

Short Course 4.16 - Reference Measurements for Climate Studies and Applications



Graziano Coppa



Near-surface Reference (Temperature) Measurements

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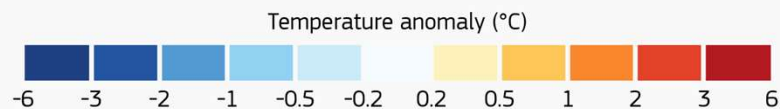
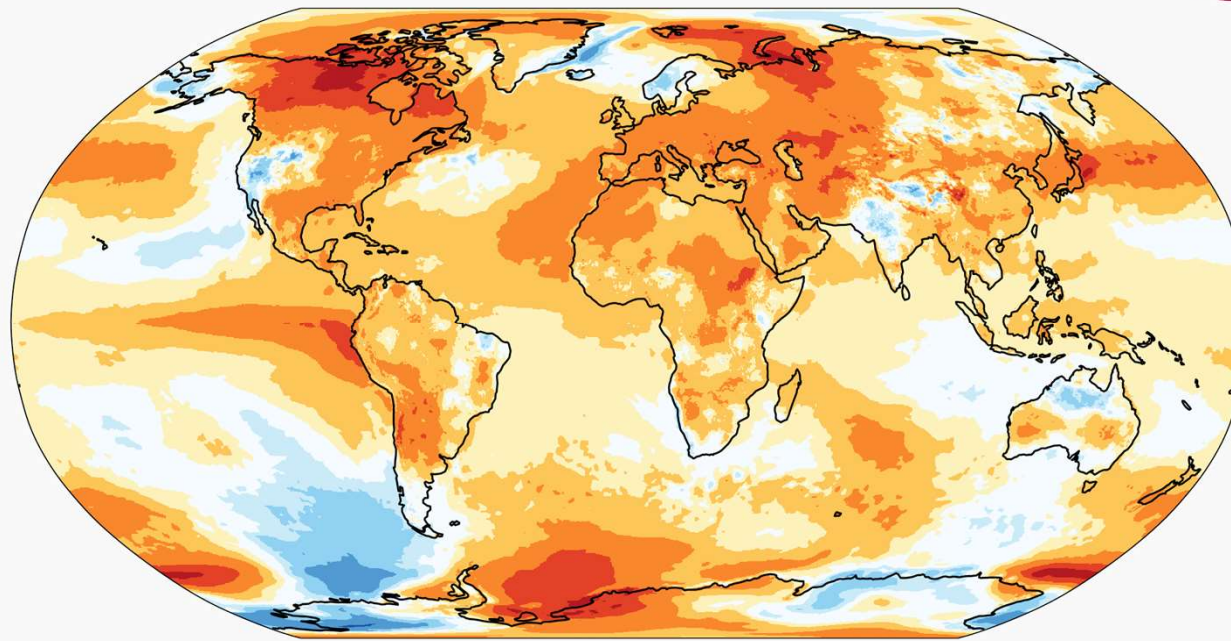
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Near-surface Reference (Temperature) Measurements

SURFACE AIR TEMPERATURE ANOMALY • 2023

Reference period: 1991–2020 • Data: ERA5 • Credit: C3S/ECMWF



PROGRAMME OF THE EUROPEAN UNION



Source: climate.copernicus.eu

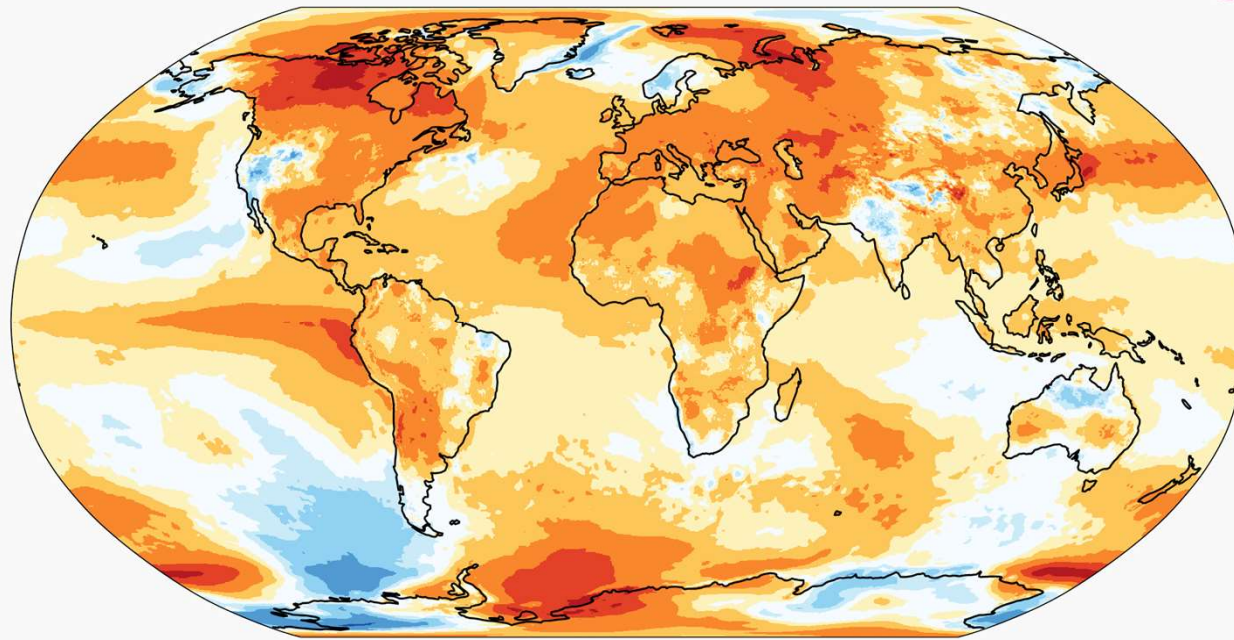
How do we define the common temperature measurements?

Many different temperature measurements are routinely collected by organisations around the world, encompassing different depths within the ocean, the ground surface and many levels within the atmosphere, all the way into the stratosphere. For monitoring the climate, C3S mainly uses **surface air temperature**, which is also called *2 m air temperature* as it is measured away from the main influences of the ground. Surface temperatures across the ocean - *sea surface temperature (SST)* and *sea ice surface temperature* - are also used for climate monitoring, as is *lake surface water temperature*.

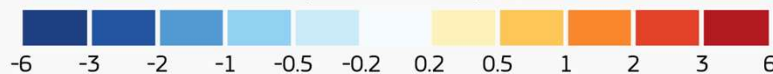
Land (or ground) surface temperature refers to the temperature of the land itself. These temperatures can be several degrees warmer or cooler than the surface air temperature. In urban areas, for example, materials such as asphalt, concrete and artificial grass tend to absorb heat more readily than natural surfaces. This also contributes to the 'urban heat island' effect, where urban environments are significantly warmer than surrounding rural areas. C3S does not currently have a dataset for land surface temperature.

SURFACE AIR TEMPERATURE ANOMALY • 2023

Reference period: 1991–2020 • Data: ERA5 • Credit: C3S/ECMWF



Temperature anomaly (°C)



PROGRAMME OF
THE EUROPEAN UNION



Source: climate.copernicus.eu

How is **temperature** measured?

Data on temperature are collected in a variety of ways. These include **in situ measurements** at weather stations, or on ships or buoys, for example. While in situ data records are only available for limited locations, satellites can theoretically measure any surface at any time. Rather than directly measuring temperature, they capture information on radiation at different wavelengths, such as infrared[...]

To understand climate change and weather extremes, it is important to **have complete and evenly distributed records in space and in time**. Even with satellites, observations do not provide a full picture across the entire globe at any given point in time. This is where reanalysis data are a powerful tool. These combine observational data with computer models to build a globally complete and consistent dataset, and are sometimes referred to as 'maps without gaps'.

What is a reference measurement?

Definition by VIM (Vocabulaire international de métrologie)

2.7

reference measurement procedure

measurement procedure accepted as providing measurement results fit for their intended use in assessing measurement trueness of measured quantity values obtained from other measurement procedures for quantities of the same kind, in calibration, or in characterizing reference materials



What are reference networks?




