THE GRUAN MANUAL

Version 1.0.0.7

Purpose of this Manual

The GCOS Reference Upper Air Network (GRUAN) manual describes standardized operating protocols, data reduction methods, meta-data collection, and data dissemination which shall be employed among participating sites and the GRUAN Lead Centre to achieve the goals of GRUAN. These goals are agreed between GCOS (Global Climate Observing System) and WMO (World Meteorological Organisation). The primary goals of GRUAN are to provide vertical profiles of reference measurements suitable for reliably detecting changes in global and regional climate on decadal time scales, initially for temperature, pressure and water vapour, with the aim of expanding to other essential climate variables (ECVs), as resources permit, in liaison with other existing scientific networks. The measurements will provide a calibrated reference standard for global satellite-based measurements of atmospheric ECVs, will ensure that potential gaps in satellite measurement programmes do not invalidate the long-term climate record, and will be a reference standard for the measurements made within the existing GCOS Upper Air network, and will provide data to fully characterize the properties of the atmospheric column.

The GRUAN manual establishes mandatory practices and operating protocols (distinguished by use of the words ‘must’ or ‘shall’) having the status of requirements in a technical resolution, which it is necessary that sites within GRUAN follow or implement. It defines the requirements for GRUAN site operations, including requirements on uncertainty and long-term stability. In this way the manual establishes the philosophy under which GRUAN shall operate and informs current and future GRUAN sites of the expected *modus operandi* for GRUAN. The manual recognizes that GRUAN is a heterogeneous network that includes sites from both the research community and the operational meteorological community. The mandatory practices required of GRUAN sites as detailed in this manual, reflect GRUAN’s primary goal of providing reference quality observations of the atmospheric column while accommodating the diverse capabilities of sites within the network.

Relevant information from this manual will be incorporated into the WMO Manual on the Global Observing System (WMO-No. 544) and the Guide on the Global Observing System (WMO-No. 488). GRUAN observing systems and operating practices will be referred to in the WMO Guide to Instruments and Methods of Observation (WMO-No. 8) and this document will be linked to the relevant scientific documentation for the specialised scientific sounding systems. A GRUAN station may be a scientific observing site outside of the WMO operational Global Observing System, but the long-term observational procedures shall follow the guidelines laid down in this GRUAN manual whether it is primarily a scientific site or whether it is already part of the Global Observing System, and the WMO Manuals shall reference these practices.

This manual defines the principles that are intended to direct the development of the methods, techniques and processes needed to achieve the stated goals of GRUAN. Where possible, the document does provide more in-depth detail on specific methodologies, and these shall be appropriate for incorporation into, or referenced by, the WMO Guide to Meteorological Instruments and Methods of Observation. The manual is supported by a series of technical documents listed on the GRUAN web site at http://www.gruan.org.

1. Introduction

The development and current operation of the GRUAN network is described by a number of distinct but often overlapping documents, including GCOS-112, GCOS-121, GCOS-134, GCOS-140, web-based material, reports from GRUAN task teams and papers published in the international peer reviewed literature. The purpose of this manual is to provide a comprehensive documentation of information essential to the ongoing operation of GRUAN

2. *The purpose of GRUAN*

2.1. As detailed in GCOS-112, the purpose of GRUAN shall be to:

i) Provide long-term high quality climate records;

ii) Constrain and calibrate data from more spatially-comprehensive global observing systems (including satellites and current radiosonde networks); and

iii) Fully characterize the properties of the atmospheric column.

GRUAN should also provide observations in near real-time (NRT; within 2 hours) for incorporation in meteorological analysis, provided this is not detrimental to achieving the primary purposes of the network, as defined above.

2.2. A fully compliant GRUAN station shall make at least doubly redundant measurements of all GRUAN priority 1 and 2 essential climate variables[1] and, specifically:

i) Four times daily radiosonde measurements of temperature, pressure and humidity, submitted in NRT to the WIS;

ii) Weekly ozone profile measurements; and

iii) Monthly water vapour profile measurements.

iv) Hourly observations of integrated precipitable water vapour.

All measurements shall comply with the mandatory protocols summarized in Section 8 of this manual and expanded on further in Section 5.3 of the GRUAN Guide to Operations.

