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PREFACE

This document provides a roadmap for the further development of the Global Climate Observing System (GCOS) Reference Upper-Air Network (GRUAN) for the period 2024 to 2030. It serves as an update to, and supersedes, the previous GRUAN Implementation Plan (GCOS-205). It details the high-level objectives required to reach the goal of maintaining a fully operational reference upper-air network for climate and developing GRUAN data products (GDPs) for Priority 1[1] variables and starting to work towards GDPs for Priority 2[2] variables. It also highlights relevant actions in the latest GCOS Implementation Plan (GCOS-244) on which GRUAN is expected to contribute. It should be interpreted in conjunction with the GRUAN Manual and Guide (GCOS-170 and GCOS-171 respectively). The new GRUAN Implementation Plan (IP) is similar to the previous IP.

[1] Priority level 1 variables are: water vapour, temperature, pressure and wind

[2] Priority level 2 variables are: 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, short-wave downward radiation, short-wave upward radiation, long-wave downward radiation, long-wave upward radiation, and radiances. Cloud properties including cloud amount/frequency, base height, layer heights and thicknesses

1. INTRODUCTION

The Global Climate Observing System (GCOS) Reference Upper-Air Network (GRUAN) is operated under the joint auspices of GCOS and the World Meteorological Organization (WMO). Instigated with the formation of a Working Group under the governance of GCOS's Atmospheric Observations Panel for Climate (AOPC) in 2003. Since 2008, the Lead Centre, hosted by DWD[3] at Lindenberg Meteorological Observatory, oversees day-to-day operational aspects of the network. The current governance structure for GRUAN is outlined in Figure 1.

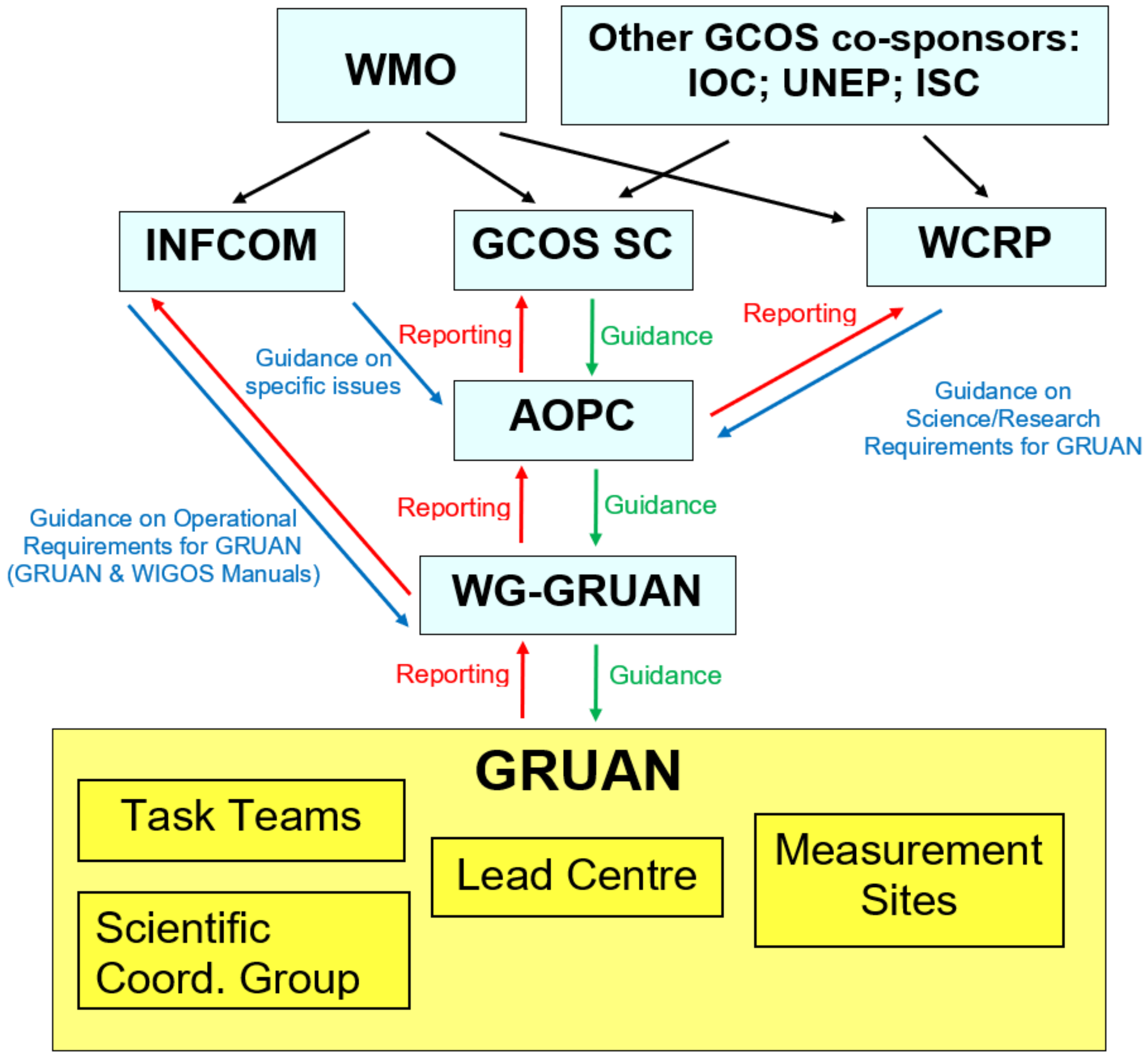

Figure 1. Schematic outline of the structure of GRUAN.

Notes

1. AOPC identifies scientific and research requirements for GRUAN, while WMO/INFCOM identifies operational requirements.
2. The composition of WG-GRUAN is according to its terms of reference.
3. Current Task teams are: Task Team on Radiosondes, Task Team on GNSS Precipitable Water (GNSS-PW), Task Team on Site Intercommunication and Reporting, Task Team on Satellite-

[3] A full list of acronyms is provided in Appendix 1.

Based Remote Sensing Measurements and Task Team on Ground-Based Remote Sensing Measurements.