World Meteorological Organization
**COMMISSION FOR OBSERVATION,
 INFRASTRUCTURE AND INFORMATION SYSTEMS**
 Second Session
 24 to 28 October 2022, Geneva

INFCOM-2/Doc. 6.1(7)
 Submitted by:
 Chair
 26.X.2022
APPROVED

- AGENDA ITEM 6: TECHNICAL REGULATIONS AND OTHER TECHNICAL DECISIONS**
- AGENDA ITEM 6.1: Standing Committee on Earth Observing Systems and Monitoring Networks (SC-ON)**

RECOGNITION OF THE CONCEPT FOR TIERED NETWORKS

DRAFT DECISION

Draft Decision 6.1(7)/1 (INFCOM-2)

Recognition of the concept for tiered networks

The Commission for Observation, Infrastructure and Information Systems

Recalling Resolution 6 (INFCOM-1) - Review of the work programme of the Commission, and output 2.1.4 - Response to the WMO Integrated Global Observing System (WIGOS) Vision 2040 during 2020-2023, including consideration of Earth system prediction requirements and urban services,

Having examined the Concept Note on tiered network provided in the annex to this decision,

Decides:

- (1) To endorse the concept for tiered networks, as provided in the annex to this decision;
- (2) To request the president of the Commission to consider the establishment of a mechanism to:
 - (a) Consult, develop and agree upon a set of criteria to be used as part of the process to assign candidate networks to appropriate tiers and ensure that these criteria are linked to existing mechanisms within WMO, such as the Rolling Review of Requirements process, the WIGOS Data Quality Monitoring System (WDQMS), the WMO Siting Classification Scheme, and the WMO Measurement Quality Classification Scheme (MQCS);
 - (b) Develop and recommend a mechanism of governance for the process that represents a sustainable approach for INFCOM and Members;
 - (c) Develop an implementation plan to formalize and standardize the tiered network approach across domains and observing programmes as described in the annex to this decision; and
 - (d) Report on progress to INFCOM-3.

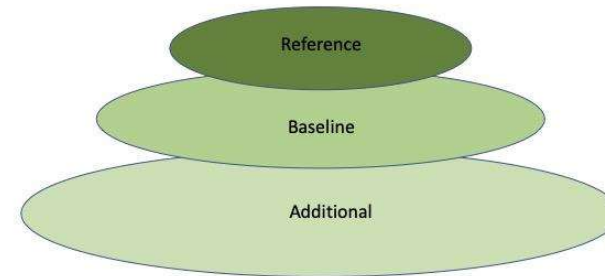
Spatial density

Siting heterogeneity

Diversity of ownership and management

Range of applications

Range of data formats



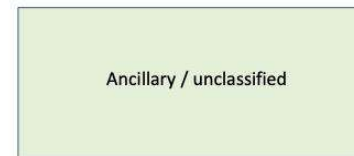
Stability and long-term support

Metrological understanding

Uncertainty quantification

Data availability

Metadata



What are reference networks?



AGENDA ITEM 6: TECHNICAL REGULATIONS AND OTHER TECHNICAL DECISIONS
AGENDA ITEM 6.1: Standing Committee on Earth Observing Systems and Monitoring Networks (SC-ON)

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 - (d) Report on progress to INFCOM-3.

These networks provide metrologically traceable observations, with quantified uncertainty, at a limited number of locations, or for a limited number of observing platforms, for which traceability has been attained.

- The measurements **are traceable through an unbroken processing chain** (in which the uncertainty arising in each step has been rigorously quantified) to SI units, Common Reference Points defined by BIPM, or community recognized standards (ideally recognized by National Metrology Institutes), using accepted best practices at any time as documented in the accessible literature.
- **Uncertainties arising from each step in the processing chain are fully quantified and included in the resulting data.** Uncertainties are reported for each data point. Individual components of the uncertainty budget are available. Where uncertainties are correlated, these are appropriately handled.
- The measurements are **representative of the broader surroundings** and the site environment is stable (e.g., there is no ongoing or planned large-scale land-use or land-cover change of human origin for terrestrial sites).
- **Full metadata** concerning the measurements is captured and retained, along with the original raw data, to allow subsequent reprocessing of entire data streams as necessary by any user.
- The measurement and its uncertainty are verified **through complementary, redundant observations of the same measurand** on a sufficiently routine basis which might vary by instrument and site type. This can be achieved via a variety of means including sustained redundant observations, round-robin intercomparisons, travelling standards.
- All data and metadata are made **freely available** to users.
- The observations programme is actively managed and has a commitment to **long-term operation**, to the extent possible.
- **Change management is robust** including a sufficient programme of parallel and/or redundant measurements to fully understand the impact of any changes that do occur upon the measurement uncertainties. Unnecessary changes are minimized.
- **Measurement technology innovation is pursued.** New measurement capabilities through new measurement techniques, or innovations to existing techniques, which demonstrably improve the ability to characterize the measurand, are encouraged. These innovations must be managed in such a way as to understand their impacts on the measurement series before they are deployed

Climatological reference stations: Definitions and requirements

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⁷World Meteorological Organization, Geneva, Switzerland

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¹⁰Australian Bureau of Meteorology, Melbourne, Victoria, Australia

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Funding information

European Metrology Programme for Innovation and Research; European Union's Horizon 2020

Abstract

Ground-based stations are one of many observing systems contributing to the generation of data to evaluate climate trends and variations locally and globally. Networks of stations are made of various numbers of observing sites, equipped with different typologies and varieties of instruments, differently managed and maintained. Among such networks a limited number of stations are required as a reference, to provide top quality traceable measurements and as the top level of a tiered approach; it is these stations which are here designated as Climatological Reference Stations (CRS). At present, there is no agreed definition of the key instrumental and technical features of a CRS, nor are there defined reference measurement procedures. This leads to the situation of a multitude of approaches among different National Meteorological and Hydrological Services (NMHSs), research institutes and other agencies that reduces the comparability of results in space and in time. The lack of CRSs, moreover, is a major contributor to the huge efforts required to harmonize data and detect biases locally, regionally and globally, as in their absence there is a need to fall back on other stations which are more likely to have such biases. This article reports on the outcomes of the work of a group of experts, nominated by the World Meteorological Organization (WMO) Commission for

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Climate reference data: A series of **traceable** measurement results able to quantify the variability and change of climate-relevant variables.

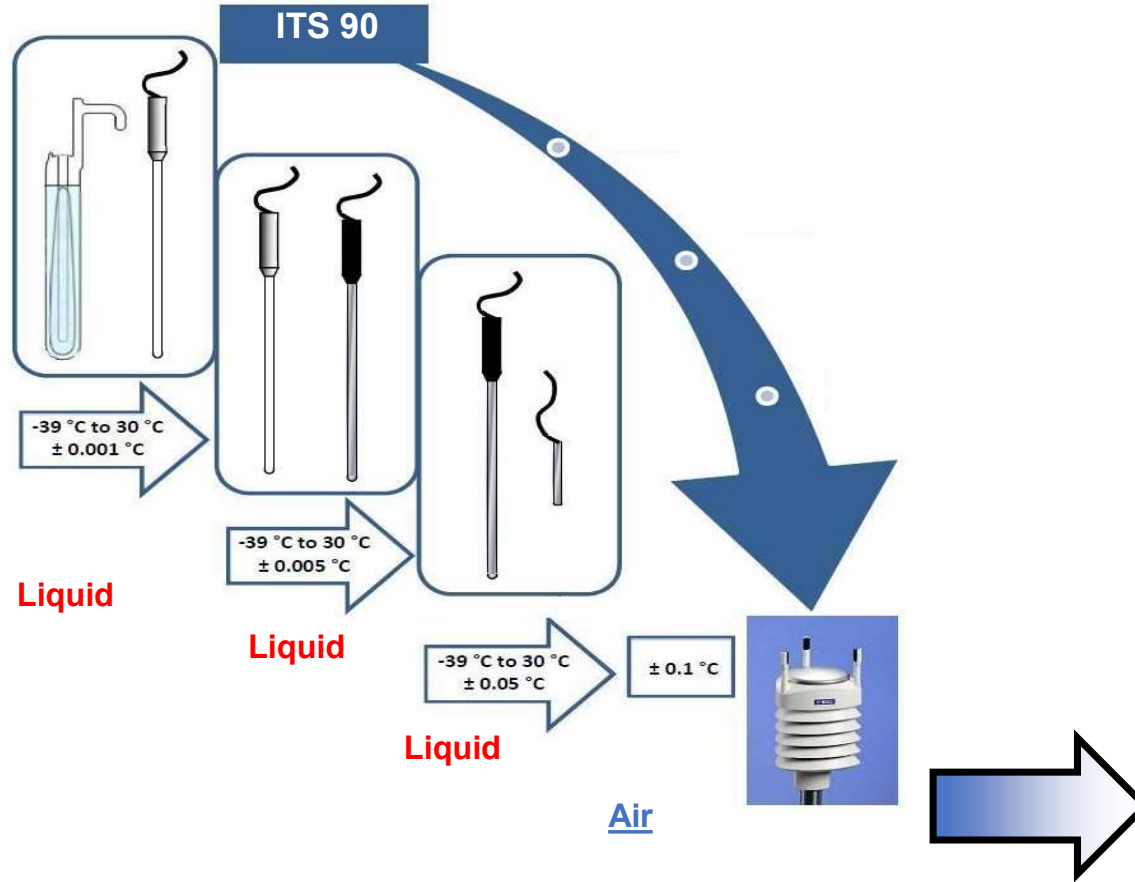
- i. The result of the measurement is a single record of the observed parameter, while the overall measurand is the variability and change of the variable.
- ii. To be traceable, a measurement result requires that each instrument involved in the measurement process is related to a reference standard of the System of Units (SI) or other standards through a **documented unbroken chain of calibrations**.
- iii. The absolute requirement of a measurement is that it be made in such a way that **after accounting for all sources of uncertainty it can be concluded that the true value of the measurand lies within the reported uncertainty interval with specified confidence**. The result of a reference-grade measurement is such that it can be used to improve the quality of other (lower-tier) measurements.

