GCOS
Reference
Upper-
Air
Network

GRUAN Report 4

GRUAN-RP-4: Outcomes of the GRUAN Network Expansion Workshop

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Abstract

A GCOS Reference Upper-Air Network (GRUAN) workshop to develop network design and expansion criteria was held in Fürstenwalde, Germany, from 13 to 15 June 2012. GRUAN's goal is to provide reference-quality measurements of upper-air Essential Climate Variables (ECVs) to meet the needs of the climate research and monitoring communities and to fill a void in the global observing system. Upper-air observations at sites within the GRUAN network provide long-term, high-quality, error-characterized climate records designed to serve GRUAN's primary user communities.

The vision for a fully implemented GRUAN is an expanded network eventually comprising 35-40 sites. This expansion must be carefully planned to most effectively advance GRUAN's scientific objectives. The purpose of this workshop was to understand the network design requirements to meet the needs of four primary users of GRUAN data, i.e.:

- climate change detection and attribution,
- satellite calibration and validation,
- atmospheric processes research, and
- numerical weather prediction.

This report summarizes the key outcomes of that workshop.

Executive Summary

GRUAN, the Global Climate Observing System (GCOS) Reference Upper-Air Network (www.gruan.org), is a ground-based network whose goal is to make reference observations of the troposphere and stratosphere for climate to meet the needs of:

i) *The climate detection and attribution community:* The long-term stability and homogeneity of GRUAN data provide time series needed to robustly detect and attribute changes in the climate of the free atmosphere, i.e., that part of the atmosphere above the boundary layer. GRUAN data can also be used to constrain and validate data from more spatially comprehensive global networks for improved climate detection and attribution.

ii) *The satellite community:* GRUAN data products are used to validate satellite-based measurements and to provide the input needed for radiative transfer calculations required to improve and evaluate retrieval algorithms. GRUAN data may also be used to directly calibrate satellite sensors.

iii) *The atmospheric process studies community:* By providing measurements of a range of upper-air climate variables with small, well-defined random errors, and high vertical resolution, GRUAN data products support the development of a deeper understanding of the processes affecting the atmospheric column. Because GRUAN will make profile measurements at vertical resolutions much higher than can be retrieved from satellites (e.g., metres to tens of metres), it will provide valuable insights into the potential limitations of satellite-based measurements for the analyses of specific atmospheric phenomena.

iv) *The numerical weather prediction (NWP) community:* The reference quality of GRUAN data makes them useful for verifying NWP model outputs and for validating and correcting other data being assimilated into NWP models. Measurements made at GRUAN sites can also be directly assimilated in real-time, or near real-time, into NWP models, provided this is not detrimental to achieving the primary purposes of the network, as defined above. GRUAN reference measurements can also be assimilated into meteorological reanalyses.

The size of GRUAN at the time of the 'network expansion workshop' (15 sites), and the geographical distribution of those sites, was broadly accepted to be insufficient to meet the needs of the communities defined above.

The needs of these four user communities were each considered separately by dedicated teams during the workshop. This report discusses strategies on how best to expand GRUAN as developed by the workshop participants with additional contributions from the four user communities detailed above. The primary purpose of the workshop was not to identify sites per se, but rather to develop the criteria by which site selection might take place, noting that there will be many other factors that affect which sites will join GRUAN in the future. For example, no cost-benefit analysis was carried out in this study. The focus of the workshop, the report and the selection of sites was restricted to upper-air observations. The recommendations made in this report must be seen as provisional as not all considerations for site location, e.g. ease of access, financial considerations, national support for GRUAN activities, proximity to other sites, have been taken into account. It is likely not possible to develop a purely objective approach to identifying optimal locations of sites that would best serve the wide spectrum of users of GRUAN data.

Recommendations

The key recommendations from the workshop are listed below. In some cases the aspirations of one recommendation may conflict with one or more aspirations from other recommendations. These tensions between the recommendations reflect the complexity of the task of establishing a single global climate monitoring network designed to meet the needs of multiple user communities.

