Sampling and measurement issues in establishing a climate reference upper air network

T. Gardiner, F. Madonna, J. Wang, D. N. Whiteman, J. Dykema, A. Fassò, P. W. Thorne, and G. Bodeker

Citation: AIP Conference Proceedings **1552**, 1066 (2013); doi: 10.1063/1.4821422
View online: http://dx.doi.org/10.1063/1.4821422
View Table of Contents: http://scitation.aip.org/content/aip/proceeding/aipcp/1552?ver=pdfcov
Published by the AIP Publishing

Sampling and Measurement Issues in Establishing a Climate Reference Upper Air Network

T. Gardiner[1], F. Madonna [2], J. Wang[3], D. N. Whiteman[4],
J. Dykema[5], A. Fassò[6], P. W. Thorne[7], and G. Bodeker[8]

[1] *National Physical Laboratory, Teddington, UK*
[2] *Istituto di Metodologie per l'Analisi Ambientale, Potenza, Italy*
[3] *NCAR Earth Observing Laboratory, Boulder, USA*
[4] *NASA/GSFC Mesoscale Atmospheric Processes Branch, Greenbelt, USA*
[5] *Harvard University, School of Engineering and Applied Sciences, Cambridge, USA*
[6] *University of Bergamo, Italy*
[7] *Nansen Environmental and Remote Sensing Center, Bergen, Norway*
[8] *Bodeker Scientific, Alexandra, Central Otago, New Zealand*

Abstract. The GCOS Reference Upper Air Network (GRUAN) is an international reference observing network, designed to meet climate requirements and to fill a major void in the current global observing system. Upper air observations within the GRUAN network will provide long-term high-quality climate records, will be used to constrain and validate data from space based remote sensors, and will provide accurate data for the study of atmospheric processes. The network covers measurements of a range of key climate variables including temperature. Implementation of the network has started, and as part of this process a number of scientific questions need to be addressed in order to establish a viable climate reference upper air network, in addition to meeting the other objectives for the network measurements. These include quantifying collocation issues for different measurement techniques including the impact on the overall uncertainty of combined measurements; change management requirements when switching between sensors; assessing the benefit of complementary measurements of the same variable using different measurement techniques; and establishing the appropriate sampling strategy to determine long-term trends. This paper reviews the work that is currently underway to address these issues.

Keywords: Climate change, trend detection, atmospheric parameter measurements, GRUAN.

INTRODUCTION

The Global Climate Observing System (GCOS) Reference Upper Air Network (GRUAN) is an international reference observing network, designed to meet climate requirements and to fill a major void in the current global observing system (1). GCOS is “a joint undertaking of the World Meteorological Organization (WMO), the Intergovernmental Oceanographic Commission (IOC) of the United Nations Educational Scientific and Cultural Organization (UNESCO), the United Nations Environment Programme (UNEP) and the International Council for Science (ICSU). Its goal is to provide comprehensive information on the total climate system, involving a multidisciplinary range of physical, chemical and biological properties, and atmospheric, oceanic, hydrological, cryospheric and terrestrial processes” (2). Upper air observations within the GRUAN network will provide long-term high-quality climate records, will be used to constrain and validate data from space based remote sensors, and will provide accurate data for the study of atmospheric processes. The network covers measurements of a range of key climate variables including temperature, with profiles measured from the surface to the lower stratosphere. A description of the current status of the network and the plans for its further development are given in another International Temperature Symposium conference paper (3). As discussed there, the implementation of the network has started and guidelines have been established to produce reference quality atmospheric measurements with defined uncertainties and traceability, achieved through appropriate calibration and intercomparison procedures and assessment of instrumental performance including reproducibility and resolution (4). However, a number of further scientific questions need to be addressed in order to establish a viable climate reference upper air network, in addition to meeting the other objectives for the network.

The particular areas of interest include collocation issues for different measurement techniques including the impact on the overall uncertainty of combined measurements; change management requirements when switching between sensors; assessing the benefit of complementary measurements of the same variable using different measurement techniques; and

Temperature: Its Measurement and Control in Science and Industry, Volume 8
AIP Conf. Proc. 1552, 1066-1071 (2013); doi: 10.1063/1.4821422
2013 AIP Publishing LLC 978-0-7354-1178-4/$30.00

establishing the appropriate sampling strategy to determine long-term trends without compromising the capability for satellite validation and atmospheric process measurement. An ad-hoc group of researchers – the GRUAN Analysis Team for Network Design and Operations Research (GATNDOR) – has been established to assess the current state of the art within an area, and to carry out focused investigations into some of the gaps in current knowledge. Although many of these investigations are still on-going, this paper reviews the activities in each area and concludes with a discussion on further work and potential collaborative research with the metrological community.

