GCOS

KEEPING WATCH OVER OUR CLIMATE

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

Chair, Publications Board

World Meteorological Organization (WMO)

7 bis, avenue de la Paix

P.O. Box 2300

CH-1211 Geneva 2, Switzerland

Tel.: +41 (0) 22 730 84 03

Fax: +41 (0) 22 730 80 40

E-mail: Publications@wmo.int

Background Information on the mandate of the GCOS Task Team on the instigation of a GCOS Surface reference Network

The United Nations Framework Convention on Climate Change (UNFCCC) in Art.4 1.(g) calls for all parties to "promote and cooperate in scientific, technological, technical, socio-economic and other research, systematic observation and development of data archives related to the climate system and intended to further the understanding and to reduce or eliminate the remaining uncertainties regarding the causes, effects, magnitude and timing of climate change and the economic and social consequences of various response strategies."

GCOS and the WMO Integrated Global Observing System (WIGOS) both recommend that networks should be part of a tiered system: reference, baseline and comprehensive networks. This tiered network concept is included in the Manual on WIGOS (WMO-No. 1160, Appendix 2.1). Principle 7 states that "Observing network design should use a tiered structure, through which information from reference observations of high quality can be transferred to other observations and used to improve their quality and utility."

A paper by Thorne et al., 2018, provides the background, rationale, metrological principles, and practical considerations regarding what would be involved in implementing and maintaining a suitably stable and metrologically well-characterized global land surface climate fiducial reference measurements network:"… a better set of observations that will be available to the future generations, will aid future adaptation decisions and help to monitor and quantify the effectiveness of internationally agreed mitigation steps."

Interest in ascertaining what would be required to establish a global surface reference network was also expressed by the Commission of Climatology, and at the 22nd Session of the GCOS/WCRP Atmospheric Observation Panel for Climate (AOPC-22, Exeter, UK, March 2017). AOPC agreed on the creation of a dedicated task-team to scope a potential GCOS global surface reference network, which was then formalized during the GCOS Steering Committee at its twenty-fifth Session. The Task Team consists of Howard Diamond, Nigel Tapper, Phil Jones, Peter Thorne, Tim Oakley, Andrew Harper, Jiankai Wang, Andrea Merlone, Victor Venema, Rachid Sebbari. The Terms of Reference of the task team can be found in Annex 4.

The GSRN represents the surface equivalent of the GCOS Upper Air Reference Network (GRUAN), which at the 17th Session of the WMO Congress (Cg-17) was recognized as a WIGOS implementation project.

The GCOS Steering Committee in 2018 recommended for the task team to continue its work and to collaborate with WIGOS, CIMO and CBS to move the concept forward.

Decision 27 of the 17th Session of the Commission for Instruments and Methods of Observation states "Support to the Global Climate Observing System Surface Reference Network: The Commission for Instruments and Methods of Observation decides to request its Management group to identify and nominate expert member(s), as needed, to the Global Climate Observing System (GCOS) Surface Reference Network Task Team, which aims to lead to improvements in the WMO Integrated Global Observation System (WIGOS)."

This report is produced by the GSRN Task Team and provides a proposal for the establishment of a GCOS Surface Reference Network, with the support of the GCOS programme, relevant programmes at WMO and the Bureau International des Poids et Mesures (BIPM). It outlines the next steps required for the implementation of a GSRN: approval of the proposed GSRN by relevant WMO programmes, the GCOS programme and other sponsors, solicitation of offers to host and staff appropriately the proposed Lead Centre, and the selection of suitable sites for an initial GSRN.

TABLE OF CONTENTS

SUMMARY

This document provides a proposal for the establishment of a GCOS Surface Reference Network (GSRN). Reference quality observations are directly traceable to the International System of Units (SI) standards and include full documentation of all components of their uncertainty. Such observations respond to the need for monitoring the changes that occur in the climate and ensure greater confidence in the assessment of future climate change and variability. Such a network will also support timely political decisions around mitigation and adaptation. A GSRN will contribute to the improvement of the current climate observing system. However, benefits would accrue much more immediately, through improved observational understanding and better methods of observation leading to improvements in numerical weather prediction and disaster and emergency response systems.

The principal benefits of a reference network are:

- well characterised time series that can be used with confidence at network sites;
- improved instrument performance that transfers down to other broader global regional and national networks;
- support and characterisation of wider networks;
- robust calibration/validation of satellite data;
- improved process understanding and model validation.

Initial implementation is aimed at six core atmospheric surface Essential Climate Variables (ECV): Air temperature, wind speed and direction, water vapour, pressure, precipitation and surface radiation budget components.

For the GSRN to fulfil its intended role of providing globally representative, high quality observations, critical attention will need to be given to the matters of station location, siting and quality of instrumentation, each of which are discussed in this document.

It is proposed that the GSRN be supported by the GCOS programme, relevant programmes at the World Meteorological Organization (WMO) and the Bureau International des Poids et Mesures (BIPM). The management of the implementation and operation of the GSRN will require the establishment of a Lead Centre. In the first phase of the implementation, the Lead Centre will

- develop a network based on existing reference quality monitoring stations;
- coordinate reference stations;
- ensure that all observations are of reference quality;
- establish common procedures and standards across the GSRN;
- certify stations as being of reference quality and contributing to the GSRN;
- establish systems to monitor station performance and perform Quality Assurance/Quality Control (QA/QC);
- ensure data is easily discoverable and freely and openly available to all; and
- develop a plan for the long-term operation and development of GSRN.

The next steps required for the implementation of a GSRN are the approval of the proposed GSRN by relevant WMO programmes, the GCOS programme and other sponsors, solicitation of offers to host and staff appropriately the proposed Lead Centre, and the selection of suitable sites for an initial GSRN.

Overall, the guiding principle should be to start small, by slowly building up the network and its capabilities in a manner that is sustainable and solicits and builds upon relevant input from all stakeholders.

1. INTRODUCTION

The global climate community has recognized the need for sustained and robust observations for many years, and this has been expressed in numerous documents and reports from the UNFCCC, the Intergovernmental Panel on Climate Change (IPCC), the World Meteorological Organization and the United Nations Environment Program, including recently at the 2015 Paris Agreement (e.g. see Article 7, paragraph 7). Sustained, long-term, observations of the global environment are critical for monitoring the changing state of the Earth system and are needed in order to address a large range of important societal issues including sea level rise, droughts, floods, extreme heat events, food security, and freshwater availability in the coming decades. Long-term high-quality data are essential to adequately monitor climate changes, as these occur in the context of larger shorter-term variations associated with weather, the seasonal cycle, and natural climate variations, such as El Niño.

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. The network draws together contributions arising from National Meteorological and Hydrological Services (NMHSs), other public research bodies, and academia.

The remainder of this report is structured as follows. Section 2 introduces the concept of tiered observing networks, their rationale, and their adoption within the WMO Integrated Global Observing System (WIGOS) manual. Section 3 identifies the current lack of a globally coordinated reference network for land surface observations and introduces the broad concepts underlying the GSRN. Section 4 then outlines some of the principal benefits to be gained by the establishment of such a network. Section 5 introduces the concepts underlying the taking of reference quality observations. In section 6 issues concerning instrumentation and siting are discussed. In Section 7 the governance structures necessary to successfully instigate and manage the GSRN are discussed. Recognising that not all issues are as yet settled, Section 8 gives an overview of those substantive remaining challenges that are presently known. Finally, Section 9 closes by briefly articulating what next steps are required to move from scoping to implementation. A practical example of what is required to achieve reference quality observations is shown in Annex 1. Annex 2 contains the terminology for the GSRN and Annex 3 describes the envisaged characteristics, specifications and minimum requirements for the instruments at a GSRN station.

2. THE TIERED OBSERVING SYSTEM CONCEPT AND CURRENT STATUS FOR LAND SURFACE METEOROLOGICAL OBSERVATIONS

Many different climate observation networks monitor the relevant parameters needed to improve our understanding of the climate system and enhance climate services. Both GCOS and WIGOS recommend that networks should be part of a tiered system: reference, baseline and comprehensive networks. The tiered network design is shown in Figure 1 (Thorne et al., 2018). This tiered network concept is also included in the WMO observing network design principles (Manual on WIGOS, WMO-No. 1160, Appendix 2.1, principle 7).

The tiered network design is based on three tiers:

- **Reference Networks**. A coordinated collection of sites that make measurements of the highest quality (aiming to meet the “goal” requirements in the WMO OSCAR requirements database). These measurements will be fully traceable to international standards (SI units or community accepted standards), have a quantified uncertainty budget, complete metadata (following the WMO metadata standard) and additional documentation covering site conditions, operational procedures and calibration records. These sites are expensive to maintain and so are expected to be relatively few in number. Sites should be representative of specific climatic and environmental situations. Reference networks should ideally be embedded in the baseline and comprehensive networks and their highly reliable observations used to validate these other networks.
- **Baseline Networks**. These networks comprise the minimum number of stations necessary to achieve a globally representative coverage to allow global, hemispheric and regional averages and trends to be determined. They aim to meet, as a minimum, the “threshold” level in the WMO Observing Systems Capability Analysis and Review Tool (OSCAR) requirements database, exchange data as needed by global numerical weather prediction, and meet national and regional quality standards. Sites need to cover all climatic and environmental situations.
- **Comprehensive Networks**. These are the remaining observing platforms. These stations provide additional regional, national and local details. They include data of opportunity that may or may not meet established requirements, but nevertheless provide some useful information.

The main strength of a reference network is its stability and complete characterisation of the uncertainties of the absolute values and relative changes. The main strength of the other networks is their large number of stations, which is vital for the reduction of sampling errors and the study of climatic modes of variability and spatial/synoptic phenomena. In principle, an integrated tiered network design with reference, baseline and comprehensive observations enables the highest possible quality estimate of global or continental climatic changes at the lowest possible overall cost.

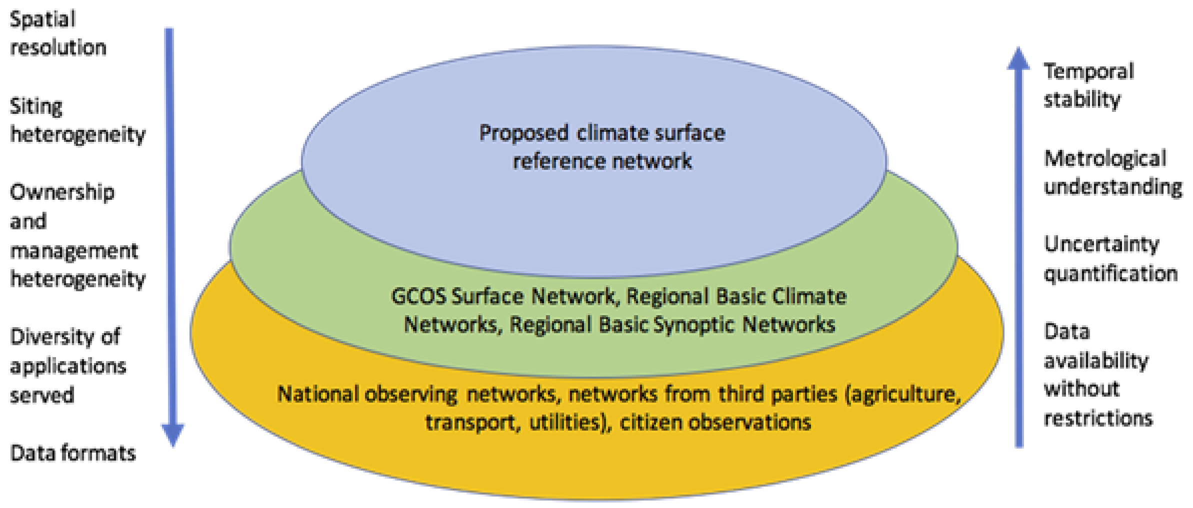

Figure 1. Conceptual outline of how surface observational capabilities for climate map onto the tiered system of systems approach of Thorne et al.(2017). The tiers from top to bottom are reference, baseline, and comprehensive. Arrows and associated text denote important facets of the measurements that increase as you move down tiers (left-hand side) or up tiers (right-hand side). The network types given for each tier are solely exemplars.

