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GCOS Reference Upper Air Network (GRUAN): Steps Towards Assuring Future Climate Records

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Abstract. The observational climate record is a cornerstone of our scientific understanding of climate changes and their potential causes. Existing observing networks have been designed largely in support of operational weather forecasting and continue to be run in this mode. Coverage and timeliness are often higher priorities than absolute traceability and accuracy. Changes in instrumentation used in the observing system, as well as in operating procedures, are frequent, rarely adequately documented and their impacts poorly quantified. For monitoring changes in upper-air climate, which is achieved through in-situ soundings and more recently satellites and ground-based remote sensing, the net result has been trend uncertainties as large as, or larger than, the expected emergent signals of climate change. This is more than simply academic with the tropospheric temperature trends issue having been the subject of intense debate, two international assessment reports and several US congressional hearings. For more than a decade the international climate science community has been calling for the instigation of a network of reference quality measurements to reduce uncertainty in our climate monitoring capabilities. This paper provides a brief history of GRUAN developments to date and outlines future plans. Such reference networks can only be achieved and maintained with strong continuing input from the global metrological community.

Keywords: Climate change, atmospheric parameters measurements, GRUAN, Meteorological observations, Metrology for Meteorology, Temperature historical data series, Traceability.

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INTRODUCTION

The Intergovernmental Panel on Climate Change, in its most recent 4th assessment report on the physical science basis of climate change, concluded that "*warming of the climate system is unequivocal*" (1). This finding was based on multiple strands of observational evidence including physical and instrumental indicators of the changing climate documented in numerous peer-reviewed publications. However, while there is wide scientific consensus about the direction of climate change, there exists significant uncertainty in the rate and geographic details of changes in many components of the climate system. In large part this is due to substantial ambiguities inherent in historical physical meteorological state measurements. The short-term requirements of weather forecasting and rapid dispersion of weather data to critical decision makers have typically superseded the need to maintain and curate long-term records to detect climate signals that are often much smaller than day-to-day and seasonal changes. The emphasis has often been on geographic coverage and reporting timeliness, in general at the expense of long-term stability, absolute accuracy and traceability. Further, changes have been ubiquitous, poorly documented and poorly quantified.

Recognizing that it is impractical, as well as economically prohibitive, to ensure that the entire global observing system makes measurements suitable for quantifying climate changes, many in the climate science community have, for nearly two decades, been calling for the establishment of reference networks (2, and references therein). Such reference sites would be operated with a focus on minimizing and robustly quantifying measurement uncertainties through time.

This paper outlines progress to date with the establishment of the Global Climate Observing System (GCOS) Reference Upper Air Network (GRUAN) under the joint auspices of GCOS and relevant commissions of the World Meteorological Organization (WMO). First, the example of tropospheric temperature trend uncertainties and their implications are given as motivation. Then a brief outline of progress to date is presented before outlining expected future developments. Finally, the importance of strong metrological community involvement is stressed in the concluding remarks.

TROPOSPHERIC TEMPERATURE CHANGES

A 1990 paper in *Science* (3) documented that there had apparently been no warming evident in the first decade of Microwave Sounding Unit satellite measurements. It was also stated that *'accurate long-term global temperature measurements can be obtained by satellites'*. This statement initiated a controversy that placed the physical understanding of satellite calibration at odds with the physical understanding of the atmosphere. Our theoretical understanding is that if the surface is warming (as has been reported by three independently produced estimates) then the troposphere should also be warming. There ensued over the following twenty plus years, and continuing to this day, a substantial and ongoing controversy (4), with the issue being the sole topic of two international assessment reports (5,6) and discussed in each of the IPCC (Intergovernmental Panel on Climate Change) assessment reports. There were also several United States Congressional hearings on the matter (4). Over this period more than 200 scientific peer reviewed journal articles were published on the issue ranging from data analysis innovations, new data products and data meta-analyses through to comparisons against climate model expectations. Commensurate with that has been a growing realization of how uncertain the available measurements from satellites and weather balloons really are (Figure 1). Perhaps an earlier understanding of the fundamental issues underlying these measurement uncertainties could have helped clarify the debate and led to more rapid improvements in the observing network. These events provide a major incentive to ensure that improvements to the existing network and new additions have a sound basis in measurement science.

