WORLD METEOROLOGICAL ORGANIZATION

INTERGOVERNMENTAL OCEANOGRAPHIC COMMISSION

Report of the 14th GCOS Reference Upper Air Network Implementation Coordination Meeting (GRUAN ICM-14)

Université de La Réunion
Saint Denis, Réunion Island

28 November – 2 December 2022

GCOS-250

UNITED NATIONS ENVIRONMENT PROGRAMME

INTERNATIONAL SCIENCE COUNCIL

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ICM-14 Group Picture

INTRODUCTION

This is the meeting report of the 14th GCOS Reference Upper Air Network Implementation Coordination Meeting (GRUAN ICM-14). Hosted by the Université de La Réunion, at Saint Denis, Réunion Island, from 28 November to 2 December 2022

All presentations are available for further review from the GRUAN meeting website, at https://www.gruan.org/community/meetings/icm-14.

The meeting agenda is given in Annex 1.

Annex 2 provides a summary on progress of actions from ICM-13.

Annex 3 lists the agreed actions from ICM-14.

PRESENTATION SUMMARY:

Session 1. Welcome

Welcome (June Wang)

June Wang, co-chair of the WG-GRUAN, welcomed the participants and conveyed the importance of this meeting that, due the restrictions for COVID, is the first in person meeting in 3 years.

Meeting Logistics (Local Host)

Stephanie Evans and Jerome Brioude explained the logistics of the meeting.

Official Opening (Host)

The meeting was opened by Joël Van Baelen, head of LACy (Laboratoire de l'Atmosphère et des Cyclones), Nicolas Arnaud, head of CNRS/INSU (National Center for Scientific Research/National Institute for Earth Sciences and Astronomy), Marc Pontaud, head of CNRM at Météo-France (National Centre of Meteorological Research, the research division of Météo-France) and Gilles Lajoie, President of Academic Council, Université de la Réunion.

La Reunion, a knowledge centre for island resilience (Philippe Holstein)

Philippe Holstein talked about the role of the remote islands, such as La Reunion, in the evolution of science and the development of environmental science. The current challenges are related to the ecological vulnerability to the impacts of climate change. La Reunion is in the perfect place to address these vulnerabilities and to export solutions to other countries, like to the EU. La Reunion can be seen as a centre, to design solutions to export to other communities. There are 8 thematic scientific communities in La Reunion, including the sustainability of the ecological system and impacts of and resilience to climate change. These assets need to be used to reinforce the inclusion of La Reunion into international networks. Currently, there are 117 projects developed for the EU, that raised almost 9 million Euros.

Opening Statement – GCOS/WMO (Anthony Rea – remote)

Anthony Rea, Director of WMO Infrastructure and GCOS, talked about the importance of GCOS and GRUAN. GCOS was very successful at COP27, where the 2022 GCOS Implementation Plan was recognized. There was a strong message to parties about the importance of systematic observations to monitor climate change and for adaptation and mitigation. Reference networks

such as GRUAN are very important, as we need to trust the observations to address the challenges of climate change and its impacts. Reference observations are also fundamental because they feed into reanalysis which is now becoming prominent for adaptation studies. The 2022 GCOS Implementation Plan as well as one of the key messages of the GCOS Climate Observation Conference call for reference observations in all the domains.

GRUAN – Why we are here (Ruud Dirksen)

Ruud Dirksen, head of the Lead Centre (LC), explained the GRUAN basics and the motivation for GRUAN. GRUAN is a ground-based network for upper air observations that was established in response to the need identified by WMO and GCOS for highest accuracy data possible. GRUAN's goals include long-term consistent data records, validation of satellite systems, process studies and NWP. The requirements for a GRUAN data product are traceability, uncertainty analysis, inclusion of raw data and meta data, proper documentation and validation. At the moment, priority variables are temperature, water vapour and pressure, with the development of data products for other variables, such as ozone, following in a second phase. GRUAN comprises 31 sites with the aim to expand to 30-40 sites. Important aspects of GRUAN include change management, certified measurement programs and dedicated data processing that corrects for all known biases and measurement errors. These factors ensure that GRUAN provides reference-quality data that is free of instrument-related artefacts and inhomogeneities.

Site certification presentation (Peter Thorne)

Barrow/North Slope Alaska and Ross Islands sites are now certificated. A certificate was presented to the respective site representatives.

Session 2. Review of Progress

2.1 GRUAN LC Updates (Ruud Dirksen)

Ruud Dirksen presented updates from the Lead Centre since the last in-person ICM (ICM-11). The network consists of 31 sites, 14 of which have been certified. Dakar, Hong Kong and Paramaribo accepted the invitation to become candidate sites, Ross Island (ROS) and Barrow (BAR) were certified. Several sites were recertified (Payerne, Potenza, Ny Alesund, Sodankyla, Beltsville, Tateno) The certification of Tenerife is pending, whereas the recertification of Boulder and Cabauw is under review. The flow of data to the Lead Centre is steady, although consistently lacking for several sites. The GRUAN archive contains more that 140k radiosoundings, with operational data streams for RS41-GDP.1, RS92-GDP.2, RS-11G-GDP.1 iMS-100-GDP.2

Since ICM-11 several GRUAN documents have been published (TD-7, TNs 6, 8, 9, 11, 12, 13) as well as a multitude of papers on GRUAN-related research. Two important publications by

the Lead Centre are the GRUAN-wide approach to the RS92-RS41 transition (Dirksen et al. 2020) and the description of the radiation temperature correction for the RS41 data processing (von Rohden et al. 2022).

An important topic for GRUAN was the network wide-transition from RS92 to RS41. A coordinated intercomparison program resulted in approximately 1200 RS92-RS41 twinsoundings performed at GRUAN sites. This intercomparison covered several years and is now completed, and the data are stored in the GRUAN database. In parallel to this effort, the GRUAN data product for the RS41 was developed at the Lead Centre, for which the correction algorithms were build based on the sensor characterisation performed in the laboratory facilities at Lindenberg. A paper on the comparison of the RS92-RS41 GDPs is in preparation.

Several activities were carried out in search for R23-free stratospheric water vapor observations, which includes

- Test flights with FLASH-B, Meisei Skydew, PCFH and
- Research cooperations with TU Dresden and FZ Jülich to investigate alternative coolants and cooling methods.

Furthermore, a research contract was awarded to investigate added value GRUAN processing. In addition to the above-described regular GRUAN duties, the Lead Centre also took care of the preparation and execution of the WMO radiosonde intercomparison campaign in 2022 (UAII2022), in collaboration with WMO, and Lindenberg and Payerne staff. [ref to reelvant section]. The work plan for the coming months includes a wide range of tasks such as:

- Start development of GRUAN data product for RS92 (RS92-GDP.3).
- Support development of GRUAN data product for M10, M20 & Graw radiosondes
- Prepare report of WMO-CIMO Radiosonde intercomparison campaign.
- Continue development of alternative, non-R23 based, cooling mechanisms for frostpoint hygrometers.
- Further development of the GRUAN website.
- Operationalize processing of CFH data.

2.2 GDP Status (Ruud Dirksen)

Ruud Dirksen started with a summary of rationale for developing GRUAN data products (GDPs).

GDPs are reference quality data, that represent the highest accuracy data available, and because of that are in high demand for climate monitoring and satellite validation. The requirements for certifying a GRUAN data product are stipulated in GRUAN Technical Notes 1 and 4 and include:

- A technical document with full description of the data processing
- A Peer reviewed paper on the data product
- A measurement system employed within GRUAN
- A central processing facility
- An existing operational data stream
- A review/validation of the data stream

Thus far there are 5 certified GDPs, 4 radiosonde-GDPs (Vaisala RS92 & RS41 and Meisei RS-11G and iMS-100) as well as GNSS-PW. It is noted that the GDPs for RS41 and iMS-100 have

been provisionally certified, awaiting the final acceptance of their respective technical documents by the Working Group. Furthermore, the GDP GNSS-PW is currently only available at GFZ (the data processing centre) as ASCII files, instead of the required NetCDF format. Eight data products for other radiosonde models and measurement systems including lidar, MWR and ECC ozonesonde are in various stages of development. The development status of the GDPs is displayed in the restricted area (password-protected) of the GRUAN website.

In conclusion, it was mentioned that the development of a GDP is a large task that requires a considerable amount of effort and resources. On average the development of the currently certified GDPs each took about four years to complete. For future GDP development for radiosondes, it is possible to build on the experience from previous work and thus partly speed up the program. For example, by using already developed measurement infrastructure and data analysis software. However, the other steps in the GDP development, such as data analysis, development and implementation of correction algorithms, and validation program can't be shortened or optimized.

2.3 Review of actions for ICM-13 (Peter Thorne)

Peter Thorne, co-chair of WG-GRUAN presented the actions from ICM-13 and their progress. A summary of progress of ICM-13 actions can be found in Annex 2.

2.4 RS41-GDP (HP1) (Michael Sommer)

This presentation showed that the development of the GRUAN data product for the RS41 was a long and arduous process. The most important steps of the characterisation of the radiosonde by means of laboratory experiments (SHC, climate chamber, radiation wind tunnel) were briefly presented. Especially the radiation wind tunnel (SISTER) was highlighted, as it is a novelty. The extensive processing using GDPS (GRUAN Data Processing System) was outlined and the complex determination of uncertainties was briefly discussed for temperature measurements as an example. The most important features of the RS41-GDP files were then explained, and the possibility of creating plots was pointed out. The processing of the first version of the RS41 GRUAN data product RS41-GDP.1 was started one year ago and is operationally running since then. Furthermore, the status of the relevant documentation was shown: RS41 Technical Document, RS41 User Guide, peer-reviewed articles regarding comparison with RS92-GDP.2. The data product RS41-GDP.1 is finally certified now and all are invited to use this dataset.

Session 3. GRUAN Priorities

3.1 R23 and its replacement

Ruud Dirksen opened this session by presenting the general issue. Within GRUAN, the CFH/FPH is the instrument of choice for the required stratospheric water vapor observations. Currently, eleven GRUAN sites employ CFH/FPH which needs R23 to operate. Because of the environmental impact of R23 (100-year CO2 equivalent of ~15000) its use is restricted or banned in the EU and Japan, with increasing restrictions in other countries as well. This problem has been discussed at various ICMs since it was first raised at ICM-7. In search for a long-term sustainable solution, sites are testing alternative cooling methods, such as the ethanol/dry-ice mixture for CFH/FPH operations or are even considering switching to instruments that operate without cryogen. Alternative instruments (Skydew, FLASH-B, PCFH) are in various stages of maturity, where the Peltier-based Skydew instrument from Meisei is now commercially available. A site survey revealed that the availability of R23 is most critical at GRUAN sites in Europe and in Japan. For these sites the use of R23 has either been completely stopped, or the limited stock lasts for at most 10 CFH soundings without the possibility of purchasing additional supply.

For US-sites, as well as NOAA-supported Lauder, availability or purchase is not an issue yet, although the cost of R23 has increased by 25%. The site in Hong Kong also has no availability issues.

Status of the Meisei SKYDEW instrument (Takuji Sugidachi)

The SKYDEW is a Peltier-based chilled-mirror hygrometer. This presentation introduced the data processing and uncertainty estimation of SKYDEW toward the development of a frost point hygrometer GDP. The golden point method was applied to the SKYDEW profile. The golden point method works well with the SKYDEW to smooth the oscillated mirror temperature. The uncertainty was estimated from the timing error of golden points. A comparison with other sensors such as Aura/MLS and SKYDEW descent data is useful to estimate the contamination error.

Development of a liquid N2 container for the CFH (Christian ROLF, Dina Khordakova, Kyriaki Blazaki, Ruud Dirksen)

The regular cooling agent R23 of the EN-SCI Cryogenic Frostpoint Hygrometer (CFH) must be replaced to a more environmentally friendly version. Here, we presented the development of a modified CFH prototype using liquid nitrogen as cooling agent in a pressure vessel. First tests in an environmental simulation chamber and during one dedicated balloon test flight showed very good results and good agreement to a CFH operated with R23. Further tests and small adjustments of the prototype are needed to measure water vapor with same precision at heights above 20km.

Status of the Peltier Cooled Frost Point Hygrometer (PCFH) and first comparison with CFH (Frank Wienhold)

As the strongest natural greenhouse gas, water vapor is closely coupled to climate change. Model studies by Solomon et al. (2010) reveal that its stratospheric abundance strongly impacts ground level temperature: they found that the mixing ratio decrease in the stratosphere between 2001 and 2009 compensated the warming caused by the well mixed greenhouse gases alone by approximately 25%, while the stratospheric increase from 1980 to 2000 enhanced it by about 30%. Humidity of the stratosphere is controlled by freeze-drying in cirrus clouds that themselves cause a significant radiative forcing and supply surfaces for heterogeneous chemistry affecting ozone. This motivates the continuation of long-term high quality water vapor measurements up to the lowermost stratosphere, such as the NOAA Frost Point Hygrometer (FPH) Water Vapor Record over Boulder, Colorado.

The Peltier Cooled Frost point Hygrometer (PCFH) is developed as an alternative to the currently used frost point hygrometers that rely on R23, a coolant that has been banned by the Kigali amendment to the Montreal Protocol. The use of solid-state Peltier elements for cooling along with ambient air instead of R23 reduces logistic demands and handling / preparation efforts leading to simple application. Its layout as double instrument with two independent sub-units helps during the development phase and will allow to identify and resolve artifacts caused e.g. by contamination. The relay control schemes described in the previous year's contribution allows to identify the frost point temperature with the 'Golden Points' method, providing accurate measurements with a vertical resolution ranging from 50 m in the troposphere to 300 m in the lowermost stratosphere. Comparison flights from Lindenberg, Germany, with the CFH reference and two Vaisala RS41 hosting radiosondes achieved a PCFH / CFH correlation characterized by a slope of 1.008 ± 0.008 and a precision of 11% for the PCFH measurements, assuming the CFH to be entirely free of error.