2.3. Minimum entry level requirements for a GRUAN site include:

i) Weekly radiosonde measurements of temperature, pressure and humidity;

ii) Weekly ozone profile measurements; and

iii) Monthly water vapour profile measurements. Where several GRUAN sites are located within close proximity, individual site flight schedules should be coordinated to share the burden of making these measurements.

All measurements shall comply with the mandatory protocols summarized in Section 8 of this manual and expanded on further in Section 5.3 of the GRUAN Guide to Operations.

3. Organisation and design of GRUAN

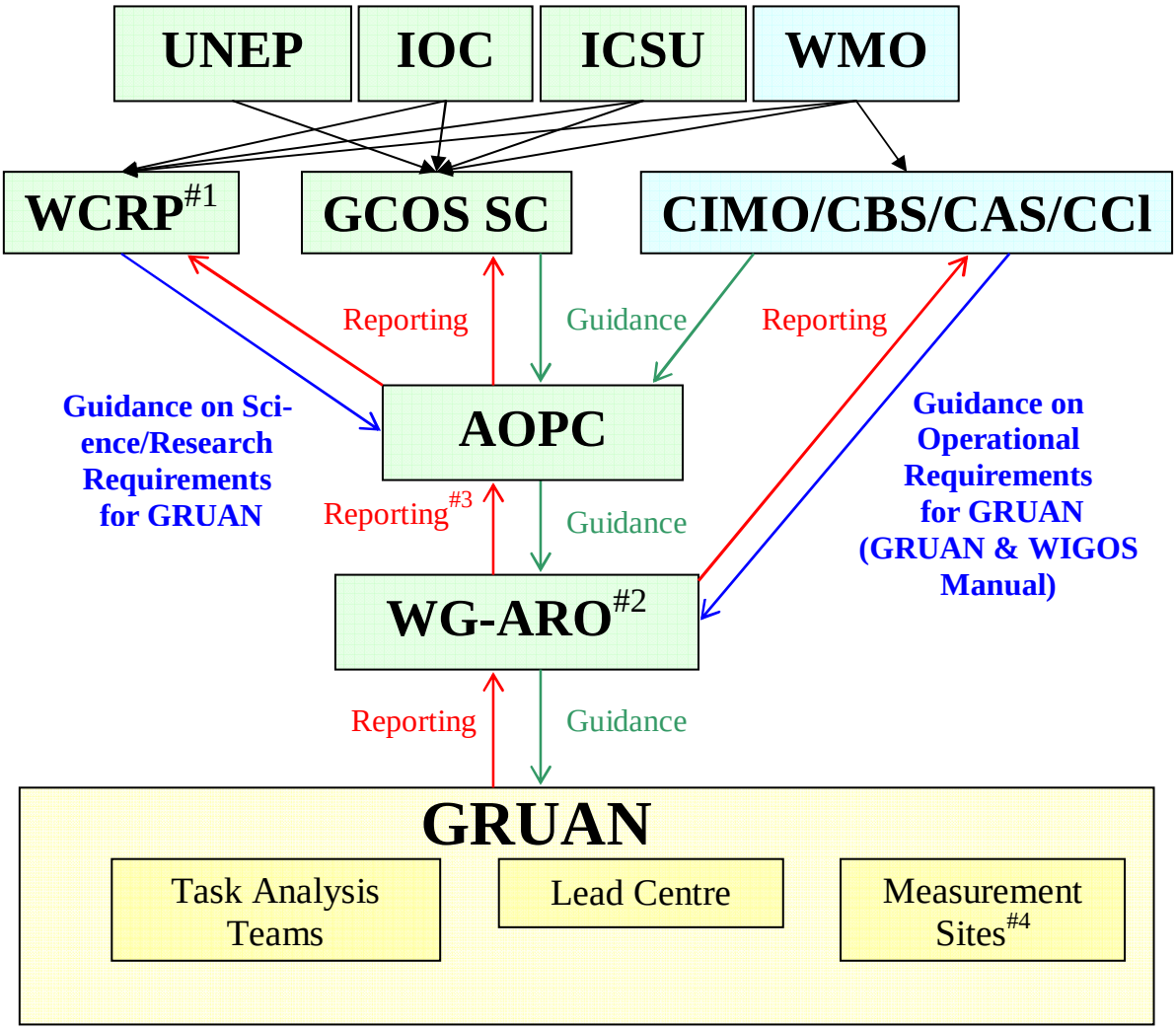
3.1. GRUAN will operate under the joint governance of GCOS and WMO (Figure 1).