3. HIGH LEVEL CONCEPT OF A GCOS SURFACE REFERENCE NETWORK

For surface meteorological and terrestrial networks there currently is no global and coordinated reference observing tier, noting that: national reference observations are not coordinated internationally, do not focus on a wide range of ECVs, or do not provide coordinated data access. The GCOS Surface Reference Network (GSRN) being proposed here would fill that gap in a cost-effective and coordinated manner. Initially it will:

- be based on existing reference quality monitoring stations;
- ensure that all observations are of reference quality;
- establish common procedures and standards across the GSRN;
- ensure data is easily discoverable and freely and openly available to all.

As a longer-term goal GSRN will:

- certify stations as being of reference quality and contributing to the GSRN;
- assure interoperability nationally, regionally and globally and ease of access to the data to users;
- establish systems to monitor station performance and perform QA/QC, based on existing systems where possible;
- ensure that reference quality ECV measurements are collected, processed and served to users in a coordinated and timely manner. Such coordination is key to realising the full value-chain of the observations for their use for developing products and services;
- aim to be truly global in nature with sufficient representation from across the global land domain. Particular attention must be paid to ensuring measurement programs are maintained in regions where sustained measurement programs are a challenging proposition such as remote island locations and in harsh environments. All climate zones must be adequately sampled to ensure a

meaningful global analysis can accrue. Thorne et al. (2018) showed that a minimum sample of the order 180 stations well-sampled across the globe would provide an independent verification of global temperature trends;

- provide training and guidance to the basic and comprehensive networks on equipment performance, system operation, and data QA/QC and processing;
- advocate for establishing additional reference stations to fill gaps in the network.

As each reference site will ensure that all measurements are traceable to standards and have a quantified uncertainty budget, having identical equipment at each site is not needed. In fact, a network consisting of non-identically instrumented sites may better meet varied national and regional needs, and ensure assessment of the different equipment available. Certain sites may act as validation centres for instrumentation development, intercomparison sites or research and development centres and this capability would be strongly encouraged. All sites, must, at a minimum, provide certified reference quality measurement programs (Section 5) for the six core 'surface atmosphere' ECVs (Table 1). Sites would be encouraged to initiate and maintain reference quality measurement programs for additional ECVs detailed in Table 1 as appropriate to the site location. Thus, GSRN sites will have a common core capability and varied extended capabilities which might be driven by a range of research interests or user-driven requirements on a site-by-site basis.

Domain	Selected GCOS Essential Climate Variables to be measured by the GSRN
Surface Atmosphere	***Air temperature*** ***Wind speed and direction*** ***Water vapour*** ***Pressure*** ***Precipitation*** ***Surface radiation budget***
Atmospheric Composition	Carbon Dioxide Methane Other long-lived greenhouse gases Ozone (and precursors) Aerosols (and precursors)
Terrestrial	River discharge Snow cover Permafrost Albedo Land cover (including vegetation type) Fraction of absorbed photosynthetically active radiation (FAPAR) Leaf area index (LAI) Above-ground biomass Soil carbon Fire disturbance Soil moisture Land surface temperature

Table 1 denoting ECVs that could be measured across the GSRN network. The six core 'surface atmosphere' ECVs, for which measurements are mandatory, are highlighted in bold. Those ECVs for which reference quality measurements are assessed to be in principle attainable today are italicised. Taken from Thorne et al., 2018 (their Table 1) and modified.

4. BENEFITS OF A GLOBAL SURFACE REFERENCE NETWORK

Observations from a GSRN will contribute to the improvement of the current climate observing system. Improved observing systems will lead to enhancements in numerical weather prediction and disaster and emergency response systems. This section touches briefly upon the principal benefits of a GSRN.

4.1 Improved understanding of instrument operation: intercomparison and development

The GSRN network would require the metrological qualification of a broad suite of instrumentation (Section 5). Such metrological qualification is proven to bring new insights that lead to improvements in the instrumentation and/or its operation. As an example, GRUAN activities have led to demonstrable improvements in radiosonde programs: GRUAN analysis of the Vaisala RS-92 product led to innovation to address perceived shortcomings in particular in the humidity sensor leading to the RS41 model. Similarly, the French team developing a product for the Modem M10 has led to the modification of operational procedures leading to improved performance of the operational Modem M10 radiosonde network. Developing reference quality data streams has thus proven to cascade innovations and improvements to broader networks.

Ultimately, the GSRN network shall, for each ECV, consist of collections of different high-quality instrumentation. The availability of collections of sustained high-quality well-characterised instrumentation is an ideal fit for intercomparison activities. Such intercomparisons might be for national, regional or global purposes. While not all GSRN stations would host such campaigns, they would all in theory be capable of doing so.

GSRN sites would also foster interest for instrument manufacturers to test and validate new measurement systems that may be used both within GSRN and more broadly. The process works both ways: technological advances, new measuring principles, new solutions to reduce the effects of the influencing quantities, evolving measurement and calibration procedures, should be immediately recognized and integrated to improve the GSRN.

The direct involvement of the metrology community and staff from National Metrology Institutes (NMIs) sets the basis for further beneficial collaboration within the GSRN. Some NMIs have developed specific instrumentation and knowledge, to improve laboratory and on-site calibration procedures, measurement principles, instrument characterisation and comparison, and measurement uncertainty evaluation. Direct interaction can be established to undertake joint activities on testing instrument performances, innovation in sensor technology and evaluation of field measurement uncertainties, also involving manufacturers. This will feed through into direct impact on technological advances in instrumentation and measurement methods.

4.2 Support and characterisation of wider networks

One of the recognized benefits of reference observations is the critical role they play in transferring information to observations made at non-reference sites and to improve their quality and utility, thus leading to an improved performance across the observational network.

In the cases when differences between data from a reference and non-reference network are minimal, this will contribute in enhancing the trust in the observed changes. After only a decade of observations, the US Climate Reference Network provides independent evidence of the veracity of the national warming estimates from homogenised data by comparing the reference stations with their neighbours (Leeper et al., 2015) and by comparing the two lower-48 US average temperature signals (Hausfather et al., 2016). In countries with a high-density of stations such as the USA, statistical homogenisation can remove a large part of any temperature trend biases (Williams et al., 2012), but for countries or regions where the spatial density is lower, the signal-to-noise ratio (SNR) is lower and the power of statistical homogenisation quickly drops (Lindau and Venema, 2018ab). The SNR will be lower for networks with a lower station density and for variables such as precipitation, humidity, wind speed, cloud cover and insolation that have smaller spatial scales of correlation. These are thus the cases where reference stations will bring most value.

For single non-reference stations, a nearby reference station can provide a well characterised comparator. This benefit will be limited to stations that are expected to have similar regional climate signals and will thus vary seasonally and by ECV. Reference stations will not only have better characterised measurements, but will also provide free and open access to reliable high-resolution measurements, such as e.g. 5-minute resolution series, and once the network is mature, the aim is that as close as possible to a fully comprehensive set of ECVs of relevance at each site will be measured, allowing for a more complete view of the climate system. This allows for higher quality computations of derived quantities at reference stations that can be used to bias correct simpler computations at other stations. For example, Almorox and Griesser (2016) compute the evaporation accurately at a small number of stations with comprehensive measurements to bias-correct evaporation estimates at other stations based on a simpler equation. In a similar way Vose et al. (2003) used a small subset of hourly measurements to compute time-of-observation biases for other stations having only daily measurements.

Finally, the presence of a reference station may improve the observations at non-reference stations by facilitating the adoption of better protocols and by improved observational practices.

4.3 Support of satellite observations

Satellite observations are generally characterised pre-launch, but they then undergo substantial stress of launch and over their lifetime experience sensor and orbit degradation due to the harsh environment of space. Despite much effort pre- and post-launch, and vicarious and cross-calibration methods, maintaining radiometric accuracy and precision of satellite signals is difficult, and degradation is found in sensors both with and without onboard calibration devices (Wang, 2015). Thus, there is always a need for ground-truth data collection to calibrate and validate remote sensing data and to aid in the analysis and interpretation of results. A fiducial reference network is critical for the validation of satellite-derived terrestrial ECVs globally. The ESA Sentinel-3 team defined a Fiducial Reference Measurement Program as:

> *The suite of independent ground measurements that provide the maximum return on investment for a satellite mission by delivering, to users, the required confidence in data products, in the form of independent validation results and satellite measurement uncertainty estimation, over the entire end-to-end duration of a satellite mission.*[1]

Current networks providing in-situ observations of terrestrial variables still lack good spatial representativeness over the globe. One such example is land surface temperature (Guillevic et al., 2018). Hence, many terrestrial satellite products are still at a low validation maturity according to the CEOS/WGCV Land Product Validation hierarchy (https://lpvs.gsfc.nasa.gov/). Moreover, existing networks (e.g., FluxNet,

---

[1] https://earth.esa.int/documents/700255/3264426/1.Metrology-Nigel+Fox-et+al..pdf/35806818-8924-4c74-b571-f0955c990773

SURFRAD) were not specifically set up for product validation and many stations are located in heterogeneous areas not suitable for validation of medium resolution products. Pursuing and expanding fiducial measurement programs is essential to ensure the quality, consistency and reliability of current and future satellite products, a needed step towards accurate climate data records of terrestrial ECVs. A fully implemented GSRN would provide co-located measurements of a broad suite of ECVs across a diverse range of climatic zones and surface types globally and thus would form a natural backbone for a global satellite calibration/validation program. The benefits to global society of improved satellite records would be substantive.

4.4 Support of climate process understanding and model validation

The key contribution of the GSRN is its capability to provide the highest quality data from meteorological and climatological observations. Apart from the obvious benefits to society of better understanding climate evolution and progress toward climate change mitigation, the availability of traceable and comparable data from a range of both critical and representative global environments will be invaluable in supporting high-quality research publications on climate processes and in the development and validation of new climate models.

Further benefits of a fiducial reference network for the climatological/meteorological community are outlined in Thorne et al. (2018). The authors point out the immediate scientific, technological and societal benefits of investment in the USCRN and GRUAN networks. They reported 61 citations relating to process understanding, trend detection, data analysis, instrument development, satellite calibration/validation, and applications for the USCRN network, and 47 citations for the GRUAN network in those same areas, respectively, over a period of only about 10 years.

5. METROLOGICAL UNDERPINNING CONCEPTS

Sustained collaboration with the metrological community is key to instigating and maintaining a long-term reference quality network.

National Institutes of Metrology are present in many nations. Their main role is to guarantee the equivalence of measurements among all nations having signed the Metre Convention and the mutual recognition arrangement. They are tasked to maintain the national standards, and act as the top national authority in the traceability chain and calibration certification processes. Since 2010 Joint research projects (Merlone et al. 2015, 2018), such as “MeteoMet, Metrology for Meteorology, funded by the European Metrology Research Programme”, have created a robust interaction and bridge between metrologists and meteorology and climatology communities. More recently, new laboratories for environmental metrology have been opened with direct interaction with relevant programmes of WMO and its GCOS programme. In this way, the involvement of NMIs will improve specific calibration of meteorological sensors with respect to available industrial sensors calibration, and metrologists will also undertake research services and activities, to better understand and evaluate measurement uncertainties, of which the calibration uncertainty is just one contributor.

The metrology community has spent many decades working on improving our understanding of measurement methods and their uncertainty. The International Vocabulary of Metrology (VIM, https://www.bipm.org/en/publications/guides/vim.html) and the Guide to the expression of Uncertainty in Measurements (GUM, https://www.bipm.org/en/publications/guides/gum.html) provide a rigorous basis on which to design and implement reference observation programs. This section opens by providing a brief summary of the key concepts of relevance to the GSRN. In order to better explain what is actually required to qualify and then process a reference observation, an example using the GRUAN RS-92 is presented in Annex 1.

5.1 Traceability and uncertainty

Traditionally in meteorology, observations have been treated as being effectively an unbiased estimate of the true state. In reality, we can never measure directly the measurand of interest. Rather, we always measure some proxy for the measurand such as a column of liquid, an electrical resistance or an optical delay. These proxy measures co-vary with the measurand in a predictable and repeatable manner.