There have been three previous GRUAN Implementation Plans (GCOS-134, GCOS-165 and GCOS-205). The first was published in 2009 and covered the four years up to the envisaged operational status of the network. The second was published in 2013 and identify the necessary activities up until 2017. The third one was published in 2017 aiming at establishing a fully operational GRUAN. These Implementation Plans have helped to ensure the transition from idea to reality of GRUAN (Bodeker et al., 2016)**.**

This IP supersedes the previous IP (GCOS-205, 2017). The GRUAN-WG agreed that this latest IP will follow the last IP strategy and focus on articulating the envisaged high-level work and achievements within the period. Detailed action plans, articulating specific SMART[4] tasks to be done, shall be developed at the annual ICMs with the express aim of meeting these aspirational goals.

The activities detailed in this IP shall be reviewed regularly at the GRUAN ICM meetings, led by the co-chairs of the WG-GRUAN.

The remainder of this IP is structured as follows:

- Section 2 summarizes the objectives achieved during the last IP period and defines the strategic objectives to be achieved by 2030.
- Section 3 outlines GRUAN in the broader context with the GCOS Implementation Plans.
- Section 4 outlines envisaged work within the IP period towards the targets articulated in the GCOS IP and the GRUAN vision articulated in Section 2. This includes matters pertaining to governance, reporting, coordination and liaison with stakeholders.

2. STRATEGIC OVERVIEW

As detailed in GCOS-112, the purpose of GRUAN is to:

i. Provide long-term metrologically traceable 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.

As of January 2023, GRUAN consists of a network of 31 sites (which includes historical sites), of which 23 were actively reporting. This fell short of the IP 2017 (GCOS-203) milestone of at least 30 sites actively reporting during the last five years. The sites are still distributed unevenly across the globe with few sites in the tropics, continental Africa, or South America (Figure 2). Sites have varying capabilities, funding mechanisms and affiliations to third party networks and organizations. Seventeen of them have yet to undergo formal GRUAN assessment and certification, and as such fell short of meeting the goal of at least 25 certified sites which was set in the last IP. In addition, GRUAN is facing the challenge of "silent" sites, which have been on the map for several years without actually submitting data.

The methodological aspects that underpin what shall constitute a GRUAN reference measurement are documented in the peer reviewed literature (Immler et al., 2010), and data products adhering to these principles for each type of instrument are developed and called as

[4] Specific, Measurable, Achievable, Realistic and Timebound

GRUAN Data Products (GDPs) (Dirksen et al., 2014). Currently there are five GDPs (for four radiosonde types and GNSS-PW) (Table 1).

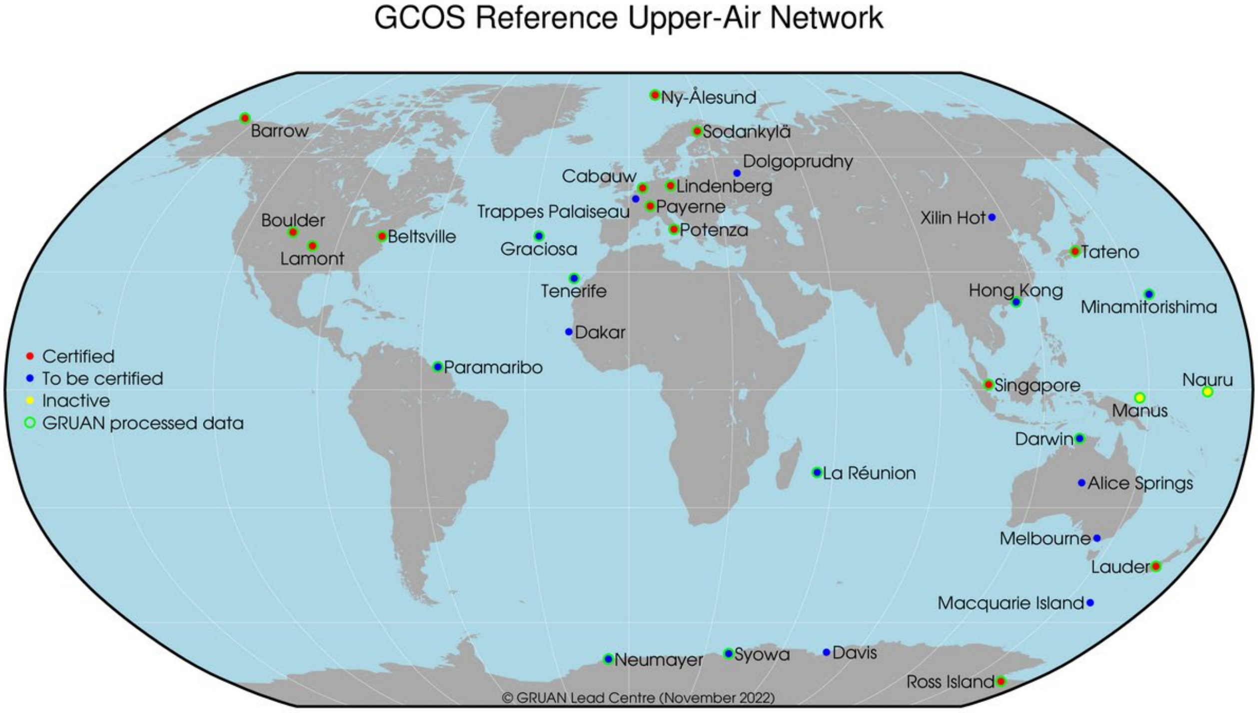

Figure 2. Current GRUAN network configuration as of November 2022.

Achievements during the last IP:

- In January 2023 GRUAN consisted of 31 sites, 23 actively reporting of which 14 are certified.
- GRUAN has five certified GDPs, one certification is in progress, and two GDPs under development.
- During the last four years, GRUAN undertook a huge task to manage the transition from Vaisala RS92 to RS41 following stringent GRUAN "Management of changes" guidelines, including collecting extensive parallel soundings at different sites, analyzing the parallel soundings and developing RS41 GDP.
- Between 2009 and 2021, a total of 117 GRUAN-related journal articles were published, which highlights the applications of GDPs and related research to all four key user groups. Two categories, "Field and intercomparison campaigns" and "Satellite validation and algorithm development", are ranked top with 27 and 21 papers, respectively.
- GRUAN has made significant contributions to improving other networks and observing systems, ranging from pioneering in defining and making reference observations, improving operational radiosondes to calibrating and validating satellite data.
- GRUAN WG membership and Task Team structure were reviewed and updated. The original auxiliary TT was successfully reorganized into two TTs, "ground-based" and "satellite", with more focused and clearly defined tasks for each of them. It also attracted new experts to GRUAN.