AREAS OF RESEARCH

Collocation of Measurements

One of the primary characteristics of the GRUAN network is the combination of different measurement techniques making independent measurements of the atmospheric profiles of the same key climate variables, to produce higher level data products. These synthesized data products can potentially give lower overall uncertainty on the atmospheric profile measurement and also fill in the spatial and temporal gaps that would result from a single measurement technique. Although these different measurements are nominally co-located there will, in practice, be some physical separation between the actual measurement locations. This is particularly an issue when combining data from in-situ sensors and remote sensing instruments. Understanding the effect of this separation, combined with the natural atmospheric variability at the measurement location, is crucial in establishing a robust overall uncertainty for the combined measurement. This issue is also important in determining appropriate co-location criteria for intercomparison between satellite and ground-based observations.

Balloon soundings of the vertical atmospheric profile using the best-available meteorological radiosondes (sensor payloads that measure atmospheric temperature, pressure, and humidity) provide one of the primary data sources for GRUAN, and the co-location of such sonde measurements with other profile or column measurements presents a particular challenge due to the uncontrolled drift of the sondes after launch. Sonde data have been used extensively for a wide range of applications including intercomparison with ground-based and space-based remote sensing systems, atmospheric model evaluations, and studies of atmospheric variability and terms. However, these studies have tended to treat the sonde measurement as being made at a fixed location that is representative of the conditions over a wider area. There are a number of issues relevant to GRUAN where enhanced knowledge of the drift behavior is beneficial, including :

- uncertainty assessment for complementary measurement techniques (e.g. sonde and ground-based remote sensing measurements);
- evaluation of the value of measurements from near-by sites, i.e. can a distributed site with different profiling instruments at near-by locations be treated as a single 'GRUAN site' ?
- improved ground-truth measurements for satellite validation driven by better knowledge of the additional uncertainty introduced by the lack of co-location;
- planning for new sites, where knowledge of the likely drift behavior and recovery locations is a useful tool.

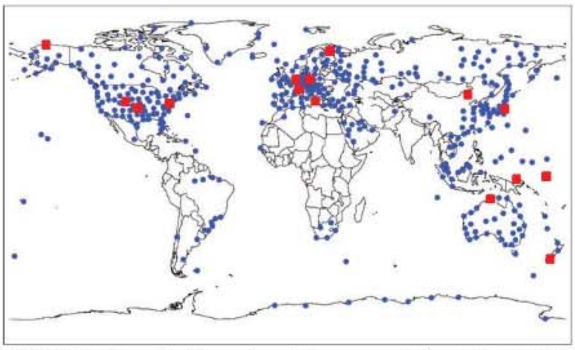

FIGURE 1. Radiosonde stations used in global drift analysis with GRUAN sites shown as red squares – adapted from Seidel et al (5)

In order to address this issue a comprehensive global study of radiosonde drift behavior was conducted by Seidel et al (5). This assessed the drift statistics from 419 stations of the global radiosonde network (including 15 GRUAN sites) for a two year period between July 2007 and June 2009. The sites are shown in Figure 1. The results provide detailed information on the drift statistics for these sites as a function of height and season, as well as drawing some general conclusions including the increasing drift distance with height up to ~50 km in the lower stratosphere, larger drift at mid-latitudes compared to the tropics and during winter compared to the summer.

The next phase of work in this area is to try and quantify the effect of the separation between two or more complementary measurements on the combined measurement uncertainty. To compute the statistical distribution of the effect of the separation difference, and hence the uncertainty, models are being developed of the joint distribution of the measurements and their correlation both in space and in time. Multivariate spatio-temporal stochastic processes are being used to represent this and will be fitted to appropriate measurement data using the Bayesian approach as in Cameletti et al. (6) or the maximum likelihood method as in Fassò and Finazzi (7).