- *Variables:* In addition to temperature, water vapour and ozone, sites with observation capabilities for radiation, clouds and wind profiles would be most advantageous for attribution studies.
- *Global coverage:* The complete range of atmospheric regimes should be sampled by having sites in each of the major climate regions (polar, mid-latitude, subtropical and tropical) in both hemispheres.
- *Environment:* Sites should cover a variety of surfaces such as forest, deserts, snow and ice as well as stations on small, remote islands to represent surrounding ocean conditions, remote mountain top sites, but also regions influenced by urban pollution such as the Mediterranean basin.
- *Measurement conditions:* There are distinct advantages of atmospheric measurements made under clear-sky conditions. They minimize uncertainties introduced by radiative transfer modelling in the presence of clouds and aid satellite calibration and validation (cal/val; see below). Relatively simple climatological vertical profiles of temperature and humidity avoid complicated features that make trend determination difficult. On the other hand, for process studies, sites exhibiting a wide range of phenomena over a short period of time are preferable.
- *Use of quantitative analyses:* In some cases, quantitative, objective methods can be used to identify favourable locations to detect phenomena of interest, e.g. trends in mid-troposphere temperatures. Sites that exhibit little short-term atmospheric variability is not the only requirement for best detecting trends. Auto-correlation structures (the degree of persistence in variability in both space and time) also play a key role in trend calculations; large persistence makes trend detection more difficult. Locations may need to be selected both for low variability and for high variability, i.e., low variability for the trend detection community but high variability for the process studies community.
- *Determining required measurement frequency:* Analyses can and should also be performed to optimize measurement schedules to meet specific needs or users and to avoid making measurements more often than required, e.g. for estimating trends from monthly means, the number of measurements required to define the monthly mean within some random uncertainty bound must be quantitatively established.
- *Modes of variability:* Sites should cover a wide variety of different climate regimes and large-scale modes of variability such as the SAM, NAM, ENSO, QBO[1], and should also permit detection of changes in features such as the width of the tropics, the Brewer-Dobson circulation, and monsoons. To detect changes in modes of variability, measurements are required both where the amplitude of the pattern peaks, and at the nodes of the patterns.
- *Satellite cal/val:* For the calibration and validation of satellite observations, it is essential that the reference measurements are temporally and spatially co-located with the satellite-based measurements. It is preferable to have a smaller number of good quality and easily maintained sites in particular in places where satellite overpasses coincide with regular GRUAN sonde launches rather than a large number of sites.
- *Historical record:* For monitoring changes in climate, long-term, stable, and homogeneous time series of measurements are required from sites with a long-term commitment to the network and consistent operational practices that meet GRUAN standards. All else being

1 All acronyms are defined in an appendix at the end of this document.

equal, sites with an existing history of such measurements should be selected over other sites.

- *Simulation experiments:* There is scope for applying assessment techniques such as Observing System Simulation Experiments (OSSEs), Observing System Experiments (OSEs), and ensemble data assimilation impact studies, to give insights on how the inclusion or exclusion of a site might affect the quality of NWP or reanalyses. However, in their present form, these techniques do not readily measure what are arguably the most valuable, but 'indirect', benefits of a GRUAN station, e.g., GRUAN measurements in some region may indirectly lead to an improvement in the quality of in situ observations at nearby sites and to better-calibrated global satellite observations. Thus, NWP-based studies to assess the utility of new sites joining GRUAN would need careful development in collaboration with the NWP community.
- *Collaboration:* There are many facets of GRUAN operation where GRUAN can benefit from the skills and expertise available through allied atmospheric observation networks such as SHADOZ, NDACC, ARM, AERONET, MPLNET, CloudNet, BSRN etc. Rather than duplicating the extensive development that has been undertaken in these networks, GRUAN must collaborate with these networks to add value to GCOS in the most cost effective way possible.
- *Cross-benefit:* GRUAN sites can serve as anchor points within the wider GUAN climate network, and the even wider global upper-air weather observing network. Strategic placement of GRUAN sites to best facilitate comparisons with observations from these larger networks should be considered.

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1 Introduction

The goal of the GRUAN workshop to develop network design and expansion criteria, held from 13 to 15 June 2012 in Fürstenwalde, Germany, was to define the scientific basis to guide the expansion of GRUAN from its then 15 sites[2] (Ny Ålesund was not a GRUAN site at the time of the workshop) to 35 to 40 sites over the coming years. That expansion must be carefully planned to advance GRUAN's scientific objectives most effectively, cognizant of current existing observational gaps, recognizing that available resources are limited, that there may be competing needs of different users, and that GRUAN sites are supported at the national level. The primary focus of the workshop, however, was to focus on the scientific basis for guiding the expansion of GRUAN with little attention being given to how that expansion could be realised.

2 The current composition of the GRUAN can be found under: http://tinyurl.com/GRUAN-sites

2 A summary of GRUAN

The need for a reference upper-air network to better meet the needs of the international climate research community has long been recognized (Karl et al., 1996; NRC, 1999; GCOS-92, 2004; Trenberth et al., 2002). In response, the inception of the GCOS Reference Upper-Air Network (GCOS-112, 2007; GCOS-134, 2009) was formalized through a series of meetings held under the joint auspices of GCOS and NOAA between 2005 and 2007, when GRUAN was first clearly articulated. In contrast to the GCOS Upper-Air Network (GUAN), which is based on weather observing stations and was designed in the 1990s to ensure continuation of observations in regions then facing technological and financial challenges, GRUAN is specifically designed for climate monitoring and research. As such, GRUAN serves the international climate community through a combination of research and operational activities, comprising high quality operational network observations and elements of research and development for the future. GRUAN provides reference observations of upper-air ECVs (GCOS-138, 2010) through a combination of in situ measurements made from balloon-borne instruments and from ground-based remote sensors. Furthermore, management decisions in GRUAN are driven by a variety of requirements for long-term measurements of assured stability, including good supporting operational practices. On the one hand, GRUAN is a research network constantly striving to improve measurement techniques and quantify and reduce measurement uncertainties. On the other hand, the measurements need to be stable over decadal time scales and homogeneous across the network. These two aspects of GRUAN operations are not mutually exclusive but can pose difficult choices and so must be carefully balanced.

