution of the surrounding environment does not influence* the instrumentation or the measurand itself, but the larger scale representativeness of the measurement results.

It is therefore a component of uncertainty of a ***different measurand***, which has to be evaluated locally.

Prescriptions are given by the "WMO Siting Classification" scheme and associated uncertainties

* with minimal exceptions



Siting Classification Scheme
(measurement exposure)

Class 1

Class 2

Class 3

Class 4

Class 5

Siting uncertainty Prescribed by Guides

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Siting uncertainty
Prescribed by Guides

The siting classification (under revision) prescribes uncertainty values to be associated to

Different obstacles:
- Buildings
- Trees
- Roads
- Water
- Slopes
- - Shade
- …

Different distances
- >100 m
- 50 m -100 m
- 30 m – 50 m
- 10 m – 30 m
- 3 m – 5 m – 10 m

This is more a descriptive classification, to immediately get an *idea-identification* of the data quality for a specific station on land,

than a contribution for a total uncertainty budget

The suggested 'uncertainty' is given to document the order of magnitude of the errors which may arise for a given class. It doesn't mean that all the measurements are affected by such an error.

Siting uncertainty
Prescribed by Guides

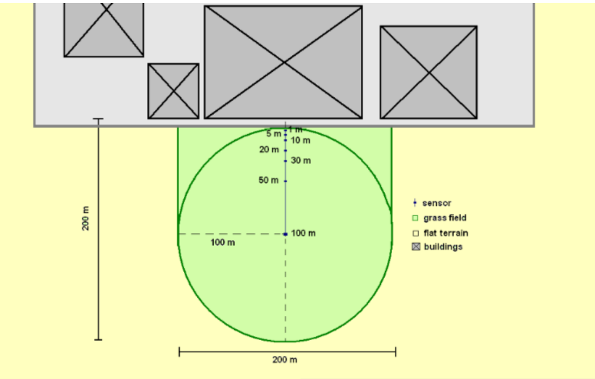
Siting uncertainty Evaluated-By Users

The station manager evaluates the contribution to the siting uncertainty by implementing and executing experimental evaluation for the specific site, following agreed procedures.

For the specific site:
The result of the investigation can be used both to define the class (according to the classification) and to include values in the uncertainty budget, for the representativeness of the observed data.

For the wider use:
The result of the investigation can be considered as further contribution to improving the prescribed siting classification values.

MeteoMet siting experiments



Three identical experiments
Thermometers at 2 m, 5 m, 10 m, 50 m, 100 m following the WMO classification

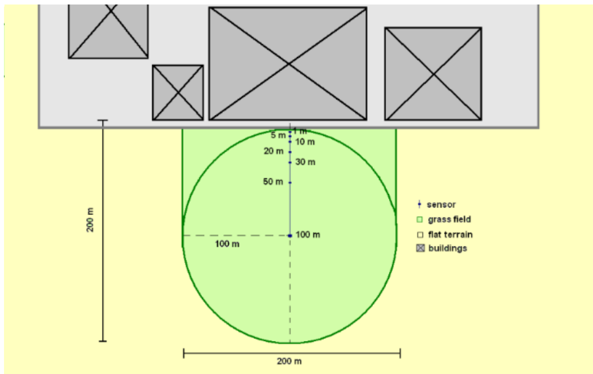
Road (Italy)

Trees (Czech Rep.)

Buildings (Spain)

Further experiments planned for water sources

MeteoMet siting experiments



Three identical experiments
Thermometers at 2 m, 5 m, 10 m, 50 m, 100 m following the WMO classification

Preliminary results show that

the WMO siting classification over-estimates the uncertainties

Prescribed by Guides

Results of the experiments, toghether with other new similar investigation, contribute to the revision of the Siting Classification,

by prescribing more robust uncertainty values to be associated to each class

Evaluated by users

The measurement method and uncertainty evaluation protocol can be adopted by other users to:

a) Evaluate the uncertainty contribution for specific sites

b) Deliver further knowledge and contribution to the improvement of the Siting Classification

World Meteorological Organization

Tasks of the WMO ET-MU

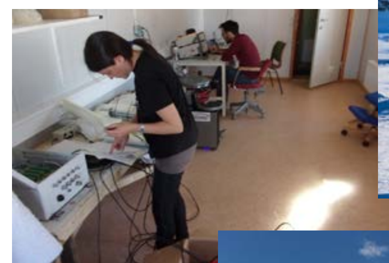
Harmonisation of the terminology related to measurement uncertainty, across WMO publications
Consistency between the overall measurement uncertainties and the two classification schemes, and their implementation
Mechanism for ensuring consistency for expression of measurement uncertainty among WMO publications