[1] Vertical profiles of temperature, pressure, water vapour, wind speed and direction, and ozone. Vertical profiles of aerosol attributes including optical depth, total mass concentration, chemical mass concentration, scattering, and absorption. Methane columns. Surface net radiation, incoming short-wave radiation, outgoing short-wave radiation, incoming long-wave radiation, outgoing long-wave radiation, and radiances. Cloud properties including cloud amount/frequency, base height, layer heights and thicknesses.

3.2. Working oversight of the network will be performed by the GCOS Working Group on Atmospheric Reference Observations (WG-ARO), incorporating representatives from relevant WMO technical commissions including, but not limited to, Commission for Instruments and Methods of Observation (CIMO), the Commission for Basic Systems (CBS), the Commission for Atmospheric Sciences (CAS; which oversees the Global Atmosphere Watch, GAW), and the Commission for Climatology (CCl) .

3.3. A GRUAN Lead Centre agreed to by GCOS and WMO, will be responsible for integrating best practices into GRUAN operations, managing the network systems, and data management.

3.4. GRUAN sites shall use a designated system of methods, techniques and facilities, imple-



Notes

1. WCRP identifies scientific and research requirements for GRUAN, while WMO identifies operational requirements.
2. Composition of WG-ARO to be determined by the AOPC in consultation with WMO and should include:
   - one representative from each of CIMO, CBS, CAS and CCl; these representatives will be responsible for reporting back to their respective Technical Commission;
   - others (according to its Terms of Reference)
3. WG-ARO reports to AOPC
4. GRUAN Measurement Sites are contributed by Members of WMO.

Figure 1: Schematic outline of the structure of GRUAN.

mented for making and archiving best quality atmospheric profile observations, from the surface to the middle stratosphere or higher, at specific locations distributed globally. At any site, this system shall not be changed without advanced notification of the Lead Centre, followed by a process of managed change under the guidance of the Lead Centre.

3.5. GRUAN network operations shall incorporate an assurance programme to validate the stability and uncertainty of the measurements, agreed with WG-ARO, and managed in detail by the GRUAN Lead Centre.

3.6. GRUAN shall be responsive to the latest technological and scientific progress in measurement techniques and observational climate requirements. Development work can continue at a site until mature and validated, when it could be introduced into GRUAN operations with the agreement of the WG-ARO.

4. Implementation of GRUAN

4.1. The implementation of GRUAN shall be guided by the WG-ARO.

4.2. Specific activities in support of GRUAN operations shall be undertaken by GRUAN task teams, as agreed by WG-ARO. These task teams will entrain operational and other relevant expertise in support of GRUAN.

4.3. A GRUAN Analysis Team for Network Design and Operations Research (GATNDOR) shall undertake focused, short-term research to address specific topics identified by the WG-ARO relevant to the design of GRUAN and its operations. The work will be conducted in coordination with other relevant GRUAN task teams.

4.4. The WG-ARO shall agree on appropriate methods for establishing standard operating procedures for observing systems within GRUAN. This could be a new task team, an instrument mentor, or an existing instrument team within other associated WMO or other network projects/operational groups.

4.5. The GRUAN Lead Centre shall identify sites where instrument operators need training, and organise cost-efficient training courses for the network at appropriate locations, as advised by the appropriate body, to encourage uniformity of instrument operation between sites.

4.6. All activities associated with the implementation of a GRUAN site shall be the primary responsibility of the country hosting that site and should, as far as possible, be met through national funding.

5. Partner networks

5.1. GRUAN will not operate in isolation of existing networks but shall collaborate and liaise with existing networks to leverage skills and expertise available from those networks, avoid undue duplication of effort, and ensure that GRUAN data products are tailored to best meet the needs of partner networks.