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

To achieve these goals, sites within the network provide vertical profiles of reference measurements of temperature, pressure and water vapour (and additional ECVs) suitable for reliably detecting changes in global and regional climate, on multi-decadal time scales, for major climatically distinct regions of the globe. The uniformity and coherence of standard operating procedures at GRUAN sites and the resultant homogeneity of GRUAN climate data records not only provides a global reference standard for operational upper-air network sites, but improves the detection of changes in the climate of the troposphere and stratosphere. Measurements at GRUAN sites will also provide a reference for global satellite-based measurements of atmospheric ECVs. This facilitates the creation of seamless, stable, and long-term (multi-decadal) databases of satellite-based measurements suitable for detecting trends and variability in climate in the troposphere and stratosphere.

In the context of the other WMO observing systems, GRUAN will need to be the climate reference backbone of the existing global operational upper-air network. Because GUAN sites often operate with different equipment, sensors, and operating protocols, the different requirements of GRUAN and GUAN operations may require careful management.

While GRUAN's current focus is on water vapour and temperature measurements, the range of climate variables that GRUAN will target is expected to grow over the coming years as measurement protocols, operating procedures, measurement processing methods and measurement quality assurance/quality control procedures for new measurement systems of other ECVs are defined and implemented. GRUAN's reference observations are characterized by having all known systematic artefacts removed, being traceable to SI (or community accepted) standards, including a comprehensive uncertainty analysis, documented in accessible literature, homogeneous/stable in time over the lifetime of the measurement series, thoroughly validated, and including comprehensive metadata that will meet future needs of users for decades to come. As part of making reference observations, GRUAN requires the use of independent redundant measurement systems to validate derived measurement uncertainties.

GRUAN has been a pilot project of the World Meteorological Organization (WMO) Integrated Global Observing System (WIGOS) and builds on networks coordinated by WMO. The active design of networks within the global climate observing system, as opposed to a more passive assumption that such networks will evolve from country-specific activities, is also a focus of WIGOS.

3 Workshop goals and purpose

The primary identified target user communities of GRUAN data are:

i) *The climate detection and attribution community:* The long-term stability and homogeneity of GRUAN data provide time series needed to robustly detect and attribute changes in the climate of the free atmosphere. GRUAN data can also be used to constrain and validate data from more spatially comprehensive global networks for improved climate detection and attribution.

ii) *The satellite community:* GRUAN data products can be used to validate satellite-based measurements and to provide the input needed for radiative transfer calculations required to improve and evaluate retrieval algorithms. The anchor provided by GRUAN measurements for space-based sensors can be used to remove any offsets and drifts between multiple satellite data sets to create a homogeneous long-term climate data record. GRUAN data may also be used to calibrate satellite sensors through their use as input to a RTM and to bridge possible gaps between non-overlapping satellite data records.

iii) *The atmospheric process studies community:* By providing measurements of a range of upper-air climate variables with small, well-defined random errors, and high vertical resolution, GRUAN data products support the development of a deeper understanding of the processes affecting the atmospheric column. Because GRUAN will make profile measurements at vertical resolutions much higher than can be retrieved from satellites (e.g., metres to tens of metres), it will provide valuable insights into the potential limitations of satellite-based measurements for the analyses of specific atmospheric phenomena. Augmenting GRUAN measurements with measurements from allied networks will further the utility of GRUAN measurements in atmospheric process studies.

iv) *The numerical weather prediction (NWP) community:* The reference quality of GRUAN data makes them useful for verifying NWP model outputs, and for validating and correcting other data being assimilated into NWP models. Measurements made at GRUAN sites can also be directly assimilated in real-time, or near real-time, into NWP models, provided this is not detrimental to achieving the primary purposes of the network, as defined above. GRUAN reference measurements can also be assimilated into meteorological reanalyses.

The needs of these four user communities were each considered separately by dedicated teams during the workshop.

A total of 24 scientific experts participated in this workshop with a larger group contributing to the writing of four white papers which provided a starting point for discussion at the meeting. Expertise at the workshop encompassed all research elements related to GRUAN and the primary users of GRUAN data products, including climate monitoring network design, observing techniques and implementation, atmospheric measurement techniques, detection and attribution of trends in upper air temperatures and ozone, data assimilation, and calibration and validation of satellite-based measurements.

The purpose of the workshop was to understand the network design requirements of each of the four communities listed above with a specific goal of addressing the following questions:

- What should be the attributes of new sites joining GRUAN?
- What specific environments need to be considered, e.g., stations on remote islands or over snow?
- What geographical coverage of sites would best serve each community’s scientific needs?

- What large scale climate regimes need to be sampled?
- What are the key considerations for geographical coverage?
- What is the scientific justification/basis for the design of a network? Have peer-reviewed studies addressed any of the workshop concerns?
- What additional research is required to ensure that the design and operation of GRUAN is based on sound scientific analyses?
- How can GRUAN best benefit from collaboration with other established ground-based measurement networks?

At the time of writing this report, GRUAN comprised 15 sites. This is insufficient to meet the needs of the communities identified as the main users of GRUAN data. While the primary goal was to develop network expansion criteria, a secondary goal was to consider site locations and the scientific basis for their selection.