Although there is broad scientific consensus about the sign (positive) of the global multi-decadal trend, there is substantial ambiguity in the rate of warming. Different, seemingly acceptable (by the necessary but not necessarily adequate metric of publication in the peer reviewed literature) choices as to how to analyze the raw data yield different estimates of the long-term change. The spread is as large as the expected emergent climate change signal.

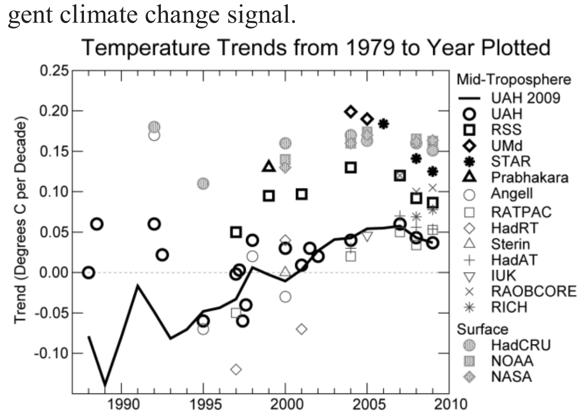

FIGURE 1. Global mean temperature trends from 1979 to the plotted year for surface measurements (filled symbols),

Microwave Sounding Unit satellite estimates (black) and radiosondes (weather balloons) (grey) – both of the latter for a 'Mid-Tropospheric' estimate. Different symbols denote different datasets produced by different groups. Also shown are trend values for the UAH (Univ. of Alabama in Huntsville) product under its newest version to show how changing dataset versions have impacted apparent trends in this product. Uncertainties are of the same magnitude as the emerging signal. Modified from (4)

Such uncertainties in the historical record confound our ability to detect changes in upper-air climate and to attribute those changes to relevant physical mechanisms. Given that temperature is arguably easier to measure than other physical parameters of the climate system, such as water vapor, winds or cloud bulk and microphysical properties, it is clear that continuing with the historical business as usual global observation system will not improve our ability to adequately observe and understand the Earth climate system. New space-borne or remote- sensing capabilities alone cannot adequately resolve this issue, as in the end they all depend on ground-truthing.

PROGRESS TO DATE IN THE ESTABLISHMENT OF THE GCOS REFERENCE UPPER-AIR NETWORK

Building on several earlier position papers (see references in (2)), in 2004 the GCOS Implementation Plan (7) called for the establishment of a network of sites making reference radiosonde measurements. In parallel, the US National Oceanic and Atmospheric Administration were pursuing such a reference network. These activities were combined in a workshop held in Boulder, Colorado in 2005. This meeting served to start us on the path and was followed by a meeting in Seattle in 2006 which resulted in a GCOS report which for the first time clearly articulated a community vision for the network (8), the central tenets of which remain valid today. Viz:

- Redundant measurements of GCOS-designated Essential Climate Variables[1] (ECVs).
- Quantified and traceable uncertainty estimates for each measurement.
- Consistency across the network allowing direct intercomparisons of 'equivalent' measures.
- Observations made for climate rather than primarily weather forecasting purposes.

The most important applications of these data in support of climate science are:

1. Characterizing long-term trends and variability in the ECVs at each site
2. Calibration and validation of more globally complete observations (in-situ and satellite-based measurements)
3. Physical process and micro-process understanding in support of climate model development
4. Ensure that any interruptions in satellite-based measurement programmes do not invalidate the long-term climate data record

It was recognized that it would be impractical to establish a completely new network that immediately measured all identified necessary parameters and so an initial focus on pressure, temperature and water vapor measurements was pursued. This also suggested an initial minimum set of instrumentation that would be necessary for initial candidate sites to join the network (Figure 2).

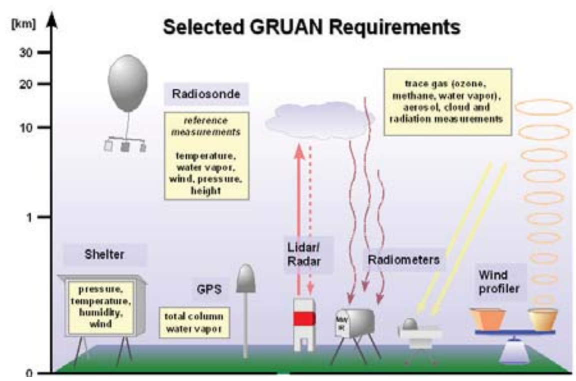

FIGURE 2. Schematic depiction of what a GRUAN site may look like to be able to meet the stated requirements in terms of mix of instrumentation.