5.2. The WG-ARO will work in close coordination with the governing bodies of partner networks with respect to the development of GRUAN operations, particularly at the GRUAN sites where GRUAN operations coincide with other network operations. Specifically, the WG-ARO shall then identify methods of improving liaison with partner networks to ensure close communication between GRUAN and those networks particularly at the expert team level.

5.3. Where possible, GRUAN will identify, adopt, and extend if necessary, tools and methodologies that have been developed in existing networks that can serve the needs of GRUAN. In particular, data QA/QC procedures developed in existing networks shall,

where suitable, be adopted in GRUAN. Where networks are working towards QA/QC procedures, GRUAN should partner with these networks to develop systems that meet the operational requirements of both parties. Where GRUAN develops QA/QC techniques that improve upon those used elsewhere, those techniques will be shared with partner networks.

5.4. The GRUAN Lead Centre shall identify methods to access measurement databases from partner networks to enable cross-calibration with GRUAN measurements and to quantitatively link GRUAN measurements to similar measurements made within partner networks.

5.5. The WG-ARO shall establish close connections to the relevant satellite technical programmes, such as SCOPE-CM (Sustained, Co-Ordinated Processing of Environmental Satellite Data for Climate Monitoring), and other product generation and validation programmes. WG-ARO members will be assigned to liaise with key clients within the satellite community to ensure that GRUAN data products are tailored, where possible, to best meet the needs of this community.

5.6. GRUAN shall be operated in such a way that homogeneity of measurements across the network will ensure that significant site specific differences between GRUAN data and those from satellite-based instruments do not result from the GRUAN data products.

5.7. GRUAN shall provide a reference-standard that will serve as a common baseline for splicing satellite-based measurement time series to create climate data records (CDRs).

5.8. GRUAN shall collaborate with the WMO SCOPE-CM programme to generate CDRs of upper air ECVs and in this way contribute to Action C10 defined in the GCOS implementation plan (GCOS-92) viz. 'Ensure continuity and over-lap of key satellite sensors ...undertaking reprocessing of all data relevant to climate for inclusion in integrated climate analyses and reanalyses'.

5.9. The WG-ARO must establish active links to the following partner networks:

i) GUAN (GCOS Upper Air Network)
ii) GAW (Global Atmospheric Watch)
iii) NDACC (Network for the Detection of Atmospheric Composition Change)
iv) SHADOZ (Southern Hemisphere Additional Ozonesondes)
v) ARM (Atmospheric Radiation Measurement) Programme
vi) BSRN (Baseline Station Radiation Network)
vii) AERONET (AErosol RObotic NETwork)

6. Reference measurements and managing change

6.1. All GRUAN measurement systems shall make reference quality measurements, i.e. that at a minimum, the uncertainty on the measurement (including corrections) has been determined, the entire measurement procedure and set of processing algorithms are properly documented and accessible, and that every effort is made to tie the observations to an internationally accepted traceable standard.

6.2. For GRUAN measurement systems making vertically resolved measurements, measurement uncertainties shall also be vertically resolved such that each measurement in a profile is treated as a single measurement result requiring both the measurement and its uncertainty.

6.3. The methods by which the measurements are obtained and the data products derived shall be documented and archived for future reference and reprocessing as necessary. Meta-data shall be archived that describe how the measurements were made, which corrections were applied, and what changes occurred in the instruments and the data reduction algorithms during the observation and post-observation periods.

6.4. GRUAN shall operate in a way such that changes in instrumentation, changes in operating procedures, changes in data processing algorithms and changes in operators do not introduce unidentified temporal or spatial discontinuities or biases into GRUAN data products.

6.5. When changing instrument types, operating procedures, or data processing algorithms, GRUAN shall develop and document or adopt the necessary procedures to fully characterize any systematic biases between the old and new measurement systems so that corrections can be made to the historical data to maintain a long-term homogeneous measurement series. The procedures used shall be informed by robust scientific investigations including a detailed understanding of the error limitations of the instrumentation in use.

6.6. Data reduction processes and data archiving within GRUAN shall be designed such that reprocessing of historical data can be easily and quickly conducted i.e. that the original raw data can be efficiently reprocessed, as required, to form a single homogeneous time series.