Climate reference station: an instrumental installation able to generate climatological reference data.

- i. Measured data must be **continuous** and **representative** of the local environment.
- ii. The station must be **stable** in its location and siting characteristics **for decades** and equipped with **top quality** instrumentation.
- iii. The instrumentation needs to be **well maintained** with regular maintenance and **calibration** to constantly keep documented data traceability.
- iv. Changes in instrumentations must be limited, motivated and documented. **Parallel observation** periods must be planned prior to any instrumental change.
- v. All **metadata** on siting, methods of observation and any changes that may have occurred in these must be documented.



Traceability



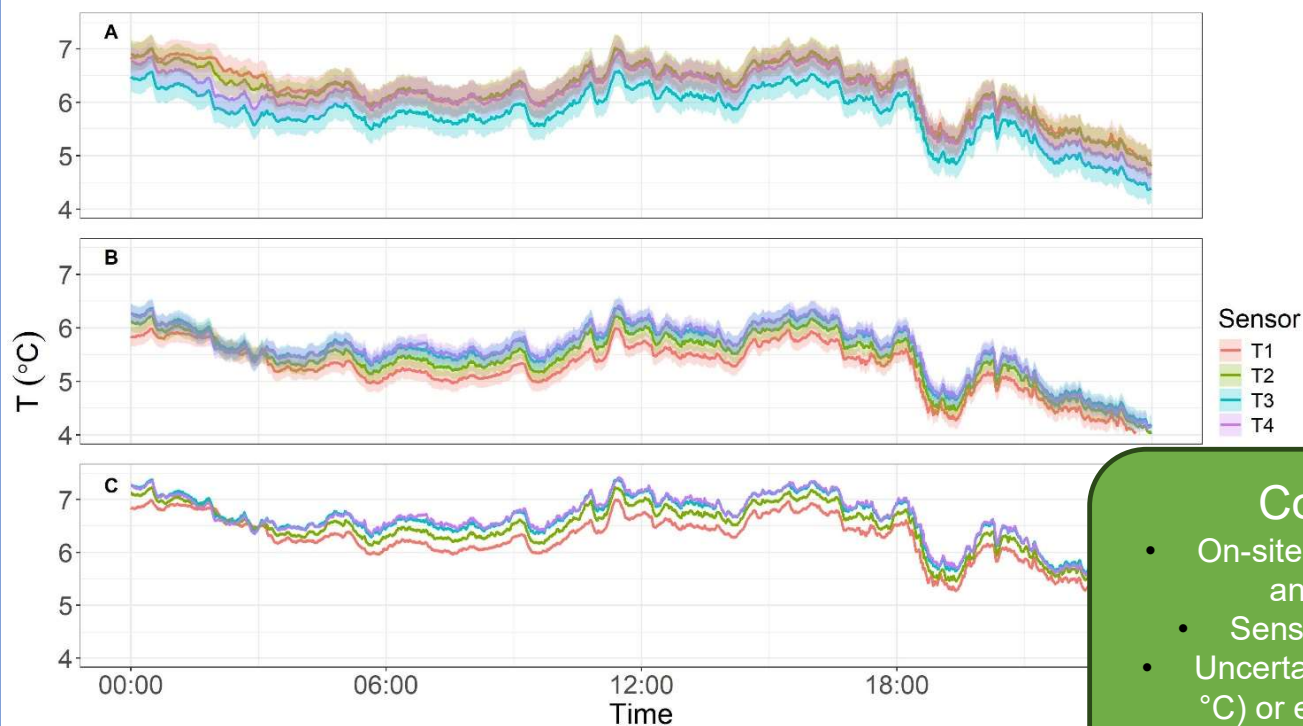
Calibration

Coppa et al. 2024 (DOI: 10.1139/as-2024-0008)

On-site calibration of air temperature sensors in the Arctic (CCT @Ny-Ålesund, Svalbard, 79°N)



Reassessment of temperature profiles and evaluation of calibration and measurement uncertainties



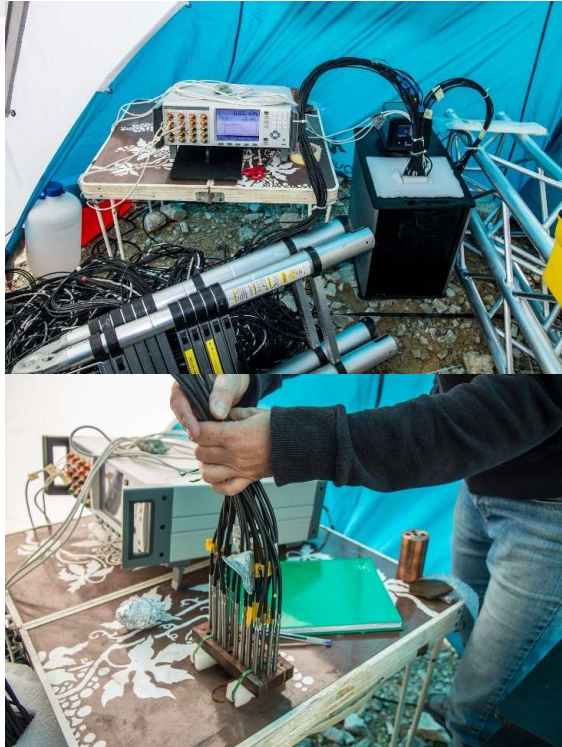
Conclusion:

- On-site calibration is feasible and recommended
- Sensor errors up to 1 °C
- Uncertainties cut in half (~0.1 °C) or even less with relative calibrations

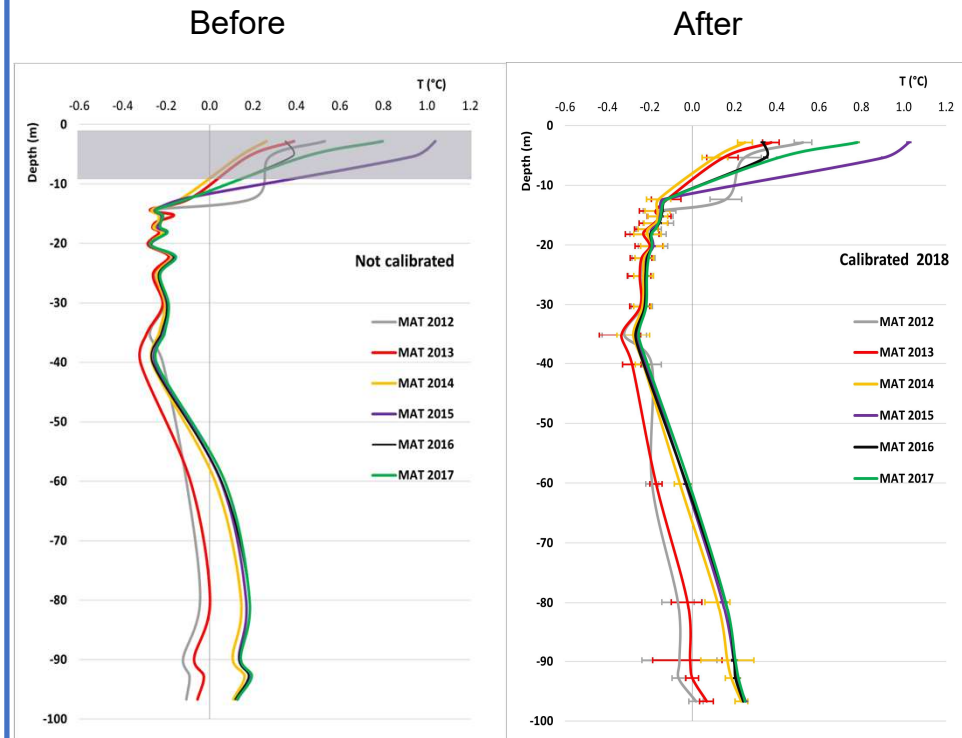
Calibration

Coppa et al. 2025 (DOI: 10.1016/j.coldregions.2024.104364)

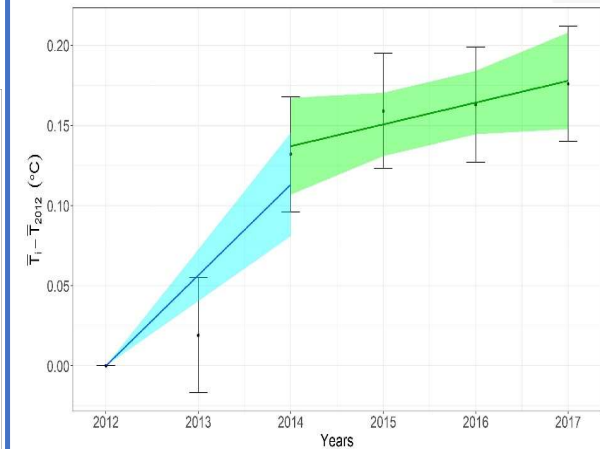
On-site calibration of permafrost temperature sensors (Sommeiller Pass @3000 m a.s.l, Italian NW Alps)