By the end of the period of this IP (through 2030), if it is successfully implemented, GRUAN shall consist of:

- A network of approximately 30 to 40 actively reporting sites (of which at least 80% shall be certified) that are more globally equitably located. The location of new sites will be chosen to fill geographical gaps and to meet documented stakeholder requirements. A proposal to handle the "silent" sites will have been implemented with the goal of re-activating silent sites or otherwise decommissioning them.
- A network serving reference quality measurements of vertical profiles from the surface through the lower stratosphere (and higher where feasible) of temperature, pressure, water vapour, wind speed and direction, and ozone[5]. To achieve this some urgent operational issues, such as new or alternative sensors for UTLS water vapor measurements and helium shortage, need to be addressed. To the extent possible, these measurements will be made using complementary measurement systems including sondes[6] and ground-based remote sensing equipment to documented GRUAN standards. GDPs for each instrument will be developed to meet GRUAN GDP requirements (GCOS-205), processed centrally and backed up by substantive metadata. New GDPs should be developed for other Priority 2 variable.
- A set of sustainable long-term measurements being used by recognized target stakeholders (climate change monitoring and detection, satellite-based measurements, NWP, process studies and atmospheric reanalysis), as demonstrated in the peer-reviewed literature, to improve our collective scientific understanding.
- A network with operational and research functions, embedded within the overarching WIGOS framework and leading to improved capabilities and practices in other broader components of the Global Observing System and its applications.

Table 1. Summary of GDPs, white, green, orange and red are for certified, to-be-certified, in-development and in-preparation GDPs

System	Data Processor	Centralized processing facility	GRUAN documentation	Peer reviewed paper	GRUAN certification	Target date for certification
Vaisala RS92 v2	Yes	LC (DWD)	GRUAN-TD-4	Dirksen et al., 2014	de facto 2014	
Meisei RS-11G v1	Yes	Tateno (JMA)	GRUAN-TD-5	Kobayashi et al., 2019	2019	
GNSS-PW	Yes	Potsdam (GFZ)	GRUAN-TD-6	Ning et al., 2016, other in preparation	2021	
Vaisala RS41 v1	Yes	LC (DWD)	GRUAN-TD-8 under review	von Rohden et al., 2022, other in prep.	2022	
Meisei IMS-100 v2	Yes	Tateno (JMA)	Update TD5 in progress	Hoshino et al., 2022	2022	

[5] Work will have progressed on the consideration of other ECVs and derived quantities identified as target parameters including aerosol attributes, as well as surface net radiation, short-wave downward radiation, short-wave upward. radiation, long-wave downward radiation, long-wave upward radiation, and cloud properties including cloud amount/frequency, base height, layer heights and thicknesses. However, it is unrealistic to expect GRUAN data-streams on these attributes to be flowing on the timescale of this IP from any appreciable number of sites, or to expect that their measurement strategies will be fully defined. There are a number of action items that lay the ground-work for such data streams beyond the horizon of this IP.
[6] This includes radiosondes, ozonesondes and water vapour sondes.

Meisei RS-11G v 2	Beta version	Tateno (JMA)	Update TD5 in progress			12/31/2023
Modem M10 v1	Beta version	France (IPSL)	Under review	Dupont et al.,2020		05/30/2024
Lidar	Yes	TBD	In progress	Leblanc et al., 2016		12/31/2023
Graw DFM-09	In preparation	LC (DWD)	In preparation			12/31/2024
Graw DFM-17	In Preparation	LC	In preparation			12/31/2024
ECC Ozone sonde		TBD	Under review/update	ASOPOS		12/31/2024
MWR	In Progress	TBD				12/31/2024
CFH/FPH/SkyDew (any frost point hygrometer)		TBD		e.g. Vömel et al., 2016		12/31/2024
Modem M20		IPSL				12/31/2025

3. GRUAN IN THE BROADER CONTEXT OF THE GCOS IMPLEMENTATION PLANS

In the third GCOS Implementation Plan (2016), there were two specific actions that were directly addressed to GRUAN as follows:

Action A15:	Implementation of GRUAN
Action	Continue implementation of the GCOS Reference Upper-Air Network of metrologically traceable observations, including operational requirements and data management, archiving and analysis and give priority to implementation of sites in the Tropics, South America and Africa.
Benefit	Reference quality measurements for other networks, in particular GUAN, process understanding and satellite cal/val.
Who	Working Group GRUAN, National Meteorological Services and research agencies, in cooperation with AOPC, WMO CBS, and the Lead Centre for GRUAN.
Time-frame	Implementation largely complete by 2025.
Performance Indicator	Number of sites contributing reference-quality data-streams for archive and analysis and number of data streams with metrological traceability and uncertainty characterisation. Better integration with WMO activities and inclusion in the WIGOS manual.
Annual Cost	10-30M US$

The GCOS Status Report (2021) assessed progress against this action as follows:

Assessment: 4 – Progress on track.
"GRUAN has expanded considerably with new sites in the tropics and Antarctica and progress on a number of new data products. GRUAN has grown considerably since the IP was published with several new sites declaring their candidature and several sites officially certified for the first time. This includes the first sites in the tropics and Antarctica. Challenges remain in assuring network coverage over South America. A new data stream has been produced for the Meisei RS11-G sonde and considerable progress has been made towards the production of a number of additional GRUAN Data Products including GNSS-PW measurements which will constitute the first non-radiosonde product. Most sites have moved away from using the RS-92 sonde to the RS-41 sonde from Vaisala. A beta version of the RS41 is under review presently. GRUAN data

has been widely used in publications and various international projects and GRUAN has participated in several campaigns. GRUAN has also become better integrated into WMO and representatives from WMO regularly attend GRUAN meetings. The next WMO intercomparison of radiosondes will be hosted by the GRUAN Lead Centre and GRUAN data processing of some sondes alongside launches of instruments capable of measuring UT/LS water vapour, radiation, ozone and aerosols are foreseen."