Data provided by observing stations in terms of the measured quantities, is the result of complex measurement processes that involve numerous aspects, factors and instruments. Formally, a measurement is a set of operations having the objective of determining the value of a quantity (GUM B.2.5), normally as a result given by an instrument when exposed to the effect of the measurand/s; that is the quantity intended to be measured in a specific state (VIM 2.3). Every measurement is affected by an uncertainty, that expresses the impossibility to achieve complete knowledge of the measuring system, the quantities of influence and in some cases even the measurand itself. Critically, for environmental measurements the uncertainty includes quantities of influence, such as the site effect, shielding, and instrument ageing etc.. The result of a measurement is therefore only ever an approximation or estimate of the value of the measurand and thus is complete only when accompanied by a statement of the uncertainty, a parameter, associated with the result of a measurement, that characterizes the dispersion of the values that could reasonably be attributed to the measurand (GUM B.2.18).

Despite being well known to be an imperfect estimate of the true state of the measurand, in most meteorological and climate applications no effort is made to quantify or use the uncertainty in a measurement series. Even where uncertainty is estimated, rarely is this quantification metrologically complete. The key innovation of a reference quality measurement is that the uncertainty is rigorously quantified and the measurement result is traceable to standards of the System of Units (SI) or internationally respected measurement standards. Being rigorously confident that the true state lies within the confidence interval reported opens myriad opportunities to use the observations in new ways that can increase their fundamental value.

5.2 Comparability

Comparability of measurements of the same measurand or set of measurands at multiple locations and/or at different times is attained when two reported measurements differ solely due to differences in the measurand, independently from the measurement techniques or instruments or siting. Even nominally identical equipment may have variations within and between production batches and different ageing drifts due to differential exposure to environmental conditions. The challenge is to create a diverse network within which comparability of measurements is maximised. This is achieved through instigation and maintenance of a robust measurement program. This includes aspects such as: agreed uniform measurement methods; documented traceability and evaluated measurement uncertainty; measurement procedures; site certifications; prescribed instrument maintenance and calibration; round-robin comparisons; and common protocols for data analysis.

5.3 Representativity

Representativeness is a key property of a reference measurement. A representative measurement reflects the nature of the measurand across a broader spatial and temporal domain than the immediate measurement location. If reference sites are to be used to help constrain and validate more regional measurements from other networks or measurements from satellites (Section 4), then it is important to choose sites which optimise the spatial representativeness of the measurements and quantify any biases due to deviations.

5.4 Metadata

Metadata need to include the details and history of the instruments used, any changes and maintenance, calibration intervals, uncertainty and procedures along with any further information needed to fully describe the measurement process. The third GCOS Climate Monitoring Principle states:

> *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.*

GSRN reporting of metadata will be consistent with guidance and standards as documented in the CIMO Guide (WMO-No.8) and WIGOS Manual (WMO-No.1160). Common conventions for expressing the uncertainty budget must be proposed, discussed, prepared and adopted by all GSRN sites. The format must be one for each measured quantity, listing the components of uncertainty specific for the quantity, but with a common and uniform expression of the overall budget. Crucially, retained metadata must be sufficient to enable periodic data stream reprocessing if new insights into the method of observation accrue necessitating a new analysis of the series.

5.5 Managing instrument change

Change management is a critical component of the network vision and should follow the GCOS Climate Monitoring Principles[2]. GSRN should upgrade when clear improvements are possible, constantly striving to be undertaking the best possible measurements of the relevant ECVs. Regardless of whether by choice due to improved instrumentation, or necessity when instrument providers cease production and/or support, the central challenge is to manage all transitions in such a manner that the effects upon long-term series continuity are minimized and the associated uncertainty well understood.

Calibration procedures are now fully detailed and optimized in prescribing how in metrology laboratories precautions must be taken to identify, reduce and correct factors that could disturb the measurement of the primary quantity. Characteristics and competence of calibration laboratories are prescribed by the ISO/IEC 17025. However, for measurements in the field, these disturbing factors are inevitable, and it is of fundamental importance to investigate the differences between the old and the new measurement system each time a replacement or upgrade occurs. Hence, change management in GSRN will always require an appropriate mix of laboratory-based and field-based assessment including a sufficient period of parallel observations and repeated calibrations of both new and replaced instruments. Prescriptions are suggested in documents such as the section 4.1 of WMO-No. 1202 that indicates periods of one or two years for different instruments: further specific studies can be undertaken by GSRN which may serve to provide more nuanced and cost-effective strategies. Furthermore, when several sites are confronted by the same challenge an appropriate burden sharing strategy may be possible as is the case in GRUAN in managing the RS-92 to RS-41 transition (Dirksen et al., in prep).

5.6 Documentation

Documentation is essential for the transfer of knowledge and helps to ensure the traceability of the data products, and ranges from describing operational procedures and the best practices to perform

---

[2] The ten basic principles (in paraphrased form) were adopted by the Conference of the Parties (COP) to the United Nations Framework Convention on Climate Change (UNFCCC) through decision 5/CP.5 at COP-5 in November 1999. This complete set of principles was adopted by the Congress of the World Meteorological Organization (WMO) through Resolution 9 (Cg-XIV) in May2003; agreed by the Committee on Earth Observation Satellites (CEOS) at its 17th Plenary in November 2003; and adopted by COP through decision 11/CP.9 at COP-9 in December 2003

measurements, via a detailed description of correction algorithms, to documenting changes to measurement systems and products. Formal documentation will contain mandatory requirements and guidelines on how to achieve the operating procedures, and specific instrumentation and data processing protocols.

5.7 Certification

Rigorous certification processes are essential to ensure that climate data from GSRN are not based on contributions from poor and degraded instruments and station siting, poor field maintenance, and insufficient or unknown instrument calibration. Certification will be required for sites, instrumentation, measurements procedures and staff. Description of site characteristics, including its maintenance in stable conditions, distance from obstacles, and all other identified parameters are part of the site certification process, together with data logging and transmitting systems, and a consideration of the site in the context of the value it brings to the network as a whole. Consistency with standard operating procedures, the calibration intervals, adoption of prescribed calibration procedures and the assessment of appropriate metadata formulation form the basis for the certification of the equipment. Staff involved in the maintenance of a GSRN site also need to be trained.

6. SITING AND INSTRUMENTATION

While the GSRN will need to build upon existing networks and undertake measurements within a range of climate regimes, latitudes and surface types, other considerations will be equally important and should be addressed if possible. For example, given the limited resources available, a critical need will be to unambiguously focus on determining trends in the global climate system in areas that might be called climate change ‘hot spots’, areas where human livelihoods and/or biodiversity are threatened or where rapid environmental change is occurring.

6.1 Local Siting Considerations

In relation to representativeness, a reference station should be positioned in a place where land cover, vegetation and soil characteristics are as uniform as possible, and representative of the conditions of the surrounding area. This is critically important where terrestrial ECVs are concerned, where satellite observations would require characterisation of substantially more area than simply the area of the observational enclosure. In relation to the core atmospheric ECVs, the common ISO/WMO standard 19289:2014(E) (also in WMO-No.8, the CIMO guide) classifies siting requirements for instruments measuring certain variables. To align the definition of the site to the existing prescription from the CIMO guide, the measuring station should be in the centre of a flat area of at least 100 m of radius, free from obstacles such as roads, trees, buildings, water sources and any other kind of object that could affect the variables and the quantities of influence.

Since most of the atmospheric ECV instrumentation is placed in close proximity to the ground, vegetation in its immediate vicinity should be kept controlled to avoid excessive growth, as according to WMO No.8 “The ground should be covered with short grass or a surface representative of the locality”. An excessive height of grass and vegetation in general, can affect humidity, condensation phenomena, backward radiation and also wind speed. This results in different values of both measured variables and quantities of influence, with respect to the defined reference conditions. Each instrument must be classified individually and should meet Class 1 as per the standard. There will be occasions where it will be necessary to relax this requirement. As an example, a mountain site can adopt a specific prescription, since a flat area of 100 m radius can seldom be found in mountainous areas, free from obstacles such as rivers, rocks and trees. Such exceptions are well defined by WMO-No.8. For these and other typologies of stations such as coastal stations or stations in areas where cryosphere is present, specific definition and flagging should be adopted in the GSRN guide. For a site that also measures terrestrial ECVs these may need to be offset horizontally at a distance from the atmospheric sensors as for a terrestrial site, the vegetation would need to be minimally disturbed, and not-controlled. Optical sensors would need to be placed within and above the canopy.

Long-term stability of the measurement programme undertaken by the station should be guaranteed. The station should have some type of protected status, meaning that the surroundings, for at least 100 m of radius, should be under specific regulations avoiding future construction of buildings, roads or any kind of infrastructure. For stations that are intended to characterise terrestrial ECVs derived from satellite remote sensing, the area of protected status should be extended commensurate with the horizontal resolution of the relevant sensor(s).

Accessibility is a key requirement for a GSRN site hosting a reference station. Accessibility must, as far as practical, be year-round so that maintenance can be guaranteed at regular scheduled intervals, as well as for unscheduled access for repair, changeover of malfunctioning instruments, or any other action required to keep the instrumentation and site in conditions meeting specifications. Such constant accessibility should also be possible for remote and mountain sites; institutions managing reference stations in such locations should consider such extra costs associated with accessibility.

Site changes need to be managed. In the case where a site needs to be relocated, the site is required to undergo a mandatory audit, that will determine whether the site fulfils the conditions to remain part of the network.

6.2 Instrumentation

The initial core requirement is to measure the six surface-based atmospheric ECVs: air temperature, water vapour (relative and/or specific humidity), surface radiation budget (shortwave and longwave downwelling and upwelling components), wind speed and direction, pressure and precipitation (liquid and solid) (Section 3). It is strongly encouraged to measure additional variables such as snow cover, land surface temperature, soil temperature and soil moisture, especially as they may relate to any terrestrial ECVs that may be measured.

For operational stations on land, measurement uncertainty requirements, instrument performance and the classification of surface measurement quality are clearly defined in the CIMO Guide (WMO-No.8). Due to the specific scope of the GCOS reference network these requirements are expected to be tighter and more strictly enforced for GSRN stations in most measured quantities. These envisaged GSRN requirements are summarised in Annex 3 to this document, organised in similar way to the CIMO definitions and tables.

It is important to stress again that a successful GSRN will consist of a range of instrumentation arising from numerous manufacturers that avoids vendor lock-in and encourages competition in the marketplace. Instrument selection will require careful consideration to ensure the sustainability of measurement systems and observations. This includes robustness, ease of maintenance and calibration, availability of replacement instruments, consumables and manufacturer support.

It is to be expected that a significant proportion of GSRN stations will be in extreme environments such as desert, mountain, remote island, polar and tropical regions, where it is essential that instruments and infrastructure are able to withstand extreme conditions. Site and equipment maintenance need to be a priority to avoid degradation and uncontrolled instrumental drifts over time due to environmental conditions that may affect the measurements. This may include constant salt laden winds causing rusting of structures and housings, rapid vegetation growth affecting humidity measurements, insect infestation and so on.

Standardized, or in some cases dedicated, calibration procedures must be adopted by all network stations to document instrumental traceability. Knowledge of the components of measurement uncertainty due to the site characteristics and the local quantities of influence also require dedicated research and field campaigns.

Measurement redundancy at GSRN stations is recommended. By using multiple, co-located traceable instruments to measure the same parameter the resultant data series can be compared. Disagreement between the data series can highlight measurement problems which would be undetectable with a single sensor, and agreement results in a lower statistical measurement uncertainty. An example of this is the triple redundancy on air temperature measurement in the USCRN. Cross-checking of redundant measurements for consistency shall be an essential part of the GSRN quality assurance procedures.

Complementary observations are also to be encouraged, for example, placing a wind instrument at the height of the air temperature measurement to gain additional information and improve the uncertainty of the air temperature measurement.

6.3 Network spatial configuration considerations

The GSRN must have a carefully considered rationale in relation to station locations. While the GSRN will be defined to serve global scale applications, the underlying concept should be adaptable at the national level to allow WMO Members to implement reference stations serving national interests. As with implementation of the GRUAN, the network configuration should take advantage of existing instruments, programs and measurement sites, as well as organizational willingness to host, to maximise value and efficiency.

Therefore, the way forward will be to identify a list of already-established high-quality sites where co-location of GSRN activities could occur. Many such high-quality sites are currently operated, for example, by GRUAN, BSRN, GAW, GCW, ARM, CloudNet, CIMO test beds and Lead Centres, NEON, TERM, FluxNet, as well as several high quality national reference networks (e.g. the Australian Bureau of Meteorology Reference Climate Stations, the USCRN, the DWD reference network and the CMA reference network; although note that all these presently take distinct definitional approaches to ‘reference’ an aspect which GSRN would help to rectify), or single national sites.