Reassessment of temperature profiles and evaluation of calibration and measurement uncertainties



Evaluation of warming due to climate change with uncertainties



Conclusion:

- On-site calibration is feasible and recommended
- Sensor drift evaluated as $\sim 1.5 \cdot 10^{-2} \text{ }^\circ\text{C/yr}$
- Permafrost base warmed up at a rate of $(4.2 \pm 0.5) \cdot 10^{-2} \text{ }^\circ\text{C/yr}$

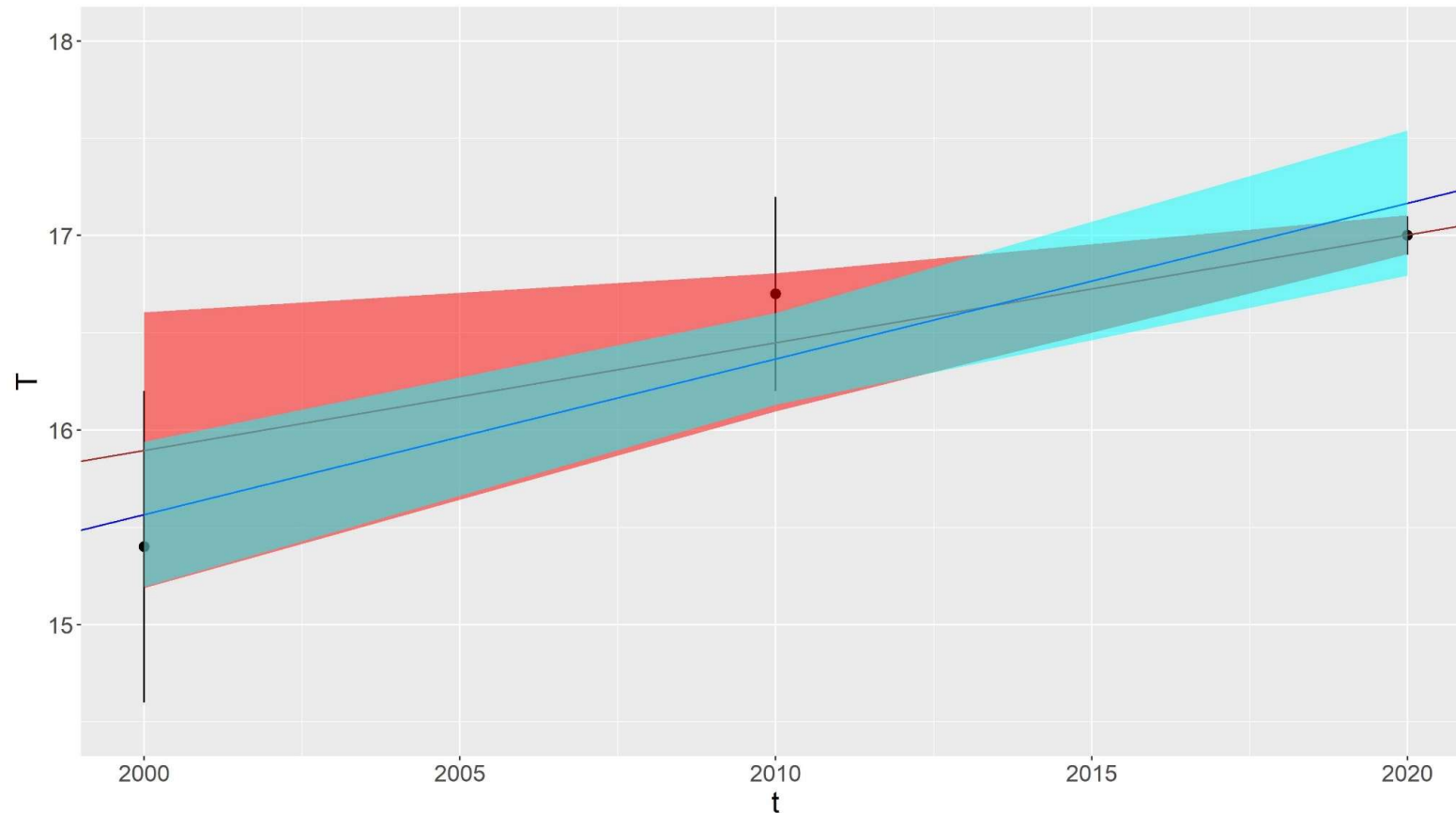
Why we need to evaluate uncertainty

“Any measurement that you make without the knowledge of its uncertainty is completely meaningless.” (W. Lewin)

- Allows us to assess methods and results against data quality requirements.
- Fitness for purpose of a measurement method (do we meet target uncertainties?).
- Interpretation and application of results.
- Equivalency of different results.
- Provides an understanding of the measurement and which parameters should be given most consideration.

The calibration uncertainty is NOT the measurement uncertainty.

Why we need to evaluate uncertainty

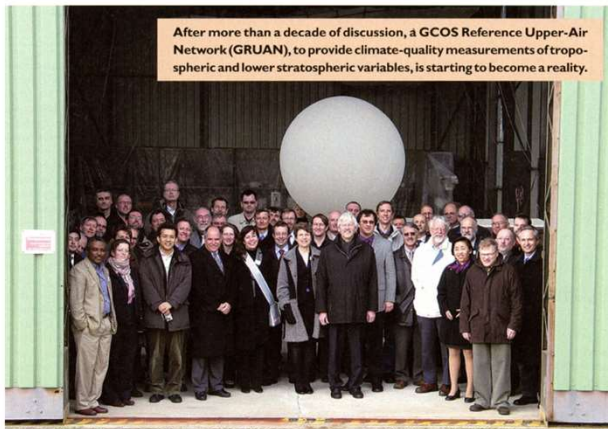


At the beginning...



REFERENCE UPPER-AIR OBSERVATIONS FOR CLIMATE Rationale, Progress, and Plans

BY DIAN J. SEIDEL, FRANZ H. BERGER, HOWARD J. DIAMOND, JOHN DYKEMA, DAVID GOODRICH,
FRANZ IMMLER, WILLIAM MURRAY, THOMAS PETERSON, DOUGLAS SISTERSON, MICHAEL SOMMER,
PETER THORNE, HOLGER VOMEL, AND JUNHONG WANG



The Deutscher Wetterdienst's Meteorologisches Observatorium Lindenberg has been designated GRUAN Lead Center and is the first GRUAN network station. Here an inflated balloon for a 1200 UTC radiosonde observation is in the balloon shed, where participants at the GRUAN implementation workshop gathered in February 2008. In addition to upper-air soundings, the observatory also makes most of the GRUAN first and second priority observations.

In a recent commentary in *Nature*, Nisbet (2007) called environmental monitoring "science's Cinderella, unloved and poorly paid" and noted that sustained, long-term, ground-based measurements are underappreciated and underfunded because they are seen neither as basic measurements to test scientific hypotheses nor as challenging high-tech opportunities for profit by commercial interests. Upper-air observations for climate are a prime example of this problem and have never received the attention they deserve. Since the early 1990s, ▶

AMERICAN METEOROLOGICAL SOCIETY

MARCH 2009 *BAMS* | 361

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... there was GRUAN...

At the beginning...



... and USCRN

U.S. CLIMATE REFERENCE NETWORK AFTER ONE DECADE OF OPERATIONS STATUS AND ASSESSMENT

BY HOWARD J. DIAMOND, THOMAS R. KARL, MICHAEL A. PALECKI, C. BRUCE BAKER, JESSE E. BELL, RONALD D. LEEPER, DAVID R. EASTERLING, JAY H. LAWVIMORE, TILDEN P. MEYERS, MICHAEL R. HELFERT, GRANT GOODGE, AND PETER W. THORNE

What has the first national climate reference network been designed for, and is it on a path to achieve its intended outcomes?

WHY A CLIMATE REFERENCE NETWORK? Long-term, accurate, and unbiased observations are essential to define the state of the global integrated Earth system, its history, and its future variability and change. However, other than the U.S. Cooperative Observer Program

(COOP) network, most historical in situ observations of surface climate variables have been undertaken largely for real-time applications such as weather forecasting, hydrology, and agrometeorology. Stations have opened, closed, moved, and are subject to land-use/land-cover (LULC) change. Changes in times of observation, instrumentation, and operators also contribute to the uncertainty. Historically, undocumented or inadequate metadata that describe changes in meteorological measurements have been all too common. As a result, building a record of homogeneous historical climate information from such data has necessitated in-depth statistically and physically based corrections of the temperature record after the fact. Given the need for decision makers to have the best data possible, it is therefore critical to have an unimpeachable benchmark source of climate data with which to do this. The U.S. Climate Reference Network (USCRN) does this on a national scale for the United States; such a concept is believed to be an example for like networks on the regional and local scale as well.