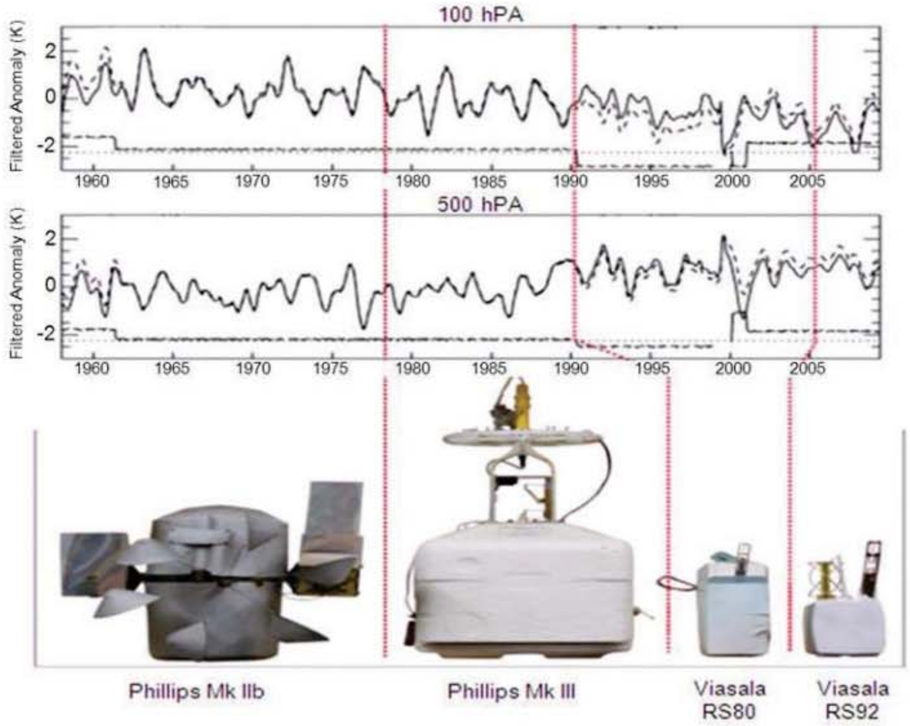

FIGURE 2. Monthly mean radiosonde temperature anomalies for Camborne, UK at 100 hPa and 500 hPa from 1958 to 2009 from the raw data (solid) and homogenized data (dashed). Corresponding radiosonde type changes are also shown. Adapted from Thorne et al (9).

Change Management Requirements

In order to establish a climate reference network it is clear that appropriate management of change is a crucial issue for long-term trend detection. For any observing network, changes are both inevitable and desirable as older equipment and methods become obsolete and improved systems and proven methodological innovations become available. There therefore needs to be careful management of changes in instrumentation, operating procedures, data processing algorithms, operators and other factors.

Experience in the use of the existing climate record shows that previously changes were often not well documented, and that they introduced significant inhomogeneity in the records and jeopardized climate trend analysis. Such inhomogeneity is often uncorrectable as a result of poor management of those changes. Much effort has had to go into homogenizing previous data series, one example of which is shown in Figure 2 (e.g. Dai et al (8); Thorne et al (9)) which shows how homogenization has modified the data series from a UK sonde station, linked to the times of changes of sonde instrumentation.

To address this issue GRUAN is implementing controls and procedures to minimize the potential impact of future changes and this has been reported recently by Wang et al (10). To date this has focused on the change requirements for the main GRUAN data source – the sonde measurements. However, many of the elements are transposable to any type of long-term measurement. The work has included developing guidance on how to document and identify changes, together with the detailed metadata recording collecting overlapped observations of old and new instruments during transition period, and the provision of complementary, independent data sets using different measurement methods (e.g. microwave profiles for temperature, and ground-based GPS precipitable water for humidity).

Given the high probability the sonde sensor technologies will evolve over time an important scientific question relates to the required level of overlap between existing and new sondes. The example given in (10) showed that in order to accurately assess the bias between an old and new sonde to the appropriate level a total of approximately 240 dual flights were required over all four seasons with day and night time measurements. For these dual measurements the two sonde types should be ideally mounted on the same balloon, or as closely spaced as possible, with complementary additional measurements provided, and the dual-sonde results analyzed in as near-real time as possible.

Complementary Measurements

As discussed above, one of the distinguishing features of the GRUAN network is to use complementary measurements techniques both to provide redundant measurements of the atmospheric profile and to increase the site's profiling capability by means of an optimal combination of the measurements with the aim of providing an "Atmospheric Best Estimate" profile for the site. The current GRUAN sites are highly instrumented with a range of in-situ and remote sensing techniques including sondes, GPS water vapour, lidars, radiometers, spectrometers, and radars. Understanding the value of the different measurement methods to the overall GRUAN goals is crucial both to the development of the data products from the existing sites and to specifying the instrumentation requirements for future network sites.