Action A23:	Measure of water vapour in the UT/LS
Action	Promote the development of more economical and environmentally friendly instrumentation for measuring accurate in-situ water vapour concentrations in the UT/LS.
Benefit	Improved UT/LS water vapour characterisation, water vapour CDRs.
Who	NMSs, NMIs, HMEI and GRUAN.
Time-frame	Ongoing.
Performance Indicator	Number of sites providing higher quality data to archives.
Annual Cost	10-30M US$

Assessment: 3 – Underway with significant progress.
"UT/LS water vapor soundings have been made with varying degrees of success using balloon-borne frost point hygrometers cooled by a dry ice/ethanol bath or a thermoelectric (Peltier) device, but further test flights are needed to prove that these alternative coolants - 242 - provide adequate cooling power under high solar radiation conditions in the stratosphere, especially in the tropics…"

The fourth GCOS Implementation Plan (GCOS IP) was published in November 2022 (GCOS-244). It has a different form to earlier plans: it has fewer, more focused, and integrated actions, with clearer means of assessment, and identification of the stakeholders who need to respond to the actions. It identifies six major themes that should be addressed:

A. Ensuring Sustainability
B. Filling data gaps
C. Improving data quality, availability and utility, including reprocessing
D. Managing data
E. Engaging with Countries
F. Other Emerging Needs

The 2022 GCOS IP provides a set of high priority actions, across atmosphere, ocean and terrestrial domains, which if undertaken will improve global observations of the climate system and our understanding of how it is changing. Within theme B (Filling data gaps), the GCOS IP states that "Reference quality observations respond to the need for monitoring the changes that are occurring in the climate system and ensure greater confidence int the assessment of future climate change and variability. They support also timely political decisions for adaptation and can help to monitor and quantify the effectiveness of internationally agreed mitigation steps. Reference quality measurement programs have already been established for different domains, however there are still gaps that need to be addressed. For surface meteorological and terrestrial networks there is currently no global and coordinated reference observing tier. Existing national reference observations are not coordinated internationally, and do not provide coordinated data access".

The GRUAN IP can at least in part be considered a response to the GRUAN-relevant components of the GCOS IP.

GRUAN is directly referenced in Action B1, activity 1 as follows:

<table>
<tr><th colspan="2">Action B1: Development of reference networks (in situ and satellite Fiducial Reference Measurement (FRM) programs)</th></tr>
<tr><td>Activities</td><td>1. Continue development of GRUAN.
2. Implement the GSRN.
3. Better align the satellite FRM program to the reference tier of tiered networks and enhance / expand FRM to fill gaps in satellite cal/val.
4. Develop further the concept of a reference network tier across all earth observation domains.
5. Establish a long-term space-based reference calibration system to enhance the quality and traceability of earth observations. The following measurables are to be considered: high-resolution spectral radiances in the reflected solar (RS) and infrared (IR) wave bands, as well as GNSS radio occultations.</td></tr>
<tr><td>Issue/Benefits</td><td>The principal benefits of reference quality networks / measurements are:
• Well characterized measurement series that are traceable to SI and/or community standards with robustly quantified uncertainties that can be used with confidence.
• Improved instrument performance that transfers down to other broader global regional and national networks.
• Characterisation of wider networks, especially of measurement quality.
• Robust calibration/validation of satellite data.
• Improved process understanding and model validation.
However:
• Although GRUAN has been successfully implemented since 2005, it remains far from globally well distributed.
• There is no Global Surface Reference Network, as yet.
• The FRM programs of satellite agencies have been carried out independent of broader concerns around tiered network design, yet these measurements should be sustained as part of reference networks and not be funded or considered separately from broader observational strategies. There is also a need to undertake additional FRM measurements to fill critical cal/val capability gaps for some ECVs.
• Whilst several in situ networks are considered to be of reference quality, as yet, apart from GRUAN, there are no additional GCOS recognized global reference networks.
• Enabling traceable Earth observations from satellites will improve the accuracy and quality of many ECV data sets. In addition to meeting crucial inter-calibration needs, this effort will aid in better understanding climate relevant processes and their spectral signatures.</td></tr>
<tr><td>Implementers</td><td>1. Lead Centre (DWD), GCOS, WMO, NMHS.
2. GCOS, Lead Centre (CMA), WMO, NMHS.
3. Space agencies, WMO, GCOS, Funding agencies.
4. GCOS, WMO, NMHS, Research organizations.
5. Space agencies.</td></tr>
<tr><td>Means of Assessing Progress</td><td>1. Number of certified GRUAN stations and geographical distribution of stations; number of data products; data usage measured through citations.
2. Operational GSRN (for an initial set of stations focussing on temperature and precipitation).</td></tr>
</table>

	3. a) Alignment of FRM programs into the tiered network of networks concept; b) Additional FRM measurements to fill gaps to support satellite cal/val of ECVs such as Above Ground Biomass, albedo, FAPAR, LAI and burned area. 4. Inventory of (potential for) global reference networks across atmosphere, ocean and terrestrial. 5. Implementation of CLARREO pathfinder, TRUTHS and Prefire. Plans for long-term follow-on missions to the short-term (~1 year) pathfinder missions (CLARREO and Prefire) and long-term continuous measurements.
Additional Details	Reference-quality measurements must be traceable to SI or community recognized standards and have their uncertainties fully quantified following the guidance laid out by BIPM. Measurements across a reference network must be metrologically comparable. 1. GRUAN is envisaged as a global network of eventually 30-40 measurement sites. As of August 2021, GRUAN comprises 30 sites, 12 of which have been officially certified. However, few GRUAN stations exist in several geographical regions (e.g. Africa, South America). There is also substantial work required to expand the number of GRUAN Data Products including from a range of ground-based remote sensing and in situ balloon-borne techniques. The WG-GRUAN is supported by, and reports to, AOPC who should continue to oversee progress. Regular Implementation and Coordination Meetings should continue. Efforts should be made to better integrate GRUAN into WIGOS operations. 2. A task team has been created under GCOS and SC-ON / SC-MINT to work towards the implementation of the GSRN. The GSRN should measure both near-surface atmospheric ECVs and site-relevant terrestrial ECVs and therefore the network will be overseen jointly by AOPC and TOPC from GCOS. CMA has agreed to host the Lead Centre for the GSRN. The GSRN TT, together with CMA, is expected to develop a proposal for the initial composition of the GSRN and start operations for the selected pilot stations by 2024. 3. Integration of FRM program measurements and associated support into long-term reference quality observing programs and networks assuring long-term cal/val operations. Including the provision of new FRM measurement programs and supporting infrastructure to fill critical current gaps in ECV satellite cal/val such as: • Networks in high and low above-ground biomass regions • Ground-based in situ measurements of above-ground biomass and vegetation dynamics following FRM protocols (Dunanson et al., 2021) • Ground-based time-series in situ measurements of surface albedo, FAPAR and LAI with their uncertainties • An open-access network of sites for burned area products 4. There are known networks and activities that produce reference quality measurements, i.e. BSRN, GAW networks. Efforts should be made to better recognize these as global reference networks. The panels will plan how to implement other reference networks across all domains. 5. Spearheading spectral RS and IR measurements are the following space missions: CLARREO pathfinder will measure spectral (350 – 2300 nm) radiances and reflectances in the visible and near-IR (NASA; launch in 2023); Prefire will measure spectral (5-45 μm) far-IR emissivity (NASA; launch in 2022); Forum will measure spectral far-IR outgoing radiation (ESA; launch in 2026); and TRUTHS will measure spectral RS (ESA; launch in 2029). It is essential that Space agencies consider long-term follow-on missions to the short-term pathfinder missions (CLARREO and Prefire). This should draw upon GSICS.