In preparation for this workshop, people from various communities were asked to consider what they would wish as an optimal configuration of GRUAN sites for their research purposes. A list of sites already belonging to various atmospheric measurement networks was generated. People then selected sites from this list as a way of indicating the configuration of their desired GRUAN, in terms of site location only, to best serve their research needs. This is a 'thought experiment' exercise where the information collated through this process formed a first impression of what people would

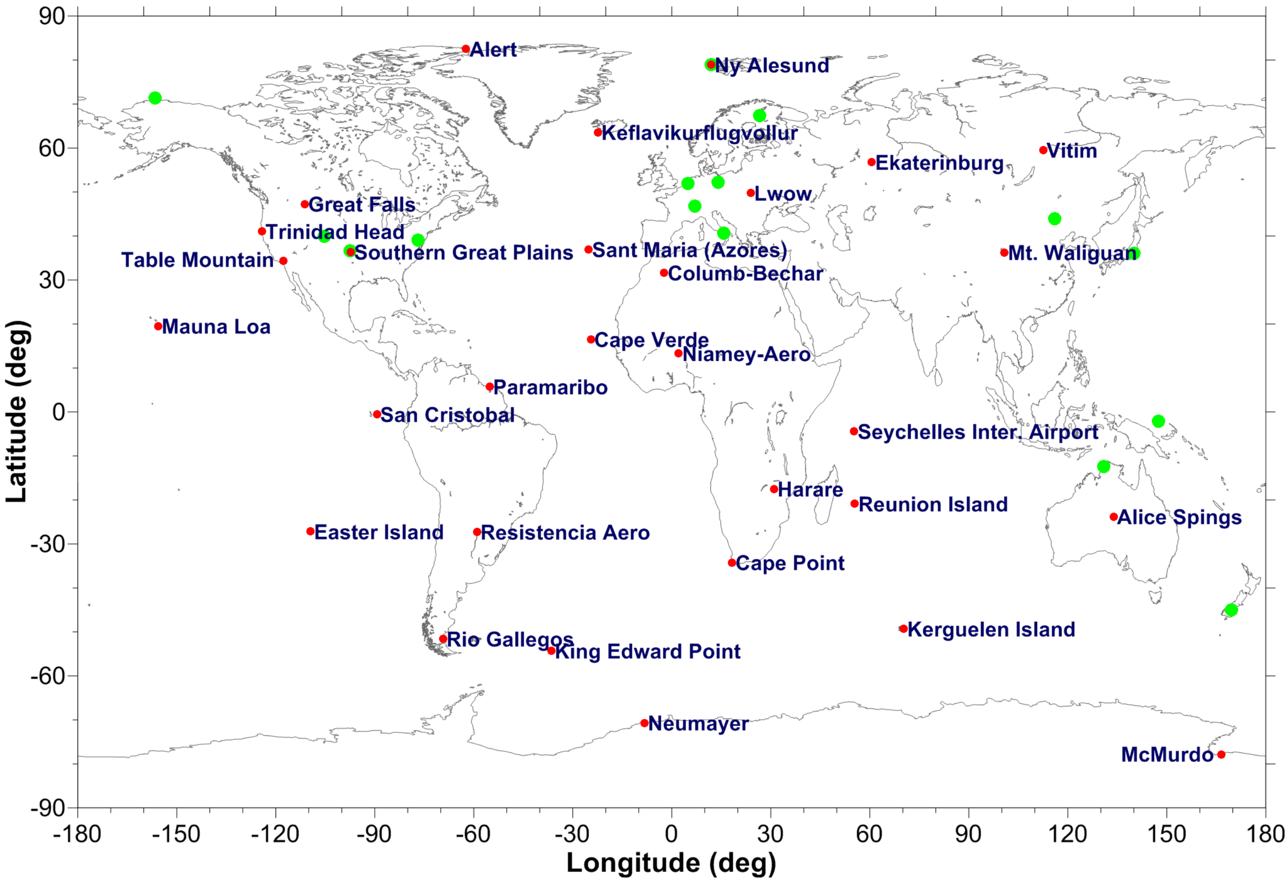

Figure 1: Map of a potential GRUAN configuration as suggested by representatives of its main data user groups (red dots with name labels). Existing GRUAN sites are shown in green dots without labels to aid clarity. Stations on this map were selected based on the provisional analysis carried out in preparation for the workshop and should be regarded as purely indicative.

like to see as a geographical configuration for GRUAN. This site selection process in no way suggests that the sites selected will become, or are expected to become, GRUAN sites. The results are shown in Figure 1. The selection of sites indicates a user community desire to have as many sites in the southern hemisphere as in the northern hemisphere and many sites on islands.

The sites listed in Figure 1 result from various subjective selection criteria. The purpose of this workshop was, in part, to develop more objective criteria to provide a more robust scientific foundation for the selection of sites within GRUAN. Therefore, the sites identified in Figure 1 must be seen as the starting point for the process undertaken at the workshop and not as a conclusion of the workshop.

4 Network Design

Before considering the specific needs of the user communities listed in the previous section, this section summarizes some general network design concepts that will apply across the four sections that follow.

