Results of the Measurement Strategy of the GCOS Reference Upper Air Network (GRUAN)

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ABSTRACT

For over a decade efforts have been undertaken by the climate community to instigate a reference quality network to ensure the future record. These efforts have been taking shape as the GCOS Reference Upper Air Network. GRUAN places a strong emphasis on what defines a reference observation of an upper air essential climate variable (ECV). Upper air observations of ECVs by in situ techniques, in particular the observations of temperature and water vapor, often suffer from poorly characterized systematic biases and random variations, which may impact the ability to detect long term changes in these parameters. The measurement strategy of GRUAN takes these weaknesses into account and tries to improve instrumental errors and random effects through a better characterization of the instruments in use, a better quantification of systematic and random errors, and a better verification of the derived instrumental parameters. Key elements of GRUAN measurements are traceability of the measurements to recognized standards, documented uncertainty estimates, measurement technology redundancy to allow independent cross-checking, extensive metadata collection, and archiving of raw data in addition to processed data. Establishing long term climate series also requires that the measurement program accommodates a strategy to manage changes in instrumentation and procedures. A detailed understanding of the instrumentation and the associated processing algorithms provide the tools to manage instrumental change in a consistent manner. Proper change management will be the key assure a long term consistent record of upper air reference observations.

INTRODUCTION

Existing records of upper climate variables, in particular water vapor and temperature of the free atmosphere do not give a clear picture of the changes that may have occurred as a result of changes in atmospheric composition. In fact, different observational records of the same climate variable may indicate contradicting trends over similar time periods (e.g. Elliott and Gaffen, 1991, Soden and Lanzante 1996). One of the main causes of this weakness is that measurements taken at different times are not always comparable due to changes in instrumentation, changes in calibration, or changes in operating procedures and processing. In addition, uncertainties of past observations are not well described and in particular systematic errors may not have been appropriately corrected for. Measurement systems and instruments for upper air observations frequently change (in the case of radiosondes for each measurement) and therefore, changes in systematic errors directly impact the ability to detect trends.

These deficits have led to the creation of the GCOS Reference Upper Air Network (GRUAN). The aims of this network are to provide reference observations that will lay the basis for long term upper air climate records, to provide a reference for globally more comprehensive observation networks, such as satellite systems, but also the global radiosonde network, and to provide high quality data for atmospheric process studies.

Since changes in systematic errors impact the ability to detect trends most severely, GRUAN places a strong focus on the identification and quantification of systematic errors as well as all other components of the uncertainty in the measurement process.

MEASUREMENT STRATEGY

Measurements at the basis of long term climate records have to be traceable to recognized standards and will have to have well described uncertainties, and well documented and complete metadata. Properly managing changes in instrumentations and procedures is an essential element of the measurement strategy of GRUAN. The approach has been discussed by Immler et al. (2010).

Traceability

Instrumentation will change, operating procedures will be improved and processing routines will be optimized. Traceability of measurements will ensure that data from different time periods will remain comparable and that the impact of changes in systematic errors will be minimized. Therefore, traceability is not a goal in itself, but a tool to assure, that measurements using different instrumentation remain comparable.

Traceability implies that the calibration of sensors can be traced to a standard maintained by the national metrological institute or a recognized institute for the quantity in question. If traceability cannot be derived from a national metrological institute it is essential that all measurements maintain traceability to the same standard.

The processing of measurements from in situ instruments frequently requires correction of systematic errors due to the exposure to the free atmosphere or due to the particular use in atmospheric profiling. These correction algorithms need to be transparent and well documented. Therefore, traceability not only refers to the traceability of the calibrations to a recognized standard, but also to the traceability of the different steps in the data processing. For GRUAN it is essential, that observations across the network are processed homogeneously, so that traceability between the different sites is maintained. Periodic intercomparisons of instruments or operating procedures used at different sites will be required to ensure, that the processing is consistent across the network. The most straightforward method of intercomparison will be the use of traveling standards.