At this time an international scientific Working Group on Atmospheric Reference Observations (WG-ARO[2]), operating under the auspices of the GCOS Atmospheric Observation Panel for Climate (AOPC) was established to oversee implementation of such a network. Following this meeting, and at the request of the WG-ARO, GCOS solicited expressions of interest for a dedicated Lead Centre to oversee day-to-day operations of the network. The German weather service, Deutscher Wetterdienst, through their Lindenberg Meteorological Observatory – a facility with over a centu-

[1] GCOS Essential Climate Variables of relevance to GRUAN documented in (8) are: air temperature, water vapor, pressure, wind speed and direction, ozone and aerosol (and their precursors), carbon dioxide, methane, and other long-lived greenhouse gases, Earth radiation budget, and cloud properties.

[2] Subsequent to ITS9 the name of the group was changed to WG-GRUAN, for continuity we retain the original here.

ry of atmospheric state measurement heritage - was selected.

The first implementation meeting was held at the Lead Centre in 2008 and an initial set of 15 sites that met the set of requirements was designated as the initial set of GRUAN sites (Figure 3). These sites had very diverse funding streams and priorities, but all met the minimum criteria. A set of minimum requirements in terms of measurement types and frequencies for the sites to meet was also decided upon.

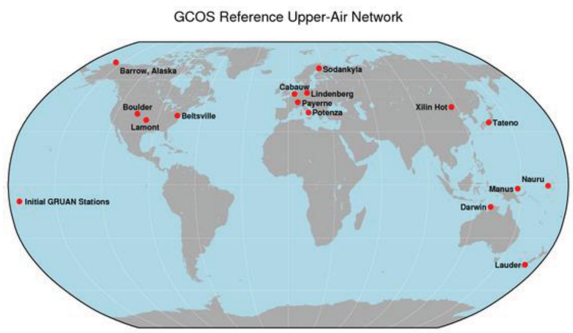

FIGURE 3. Locations of initial GRUAN stations as designated at the first implementation meeting in Lindenberg. Tateno (Japan) was added subsequently following an offer for consideration by the Japanese Meteorological Agency.

Subsequent to this meeting there have been a series of implementation and coordination meetings, each held at or near one of the initial sites (Norman, OK, USA; Payerne, Switzerland; Lauder, New Zealand; Tokyo, Japan) and including a site visit and inspection. The first meeting led to the production of an implementation plan (9) setting out the pathway to network maturity envisaged for 2014. The second meeting led to the instigation of a number of Task Teams charged with addressing key science questions and garnering input from a greater set of experts than the Working Group. In the first instance these task teams are considering radiosondes, GNSS (global navigation satellite system) precipitable water, scheduling issues, ancillary measurements (lidar, microwave, FTIR and satellites) and site specific issues. The meeting also formalized a more targeted science group, termed GATNDOR (GRUAN Analsyis Team for Network Design and Operations Research), tasked with addressing network specific science questions

The guiding principles underlying GRUAN measurements have been articulated in a peer-reviewed publication (10). These principles are largely based on the Guide to Uncertainty in Measurements (11) and emphasize traceability, understanding, and quantification of uncertainty sources (Figure 4). These measurement principles have, to date, been applied solely to in-situ balloon soundings made at a subset of sites. As of mid-2011 these data have been processed and made available through a data portal at NOAA's National Climatic Data Center and www.gruan.org.

PATHWAY TO FULL NETWORK IMPLEMENTATION

Full network implementation is planned for 2014, at which point additional sites and instruments will have been added to the existing suite. There are numerous tasks that remain to be addressed before then, the most significant of which are outlined here. A full listing can be found in the GRUAN Implementation Plan (9).