Issues with the measurand

Some conclusions

- Pesent knowledge is not enough for completing the measurement and uncertainty contribution model, on a top-down approach.
- Field and laboratory activities are required to promote a bottom-up solution
- The multitude of commercial products poses issues in identifying representativeness of evaluated contributions
- Technical solution constantly evolve and continuous investigation is needed (for example on non-contact systems for temperature and precipitation)

Examples: Environmental influences
Precipitation
Wind speed
Solar radition
…



- Research is coordinated from the key Institutions

  And/Or

- Experiments are made directly by users
- Results of experiments increase leterature and contribute to improve the prescriptions
- The revision of prescriptions highlights the need of further measurements
- Call for projects and comparisons are issued by Institutions

Examples: EURAMET
Joint Research Projects
WMO field intercomparisons
…

Examples: Manufacturers
Users
NMHSs - NMIs

Papers - Reports

Expert teams – Working Groups

Cooperation model

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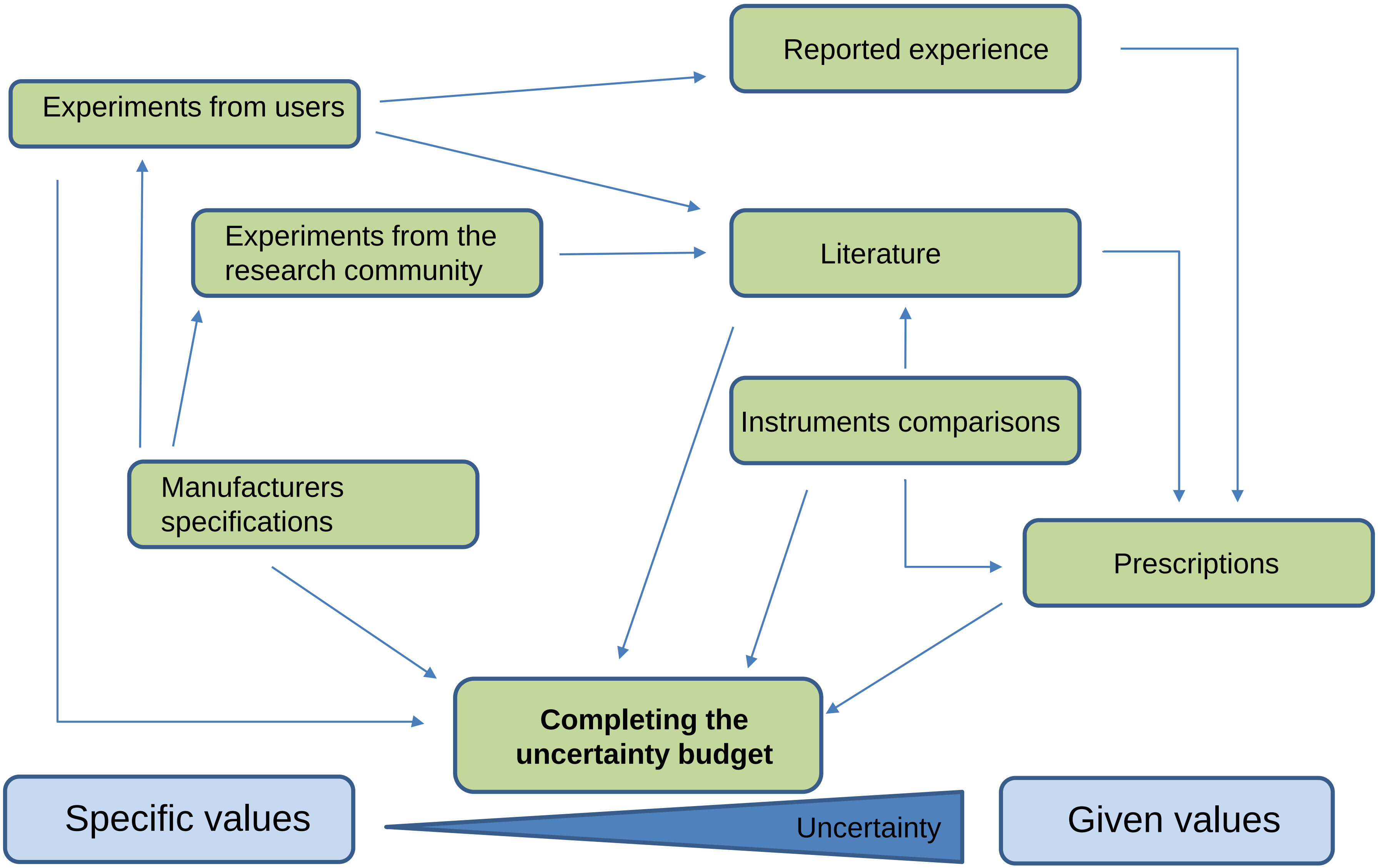