Measurement uncertainty

Instruments used in observations of upper air climate variables need to respond to a large span of values that need to be measured. Furthermore, they encounter a large range of environmental conditions, in which they are required to function. Therefore, the instrument performance is not the same over the entire value range. This range in performance is quantified by the measurement uncertainty for each measurement point. GRUAN observations will therefore provide not only the best estimate of the quantity to be measured, but also the best estimate for the uncertainty associated with this measurement. This can only be achieved, if the different sources of measurement uncertainty are well characterized and quantified. A detailed understanding of the measurement system is required to provide and test this information.

Great care has to be taken to identify the sources of systematic error and to correct these effects to the best possible currently achievable level. Since data will be maintained over long periods of time, it is essential to document these correction procedures and to make sure that remaining systematic errors are minimized over the entire data record.

For long time series random errors in the measurements may average out; however, a detailed understanding of the nature of the random error is essential to avoid unexpected systematic errors.

The identification and quantification of sources of measurement uncertainty remains a challenge. GRUAN relies on in situ comparisons of different systems and on laboratory and ground based measurements to investigate distinct sources of uncertainty. For example the solar radiation dry bias of the Vaisala radiosonde is investigated with dual soundings using cryogenic frostpoint hygrometers as well as with dedicated solar radiation experiments in ground based set ups. The calibration of the sensors is verified in recalibrations of the sensors in a climate chamber and tested prior to launch in manufacturer independent ground checks. The combination of these results provides the basis for a vertically resolved estimation of the measurement uncertainty. In some cases the uncertainty estimate is provided with both correlated and uncorrelated components.

In managing changes in instrumentation the understanding of the individual sources of the measurement uncertainty allows a better evaluation of the possible impacts the instrumental change is likely to have. With this information targeted studies can be designed to minimize the expected impact of this change on trend estimation and potentially to improve on previous records.

Raw data

With future technological progress a better understanding of the measurement process may allow a better characterization of the current measurement. To make use of these improvements, reprocessing of current observations will be required. This can only be accomplished if all relevant raw data have been archived.

What comprises raw data is not trivial. The basic requirement for raw data is that they contain all information of the measurement process that allow reprocessing for the purpose of improving systematic error corrections and possibly reducing random error estimates. Therefore, not only the raw data have to be archived, but also the description of the data format and the software to process them. In many cases a compromise will have to be achieved, that maintains the basic requirement for raw data but reduces the complexity that some raw data may have, without impeding on the ability to reduce systematic and random errors with future knowledge.

Documentation

Extensive metadata are collected to fully describe any measurement event. In addition to basic information such as a complete description of time and location a complete description of the full measurement system is required as well as a complete description of the processing.

The widespread use of the TEMP format is insufficient for climate purposes. The more advanced BUFR formats allow a better capturing of metadata, but still lack some of the information required within GRUAN. Nevertheless, a standardized metadata format that accompanies each observation is essential. GRUAN relies on the climate and forecasting metadata standard (CF conventions), which allows the ingestion of these data in larger analysis and reanalysis systems.

Other elements of the documentation, in particular the history of the processing and instrumentation will need to be provided in clear text and will be archived together with the data.

Close cooperation with the instrument manufacturers is required since some of the information needed to fully describe the measurement process may not be publicly available. It is also of great importance, since changes in the instrumentation must be well documented, but may not be known to the operational user of data. This cooperation also provides the manufacturers with access to lessons learned within GRUAN.

Redundant observations

The analysis and quantification of the different components of measurement uncertainty must be routinely evaluated. Flaws in this analysis may go by undetected and instruments or procedures may have changed unnoticed. Periodic redundant observations preferably using different instrumentation will provide data, which can be used to continuously evaluate the uncertainty analysis.

In well conducted observations redundant measurements should agree within their expected uncertainties. Differences between redundant measurements that are larger than the statistically expected differences may be called ‘inconsistent’ depending on the level of statistical significance. They may not immediately be a reason for concern, but may indicate that the understanding of the factors contributing to the measurement uncertainty may not be fully understood.