In relation to representativeness of global climates there are several climate classification systems that can be used to select candidate stations. The original Köppen climate classification system has seen many improvements and simplifications, for example Feddema (2005). However, another more useful approach would be to identify potential stations that would represent the range of climates, but in addition would monitor climate trends in critical global “hot spots” for climate change. For example, De Souza et al. (2015) and Neuman and Szabo (2016) have identified global “hot spots” where livelihoods and biodiversity are severely threatened and have been linked to UN Sustainable Development Goals (UNSDG). These include certain semi-arid, snowpack-glacier, and coastal-delta regions. Alternatively, WG1 of IPCC AR6 is developing a “Global and Regional Atlas of (Climate Change) Hazards” that can provide guidance for selection of candidate stations.

Finally, there is also the vexed question of urban climate stations that is discussed further in the section on “Remaining challenges and open questions” below. These ideas can be developed and refined further in the near-term so that the benefits of a GSRN can be maximized.

7. NETWORK MANAGEMENT AND COORDINATION

A successful GSRN requires sustained governance, management and coordination, and oversight. Given the global nature of the network, with observations made by multiple sovereign nations, it will be necessary to take a federated approach to aspects of network and data management. Furthermore, to realise the system-of-system benefits (Section 4) the GSRN has to be integrated into the broader WIGOS activities so that key insights can be effectively integrated into remaining components of the global observing system. Key aspects of network management and coordination are discussed below.

7.1 Global governance

The GSRN will be sponsored by one or more relevant global bodies. Considering the different roles in the instigation and maintenance of the GSRN, it is likely that the GCOS programme, relevant WMO programmes and BIPM will all have a formal role in the network governance.

7.2 GSRN Steering Committee

A steering committee, should be formed, tentatively consisting of representatives of the sponsors, the director of the Lead Centre (see below) and scientific and technical experts. The role of this group would be to provide guidance on the development of GSRN, monitor network performance as well as providing scientific, technical and management guidance to the Lead Centre. The WG-GRUAN of AOPC provides a working model of such a group that oversees the development and operations of GRUAN.

7.3 Lead Centre

The establishment and operation of a Lead Centre to manage implementation and operations of GSRN is critical to the success of the network. It will need to work in conjunction with the steering committee to:

- develop a network based on existing reference quality monitoring stations;
- coordinate reference stations;
- ensure that all observations are of reference quality;
- establish common procedures and standards across the GSRN;
- certify stations as being of reference quality and contributing to the GSRN; a station applying to become a GSRN station will provide evidence to the Lead Centre that they do fill the needed requirements. The Lead Centre will make a recommendation to the Steering Committee on whether to accept or reject the application.
- establish systems to monitor station performance and perform QA/QC, based on existing systems where possible;
- ensure data is easily discoverable and freely and openly available to all;
- develop a plan for the long-term operation and development of GSRN, including development and provision of guidelines to harmonize long-term series of surface observations and promotion of research activities, that apply GSRN data to climate research and monitoring issues;
- report to the GSRN steering committee;
- promote research activities, including a visiting scientist programme, that apply GSRN data to climate research and monitoring issues;
- provide training at the lead centre of on-site scientists to ensure required performance;

- undertake development and provision of guidelines to harmonize long-time series of surface observations, especially for archived data sets.

Staffing Commitment.

A GSRN Lead Centre should ideally be collocated with an existing organization already engaged in similar or related functions for climate observing system, with an initial staff of at least a Director, supported by an appropriate number of full-time scientific professionals and administrative support. A Lead Centre may consist of a single institution or a global consortium of institutions with a designated lead. To realise synergies and ensure an integrated system-of-systems approach, interoperability with WIGOS activities and structures would be advisable.

8. CHALLENGES TO BE ADDRESSED BY AN OPERATIONAL GSRN

There remain a substantive number of challenges that are required to be overcome to achieve a GSRN network. This section provides a non-exhaustive overview of those presently felt to be most critical. It is certain that additional challenges will be uncovered were the development and deployment of GSRN to proceed.

8.1 Technical Challenges

Metrological qualification of high-quality instrumentation

The need for metrological qualification of measurement programs as truly reference quality has considerable technical challenges. As noted in Section 5 and illustrated in Annex 1, to qualify each and every measurement as being of reference quality requires effort to understand, quantify, and document all relevant and known effects. Given the likely broad range of instrumentation to be used across the network it is likely that a significant effort will be required just to qualify instrumentation that is already well understood and widely applied.

Development of technological solutions for high-quality measurement of several ECVs

There exist substantive challenges pertaining to development and transition to operations for a broad range of terrestrial and composition ECVs outlined in Table 1. For these ECVs, e.g. some satellite-derived terrestrial and trace-gas composition variables, techniques and equipment in some cases is still only in development. More substantive work will be required to operationalise the instrumentation/techniques and perform the necessary metrological qualification steps. Work may include refinement of techniques and aspects such as miniaturisation and reductions in cost of equipment.

8.2 Scientific Challenges

Sampling strategies

For several ECVs substantive questions remain around assessing critical aspects pertaining to network design. Most questions revolve around the sampling requirements. Many of the ECVs such as soil moisture and soil temperature may have very local spatial scales. Depending upon the applications foreseen and the site characteristics the sampling requirements may vary dramatically from a handful of well-spaced samples to very many samples. Work is required to better understand the sampling requirements and possible sampling strategies such that a truly representative measurement series can be obtained.

Development of new measurement technologies

The GSRN will serve as research framework for investigating physical approaches to the measurements of identified ECVs. Together with the capability to undertake constant evaluation of new technology (Section

4), studies are needed also to evaluate the feasibility and practical application of new measurement principles by comparison of existing methods. Non-contact methods for measuring temperature and humidity, validation of non-catching gauges, use of ultrasounds for different purposes, and definition of procedural standards for soil moisture are examples where scientific progress is seen as required.

Urban measurements

The matter of urban climate measurement has been a perennial issue for climate networks; indeed urban "contamination" of observations has traditionally been seen to be avoided at all cost. Given that almost 70% of the global population will be urbanized by 2050 (UN, 2018) and that cities are key to climate mitigation and adaptation, there is now widespread acceptance that appropriate and valid urban measurements must be made within established networks, or in a parallel observational network. However, such measurements will require development of their own protocols for site selection, instrumentation and exposure; this will be especially challenging given the extreme heterogeneity, and potential rapid changes in some urban environments. It is suggested that relevant WMO programmes and the GCOS programme engage with relevant expertise, for example within the International Association for Urban Climate (IAUC), to identify a possible way forward.

9. NEXT STEPS

This report outlines the technical requirements and an initial implementation concept in order to meet the requirements for a GSRN.

To proceed to implementation, the following are required:

- Approval of the proposed GSRN by relevant WMO programmes, the GCOS programme and other sponsors, leading to the adoption of an agreed governance structure.
- An offer to host and staff appropriately the proposed Lead Centre.
- Offers of suitable sites for an initial GSRN.

During this period, regular meetings will be essential to develop and fully articulate and document concepts of operation and certification procedures.

Overall, the guiding principle should be to start small, but start. That means slowly building up the network size and capabilities in a manner that is sustainable and solicits and fully accepts input from all relevant groups.

REFERENCES

Almorox, J., and J. Grieser, 2016: Calibration of the Hargreaves–Samani method for the calculation of reference evapotranspiration in different Köppen climate classes. Hydrology Research, 47 (2) 521-531. https://doi.org/10.2166/nh.2015.091

De Souza, K., Kituyi, E., Harvey, B., Leone, M, Murali, K and J. Ford, 2015: Vulnerability to climate change in three hot spots in Africa and Asia: key issues for policy-relevant adaptation and resilience-building research Regional Environmental Change 15: 747. https://doi.org/10.1007/s10113-015-0755-8

Dirksen, R. J., Sommer, M., Immler, F. J., Hurst, D. F., Kivi, R., and Vömel, H.: Reference quality upper-air measurements: GRUAN data processing for the Vaisala RS92 radiosonde, Atmos. Meas. Tech., 7, 4463-4490, https://doi:10.5194/amt-7-4463-2014 , 2014.

Johannes J. Feddema, Keith W. Oleson, Gordon B. Bonan, Linda O. Mearns, Lawrence E. Buja, Gerald A. Meehl, Warren M. Washington, 2005: Science, 09 Dec 2005:Vol. 310, Issue 5754, pp. 1674-1678

DOI: 10.1126/science.1118160

Guillevic, P., Göttsche, F., Nickeson, J., Hulley, G., Ghent, D., Yu, Y., Trigo, I., Hook, S., Sobrino, J.A., Remedios, J., Román, M. & Camacho, F. ,2017: Land Surface Temperature Product Validation Best Practice Protocol. Version 1.1.0 In P. Guillevic, F. Göttsche, J. Nickeson & M. Román (Eds.), Best Practice for Satellite-Derived Land Product Validation (p. 58): Land Product Validation Subgroup (WGCV/CEOS), https://doi:10.5067/doc/ceoswgcv/lpv/lst.001

Hausfather Z., K. Cowtan, M.J. Menne, and C.N. Williams Jr., 2016: Evaluating the impact of U.S. Historical Climatology Network homogenization using the U.S. Climate Reference Network. Geophys. Res. Lett., 43. https://doi.org/10.1002/2015GL067640

Leeper, R.D., J. Rennie, and M.A. Palecki, 2015: Observational perspectives from U.S. Climate Reference Network (USCRN) and Cooperative Observer Program (COOP) Network: Temperature and precipitation. J. Atmos. Oceanic Technol., 94, 703-721. https://doi.org/10.1175/JTECH-D-14-00172.1

Lindau, R. and V. Venema, 2018a: The joint influence of break and noise variance on the break detection capability in time series homogenization. Advances in Statistical Climatology, Meteorology and Oceanography, 4, pp. 1-18. https://doi.org/10.5194/ascmo-4-1-2018

Lindau, R., and V. Venema, 2018b: On the Reduction of Trend Errors by the ANOVA Joint Correction Scheme Used in Homogenization of Climate Station Records. International Journal of Climatology, published online. https://doi.org/10.1002/joc.5728 EarthArXiv preprint doi: https://doi.org/10.31223/osf.io/r57vf

Merlone A, Lopardo G, Sanna F, Bell S, Benyon R, Bergerud R A, Bertiglia F, Bojkovski J, Böse N, Brunet M, Cappella A, Coppa G, del Campo D, Dobre M, Drnovsek J, Ebert V, Emardson R, Fernicola V, Flakiewicz K, Gardiner T, Garcia-Izquierdo C, Georgin E, Gilabert A, Grykałowska A, Grudniewicz E, Heinonen M, Holmsten M, Hudoklin D, Johansson J, Kajastie H, Kaykısızlı H, Klason P, Kňazovická L, Lakka A, Kowal A, Müller H, Musacchio C, Nwaboh J, Pavlasek P, Piccato A, Pitre L, de Podesta M, Rasmussen MK, Sairanen H, Smorgon D, Sparasci F, Strnad R, Szmyrka-Grzebyk A, Underwood R. 2015. The MeteoMet project – metrology for meteorology: challenges and results. Meteorol. Appl.., 22: 820–829. https://doi:10.1002/met.1528

Merlone A, Sanna F, Beges G, Bell S, Beltramino G, Bojkovski J, Brunet M, del Campo D, Castrillo A,Chiodo N, Colli M, Goppa G, Cuccaro R,Dobre M, Drnovsek J, Ebert V, Fernicola V, Garcia-Benadí A, Garcia-Izquierdo C, Gardiner T, Georgin E, Gonzalez A, Groselj D, Heinonen M, Hernandez S, Högström R, Hudoklin D, Kalemci M,Kowal A, Lanza L, Miao P, Musacchio C, Nielsen J, Nogueras-Cervera M, Oguz Aytekin S, Pavlasek P, de Podesta M, Rasmussen MK, del-Río-Fernández J, Rosso L, Sairanen H, Salminen J, Sestan D, Šindelářová L, Smorgon D, Sparasci F, Strnad R, Underwood R, Uytun A,Voldan M. 2018.The MeteoMet2 project – Highlights and results. Meas. Sci. Technol. 29 025802. https://doi:10.1088/1361-6501/aa99fc

Neuman, B., and S. Szabo, 2016: Climate change hotspots: why they matter and why we should invest in them. The Conversation, November 16, 2016, https://theconversation.com/climate-change-hotspots-why-they-matter-and-why-we-should-invest-in-them-68770

Thorne P.W., H.J. Diamond, B. Goodison, S. Harrigan, Z. Hausfather, N.B. Ingleby, P.D. Jones, J.H. Lawrimore, D.H. Lister, A. Merlone, T. Oakley, M. Palecki, T.C. Peterson, M. de Podesta, C. Tassone, V. Venema, and K.M. Willett, 2018: Towards a global land surface climate fiducial reference measurements network. Int J Climatol., 38, pp. 2760–2774. https://doi.org/10.1002/joc.5458

UN Department of Economic and Social Affairs, 2018: 2018 Revision of World Urbanization Prospects. https://population.un.org/wup/

Vose, R.S., C.N. Williams Jr., T.C. Peterson, T.R. Karl, and D.R. Easterling, 2003: An evaluation of the time of observation bias adjustment in the U.S. Historical Climatology Network. Geophys. Res. Lett., 30, no. 20, 2046. https://doi.org/10.1029/2003GL018111

Wang, D. D. (2015). Satellite Degradations and Their Impacts on High-Level Products, in Prasad Thenkabail (Ed.), Remotely Sensed Data Characterization, Classification, and Accuracies (pp. 678). Boca Raton, FL, CRC press.