6.7. Every reprocessing generating a new homogeneous time series shall be reflected in an increment in the data version and such updates shall be communicated to users who have accessed earlier versions of the data and registered to receive notifications of updates.

6.8. GRUAN shall work with CIMO, CBS and HMEI to make manufacturers aware of GRUAN's needs and to understand the constraints on instrument performance that manufactures face.

6.9. GRUAN shall work with CIMO to encourage and coordinate instrument intercomparisons to develop the in-depth understanding required to manage changes from one instrument to another and to inform decisions on the relative advantages and disadvantages of changing instrumentation.

7. Measurement uncertainty

7.1. The three primary steps for managing measurement uncertainty in GRUAN are:

i) *Describe/Analyze* all sources of measurement uncertainty to the extent possible.
ii) *Quantify/Synthesize* the contribution of each source of uncertainty to the total measurement uncertainty.
iii) *Verify* that the derived net uncertainty is a faithful representation of the true uncertainty.

7.2. All GRUAN observations must be reported together with an uncertainty budget. The Lead Centre and/or the designated central processing facility shall liaise with the GRUAN site in developing this uncertainty budget, as agreed with the relevant task team.

7.3. The uncertainty in the latitude, longitude, altitude and time coordinates associated with each measurement must also be considered when identifying and describing sources of measurement uncertainty.

7.4. To reduce operational measurement uncertainties, optimal standard operating procedures shall be identified by the GRUAN Lead Centre and disseminated to all sites making that particular measurement and adopted where practical, with any exceptions clearly documented and justified.

7.5. The Lead Centre shall be responsible for ensuring that estimates of measurement uncertainty are validated through suitable procedures developed by, or identified by, nominated task teams. The cross-checking of redundant measurements for consistency is also an essential part of the GRUAN quality assurance process. Combining redundant measurements into a single GRUAN data product can reduce uncertainties on the derived product.

8. Site assessment and Certification

8.1. Site assessment and certification falls within the mandate of the WG-ARO together with the GRUAN Lead Centre. Site assessment and certification shall be consistent with the guidance developed and standard agreed with CIMO (WMO-No. 8) and CBS (WMO-No. 488).

8.2. Sites propose specific measurement programmes for inclusion in GRUAN and it is these that will be required to conform to the operating protocols defined in this document and in the GRUAN Guide to Operations, and will be agreed as appropriate for GRUAN by the WG-ARO. Proposed measurement programmes will form the basis for assessing the added value that the site brings to the network.

8.3. The WG-ARO will exercise its discretion in evaluating the proposed inclusion of a site against the criteria defined in this document and in the GRUAN Guide to Operations.

8.4. To identify potential operational anomalies early, sites will be reviewed annually. A typical review will include consideration of the GRUAN site annual report and an assessment of data from the site.

8.5. Where site assessments identify measurement programmes that consistently fall short of GRUAN operating standards, GRUAN certification of that programme (see Section 5.6 of the GRUAN Guide to Operations) will be suspended.

8.6. If all measurement programmes at a site lose their GRUAN certification, the site will be suspended from the GRUAN network.

GRUAN sites shall:

8.7. Provide reference quality observations, including uncertainty estimates for each datum. Profile measurements require uncertainty estimates for each measurement point on the profile.

8.8. Provide access to raw data and assure long-term storage of the raw data either at the site, another GRUAN facility, or at another internationally accessible archive.

8.9. Provide complete meta-data for each measurement.

8.10. Perform regular traceable pre-launch ground checks for balloon-borne systems and record the results. Other instruments which provide vertical profiles extending from the surface require regular checks to assure correction operation.

8.11. Provide redundant reference observations of the ECVs selected for measurement at the site at intervals sufficient to validate the derivation of the uncertainty on the primary measurement as agreed with the GRUAN Lead Centre.

8.12. Provide annual reports summarizing GRUAN operations at the site.

8.13. Conduct measurement programmes with an operational philosophy of continually striving to sustain the measurement quality at a given level. If improvements to measurement accuracy can be obtained, these need to be documented and their adoption agreed with the Lead Centre.