Two sources of future funding of the project could be obtained during this year. (1) With support from the Environmental Technology Promotion program of the Swiss Federal Office for the Environment, the know-how to set up the instrument will be transferred to mylab elektronik GmbH, a Swiss SME industrial partner, to ensure reliable production. After resolving known issues, a Golden Point generation scheme with safe frost point tracking will be established. (2) The Swiss GAW / GCOS project *The Swiss H_2O Hub – high quality water measurements from ground to space* is held in a consortium headed by the Institute of Applied Physics (IAP) at the University of Bern. It will combine balloon borne in-situ and remote sensing approaches with contributions from Empa (tunable quantum cascade diode laser absorption spectroscopy), ETH Zurich (PCFH), the MeteoSwiss Aerological Station Payerne (RALMO lidar, balloon sounding facility) and IAP (MIAWARA microwave radiometry, 25 - 80 km altitude). This will integrate the PCFH technological development into its future scientific application.

3.2 Meisei GDP (Takuji Sugidachi)

This presentation gave the progress of the Meisei GDP development. The paper about the evaluation of iMS-100 GDP was accepted in AMT journal in October 2022. The technical document for Meisei GDPs (GRUAN-TD5-Rev2) has been written except some minor revisions. Data processing for iMS-100 GDP Ver.2 (GDP.2) has started in October 2022.

Since July 2020, the JMA conducts the dual sounding once a week to characterize these measurements. The preliminary results of intercomparison sounding with iMS-100 and RS41-SG at Tateno was introduced. The JMA will proceed with further analysis in the future.

3.3 Modem M10 GDP (Jean-Charles Dupont)

Jean-Charles Dupont presented an update on the development of the Modem M10 GDP.

3.4 Development of Modem M20 Data product (Antoine Farah)

Antoine Farah presented the status of the Modem M20 radiosonde.

Session 4. Operational matters

4.1 Parallel soundings database augmentation with ancillary data (Dave Smyth)

Dave Smyth provided an update on the draft paper on the parallel soundings database and the addition of ancillary data. To help corroborate and constrain the effects of RS92-RS41 differences using independent instrumentation, sites are being requested to submit data from other ground-based instruments measuring temperature and humidity or covariates which were operational at the time of ascent. The first draft of a Technical Note to guide sites on the procedures to achieve this was circulated to sites preceding ICM-14. Feedback was noted but was felt to be too limited to publish the TN without further input. Consequently, excerpts specific to site operation and resources were presented and discussed in ICM-14 plenary, with an instruction to respond to requests for further comment post-ICM. Once individual feedback has been received and a final pass through the Working Group has been completed, the TN will proceed to publication (anticipated in Q1 2023).

4.2 Standard Humidity Chamber (Michael Sommer)

The SHC and its application in GRUAN was briefly introduced. SHCs were extensively used during WMO radiosonde intercomparison campaign in Lindenberg this year (UAII2022). A robust documentation describing SHC use and benefits is still lacking. Therefore, a peer-reviewed paper and a GRUAN Technical Note should be written during year 2023 and lead authors and co-authors were requested.

Keynote Forum 1: Vision and Plans

The Keynote forums were included to allow broader discussions on the management, planning and future direction of GRUAN. Several presentations provided background information on the subject matter followed by an open discussion. The key discussion points are captured below, and where relevant/necessary, have also been included in the ICM-14 actions. This session focused on Implementation Plans.

GCOS IP (Caterina Tassone)

Caterina Tassone presented the 2022 GCOS Implementation Plan. The Implementation Plan provides a set of high priority actions which, if undertaken, will improve global observations of the climate system and our understanding of how it is changing. It was produced by the GCOS panels experts and a writing team following extensive consultations across scientific communities spanning observations and end users, and an open public review. Based on needs and gaps identified in the 2021 GCOS Status Report, the Intergovernmental Panel on Climate Change (IPCC) 6th assessment report and recent scientific studies on the climate cycles, the 2022 GCOS Implementation Plan presents the major practical actions that should be undertaken in the next 5-10 years to address these gaps. It identifies six major themes that should be addressed. The themes are ensuring sustainability; filling data gaps; managing data; engaging with countries and emerging needs.

Several actions of the GCOS IP are of relevance to GRUAN. Action B1 calls for the development of reference networks (in situ and satellite Fiducial Reference Measurement programs). The GRUAN LC is the primary implementer in ensuring that the development of GRUAN continues. Other actions include call for access to campaign field data used for instrument intercalibration, and improved access to co-located satellite and reference quality in situ observations, as well as tools for evaluation purposes.

GRUAN IP (June Wang)

June Wang gave a summary of the status of the 4th GRUAN IP and unresolved issues. The new version of the GRUAN IP is available after incorporating comments made by the WG. The unresolved issues include the following. (1) The new IP states "By the end of the period of this IP (through 2026), if it is successfully implemented, GRUAN shall consist of:

A network of approximately 35 to 40 sites (at least 25 of which shall have been certified with subsequent regular auditing) that are more globally equitably located." The LC thinks that certifying another 11 sites within the coming 4 years sounds quite ambitious. (2) the list of current and future GDPs needs to be updated, and the target dates for future GDPs need to be agreed upon given the huge amount of time needed for develop a GDP based on past experiences. (3) GCOS Secretariat agreed to revise Section 3 ("THE BROADER CONTEXT OF THE FOURTH GCOS IMPLEMENTATION PLAN") based on the newest GCOS IP. (4) What is the status of "Action 8: Undertake research to understand the effects of scheduling for different instruments and end-uses and provide quantitatively based advice on scheduling"? Is it still relevant and kept in next IP? (5) To keep all TTs active, The TT Sat suggested that each TT should propose an action for next IP period related to the "Science Issues" section. The example for the TT Sat was given. (6) For next IP, what priority 2 variables and beyond should GRUAN target? The new version of the IP and the presentation were provided to GCOS Secretariat for next round's revision.

Discussion

- Should GRUAN only focus on radiosonde GDPs for those variables where gaps in the current observing systems exist, while other "federated" network may contribute to GRUAN if mature products on other ground-based systems is already high.
- GRUAN/GCOS considered primarily to enable climate data series, but GRUAN has operational values (i.e. dedicated GDPs for Satellite CAL/VAL). Is this understood?
- Expanding the network requires better understanding of the needs and benefits of GRUAN, plus what does the operator/data provided get from being involved. What can we do to encourage more countries/NMHS to get involved?
- Scheduling of radiosonde soundings is application specific, but the global network remains fixed around 00 and 12 utc.
- Should GRUAN seek to secure funding for additional stations/measurements/expertise? Current finance model is everything is self-funded.

Session 5. Site visit: The Maido Observatory

The group was taken to visit the Maido Observatory, located at over 2000m, where several instruments allow for comprehensive studies of atmospheric chemistry. On this occasion, the 10-year anniversary of the Observatory and the reclassification of La Réunion to Global GAW station were celebrated.

Several presentations focussed on the impact of the eruption of Hunga Tonga-Hunga Ha'apai.

Injection of unprecedented amounts of water vapor into the stratosphere by the eruption of Hunga Tonga-Hunga Ha'apai (Holger Vömel)

Holger Vömel, Stephanie Evan, Matt Tully

Large volcanic eruptions, although rare events, can influence the chemistry and the dynamics of the stratosphere for several years following the eruption. The eruption of the submarine volcano Hunga Tonga-Hunga Ha'apai on 15 January 2022, injected at least 50 Tg to 100 Tg of water vapor directly into the stratosphere. This event raised the amount of water vapor in the developing stratospheric plume by several orders of magnitude and possibly increased the amount of global stratospheric water vapor by more than 5%. The amount of water vapor transported into the stratosphere was sufficiently large that during the days following the eruption relative humidity over liquid water in the stratosphere reached several tens of percent and became detectable by parts of the operational network using Vaisala RS41 radiosondes. Several soundings using the Cryogenic Frostpoint Hygrometer (CFH) confirmed the extreme amounts of water vapor within the plume. The operational radiosoundings allowed tracking the dispersion of the volcanic plume during the first two months after the eruption and characterizing its vertical distribution. This extraordinary eruption may have initiated an atmospheric response different from that of previous well-studied large volcanic eruptions.

This study has been published in Science at doi.org/10.1126/science.abq2299 and the radiosonde data are available at doi.org/10.5065/p328-z959.

Rapid ozone loss following humidification of the stratosphere by the Hunga Tonga Eruption (Stephanie Evan)

The massive January 2022 Hunga Tonga–Hunga Ha'apai eruption produced major perturbations in atmospheric composition, increasing the stratospheric water burden by 10%. Fresh stratospheric volcanic plume measurements are rare, but unique circumstances allowed in-situ tropical profiles of H2O, aerosols, and O3 at the Maïdo Observatory (21°S, 55°E) within a week of the eruption. Analysis including remote sensing observations of O3, HCl, ClO and NO2 radicals shows chemical O3 loss (-0.5 ppmv between 25-30 km in a week) in the volcanic plume under unusually warm temperatures (T ~ 220 K at 28 km). This rapid loss indicates that heterogeneous chlorine activation is efficient on humidified volcanic aerosols. Although a rare occurrence, better understanding of these processes provide insight on ozone perturbations possible in a world with changing climate.

Tonga Rapid Response Experiment (TR2Ex) (Karen Rosenlof[1])

[1]NOAA CSL, Boulder

Contributors from NOAA Chemical Sciences Laboratory, NOAA Global Monitoring Laboratory, University of Houston, St. Edwards University, LACy&OSUR CNRS/Université de la Réunion/Météo-France

The Hunga Tonga - Hunga Ha'apai volcano, located in South Pacific, erupted on Jan. 13 and 15, 2022, putting significant amounts of material into the stratosphere. The lower stratospheric winds at the time of the eruption were blowing toward the west, with expected transit of the volcanic plume to over Reunion Island in about a week. As there had not previously been fresh in situ stratospheric measurements of a volcanic plume that soon after eruption, efforts were made to bring aerosol and SO2 in situ balloon payloads to Reunion Island immediately after the eruption. Because the personnel at the Maido Observatory had experience and equipment (in part because they do regular GRUAN balloon launches), in conjunction with scientists from the US and France, they were able to execute a rapid response intensive operation period over a 5-night period starting 6 days after the eruption. This also was a test of expanding Reunion Island into a NOAA B2SAP (Balloon Baseline Stratospheric Aerosol Profiles) station, and optical particle counter soundings using the POPS instrument have continued on a bimonthly basis

throughout 2022. Measurements taken showed extremely large water vapor perturbations due to the eruption, and further analysis has shown that the water vapor excess accelerated conversion of SO2 gas to sulfate aerosol, and also showed evidence of rapid ozone loss within the plume. Modeling work is ongoing to understand possible impacts on stratospheric ozone and dynamics over the next few years.

The Early Evolution of the Hunga-Tonga Stratospheric Aerosol Plume observed by Lidar at La Réunion (Valentin Duflot)

A presentation was given by Valentin Duflot.

An overview of research activities at LACy (Joel Van Baelen)

A presentation was given by Joel Van Baelen.

Session 6. Science and Innovation -1

6.1 The impact of analysis of NWS migration to Vaisala RS41 (Tony Reale)

A presentation (remote) was given by Tony Reale.

6.2 Sequential radiosonde launches and their use in satellite data calibration/ validation (Bomin Sun)

Sequential radiosonde launches targeted for NOAA satellites (including both SNPP and NOAA20) at SGP are analysed in terms of their use in NUCAPS sounding retrieval products validation. It is concluded that compared to the synoptic sondes, the sequential sondes, either the earlier (ie, 45-min prior to satellite overpass) or the latter (ie, 5-min prior to satellite overpass) launch, significantly improve the sounding product validation accuracy of atmospheric temperature and water vapor. The profiles directly time interpolated or extrapolated from the sequential sondes to the exact satellite overpass times appear to improve only slightly the validation accuracy in the troposphere. Further effort is needed to improve the time interpolation/extrapolation method to remove the balloon drift effect, which is greater in the UTLS. Also, more work is needed to demonstrate the value of GRUAN processed dedicated sondes in satellite radiance data validation, which is closely relevant to the GSICS program.

6.3 Options for radiosonde launches with EUMETSAT Metop-SG overpasses (Axel von Engeln)

The presentation shortly introduced EUMETSAT's future EPS-SG program and discussed the requirement for collocated radiosonde measurements with satellite overpasses for the calibration of 2 microwave instruments (MWI, ICI) on the B satellite. These sondes are primarily required within the commissioning period of the B satellite, thus within the second half of 2025 (TBC). A longer-term support of satellite calibration and validation with sondes was also discussed. A first analysis of the GRUAN stations and how synoptic times versus overpass times at each station are distributed was shown. The discussion focussed on how GRUAN can support such an activity and noted that currently GRUAN is not set up to provide such a "data service" with a single point of contact for EUMETSAT. The way forward to meet EUMETSAT's single point of contact contract setup was further discussed in working groups, and related actions were raised.

6.4 Effects of inhomogeneities within the Field of View in satellite Water Vapour (Xavier Calbet)

Authors: Xavier Calbet (AEMET), C. Carbajal-Henken, B. Sun, T. Reale, S. DeSouza-Machado

Proof is presented that water vapor concentration at small scales (< 6 km) behave stochastically and can be well modelled as a Gaussian Random Field (https://amt.copernicus.org/preprints/amt-2022-111/). This behaviour has a measurable impact in the modelling of the radiative transfer as measured from satellite instruments (https://amt.copernicus.org/articles/11/6409/2018/). The radiances that satellite instruments measure can be well modelled by feeding as input to a radiative transfer model the data acquired from two GRUAN processed sequential sondes. Sequential sondes are two consecutive sondes launched approximately 50 and 5 minutes before satellite overpass time. These calculated radiances compare well with the measured ones from hyperspectral infrared and microwave satellite instruments. Despite of this, some residuals still remain. These residuals can be removed when considering the variability of water vapor concentrations within the field of view of the satellite instruments. Once this is done, the residuals follow very tightly a Gaussian distribution with a standard deviation equal to one sigma satellite instrument uncertainty. This, in turn, implies that co-location and GRUAN sonde uncertainties are negligible in these comparisons. It is also shown that this effect can produce a permanent bias onto the hyperspectral infrared or microwave derived vertical profiles of water vapor concentrations.