Williams C.N., M.J. Menne, and P.W. Thorne, 2012. Benchmarking the performance of pairwise homogenization of surface temperatures in the United States. J. Geophys. Res., 117, D05116. https://doi.org/10.1029/2011JD016761

Annex 1: Example of steps required to produce and disseminate a reference quality measurement

Having outlined the concepts underpinning a reference measurement program it is valuable to provide a worked example. Here, recourse is made to the GCOS Reference Upper Air Network (GRUAN) RS-92 radiosonde product which is a long-standing product.

The first essential step is to fully understand the measurement system process. We can never directly measure the measurand, but rather measure some quantity that varies in a predictable manner with the measurand. It is helpful to consider this in the context of the chain of processing steps that takes you from the original measured quantity (in this case digital counts as a function of the target measurand) to the final derived product. This chain may include periodic or per measurement calibration procedures. An example of such a traceability chain for the RS-92 temperature product is given in Figure A1. Here each processing step in the chain is clearly laid forth. Chains can be either much simpler or much more complex than that given here with the complexity driven by the number and nature of processing steps in the measurement technique. The chain should always end with a primary standard under the SI system or a community accepted standard.

Having derived the traceability chain, it is next necessary to rigorously quantify the uncertainty arising from each step in the chain. This can be attained through some mix of laboratory-based experiments (including chambers if appropriate), field-based intercomparisons, or if necessary expert solicitation. The magnitude of the effect, the shape of the uncertainty, whether it is systematic, random or structured random, and any relationships to other steps in the chain should be identified. Table A1 provides an example of how this may be attained and documented in practice through an ‘Effects Table’ for the specific step of the application of the GC-25 pre-launch calibration step for the RS-92 product.

Once all effects have been accounted for and assumptions documented it is useful, to build confidence in the product if a paper describing the product specification and showing the uncertainties that result is produced. For the GRUAN RS-92 effect a paper was produced describing the product derivation by Dirksen et al. (2014).

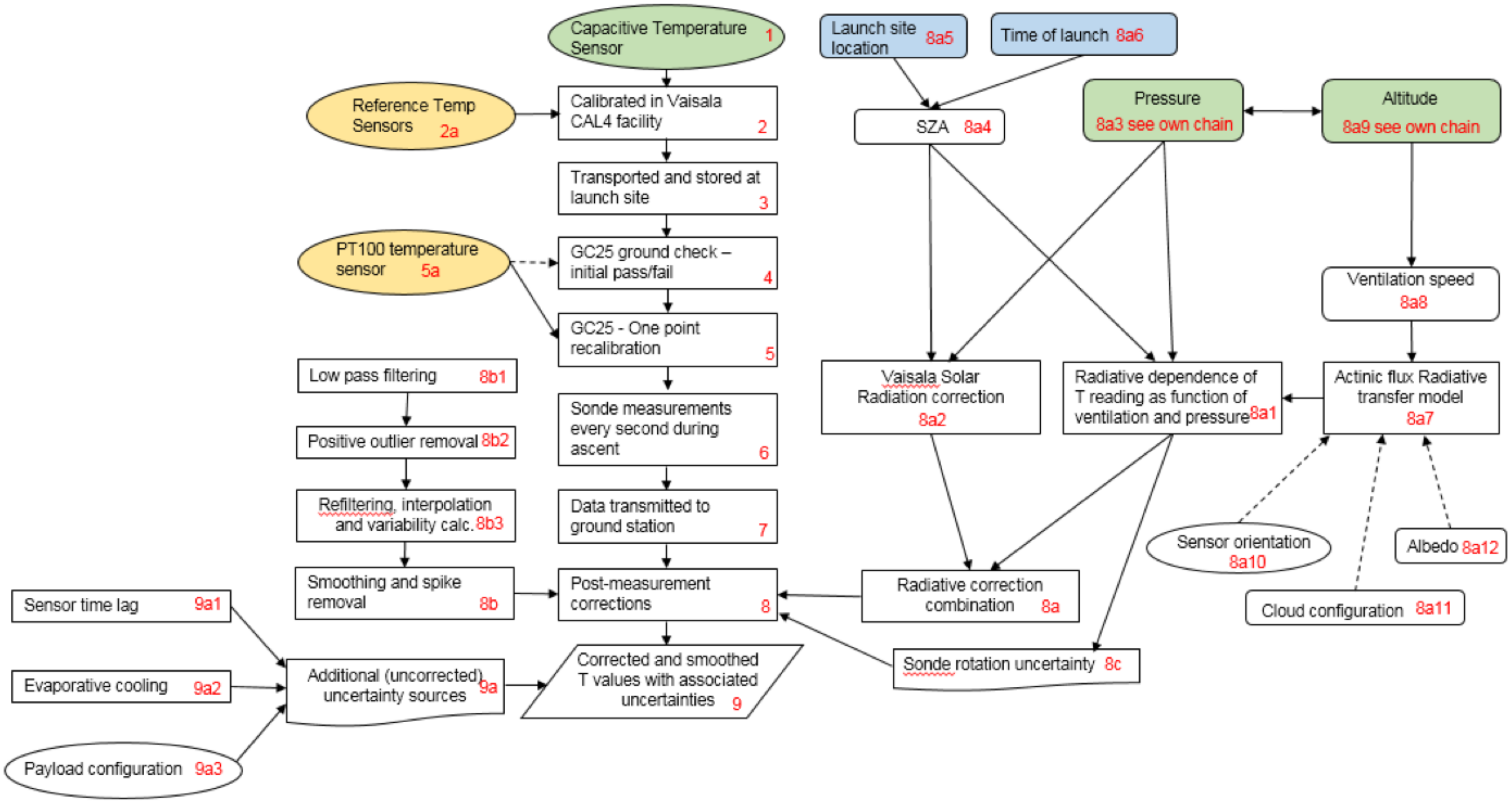

Figure A1. next page) Example of a traceability chain denoting input data and processing steps necessary to produce a GRUAN RS-92 data product for temperature. Sourced from the EU H2020 project GAIA-CLIM. Original work by UK NPL

Information / data	Type / value / equation	Notes / description
Name of effect	GC25 recalibration	Not known if shift or scale adjustment
Contribution identifier	5, u_{GC25}	
Measurement equation parameter(s) subject to effect	Temperature	
Contribution subject to effect (final product or sub-tree intermediate product)	Temperature	
Time correlation extent & form	Systematic over flight	
Other (non-time) correlation extent & form	Systematic over flight	
Uncertainty PDF shape	Rectangular	Difference during ground check
Uncertainty & units (1σ)	typically 0.17 K (1σ)	Combined with Vaisala calibration uncertainty
Sensitivity coefficient	1	
Correlation(s) between affected parameters	None	
Element/step common for all sites/users?	Yes	
Traceable to …	PT100 (5a)	
Validation	Intercomparisons	Indirect

Table A1. next page). 'Effects Table' for step 5 in the traceability chain for the GRUAN RS-92 product given in Figure A1. Sourced from GAIA-CLIM. Original work by UK NPL.

Once the reference product has been defined it is necessary to capture the raw data and metadata and for the GRUAN RS-92 product this is achieved via the RSlaunchclient which is a web based application. This ensures that all essential metadata is collected and associated along with the raw data which can be stored in perpetuity. Other modes of transmission can, of course, be undertaken but what is key is that each observation be able to be uniquely associated with the instrumentation configuration. Upon receipt the GRUAN Lead Centre uses the data and metadata to process the data to create a GRUAN data product for the RS92 (Figure A2). The metadata and raw data preservation permits periodic reprocessing. The current GRUAN data product is version 2, with a version 3 product in preparation at time of writing. Such version increments accrue with improved measurement system understanding and can arise from feedback pointing to the need for a user feedback mechanism to be implemented.

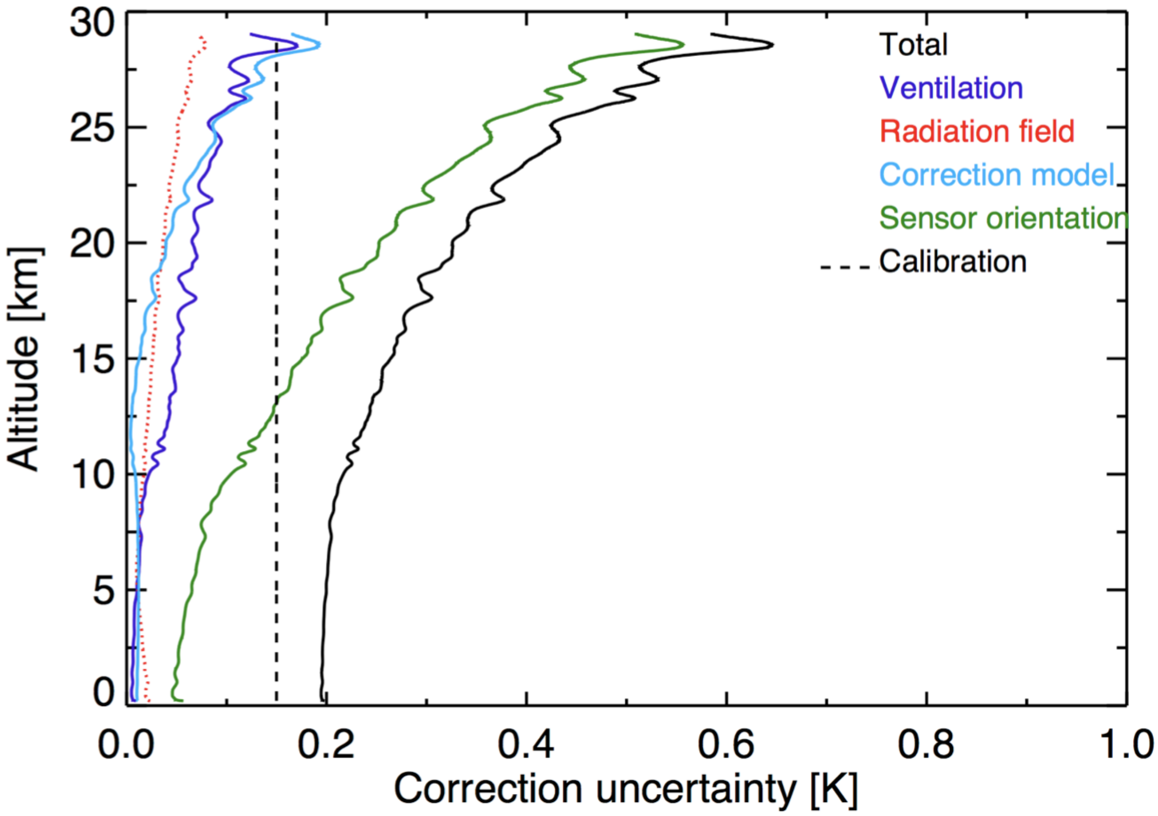

Figure A2. Contributions of the various uncertainty terms to the total uncertainty estimate of the GRUAN temperature correction for a specific sounding performed at Lindenberg on 27 September 2013 (from Dirksen et al., 2014). The total uncertainty is the geometric sum of the squared individual uncertainties. The correction model is the estimated vertically resolved error on the temperature based on the estimated actinic flux. This error is subtracted from the measured temperature profile to produce the corrected ambient temperature. Sourced from GRUAN Lead Centre, DWD.

