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
- ...

JCGM WG1 – WMO ET-MU Joint workshop – 5,6 April 2022
Air Temperature is the most measured variable

In Meteorology and Climatology, where it is the fundamental variable to understand climate change and variability.
The lowest natural temperature ever directly recorded at ground level on Earth is \(-89.2\, ^\circ C\) at the Soviet Vostok Station in Antarctica on July 21, 1983 by ground measurements at 3900 m of altitude. (Satellites observation recorded -94.7 °C in August 2010)
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
Results

<table>
<thead>
<tr>
<th></th>
<th>Corrected Value (°C)</th>
<th>Uncertainty (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kuwait calibration (A)</td>
<td>53.87</td>
<td>±0.080</td>
</tr>
<tr>
<td>Kuwait comparison (B)</td>
<td>53.84</td>
<td>±0.064</td>
</tr>
<tr>
<td>Pakistan calibration (A)</td>
<td>53.72</td>
<td>±0.40</td>
</tr>
<tr>
<td>Pakistan comparison (B)</td>
<td>53.72</td>
<td>±0.29</td>
</tr>
</tbody>
</table>
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
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)
− 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 than 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:
  - \( pv/T = \text{konst} \)
  - \( C_p = \text{konst} \)
  - (resembles air at low pressures)

- System boundaries:
  - no heat is transferred
  - no work is transferred

- Ideal thermometer
  - Adiabatic:
    - no radiation
    - no convection
    - no conduction
  - Ideal geometry:
    - total stagnation of directed kinetic energy
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
A further technical issue...
Traceability?
### BIPM - CCT Strategy Document for Rolling Programme Development for 2018 to 2027

<table>
<thead>
<tr>
<th></th>
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</thead>
<tbody>
<tr>
<td>Environment</td>
<td></td>
<td></td>
</tr>
<tr>
<td>The RECOMMENDATION T3 (2010) to the CIPM entitled “On climate and meteorological observations and measurements” is the basis for establishing long term 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.</td>
<td>- The relationships with key world and international institutions such as WMO, GOS, 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.</td>
<td>CST 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.</td>
</tr>
<tr>
<td>The “Metrology for Meteorology and Climate” – MMC Conferences series and associated workshops and satellite events:</td>
<td>- 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.</td>
<td>- Air temperature measurement 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 and 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 for 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 for this key measurement for atmospheric studies and climate monitoring.</td>
</tr>
</tbody>
</table>

The planned creation of a GOS Surface Reference Network (GSRN) of observing stations on land 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 meteorologists, 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.
EURAMET P1459

Started in 2018
(2016 Euramet TC-T workshop on air temperature)

24 EU NMIs/DIs

Coordinator: Andrea Merlone INRiM
Air Temperature Metrology – ATM

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
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
MEASUREMENT QUALITY CLASSIFICATIONS
FOR SURFACE OBSERVING STATIONS ON LAND

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

Siting Classification Scheme
(measurement exposure)

- Class 1
- Class 2
- Class 3
- Class 4
- Class 5

Required
User Requirements
- OSCAR
- Goal
- Breakthrough
- Threshold
- Other Sources

Actual Components

Actual Total

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

(*) almost
- Radiation screen,
- Static pressure head,
- Rain gauge fence screen.

Only minor issues. Solved by:
- Manufacturer/technical specifications,
- Intercomparisons
- User's studies
Minor issues.
Solved by:
Evaluating drift in time
Calibration uncertainty
Maintenance procedures

- 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.
Measurement Quality Classification Scheme (system)

- Measurement System & Calibration (Annex 1A)
- Instrument(s) Coupling
- Maintenance & Verification

Environment Effects

The key problem!

Siting Classification Scheme (measurement exposure)

- Class 1
- Class 2
- Class 3
- Class 4
- Class 5
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

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 uncertainty less representative of the measured data
Environmental effects
(Associated Quantities of Influence)

- Sensor mechanical stress during transport and operation,
- Precipitation on screen,
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- Clear definition of the measurand
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- 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 uncertainty
Prescribed by Guides
Siting uncertainty
Prescribed by Guides

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

<table>
<thead>
<tr>
<th>Different obstacles</th>
<th>Buildings</th>
<th>Trees</th>
<th>Roads</th>
<th>Water</th>
<th>Slopes</th>
<th>Shade</th>
<th>…</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Different distances</th>
<th>&gt;100 m</th>
<th>50 m -100 m</th>
<th>30 m – 50 m</th>
<th>10 m – 30 m</th>
<th>3 m – 5 m – 10 m</th>
</tr>
</thead>
</table>

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

Prescribed by Guides

Results of the experiments, together 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

Preliminary results show that the WMO siting classification over-estimates the uncertainties.