6.5 Preliminary information on VICIRS (Domenico Cimini)

The presentation introduced the project "Development of VIcarious Calibration tools for MWI and ICI using RadioSoundings" (VICIRS), recently awarded for funding by EUMETSAT. The project will start Dec 6th (kick-off) and will go on for 14 months. There were presented the team, aims, approach, methodology and tasks. Two sets of radiosounding data sources will be considered: GRUAN and the Copernicus Climate Change Service (C3S), Radiosounding HARMonization RHARM (Madonna et al., 2022). The latter contains adjusted radiosounding observations of temperature, humidity and wind with estimated uncertainties, building on GRUAN expertise and intercomparison data from ~700 sites (including ships). As radiance simulator, the project plans to use the GRUAN processor (Carminati et al., 2019), updating the modules (RTTOV and RadSim) to most current versions. The first task will review the state of the art of methods, including collocation criteria, clear-sky screening, surface emissivity screening, dimension of target area. Results from the project will be presented at ICM-15.

6.6 Interpolation Uncertainty for RS41 and GNSS-R (Alessandro Fassò)

RS41 - Review

Recently, the interpolation uncertainty for missing data imputation of T and RH has been considered for RS41 providing both the method and the assessment for small to medium gaps. Interpolation uncertainty for these ECV is available as LUT and/or GP based formulas: this is implementable in a future GDP version and extendable to other (all?) RS41 variables, updatable on the more recent and extended RS41 dataset, easily adaptable to RS92.

GNSS-RO - preliminary results

I consider the interpolation of GNSS-RO at ERA5 levels and its uncertainty in collaboration with Kalev Rannat and Hannes Keernik. Our approach is framed in the more general concept of the collocation uncertainty budget, which includes, among others, difference in smoothing, spatial displacement, and temporal delay. The comparison of GNSS-RO and RS has been considered recently. In this preliminary study, T and RH were considered from 215 GNSS-RO retrievals collocated to Lindenberg site in year 2016. Each GNSS-RO profile has 60 pressure levels. Another 215 high-resolution GRUAN RS41 profiles with raw data for T and RH are used as the "truth" and filtered at the same 60+37 RO and ERA levels to mimic the GNSS-RO dataset from the interpolation point of view. The idea is to use a measurement error model with stochastic local linear dynamics in the frame of state space models and Kalman filter. This

allows to embed measurement uncertainty of RO in the interpolation algorithm and to propagate it into the interpolated values.

Preliminary results based on above data show the viability of this approach and suggest to analyse it further. In particular: to use RS41 GDP data and their uncertainty, to analyse RH, to compare KS and GP formula for uncertainty, to extend to other GRUAN stations and other ECVs, and to consider pressure uncertainty.

1. Fassò et al., 2020, AMT. https://doi.org/10.5194/amt-13-6445-2020

2. Colombo & Fassò, 2022, MST. 33, 074001. https://iopscience.iop.org/article/10.1088/1361-6501/ac5bff/pdf

3. Tradoswky et al, 2017, https://www.jstor.org/stable/26179972

4. Nielsen, J. K. et a., 2022, AMT, https://amt.copernicus.org/articles/15/6243/

6.7 The GDP for the multidisciplinary drifting observatory for the study of arctic climate (MOSAIC) (Marion Maturilli)

Marion Maturilli reported on the radiosonde GDP data set for the for the 'Multidisciplinary Drifting Observatory for the Study of Arctic Climate' (MOSAiC). The MOSAiC expedition took place October 2019 to September 2020, with the research vessel Polarstern frozen into the Arctic Sea ice to follow the transpolar drift for an entire annual cycle. In an enormous logistic endeavour involving several hundred researchers and technicians from 20 countries, observations of atmosphere, ocean, sea ice, ecosystem and biogeochemical cycle were operated in the Central Arctic, including the launch of more than 1500 radiosondes. The 6-hourly radiosonde launches were done according to GRUAN standards, involving the SHC, meta data documentation and data collection by the RSLaunchClient software. After the return of the expedition, the data were processed at GRUAN LC to obtain a time-limited but spatially outstanding GDP of the Central Arctic. The first processing version has been used to contribute to the evaluation of the GDP Beta version. Some examples of the first GDP were shown, highlighting the temperature uncertainty in different seasons and in different altitudes of the profiles. It was pointed out that the uncertainties are largest in the lowermost part of the profiles, just after the balloon launch. In particular, problems of the GNSS altitude values - likely related to reflected GNSS signals in the vicinity of the ship's metal body and at the snow/ice surface - were discussed. The MOSAiC GDP data set is made available via the PANGAEA data repository at https://doi.pangaea.de/10.1594/PANGAEA.943870. The data are subject to the MOSAiC data moratorium until end of 2022 but will be open access from 1 January 2023.

6.8 Improvement of temperature and humidity data quality from RALMO, validation of the uncertainty budget and advanced experiments towards operational simulation (Gianni Martucci)

An overview of the transceiver system of the Raman Lidar for Meteorological Observation (RALMO) is provided along with the procedure to define the different error contributions stemming from RALMO acquisition system and from the atmospheric disturbances to the measured signal. The systematic and random error components are combined into the overall error of the retrieved humidity (q) and temperature (T) products. The overall errors σ_T and σ_q are validated via direct comparison with co-located Vaisala RS41 radiosounding at 23:00 UTC. A case-based way to validate the errors σ_T and σ_q is by calibration of *T* and *q* and the assessment of the distribution of the differences T_{RAL}-T_{RS41} and Q_{RAL} – Q_{RS41} with respect to $k\sigma_T$ and $k\sigma_q$ for k=1 and k=2. More than 90% of the differences distribute within k=1 and 99% lie within k=2. Finally, a 13-month validation of q and T profiles is performed by direct comparison with the Vaisala RS41 at 11:00 and 23:00 UTC. The comparison shows the mean

bias and standard deviation of the differences T_{RAL}-T_{RS41} and Q_{RAL} – Q_{RS41}. The daytime and nighttime mean bias is consistent with the zero-bias for both T and q. The calculated total errors σ_T and σ_q are consistent with the standard deviation of the differences T_{RAL}-T_{RS41} and Q_{RAL}-Q_{RS41}, respectively, for both daytime and nighttime statistics. The validated T_{RAL}, σ_T and Q_{RAL}, σ_q have been assimilated into the COSMO-1E model for dedicated experiments demonstrating a clear positive impact for total precipitation forecasts at different lead times. The T and q from RALMO are ready for operational assimilation into COSMO-1E.

6.9 Progress with humidity time-lag experiments for radiosonde RH sensors in GRUAN (C. von Rohden, GRUAN Lead Centre, Meteorological Observatory Lindenberg, Germany)

Large response times of radiosonde relative humidity sensors at low temperature cause time lags and smoothing in measured profiles, which may lead to considerable systematic errors. This applies in the cold regions of the upper troposphere and especially in the tropopause in presence of strong vertical humidity gradients. To correct this effect, the sensor-characteristic response times at different temperatures are measured using an experimental laboratory setup, developed at the Lindenberg site in the framework of GRUAN. Step changes in relative humidity are created in an air flow to which radiosondes are exposed, and the response of the humidity sensor to these changes is recorded at various temperatures between −74 °C and ambient. The setup has recently been further developed, with improved temperature stability and humidity step sizes, and a high reproducibility is achieved for response time measurements in both step directions.

New measurements for the Vaisala RS92 and RS41 radiosondes give consistent results for the response time parameter τ and its relation to temperature. The results disclose small but systematic deviations of the measured sensor behaviour from the simple step response model that is used to estimate τ. Also, at least for the RS92, the measurements indicate systematic deviations of the response time for upward and downward humidity steps. For both sondes, it turns out that the commonly used simple exponential parametrisation does not adequately describe the relation of the response time to temperature. The setup is ready for routine measurements and is currently in use for tests with radiosondes of various manufacturers as part of the WMO inter-comparison campaign (UAII2022).

Session 7. Task Team Reports

7.1 Radiosonde TT - Justification for high ascent attainment (C7) (Masatomo Fujiwara)

Progress and issues on task C7, Justification for high ascent attainment, were discussed. A journal paper draft has been partly written. The sections where more expert inputs are needed have been identified. Many suggestions were provided during the discussion time.

7.2 Sites Task Team (Marion Maturilli)

At the start of her presentation Marion said ‘Goodbye and thank you’ to Dale Hurst who had stepped down as co-chair of this task team following his retirement. The new co-chair for Site task team is Richard Querel, and the meeting welcomed Richard into his new role.

The main activities were:

- A survey on the use of R23.
- A Survey on cloud observations: several recommendations given on the future reporting of cloud observations by the sites.

- Support to the draft on "Parallel sounding database augmentation with ancillary data". Although this still requires additional feedback from GRUAN.

On this last point it was suggested that if the sites have data that are publicly available, they could provide the metadata and they do not need to submit time slices of these data again to GRUAN. Also, those sites that don't have ancillary data publicly available will have a considerable amount of work. There are questions that need an answer, such as whether these ancillary data requested are time sensitive, whether they should only be made available for parallel radio soundings or also for satellite collocation or for each soundings and what kind of QC should be applied.

It was noted that the objective of these database is to manage transition, so at the moment this should be an internal database, with a limited number of variables and limited to the parallel soundings.

GRUAN as a community needs to discuss and decide the purpose for this and what is consequently the request, which then will have to be included in the information document for the requirements for new sites.

7.3 Scheduling Task Team – Uncertainty terminology and presentation in GRUAN Products (C4) – Tom Gardiner

Tom Gardiner provided a summary of recent activities relevant to the Measurement Scheduling and Combination Task Team with a particular focus on uncertainty reporting. These included presentations at the 2nd GCOS conference and involvement in the atmospheric theme of the BIPM-WMO workshop on Metrology for Climate Action which will lead to recommendations for future metrological activities in this area. Two particular areas were highlighted which address key GRUAN objectives: the work on Radiosonde Harmonisation (RHARM - Madonna et al., 2022, JGR) which applies GRUAN-derived adjustments to improve the quality of data from the Integrated Global Radiosonde Archive; and a study of how the derivation of traceable measurement uncertainties for near-surface temperature measurements from the US Climate Reference Network (USCRN) enables an assessment of the uncertainty in meeting extreme event criteria, increasing the confidence in the estimation of climate indices.

The talk then described work on a paper on 'Uncertainty reporting in reference upper atmospheric measurements' which aims to address the challenge of providing information on the measurement uncertainty in a way that is accessible and usable to the wide range of potential applications and interested user groups, with an example uncertainty reporting assessment of the Vaisala RS-92 radiosonde temperature GDP. A major challenge is the wide range of timescales for GRUAN data uses from single point measurements through to long-term trends, and how to estimate and report uncertainty over this range. Understanding and evaluating the uncertainty correlations is key to addressing this issue.

7.4 Ground-based Task Team (Nico Cimini)

The presentation gave an update on activities of the GRUAN Task Team on Ground-Based Remote Sensing Measurements (TT-GB). TT-GB oversees the integration and production of ground-based measurements from lidar, microwave radiometer (MWR), and infrared remote sensing techniques, in compliance with GRUAN best measurement practices.

Concerning MWR, TT-GB suggests following the development of the activities towards the implementation of ACTRIS (EU long-term research infrastructure dedicated to atmospheric monitoring) and E-PROFILE (atmospheric profiling programme of EUMETNET). Both ACTRIS and E-PROFILE networks include MWR instruments, and all GRUAN sites in EU belong to either or both ACTRIS and E-PROFILE.

The development of the MWR GDP will benefit from the outcome of the above activities in terms of expertise, best practices, and data life cycle. The update of the MWR GDP technical document (TD) is postponed to when the MWR GDP will be more established.

Then, plans for the analysis of MWR data collected during the WMO 2022 Upper-Air Instrument Intercomparison Campaign (UAII-2022) were presented. Two MWR (both HATPRO type) were operated. The data set has been collected at DWD and will be analysed by Meteoswiss to evaluate the MWR data products against the products from operational and dedicated radiosondes (>4 per day). The work is in progress and the first results can be expected early next year.

Concerning lidars, as of autumn 2022, the standardized lidar data processor GLASS has been producing test water vapor retrievals for the prospective GRUAN lidars at the sites of Ny Aalesund, Payerne and Cabauw. Pending a fully automated raw data transfer between the sites and the GRUAN Lead Center, a more systematic processing of the data is anticipated. A peer-reviewed manuscript describing GLASS is near completion, and a draft version of Best Measurement Practice Guide for GRUAN Lidars is already available.

There is currently no activity to report for the infrared instruments (FTIR and AERI).

7.5 GNSS-PW Task Team (Kaley Rannat, Jonathan Jones)

A short overview was given about TT activities and plans since ICM-13 and about GRUAN GNSS stations in routine processing and the sites still on a waiting list (as in November 2022). No changes have been made in membership of the TT.

The GNSS TT has worked on topics listed on the GRUAN Master Action Item list re-scheduled after ICM-13:

- Action C9 GNSS GDP format
- GFZ to progress provision of a netCDF format version of the GNSS GDP
- Status: in progress (mostly completed). Detailed overview was given by Galina Dick (GFZ).
- Action C10 Metrological closure of GNSS-IWV and radiosondes

For GRUAN sites that perform both GNSS-IWV measurements and radiosoundings, the comparison of the GRUAN data products (and their respective uncertainties) for these data streams is needed to establish whether metrological closure is attained.

Status: in progress. Detailed overview was given by Galina Dick (GFZ).

Given the plans and questions for the near future, the objectives are the following:

- Finalize and publish an article on GNSS and RS metrological closure;
- Continuously improve GNSS data flow and quality management overview (for GRUAN GNSS GDP users). It is essential better to convince the end users of the high quality of the GDP and conformity with the requirements reported in the TD6 (https://www.gruan.org/documentation/gruan/td/gruan-td-6). Some ideas for data quality management and visualization could be taken from other GNSS reference networks, but GRUAN must find its own way to visualize the most essential steps of QC and data processing for the GDP.
- Improve GRUAN GNSS sites' maintenance. Not all (mostly none) GRUAN GNSS sites belong to any national or continental geodetic networks - they (potentially) miss regular technical surveillance. A lot, but not everything can be done remotely. The question is – who maintains or who should maintain GRUAN GNSS sites, is it or will it get regulated? It is also a question of finances; the surveillance and maintenance must be done professionally.