Links with other IP Actions	C2: Improvements to satellite data processing depends on the availability of reference observations. D4: Improve access to co-located satellite and reference quality in situ observations.

There are 3 remaining actions for which reference observations are relevant and can be supported by the successful implementation of GRUAN. These are as follows:

Action C2: General improvements to satellite data processing methods	
Activities	1. Improve radiance measurement records and Radiative Transfer (RT) models for simulating them. 2. Improve uncertainty quantification of satellite retrievals. 3. Periodically reprocess full satellite data records whenever an update of underlying methods occurs, especially when those risks introducing discontinuities into the time series. 4. Consolidate satellite observations into instrument-independent space-time grids for easy intercomparisons and fusion. 5. Ensure harmonisation and quality of ancillary data used to generate satellite products such as solar irradiance and meteorological data.
Issue/Benefits	Many data products depend on extended processing streams from observations to data products. Improving data processing methods facilitates ease of use, regular reprocessing and robust uncertainty quantification of available observations. This action identifies key areas for improvements. Ensuring the availability of relevant, high-quality estimates with long-term continuity across multiple instruments and satellites results in better quality of the satellite climate data records.
Implementers	From 1 to 5: **Space agencies,** Academia, Research organizations.
Means of Assessing Progress	For 1 and 2: New publications showing improvements in radiative transfer and uncertainty characterisation. 3. Increased number of available reprocessed Fundamental Climate Data Records (FCDRs). 4. Increased number of available consolidated gridded satellite datasets. 5. Products with consistent traceability to ancillary data and associated quality assessment.
Additional Details	1. Radiance measurement records need to be carefully assessed, characterized, and calibrated. Radiative Transfer (RT) schemes for simulating them also need to be improved, as this is a key component of processing radiance measurements and quality evaluation/assessment. Line-by-line radiative transfer models are critical and need to be available as reference for faster RT schemes. 2. Improve uncertainty quantification of satellite retrievals on all processing levels. Specifically (i) consider more carefully non-linearities and non-Gaussian uncertainties in the retrievals and (ii) consider and report spatially correlated uncertainties. Presently these are not properly considered in the satellite retrievals. Proper characterization of the uncertainties is key when data are further used e.g., in assimilation (e.g., in inverse modelling for emission estimation). 3. The quality of retrieved quantities also depends critically on the methods, ancillary, and auxiliary data used in the retrieval algorithm. As all these dependencies improve or ECV requirements changes, the satellite observations

	can (and should) regularly be reprocessed to ensure that the satellite data record is as useful as it can be (i.e., information content is fully exploited). 4. The typical lifetime of individual satellite instruments is shorter than the time scale required for climate applications. Therefore, satellite observations need to be consolidated across multiple instruments and satellites into high-quality estimates with long-term continuity in order to maximise their value for the climate community. This consolidation must be done in an optimal and standardised way, ensuring consistency across multiple instruments and satellites.
Links with other IP Actions	The following Actions are relevant to improve satellite data processing methods: B1: Reference observations (Uncertainty characterizations and improved uncertainty quantification of satellite retrievals). D4: Access to co-located data.

Action C3: General Improvements to in situ Data Products for all ECVs	
Activities	1. Periodically reprocess in situ data products to account for new knowledge, new techniques and improved access to historical data holdings. 2. Improve uncertainty quantification of in situ-based products. 3. Undertake efforts to account for spatio-temporal sparsity of in situ measurements via interpolation. 4. Ensure adequate sampling of the structural uncertainty inherent in in situ product development via supporting the development of multiple methodologically distinct products and their intercomparison.
Issue/Benefits	It is necessary to periodically reassess in situ-based estimates of climate change and to have multiple independently produced estimates for each ECV. Ensuring that datasets produced from in situ holdings reflect the latest availability of access, the latest knowledge, and the latest processing techniques assures the best possible estimates of long-term climate change are available to users. The availability of multiple independent estimates per ECV identifies those ECVs for which the true evolution is well known and thus informs directly assessments undertaken by e.g. IPCC.
Implementers	From 1 to 4: **Research organizations**, Academia, NMHSs.
Means of Assessing Progress	1. New publications of updated in situ datasets and availability of those datasets following FAIR data principles. 2. Increased number of available in situ-based datasets for which a documented and quantified uncertainty assessment is available. 3. Increased spatio-temporal completeness of in situ-based products based upon use of additional data and application of interpolation techniques. 4. Increase in number of ECVs for which two or more global in situ datasets exist.
Additional Details	In situ data products are not some frozen set of estimates which should remain unchanged. Over time new data, new insights and new and improved computational techniques appear. A high-profile example of this is the recent IPCC WGI report wherein the surface temperature datasets changed their estimates on a like-for-like basis by circa 0.1C. This change in the estimate of warming to date of the order 10-15% of the estimate before arose from a combination of improved understanding of data biases, improved access to historical data, improved interpolation techniques, and the emergence of new estimates.
Links with other IP Actions	B1: Reference observations. B9: Estimation of heat fluxes and wind stress. D5: Data rescue.