Meteorological observing networks have, to date, developed in a rather ad hoc fashion and are often biased towards where people live as this provides ease of access for maintenance and provides data immediately relevant to population centres. This tendency favours the northern hemisphere and lower elevations and results in a distribution of sites unlikely to be representative of the global climate. This is also true of the distribution of the 15 initial GRUAN sites. They are predominantly in the northern hemisphere mid-latitudes. An important aspect of the GRUAN site assessment and certification process (see Section 5 of GCOS-171, 2013) is the added value that a site brings to the network. The outcomes of this network expansion workshop also support objective assessment of the added value that a site might bring to the network, e.g., the extent to which a site's existing measurement programmes provide additional knowledge through data in previously unsampled regions or of previously unsampled atmospheric phenomena.

Observing networks such as GRUAN are expensive to establish and maintain and the workshop's goal therefore was to objectively identify highest value locations, noting that "value" is relative to the intended user community. The design must nevertheless be sensitive to practical constraints.

While the potential use of mobile stations and test-bed sites in GRUAN was not discussed at the workshop, consideration should be given to the value that such facilities might bring to the network. A mobile station is a portable instrument, or set of instruments, that is transported from one fixed site to another to perform critical measurements for validation and inter-comparison purposes. Such a facility assists in establishing network-wide homogeneity. Experienced mobile station operators, who have been well trained in making reference quality observations, can transfer knowledge and use of best measurement practices to individual sites. A test-bed site is a fixed site whose purpose is to host regular validation and inter-comparison campaigns to improve the quality and consistency of the measurements and standard operating procedures. A successful network is not only a set of sites on a world map, but also a complete, coherent framework within which each participating site must operate in full compliance with the guidelines and principles of the network.

4.1 OSEs and OSSEs

To evaluate and plan the design of an observing system, so-called Observing System Experiments (OSEs; Masutani et al., 2010b) are performed by numerical forecasting centres. These experimental runs of (typically) weather forecasting models exclude or add certain types of observations in the assimilation process to assess the incremental value of different observation types or platforms for the model's forecasting performance. In this way, OSEs focus on the impact of currently available measurements on the ability of forecasting centres to conduct numerical weather prediction.

OSEs do not consider the indirect effect of individual types of observations, e.g., in cases where observations are used to calibrate other measurements. This typically concerns in situ observations which serve as a reference for ground-based remote sensing instruments or are being used for ground-truthing satellite instruments.

The traditional technique to assess the impact of specific observations is to conduct OSEs where the forecast impact of perturbations in the assimilated observational data set is measured against the forecast performance of an unperturbed (control) assimilation. In recent years, several new techniques that augment the OSE results have been developed and are now widely adopted, notably adjoint-based tools such as Forecast Sensitivity to Observations (FSO), Degrees of Freedom for Signal (DFS) and others. FSO tools are runs conducted with the forecast model at a later point in time, including variations of the initial conditions of certain observations, to see how stable the results are with regard to the uncertainty of these observations or on which observations the model outcome depend most critically.

So-called Observing System Simulation Experiments (OSSEs) go beyond OSEs by examining the impact of a virtual observing system. For more information see Masutani et al. (2010a, b) who discuss OSSEs and their variants. To date, few OSSEs have been developed outside of the application for numerical weather prediction by meteorological services. A few examples of additional application areas are where OSSEs have been developed for stratospheric winds (Lahoz et al., 2005) or air quality (Zoogman et al., 2011). At the time of writing, no OSSE studies were known with specific focus on climate applications. The relatively high costs of performing OSSEs can usually only be accommodated by space agencies who find OSSEs worthwhile to inform them of future impacts and, countering the relatively high costs of OSSEs, owing to the cost of satellite missions. NWP centres also support the implementation of OSSEs.

OSSEs must be used with caution. As detailed by Masutani et al. (2010b), the National Centres for Environmental Prediction's (NCEP) experience with OSSEs demonstrates that they often produce unexpected results. Theoretical predictions of the data impact and theoretical backup of the OSSE results are very important as they provide guidance on what to expect. On the other hand, unexpected OSSE results often stimulate further theoretical investigations. It is likely that because there are few GRUAN sites, an OSSE may indicate that the inclusion or exclusion of GRUAN sites has little impact on the quality of NWP. It would be wrong to therefore conclude that GRUAN brings little value to NWP. A GRUAN site is expected to lead to improved quality in upper-air measurements from other sites in the region which could lead to a significant improvement in the quality of NWP. This added value may not necessarily be captured via an OSSE. An alternative to OSSEs is ensemble data assimilation impact studies (Tan et al., 2007; Harnisch et al., 2013, Megner et al., 2014). Whether OSEs and OSSEs, or the ensemble data assimilation approach, are relevant to the design of GRUAN needs to be studied in greater depth as discussed in Section 8.

4.2 Difference between a site and a locale

A "site" is defined as the location of one or more GRUAN measurement systems, while a "locale" is defined as a contiguous geographical region with generally homogeneous climate and surface properties within which a GRUAN site might be established. This report considers both locales and potential sites within those locales of interest. These are usually existing measurement sites within existing networks. The selection of a locale is driven by a scientific rationale, while the suggestion of a site within a locale is driven more by logistical and operational considerations. In addressing network expansion criteria, this report focuses mainly on identifying locales, but also identifies potential sites within those locales as examples of the application of the network expansion criteria.