The National Oceanic and Atmospheric Administration (NOAA)/National Climatic Data Center

AFFILIATIONS: DIAMOND, KARL, PALECKI, EASTERLING, LAWVIMORE, HELFERT, AND GOODGE—NOAA/National Climatic Data Center, Asheville, North Carolina; BAKER AND MEYERS—NOAA/Atmospheric Turbulence and Diffusion Division, Oak Ridge, Tennessee; BELL, LEEPER, AND THORNE—NOAA/National Climatic Data Center, Asheville, and Cooperative Institute for Climate and Satellites, North Carolina State University, Raleigh, North Carolina
CORRESPONDING AUTHOR: Howard J. Diamond, NOAA/National Climatic Data Center, 1100 Wayne Avenue, Suite 1202, Silver Spring, MD 20910
E-mail: howard.diamond@noaa.gov

The abstract for this article can be found in this issue, following the table of contents.
DOI:10.1175/BAMS-D-12-00170.1

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USCRN



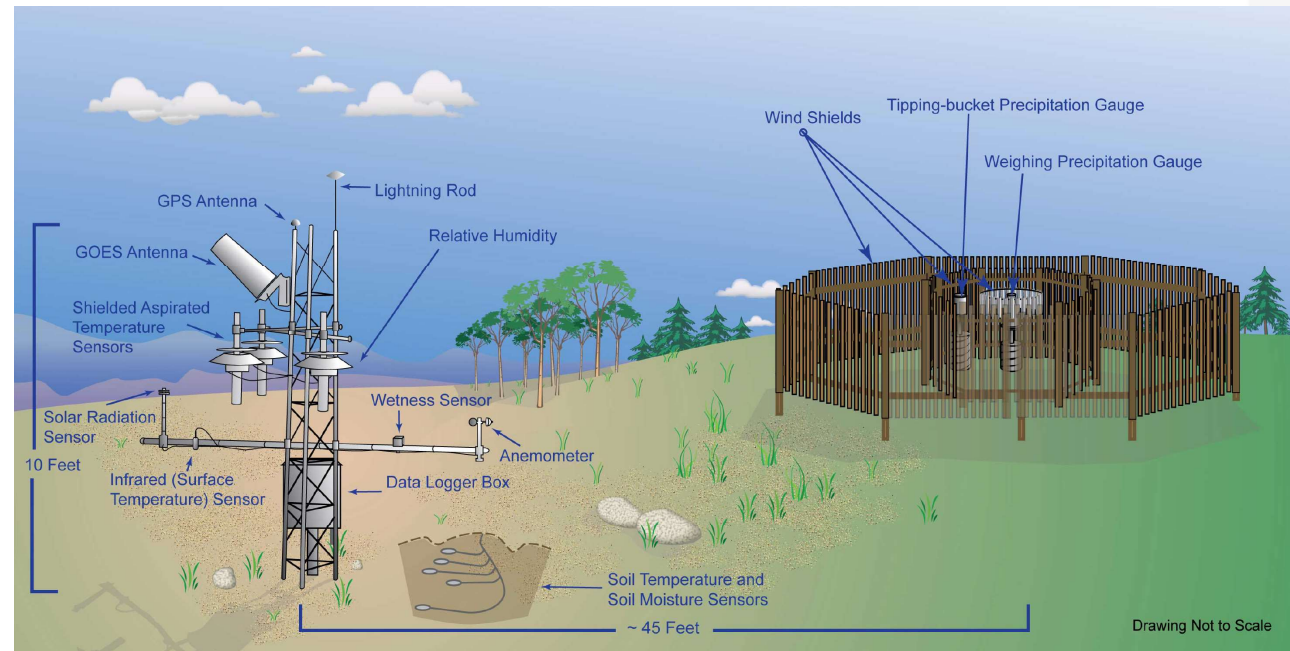
U.S. Climate Reference Network

The U.S. Climate Reference Network (USCRN) is a systematic and sustained network of climate monitoring stations with sites across the conterminous U.S., Alaska, and Hawaii. These stations use high-quality instruments to measure temperature, precipitation, wind speed, soil conditions, and more. Information is available on what is [measured](#) and the USCRN station [instruments](#).

The vision of the USCRN program is to provide a continuous series of climate observations for monitoring trends in the nation's climate and supporting climate-impact research.

USCRN stations are managed and maintained by the [Atmospheric Turbulence and Diffusion Division](#) of the [Air Resources Laboratory, NOAA Office of Oceanic and Atmospheric Research](#). The [National Centers for Environmental Information](#) maintains and distributes the USCRN observations and derived climate products.

Source: www.ncei.noaa.gov/access/crn/



USCRN



U.S. Climate Reference Network

The USCRN collects temperature data using 3-sensors individually housed in fan-aspirated solar shields. The USCRN provides temperature measurements based on **simultaneous readings from three Platinum Resistance Thermometers (PRTs)**. The data collected is provided to users as a **5-minute (sub-hourly) average, hourly average, daily average or monthly average**. For the hourly, daily and monthly files maximum and minimums are also provided, as well as **daily and monthly means which are calculated as $(T_{max}+T_{min})/2$** . Uncertainty calculations are performed using data from simultaneous measurements in the USCRN data file and using metadata made available by NOAA.

[Near-surface temperature from US Climate Reference Network since 2006 onward: Product User Guide and Specification \(PUGS\)](#)

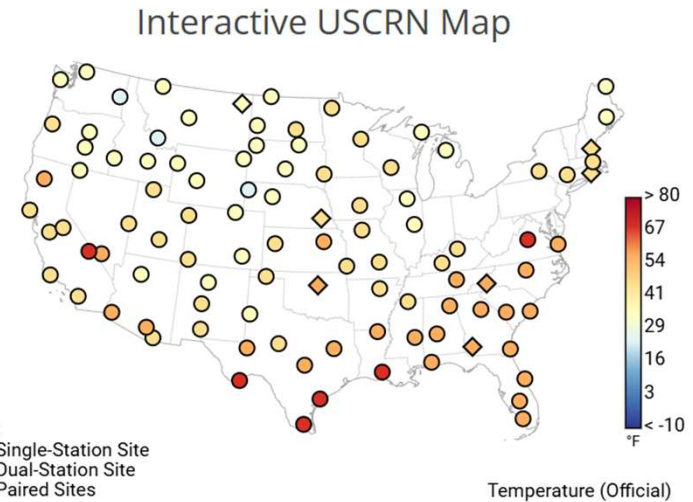
USCRN



U.S. Climate Reference Network

Data from the USCRN are used in a variety of climate monitoring and research activities that include placing current climate anomalies into an historical perspective.

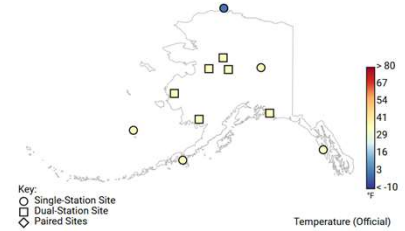
The USCRN provides the United States with a reference network that meets the requirements of the Global Climate Observing System (GCOS). The network consists of 114 commissioned stations in the contiguous United States, 25 stations in Alaska (with a plan to eventually have a total of 29), and 2 stations in Hawaii.



CONUS ALASKA HAWAII

22 aprile 2025 alle ore 12:00 CEST

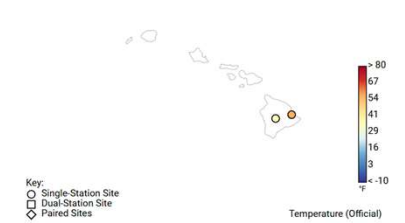
Interactive USCRN Map



CONUS ALASKA HAWAII

22 aprile 2025 alle ore 12:00 CEST

Interactive USCRN Map



CONUS ALASKA HAWAII

22 aprile 2025 alle ore 12:00 CEST

Source: www.ncei.noaa.gov/access/crn/

USCRN

8.22. 5, 5 minute mean

| Information / data | Type / value / equation | Notes / description |
|---|---|---------------------|
| Name of effect | 5 minute mean | |
| Contribution identifier | 5, $\bar{T}_{sub-hourly}$ | |
| Measurement equation parameter(s) subject to effect | $T_{sub-hourly} = \bar{T}'$ | |
| Contribution subject to effect (final product or sub-tree intermediate product) | \bar{T}_{hourly} , \bar{T}_{daily} | |
| Time correlation extent & form | Combination of previous uncertainties | |
| Other (non-time) correlation extent & form | Combination of previous uncertainties | |
| Uncertainty PDF shape | Asymmetric | |
| Uncertainty & units (1σ) | $U_{positive}(T_{sub-hourly}) = \sqrt{\left(\frac{u_{acc}}{\sqrt{n}}\right)^2 + (0.68U_{cal}(T))^2 + U_{prec}(T)^2 + (0.68U_{int}(T))^2 + U_{dl}(T)^2}$ $U_{negative}(T_{sub-hourly}) = \sqrt{\left(\frac{u_{acc}}{\sqrt{n}}\right)^2 + (0.68U_{cal}(T))^2 + U_{SR}(T)^2 + (U_{snow}(T))^2 + (0.68U_{int}(T))^2 + U_{dl}(T)^2}$ | N = 6 |
| Sensitivity coefficient | 1 | |
| Element/step common for all sites/users? | yes | |
| Traceable to ... | | |