Action D4: Create a facility to access co-located in situ cal/val observations and satellite data for quality assurance of satellite products	
Activities	1. Improve access to co-located satellite and reference quality in situ observations, as well as tools for evaluation purposes. This facility will use data from reference networks and FRM programs for a broad range of ECVs for calibration/validation of satellite programs. 2. Develop tools to use the co-located data collection developed under Activity 1 to undertake various analyses of satellite-based measurements.
Issue/Benefits	The uncertainty for satellite measurements of ECVs are determined and/or verified through intercomparison against in situ measurements. These intercomparison field experiments also provide test bed opportunities for assessing measurement capabilities of new technologies, for testing and developing best practices, and to assess uncertainties in Numerical Weather Prediction and Climate Models. The current limited availability of co-located in situ and satellite data for calibration and validation data restricts the ability of users to assess the quality of satellite products. This action will improve the ability to exploit high quality reference measurement sites/networks including, but not limited to, FRM programs (see Action B1) to provide such calibration and validation data for a broad range of satellite products. What is required is a database of reference measurements and co-located satellite measurements to enable cal/val activities along with provision of a suite of tools. The provision of a centralised facility would minimise overall cost while maximising overall exploitation potential and is therefore preferable to such efforts at the satellite mission-level. It also enables applications which may wish to consider multiple ECVs from multiple satellites and their data fusion. A centralised well-supported facility would enable the long-term satellite cal/val capability necessary to extract the value from considerable investments in satellites and reference networks including FRM programs on a sustained basis.
Implementers	From 1 to 2**: Space agencies**, WMO, NMHS, Research organizations.
Means of Assessing Progress	1. Establishment of a unified database of and access to co-located, reference quality, ground-based measurements suitable for satellite cal/val. 2. Increased number of available compatible satellite and in situ datasets.
Additional Details	This activity addresses the need to improve the exploitation of the high-quality data needed to calibrate and validate satellite observations by making these data easily available: access is currently a major barrier to their use. A more coordinated, centralised approach to the storage and provision of data for satellite cal/val, with greater involvement of and partnership with reference networks (Action B1), along with the development of associated tools would yield cost efficiencies as well as scientific benefits. Users could come to centralised repositories which serve data for multiple satellite missions, enabling their usage in a more seamless manner. Tools could be shared between similar missions and made available to users. The centralised repository would serve to highlight the presence of critical gaps in provision of high-quality in situ data to inform the quality of ECVs measured from space. This, in turn, would help inform the strategic further investment in new reference networks and FRM programs to fill these gaps. Further details are given in Sterckx et al. (2020)[7].

[7] Sterckx, S., et al., 2020: Towards a European Cal/Val service for earth observation, *International Journal of Remote Sensing*, 41:12, 4496-4511, doi: 10.1080/01431161.2020.1718240

Links with other IP Actions	This activity has strong links to other actions: A1: sustained support for the source in—situ observations that underpin this action. B1: provision of reference quality in situ measurements including from FRM; and several other actions that underpin the in situ observations (B4, B6, B7, C4, F4).

4. ENVISAGED SPECIFIC PROGRESS WITHIN THE GRUAN IMPLEMENTATION PLAN PERIOD

4.1 Management tasks

The ongoing operation and development of GRUAN requires funded management to communicate, develop plans and monitor progress. Tasks[8] include, but are not necessarily limited to, the following:

- Day to day management of the network by the Lead Centre
- Bi-monthly WG conference call to discuss progress, report issues and update as agreed
- Regular ICMs that bring together WG-GRUAN, Lead Centre, sites and other stakeholders and define an agreed action plan
- Internal progress reporting to WG-GRUAN
- Reporting to sponsors including attending meetings as required
- Review and curation of GRUAN documentation
- Annual reviews of the network status
- Ensuring GRUAN scientific achievements are made available in peer-reviewed publications and promoted at conferences and via the website, verifying their impact on the scientific and user communities.

Action 1:	
Action:	Ensure day-to-day operation of the GRUAN network including addressing the high-priority actions from the latest ICM, regular reports to the AOPC on progress, issues and updates on GRUAN IP, and undertaking regular Implementation and Coordination meetings.
Who:	Lead Centre, WG-GRUAN and GCOS Secretariat
Time-Frame:	Continuous
Performance indicator:	Delivery of the strategic goals of GRUAN; number of high-priority actions addressed; reports to AOPC; ICM meetings.
Benefits:	The operational delivery of GRUAN; GDP available to the user community.

4.2 Reference observations

Reference observations are the core activity for GRUAN. The underlying principles of traceability and uncertainty quantification have been documented in Immler et al (2010) and the processing applied to the Vaisala RS92 (Dirksen et al., 2014), Meisei RS-11G (Kobayashi et al., 2019), GNSS-PW (Ning et al., 2016) and Vaisala RS41 (von Rohden et al., 2022). Further details are available in the GRUAN Guide (GCOS-171) and the GRUAN Manual (GCOS-170).

By 2030, at a minimum all 8 uncertified GDPs listed in Table 1 are expected to be certified. GRUAN products for any specific instrument type are processed by a single dedicated centre, which processes all data for the measurement series from all sites contributing to the measurement stream in a consistent manner to assure comparability. For example, RS92 and

[8] Some of these tasks are supported by the GCOS Secretariat

RS41 data are processed by the Lead Centre, Meisei RS-11G are processed by JMA, and GNSS-PW by GFZ. Other GDPs, when available, may be processed by other processing centres.

Each GDP must have Technical Documentation describing the instrument practices and a peer reviewed paper documenting the properties of the GRUAN data product. The data stream should be run as a beta release for a period of time sufficient to ascertain that the measurements can be made in the manner described in the technical document and that the central processing and data exchange protocols are both stable and functional. The data stream must be reviewed to ensure compliance. The path to GDP certification is detailed in GRUAN-TN-4 (2016). In addition, GRUAN data products are subject to strict version control. GRUAN data sets have DOI numbers. GRUAN will look to partner with existing networks and activities where possible in developing data best practices and data support infrastructure in a cost-effective manner and to avoid duplicative effort. Products need to be inter-operable and synergistic and this needs to be borne in mind when developing new data streams.

Action 2:	
Action:	Continue the development of the measurement techniques in Table 1, and any identified additional candidate measurement techniques, to enable GDP certification.
Who:	Task Teams, data processing centers, Lead Centre, WG-GRUAN, sites, contributing / collaborating networks.
Time-Frame:	By 2030
Performance indicator:	Number of systems which have certified GDPs (based on Table 1 which could have systems added during the period of this IP).
Benefits:	Increased availability of reference data.

4.3 Data dissemination, usage and review

GRUAN data are, by policy, made publicly available without restriction once processed and released. GRUAN data started flowing to users through the official GRUAN Data Centre in mid-2011. At present, this consists of five GDPs (Table 1), although substantial data from other instruments is archived by the Lead Centre and/or the sites. This allows data to be reprocessed upon development of new products. By 2030, GRUAN data will expand to consist of multiple data streams of GRUAN Priority 1 and 2 ECVs and include data from a range of instruments providing measurement complementarity.