Providing data with high quality (for being at a level of a reference site) needs regular care and attention. GRUAN needs high quality.

- Exploit connections to similar related initiatives (like GRUAN RS in Copernicus C3S https://cds.climate.copernicus.eu/cdsapp#!/dataset/insitu-observations-gruan-reference-network?tab=overview)?

7.6 Sat Task Team – Satellite data collection with RS92/41 pairs (A2) (Lori Borg/Axel von Engeln)

TT-SAT co-chairs, Axel Von Engeln and Lori Borg, presented an update of TT-SAT activities including progress with task A2, which is the effort to provide the lead centre (LC) satellite data coincident with the dual radiosonde (RS92/RS41) database. TT-SAT is currently composed of 12 active members from a variety of international, academic, government, and private sector institutions. Task A2, which was initially raised at ICM-9, remains to be completed. Fulfilling this task is quite complex and many questions remain regarding which satellite data (infrared, microwave, radio occultation), satellite data products (level 1,2,3), and colocation criteria (e.g. 1 hours and 100 km) should be used. There is also the need to build flexibility into this system to accommodate reprocessing of satellite data sets. To make progress on this task two paths forward were presented. The first path forward involved leveraging the NOAA Products Validation System (NPROVS). NPROVS routinely compiles datasets of collocated radiosondes and satellite sounding products. Efforts are underway by Tony Reale and Bomin Sun to make NPROVS files available to GRUAN for the RS92/RS41 database, but this is a large task. It is also not clear that storing satellite data at GRUAN is the best solution to this task. TT-SAT is now recommending a second path forward which involves enhancing the capabilities to query the GRUAN database of radiosondes. It is envisioned that a user would be able to query the GRUAN radiosonde database for radiosondes that fit a variety of searchable parameters including satellite colocation criteria. The user would then be able to use this information to identify cases to assess and then get the satellite data directly from the satellite data archives, like the NOAA data archive, CLASS. This functionality is envisioned to reside at the LC and would make the GRUAN radiosonde archive more relevant/usable to the satellite community. TT-SAT has taken an action to work with the LC on this effort. Last, an overview of the Radiosonde Intercomparison & VALidation field campaign was presented. This campaign was a joint GRUAN/JPSS/ARM IOP with a focus on the RS92/RS41 transition at the ARM field sites at ENA, NSA, and SGP. The campaign began in February 2018 and was completed in January 2022. RIVAL sonde launches were coordinated with NOAA20 overpasses of the field sites. The RIVAL team will be analysing this data set in the coming months.

Keynote forum 2 – GRUAN Evolution

This session focused on evolution of GRUAN.

View by Task Team sites (Marion Maturilli)

Benefits: Transfer of knowledge to other measurements program at the same site; exchange with other sites; exchanging info on site management; GRUAN DP fundamental for climate series.

Expand sites: Advertise the benefits of belonging to GRUAN. Beneficial to have sites where research is done. Decision on whether sites should be chosen only for their RS program or for having a large facility equipped with several ground-based remote sensing instruments. A lot of sites are already sharing measurements and products with other networks they are contributing to. Among these stations, those not contributing to GRUAN will not see the benefit of belonging to another network. Push more for distributed sites. The additional work/resources required by GRUAN could prevent some sites to join. So, sites must be clear

on the benefit. It would help if the procedure to join GRUAN could be simplified, for example it takes 5-10 years to have a GDP. We need to decide how to simplify procedures without compromising the quality. Look for synergies with existing network (e.g. EARLINET, NDACC) that could be used so that sites do not need to start from scratch.

The GRUAN processing of radiosondes GDP is unique. However, for other instruments there are high-quality products already developed and made available by other networks, so what is it the added value from GRUAN? Added value might be the availability of clear documentation and transparent data processing, where no site-specific routines are applied.

Future of GRUAN:

1. Getting more sites
2. How to go on with the different GDPs that are being developed

View by Lead Center (Ruud Dirksen)

Ruud provided a short summary of his view on the evolution of GRUAN.

GRUAN-GSRN Connection

Tim Oakley provided a summary of the work to implement a GCOS Surface Reference Network (GSRN). The key points of this presentation were as follows:

- GSRN could be considered as a future sibling of GRUAN. GRUAN has been used as a 'expert reference/example' in much of the development of the GSRN system.
- The initial GSRN will focus on only two ECVs (temperature and precipitation).
- Initially this will be a pilot network before implementing an 'operational' GSRN.
- GSRN fully embedded with WMO (tiered network, access to WMO members)
- It will publish procedures and practices (knowledge transfer)
- Identify GSRN affiliated research facilities delivering scientific advances in measurements technique (Difference with GRUAN)
- Governance in place. Science and research is expected to be carried out through a dedicated team, in collaboration with BIPM and WMO SC-MINT.
- Does GRUAN need to relook at what was done 10 years ago and see whether is still fit for purpose?
- Requirements for temperature and precipitation measurements in place, with associated quantified of influence.
- Possible links with GRUAN: Shared best practice and knowledge (vice versa); Integrated site (several GRUAN site could be GSRN sites); Consistent data products; and Joint meetings and workshops to benefit from each other.

Discussion

- Do stations need to go through the country Permanent Representative (PR)? Preferences to go through the PR that represent the country and not the Met Service.
- Funding model limited, who runs the station needs to pay. The research community is being helped by BIPM. So, there is no trust funds that will pay for that.
- GSRN stations are likely to be fully automated, with a relevant maintenance, precipitation (monthly), temperature (6-monthly) etc.
- There is more support in the governance from WMO and Secretariat. Perhaps facilitate meeting of task teams (GCOS Secretariat) so that they will have meetings in between ICMs.

- GRUAN needs to be more coordinated effort in terms of science and research, to avoid duplication and be more effective.
- Identify clearly what is the added value for being in GRUAN? Uncertainty, collocation.
- Sustained operation: make the case with the EU, the satellite agencies
- Long term funding has never been resolved: how can we better coordinate within ourselves?
- Regular radiosonde soundings are not possible for everyone; it could be feasible to be associated to sites close by where RS are regular.

Breakout Groups

The meeting split in 3 breakout groups: Satellite collocation issues, quality flags and uncertainty and sites (including R23, helium and hydrogen balloons).

Breakout Session - Satellite Collocations

Summary of Discussions:

Five topics were discussed during the ICM-14 breakout session on Satellite Collocations. These topics included; 1. The EUMETSAT radiosonde effort, 2. General satellite collocation, 3. The use of ground-based measurements for satellite validation, and 4. How to support the sonde height attainment paper. Discussion of topic-1, the EUMETSAT radiosonde effort, also occurred with the members of the breakout session on sites. TT-Sites took 2 action items regarding this topic. TT-Sites will survey the GRUAN sites and determine which sites could accommodate these launches, costs, and whether the sites are set up to receive funding. TT-Sites will also talk with the Lead Center (LC) regarding pros and cons of different funding mechanisms for this effort. A general discussion occurred regarding how satellite collocations are performed, topic-2, and what are the best practices. TT-SAT took an action item to organize a telecon with interested individuals to discuss this in more detail. Use of ground-based measurements for satellite validation, topic-3, was also discussed and TT-SAT took an action item to raise awareness for the need for ancillary ground-based remote measurements during satellite validation campaigns. The last topic discussed was the sonde height justification paper, topic-4, being written by Masatomo Fujiwara. An action item was added for Lori Borg and Nico Cimini to follow up with Masatomo to support this effort by showing the impact of sonde height on RT calculations in the infrared (Lori) and microwave (Nico). A separate discussion with Masatomo occurred after the breakout session and steps were outlined for how to proceed with these calculations. In addition to the four topics listed above, TT-SAT took an additional action item to work with the LC to improve the search capabilities of the GRUAN radiosonde database with respect to satellite overpasses.

More detailed notes regarding these discussions can be found in the following document: https://docs.google.com/document/d/133nzwm5aW2VEYKeHME19g4SOYVrkj_ZZRhPnExXhykw/edit?usp=sharing.

Break-out session - Quality Flagging, Interpolation and Uncertainties discussion

Summary of Discussions:

The breakout session on quality flagging, interpolation and uncertainties was divided into two parts: the first covered the interpolation of data in GRAUN Data Products (GDPs) and the data quality flagging associated with it; the second covered the common requirements for uncertainty reporting across GDPs.

The discussion on data interpolation built on the paper led by Alessandro Fassò and considered the requirements for different variables, starting with RS41 measurements of temperature. The current situation is that a gap of up to 10 secs can be filled through interpolation with a

correspondingly increased uncertainty. Such gaps occur in a large proportion of profiles and are generally linked to telemetry. During the discussion, it was agreed that the 10 sec limit was reasonable.

In terms of the quality flagging, there should be clear flagging in the 'temp_raw' files as to which individual measurements were missing due to telemetry or due to other reasons (e.g. outliers). Since interpolated data may be smoothed in the final 'temp' output, there should then be flagging in the 'temp' file to indicate all final data points that are influenced by interpolated data. It was also noted that the current 'temp_raw' files include the interpolated data and there was a recommendation that this should be changed so only the raw 'as-recorded' data was listed in this file.

The situation for water vapour is more complex due to its high variability and the changing vertical resolution of the measurements because of the increasing time-response during an ascent. It was agreed that some form of variable interpolation criteria may be required but there was insufficient information for this to be defined at this point. Examples of the impact of missing water vapour data points at different altitudes would help with this.

The methodology developed for the two RS41 variables should then be applied to other parameters such as pressure, altitude, GPH, latitude, longitude and wind and to other GDPs.

The uncertainty discussion resulted in the general agreement that all GDPs should report the following top level uncertainties with all data points:

- The full uncertainty for that point
- The random uncertainty component (uncorrelated uncertainty)
- The temporal systematic component (temporally correlated uncertainty)
- The spatial systematic component (spatially correlated uncertainty) – only relevant to profile measurements.

The supporting information and metadata should provide a more detailed breakdown of the specific uncertainty contributions relevant for each GDP including, where available, information on the relevant correlation lengths. It was agreed that reporting associated representativeness/collocation uncertainties was out of scope, but case studies and possibly tools covering more complex uncertainty application would be of value. It was also agreed that a common variable naming convention, including uncertainties, should be agreed for use across all GDPS.

Break-out session – Sites

Summary of Discussions:

Helium/Hydrogen: Helium shortage is still a problem at some sites and some sites operate with hydrogen. The groups discussed the requirements for changing from helium to hydrogen. Sites representatives shared their experience. There are safety issues on the ground, such as for the Hydrogen generators, the Hydrogen bottles that require two people, and there are regulations for flying, such as in USA where sites need exceptions to be allowed to fly hydrogen balloons. It was decided that the TT sites, led by Richard Querel will produce a TN on SOPs for the operation of balloons with hydrogen by June 2023.

R23 Replacement: After discussing the alternative of dry ice/ethanol CFH instruments, the groups decided the following action plan:

- By the end of December 2022: check with manufacturers for availability of test instruments.
- By 05/2023: Test flights with dry ice / ethanol CFH instruments at a tropical site. (REU/Costa Rica) – Holger Vömel, Stéphanie Evan

- By 06/2023: Test flights with dry ice / ethanol CFH instruments at a midlatitude site. (BOU/LIN) - Troy Thornberry
- By 12/2023Test flights with dry ice / ethanol CFH instruments at a high-latitude site. (SOD) - Holger Vömel, Rigel Kivi

Session 8. Science and Innovation – 2

8.1 Concept of a campaign of atmospheric characterization at ESO sites in Northern Chile (Florian Kerber)

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The European Southern Observatory (ESO) is an intergovernmental organization established in 1962 with the mission to design, build and operate advanced ground-based observatories, and to foster international collaboration for astronomy.

While the ESO headquarters is located in Garching, close to Munich, Germany, all our telescopes are currently located in the Chilean Atacama Desert, as it offers excellent conditions to observe the sky. ESO operates three observatory sites in Chile: La Silla, Paranal with the Very Large Telescope (VLT) and Chajnantor, the ALMA site. In addition, ESO is building the world's biggest optical/IR telescope, the Extremely Large Telescope (ELT), located on Cerro Armazones, which will be operated as part of the Paranal Observatory. Finally, ESO will be a partner of the Cerenkov Telescope Array (CTA) organization, as it will host its Southern array currently under construction in the valley between Paranal and Armazones.

ESO, in addition to its on-going routine monitoring of the atmospheric conditions over its observatory sites, is designing a dedicated campaign in 2024/25 to characterise the properties of the atmosphere that are relevant for astronomical observations and weather forecasting. ESO plans plan to combine data from in-situ measurements (radiosondes, UAVs) and ground-based remote sensing equipment. In its conceptual stage the campaign calls for one or two 10-day periods of two radiosonde launches (one day/one night) per 24 h period from the CTA site (2100 m asl) with fixed sensors on Paranal (2635 m) and Armazones (3046 m). The following instruments and sensors will be available in support of the campaign: Automated Weather stations (4 sites), Microwave radiometers (temperature and humidity profiles, PWV, 2 or 3 sites), LIDAR (aerosols, water vapour, 1 or 2 sites), all-sky cameras (aerosols, transparency, clouds, 2 sites), MASS-DIMM (turbulence, Cn2 profiles, 2 sites), and possibly a GNSS network. Combined with a high-fidelity local weather forecast we will be able to characterise a ~20 km slab of the atmosphere within the triangle confined by the three main sites to obtain a comprehensive multi-parameter data set at this hyper-arid location in the Atacama desert.

In order to make this data set even more valuable we solicit input from the atmospheric, meteorological and climate communities and specifically from the GRUAN network. We intend to produce GRUAN data products to ensure that these observations can be compared to existing data bases and can be used by other interested parties. We would be interested in hosting additional equipment (including experimental ones, e.g. CFH without RS23) provided by the community and to coordinate the radiosonde launches with other activities such as satellite overpasses.

ESO will provide the relevant logistics for the campaign (power, internet, help by trained technicians etc...) but also support for customs procedures for bringing hardware to Chile or accommodation for staff operating additional equipment. We invite all interested parties to get in touch and be part of the planning of the campaign in order to get the best possible return

for our communities. ESO is committed to sharing all relevant data (either historical data from our archives or produced during the campaign) on the basis of scientific collaboration (no commercial exploitation) but is also open to dedicated agreements with additional partners for their specific purposes, as needed. We welcome your input and support and encourage you to contact the main author by 1.3.2023, via email: fkerber@eso.org.