[Near-surface temperature from US Climate Reference Network since 2006 onward: Product User Guide and Specification \(PUGS\)](#)

Where

- u_{acc} -> PT1000 measurement noise
- U_{cal} -> calibration uncertainty
- U_{prec} -> due to precipitation
- U_{int} -> sensor-datalogger interface
- U_{dl} -> datalogger
- U_{SR} -> radiation
- U_{snow} -> surface albedo

Short Course 4.16 - Reference Measurements for Climate Studies and Applications - EGU25 Vienna



USCRN



8.24. 7, Daily mean, average, maximum and minimum

| Information / data | Type / value / equation | Notes / description |
|---|---|---|
| Name of effect | Daily mean, average, maximum/minimum | |
| Contribution identifier | 6, T _{daily} , T _{daily} max, T _{daily} min, T _{daily} mean | |
| Measurement equation parameter(s) subject to effect | $T_{daily} = \overline{T_{sub-hourly}}$ | |
| Contribution subject to effect (final product or sub-tree intermediate product) | T _{monthly} | |
| Time correlation extent & form | Combination of previous uncertainties | |
| Other (non-time) correlation extent & form | Combination of previous uncertainties | |
| Uncertainty PDF shape | Asymmetric | |
| Uncertainty & units (2σ) | $U_{positive}(T_{daily}) = \sqrt{\left(\frac{u_{acc}}{\sqrt{n}}\right)^2 + (0.68U_{cal}(T))^2 + \left(\frac{U_{prec}(T_{sub-h})}{\sqrt{n}}\right)^2 + (0.68U_{lead}(T))^2 + (0.68U_{tol}(T))^2 + (0.68U_{TCO}(T_h))^2 + U_{dl}(T)^2}$ $U_{negative}(T_{daily}) = \sqrt{\left(\frac{u_{acc}}{\sqrt{n}}\right)^2 + (0.68U_{cal}(T))^2 + (U_{SR}(T_h))^2 + (U_{snow}(T_{sub-h}))^2 + (0.68U_{lead}(T))^2 + (0.68U_{tol}(T))^2 + (0.68U_{TCO}(T_h))^2 + U_{dl}(T)^2}$ <p>For average and mean. Max and min is calculated based on sub-hourly equation, see section 8.</p> | N = 12 for mean N = 1728 for average. N = 6 for max/min |
| Sensitivity coefficient | 1 | |
| Element/step common for all sites/users? | Yes | |
| Traceable to ... | Various | |

[Near-surface temperature from US Climate Reference Network since 2006 onward: Product User Guide and Specification \(PUGS\)](#)

Where

- U_{acc} -> PT1000 measurement noise
- U_{cal} -> calibration uncertainty
- U_{prec} -> due to precipitation
- U_{int} -> sensor-datalogger interface
- U_{dl} -> datalogger
- U_{SR} -> radiation
- U_{SNOW} -> surface albedo
- U_{lead} -> fixed resistor lead (cable) resistance
- U_{tol} -> fixed resistor tolerance
- U_{TCO} -> fixed resistor temperature coefficient



Table A1
Typical Values of the Contributions to the USCRN Uncertainty Budget

| Main uncertainty contributions | Typical values (K) | Comment |
|---|--------------------|--|
| PT1000 (Platinum Resistance Thermometer (PRT) and NIST traceable calibration) | 0.09–0.13 | |
| Self-heating | <0.001 | Constant |
| Outgoing thermal radiation | <0.002 | Constant |
| Precipitation | <0.2 | Constant |
| Sensor radiation | <0.05 | |
| Aspirated solar shield | 0 | No additional effect |
| Surface albedo | 0.4 | Constant assuming there is incoming solar radiation to reflect |
| Sensor datalogger interface | 0.029 | |
| Fixed resistor error | 0.019–0.15 | |
| Fixed resistor tolerance | 0.02 | |
| Fixed resistor temperature coefficient | ±0.018 | |
| Lead | ±0.015 | |
| Datalogger | ±0.1–0.2 | |
| Combined uncertainty | ±0.06–0.43 | |

Source: Madonna *et al.*, 2022, [DOI:10.1029/2022JD038057](https://doi.org/10.1029/2022JD038057)

JGR Atmospheres

RESEARCH ARTICLE
10.1029/2022JD038057

Key Points:

- An extensive assessment of uncertainties for four climate extreme indices is provided using reference near-surface temperatures
- Estimate uncertainties of climate indices for reanalysis validation and quantification of extremes by propagating measurement uncertainties
- USCRN traceable measurements with quantified uncertainties increase confidence in estimating extreme indices and decisions for adaptation

Supporting Information:

Supporting Information may be found in the online version of this article.

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Formal analysis: Yassmin Hesham Essa, Faezeh Karimian Sarakhs
Investigation: Fabrizio Marra
Methodology: Marco Rosoldi
Software: Fabrizio Marra, Faezeh Karimian Sarakhs, Emanuele Tramutola
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MADONNA ET AL.

Uncertainties on Climate Extreme Indices Estimated From U.S. Climate Reference Network (USCRN) Near-Surface Temperatures

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Abstract Changes in the frequency of temperature extremes are often attributed to global warming. The recent availability of near-surface temperature data records from reference networks, such as the U.S. Climate Reference Network (USCRN), enables the quantification of measurement uncertainties. Within an activity of the Copernicus Climate Change Service, the estimation of the measurement uncertainty has been provided for USCRN temperature data, using metadata made available by the National Oceanic and Atmospheric Administration (NOAA). In this paper, four climate extreme indices (Frost Days, Summer Days, Ice Days, Tropical Nights) and the related uncertainties are calculated for the period 2006–2020 from the USCRN data set and compared with traditional indices. Moreover, the asymmetric USCRN measurement uncertainties are propagated to estimate the uncertainties of climate indices. The comparison shows expanded uncertainties homogeneously distributed with the latitude and typically within 15 days for Frost Days and within 10 days for Ice Days, while smaller uncertainties are estimated for Summer Days and Tropical Nights, with values typically within six to seven days per year. Positive uncertainties are typically larger than negative ones for all the indices. The values of Frost and Ice Days with the related uncertainties for USCRN have also been compared with the corresponding values calculated from reanalyses data, showing differences typically within 60 days for median values, quite often smaller than USCRN and inconsistent within the related uncertainties. Overall, the results show that USCRN measurement uncertainties increase confidence in the estimation of climate extreme indices and decisions for adaptation.

Plain Language Summary The relationship between the intensity and frequency of extremes and climate change as well as their attribution to human activities is fundamental for improving the assessment of risk and the elaboration of adaptation strategies. Temperature extremes are often reported and estimated using observations or model data using indices, which are widely adopted in the research community and by decision-makers. However, the number of temperature extremes is quantified assuming input observations as perfect, whereas these are always affected by uncertainties due to instrumental noise and systematic effects that cannot be always properly accounted for. This also implies that climate extreme indices may under or over-represent the number of temperature extremes. The advent of reference measurement networks, as well as the overall increase in observational data quality due to recent technological improvements, allows us to quantify measurement uncertainties in detail. In this paper, temperature extremes over the US are estimated from near-surface temperature measurements provided by the USCRN network in the period 2006–2020 with related uncertainties. The use of uncertainty illustrates the range of values that climate extreme indices may assume. Possible sources of uncertainties and comparisons with data from atmospheric reanalysis are also discussed.