One of the GATNDOR research topics aims to develop robust uncertainty estimates of the vertical profiles of both temperature and humidity using data from existing GRUAN sites and to quantify the uncertainity reduction resulting from increasing redundancy of measurements from different techniques. This requires the assessment of the uncertainty of the temperature and humidity vertical profiles retrieved using each of the considered techniques and then the investigation of possible sensors' synergies to reduce the uncertainty. The gerenal process for evaluating the absolute uncertainty in the GRUAN measurements is discussed in Immler et al (4), and teams within the network are working on instrument-specific procedures. The complementary measurement investigation is focusing on the most common instruments available at the GRUAN sites: radiosoundings and microwave profilers for temperature measurements; radiosoundings, Raman lidars, microwave profilers and GPS receivers for humidity measurements.

The quantification of the value added by complementary observations is being assessed with respect to :

- the identification of possible biases between different techniques;
- the representativeness of measurements over different time and distance scales;
- the requirements and methods for sensor calibration, and inter-calibration between sensors;
- quality control/assurance with a focus on instrument performance in different meteorological conditions.

The initial results of this study have been reported at the recent World Climate Research Programme open science conference (11). In this the combined uncertainty of a remote-sensing or in situ observation that is being compared to another measurement is considered as follows :

$$dE = \sqrt{dr^2 + ds^2 + dt^2 + di^2} \qquad (1)$$

where δr is the measurement uncertainty, made up of all the contributions due to statistical noise and bias correction uncertainties from various sources including instrument calibration and repeatability; δs and δt relate to the spatial and temporal co-location uncertainties respectively; and δi indicates the uncertainty related to the model used for comparison with observations. The combination of uncertainties in Equation 1 assumes that all the terms follow a Gaussian distribution and are independent of each other. However, this will not always be the case, and the calculation of the overall uncertainty budget needs further investigation to identify the best method to combine the different uncertainty sources.

For many atmospheric measurement situations the contribution of the spatial and temporal uncertainties may dominate the overall uncertainty budget. Therefore the trade-off between signal-to-noise of remote sensing (often linked to averaging time) and the impact of the space and time co-location uncertainty at all altitude levels has to be determined before the comparison or combination of different in-situ and remote sensing sensors can be properly undertaken. One of the outcomes of the study in (11) was the development of a hybrid lidar-sonde estimation obtained using the radiosonde profile to extend the height of the lidar water vapour mixing ratio profile from the lidar level where relative uncertainty of the lidar measurement exceeds the combined sonde and co-location uncertainty (in this case around 25%). The use of such hybrid profiles is a possible solution for reducing the impact of radiosonde spatial representativeness on the measurements.

Sampling Strategies For Long-Term Measurements

Another area of study is the development of appropriate sampling strategies that would enable the anticipated long-term trends to be detected for given levels of measurement uncertainty. Following the work by Boers and van Meijgaard (12), Whiteman has lead a study of the measurement frequency and duration needed to reveal trends in atmospheric upper tropospheric water vapour using radiosonde data (13). This study uses atmospheric behavior and trends predicted by different climate model simulations, and assumes different levels of measurement uncertainty for the sonde measurements. The output from each set of input parameters is the estimated time to detect a given trend, given the variability and cross-correlation behavior of the measurements. This follows the methods developed by Weatherhead et al (14), and is given by :

$$n^* = \left[\frac{3.3\sigma_N}{|\omega_0|}\sqrt{\frac{1+\phi_N}{1-\phi_N}}\right]^{\frac{2}{3}} \qquad (2)$$

Where n^* is the number of years to detect the trend with 90% confidence, σ_N is the fractional standard deviation of the statistical noise in the time series, ω_0 is the estimate of the linear trend (fractional change per year) and Φ_N is the autocorrelation of atmospheric fluctuations.

The main conclusion of the study was that, given the high level of natural atmospheric variability, increasing the measurement frequency is much more important than reducing the random uncertainty of the measurements. However, in the event of high random uncertainties, procedures need to be adopted that tend to randomize potential sources of systematic uncertainty so that any long-term biases are reduced.