The WG-GRUAN shall instigate data stream reviews at least every four years (per data stream). The data streams shall be evaluated for efficacy and operational anomalies by external to GRUAN WG experts once sufficient data are available. Feedback shall be provided to the Lead Centre for dissemination to sites and the processing facility concerned.

The current system for GRUAN data hosting is inadequate. Various alternatives are being considered to ensure accessibility and enforce better citation, DOIs and data usage tracking.

Action 3:	
Action:	Deploy GDPs as they develop via the data portal and monitor indicators of usage such as publications that use the data and availability in third-party repositories.
Who:	Lead Centre, Task Teams, sites.
Time-Frame:	Continuous
Performance indicator:	Data are publicly accessible and there is demonstrable evidence of growing usage within the community.
Benefits:	Long-term network utility and viability, return on investment.

Action 4:	
Action:	Implement a process for the periodic review of GDPs, to assess their usage, document issues and check consistency between GDPs. Review should include external peer review.
Who:	WG-GRUAN, Task Teams
Time-Frame:	Develop process (2025); Implement (2026)
Performance indicator:	Implemented process by end of 2026.
Benefits:	Ensuring that GRUAN data streams/products remain cutting edge, consistent and are regularly reviewed both internally and externally. Updated GDPs where required.

Action 5:	
Action:	Instigate and improve GRUAN data hosting system, including DOIs and usage tracking options.
Who:	Lead Centre, GCOS Secretariat, TT sites.
Time-Frame:	2024-2025
Performance indicator:	New system implemented
Benefits:	Improved accessibility, citation and data usage tracking.

4.4 Network expansion and certification

As mentioned above, GRUAN consists of a network of 31 sites (which includes historical sites), of which 23 were actively reporting and 14 have been certified following the procedures detailed within the GRUAN Guide (GCOS-171). The aspiration for GRUAN is to eventually consist of 30-40 sites which are globally distributed and that meet stakeholder needs. These needs were ascertained from a dedicated meeting (GRUAN-RP-4) and are envisaged to be revisited periodically. By the end of the period covered by this IP, the network should consist of 30 to 40 actively reporting sites (of which at least 80% shall be certified) that are more globally equitably located. The location of new sites will be chosen pro-actively to meet documented stakeholder requirements. A proposal to handle the "silent" sites will have been implemented with the goal of re-activating silent sites or otherwise decommissioning them.

Action 6:	
Action:	Recruit and retain more sites with a priority in South America, Africa and Eurasian regions.
Who:	WG-GRUAN, Lead Centre
Time-Frame:	Continuous
Performance indicator:	At least 35 active sites present on map at the end of the IP period.
Benefits:	Improved global network coverage, reference quality measurements in new regions important to stakeholders.

Action 7:	
Action:	Review and re-review sites as detailed in the GRUAN manual so that at least 80% of the active sites are certified over the last year of the IP period.
Who:	WG-GRUAN, Lead Centre
Time-Frame:	Continuous, for any given site at least once per four years.
Performance indicator:	Number of certified sites; number of sites delivering data streams via the relevant GRUAN data portal(s).
Benefits:	Certification ensures a minimum quality to end users and a degree of compatibility/comparability of their data streams and quality to the contributing sites.

Action 8:	
Action:	Develop and implement a proposal to review and revive silent sites.
Who:	WG-GRUAN, Lead Centre, GCOS sites
Time-Frame:	2024
Performance indicator:	Silent site removal process is implemented and working; number of silent sites.
Benefits:	The proposal would revive the silent sites or decommission them from GRUAN. It would ensure a high quality and active network.

4.5 Science issues

There remain several open science questions, and challenges, relating to either specific instrumentation or generic issues such as scheduling of measurements, their combination etc. These constitute scientific issues that need to be resolved for network operations and design rather than science applications that employ the data. Such scientific application activities are key to a successful and vibrant GRUAN but are not under the purview of network management activities and hence cannot be mandated under an 'implementation' umbrella. A key challenge in the period of the current IP is the development of Priority 2 variables, such as radiation budget, clouds and aerosol properties.

A number of actions are addressed within the GRUAN Task Teams (under the WG-GRUAN) and as such are not detailed in this IP. However, certain actions which are considered fundamental or strategically significant are included below.

Action 9:	
Action:	Develop, test and implement new UTLS water vapor sensors and new cooling agent for R23 replacement.
Who:	Task Team on radiosonde, WG-GRUAN, Lead Centre
Time-Frame:	2024-2026
Performance indicator:	New sensors and non-R23 cooling methods for frostpoint techniques are tested (by end of 2024); implemented at all relevant GRUAN sites (2026).
Benefits:	Continuity of the UTLS water vapor measurements.

Action 10:	
Action:	Justify the use of the Standard Humidity Chamber (SHC) and document the necessary procedures.
Who:	Task Team on sites, Lead Centre
Time-Frame:	2024
Performance indicator:	Peer reviewed paper and technical note published. Increase use of SHC at GRUAN sites.
Benefits:	Improved uncertainty calculation for radiosondes measurements; potential for SHC to become more widely used at non-GRUAN sites.

Action 11:	
Action:	Strengthen the use of satellite and GRUAN products for validation and calibration activities of both data sets, leading to improved uncertainty estimates.
Who:	Task Team on Satellite, Lead Centre, WG-GRUAN
Time-Frame:	Continuous
Performance indicator:	Publications and evidence for progress in annual ICM reports.
Benefits:	Better characterization of measurement uncertainties, optimal use of observational assets to meet stakeholder needs.

4.6 Organizational issues

GRUAN is now relatively mature and stable in terms of management. DWD has committed to long-term hosting of the Lead Centre. However, there are some recognized issues that need addressing around coordination with similar networks and ensuring periodic review of governance. During the last IP period, the original auxiliary TT was successfully reorganized into two TTs, "Ground-based" and "Satellite", with more focused and clearly defined tasks for each of them.

Action 12:	
Action:	Ensure sustained interactions with other networks interested in upper-air measurements of ECVs to realize synergies through cross-cutting governance activities, collaborative projects, joint peer-reviewed publications etc.
Who:	WG-GRUAN, Lead Centre, Task Teams
Time-Frame:	Continuous
Performance indicator:	Memoranda of understanding enacted, appropriate cross-representation, joint participation in research project.
Benefits:	Scientific insights, mitigation of capability redundancies, better governance in the framework of WIGOS.