4.3 Establishing a global network

The Earth is an asymmetrically populated planet, where approximately 90% of the human population lives on the northern hemisphere. In concert with this, only about 10% of the world's Gross Domestic Product is generated south of the equator. If relying solely on commitments to support sites in home countries, GRUAN is unlikely to evolve into a truly global network, covering every major climatic region of the globe and serving the needs of the four user communities identified in Section 3. Therefore, additional funding sources and approaches to "twin" with sites in southern hemisphere countries need to be exploited.

5 Climate change detection and attribution community needs

5.1 Introduction

Long-term stable measurements of temperature, water vapour and ozone in the troposphere and stratosphere are essential for climate change detection and attribution studies. Deficiencies in historical observations have presented challenges for estimating trends since uncertainties are large. A number of papers (e.g., Free et al., 2002; Wang et al., 2012) point to the inherent, and to some level irreparable, problems that arise from complicated merging of data sets with changing or unknown quality, different measurement approaches and large uncertainty. Even though the sum of all terms that contribute to the trend uncertainty might be reduced by a carefully applied homogenization process, the homogenization itself inevitably introduces a new source of uncertainty.

Understanding the changing Earth system requires a cohesive, well-characterized measurement approach at locations around the world that are critical to understanding changes in the atmosphere. GRUAN data products will be required for detecting and attributing changes in climate and changes in modes of climate variability.

Satellite measurements provide important global coverage of temperature, water vapour and ozone through much of the atmosphere. However, satellites exhibit significant deficiencies for trend detection and interpretation, viz.:

1. The calibration of satellites once in orbit is a challenging task. Historically, most satellites have been either designed purely for research needs or for operational meteorology although, more recently, many research satellites are used operationally. Slight differences in instrument, satellite and satellite-operation design impose severe difficulties on constructing homogeneous satellite time series.
2. Individual satellites often measure for periods too short to detect trends, and may stop operating unexpectedly, preventing appropriate continuity or overlap in measurements.
3. The vertical and horizontal resolution of satellite measurements may be too coarse to allow for appropriate interpretation and attribution of observed changes.

The profile measurements provided by GRUAN will be a significant benefit to satellite observations, serving two essential roles:

1. Providing standards both to facilitate the calibration and validation of data from individual satellites and to support the merging of data from different satellites. Both roles will support satellite data in the goal of creating long-term climate data records of temperature, water vapour, and ozone (see Section 6).
2. Bridging any gaps that may result in the long-term satellite data record. With unexpected termination of satellite records, bridging gaps becomes critical to the goal of creating a continuous monitoring system of the global atmosphere. Thus, GRUAN data can be useful in establishing homogeneous long-term data records for trend analyses.

Both of these roles are critical for identifying and interpreting global records of atmospheric changes. Numerous papers have pointed out the problems when using satellite records without appropriate in situ or carefully calibrated remote-sensing data. Shi and Bates (2011) described the construction of a long-term data set of upper tropospheric water brightness temperatures where large (and inherently somewhat uncertain) corrections needed to be applied to create a homogeneous time series. Thompson et al. (2012) presented the mismatch in data sets of middle-and lower-stratosphere temperatures based on reprocessing of satellite radiances that question the understanding of observed stratospheric temperature trends and ability to test simulations of the stratospheric response to emissions of Greenhouse Gases (GHGs) and Ozone Depleting Substances (ODSs). Long-term temperature records from GRUAN sites will be beneficial for discriminating between dissimilar data products resulting from different processing of the same raw data. GRUAN data will also be useful for supporting the development of climate data records in radiance space, so called Fundamental Climate Data Records (FCDRs).

There are also significant differences between co-located satellite-based stratospheric water vapour measurements that are of the same order as decadal trends (Lambert et al., 2007), so this is another measurement that would greatly benefit from a long-term ground-based record (Hurst et al., 2011), particularly if there are likely to be periods without satellite overlap to homogenize records. The Committee on Earth Observation Satellites (CEOS) third Atmospheric Composition Constellation Workshop (ACC-3) report[3] identified the importance of gap filling and the need for continuity of satellite records or proxies that can allow reliable future bridge filling for gaps in satellite records.

In addressing the needs of the climate detection and attribution community, the following aspects of changes in climate that need to be monitored are considered:

1. Changes in atmospheric state variables and composition, specifically changes in temperature, water vapour and ozone, and, where feasible, changes in aerosols. Temperature and water vapour are both “priority 1 variables” in GRUAN[4] while ozone and aerosols are “priority 2” variables. For the purposes of this workshop, the focus was on the location of sites targeted at tracking changes in temperature, water vapour and ozone with some consideration for the location of sites to track long-term changes in aerosols. The scientific basis for these parameter choices are based on their relevance to radiative balance and changes in transport. These fundamental parameters affect climate, weather, pollution, and thus life processes dependent on temperature and water availability.
2. Changes in the large-scale modes of variability detailed further in Section 5.2. These modes are important to climate because they may change in the future with increasing GHG concentrations (Gillett et al., 2013). Even modest changes in any of these modes of variability could have repercussions for the entire climate system and have strong impacts on regional climate. Because current understanding of the response of these modes of variability to future changes in the atmosphere is very uncertain, the targeted monitoring of these features is a high priority for expansion of GRUAN to better understand the Earth-atmosphere system and to better forecast continued or future changes to climate.
3. Changes in other aspects of atmospheric dynamics and transport such as expansion of the tropics, changes in the strength of the Brewer-Dobson circulation, and the monsoon.