1. Introduction

Uncertainty is a mandatory dispersion indicator to report with measurement results or estimates of a physical quantity. A measurement is “an experimental process that produces a value that can reasonably be attributed to a quantitative property of a phenomenon, body, or substance.” Measurement uncertainty is a “parameter, associated with the result of a measurement, that characterizes the dispersion of the values that could reasonably be

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The GCOS Reference Surface Network (GSRN)



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International Journal
of Climatology

RESEARCH ARTICLE

Towards a global land surface climate fiducial reference measurements network

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There is overwhelming evidence that the climate system has warmed since the instigation of instrumental meteorological observations. The Fifth Assessment Report of the Intergovernmental Panel on Climate Change concluded that the evidence for warming was unequivocal. However, owing to imperfect measurements and ubiquitous changes in measurement networks and techniques, there remain uncertainties in many of the details of these historical changes. These uncertainties do not call into question the trend or overall magnitude of the changes in the global climate system. Rather, they act to make the picture less clear than it could be, particularly at the local scale where many decisions regarding adaptation choices will be required, both now and in the future. A set of high-quality long-term fiducial reference measurements of essential climate variables will enable future generations to make rigorous assessments of future climate change and variability, providing society with the best possible information to support future decisions. Here we propose that by implementing and maintaining a suitably stable and metrologically well-characterized global land surface climate fiducial reference measurements network, the present-day scientific community can bequeath to future generations a better set of observations. This will aid future adaptation decisions and help us to monitor and quantify the effectiveness of internationally agreed mitigation steps. This article provides the background, rationale, metrological principles, and practical considerations regarding what would be involved in such a network, and outlines the benefits which may accrue. The challenge, of course, is how to convert such a vision to a long-term sustainable capability providing the necessary well-characterized measurement series to the benefit of global science and future generations.

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Int J Climatol. 2018;38:2760–2774.

- Follow the GRUAN ethos of “start small, but start”
- Instrumentation need not be identical across the network
- Siting considerations: representative, free from obstacles, secure, easy to access
- Near-real-time
- Metrological considerations: traceability, comparability, representativity, regular calibration

The GCOS Reference Surface Network (GSRN)



WORLD METEOROLOGICAL ORGANIZATION

INTERGOVERNMENTAL OCEANOGRAPHIC COMMISSION

GCOS Surface Reference Network (GSRN):
Justification, requirements, siting and instrumentation options

February 2019

GCOS-226

UNITED NATIONS ENVIRONMENT PROGRAMME

INTERNATIONAL SCIENCE COUNCIL

Climate observations encompass a broad range of environmental observations. They include routine weather observations collected consistently over a long period of time, observations collected as part of research investigations to elucidate important weather and climate processes, and highly precise, sustained observations of the climate system (e.g. atmosphere, hydrology, oceans and the biosphere) collected for the express purpose of documenting long-term (decadal to centennial) changes. Observations of climate proxies extend the instrumental climate record to remote regions and back in time. **Climate data collection and data processing is distinctly different from that minimally required for meteorological data applications.** The requirements for climate use typically go well beyond those for weather use **as high levels of accuracy and consistency are needed to detect long-term changes** embedded in diurnal, seasonal and multi-annual variations.

Reference quality observations respond to the need for monitoring the changes that are occurring in the climate system and ensure greater confidence in the assessment of future climate change and variability. This will also support timely political decisions around both mitigation and adaptation. Reference quality measurement programs have already been established for different domains, and several successful examples have now reached permanent operational status.

The Global Cryosphere Watch (GCW) programme of WMO (<https://globalcryospherewatch.org/>) established best practice in measuring quantities of interest for cryosphere observations. In this way, it coordinates and increases the comparability of data provided by existing stations, that were not previously working in a collaborative way. **The United States Climate Reference Network (USCRN - <https://www.ncdc.noaa.gov/crn/>)** is a network of installed stations where identical measurement procedures are adopted with the same instrument layout, under continuous maintenance and active management. The network provides a continuous series of surface climate observations for monitoring trends and delivering traceable data that are comparable in space and time. Finally, the **GCOS Reference Upper Air Network (GRUAN - <http://www.gruan.org/>)** undertakes reference quality measurements of aspects of the atmospheric column.

INFCOM -1: **GCOS Surface Reference Network Task Team (TT-GSRN)**

established under the leadership of the GCOS SC and SC-ON to be responsible for initial implementation

2020

2021

24th March:
March:

1st Meeting of TT-GSRN, several meetings followed in 2021/22
Letter to members to express their interest in hosting the GSRN Lead Centre (GSRN LC)

November:

China Meteorological Administration (CMA) is selected to become GSRN **Lead Center**

2022

GSRN-LC and Experts from TT-GSRN did a review of nominated stations and TT-GSRN approved **a list of 17 stations for the Pilot GSRN.**

2023

First meeting of the GSRN – Torino September 2023 – Hosted by INRiM

Pilot GSRN
(Test Phase, some stations in different climate regions)

Initial GSRN
(first operational products, certified stations)

(Final) GSRN
(global network with operational products)





The GCOS Surface Reference Network



GCOS Surface Reference Network Task Team 10-year goals

1. Provide **sustained reference quality observations**, with **full traceability** and **defined and quantified uncertainties** on a **global scale (on land)** for at least the ECVs **surface temperature and precipitation**, in order to quantify their variability, long-term change and inform on extremes
2. Deliver an implementation plan for the inclusion of additional ECVs
3. Be a **recognized reference network** within the **WMO tiered system** which primarily supports the climate community in quantifying climate change
4. Publish operational procedures and practices for knowledge transfer and capacity development
5. Ensure a **free and open access archive** of accredited GSRN data products
6. Identify **GSRN affiliated research facilities** delivering scientific advances in **measurement techniques and improving knowledge on climate reference data and instrumentation**

General Requirements of GSRN stations



Siting of instruments:

The importance of siting characteristics and instrument exposure cannot be overstated

- Siting **must be classified** by the Siting Classification for Surface Observing Stations on Land in GIMO, Volume I, Annex 1.D (WMO-No. 8)
- Siting **should meet Class 1**, if this cannot be achieved, all possible efforts should be made to improve the classification or at least to ensure that classification level does not deteriorate.

Metadata:

The details and history of local conditions, instruments, operating procedures, data processing algorithms and other factors pertinent to interpreting data (i.e., metadata) should be documented and treated with the same care as the data themselves.

- WIGOS Metadata Standard (WMO-No. 1192), considering mandatory, conditional and optional elements
- Guide to the WMO Integrated Global Observing System (WMO-No. 1165).

Calibration:

To achieve comparability, measurements need to be traceable to recognised standards for the observed quantities.

- GSRN stations are required to meet at least the **“Assured traceability level”** as described the Strategy for traceability assurance in GIMO, Volume I, Annex 1.B. (WMO-No. 8).

Measurement Quality Classification Scheme

The 1-minute resolution temperature data product is the basic GSRN temperature product and will be used to generate all additional temperature data products for GSRN for example, an hourly mean, daily mean or monthly mean product. The data product contains the measured temperature value (derived from the parallel temperature measurements) and measurements from the parallel measured associated quantities of influence (AQIs). This temperature data product also makes use of the different uncertainty components for this measurement and the corrections applied to the measured value, based on the WMO Measurement Quality classification scheme (MQC) ([WMO No-8, Volume I, Annex 1.G](#)).

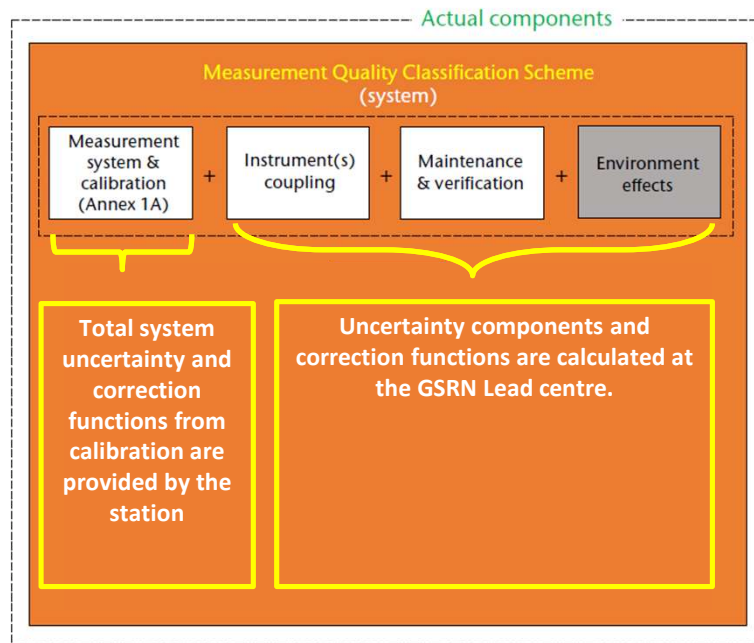
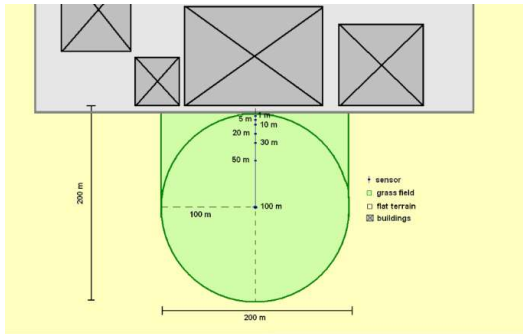


Figure 1.G.1. User requirements and classification schemes overview

Uncertainty due to siting is left off



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

Experiments to support the siting classification



Road (Italy)



Trees (Czech Rep.)