Action 13:	
Action:	Periodically review WG-GRUAN membership and terms of reference and whether task teams are still relevant/additional task teams needed.
Who:	WG-GRUAN, Lead Centre, Task Teams, AOPC
Time-Frame:	Review internally at GRUAN ICMs as a standing item. Reported annually to AOPC including relevant decisions and issues.
Performance indicator:	Regular review at ICMs and reporting to AOPC.
Benefits:	Ensure continuous relevance of activities and relevant expertise is recruited and retained to address the present challenges.

4.7 Outreach

Accessibility, usage and exploitation of GRUAN data is fundamental to the success of such a reference network. It is therefore important that opportunities are taken to inform stakeholders and end users about GRUAN.

Action 14:	
Action:	Sustained engagement with the user community to ensure usage and exploitation of data arising from GRUAN activities.
Who:	WG-GRUAN, Lead Centre, Task Teams, AOPC
Time-Frame:	Continuous
Performance indicator:	Papers published, presentations given, participation in international activities and occasional special sessions on GRUAN in international conferences.
Benefits:	Ensures usage by user community to drive value.

4.8 Expanding to include additional Upper Air Essential Climate Variables

In its founding, GRUAN was intended eventually to fully characterize all upper-air ECVs and their constituent components. As shown in Table 1, GRUAN has been focusing on development of GDPs for Priority 1 variables using both radiosondes and ground-based remote sensing instruments. It also started one Priority 2 variable, ozone. GRUAN will explore the potential to add measurement capabilities to respond to the 2022 GCOS IP as detailed in Section 3, such as clouds, radiation, aerosol and trace gases. However, initial scoping is required to determine when and how to bring in additional measurements in the future. Cloud measurements can be considered as the first, since the GRUAN community has been working on standardizing cloud observations at GRUAN sites as a part of radiosonde launches and seeking options for continuous cloud measurements. Both manual and automatic cloud observation are under consideration: for the automatic, existing networks and research infrastructure, such as ACTRIS-Cloudnet[9], are already providing quality assured products (e.g. cloud base height) based on algorithms consolidated since more than a decade. Also, since 2013, E-PROFILE[10] is working on developing an homogeneous dataset that can be easily used by the scientific community. The dialogue with these initiatives could be intensified in the benefit of development of GDPs for clouds.

Action 15:	
Action:	In collaboration with partner networks, assess the relevance and tractability of the full suite of remaining GRUAN target variables defined in GCOS-112 (updated with new ECV definitions in the 2022 GCOS IP) in the context of measurement capabilities and measurement programmes underway in partner networks.
Who:	WG-GRUAN, Lead Centre, Task Teams
Time-Frame:	2026
Performance indicator:	Report available and some data streams for new ECVs not yet considered, at a minimum, under demonstrable development (stretch target: at least one additional ECV now has a GRUAN product).
Benefits:	After network expansion the next benefit would be in starting to observe all important facets of the column at the sites which requires expanding the ECV set.

4.9 WIGOS interactions

The GRUAN network is recognized and contributes high quality data and products to WIGOS. The guidance and processes which defines the contribution to WIGOS are detailed in the GRAUN Manual (GCOS-170) and Guide (GCOS-171). However, these were published in 2013 and now need to be reviewed and updated as appropriate. WMO and GCOS have developed the concept of tiered networks and are now working on how they should be implemented across all WIGOS. GRUAN, as a recognized reference network should contribute to this activity to ensure consistency and offer expertise.

Action 16:	
Action:	Review and update GRUAN Manual and Guide (GCOS-170 and GCOS-171).
Who:	WG-GRUAN, Lead Centre, AOPC and GCOS Secretariat, WMO SC-ON
Time-Frame:	2024-2026
Performance indicator:	Updated GRUAN Manual and Guide.
Benefits:	Recognition by NMHSs who provide sites and/or analysis capabilities. Visibility with stakeholders such as the satellite cal/val community.

[9] https://cloudnet.fmi.fi/
[10] https://e-profile.eu/

Action 17:	
Action:	Contribute to the WMO-GCOS activity on the implementation on the tiered networks. Show how GRUAN has benefits for broader measurement networks.
Who:	WG-GRUAN, Lead Centre, AOPC and GCOS Secretariat, WMO SC-ON
Time-Frame:	2024-2030
Performance indicator:	Progress on the implementation of tiered networks within WIGOS. Peer reviewed publications highlighting the benefits of GRUAN to broader observing network.
Benefits:	Strengthening of GRUAN's position within the global observing system. Benefits of GRUAN programmes to other end users.

Action 18:	
Action:	Periodically review aspects around sustainability and environmental impacts of GRUAN operations
Who:	WG-GRUAN, Lead Centre, AOPC and GCOS Secretariat, WMO SC-ON
Time-Frame:	2024-2030
Performance indicator:	Reporting of sustainability and environmental impacts. Testing and deployment of new more sustainable practices.
Benefits:	As a leading network it is important that GRUAN leads by example in regard to environmental sustainability concerns minimizing the environmental footprint where and when possible.

5. SUMMARY

We have detailed herein a set of actions designed to provide a high-level vision for the development of GRUAN in the timeframe 2024-2030. This Implementation Plan also responds to the GRUAN relevant items contained in the latest GCOS Implementation Plan (2022).

The activities detailed in this IP shall be reviewed regularly at the GRUAN ICM, led by the co-chairs of the WG-GRUAN and a detailed action plans shall be developed with the aim of meeting the actions detailed above.

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Acronyms

AOPC	Atmospheric Observations Panel for Climate
DOI	Digital Object Identifier
DWD	Deutscher Wetterdienst
ECV	Essential Climate Variable
GCOS	Global Climate Observing System
GCOS SC	GCOS Steering Committee
GDP	GRUAN Data Product
GFZ	Deutsche GeoForschungsZentrum
GNSS-PW	Global Navigation Satellite Systems (GNSS) precipitable water
GRUAN	GCOS Reference Upper Air Network
ICM	Implementation and Coordination Meeting
IP	Implementation Plan
IPSL	Institute Pierre-Simon Laplace
JMA	Japan Meteorological Agency
LC	Lead Centre
NMHS	National Meteorological and Hydrological Service
NOAA	US National Oceanic and Atmospheric Administration
NWP	Numerical Weather Prediction
SMART	Specific, Measurable, Actionable, Realistic, and Timebound
UTLS	Upper Troposphere and Lower Stratosphere
WG-GRUAN	Working Group on GRUAN
WIGOS	WMO Integrated Global Observing System
WMO	World Meteorological Organization

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