At the same time, if redundant measurements always agree within the combined uncertainties, this may indicate that the uncertainty estimate is too conservative and that some effects are not as large as estimated. Again, this may indicate some incomplete understanding of the sources of measurement uncertainty.

Redundant observations are therefore an essential element in the validation not only of the measurement itself, but more importantly in the validation of the estimate of the measurement uncertainty. Redundant observations may also be done using a traveling standard for a particular measurement system. Regular intercomparisons guarantee the best possible stability of a long term data set as well as the best possible homogeneity of the network.

As long as redundant observations remain at the same level of consistency, in particular throughout periods of managed change, trend estimates are likely to maintain a high level of confidence.

Change management

Long term data series are most strongly impacted by changes in instrumentation or by modifications of the operating procedures and analysis routines. A pro-active change management is essential to avoid introducing unwanted errors into the data series.

Proper change management will maintain the level of understanding of the measurement process despite changes in instrumentation or procedures. This requires that the expected impact of planned changes is carefully assessed. Carefully designed procedures will be followed to quantify the expected change impacts, which should then be validated and tested in simultaneous observations using the old and new instrumentation.

RESULTS

The first GRUAN data product is based on measurements using the Vaisala RS92 radiosonde. This data product is available at NOAA/NCDC and can be accessed through www.gruan.org/data. These data provide not only the measured parameters, but also the vertically resolved estimated uncertainty for each parameter and are the first radiosonde data product to provide this information.

Since manufacturer specific algorithms are largely considered a black box, the processing of these data has been redesigned. All corrections to known systematic biases and all filters have been developed to be open and to allow a quantification of their contributions to the overall measurement uncertainty. The calibration of the radiosonde is not questioned and assumed to have an uncertainty that derives from the one point recalibration during the ground check. In addition, the calibration is checked in a manufacturer independent standard humidity chamber, which checks the temperature reading at room conditions as well the relative humidity at 100%.

Temperature

In all daytime measurements of temperature and humidity solar radiation is the largest source of a systematic error, which must be corrected. A correction for solar heating of both the temperature sensor as well as the humidity sensors is applied, based on surface measurements of the solar heating error of these sensors. Measurements of the solar radiation correction have been conducted at the Meteorological Observatory Lindenberg of the German Meteorological Service. These measurements lead to a solar radiation correction for the temperature measurement, which is very similar to that provided by Vaisala (Figure 1).

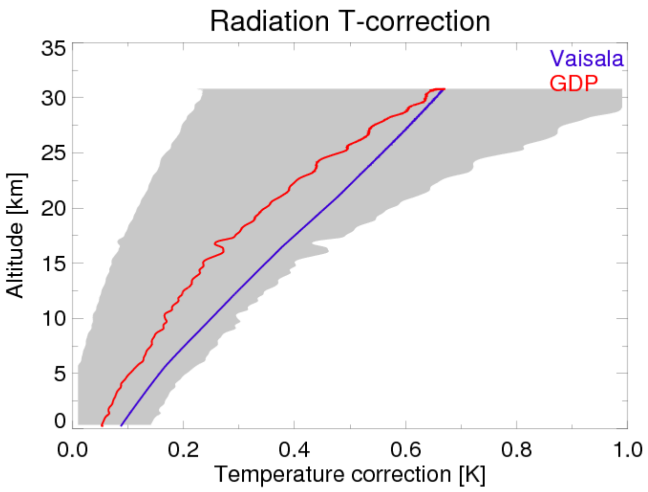

FIGURE 1. Correction for the solar radiation error in temperature measurements for central Europe, both from Vaisala and the GRUAN data product (GDP). The grey shaded area indicates the uncertainty of the radiation correction.

The GRUAN algorithm for the solar radiation correction considers an average cloud layer and as well as the ventilation of the sensor and uses a radiative transfer model to translate the surface measurements to the conditions seen by the sensor in flight. The grey shaded area in Figure 1 indicates the uncertainty of the radiation correction for individual profiles and includes factors such as the orientation of the sensor, changes in cloudiness, and the uncertainty in the ventilation of the sensor. Nevertheless, the differences between the GRUAN radiation correction and the Vaisala radiation correction are statistically significant and require further investigations. This procedure to evaluate the radiation error can be applied to any sensor and allows a consistent processing of different temperature sensors. The evaluation of other sensors is currently in progress.