Completing an uncertainty budget from different sources

Contribution	Standard unc.	Distribution	Contribution	Source
Calibration				Calibr. Certificate
Radiation				Manufacturer data sheet
Precipitation				User experiments
Wind				Estimated from guidance material
Condensation/ evaporation				Literature
Presence of trees				Siting Classification
Heating from roads				Siting Classification
Solar shield				Intercomparison results

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Near Surface Temperature (NST) measurement uncertainty calculation tool (Delivered for Copernicus Climate Change Service C3S – 311 Lot2)

Station name	
Short description	
Station identifier (OSCAR)	
Coordinates	
Sensor type	0
Measuring principle/equation	0
Manufacturer	0
Serial number	0
Metadata completeness level	**0 %**
Uncertainty completeness level	**0 %**
Overall completeness level	**0 %**
Expanded uncertainty	**2,13 K**

Metadata	**Unit**	**Value**	**Bm (Note 13**
Metadata completeness	0	%	
Measurement			
Expected range	°C	0-20°C	
Recording time	s		
Averaging time	s		
Sensor type			
Measuring principle/equation			
Manufacturer			
Serial number			
Date of construction	yyyy-mm-dd		0,5
Last calibration	yyyy-mm-dd		1
Last verification	yyyy-mm-dd		1
Last inspection/mantenance	yyyy-mm-dd		0,5
Associated datalogger			
Manufacturer			
Serial number			
Date of construction	yyyy-mm-dd		0,2
Last calibration	yyyy-mm-dd		0,5
Last verification	yyyy-mm-dd		0,5
Last inspection/mantenance	yyyy-mm-dd		0,2
Solar shield			
Type			
Years from construction/installation			0,5

Uncertainty components		**value (k=1)**	**Unit**
Sensor			
Calibration			K
Drift (2)			K/year
Sensitivity			K
Self heating			K
Resouution			K
Datalogger (3)			
Uncertainty			K
Drift			K/year
Temperature coefficient (4)			K
Solar shield			
Max diff Vs Stevenson (5) [1]			K
Error Vs radiation (6) [1]			K/W
Ageing (7) [2]			K/year
Quantities of influence	Note 11		
Precipitation (8)	0		K/hour
Albedo (9) [3]	0		K
Soil temperature (10)			K
Wind (10)			K/(m/s)
Condensation/humidity (10)			K
Surrounding environment	Note 12		
Road		0	

Quantities of influence requiring ancillary measurements

- Relative humidity
- Solar radiation
- Wind speed at same height of thermometer
- Precipitation
- Reflected radiation (for snow presence)
- Soil temperature

Associated datalogger	
Manufacturer	
Serial number	
Date of construction	yyyy-mm-dd
Last calibration	yyyy-mm-dd
Last verification	yyyy-mm-dd
Last inspection/mantenance	yyyy-mm-dd
Solar shield	
Type	
Years from construction/installation	

Sensor type	
Measuring principle/equation	
Manufacturer	
Serial number	
Date of construction	yyyy-mm-dd
Last calibration	yyyy-mm-dd
Last verification	yyyy-mm-dd
Last inspection/mantenance	yyyy-mm-dd

Near Surface Temperature (NST) measurement uncertainty calculation tool
(Delivered for Copernicus Climate Change Service C3S – 311 Lot2)

Station name

Short description

Metadata	Unit	Value	Bm (Note 13
Metadata completeness		0 %	

Uncertainty components	value (k=1)	Unit
Sensor		

Completeness level

When not all contributions can be evaluated, a «completeness level», should be indicated for data users.

This can be a percent value, based on the weight of the contributions not estimated on the overall expanded uncertianty. The relative weight should be known by experience and literature.

Hopefully only minor contribution should be neglected, but this is not always the case.

For example the instrument resolution of 1 mk is well obtained from dataloggers specs, while the effect of snow albedo, contributing for over 1 K is unknown.

Solar shield
Type
Years from construction/installation

Date of construction	yyyy-mm-dd
Last calibration	yyyy-mm-dd
Last verification	yyyy-mm-dd
Last inspection/mantenance	yyyy-mm-dd

Andrea Merlone

Huh!?
0.1 °C resolution??
Where are the other
7 digits???

Metrologist point of view

Thank you