Annex 2: GCOS Surface Reference Network (GSRN) terminology.

Annex to the GSRN outline document

Version 2018 – 10 – 12

Term	Definition	Note
Accuracy of measurement	Closeness of the agreement between the result of a measurement and a true value of the measurand Note 1: “Accuracy” is a qualitative concept: it is not expressed as a quantity Note 2: The term precision should not be used for “accuracy”.	VIM, definition 3.5
Calibration Regime	This is the recommended maximum interval between a full multi-point calibration performed against internationally traceable references in an accredited laboratory.	GSRN
Climate reference station	A climate observing station providing reference quality measurements. Reference stations are the stable backbone of the climate observing system and allow for studying changes in the climate with unprecedented accuracy. Note 1. The station needs to be equipped with high-quality instrumentation, procedures and technology that will achieve the best estimates of values of the observed parameters. Selection of instrumentation and methods that are completely and openly documented and that can thus be replaced indefinitely. Note 2. The station must be located at a site that is representative for its regional climate and adhering to strict siting requirements, according to the GSRN specifications. Locations should be chosen where no changes in the surrounding areas are expected for the next century. Note 3. Changes in instrumentations, procedures and technology must be limited, motivated and documented. Parallel observation periods must be planned prior to any change.	GSRN

Comparability	Property of a measurement result to be comparable with other measurements of the same quantity. Note 1. To achieve comparability an absolute measurement must be traceable. Note 2. Relative measurements can be comparable if the instruments are stable and measurement conditions are homogeneous.	GSRN
Data logger	A data logger (also datalogger or data recorder) is an electronic device that records data over time or in relation to location either with a built-in instrument or sensor or via external instruments and sensors. Increasingly, but not entirely, they are based on a digital processor.	From Wikipedia
(Instrument) Drift	This is the continuous or incremental change over time between calibrations, due to changes in metrological properties of the measuring instrument. Noting that annual change in the calibration is normally quoted in specification sheets.	WMO-No.8
Homogeneity	Homogeneity is a property of an ECV series whereby all variations of the series are caused solely by the vagaries of weather and climate. Homogeneity generally refers to the average values of the ECV, but also includes additional moments of the distribution (homoscedasticity) that the series follows. Numerous non-climatic factors can influence a series [e.g. how the measurements are taken (is the thermometer screen aspirated or not?), the time(s) of observation, the way the data may be averaged to daily or monthly averages] and may change. Additionally, the non-climatic factors may include siting characteristics, particular whether areas around the site have undergone major land-use changes [e.g., urbanization] during the period of recording. Without some form of assessment of homogeneity, erroneous conclusions can be drawn regarding the course of ‘true’ change and variability of the ECV. As some of the non-climatic factors are likely to differ from site to site, the influence is likely to reduce as the data are averaged across a region. Some factors are, however, more pervasive and unlikely to cancel (e.g., urbanization). These factors are referred to in the scientific climate literature as biases.	Specific for GSRN

Instrument (measuring instrument)	Device used for making measurements, alone or in conjunction with one or more supplementary devices. It is normally composed of one or more sensors. [Note The instrument is the complete system used to transfer the changes of a phenomenon into understandable information. According to the user needs and technological solutions, the instrument can be complex or a part of something else (e.g., including ADC converters, loggers, sensors, where the sensor is only the sensing element of the instrument)].	VIM, definition 3.1
Maintenance Regime	This is the recommended maximum interval between inspections of the entire measurement system to confirm that this is correct: site exposure; shield/screen and other mechanical mounting fixtures are clean and serviceable; instrument is clean and serviceable; and the logger/weather station is clean and serviceable.	WMO-No.8
Measurand	Particular quantity subject to measurement Note. The specification of the measurand requires statements on the description (and evaluation) of the effect of influencing quantities, on the site characteristics, on the time of measurements and in general about all the metadata.	VIM, definition 2.6
Measurement	Process of experimentally obtaining one or more quantity values that can reasonably be attributed to a quantity The measurement, including the measuring system and the conditions under which the measurement is carried out, might change the phenomenon, body, or substance such that the quantity being measured may differ from the measurand as defined. In this case, adequate correction is necessary. [Note to the term Measurand in the VIM – 2.3] A measurement result is generally expressed as a single measured quantity value together with a measurement uncertainty. If the measurement uncertainty is considered to be negligible for some purpose, the measurement result may be expressed as a single measured quantity value. In many fields, this is the common way of expressing a measurement result. [Note to the term Measurand in the VIM – 2.9] Quantity: property of a phenomenon, body, or substance, where the property has a magnitude that can be expressed as a number and a reference	From VIM

Metadata	In the climate context, metadata is a suite of supporting data required to effectively manage climate data and assess the data's fitness for purpose. Climate metadata are made up of the following components: **Observations metadata:** Time-series data that describe how, when and where meteorological observations were made and the conditions they were made under. **Discovery metadata**: Information intended to facilitate the discovery and assessment of a dataset to determine if it is fit for reuse for a purpose that may be at odds with the reason for which it was originally created. **Data provenance metadata**: Information relevant to climate data that allows end-users, including data managers, scientists and the general public, to develop trust in the integrity of the climate data. Climate metadata, in the context of the GSRN, includes the history of all aspects of the operation of the station. It does not include the current specific siting requirements, just the history of the changes.	(WMO Climate Data Management Systems Specifications, WMO – No. 1131)
Reference Network	A group of reference stations, which are spread well over the region of study, run by either a single organization, or a designated part of internationally recognized group of stations.	GSRN
Observation	Observation: Evaluation of one or more meteorological elements (WMO-No 182) Surface observation: A meteorological observation, other than an upper-air observation, made from the Earth's surface. (WMO-No 544) Note. Observations are often treated exactly the same as measurements as though they are synonymous. In some contexts, they are, but the terminology from a Climate perspective is given here. The metrological definitions are more specific, but in the context here, the less specific-WMO ones should be easily understood.	International Meteorological Vocabulary, WMO-No 182 Manual on the Global Observing System; WMO-No 544
Quantity	Property of a phenomenon, body, or substance, where the property has a magnitude that can be expressed as a number and a reference	VIM, definition 1.1

Quantity of influence	Quantity that is not the measurand but that affects the result of the measurement. Note. A quantity of influence in most cases is already measured as a primary other quantity in a reference station. In case it is not, specific measured values need to be recorded.	VIM, definition 2.7
Raw data	Values measured by sensors and recorded by a datalogger or any other system which have not been processed or corrected or subjected to post-processing.	Partially from METEOTERM
Reference climatological station	A climatological station the data from which are intended for the purpose of determining climatic trends. This requires long periods (not less than 30 years) of homogeneous records, where human-induced environmental changes have been and/or are expected to remain at a minimum. Ideally, the records should be of sufficient length to make possible the identification of secular changes of climate.	Manual on the Global Observing System; WMO-No 544
Reference measurement	A measurement value of an observed quantity at a reference station, resulting from an instrument made that is traceable back to a recognized international standard (SI standard where possible), and with a documented measurement uncertainty budget. Note 1. Reference data can be produced from a single reference measurement, by averaging multiple reference measurements over a specified time period, or by processing reference measurements from multiple instruments (identical or different and also involving different measuring principles). Note 2. The measurement uncertainty budget includes the contributions from the calibration, site characteristics and quantities of influence. The quantities of influence may be other reference observables at the station or may need to be additionally measured (with standard quality). Corrections can be applied if documented studies give indications about how to evaluate the correction coefficients/curves and associated uncertainties. Uncorrected and *uncalibrated* data (direct instrument reading without applying any calibration curves and the corrections from quantities of influence) must be kept.	GSRN

	Note 3. The measurement uncertainty must be evaluated according to the GUM (Guide on the expression of uncertainty in measurement, JCGM 100:2008). This describes the current best knowledge of instrument performance under the conditions encountered during an observation and it describes the factors impacting a measurement as a result of operational procedures. Note 4: A field reference measurement should not be confused with a reference value during a calibration process.	
Reference network	A network of stations making reference-grade measurements	GSRN
Repeatability (of results of measurements)	Closeness of the agreement between the results of successive measurements of the same measurand carried out under the same conditions of measurement	VIM, definition 3.6]
Reproducibility (of results of measurements)	Closeness of the agreement between the results of successive measurements of the same measurand carried out under changed conditions of measurement A valid statement of reproducibility requires specification of the conditions changed. The changed conditions may include: — principle of measurement — method of measurement — observer — measuring instrument — reference standard — location — conditions of use — time. Note. When reproducibility is evaluated as difference among two calibrations repeated after a specified interval (such as one year) it can be used to evaluate instrumental drifts.	VIM, definition 3.7]
Resolution	This is resolution that should be available from the measurement systems data output. Smallest change in a quantity being measured that causes a perceptible change in the corresponding indication	WMO-No.8 & VIM 4.14

Sensitivity	Sensitivity of a measuring system: quotient of the change in an indication of a measuring system and the corresponding change in a value of a quantity being measured	VIM 4.12
Starting threshold	The smallest environmental stimulus required for a sensor to produce an output. Note 1.The discrimination threshold is largest change in a value of a quantity being measured that causes no detectable change in the corresponding indication	WMO-No.8
Station	A group of instruments (and equipment) involved in measurements at the same specific location. Additional qualification of 'station' is common in the climate context. Meteorological observing station: Place where meteorological observations are made with the approval of the WMO Member or Members concerned (WMO-No 182) Surface station: A surface location from which surface observations are made. (WMO-No 544)	International Meteorological Vocabulary; WMO-No 182 Manual on the Global Observing System; WMO-No 544
Target uncertainty	This is the target measurement system uncertainty for a surface observation and includes: shield/screen or other atmospheric coupling items; sensor calibration including its expected degradation over time; logger/weather station and interfaces including their expected degradation over time; algorithms; and message encoding (resolution and rounding). The Target Uncertainty does not, however, include contributions from site exposure as these are covered by the siting classification scheme.	WMO-No.8

Traceability (measurement traceability)	Property of a measurement result whereby the result is related to a reference through a documented unbroken chain of calibrations, and the measurement uncertainty is composed of each of the calibration uncertainties and contributions due to the measurement conditions Note 1: the VIM definition is: *property of a measurement result whereby the result can be related to a reference through a documented unbroken chain of calibrations, each contributing to the measurement uncertainty.* Note 2: it can be considered for inclusion the Instrument traceability: *property of an instrument to be related to a reference through a documented unbroken chain of calibrations, each contributing to the instrumental uncertainty.*	This is the new proposed definition, which differs from the VIM, but is much more adapted to GSRN uses.
Uncertainty	Parameter, associated with the result of a measurement, that characterizes the dispersion of the values that could reasonably be attributed to the measurand The uncertainty is evaluated by completing the uncertainty budget [Note 1: *In the climate/weather context, Uncertainty of the estimate of the range of values within which the true value of a variable lies. (Manual on the WMO Integrated Observing System; WMO-No. 1160*)] [Note 2: *the uncertainty is evaluated, not estimated*]	VIM, definition 3.9