The combination of surface measurements and radiative transfer model allows a quantification of the uncertainty contributions going into the estimation of the solar heating correction. In addition, a constant calibration uncertainty of 0.1 K is assumed throughout the entire measurement range, based on a typical uncertainty of the one point recalibration during the operational Vaisala ground check. The vertically resolved sources of uncertainty in the GRUAN temperature measurements are shown in Figure 2.

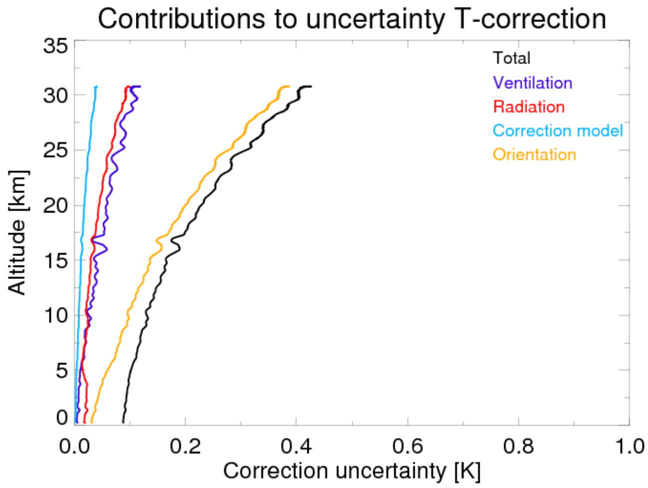

FIGURE 2. Source terms for the uncertainty of the temperature measurement using Vaisala RS92 radiosondes.

The uncertainty of solar radiation correction is determined by the uncertainty of the solar heating measurements on the ground; the uncertainty of the radiative transfer model, which estimates the total actinic flux encountered by the sensor in flight; the uncertainty in the ventilation air speed encountered by the sensor; and lastly the unknown orientation of the sensor relative to the sun. The lack of understanding of the orientation of the sensor relative to the sun's position may in this case be the limiting uncertainty for stratospheric temperature measurements.

Relative humidity

The daytime measurements of relative humidity also suffer from a solar radiation error, which heats the humidity sensor to temperatures significantly above ambient and leading to a radiation induced dry bias (Vömel et al., 2007). The GRUAN data product corrects this solar radiation dry bias, corrects the increasing time lag of the humidity sensor with decreasing temperature, and corrects a temperature dependent calibration dry bias. The time lag constants are based on information provided by Vaisala (Miloshevich et al., 2004) and have not been assessed independently. The combined uncertainty estimate is done similar to that shown for temperature above.

The validation of these corrections is done in simultaneous soundings using the Cryogenic Frostpoint Hygrometer (CFH). Observations launched routinely at Lindenberg and other sites as well as campaign based observations, such as those during the Yangjiang international radiosonde intercomparison (Nash et al., 2011), provide data to validate the humidity algorithms used within GRUAN (Figure 3).

These redundant observations show an overall good agreement between the cryogenic frostpoint hygrometer and the Vaisala RS92 GRUAN data product throughout most of the troposphere. The vertically resolved uncertainties (not shown here) provide an indication up to what altitude these data may be used, which may depend on the application for which these data are to be used. At the coldest temperature below the tropical tropopause some deviations can be