5.2 Atmospheric dynamical systems of interest

Ideally, data from GRUAN sites should lead to the detection of changes in large-scale atmospheric systems that cannot be characterized easily by short-term instrument deployments. The atmospheric dynamical systems considered in defining the needs of the climate change detection and attribution community include:

The El Niño Southern Oscillation (ENSO). ENSO has a strong, direct impact on human life, producing regions of increased precipitation and flooding. While the mechanisms driving ENSO are fairly well understood (Neelin et al., 1998), unanswered questions remain, such as how ENSO

3 Available at http://www.ceos.org/images/ACC/acc-3%20report%20vsfinala.pdf
4 Upper-air ECVs were classified in a priority ranking from 1 to 4, cf. GCOS-134, Appendix 1

might change in the future in response to anthropogenic forcing (Stevenson et al., 2012). Determining the mechanisms that may drive future changes in ENSO can be informed by developing an understanding of the mechanisms that have forced changes in ENSO to date. This is essentially a detection and attribution problem. The availability of long-term climate data records of the vertical structure of atmospheric state variables is essential to both the detection and attribution of changes in ENSO. Such data would also be valuable in assessing the fidelity of the simulation of ENSO in climate models. Current climate model simulations demonstrate large biases in the mean tropical Pacific climate which may impact their ability to simulate ENSO (Roberts and Battisti, 2011). It may also be the case that ENSO is fairly insensitive to GHG forcing because changes in the winds and the thermocline have opposing effects on ENSO (DiNezio et al., 2012). ENSO is so varied in nature that detecting anthropogenic trends is likely to require a long data record (Wittenberg, 2009). Long-term upper-air climate data records from GRUAN will be valuable in characterizing the vertical structure of ENSO and in understanding the mechanisms by which changes in the mean state can influence the inter-annual variability of ENSO.

Expansion of the tropics. The tropical region is defined by specific attributes, including rapid zonal transport of humidity, large, deep convection which feeds into the rising branch of the Brewer-Dobson circulation, and the QBO in zonal winds. From an atmospheric perspective, the edges of the tropical zone are typically characterized as the “Hadley cell edges”. The tropical edges of this zone are significant because they define the boundaries of the subtropical deserts. Potential changes in the edges of the tropical region would affect changes in precipitation, and could lead to regional impacts on ecosystems, water resources, health and agriculture. This tropical region also defines where most of the mass transport from the troposphere to the stratosphere occurs. The tropical upper troposphere is the primary location through which water and trace gases enter the stratosphere, some of which are ODSs and/or radiatively active. If the tropical upwelling region widens, assuming no changes in vertical velocities, the mass of such species entering the stratosphere would increase. This might be further exacerbated if the widening of the tropics incorporates regions of large pollutant emissions that were previously outside the tropics. Therefore, how the tropics respond to natural and anthropogenic forcing is significant both for regional surface climate in the subtropics and for the global scale via changes in stratospheric composition and radiative forcing.

A number of studies over the past decade have highlighted that the tropical region is undergoing changes, some of which may be described as a geographic expansion of the tropics. These studies have used chemical constituent measurements, meteorological observations, and meteorological fields from reanalyses to diagnose the changes in the latitudinal extent and character of the upper-air region in the tropics over the past half-century. Specific lines of evidence include:

- Intensification and poleward expansion of the Hadley cell as defined by Outgoing Longwave Radiation (OLR) and the meridional mass stream-function (Hu and Fu, 2007; Johanson and Fu, 2009; Mitas and Clement, 2005).
- Expansion of the region of high-altitude tropical tropopause (Lu et al., 2009; Seidel et al., 2008; Seidel and Randel, 2007).
- The region of low total column ozone, demarcated by steep ozone gradients (Hudson et al., 2006), which has expanded poleward.
- Changes in both the strength and position of the subtropical and polar jets diagnosed from reanalyses (Archer and Caldeira, 2008; Strong and Davis, 2007).
- A poleward shift in storm tracks also diagnosed from reanalyses (Fyfe, 2003; McCabe and Clark, 2001).

The rate of widening of the tropics is greater in observations than in models for the diagnostics that have been tested (Johanson and Fu, 2009) suggesting that the processes responsible for driving tropical widening may not be well represented in models.

Trends in an upper-air ECV at a site close to steep horizontal gradients in that ECV could be caused by in situ changes in that ECV above the site, or by a spatial shift in the location of the steep gradients such that air of different dynamical origin is sampled more frequently than had previously been the case. It is therefore valuable to have sites close to the tropical/extra-tropical boundary so that observed trends in ECVs can be attributed to both in situ changes and/or to expansion of the tropics.