*ESO is supported by 16 Member States (Austria, Belgium, the Czech Republic, Denmark, Finland, France, Germany, Ireland, Italy, the Netherlands, Poland, Portugal, Spain, Sweden, Switzerland and the United Kingdom), our host country Chile and strategic partners.

8.2 Direct validation of radiosonde data against radio occultation bending angles (Axel Von Engeln)

The presentation discussed the possibility to forward propagate temperature, pressure, water vapour sonde information to bending angles, so that radio occultation (RO) measurements can be compared to sonde data in bending angle space. This removes the need of processing the bending angles to refractivity and temperature, water vapour, which introduces smoothing and requires a priori data. Such an approach is in particular interesting to support RO data in the lower troposphere, where the data quality is impacted by e.g. low Signal-to-Noise ratios, high atmospheric variability, super-refraction. But it can also be used to analyse the complete sonde profile directly, retaining the high resolution of sonde and RO. Simulations using ECMWF data, that were selected at representative sonde locations and times, and either used a complete (representing the full atmosphere), or cut at the maximum sonde altitude found at that time/location sonde profile, showed that a bias free comparison is possible below about 25km. An analysis of AWI Polarstern sonde data showed that the currently accessible format/accuracy is insufficient to draw conclusion; GRUAN v2 RS92 data on the other hand showed consistent results against collocated reprocessed GRAS RO data, albeit with a small negative bias. The discussion focussed on the negative bias found, and suggested to analyse also RS41 data, as well as to split sonde data into day and night ones. In addition, an option to provide AWI data with higher accuracy format was discussed.

8.3 Empirical estimation of uncertainty in radiosondes, radio occultations and model forecast with the Three Cornered Hat method (Johannes K. Nielsen)

The Three Cornered Hat (3CH) method allows separation of the random errors of three independent data sets, representing measurements of the same physical variable. The method has been generalized to also provide spatial error correlations of the individual data sets. Results were presented from an application where the generalized Three Cornered Hat (G3CH) were used to obtain refractivity error covariance matrices for three collocated data sets. The three data sets were: ERA5 forecast, radio occultations (Metop and COSMIC-1) and the RS92 GDP v.2.

Temperature error covariance matrices were then estimated from these collocated data sets with the G3CH. The ERA5 forecast was interpolated to the RS92 locations, and chosen in such way that neither RO or RS92 data could have influenced the used ERA5 forecasts through data assimilation. Collocation uncertainties were removed by performing G3CH on a series of data subsets with increasingly restrictive collocation criteria, and thereafter extrapolating error covariance matrices to zero collocation distance. All data sets were vertically smoothed to match the vertical footprint of ERA5, which was estimated to approximately 500 m. The resulting estimate of RS92 random uncertainty at a vertical scale of 500 m was estimated to 0.4 K (standard deviation), at an altitude of 8 km where the collocation is optimal. This RS92 random uncertainty is expected to be an overestimate because of differences between horizontal footprints of the 3 data sets.

8.4 Calibration of radiosonde humidity sensors using upper air simulator and applications to soundings (Sang-Wook Lee[1])

[1]Korea Research Institute of Standards and Science

The upper air simulator (UAS) developed at the Korea Research Institute of Standards and Science (KRISS) was used to test humidity sensors of radiosondes at low temperatures. The humidity generation was demonstrated in a two-temperature mode in which the temperatures of the saturator and the test chamber are controlled independently. The test range in terms of the temperature, dew/frost-point temperature, and relative humidity (RH) is –70 °C to +20 °C, –80 °C to +20 °C, and 5% to 100%, respectively. The total combined uncertainty of the UAS humidity generation is within 1.0 %RH at a coverage factor k = 2. The calibration of humidity sensors of Vaisala RS41 and dual thermistor radiosondes (DTR) was demonstrated. The maximum difference between the humidity measured using the RS41 sensors and UAS reference humidity is approximately 3 %RH at –67 °C, which gradually decreases to approximately 1 %RH as the temperature is raised to 21 °C. The repeatability of a single RS41 unit and reproducibility of three different units are 0.5 %RH and 0.9 %RH, respectively, in terms of the standard deviation. In the same calibration range, the residual of the DTR was within 3 %RH. However, it was slightly increased to 4 %RH when the calibration at 20 °C was used for estimating the low temperature effect down to –67 °C. In dual sounding tests of the RS41 and the DTR, the humidity measurement of the DTR was lower than the RS41 by about 5 %RH on average at night-time in the troposphere probably owing to a difference of low temperature effects. In stratosphere, the difference between two radiosondes was mostly due to the delayed response time of the DTR. At daytime, the humidity measurement of the DTR was significantly dry-biased due to the heating of humidity sensors. The compensation of the dry-bias is under study using the radiation correction setup of the UAS at KRISS. Realizing the calibration of commercial radiosondes by using the UAS can enhance the traceability to the International System of Units and emphasize the role of metrology for meteorology and climate research.

8.5 Combining the RS41 with CFH's Golden Points for reference quality humidity retrievals and latest progress with PCFH (Yann Poltera)

Yann Poltera[1], Beiping Luo[1], Frank Wienhold[1] and Thomas Peter[1]
[1]ETH Zürich, Zurich, Switzerland

Chilled mirror hygrometers (CMHs) allow to measure the dew point or frost point of air, i.e. they provide information on the degree of saturation of the air with respect to the condensed phases of water. To this end, they determine the thermodynamic equilibrium of their condensate through measurements of the mirror reflectivity. This reflectivity information allows to

(i) identify points when the mirror is in equilibrium with the gas phase, the so-called "Golden Points";

(ii) correct the data for non-equilibrium conditions between the Golden Points.

Concerning (i), we identify the chilled mirror data points, which are in thermodynamic equilibrium, as the points when the mirror reflectivity reaches an extreme value, i.e. either a maximum or minimum (assuming 5 s equivalent smoothing to reduce electronic noise). For the CFH instrument, we estimate that at these extreme points, the mirror temperature is indeed the frost point with an accuracy better than 0.2 K. These accurately (to within 0.2 K) determined frost points can be used to detect and correct offsets, biases and time-lag errors in other instruments flown on the same payload, such as the FLASH-B hygrometer or the RS41 radiosonde.

Concerning (ii), we correct the chilled mirror data points that are not in thermodynamic equilibrium by using the data from the accompanying radiosonde as a priori reference (after it has been corrected for residual bias and time-lag errors by means of (i)).

From a set of 70 night-time CFH-RS41 soundings launched between 2016 and 2020, we found that the deviations between the reported mirror temperature and the estimated true frost point are typically better than 0.5 K. However, in situations where the mirror temperature deviates significantly from the true atmospheric frost point, deviations larger than 5 K are possible. In these cases, the non-equilibrium correction may remove 80%-90% of the non-equilibrium error.

We have also derived an improved time-lag and bias correction for the RS41 radiosonde, based on CFH's Golden Points. This new empirical sensor model accounts for time-lag over-correction errors, especially between 205 K and 227 K sensor temperature, and for dry biases at low temperatures and/or very dry conditions in the RS41 humidity vendor product.

8.6 Implement GRUAN's procedures on our Faa's radiosounding station in the South Pacific. (Patrick Jann)

The Faa'a station is located in French Polynesia in the middle of the South Pacific. French Polynesia has 117 islands in an area the size of Europe. The radiosonding station is located on the largest island in this area is the island of Tahiti. The international airport of the island of Tahiti is located in the city of Faa'a in the northern part of the island. Our observation station is located in the airport area between the airport runways and the edge of the lagoon.

Due to its geographical position, the Polynesian climate is tropical with a humid maritime type. There are generally two main seasons:

- From November to April, a so-called "hot" season or southern summer which corresponds with higher humidity;
- From May to October, a so-called "cool" season or southern winter that corresponds with less humidity.

Tahiti's climate is of the humid tropical type. The annual cycle is well marked. It is characterized by heavy rainfall in the hot season, which often becomes light in the cool season. The rainy season begins in November and ends in April. December and January are the wettest months. Temperatures are warm but not excessive (annual average of 26°C at Faa'a).

We started doing the first manual radiosoundings in Faa'a in 1957. We automated the radiosonding station in October 2018. We perform two radiosondings per day: 00 UTC and 12 UTC all year round with M20 sondes.

We have a GNSS station just a few metres from the radiosonding station which allows us to obtain hourly data from ZTD and to compute the quantities of atmospheric water vapour.

The advantage of the site is that it is located in an area where there are few observations: Airport environment but very close to the sea; Humid tropical climate; Located in a 'GRUAN desert'; RS at 00 UTC and 12 UTC all year round (M20 radiosonde); Hourly ZTD data with GNSS receiver at the RS station; and GRUAN procedures are adopted at Faa'a station since end of October 2022

In addition to the GNSS, we have the possibility to make water vapour intercomparison with a sun photometer installed since April 2022

Keynote forum 3 – WMO Radiosonde Intercomparisons

This session focused on the recent WMO Radiosonde Intercomparison and the use of GDPs as the reference.

Overview of the Intercomparison (Ruud Dirksen)

Ruud Dirksen presented the status of the WMO radiosonde intercomparison campaign that was organized at Lindenberg observatory, co-hosted by DWD and MeteoSwiss. Due to Covid-19 the campaign, that originally was scheduled to start December 2020, had to be postponed for more than one year and eventually commenced with the laboratory tests in February 2022. Eventually 10 manufacturers participated, which included the well-known major manufacturers as well as participants from India, China and South Korea.

Several GRUAN elements have been adopted in the campaign, such as a pre-launch check in the SHC and laboratory characterisation of the participating radiosondes regarding calibration, RH-sensor time lag and radiation error. The purpose of the laboratory tests is to understand and interpret the differences observed during the radiosounding campaign, and these results will not be used for the final assessment of the systems,

A further innovation with regard to previous editions of the campaign is that the radiosoundings are performed by independent operators.

The laboratory campaign consisted of 6 two-weeks slots, split into 4 slots before and 2 slots after the field campaign, and was very well received by the participants. Several manufacturers used the available time to perform additional measurements and to further investigate the performance of their radiosonde.

During the radiosounding campaign, 79 rig were launched between 16 August and 13 September, yielding at least 18 daytime and 18 night-time soundings per participant, providing ample statistics for the data analysis. The custom-designed campaign rig had a capacity of 10, and typically consisted of 5 participant-sondes and two GDP radiosondes (RS41 + iMS-100) that provide the common working standard (CWS). Vacant spots on the rig were filled with one or more participants to investigate reproducibility.

Weather conditions ranged from near-tropical temperature (>30C) in the beginning to 13C at night at the end of the campaign. Similarly, cloud conditions during the launches varied between completely cloud free to rain showers, so that a variety of meteorological conditions occurred during the campaign.

In the second campaign week the sounding activity had to be halted for 2 days because of safety reasons, since unfavourable trajectories would cause the rigs to land in the Berlin area.

The operators were trained during a 4-day program to operate two different sounding systems, with which they had no prior experience.

The campaign team participated in daily data analysis briefings to discuss interesting effects observed in the data, this greatly enhanced the campaign feeling of all involved.

Looking back, the campaign went very successful. Several ambitious goals were met, such as

- Independent operators
- A new data analysis system
- Laboratory campaign
- GDP for common working standard

Because of COVID restrictions in China, the laboratory tests for one manufacturer will be performed in January 2023.After that the project team will work on the data analysis and the preparation of the report. Goal is to have a review of the report by the manufacturers in the summer of 2023.

Life in a multi-GDP world: the UAII 2022 perspective (Frederic Vogt)

Radiosonde GRUAN Data Products (GDPs) were used as working measurement standards during the 2022 Upper-Air Instrument Intercomparison (UAII) campaign from the WMO. Specifically, two GDPs, the iMS-100 GDP and RS41 GDP, were flown on each flight of the campaign, and combined using a weighted-averaging scheme into "combined working measurement standards". In this presentation, the statistical approach to assess the compatibility of two GDP profiles (according to the GRUAN principles) used for the UAII was presented, together with a series of bugs and unexpected features of the current iMS-100 and RS41 GDP versions.

View of intercomparison from the manufactures (Hannu Jauhiainen)

An opportunity was offered also for the manufacturers to give their thoughts on the intercomparing arrangements. Comments were gathered and formulated amongst four manufacturers participating physically in the GRUAN meeting, in practice much during the meetings breaks. Comments were related to practical arrangements for the sounding campaign and for the laboratory campaign, including phases: informing before and during the intercomparison, delivery of equipment and sondes, premises, installation of the equipment, training of the operators and on-line monitoring/support during the inter-comparison soundings. In general, the practical arrangements for the campaigns were considered successful and in line with the set plans, taking into account the schedule challenges due to COVID. In addition, some small remarks were made to possibly be utilized for the further campaigns.

Session 9. GRUAN Data Products

9.1 LIDAR GDP progression (B2) (Thierry Leblanc)

A short presentation (remote) was given by Thierry Leblanc.

9.2 Microwave Radiometer GDP (B1) (Nico Cimini)

The presentation gave an update on the status of a GRAUN MWR GDP. Current activities are developed within three European initiatives (ACTRIS, EPROFILE, PROBE). The MWR uncertainty characterization is being performed in the framework of the ACTRIS MWR quality assessment (2021-2023) at the ACTRIS Centre for Cloud Remote Sensing (Julich, Germany, contact: Bernhard Pospichal, University of Cologne). A calibration campaign was performed by DWD and Uni Köln last year during FESSTVaL campaign (Lindenberg) in order to provide the total uncertainty (including calibration repeatability, drifts, noise) and draft instructions for operating a MWR network. A report describing the calibration characterization analysis has been submitted as a PROBE document and will be circulated among MWR operators. The MWR networking, including development of data format and metadata and the design of a system for the routine data collection and display from multiple platforms, is carried on in the E-PROFILE 2nd phase (2021-2023, contact: Rolf Rüfenacht, Meteoswiss).

Both ACTRIS and EPROFILE MWR developments are planned to run until the end of 2023. Updates will be given at ICM-15, including the feasibility of a GRUAN GDP based on ACTRIS data.