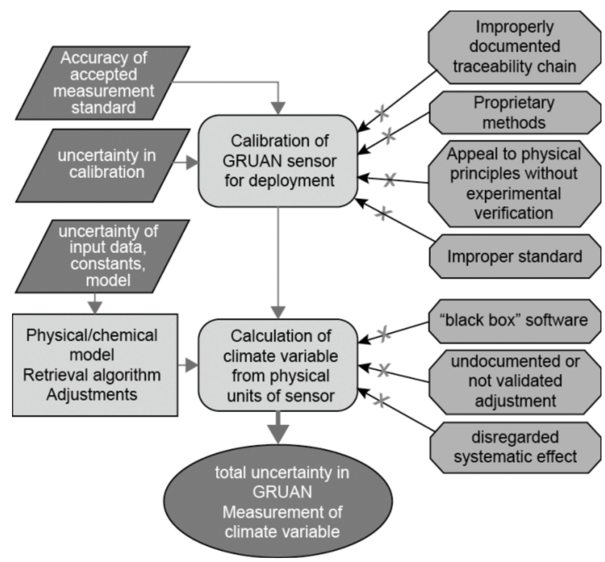

FIGURE 4. Schematic diagram illustrating the fundamental measurement characteristics of a GRUAN measurement. Items in the rightmost portion (red boxes) indicate measurement aspects that are unacceptable for a GRUAN measurement.

Assessing Measurement Scheduling Protocols

The GRUAN network (as detailed previously) is expected to answer to multiple 'customers' who have different requirements for data sampling. For instruments in continuous operation this is not an issue, but for others such as lidars, many of which require certain operating conditions or in-situ balloon sounders with high unit costs and low recovery/reuse rates, scheduling requirements need to be ascertained. There is an inevitable trade-off between the different key requirements. Trend characterization requires sampling at consistent points in the (in many cases very substantial) diurnal and seasonal cycles. Satellite calibration / validation requires measurements that are as close as possible in both space and time to the satellite overpass. Process understanding requires very frequent observations when key meteorological events are occurring. Resolving this issue to alight on a set of easily understandable, quantified and scientifically credible guidelines is key and requires substantial additional scientific assessment.

Creating GRUAN Measurements For All Instrument Types

Additional instruments beyond the in-situ sounders currently being used need to be processed to GRUAN standards (Figure 4). This requires the instigation of calibration and operating procedures for each instrument type and the development of a standard processing suite. Achieving reference quality measurement results for this diverse range of instruments will require careful adherence to best calibration practices and attention to relevant developments in technology and measurement standards. It is envisaged that each data type will be processed centrally by a nominated facility, which need not be the Lead Centre, and distributed through a centralized data portal. There are several task teams dedicated to either individual high priority instruments or consideration more generically of a full suite of candidate measurement techniques. GRUAN will look to cooperate with existing networks and infrastructures to take advantage of expertise and quality assurance programs already developed where appropriate.

Identifying Suitable Sites and Priorities for Network Expansion

It is recognized that current sites (Figure 3) are sites of opportunity – containing the instruments and expertise necessary to develop the GRUAN concept. They do not, however, sample all climatically important regions / climate regimes, or surface types etc. which will be of importance for certain needs, such as assessment of regional changes. A workshop is planned for June 2012 (www.gruan.org) to bring together stakeholders and identify stakeholder priorities for expansion. Subsequently, it will be necessary to recruit additional sites and assist them in meeting GRUAN standards. To this end a site assessment and certification protocol has been developed. This protocol, rather than prescribing the instrumentation to be used and the specific measurements to be made, emphasizes the principles and operating protocol under which GRUAN sites must operate. This recognizes that no site is likely to answer solely to GRUAN needs and that GRUAN cannot be a set of identical sites when the sites themselves depend on distinct funding sources and serve different stakeholders. Indeed, GRUAN will grow as a hybrid set of more research-type facilities and Meteorological service facilities (as has been the case to date). Such diversity is a strength in terms of developing and propagating practices and lessons learned. By adhering to GRUAN protocols it is hoped that measurements from a diverse set of sites can be rigorously intercompared. Therefore, at the heart of this is traceability and redundancy of observations, allowing the necessary quantification of uncertainty in a rigorous manner.

Developing And Propagating Regulatory Materials

Key to a successful network is also clear and transparent process documentation. An overall manual providing guidelines for the operation of the network is in the advanced stages of production. Relevant aspects of this manual will be incorporated into more general World Meteorological Organization regulatory materials by a dedicated Expert Team. In addition a GRUAN Technical Document series is being used to document necessary GRUAN procedures for aspects such as operating procedures for specific instrument types, data dissemination and retention protocols, and protocols for processing metadata. These technical documents are required for user transparency and to allow subsequent reprocessing of the data when, almost inevitably, new insights require it.