Results showed effects up to ~2 °C



Buildings (Spain)

Coppa et al. 2021 (DOI: 10.1002/joc.7044)
Garcia Izquierdo et al. 2024 (DOI: 10.3390/atmos15020209)



Mandatory Variable – Air temperature

Quantities of influence

- Precipitation (liquid and solid)
- Relative humidity
- Global solar radiation (upward looking pyranometer)
- Reflected solar radiation (downward looking pyranometer)
- Wind (modulus and direction)

| | |
|---------------------------------------|--|
| GCOS ECV Product | Air temperature near Surface |
| Definition (OSCAR) | Air temperature at a known height above surface, with the height specified in the metadata |
| Description | Temperature of the air measured between 1.25 m and 2 m from the ground (might be different for specific stations) |
| Unit | Degree Celsius – Symbol °C |
| Target system uncertainty (k=2) | 0.2 K |
| Product resolution | Minimum: 0.01 K Recommended: 0.001 K |
| Maximum calibration uncertainty (k=1) | 0.05 K |
| Maximum drift (k=1) | 0.02 K/year |
| Sampling frequency | 10 s |
| Time constant / response time in air | 20 s |
| Averaging and recording time | 1 minute |
| Calibration regime | Yearly |
| Verification regime | 6-monthly |
| Maintenance regime | 6-monthly |
| Redundancy | The threshold requirement is to employ two temperature instruments which will meet the minimum requirements for testing consistency between measurements. The recommended extended requirement is to employ three instruments for added confidence and robustness. |



| | |
|---------------------------------------|--|
| GCOS ECV Product | Accumulated precipitation |
| OSCAR Variable | Precipitation intensity at surface (liquid or solid) |
| Definition | Integration of solid and liquid precipitation rate reaching the ground over a time period defined in the metadata. |
| Definition | Intensity of precipitation reaching the ground. |
| Description | Integration of solid and liquid precipitation rate reaching the ground over several time intervals. |
| Description | The measurement unit of rainfall intensity is linear depth per hour, usually in millimeters per hour. Rainfall intensity is normally measured or derived over one-minute time intervals due to the high variability of intensity from minute to minute |
| Unit | mm |
| Unit | mm/h |
| Target system uncertainty (k=2) | The greater of 1 mm or 2% (liquid) |
| Target system uncertainty (k=2) | The greater of 0.2 mm/h or 5% (liquid) |
| Product resolution | 0.1 mm |
| Variable resolution | 0.1 mm/h |
| Maximum calibration uncertainty (k=1) | 1% 0.1 mm/h |
| Maximum calibration uncertainty (k=1) | |
| Maximum drift (k=1) | 1% / year |
| Sampling frequency | 1 s |
| Starting threshold | 0.1 mm/h for liquid precipitation intensity only |



Mandatory Variable –
Precipitation

Quantities of influence

- T air
- RH
- Solar radiation
- Wind



Climate Reference Station
a MeteoMet initiative

EMPIR 19SIP03 –
«Climate Reference Station»

Coordinator: A. Merlone INRiM

Primary supporter: WMO

Partners: DTI (DK) – SMU (SK) – UNIGE (IT)

November 2020 – October 2023

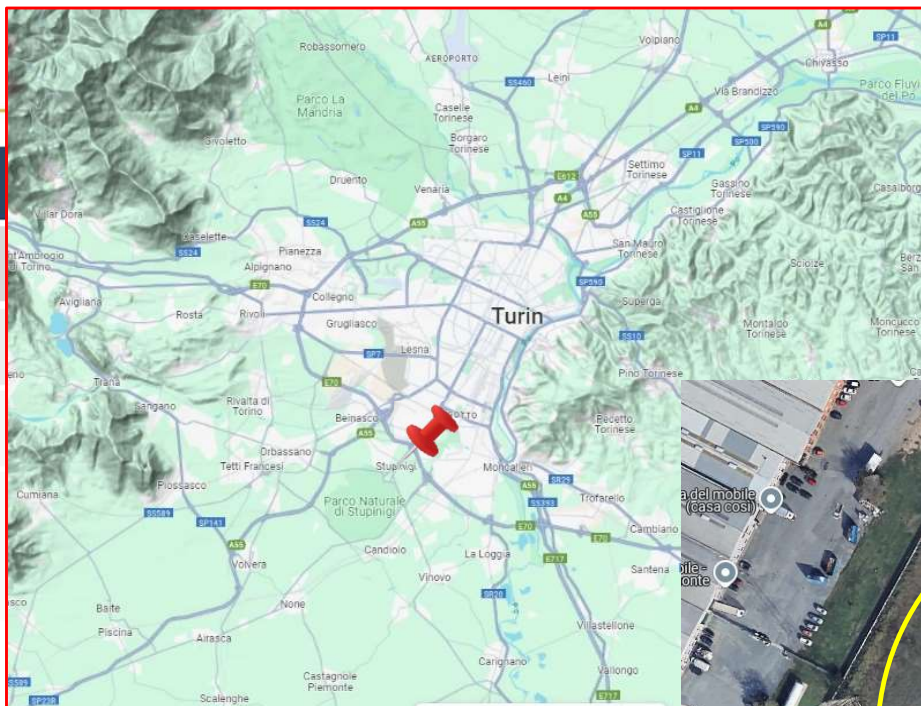
Obbiettivi

- Define and evaluate characteristics of instruments for reference temperature measurements for climate studies
- Study instrumentation in controlled lab conditions
- Field installation of a prototype reference station for research purposes
- Study influence quantities
- Evaluate uncertainty budget components
- Report to WMO e GCOS expert team to guide recommendations and guidelines for the definition of requirements of a reference climate network



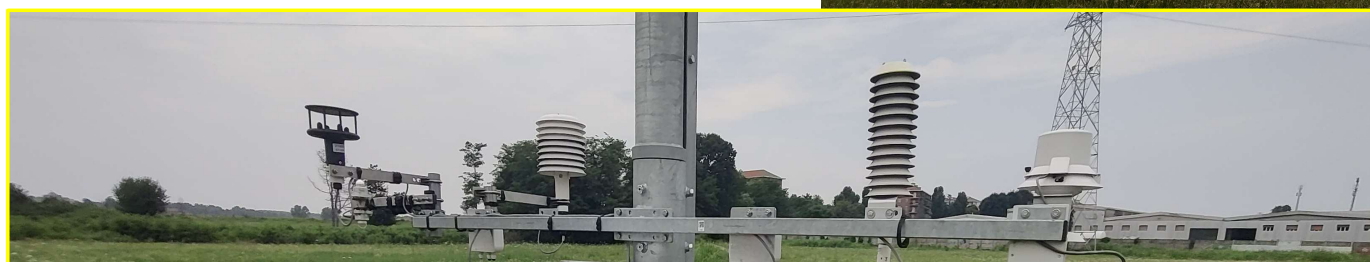
INRiM's Climate Reference Station

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| Variable | Instrument | Calibration uncertainty |
|--|---|----------------------------------|
| Temperature | PRT 100 (4 wire) | 0.02 °C |
| Temperature – humidity (AQI) | Vaisala HMP 155 | 0.05 °C 3 % RH |
| Precipitation | SIAP TP200 | Total: 2%-10% Intensity: 2% |
| Pressure | Paroscientific DIGIQUARTZ | 10 Pa |
| Wind speed and direction | GILL HS50 3 Axis ultrasonic anemometer | Speed: < 1 m/s Direction: <1° |
| Wind speed and direction | Gill Windsonic | 2% |
| Solar radiation (direct and reflected) | 2 Hukseflux LP02 05 Second class pyranometers | <1.8 % |





Climate Reference Station
a MeteoMet initiative

EMPIR 19SIP03 –
«Climate Reference Station»

Coordinator: A. Merlone (INRiM)

Primary supporter: WMO

Partners: DTI (DK) – SMU (SK) – UNIGE (IT)

November 2020 – October 2023

Obbiettivi

- Definire e valutare le caratteristiche di strumenti per la misurazione della temperatura di riferimento per scopi climatologici.
- Studiare la strumentazione in condizioni di laboratorio controllate.
- Installazione in campo di un **prototipo di stazione di riferimento** su cui proseguire la ricerca.
- Studio delle grandezze di influenza.
- Valutazione componenti del bilancio di incertezza.
- Report verso WMO e GCOS expert team per indirizzare raccomandazioni e linee guida che definiscano i requisiti di un network climatologico di riferimento

- The **WMO measurement lead centers** should be asked to do research on the determination of the environmental effects on measurements, especially for temperature and precipitation, considering the technologies already used at the different pilot sites of GSRN. Other interested scientific research facilities should be incorporated.
 - A **workshop** with experts from TT-GSRN, ET-MU und ET-SSM should be carried out to discuss the **priorities for these research activities** based on the actual scientific theoretical and experimental knowledge.
 - The **siting classification** should be improved to consider temporal/seasonal effects. A focus should be laid on temperature and precipitation measurements.
-
- Next meeting on 21st May in Munich