9.3 Frostpoint Hygrometer GDP progression (B3) (Ruud Dirksen & Takuji Sugidachi)

A presentation was given by Ruud Dirksen.

9.4 Ozonesondes GDP progression (D1) (Holger Vömel and Richard Querel)

The GAW ASOPOS panel completed the recommendations for standard operating procedures for ECC ozone sondes (GAW report 268). All ozone sonde observations within GRUAN will follow these recommendations for ozone sonde preparation and launch. The roadmap to a GRUAN ozone sonde data product was laid out in last year's presentation; here we provide some more specifics.

The ASOPOS report has provided recommendations for the capture of metadata in three categories:

1) Required metadata are those needed to reprocess an ozone sonde profile.

2) Essential metadata are those needed to understand the ozone sonde setup.

3) Desired metadata are those needed to understand the entire measurement system.

For GRUAN all three metadata categories will be required.

The ASOPOS report also indicated the need for a manufacturer independent ground check and the metadata section already provides the fields to capture this information. A manufacturer independent ground check is desperately missing in the effort to understand changes in some of the ozone sondes (drop off observed for EnSci ozone sondes using low buffered solutions; not as long-lasting systematic variations for SPC ozone sondes).

Currently three stations perform ground checks, namely Boulder, Payerne, and Lauder. Lindenberg has the hardware to implement such a ground check but has not yet done so. The ground check exposes an ozone sonde to a well-defined amount of ozone during the sonde preparation, typically around 100 ppbv or 230 ppbv, generated by a well calibrated ozone generator. The three stations performing a ground check have slightly varying procedures and are encouraged to coordinate their effort to define one single ground check procedure that could be recommended to other stations.

In addition to the manufacturer independent ground check, the ASOPOS report already indicated new developments, which should be implemented to remove known systematic effects. Most importantly, a time response correction will be implemented to remove the contribution from the secondary slower reaction, which is due to side reactions of ozone with the phosphate buffer, and to remove the time lag of the fast potassium iodide reaction. This dual time response correction is essential for measurements in the boundary layer, in the upper troposphere, and in the stratosphere. Laboratory measurements have already shown that it produces a better agreement with reference instruments under controlled lab conditions.

Centralized processing needs to be implemented to apply this time response correction; however, a method must be implemented that allows stations to manually flag problematic data after the automated processing. This manual step must be done at the station, not at the GRUAN lead center, where resources are not available for this manual processing step.

Lastly, almost all stations use standard pump efficiency correction tables under the assumption that they apply equally to all instruments. However, individual pump efficiency measurements conducted at JMA have shown that there is a significant production variability and even some long term changes in pumps produced by EnSci. Other stations are highly encouraged to work on replicating individual pump efficiency measurements, which could be based on the efforts by JMA.

9.5 Discussion

A follow-up discussion session raised the following points, some of which had already been raised at earlier sessions:

- Issue/challenge for sites to understand the benefits of belonging to GRUAN:
- Capacity and expectation for the Lead Centre: are the expectations increasing and do we need to write letter to ask for more resources?
- GDP: does everything need to be GDP, should GRUAN only focus RS or balloon?
- Does GRUAN need to change to a different structure? Should 'regional' (sub LC) be considered?
- Support to GRUAN LC would be useful. In order to become a GDP you need to fulfil the requirements, if they do no reason not to be a GDP.
- Prioritization of GDP? Who decides?
- Many sites are measuring but do not transmit to the LC.

Session 10. Other ICM-13 actions

10.1 Standardizing cloud observations / reporting (C6) (Masatomo Fujiwara)

GRUAN Report No.5 published in June 2022 discusses and makes recommendations for the cloud observations at GRUAN sites, in particular in conjunction with radiosonde GDPs, for satellite validation purposes, for potentially improving radiosonde GDPs, for potential cloud related GDP development in the future, among others. The talk overviewed this Report.

10.2 10.2 QC/QA flagging and presentation in data files (B4) (Tzvetan Simeonov)

Flags for raw data and flags for final products are envisaged for each parameter in the GDP's. Moreover, a standardized naming convention for the GDP's is envisaged with first draft of the suggested convention to be shared with a new TN.

10.3 GNSS GDP format (C9) (Galina Dick)

Florian Zus, Jens Wickert, Benjamin Männel, Markus Bradke, Markus Ramatschi
GFZ German Research Centre for Geosciences, Potsdam, Germany

This presentation gave an overview of GNSS-derived Precipitable Water (GNSS-PW) GRUAN Data Product Formats.

The first part of the presentation described automatic processing of GNSS data at GFZ for retrieval of tropospheric products. Operational GNSS data processing at GFZ is done with GFZ EPOS.P8 software and provides all kinds of tropospheric products: zenith total delays, converted precipitable water vapor, slant total delays and tropospheric gradients both in near-real time and in re-processing mode. The estimation of GNSS-PW uncertainties after the Tong Ning algorithm (T. Ning et al., AMT, 2016) was added to the automated processing chain in April 2019. The GRUAN-PW products are available both in COST716 and TRO-SINEX formats at GFZ ftp. All products are also delivered to the GRUAN LC at Lindenberg.

Since ICM-13 two new data formats of GNSS-PW GDP have been developed at GFZ:

- Simple to read GFZ ASCII format
- NetCDF v03 and v04 formats

Open questions which should be discussed with LC were presented:

- Separate file for each GRUAN site?
- Yearly/monthly/daily files?
- Only for re-processed products or also for NRT?
- nc3 and/or nc4?
- Include also the gradients or ZTD/PW only?
- Header information

10.4 Metrological closure of GNSS-IWV and radiosondes (C10) (Galina Dick)

The results of validation between GDP RS41 and GNSS-PW GDP for three GRUAN stations (Lindenberg, Ny-Ålesund and Sodankylä) for 2015 show a very good agreement with the small biases which vary between -0.6 kg/m2 and 0.13 kg/m2.

The results of validation between all GRUAN sites and ERA5 for 2021 also show an excellent agreement with the mean bias over all stations of -0.3 kg/m2.

Update on the status of the GNSS network (appendum)

Galina Dick also presented on update on the status of the GNSS network as follows. The third part of the presentation showed the current status of GNSS network.

16 from 31 GNSS GRUAN stations have been included in automated PW processing at GFZ:

- Lindenberg (LDB0, LDB2, LIN0)
- Ny-Ålesund (NYA2, NYAL, NYA1)
- Sodankylä (SODF, SODA)
- Lauder (LDRZ)
- Barrow (UTQI)
- Graciosa (ENAO)
- Lamont (SGPO)
- Beltsville (HUBC)
- Singapore (SMM1, SMS1)
- Payerne (PAYE)
- Cabauw (CBW1)
- Ross Island (SCTB)
- Tateno/Tsukuba (TATN, TSK2)
- Syowa (SYOW)
- Neumayer (NMSH), no PW-GDP, work in progress
- Potenza (TITO), no PW-GDP, work in progress

Re-processing with new PW uncertainty estimation has been done for 2019 and is ongoing for 2018, 2020, 2021.

Planned GNSS sites in operational processing: Tenerife, Paramaribo, Reunion, Hong Kong.

GNSS-PW GDP are available in SINEX-TRO and COST 716 Formats at GFZ ftp.

NRT products:

ftp://ftp.gfz-potsdam.de/GNSS/products/nrttrop/

sinex_trop_GRUAN_EPOS8/w****

product_GRUAN_COST_EPOS8/y****/m**

REPRO products:

ftp://ftp.gfz-potsdam.de/GNSS/products/nrttrop/REPRO/

sinex_trop_EPOS8/w****

product_COST_EPOS8/y****/m**

10.5 RS92-RS41 comparison paper (D3) (Tzvetan Simeonov)

Two individual papers are in various stages of preparation. The paper on Temperature and Relative humidity is with priority and should be submitted by the end of February 2023, Pressure, wind and location parameters soon to follow in the second paper. The main conclusion is that the biases between the two GDP's are consistent with the estimated uncertainties for all observed parameters.

Session 11. GRUAN management and governance

11.1 Silent stations (C8) (Ruud Dirksen)

At ICM-12 the issue of silent sites was raised. Most of the GRUAN sites are performing exemplary regarding measurement activity and data submission. Unfortunately, not all sites perform up to par, some have been on the map for several years without actually submitting data. This incorrectly makes the network seem larger that it effectively is. Furthermore, this is not fair to the sites that are committed to the network and that put a lot of effort in conscientiously maintaining a measurement program to provide reference data.

The approach employed thus far was showing the data flow chart (the so-called "GRUAN-DNA") and relying on peer-pressure to motivate sites to stay in line. Unfortunately, this approach of gentle pressure did not succeed in preventing the current situation with several sites showing blanks in the data flow chart. Therefore, a new policy is proposed to apply increasingly more pressure, to encourage reticent sites are to improve their performance. This mechanism includes a series of escalating steps, which starts with regular (monthly) email reminders to the manager of the defaulting site, and ultimately can lead to a site losing the status as a GRUAN site.

The proposed intermediate steps are (for a certified site)

- (after 6 months) a formal letter to the site manager;
- (after 10 months) a letter to the supervisor of the site manager (cc site manager);
- (after 12 months) Revoke the site's certification;
- (after 18 months) an email/Letter to Permanent Representative;
- (after 24 months) Revoke status of being a GRUAN site (+ letter to PR).

with slight modifications in the time-line for uncertified and new sites.

It is also proposed to display the sites' involvement on the GRUAN website, in the form of a traffic sign indicating performance on aspects such as data submission, site reporting, certification status, and involvement in task teams, working group or data product development.

11.2 Data Policy (C3) (Ruud Dirksen)

Ruud Dirksen summarized the issue that first raised during ICM-11:

The GRUAN data base contains a wide variety of data, and only a small fraction of it is publicly available. On the other hand, sites want to be acknowledged for their efforts, and expressed the wish to be able to control the distribution of data from additional instruments (e.g. ozone sonde).

Following that, the technical note TN-10 was drafted, that outlines the policy for the distribution of various kinds of (intermediate) data. TN-10 defines various kinds of data, ranging from raw measurement data to manufacturer or GRUAN processed product data,as well as the access to these data categories by various kinds of GRUAN-internal and external users.

Feedback on the draft included the request for the FAIR use of data by public users, which is included in for example the BSRN data policy https://bsrn.awi.de/data/conditions-of-data-release/. A potential way to achieve recognition for sites' efforts is the use of site-specific DOI-numbers. The updated TN will be first be circulated in TT-sites.

Deliberate data latency, i.e. the delayed release of data from certain measurements, for example to ensure first-publication rights for the site in case of e.g. campaign activities can be implemented by means of the Intermediate-Raw data format. However, this latency should not be applied to essential and/or regular GRUAN measurements such as radiosoundings, GNSS-PW, and stratospheric H_2O observations, since these are part of the site's commitment to GRUAN.

11.3 Usage of GRUAN data (C2) (Dave Smyth)

To encourage funders of institutions who may not be readily aware of the value of GRUAN data products, and how many times they are used, it is key to promote the impact of such products beyond the end users. The metric that would support this and which is particularly relevant for stations that only perform measurements is the allocation of DOIs. Employing DOIs would enable the tracking of data use and provide metrics of citations, user groups, and the impact of the data on science progress. PANGAEA, hosted by AWI, has been selected to trial DOI allocation. To this end, RS41 processing from the MOSAiC project is being stored on PANGAEA to track and evaluate its usage via DOIs. It is expected that this method will be rolled out to monitor usage of other GRUAN products, although this is taking longer to facilitate than anticipated due to non-technical issues that need to be resolved in the first instance.

Sites photos (C1) (Michel Sommer)

The long-term task "Site photo documentation" was briefly introduced. In addition to the old upload path using FTP, a new tool "GRUAN Site Diary" is available as part of the GRUAN website. The related Technical Note 9 describing "Site photos" has to be updated related to the new tool "GRUAN Site Diary", that is planned in year 2023.

Radiosonde fundamental documentation (D2) (Christoph von Rohden)

There has been no substantial progress since last report (ICM-13). A high number of other tasks had higher prioritiy, in particular the UAII 2022.

Existing material at LC:

- Data management (data collection, file format definitions, operation of processing centres, GDP processing, archiving, data distribution)
- Description of experiments for sensor characterization (humidity and temperature calibration, humidity time-lag, radiation error)
- GRUAN ground check procedures

- Guidance for multi-instrument flight configurations and rigging (TD 7 multiple payload, TN 7 recommendations for dual soundings)
- Guidance for multi-instrument flight configurations and rigging (TD 7 multiple payload, TN 7 recommendations for dual soundings)
- Experience from WMO inter-comparison campaign

Next steps:

- Review of current status/contributions (all authors); continue writing
- Extend team of authors?
- Summarize and distribute information where input or expertise is needed (e.g. TT-Radiosonde)

Refresh of presentation materials (D5) (Dave Smyth)

There was no progress on this due to actual and perceived lack of necessity due to the comprehensive web presence and growing awareness of GRUAN data products within the UTLS community. After discussion in plenary however, and requests for same, it was decided to pursue in the first instance an updated PowerPoint deck for distribution on a case-by-case and requirement basis. Subsequent to this, a full refresh of the brochure, hand-outs and poster material will be carried out, with a review of all refreshed material anticipated in mid-2023.

Session 12. Closing remarks

12.1 Actions (Peter Thorne)

Peter Thorne presented a first draft of the ICM-14 actions, which were further updated following interjections from the participants. The final list of ICM-14 actions are given in Annex 3.

12.2 ICM-15 (Ruud Dirksen)

It is proposed that ICM-15 will take place in Switzerland, with the kind offer to host the meeting from Meteoswiss. This is likely to take place in May-June 2024. More details will be provided nearer the time.

12.3 How to collaborate with La Reunion's Research and Innovation stakeholders?

This agenda item was cancelled as the presenter was not available.

12.4 Formal close June Wang/Peter Thorne)

June Wang thanked the Université de La Réunion for hosting a very successful ICM-14, not only from the perspective of the GRUAN work but also to allow the participants to enjoy Réunion. A particular thanks was given to Stephanie and Jerome for all their hard work in planning and organising the meeting, as well as their personal support to whoever needed it during the meeting.