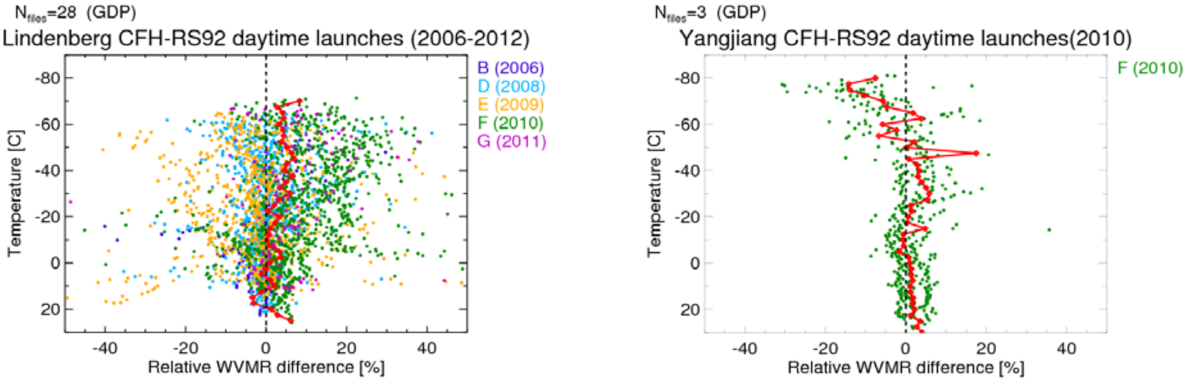

FIGURE 3. Difference of tropospheric relative humidity in simultaneous observations measured by the Cryogenic Frostpoint Hygrometer and the GRUAN processed Vaisala RS92. Different Vaisala RS92 production years are indicated in different colors.

seen in the limited comparison conducted at Yangjiang. These differences indicate that the behavior of the Vaisala sensor at the coldest temperatures is not yet well enough understood and that useful observations will for the time being be limited to altitudes below the tropical tropopause.

CONCLUSION

The observations currently obtained within GRUAN will allow an estimation of changes of temperature and water vapor in the troposphere and stratosphere that is not impacted by changes in instrumentation or operational procedures. This is achieved by a detailed understanding of the measurement process, traceability to a recognized standard and a continuous verification of the consistency within redundant observations. These procedures accommodate changes in the observational program, which will invariably happen over the course of a long term data record.

Understanding and being able to quantify the vertically resolved contributions to the overall measurement uncertainty is essential in the management of change. New instrumentation and new procedures will have to be assessed following the requirements outlined and implemented within GRUAN. This approach can be used for any radiosonde of any manufacturer (and even other types of instrumentation). GRUAN is able to include radiosondes from all manufacturers, as long as the measurement uncertainties can be properly described and measurement processes can be properly documented.

Maintaining this detail of understanding will ensure that long term climate records of temperature and water vapor, as well as all other upper air observations that will be done within GRUAN, remain homogeneous and traceable to accepted standards. These data will form a reference for larger scale observation systems, and provide the basis for new understanding of the processes within the atmospheric column.

REFERENCES

Elliott, W.P., and D.J. Gaffen, On the utility of radiosonde humidity archives for climate studies. Bull. Amer. Meteor. Soc., **72**, 1507-1520, (1991).

Immler, F. J., et al., Reference Quality Upper-Air Measurements: guidance for developing GRUAN data products, *Atmos. Meas. Tech*., **3**, 1217–1231, (2010).

Miloshevich, L. M., A. Paukkunen, H. Vömel, and S. J. Oltmans, Development and Validation of a Time-Lag Correction for Vaisala Radiosonde Humidity Measurements, *J. Atmos. Oceanic Technol,* **21**, 1305–1327, (2004).

Nash, J., T. Oakley, H. Vömel, and W. Li, WMO Intercomparison of High Quality Radiosonde Systems, Yangjiang/ China, 12 July - 03 August 2010, WMO/ TD - No. 1580: Instruments and Observing Methods Report No. 107 (2011).

Soden, B. J., and J. R. Lanzante, An assessment of satellite and radiosonde climatologies of upper-tropospheric water vapor, J. Clim., **9**, 1235– 1250, (1996).

Vömel, H., H. Selkirk, L. Miloshevich, J. Valverde, J. Valdés, E. Kyrö, R.Kivi, W. Stolz, G. Peng, and J. A. Diaz, Radiation dry bias of the Vaisala RS92 humidity sensor, J. Atmos. Oceanic Technol., **24**, 953-963, (2007).