HOW CAN THE METROLOGICAL COMMUNITY CONTRIBUTE?

The early and continuing promoters of GRUAN are largely atmospheric scientists, including climate scientists and instrument specialists, with limited participation from the metrology community. Over time, we have become increasingly attuned to the need for ongoing metrological input if the network is to prove successful in the long-term. To that end the recent signing of a letter of intent between GRUAN and the Meteomet[3] project is a welcome example. The metrological community can contribute in multiple ways including but not limited to:

1. Helping develop sensors that are capable of measuring the atmospheric characteristics of interest in a manner consistent with GRUAN principles and that are economically viable.
2. Analyzing the GRUAN data and providing critical evaluations.

[3] http://www.meteomet.org/

3. Contributing to the operations of the working group and relevant task teams.
4. Proposing and discussing dedicated calibration procedures and devices.

If you are interested in contributing please do get in contact. Contact details can be found at www.gruan.org or you can contact chairs@gruan.org.

CONCLUDING REMARKS

The GCOS Reference Upper Air Network (GRUAN) is a natural intersection between metrology and climate. Historically, meteorological measurements have clearly not been made to the necessary accuracy and traceability required to unambiguously detect and quantify emerging climate change signals. This hinders our ability to use those data to make robust scientific findings and therefore provide advice to climate science stakeholders. The problem is particularly acute for measurements of the atmospheric column characteristics, which have been made primarily either with single-use in-situ balloon-borne sounders or from space by geostationary or polar orbiter satellite platforms. For over two decades the climate community has been arguing in various forums for the need for reference quality measurements. Over the past 7 years, significant accomplishments have advanced a global network of reference quality sites. But much remains to be done. It is essential that the metrological community plays an active role if GRUAN is to successfully reduce the otherwise potentially large uncertainties that would accrue from a continuation of a "business as usual" approach to the meteorological observations of the atmosphere.

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REFERENCES

1. IPCC, 2007: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor and H. L. Miller (eds)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 996 pp.
2. Seidel, D. J. et al.,. *Bull. Amer. Met Soc*, **90**, 361-369 (2009)
3. Spencer, R. W., and J. R. Christy. *Science*, **247**, 1558–1562 (1990).
4. Thorne, P. W. et al., *WIRES: Climate Change,* **2**, 66-88 (2011)
5. National Research Council. Reconciling Observations of Global Temperature Change. Washington, DC: National Academy Press; 2000, pp.85.
6. Karl TR, Hassol SJ, Miller CD, Murray WL, eds. Temperature Trends in the Lower Atmosphere: Steps for Understanding and Reconciling Differences. Washington, DC: U.S. Climate Change Science Program and Subcommittee on Global Change Research; 2006, http://www.climatescience.gov/Library/sap/sap1-1/finalreport/default.htm.
7. Global Climate Observing System, Implementation Plan for the Global Observing System for Climate in support of the UNFCCC; 2004: WMO/TD No. 1219, GCOS-92, 153pp. http://www.wmo.int/pages/prog/gcos/Publications/gcos-92_GIP.pdf
8. Global Climate Observing System, GCOS Reference Upper Air Network (GRUAN): Justification, requirements, siting and instrumentation options; 2007: WMO/TD No. 1379, GCOS-112, 42pp. http://www.wmo.int/pages/prog/gcos/Publications/gcos-112.pdf
9. Global Climate Observing System, GRUAN Implementation Plan 2009-2013; 2009: WMO/TD No. 1506, GCOS-134, 60pp. http://www.wmo.int/pages/prog/gcos/Publications/gcos-134.pdf
10. Immler, F. J. et al., *Atmos. Meas. Tech*. **3**, 1217-1231 (2010)
11. JCGM/WG 1: Evaluation of measurement data Guide to the expression of uncertainty in measurement, InternationalBureau of Weights and Measures/Bureau International des Poids et Mesures, www.bipm.org/utils/common/documents/jcgm/JCGM 100 2008 E.pdf, Working Group 1 of the Joint Committee for Guides in Metrology, 2008.