June Wang stepped down from her position as GRUAN co-chair and was thanked for her services. June was a founding member of GRUAN and attended all ICMs. Fabio Madonna was made co-chair.

Following this June Wang formally closed the ICM-14.

Annex 1: Agenda

Monday 28 November

Session 1 – Welcome (09:00-10:30 RET– 05:00-06:30 UTC)			
	08:30 – 09:00	Registration	
1-1	09:00 – 09:10	Welcome	June Wang
1-2	09:10-09:20	Meeting logistics	Local host
1-3	09:10 – 09:30	Official Opening	Host
1-4	09:30-09:45	La Reunion, a knowledge center for island resilience	Philippe Holstein
1-5	09:45 – 10:00	Opening Statement – GCOS/WMO	WMO (Remote)
1-6	10:00 – 10:15	GRUAN – Why are we here	Ruud Dirksen
1-7	10:15 – 10:30	Sites certification presentations: Ross Island and Barrow	Peter Thorne/June Wang

10:30 – 11:00 - Morning Break

Session chair: Peter Thorne

Session 2 – Review of progress (11:00-12:30 RET – 07:00-08:30 UTC)			
2-1	11:00-11:30	GRUAN LC Updates	Ruud Dirksen
2-2	11:30-11:45	GDP status (table)	Ruud Dirksen
2-3	11:45-12:15	Review of actions from ICM-13	Peter Thorne
2-4	12:15-12:30	RS41-GDP (HP2)-Final Certification	Michael Sommer

12:30 – 13:30 - Lunch

Session chair: Peter Thorne

Session 3 – GRUAN Priorities (13:30-15:30 RET – 09:30-11:30)			
3-1	13.30-14:55	**R23 and its replacement (HP5)** Current status for stations Overview of potential replacements Discussion and agreed plans • The development of a liquid N2 container for the CFH. • With contributions of Frank Wienhold (PCFH), Takuji Sugidachi (Skydew) and Holger Vömel (CFH).	GRUAN Lead Centre leads Christian Rolf (online)
3-2	14:55-15:10	Meisei GDP (HP3)	LC/JMA/Mesei
3-3	15:10-15:30	Modem M10 GDP (HP4) (10 min) Development of M20 Data product (D4) (5min) Discussion (5min)	Antoine Farah

15:30 – 16:00 – Afternoon Break

Session chair: Peter Thorne

Session 4 - Operational matters (16:00-16:30 RET – 12:00-12:30 UTC)			
4-1	16:00-16:15	Parallel soundings database augmentation with ancillary data (A1)	David Smyth
4-2	16:15-16:30	Standard Humidity Chamber (C5)	Michael Sommer

16:30 – 17:30
Keynote forum 1 - Vision and Plans (GRUAN vision, GRUAN IP, GCOS Vision & IP, EGOS IP) (2 or 3 - 10 min presentation; 30 min open discussion).

- GCOS IP – Caterina Tassone/Tim Oakley (10min)
- GRUAN IP – June Wang (10 min)

Tuesday 29 November

The site visit will be at the high-altitude Maïdo Observatory, 2-hour by bus from downtown Saint-Denis.
On this day, we will celebrate the 10-year anniversary of the Observatory and the reclassification of La Réunion to Global GAW station (it was previously a regional station).

Session 5 - Site visit: The Maïdo Observatory			
	7:00	Bus departs from Saint-Denis, near Hôtel de ville (walking distance from all hotels)	
	9:30-10:00	Coffee break	
5.1		Site visit to include: **10:00-10:30: Official addresses** **10:30-11:00: Official Ceremony, Global GAW certificate presentation** **11:00-12:30 Visit of the observatory**	
	12:30-14:00	Lunch, 10-year anniversary of the observatory	
	14:00	Bus departs the Maïdo Observatory for Hotel Boucan Canot.	
Session 5 - Local presentations and conference dinner			
5.1	15:30-15:45	Unprecedented injection of water vapor into the stratosphere by the eruption of Hunga Tonga-Hunga Ha'apai	Holger Vömel
5.2	15:45-16:00	Rapid ozone loss following humidification of the stratosphere by the Hunga-Tonga	Stephanie Evan
5.3	16:00-16:15	Early Evolution of the Hunga-Tonga Stratospheric Aerosol Plume observed by Lidar at La Réunion	Valentin Duflot
5.4	16:30-16:45	The Hunga-Tonga eruption impacts on the stratosphere	Karen Rosenlof
5.5	16:45-17:00	An overview of research activities at LACy	Joel Van Baelen
5.6	17:00-17:15	How to collaborate with La Reunion's Research and Innovation stakeholders? Overview of forthcoming Horizon Europe calls for projects	Evelyne Tarnus
	17:30-19:00	Free time (hotel Boucan Canot is located near the Boucan Canot beach)	
	19:00-21:00	Diner Cocktail	
	21:30	Bus departs Hotel Boucan Canot for downtown Saint-Denis	

Wednesday 30 November

Session chair: Ruud Dirksen

Session 6 - Science and Innovation-1 (09:00-10:45 RET – 05:00-06:45 UTC) (Presentations 15min+5min)			
6-1	09:00-09:20	The impact analysis of NWS migration to Vaisala RS41	Tony Reale
6-2	09:20-09:40	Sequential radiosonde launches and their use in satellite data calibration/validation	Bomin Sun
6-3	09:40-10:00	Options for radiosonde launches with EUMETSAT Metop and Metop-SG overpasses	Axel Von Engeln
6-4	10:00-10:20	Fine detailed fitting of observed IASI radiances to calculated ones using GRUAN sondes and radiative transfer modelling water vapor inhomogeneities within the satellite field of view.	Xavier Calbet
6-5	10:20-10:40	The Faa site - updates	Patrick Jann

10:30 – 11:00 - Morning Break

Session 6 – Science and Innovation-1 (11:15-12:30 RET – 07:15-08:30 UTC) - continued			
6-6	11:15-11:35	On the uncertainty of RS41 missing data interpolation	Alessandro Fasso
6-7	11:35-11:55	The GDP for the multidisciplinary drifting observatory for the study of arctic climate (MOSAiC)	Marion Maturilli
6-8	11:55-12:15	Improvement of temperature and humidity data quality from RALMO, validation of the uncertainty budget and advanced experiments towards operational simulation	Gianni Martucci
6-9	12:15-12:30	Discussion	

12:30 – 13:30 - Lunch

Session chair: Ruud Dirksen

Session 7 - Task Team Reports (13:30-15:30 RET – 09:30-11:30 UTC)			
7-1	13:30-13:50	Radiosonde TT Justification for high ascent attainment (C7)	Masatomo Fujiwara
7-2	13:50-14:10	Sites TT	Marion Maturilli
7-3	14:10-14:30	Scheduling TT Uncertainty terminology and presentation in GRUAN products (C4)	Fabio Madonna Tom Gardiner
7-4	14:30-14:50	GB-TT	Domenico Cimini
7-5	14:50-15:10	GNSS-PW TT	Kalev Rannat
7-6	**15:10-15:30**	SAT TT Satellite data collocations with RS92/41 pairs (A2)	Lori Borg/Axel Von Engeln

15:30 – 16:00 – Afternoon Break

16:00 – 17:30 RET – 12:00-13:30 UTC
Keynote forum 2 - GRUAN evolution (Sites, data products and collaboration)
(2 or 3 - 10 min presentation; 30 min open discussion.)

- View by Task Team Sites – Marion Maturilli(10min)
- View by Lead Center – Ruud Dirksen(10min)
- GRUAN-GSRN Connections – Tim Oakley/Caterina Tassone (10min)

Thursday 1 December

09:00-10:45 RET – 05:00-06:45 UTC
Breakout sessions, themes to be determined (in person)
1. Exchange on technical issues at the sites (Chaired by TT-sites chairs)

10:45 – 11:15 – Morning Break

11:15 – 12:30 RET – 07:15-08:30 UTC
Breakout sessions continue
12:00-12:30 RET – 08:00-08:30 UTC
1 slide to report back to plenary

12:30 – 13:30 - Lunch

Session chair: June Wang

Session 8 – Science and Innovation-2 (13:30-15:30 RET – 09:30-11:30 UTC)			
8-1	13:30-13:50	2024 water vapor instrument intercomparison at European Southern Observatory (ESO) site in Paranal, Chile	Florian Kerber (online)
8-2	13:50-14:10	Direct validation of radiosonde data against radio occultation bending angles	Axel Von Engeln
8-3	14:10-14:30	Empirical estimation of uncertainty in radiosondes, radio occultations and model forecast with the Three Corned Hats method	Jo Nielsen
8-4	14:30-14:50	Calibration of radiosonde humidity sensors using upper air simulator and applications to soundings	Sang-Wook Lee
8-5	14:50-15:10	Combining the RS41 with CFH's Golden Points for reference quality humidity retrievals and latest progress with PCFH	Yann Poltera
8-6	15:10-15:30	Experiments and analysis for determining the timelag of the RH sensor	Christoph von Rohden

15:30 – 16:00 – Afternoon Break

16:00 – 17:00 RET – 12:00-13:30 UTC: Keynote forum 2 - WMO Radiosonde Intercomparison- 2 presentations followed by discussion
- Overview of the intercomparison- Ruud Dirksen(15 min)
- Life in a multi-GDP World: the UAII 2022 perspective - Frederic Vogt (15 min)
- View of the intercomparison from the manufactures

17:00 Visit to the Meteo France site

Friday 2 December

Session chair: Marion Maturilli

Session 9 – GRUAN Data Products (09:00-10:45 RET – 05:00-06:45 UTC)			
9-1	09:00-09:10	LIDAR GDP progression (B2)	Thierry Leblanc (online)
9-2	09:10-09:30	Microwave Radiometer GDP (B1)	Nico Cimini
9-3	09:30-09:50	Frostpoint Hygrometer GDP progression (B3)	Ruud Dirksen & Takuji Sugidachi
9-4	09:50-10:10	Ozonesondes GDP progression (D1)	Richard Querel
9-5	10:10-10:40	Discussion	

10:45 – 11:15 – Morning Break

Session chair: Marion Maturilli

Session 10 – Other ICM-13 actions (11:15-12:30 RET – 07:15-08:30 UTC)			
10-1	11:15-11:30	Standardizing cloud observations / reporting (C6)	Masatomo Fujiwara
10-2	11:30-11:45	QC/QA flagging and presentation in data files (B4)	Tzvetan Simeonov
10-3	11:45-12:00	GNSS GDP format (C9)	Galina Dick
10-4	12:00-12:15	Metrological closure of GNSS-IWV and radiosondes (C10)	Galina Dick
10-5	12:15-12:30	RS92-RS41 comparison paper (D3)	Tzvetan Simeonov

12:30 – 13:30 - Lunch

Session chair: Marion Maturilli

Session 11 – GRUAN management and governance (13:30-14:30 RET – 09:30-10:30 UTC)			
11-1	13:30-13:45	Silent stations (C8)	Ruud Dirksen
11-2	13:45-14:00	Data Policy (C3)	Ruud Dirksen
11-3	14:00-14:15	Usage of GRUAN data (C2)	Dave Smyth
11-4	14:15-14:30	• Sites photos (C1) • Radiosonde fundamental documentation (D2) • Refresh of presentation materials (D5)	Michael Sommer Christoph von Rohden Dave Smyth

Session 12 - Closing remarks (14:30-15:30 RET – 10:30-11:30 UTC)			
12-1	14:30-15:00	Actions	Peter Thorne
12-2	15:00-15:05	ICM-15	Ruud Dirksen
12-3	15:05-15:25	How to collaborate with La Reunion's Research and Innovation stakeholders? Quick discussion about matchmaking and defining the next steps	Evelyne Tarnus
12-4	15:25-15:30	Formal close	June Wang/Peter Thorne

Annex 2: Summary of progress of ICM-13 Actions

Note: Markings based on Information provided at ICM-14 and agreed with GRUAN Chairs, Working Group Chairs and GCOS Secretariat.

	No.	Complete	Some Progress	No Progress
High Priority	**5**	**3**	**2**	**0**
A: Actions	**2**	**0**	**2**	**0**
B: Actions	**4**	**0**	**4**	**0**
C: Actions	**10**	**0**	**10**	**0**
D: Actions	**5**	**0**	**4**	**1**

High priority:

	Description	Activity (s)	Responsibility	Date
HP1	Manage and progress High Priority Actions	Quarterly meetings to discuss progress, report issues and update as agreed. Regular 'on-line' meetings were held with GRUAN-WG.	GCOS Sec Lead for each HP action	Mar 2022 Jun 2022 Sep 2022
HP2	Development of RS41-GDP	Milestones in the development of the Vaisala RS41 GDP (a) Finalise TD and submit to WG for review (b) Final Certification Certificate for 'final certification' was presented @ ICM-14	Lead Centre	 Apr 2022 By ICM-14
HP3	Development of Meisei GDP	Milestones in the development of the Meisei IMS-100 GDP (a) Technical document submitted for review for IMS-100, including an update for RS-11G (b) Provide update at ICM-14 Certificate for 'final certification' was presented @ ICM-14	Lead Centre JMA Meisei	 Feb 2022 ICM-14
HP4	Development of Modem M10 GDP	Milestones in the development of the Modem M10 GDP (a) Technical document (c) Data Processing (d) Provide update at ICM-14 Update provided @ ICM-14. Work is still required to finalise	Lead Centre Meteo-France Modem	 Apr 2022 Apr 2022 ICM-14

		the technical document.		
HP5	Use of R23 and its replacement	(a) Provide operational guidance to GRUAN sites on how to manage the finite supply of R23 and monitor the status at each site in collaboration with TT sites. (b) Ongoing testing, including where possible comparison to CFH, of possible R23 replacements; SKYDEW; Liquid Nitrogen (Julich); Ethanol dry-ice. (c) Provide experimental flight data to LC to ensure optimal progress. (d) Provide update at ICM-14 Update provided @ ICM-14 during a dedicated session. Whilst further progress has been made a technical solution for the removal of R23 has not been identified.	Lead Centre TT Sites All sites using R23 All sites doing test LC	Jan 2022 Ongoing Ongoing ICM-14

RS92-RS41 transition items:

	Description	Activity (s)	Responsibility	Date
A1	Parallel soundings database augmentation with ancillary data	(a) TN ready for review. (b) Approved TN (c) Implementation – update at next ICM Update provided @ ICM-14. Further input from GRUAN sites requested.	David Smyth June Wang LC	Jan 2022 Mar 2022 ICM-14
A2	Satellite data collocations with RS92/41 pairs	Meeting to discuss next steps	TT-SAT LC	Jan 2022

New GRUAN data products:

	Description	Activity (s)	Responsibility	Date
B1	Microwave Radiometer GDP progression	Milestones in the development of the Microwave Radiometer GDP (a) Updates on data format and calibration uncertainty characterization to be provided by ICM-14.	TT GB	ICM-14
B2	LIDAR GDP progression	Milestones in the development of the LIDAR GDP	TT GB Thierry Leblanc	

		(a) Implement data steam for at least one site	LC	June 2022
B3	Frostpoint Hygrometer GDP progression	Milestones in the development of the Frostpoint Hygrometer GDP (a) Paper (Holger's) - review (b) Meeting to: Identify additional personnel (with good knowledge of statistics) to complete task? Scope the necessary work and reach out to ETHZ through Meteoswiss? (c) Report at ICM-14	Dale Hurst; Ruud Dirksen; Takuji Sugidachi	Mar 2022 Mar 2022 ICM-14
B4	QC/QA flagging and presentation in data files	QTF have made progress on detailing the QC/QA process/need but questions remain on the governance. Complete summary of different approaches currently in use across sites.	Tzvetan Simeonov (LC) + Ad-hoc group members (QTF)	ICM-14

Other Actions:

	Description	Activity (s)	Responsibility	Date
C1	Sites photos	Utility to regularly update site photos is complete. Complete audit that all GRUAN sites who are actively sharing data have uploaded site photos.	LC	Jun 2022
C2	Usage of GRUAN data	Further develop ideas around the appropriate usage and citation metrics of GRUAN data. GDP data stored in PANGAEA with allocated DOIs.	LC	By ICM-14
C3	Data Policy	Finalise Technical Note	LC TT Sites WG	Apr 2022
C4	Uncertainty terminology and presentation in GRUAN products	Paper submitted for publishing	TT-Scheduling	June 2022
C5	Standard Humidity Chamber	Paper to justify the use of the SHC in terms of the data quality and the benefits and including need for standardisation of operating procedures. TN to describe procedural requirements (e.g. operational procedure; quality of the applied references in the SHC). Complete TN and submit paper. Update provided @ ICM-14.	Richard Querel; David Smyth; TT-sites; Lead Centre	By ICM-14

C6	Standardizing cloud observations / reporting	Develop a proposal on the reporting of cloud observations: Write a GRUAN TN with several colleagues. Title: Towards the standardisation of cloud observations and their reporting associated with radiosonde ascents. 1. Manual visual cloud observation (to be included in the GDP metadata) 2. Automated ground-based remote sensing instruments (incl. ceilometers, all sky camera; to recommend further research) 3. Balloon-borne cloud/radiation instruments (to reduce radiosonde T uncertainty; to recommend further research) Draft TN by ICM-14.	TT-radiosonde; TT Sites; TT SAT; Lead Centre	By ICM-14

C7	Justification for high ascent attainment	TT radiosondes to progress an analysis of the additional benefits of high-altitude attainment Draft Paper	TT-radiosonde	By ICM-14
C8	Silent stations	WG, LC and secretariat to propose a review mechanism for retention of sites which remain silent and never progress to certification. Draft TN to TT-Sites for Review TN approved	WG-GRUAN; Lead Centre; GCOS Secretariat	Jan 2022 By ICM-14
C9	GNSS GDP format	GFZ to progress provision of a netCDF format version of the GNSS GDP Jonathan Jones to provide steps necessary (SMART) Update at ICM-14	TT GNSS-PW; Lead Centre (review)	ICM-14
C10	Metrological closure of GNSS-IWV and radiosondes	For GRUAN sites that perform both GNSS-IWV measurements and radiosoundings, Analyse the comparison of the GRUAN data products (and their respective uncertainties) for these data streams to establish whether metrological closure is attained. Jonathan Jones to provide steps	GNSS-IWV; TT- radiosonde	

		necessary (SMART) Update at ICM-14		ICM-14

Actions where progress is required, but not time-bound:

	Description	Activity (s)	Responsibility	Date
D1	Ozonesondes GDP progression	Milestones in the development of the Ozonesode GDP (a) Datastream (b) Paper (c) GRUAN documents	Richard Querel; WG Chairs	Update at ICM-14
D2	Radiosonde fundamental documentation	Draft available for review by WG	LC	Update at ICM-14
D3	RS92-RS41 comparison paper	Paper	LC	As time permits

D4	**Development of M20 Data product**	Milestones in the development of the Modem M20 GDP Agree timeline and progress those items as time permits	M20 consortium (Modem, J-C Dupont)	As time permits
D5	**Refresh of presentation materials**	Priority is on a GRUAN PowerPoint presentation	Dave Smyth	As time permits

Annex 3: Agreed ICM-14 Actions

High priority:

	Description	Activity (s)	Responsibility	Date
HP1	**Improved management and reporting** Manage agreed ICM-14 Actions, with a focus to progress High Priority Actions. Ongoing after ICM-14 to ensure a proactive engagement by the GRUAN chairs and GCOS Sec in the management of ICM-14 actions. Regular meetings with the task teams and the Lead Centre.	At least quarterly meetings to discuss progress, report issues and update as agreed.	GCOS Secretariat WG co-chairs	Continuous to ICM-15
HP2	**R23 Replacement** Ongoing after ICM-14 as a viable replacement for the R23 in the frost-point hygrometer instruments has not been agreed. Audit of GRUAN stations who are reliant on R23 show that 6 stations currently have no supply issue, 2 stations have limited capability and 1 stations have stopped soundings. (Note 1 GRUAN station has already switched to using the Skydew instrument) Update at ICM-14 showed several promising improvements but further tests & analysis are required.	(a) By end of December 2022 check with manufacturers for availability of test instruments (b) Test flights with dry ice / ethanol CFH instruments at a midlatitude site. (BOU/LIN) (c) Test flights with dry ice / ethanol CFH instruments at a tropical site. (REU/Costa Rica) (d) Test flights with dry ice / ethanol CFH instruments at a high-latitude site. (SOD) (e) Report at ICM15	(a) TT Sites (b)Troy Thornberry (c) Stephanie Evan, Holger Vömel (d)Holger Vömel, Rigel Kivi (e) TT Sites	(a)End of December 2022 (b) June 2023 (c) May 2023 (d) Dec 2023 ICM-15
HP3	**Standard Humidity Chamber (SHC)** Finalise the activity to justify the use, and document the procedures, for SHC	Submit paper to justify the use of the SHC in terms of the data quality and the benefits and including need for standardisation of operating procedures. Complete TN to describe procedural requirements (e.g. operational procedure; quality of the applied references in the SHC).	TT-sites (Richard Querel); Lead Centre	Dec 2023 Mar 2024
HP4	**Justification for high ascent attainment** Ongoing after ICM-14 as experts are needed to draft chapter text for the paper. A draft structure of the report was presented.	TT radiosondes to progress an analysis of the additional benefits of high-altitude attainment. Paper submitted	TT-radiosonde	Dec 2023

HP5	**GRUAN Implementation Plan** Publication of new GRUAN IP to cover 2024 to 2030, starting with the draft prepared by June.	(a) Secretariat to review current version. (b) Feedback from GRUAN experts. (c) Final IP for approval	GCOS Sec All WG Chairs Lead Centre GCOS Sec	Jan 2023 Apr 2023 Oct 2023

GRUAN Data Product (GDP) development actions:

	Description	Activity (s)	Responsibility	Date
A1	**Microwave Radiometer GDP progression** Assessment of viability of use of the developed ACTRIS data products (L1 and L2) once available as a GRUAN product.	Milestones in the development of the Microwave Radiometer GDP Assessment by TT-GB and the Lead Centre of the ACTRIS product once available (nominally Dec 2023) as to whether it meets GDP requirements.	TT GB Lead Centre	ICM-15
A2	**LIDAR GDP progression** Implement data flow from sites to LC and on to Table Mountain.	Milestones in the development of the LIDAR GDP (a) Write a document explaining the procedure for sites to send data to LC – TT. (b) Lead Centre work with sites and Thierry to set up a dataflow of data from the initial candidate sites.	Lead Centre Lead Centre Thierry Leblanc TT GB	Feb 2023 Dec 2023
A3	**Frostpoint Hygrometer GDP progression** Set up data processor for chilled mirror techniques and consider the need for different processing / uncertainty estimation depending upon cooling technique and instrument configurations	Milestones in the development of the Frostpoint Hygrometer GDP Institute processing based upon existing techniques. Evaluate the extent to which coolant techniques / choice of coolant and instrument configuration exert a control on the data and / or uncertainty	Lead Centre Holger Vömel Poltera Yann Takuji Sugidachi	ICM-15
A4	**Modem M10 GDP progression** Perform assessment of data quality issues highlighted in Payerne parallel flights and assess whether it is feasible that M10 sondes can be processed to GRUAN products	Further assessment of Modem M10 characterization including various parallel flights including M10-M10 paired flights to fully understand data repeatability	Modem Meteo-France IPSL Lead Centre MeteoSwiss	ICM-15

A5	**QC flagging, nomenclature, infilling** Progress issues around qc flagging, variable nomenclature and infilling protocols.	Produce one (or more) technical note(s) on standardization of qc flagging, variable names and variable types, and rules for infilling of profile data for missing values.	TT Scheduling Lead Centre	ICM-15
A6	**GNSS-PW data product serving (netcdf files)** Finalise production of netcdf format files including reprocessing of PoR for GRUAN sites	Agree netcdf format with Lead Centre and then provide the period of record reformatted.	GFZ TT GNSS	Jun 23
A7	**Ozonesonde GDP progression** Further progress ozonesonde GDP	Standardise ground checks, pump efficiency measurement checks, continue on GRUAN TD and processing algorithm.	Holger & Richard Lead Centre TT radiosondes TT sites	Further update at ICM-15
A8	**Other Radiosonde GDP Development** Development and updates of other relevant radiosondes, including existing GDPs.	Development and updates of other relevant radiosondes: • Vaisala RS92 GDP V3 • GRAW DFM-09/DFM-17 • Modem M20 • iMS100-TD	Lead Centre Vaisala GRAW Modem Meisei	Further update at ICM-15

Other timebound actions:

	Description	Activity (s)	Responsibility	Date
B1	**RS92-RS41 Parallel soundings database augmentation with ancillary data** Sites to submit relevant parallel soundings information to Lead Centre	Technical Note for sites with guidance revised by end of Jan 2023, reviewed by sites by end of April, published summer 2023, and then initial submissions by ICM-15	David Smyth TT Sites Lead Centre	Feb 2023 Apr 2023 ICM-15
B2	**Satellite co-locations with RS92/RS41 pairs** (in first instance) Progress the how to associate appropriate satellite co-	Work with Lead Centre to implement improved	TT SAT Lead Centre	

	locations with special ascents starting with the RS92/RS41 database	radiosonde database search capabilities wrt satellite overpasses. Initial discussion meeting planned.		Feb 2023
B3	**Sites photographs** Complete audit that all GRUAN sites who are actively sharing data have uploaded site photos	Verification that sites are submitting photos. Work to improve sites inputs on a sustained basis.	Lead Centre TT Sites	Jun 2023
B4	**GRUAN data usage hosting, serving and tracking** Continue to explore options that are more fit for purpose. Including DOI's and usage tracking options.	Lead Centre and Secretariat to continue to explore data hosting options that may enforce better citation, DOI's and data usage tracking.	Lead Centre GCOS Sec TT Sites	By ICM-15
B5	**Data policy for development versions of GDPs** Instigate method(s) of data service that respect the sites requirements and the new WMO unified data policy for specialized data and different development versions of GDPs.	Produce a Technical Note describing / formalizing a data policy for consideration and adoption by sites.	Lead Centre TT Sites	Jun 2023 (final draft) Dec 2023 (adopted)
B6	**Silent stations** WG, LC and Secretariat to propose a review mechanism for retention of sites which remain silent and never progress to certification.	Technical Note to be prepared on protocol to identify and engage with sites. Note prepared by March 2023, reviewed by TT sites by September 2023, fully adopted by ICM-15 and process initiated for longest standing silent sites.	Lead Centre WG TT Sites GCOS Sec	Mar 2023 Sept 2023 ICM-15
B7	**Resolve data reporting for sites unable to use RSlaunchclient** Work with those sites making observations but not currently able to submit for technical reasons to find solutions	Ongoing discussions to find an acceptable technical solution that does not put too much onus on the Lead Centre on an ongoing basis	Lead Centre TT Sites	Update at ICM-15
B8	**Metrological closure of GNSS and radiosonde GDPs** Formal metrological closure assessment of GNSS-PW and radiosondes	Using the method of Immler et al. and the approach from Payerne in the	TT GNSS TT radiosonde	Oct 2023

		intercomparison to compare radiosonde GDPs. Submission to journal		
B9	**RS92-RS41 comparison paper** Complete the preparation and submission of RS92-RS41 comparison papers taking into account feedback received to extent possible	Submission to journal	Lead Centre	April 2023
B10	**GRUAN Sites** Certification of new sites and recertification of existing sites during the period to the next ICM	Sites certification and recertification which should be completed before/by the next ICM. (a) BOU, LAU, PAY, POT, SGP, SNG, SOD	Lead Centre TT Sites GCOS Sec	

Actions where progress is required, but not time-bound:

	Description	Activity (s)	Responsibility	Date
C1	**Radiosonde fundamental documentation** Completion of radiosonde fundamental TD	Continued drafting of the TD	Lead Centre TT Radiosonde	Update at ICM-15
C2	**Refresh of presentation materials** Revise and refresh various materials (flyer for sites, brochure, poster, PowerPoint)	Identify a priority list of materials to be refreshed and revised and do this as time permits. Improved documentation of status and revision needs (document lifetimes). Consider videos or other methods.	WG Lead Centre	As time permits

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