Three identical experiments
Thermometers at 2 m, 5 m, 10 m, 50 m, 100 m following the WMO classification.
<table>
<thead>
<tr>
<th>Tasks of the WMO ET-MU</th>
</tr>
</thead>
<tbody>
<tr>
<td>Harmonisation of the terminology related to measurement uncertainty, across WMO publications</td>
</tr>
<tr>
<td>Consistency between the overall measurement uncertainties and the two classification schemes, and their implementation</td>
</tr>
<tr>
<td>Mechanism for ensuring consistency for expression of measurement uncertainty among WMO publications</td>
</tr>
</tbody>
</table>
Issues with the measurand

Some conclusions
• Present 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 radiation
...
• Research is coordinated from the key Institutions
  And/Or
• Experiments are made directly by users
• Results of experiments increase literature 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
### Completing an uncertainty budget from different sources

<table>
<thead>
<tr>
<th>Contribution</th>
<th>Standard unc.</th>
<th>Distribution</th>
<th>Contribution</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calibration</td>
<td></td>
<td></td>
<td></td>
<td>Calibr. Certificate</td>
</tr>
<tr>
<td>Radiation</td>
<td></td>
<td></td>
<td></td>
<td>Manufacturer data sheet</td>
</tr>
<tr>
<td>Precipitation</td>
<td></td>
<td></td>
<td></td>
<td>User experiments</td>
</tr>
<tr>
<td>Wind</td>
<td></td>
<td></td>
<td></td>
<td>Estimated from guidance</td>
</tr>
<tr>
<td>Condensation/evaporation</td>
<td></td>
<td></td>
<td></td>
<td>Literature</td>
</tr>
<tr>
<td>Presence of trees</td>
<td></td>
<td></td>
<td></td>
<td>Siting Classification</td>
</tr>
<tr>
<td>Heating from roads</td>
<td></td>
<td></td>
<td></td>
<td>Siting Classification</td>
</tr>
<tr>
<td>Solar shield</td>
<td></td>
<td></td>
<td></td>
<td>Intercomparison results</td>
</tr>
</tbody>
</table>
Near Surface Temperature (NST) measurement uncertainty calculation tool
(Delivered for Copernicus Climate Change Service C3S – 311 Lot2)

### Metadata

<table>
<thead>
<tr>
<th>Metadata</th>
<th>Unit</th>
<th>Value</th>
<th>% (Note 13)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Metadata completeness</td>
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</table>

### Measurement

<table>
<thead>
<tr>
<th>Expected range</th>
<th>°C</th>
<th>0-40%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recording time</td>
<td>s</td>
<td></td>
</tr>
<tr>
<td>Averaging time</td>
<td>s</td>
<td></td>
</tr>
</tbody>
</table>

### Sensor type

<table>
<thead>
<tr>
<th>Measuring principle/equation</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Manufacturer</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Serial number</td>
<td>yyyy-mm-dd</td>
<td>0,5</td>
</tr>
<tr>
<td>Date of construction</td>
<td>yyyy-mm-dd</td>
<td>0,5</td>
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<tr>
<td>Last calibration</td>
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<tr>
<td>Last verification</td>
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<tr>
<td>Last inspection/maintenance</td>
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</table>

### Datalogger (3)

<table>
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<tr>
<th>Uncertainty</th>
<th>Unit</th>
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<tbody>
<tr>
<td>Drift</td>
<td>K/year</td>
</tr>
<tr>
<td>Temperature coefficient</td>
<td>K</td>
</tr>
</tbody>
</table>

### Solar shield

| Max diff Vs Stevenson (5) | K |
| Error Vs radiation (6)   | K/W |
| Ageing (7) [2]           | K/year |

### Quantities of influence

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

### Associated datalogger

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Serial number</td>
<td>yyyy-mm-dd</td>
<td>0,2</td>
</tr>
<tr>
<td>Date of construction</td>
<td>yyyy-mm-dd</td>
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<td>Last calibration</td>
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</table>

### Solar shield

<table>
<thead>
<tr>
<th>Type</th>
<th>Years from construction/installation</th>
<th>K</th>
</tr>
</thead>
</table>

### Quantities of influence

- 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

- Road 0

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Andrea Merlone

Metrology for Meteorology

JCGM WG1 – WMO ET-MU Joint workshop – 5,6 April 2022
Near Surface Temperature (NST) measurement uncertainty calculation tool
(Delivered for Copernicus Climate Change Service C3S – 311 Lot2)

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<th>Uncertainty components</th>
<th>Value (k=1)</th>
<th>Unit</th>
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<tr>
<th>Sensor</th>
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<tr>
<th>Quantities of influence requiring ancillary measurements</th>
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<tr>
<td>Relative humidity</td>
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</table>

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