Uncertainty budget	List of all the contributions to the total uncertainty, with associated values contributing to the total measurement uncertainty. Uncertainty of measurement comprises, in general, many components. Some of these components may be evaluated from the statistical distribution of the results of series of measurements and can be characterized by experimental standard deviations. The other components, which also can be characterized by standard deviations, are evaluated from assumed probability distributions based on experience or other information and include all the quantities contributing to the measurement result, such as all instrumental contributions (such as the resolution, the stability, the calibration uncertainty, the dynamics etc), the contribution due to the site characteristics and its influences (slopes, shadows, obstacles…) all the contributions (corrections and/or uncertainty) due to the other quantities influencing the measurand (i.e. rain, wind, humidity on air temperature measurement etc.).	
Uncertainty Example	This is included to demonstrate how the measurement system uncertainty is influenced by multiple sources of uncertainty as identified in the definition above. The measurement uncertainty is normally determined following ISO/IEC (2008) / JCGM (2008) taking into account all relevant sources of uncertainty and their characteristics.	WMO-No.8
Verification Regime	This is the recommended maximum interval between field verifications performed against traceable travelling references in suitable conditions. The first field verification should always be performed immediately when a sensor is first installed in the field.	WMO-No.8
Albedo (or just reflected radiation)	The fraction of solar radiation reflected by a surface or object, often expressed as a percentage. Snow-covered surfaces have a high albedo, the albedo of soils ranges from high to low, and vegetation-covered surfaces and oceans have a low albedo. The Earth's planetary albedo varies mainly through varying cloudiness, snow, ice, leaf area and cover changes.	METEOTERM (IPCC 5th Assessment Report, WG 1 Glossary)
Atmospheric pressure	Pressure (force per unit area) exerted by the atmosphere on any surface by virtue of its weight; it is equivalent to the weight of a vertical column of air extending above a surface of unit area to the outer limit of the atmosphere.	METEOTERM (International Meteorological Vocabulary, WMO - No. 182)

Precipitation	Hydrometeor consisting of a fall of an ensemble of particles. The forms of precipitation are: rain, drizzle, snow, snow grains, snow pellets, diamond dust, hail and ice pellets.	METEOTERM (International Meteorological Vocabulary, WMO - No. 182)
Relative humidity	The relative humidity specifies the ratio of actual water vapour pressure to that at saturation with respect to liquid water or ice at the same temperature.	METEOTERM (IPCC 5th Assessment Report, WG 1 Glossary)
Soil moisture	Water stored in the soil in liquid or frozen form.	METEOTERM (IPCC 5th Assessment Report, WG 1 Glossary)
Soil temperature	The temperature of the soil. This can be measured or modelled at multiple levels within the depth of the soil.	METEOTERM (IPCC 5th Assessment Report, WG 1 Glossary)
Solar radiation	Electromagnetic radiation emitted by the Sun with a spectrum close to the one of a black body with a temperature of 5770 K. The radiation peaks in visible wavelengths. When compared to the terrestrial radiation it is often referred to as shortwave radiation.	METEOTERM (IPCC 5th Assessment Report, WG 1 Glossary)
Surface air temperature (land)	The surface air temperature as measured in well ventilated screens over land at 1.5m above the ground.	METEOTERM (IPCC 5th Assessment Report, WG 1 Glossary)
Wind speed	Ratio of the distance covered by the air to the time taken to cover it. The "instantaneous speed" or, more briefly, the "speed", corresponds to the case of an infinitely small time interval. The "mean speed" corresponds to the case of a finite time interval.	METEOTERM (International Meteorological Vocabulary, WMO - No. 182)
Wind direction	Direction from which the wind blows.	METEOTERM (International Meteorological Vocabulary, WMO - No. 182)

[1] JCGM 200:2012, International vocabulary of metrology – Basic and general concepts and associated terms (VIM) 3rd edition 2008 version with minor corrections
International vocabulary of basic and general terms in metrology (abbreviated VIM) [1], published by the International Organization for Standardization (ISO), in the name of the seven organizations that supported its development and nominated the experts who prepared it: the Bureau International des Poids et Mesures (BIPM), the International Electrotechnical Commission (IEC), the International Federation of Clinical Chemistry (IFCC), ISO, the International Union of Pure and Applied Chemistry (IUPAC), the International Union of Pure and Applied Physics (IUPAP), and the International Organization of Legal

Metrology (OIML). The VIM should be the first source consulted for the definitions of terms not included either here or in the text.
[2]JCGM 100:2008 GUM 1995 with minor corrections Evaluation of measurement data — Guide to the expression of uncertainty in measurement.

Annex 3: Station instrumentation characteristics and prescriptions

GCOS Surface Reference Network

Station instrumentation characteristics and prescriptions

Overview

This annex to the GSRN outline document describes the characteristics, specifications and minimum requirements for the instruments in a GSRN station. The document partially aligns with the CIMO classifications class A category in the “Measurement quality classifications for surface observing stations on land”, with specific prescription to be adopted by the GSRN. This annex does not include the siting characteristics. This document intends to give a preliminary list of instrument features, for the GSRN stations to be adopted for the station certification process. Such features, including maintenance and calibration intervals, can already be fully or partially fulfilled by existing stations independently from the instruments used in different nations and specific climate environments. The listed performances are based on the technology advances at the time of its drafting and must be constantly revised to include evolving technologies, better instrumentation and improved calibration procedures. Appropriate management of instrument change is prescribed in the Outline document.

*The quality of meteorological measurements from a measurement system are determined by the instruments used, the system configuration and siting, and the definition and knowledge of the measurand. The quality of a measurement evolves with time due to internal and external factors affecting the measurement system. Therefore, once an instrument is selected and its performance characteristics are known, it is necessary to perform preventive maintenance, calibration and/or verification during operation. The information required to define an optimal maintenance, calibration and verification regime comes from laboratory and field tests, user experience, and manufacturer’s documentation.****[1]***

Measurement redundancy is suggested for some of the observed quantities but can be extended to other quantities. Redundancy represents one way to assess aspects of both traceability and comparability. By using multiple, co-located traceable instruments to measure the same parameter, the resultant data series can be compared. Disagreement between the data series can highlight measurement problems which would be undetectable with a single sensor. Agreement results in a lower statistical measurement uncertainty.

Regular calibration is another key aspect of the implementation of metrological best practice in a fiducial reference network. Documented, and in some cases dedicated, calibration procedures must be adopted by all network stations. Knowledge of the components of measurement uncertainty due to the site characteristics and the local quantities of influence also require dedicated research and field campaigns. Sensor drift can only be detected in terms of the repeatability of the calibration results. Recalibration periods are thus reported, based on present technology knowledge, to guarantee that the target uncertainty is met all along inter-periods between calibrations.

Components of uncertainty are here prescribed in terms of minimum requirements, to coherently achieve the target uncertainty.

Table 1: Instruments characteristics prescriptions for a GSRN station

Measurand	**Instruments specifications**	**Maximum allowed documented uncertainty contributions (K=1)**	**Notes**	**Required auxiliary measurements**
Air temperature	**Target Combined Expanded Uncertainty**	**0.2 °C**		
	Sensor: Platinum Resistance Thermometer (PRT) Type PT100 IEC-751, Class A Temperature coefficient (alpha): 0.00385 Measuring range: -40 °C + 50 °C (or lower limit for specific locations) Uncertainty: 0.05 °C over the whole range	Sensor: Max drift: 0.02 K/year Calibration: 0.02 K Sensitivity: 0.005 K Resolution: 0.005 K Logger: 0.05 K Solar Shield (incl ageing): 0.1 K	Note 1. Documented time constant of sensor and sensor + shield (in terms of response rate as a function of time with known temperature variation, for ISO 17741: time to reach 63% of a 10 °C sudden change). Laboratory calibration certificate according to ISO 17025 (full documented traceability to NMI primary standards). Note 2. Measurement redundancy, by installing three thermometers in as many solar screens, is highly recommended. Note 3. Protective shield (solar shield) preferred types according to environmental condition can	Relative humidity Solar radiation Wind speed at same height of thermometer Precipitation Soil temperature Snow presence - reflected radiation (mandatory in case of snow) Correction to be evaluated and applied for specific shield and sensor.
	Reading frequency	10 s		
	Averaging and recording time	1 minute		
	Calibration Regime	Yearly		
	Verification Regime	6-monthly		

	Maintenance Regime	Yearly	include: forced ventilation or helical or Stevensons screens	
Relative humidity	**Target Combined Expanded Uncertainty**	**3% RH (0% -90% RH) 6% RH (90% - 100% RH)**		
	Measurement range: 0 ... 100% RH Temperature range: -20 °C to 60 °C	Sensor Max drift: 0.5% RH/year Resolution: 0.1% RH Calibration: (see note) Logger: 0.2% RH Solar Shield 1% RH	Overall uncertainty (including non-linearity, hysteresis, repeatability): Range: 10 ° C to 30 ° C 0% - 90% RH: 1% RH 90% - 100% RH: 2% RH Range: -20 ° C to 60 ° C 0% - 90% RH: 3% RH 90% - 100% RH: 6% RH	Air temperature Solar radiation Wind speed at same height of thermometer Precipitation Soil moisture Correction to be evaluated and applied for specific shield and sensor.
	Reading frequency	10 s		
	Averaging and recording time	1 minute		
	Calibration Regime	Yearly		
	Verification Regime	6 monthly		
	Maintenance Regime	Yearly		

Atmospheric pressure	**Target Combined Expanded Uncertainty**	**15 Pa**		
	Measurement range: 50 kPa - 110 kPa Linearity over the entire range: <± 10 Pa Hysteresis: <± 5 Pa Repeatability: <± 5 Pa Uncertainty at 20 ° C: 10 Pa * Range of use: -40 ° C to +60 ° C	Sensor Resolution: 1 Pa Max drift: 2 Pa/year Vent: 5 Pa Calibration (at 20 °C): 5 Pa Logger: 1 Pa	Pressure/temperature correction curve must be evaluated with associated uncertainties according to temperature range of the site Sensor must be positioned in a containing box where wind flow is reduced at minimum	Air temperature Wind speed and direction
	Reading frequency	10 s		
	Averaging and recording time	1 minute		
	Calibration Regime	Yearly		
	Verification Regime	6 monthly		
	Maintenance Regime	Yearly		

Wind speed and direction	**Target Combined Expanded Uncertainty**	**Speed: 0.1 m/s** **Direction: 5 °**		
	Starting Threshold £ 0.01 m/s Range of use: -40 °C to +60 °C Positioned at 10 m from ground level	Speed Sensor: <1% Max Drift: 0.1˚/year Alignment: 3° (bias) Resolution: 0.01 m/s° Direction Sensor: 2° Max Drift: 0.1˚/year Alignment: 3° (bias) Resolution: 1°	Two anemometers are required to measure wind speed and direction: one at the same height as the air temperature shield and one at 10 m. The anemometer at ~2 m can be 3-cup or ultrasonic with uncertainty up to 5% and starting threshold <0.5 m/s The one at 10 m must be a top quality instrument with preference for three axis ultrasonic sensors equipped with heating system in case of exposure to icing, or 3-cup & wind vane for specific needs	· Air temperature · Precipitation
	Reading frequency	1 s		
	Averaging and recording time	1 minute (3 s for max gust)		
	Calibration Regime	Yearly		
	Verification Regime	Yearly		
	Maintenance Regime	Yearly		

Solid and Liquid precipitation	**Target Combined Expanded Uncertainty**	**2 % or 0.1 mm/hr**		
	Operating conditions: Humidity: 0 to 100 % Temperature: -40 °C to +60 °C Type of instruments: Solid and liquid: Weighing gauges Only liquid: Weighing or tipping bucket Starting threshold 0.1 mm/hr for liquid precipitation intensity only	Sensor Max drift: 1%/year Calibration: 1% or 0.1 mm/hr Max wind effect: 1% Sensitivity: Amount:: 0.1 mm for ≤ 5 mm 2 % for > 5 mm Intensity: 0.1mm/hr for 0-2 mm/hr 5% for > 2 mm/hr Resolution: 0.1 mm (amount) 0.1 mm/hr (intensity) Mid range uncertainty: 3% Lower range required: 0 mm Upper range (Max intensity): 500 required value Lower range required uncertainty: 10% Upper range required uncertainty 3% Sub ranges required uncertainties: ± 5% 6 - 20 mm/hr ± 3% 20 – 500 mm/hr	Bias correction in the data-logger based on dynamic calibration results For catching type gauges, calibration according to WMO recommendation for precipitation gauges (WMO CIMO guide 8 – Annex 6-D) and CEN/TR 16469:2013 Output information: time of tipping Capacity “bucket”: 0.1 mm (àmin intensity = 6 mm/h) Bias correction in the data-logger based on dynamic calibration results Datalogger: minimum allowed frequency of the time of tipping 1 s	· Air temperature · Wind speed and direction
	Reading frequency	1 s		
	Averaging and recording time	1 s at event start Integrating data at 1 minute Total day precipitation recorded		
	Calibration Regime	Yearly		