8.14. Manage changes in instrumentation, operating procedures, and processing algorithms pro-actively to avoid the introduction of spatial or temporal biases in GRUAN data products.

8.15. Actively communicate with other GRUAN groups such as the Lead Centre, WG-ARO, task teams and/or other sites, (e.g. through attendance of meetings, blog postings etc.).

Once a site has committed to operating a set of measurement programmes under these protocols the added value that a site brings to GRUAN will be a function of:

8.16. The extent to which a site can fulfil the measurement programmes expected of a GRUAN site, as defined above and in the GRUAN Guide to Operations.

8.17. The extent to which the site measurement programmes provide measurements in regions, or of atmospheric phenomena, which were not previously sampled.

8.18. The extent to which a site brings unique observational and/or analysis capabilities to the network as a whole and the likelihood of being able to propagate those capabilities across other sites in the network.

8.19. The extent to which a site is prepared to forgo locally established operating procedures and adheres to the standard operating procedures established by the Lead Centre.

8.20. The availability of historical measurements that conform to the GRUAN standard or that can be processed in such a way that they conform to the GRUAN standard.

8.21. The extent to which a site can commit to a multi-decade programme of measurements.

8.22. The extent to which a site can provide redundant observations of the priority one variables (temperature, pressure and water vapour).

8.23. The extent to which a site is capable of measuring other ECVs identified in GCOS-112 as being desired quantities.

8.24. The level of institutional support for the site and commitment to maintaining long-term reference quality measurement programmes.

8.25. The level of institutional support for the site (and any partner institutions) to undertake fundamental scientific research of the measurements from the site and other GRUAN sites.

Certification of GRUAN sites will not be a single event. In addition to the regular annual review, periodic (e.g. every 3-4 years) complete auditing of the measurement programmes included in the GRUAN certification for a site shall be conducted to ensure that the programmes continue to meet GRUAN standards.

9. Instrumentation

9.1. Periodic (every 3-4 years) reviews of instrumentation likely to be of use within GRUAN should be undertaken by all task teams with an instrument focus. A written review submitted to the Lead Centre can then inform discussion related to deployment of new instrument types across the network.

9.2. To the extent possible, the number of different types of instruments and associated measurement techniques employed across the network must be minimized to encourage homogeneity of data products and to reduce administrative overhead. However, every effort must be made to ensure that GRUAN operations are not dependent on a single instrument manufacturer. Specifically, for radiosonde consumables, it is essential to use instruments from more than one manufacturer to minimise the likelihood of disruption to GRUAN operations from production failures, introduced weaknesses in the radiosondes, or changes in manufacturing procedures.

9.3. A number of factors guide the selection of instruments for use in GRUAN including, but not limited to, instrument heritage, sustainability of measurement systems, robustness of uncertainty, information content, manufacturer support, and site location.

9.4. Redundancy in measurement systems at sites shall be used to validate derived measurement uncertainties, and to detect any unresolved changes in the systematic bias between observing systems. The cross-checking of redundant measurements for consistency shall be an essential part of the GRUAN quality assurance procedures

9.5. Independent measurements of the same (or related) variables shall be reported in a consistent way.

9.6. Where a cluster of instruments at different locations is operating as a single GRUAN site, robust scientific analysis of the resultant increase in apparent measurement uncertainty must be undertaken. Any method used to simulate how measurements made at one location would translate to measurements made at another location introduces additional uncertainty. It is necessary to clearly document how the lack of co-location contributes to the net measurement uncertainty. It must be very clearly indicated which observations are made from each location, and the data should not be merged as though they were all from one location.

9.7. Operational procedures should be harmonised across the GRUAN network so that a measurement of a given parameter at one site is comparable, as far as the stability of the equipment allows, to a measurement of the same variable at a different site. When two identical instruments are deployed at two different sites, they shall also use the same calibration procedures.

9.8. Where relevant to a particular measurement system, GRUAN sites shall maintain a "GRUAN site working standard" for each basis unit, e.g. a thermometer periodically calibrated to a National Metrology Institute or other accredited agency standard to ensure traceability to an SI standard.

9.9. The Lead Centre shall implement a mechanism to address the compatibility with the rest of the network of those systems not yet traceable to SI standards.