Work is now underway to extend the above study to the lower stratosphere using a combination of frost point hygrometer sonde time series and satellite data from the Microwave Limb-Sounder (MLS) instrument (15). Preliminary results indicate that much lower random uncertainty measurements are needed to detect trends than in the upper troposphere, although increasing the frequency of measurement still brings a significant decrease in time to detect trends.

Although this work has focused on water vapour, many of the methods and conclusions are relevant to other atmospheric variables such as temperature.

DISCUSSION

There are many scientific and technical challenges in establishing a reference climate network such as GRUAN. The work of the GATNDOR team is addressing some of these issues, and the outcomes from studies described above have already started to feed into the design and development of the GRUAN network. Each of the studies discussed was initiated by a member of the GATNDOR team but the work has involved much wider collaborations of international researchers. Research in each of the topic areas is on-going, and input from the metrological community will be an important part of delivering the overall goal of GRUAN – to provide long-term reference climate measurements of the upper atmosphere with robust and traceable uncertainties. The on-line GRUAN blog (http://gruan.wordpress.com/) provides a mechanism for discussion and interaction between any interested researchers.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the major contribution of Dian Seidel, NOAA Air Resources Laboratory, to the GATNDOR activities, and in particular the work on the collocation issues.

REFERENCES

1. 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
2. Global Climate Observing System (GCOS), http://www.wmo.int/pages/prog/gcos/index.php?name=AboutGCOS
3. Thorne P.W. et al; GCOS Reference Upper Air Network (GRUAN): Steps Towards Assuring Future Climate Records, in *Temperature: Its Measurement and Control in Science and Industry, Vol. 8*, edited by C.W. Meyer, Melville, NY: American Institute of Physics, 2013, pp. 1042-1047.
4. Immler F.J., J. Dykema, T. Gardiner, D. N. Whiteman, P. W. Thorne and H. Vomel; Reference Quality Upper-Air Measurements: guidance for developing GRUAN data products; Atmos. Meas. Tech., 3, 1217–1231, 2010
5. Seidel D.J. , B. Sun,M. Pettey and A. Reale; Global radiosonde balloon drift statistics; JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 116, D07102, doi:10.1029/2010JD014891, 2011
6. Cameletti M., Lindgren F., Simpson D., Rue H. Spatio-temporal modeling of particulate matter concentration through the SPDE approach. Advances in Statistical Analysis. 2011, in printing.

7. Fassò A, Finazzi F, (2011) Maximum likelihood estimation of the dynamic coregionalization model with heterotopic data. Environmetrics. Vol. 22:6, 735-748
8. Dai, A., J. Wang, P.W. Thorne, D.E. Parker, L. Haimberger, and X.L. Wang, 2011: A new approach to homogenize daily radiosonde humidity data. J. Climate, 24, 965-991.
9. Thorne, P. W., D. E. Parker, et al. (2005). "Uncertainties in climate trends - Lessons from upper-air temperature records." Bulletin of the American Meteorological Society 86(10): 1437-+
10. Wang, J., A. Dai et al, The GCOS Reference Upper Air Network: Management of Changes in GRUAN for Better Climate Trend Detection; Session C15: Atmospheric Observations Including Upper Troposphere and Stratosphere WCRP Open Science Conference: 24-28 October 2011, Denver, CO
11. Madonna F., D. Ciminai et al (WCRP); GCOS Reference Upper Air Network: Quantifying the value of complementary observations for GRUAN operations; Session C15: Atmospheric Observations Including Upper Troposphere and Stratosphere WCRP Open Science Conference: 24-28 October 2011, Denver, CO
12. Boers R, and E. van Meijgaard; What are the demands on an observational program to detect trends in upper tropospheric water vapor anticipated in the 21st century?; Geophysical Research Letters, VOL. 36, L19806, doi:10.1029/2009GL040044, 2009
13. Whiteman, D. N., K. C. Vermeesch, L. D. Oman, and E. C. Weatherhead; The relative importance of random error and observation frequency in detecting trends in upper tropospheric water vapour; J. Geophys. Res., 116, D21118, doi:10.1029/2011JD016610, 2011
14. Weatherhead E.C, G.C. Reinsel, et al; Factors affecting the detection of trends : Statistical considerations and applications to environmental data; J. Geophys. Res., 103, D14, 17149-17161, July 27, 199811.
15. Waters, J.W, L. Froidevaux, et. al., The Earth observing system microwave limb sounder (EOS MLS) on the aura Satellite, IEEE Trans. Rem. Sens. Geosci., 44, 1075-1092, 2006.