	Verification Regime	Yearly		
	Maintenance Regime	Monthly		
Global downward solar radiant exposure (daily)	**Target Combined Expanded Uncertainty**	**Hourly totals: 3 %** **Daily totals: 2%**		
	Spectral range: 400 nm to 1100 nm Zero off-set response: * Response time (to reach 95 % of the final value) <500 ns * Response to 200 Wm^{-}2 net radiation 7 Wm^{-2} Response to 5 °C/h change in ambient temperature ±2 Wm^{-2} Directional response for beam radiation (error due when assuming that the normal incidence response at 1000 Wm^{-2} is valid for all directions): ±10 Wm^{-2} Spectral selectivity (deviation of the product of spectral absorptance and transmittance, respectively, from the mean) WMO (0.3–3 mm) ±2 % Temperature range of use: -40 °C to 60 °C Sensitivity: 600 to 100 mV/Wm^{-2}	Calibration: 1.5 % Drift (change in sensitivity per year): ±0.8 % Resolution: ±1 Wm^{-2} (1 kJ/m^2) Linearity (deviation from sensitivity at 500 Wm^{-2} over 100–1000 Wm^{-2} irradiance range): ±0.5 % Tilt response (percentage max deviation from horizontal response when the tilt is changed from horizontal to vertical at 1,000 Wm^{-2}) ±0.5 % Maximum temperature influence over the whole operating temperature range: 2 %		Air temperature Relative humidity Precipitation

	Reading frequency and recording	10 s		
	Averaging	1 hour total, 1 day total		
	Calibration Regime	Yearly		
	Verification Regime	Yearly		
	Maintenance Regime (cleaning)	Weekly		
Sunshine duration (daily)	**Target Uncertainty**	**2 % or 0.1 h**		
	Threshold Target Uncertainty (direct solar irradiance)	**120 Wm^{-2} ± 20 %**		
		Sensor: 1.5 % Drift: 0.5 %		
	Reading frequency and recording	1 s		
	Calibration Regime	Yearly		
	Verification Regime	Yearly		
	Maintenance Regime	Monthly		
Visibility (MOR) (1 and 10 minute average)	**Target Uncertainty**	**Greater of 10 % or 20 m**		
	Uncertainty Example for smart instrument	Sensor: 7 % or 20 m Drift: 3 % Logger: n/a Total: 10 % or 20 m		

	Resolution	1 m		
	Calibration Regime	Yearly		
	Verification Regime	Yearly		
	Maintenance Regime	Monthly or on alert or error		
Soil moisture	**Target Combined Expanded Uncertainty**	**3% (10% -90%) 6% (0% - 10% / 90% - 100%)**		
	VWC (Volumetric Water Content - θ) Measurement range: 0 ... 100% Dielectric permittivity (e): 1 -80 Range: 0.05 – 0.65 m^3/m^3 (for fine sandy loam to clay soil). Depth: 10 cm - 20 cm - 50 cm - 1 m Temperature range: -5 °C to 50 °C	Sensor Max drift: 0.5% year Resolution: 0.1% Calibration: (see note)	Calibration: gravimetric method in laboratory in accordance with ISO 11465. Correction to be evaluated and applied for specific sensor and soil type and composition.	Air temperature Relative humidity Precipitation
	Reading frequency	10 s		
	Averaging and recording time	1 minute		
	Calibration Regime	Yearly		

	Verification Regime	6 monthly		
	Maintenance Regime	Yearly		
Soil temperature	**Target Combined Expanded Uncertainty**	**0.05 °C**		
	Sensor: Platinum Resistance Thermometer (PRT) Type PT100 IEC-751, Class A Measuring range: -10 °C + 50 °C Depth: 2 cm, 5 to 10 cm, 10 to 20 cm, 50 cm, 1 m	Sensor: Max drift: 0.02 K/year Calibration: 0.02 K Sensitivity: 0.01 K Resolution: 0.01 K		Precipitation Soil moisture
	Reading frequency	10 s		
	Averaging and recording time	1 minute		
	Calibration Regime	Yearly		
	Verification Regime	6 monthly		
	Maintenance Regime	Yearly		

Possible additional measurements:

Surface temperature: Infrared sensor pointing from 2 m to ground.
Prescription. No specifications, as long as documented technology
Soil temperature and moisture at 10 cm - 20 cm - 50 cm - 1 m
Prescription: use of PRT 100 W and top quality soil moisture probes.
Net radiation: the surface radiation budget on the site. Prescription: use of the four-component net radiation sensor.

Schematic table for measured parameters and associated quantities of influence

(Primary measurements (first column) requiring other measurements to detect the respective influencing factor).

	Air Temp	Relative Humidity	Solar radiation	Wind speed & direction	Pressure	Precipitation	Soil temperature	Soil moisture
Air Temperature		X	X	X		X	X	
Relative Humidity	X		X		X	X		X
Solar radiation	X	X				X		
Wind speed & direction	X					X		
Pressure	X			X				
Precipitation				X				
Soil temperature	X	X				X		
Soil moisture	X	X				X		

Table definitions:

Target Uncertainty: This is the target measurement system uncertainty for a surface observation and includes: shield/screen or other atmospheric coupling items; sensor calibration including its expected degradation over time; logger/weather station and interfaces including their expected degradation over time; algorithms; and message encoding (resolution and rounding).

Uncertainty Example: This is included to demonstrate how the measurement system uncertainty is influenced by multiple sources of uncertainty as identified in the definition above. The measurement uncertainty is normally determined following ISO/IEC (2008) / JCGM (2008) taking into account all relevant sources of uncertainty and their characteristics.

Starting Threshold: The smallest environmental stimulus required for a sensor to produce an output.

Resolution: This is resolution that should be available from the measurement systems data output.

Calibration Regime: This is the recommended maximum interval between a full multi-point calibration performed against internationally traceable references in an accredited laboratory.

Verification Regime: This is the recommended maximum interval between field verifications performed against traceable travelling references in suitable conditions. The first field verification should always be performed immediately when a sensor is first installed in the field.

Maintenance Regime: This is the recommended maximum interval between inspections of the entire measurement system to confirm correct: site exposure; shield/screen and other mechanical mounting fixtures are clean and serviceable; instrument is clean and serviceable; and the logger/weather station is clean and serviceable.

(Instrument) Drift: This is the continuous or incremental change over time between calibrations, due to changes in metrological properties of the measuring instrument. Noting that annual change in the calibration is normally quoted in specification sheets.

The maintenance, calibration and/or verification regimes are recommendations to achieve the target uncertainties in the table. Operators of networks should monitor performance and adjust the regimes to accommodate their different operational environments.

Notes:

1) A classification for solid precipitation and snow depth is not yet defined, due to the lack of shared knowledge on the subject.

2) A classification for present weather is not defined as there is no reference (apart from human observer).

3) A classification for soil temperature is not defined because any physical movement of the probe generates large errors.

Annex 4: GCOS AOPC Task Team on the instigation of a GCOS Surface Reference Network

Background

AOPC-22 (Exeter, UK, March 2017) agreed on the creation of a dedicated task-team to scope a potential GCOS global surface reference network. The potential for such a network has been proposed by GCOS AOPC and by the Commission for Climatology. A white paper has been developed by members of the community at the request of these parties, and is to be submitted for publication. This Task Team is charged with taking this forwards towards practical implementation providing a concrete roadmap as to what would be required and to canvas stakeholders. Working models on which to base deliberations include the GCOS Reference Upper Air Network, US Climate Reference Network, and Global Cryospheric Watch.

Membership

Chair - Howard Diamond – National oceanic and Atmospheric Administration - USA
AOPC Representative – Phil Jones – University of East Anglia - UK
GRUAN Representative – Peter Thorne – University of Maynooth - Ireland
GSN Representative – Tim Oakley - UK
CBS/WIGOS/CIMO Representative – Andrew Harper – National Institute of Water and Atmospheric Research (NIWA) - New Zealand
NWP Representative - Jiankai WANG – Chines Meteorological Admisnitration (CMA)- China
BIPM representatives –Andrea Merlone - Istituto Nazionale di Ricerca Metrologica-Italy
Climate scientist representatives – Victor Venema - Meteorological Institute-University of Bonn - Germany
TOPC : Nigel Tapper - Monash University - Australia
Satellite : (Bojan Bojkov – EUMETSAT -Germany)
Region I representative: Rachid Sebbari - Directorate of National Meteorology (DMN) - Morrocco

GCOS Secretariat: Caterina Tassone
CCl Secretariat: Peer Hechler

Proposed Terms of Reference Scientific charge:

1. Create a scientifically robust basis for a proposed network spatial composition, taking into account fairness in national contributions and the need for globally representative measurements.
2. Accounting for stakeholder needs including inter-alia climate monitoring, process understanding and understanding remaining measurements (including space-borne measurement systems), define a robust siting rationale.
3. Propose a phased implementation that ‘starts small, but starts’ and builds over time to a holistic set of measurements of all relevant ECVs at each site to the extent practicable.
4. Alight on a potential governance structure in collaboration with key stakeholders.
5. Propose one or more management options that undertake day-to-day operational oversight and ensures a globally traceable, comparable network of measurements, recruiting possible host institutions.
6. Provide indicative costings on the proposed solutions sufficient to inform a decision as to whether to move forwards
7. Address additional needs identified by the group and agreed with AOPC as they arise.

Modus operandi

1. The task team shall exist for an initial period of two years.
2. The task team shall work primarily remotely, facilitated by GCOS secretariat. It is expected that an initial ‘in person’ meeting will be organized to discuss and agree the work-plan and deliverables, further meetings will be decided as required.
3. Within 3 months of the initiation of the task-team a detailed work plan and deliverable will be agreed.

4. The task team shall work in conjunction with relevant groups within WMO to ensure broad buy-in including CCl, WIGOS and CBS.

5. The task team chair shall be expected to report annually on progress to AOPC by means of a brief written report and, if support available, verbal reporting in person.

6. The task team shall be expected to lead the production of a final report (implementation plan) which may form the basis for a decision as to whether, and if so how, to proceed with a GCOS Surface Reference Network.

Background documents

White paper
http://ane4bf-datap1.s3-eu-west-1.amazonaws.com/wmocms/s3fs-public/ckeditor/files/12_reference_networks_white_paper.pdf?X5m5GtgVl1hoc0qAYiJ3mZEK8K_22O5R

GRUAN documentation
The GCOS Reference Upper-Air Network (GRUAN) GUIDE,
https://library.wmo.int/opac/index.php?lvl=notice_display&id=15182

The GCOS Reference Upper-Air Network (GRUAN) MANUAL
https://library.wmo.int/opac/index.php?lvl=notice_display&id=15181

GCOS Reference Upper-Air Network (GRUAN): Justification, requirements, siting and instrumentation options - April 2007
https://library.wmo.int/opac/index.php?lvl=notice_display&id=12841

Bodeker, G.E., S. Bojinski, D. Cimini, R.J. Dirksen, M. Haeffelin, J.W. Hannigan, D.F. Hurst, T. Leblanc, F. Madonna, M. Maturilli, A.C. Mikalsen, R. Philipona, T. Reale, D.J. Seidel, D.G. Tan, P.W. Thorne, H. Vömel, and J. Wang, 2016: Reference Upper-Air Observations for Climate: From Concept to Reality. Bull. Amer. Meteor. Soc., 97, 123–135, doi: 10.1175/BAMS-D-14-00072.1

USCRN
Diamond, H.J., T.R. Karl, M.A. Palecki, C.B. Baker, J.E. Bell, R.D. Leeper, D.R. Easterling, J.H. Lawrimore, T.P. Meyers, M.R. Helfert, G. Goodge, and P.W. Thorne, 2013:U.S. Climate Reference Network after One Decade of Operations: Status and Assessment. Bull. Amer. Meteor. Soc., 94, 485–498, doi: 10.1175/BAMS-D-12-00170.1.

https://www.ncdc.noaa.gov/crn/documentation.html - USCRN documentation

Global Cryosphere Watch

http://globalcryospherewatch.org/cryonet/site_types.html

GCOS Secretariat
Global Climate Observing System
c/o World Meteorological Organization
7 *bis,* Avenue de la Paix
P.O. Box No. 2300
CH-1211 Geneva 2, Switzerland
Tel: +41 22 730 8275/8067
Fax: +41 22 730 8181
Email: gcos@wmo.int