9.10. Each station shall maintain accurate meta-data records and provide these to the GRUAN archives. Copies of calibration certificates shall be submitted to the GRUAN meta-database.

10. Measurement Scheduling

10.1. To provide a high quality data product and a backbone to GUAN, a programme of regular, year-round, high quality radiosonde measurements shall be maintained. For temperature, the most reliable radiosonde measurements are obtained in the dark. The nature of this programme at each site will be negotiated with the Lead Centre, and will depend on the availability of suitably skilled staff.

10.2. The programme of operation of remote sensing systems at a site will be agreed with the Lead Centre and those sites which are included in GRUAN because of the deployment of specialised systems (balloon-borne, or remotely sensed), may be allowed to fly lower numbers of radiosondes than those sites making core radiosonde measurements.

10.3. Schedules of twin radiosonde flights for assurance purposes are to be agreed with the GRUAN Lead Centre. For example, the schedules for a tropical site may be different for those at mid-latitudes and there will be a limit on the number of cross-checking flights required in mid-latitudes given the need to conserve limited financial resources.

11. Data Management

11.1. Different levels of GRUAN data must be defined to distinguish between different various steps in the processing of a GRUAN data product. The NRTD (near real-time data) product specifies measurements made at a GRUAN site, processed with automated techniques, for near real-time dissemination on the WMO WIS. Because these data will not have been subjected to the time-intensive QA/QC procedures employed within GRUAN, are not labelled as 'GRUAN data'.

11.2. Dissemination of GRUAN data products to end-users/customers shall occur through an official GRUAN data centre hosted at NCDC (National Climatic Data Center). NCDC will be accessible through the WIS.

11.3. A GRUAN data dissemination policy shall be developed and adhered to to protect the publication rights of the generators of measurements but without compromising the free sharing of the data.

11.4. GRUAN sites shall commit resources to the management and maintenance of meta-data. Incomplete, outdated, or inaccurate meta-data can be as detrimental, indeed in some cases worse, than no meta-data at all.

12. Post Processing Analysis and Feedback

12.1. Users of GRUAN data must always document the version of data used to ensure that the analyses can be independently replicated. Key to this process will be the ability to make users aware of updated versions of data sets that they previously accessed, now becoming available.

12.2. A facility that allows data users to report potential bugs or anomalies found in data during analyses of the data must be designed and implemented.

12.3. The GRUAN quality control system should include procedures for feeding back into the measurement and quality control process to prevent the errors from recurring.

13. Quality Management

13.1. The GRUAN quality management policy shall achieve a level of data quality that allows the primary goals of GRUAN to be met for all potential users of GRUAN data products.

13.2. Laboratory tests and intercomparisons are fundamental methods for establishing and confirming uncertainty estimates for GRUAN data products.

13.3. Field experiments are particularly useful for assuring the quality of GRUAN data products.

13.4. The use of GRUAN data in meteorological reanalyses also adds to the assurance of GRUAN data quality since the measurements, with their uncertainties, can be tested for

comparability with the data assimilation model values in an assimilation setting within the known internal variability of the system.

13.5. The purpose of quality management is to ensure that GRUAN data meet the requirements in terms of uncertainty, resolution, continuity, homogeneity, representativeness, timeliness, format etc. for their intended use, at a minimum practicable cost.

13.6. Establishing close working relationships with instrument manufacturers will also be central to quality assurance within GRUAN.

13.7. Performance monitoring within GRUAN will primarily be the responsibility of the Lead Centre, but where other specialists may be co-opted to assist in performance assessments.

References

GCOS-112, GCOS Reference Upper-Air Network (GRUAN): Justification, requirements, siting and instrumentation options. WMO/TD-No.1379, 2007.

GCOS-121, GCOS Reference Upper Air Network (GRUAN): Report of the GRUAN Implementation Meeting, Lindenberg, Germany, 26-28 February 2008.

GCOS-134, GRUAN Implementation Plan 2009-2013. WMO/TD No. 1506, 2009.

GCOS-140, Report of the Second GCOS Reference Upper Air Network Implementation and Coordination Meeting (GRUAN ICM-2), WMO/TD No. 1526, 2009.