The Southern Annular Mode (SAM). The SAM is a pattern of climate variability in the southern hemisphere characterized by an anomaly over the pole and an anomaly of the opposite sign in an annulus over the southern mid-latitudes. Physically, this implies a seesaw of atmospheric mass between the middle and high latitudes of the southern hemisphere (Thompson and Solomon, 2002). The SAM is the leading pattern of tropospheric circulation variability over southern middle and high latitudes, accounting for the largest fraction of variance on time scales longer than a few weeks (Thompson et al., 2000). The positive phase of the SAM is associated with a reduction in sea-level pressure over Antarctica and increased sea-level pressure at mid-latitudes. Associated with this change in meridional sea-level pressure gradient is a strengthening of the westerly winds over the Southern Ocean. Although the SAM is an intrinsic property of the atmosphere, it is also sensitive to external drivers including changes in radiative forcing associated with accumulating GHGs, ozone depletion, and alterations in Earth's orbital parameters (Arblaster and Meehl, 2006; Arblaster et al., 2011; Son et al., 2009). The SAM is also sensitive to changes in tropical sea-surface temperatures, which are affected by the ENSO (L'Heureax and Thompson, 2006), and extra-tropical sea-surface temperatures (Sen Gupta and England, 2007). Both recently observed trends in the SAM, as well as climate model predictions for continued positive trends, are expected from an increase in GHG concentrations in the atmosphere. Some studies point to the direct impact of changes in the SAM on regional climate, including precipitation changes (Fyfe et al., 2012; Kang et al., 2011). Monitoring trends in the SAM using reference-quality GRUAN measurements will be important for understanding the mechanisms associated with the SAM (see also Section 7.2), as well as for promoting studies that look at the regional implications of changes in the SAM (Cai et al., 2005; Thompson and Solomon, 2002; Turner et al., 2005).

The Northern Annular Mode (NAM)/North Atlantic Oscillation (NAO). The NAM, also called the Arctic Oscillation, is the main atmospheric mode of variability in the northern extra-tropics (Thompson and Wallace, 2000). While the NAM structure is very similar to the NAO pattern in the Atlantic, it exhibits stronger anomalies over the North Pacific, leading to a more zonally symmetric structure. It has been argued that the two patterns may represent two different paradigms of the northern hemisphere variability: the sectoral paradigm (NAO) and the annular paradigm (NAM) (Deser, 2000; Ambaum and Hoskins, 2002). Which paradigm is the most relevant is debatable. In the Atlantic, the NAM/NAO is also strongly related to latitudinal displacements of the eddy-driven jet, although other modes of variability (such as the East Atlantic pattern) are also needed to fully account for the jet variability (Woolings and Blackburn, 2012). NAM/NAO positive phases are characterized by a strong sub-polar jet that is well separated from the subtropical jet. During negative phases, the two jets tend to merge and lead to a more zonal circulation across the Atlantic. The observed positive changes in the NAM/NAO in the past decades have been linked to GHG-driven climate change. Future changes in the NAM/NAO are likely to be highly dependent on both further GHG concentration increases, as well as on how the decline in Arctic sea ice evolves, and resultant changes in ocean temperatures (Sigmond and Scinocca, 2010).

The quasi-biennial oscillation (QBO). The QBO represents changes in circulation of the tropical stratosphere from eastward to westward winds with a period of ~28 months (Baldwin et al., 2001). The alternating zonal wind regimes develop in the middle stratosphere and propagate downwards until they dissipate at the tropical tropopause. Downward motion of the easterlies is usually more irregular than that of the westerlies. The amplitude of the easterly phase is about twice as strong as that of the westerly phase. Changes in the QBO could result from geoengineering actions (Aquila et al., 2014), changes in solar activity (McCormack, 2003; Fischer and Tung, 2008; Kuai et al., 2009), and increases in CO_2 loading of the atmosphere (Giorgetta and Doege, 2005).

The Brewer-Dobson circulation. The Brewer-Dobson circulation describes the global stratospheric meridional circulation with air masses rising in the tropics throughout the stratosphere and mesosphere and moving towards the pole of the winter hemisphere, where the air cools and sinks into the troposphere. The Brewer-Dobson circulation is driven by momentum deposition from breaking Rossby and gravity waves over the mid-latitudes (Haynes et al., 1991). It leads to air-mass exchange between both hemispheres. Because of the higher wave activity in winter in the northern hemisphere compared to the southern hemisphere, the circulation is also not symmetric. Modelling studies suggest that increased GHG loading of the atmosphere is expected to accelerate the Brewer-Dobson circulation (Eichelberger and Hartmann, 2005) though, to date, observational evidence for such a strengthening of the Brewer-Dobson circulation has been ambiguous (Engel et al., 2009; Young et al., 2012). Such acceleration would in turn increase the flux of aerosols, trace gases and water vapour into the stratosphere, thereby altering the radiative balance of the upper troposphere and lower stratosphere (UTLS).

5.3 Site Attributes

For monitoring changes in climate, long-term, stable, and homogeneous time series of measurements are required from sites with a long-term commitment to the network and consistent operational practices that meet GRUAN standards. All else being equal, sites with an existing history of such measurements should be selected over those sites with no historical record. In addition to the three primary variables considered here (temperature, water vapour and ozone), sites with observation capabilities of radiation, clouds and wind profiles would be advantageous.

Identification of sites for trend detection will be based on the spatial structure of the variability and autocorrelation in the noise on the signal (see e.g. Weatherhead et al., 1998), as well as the importance of specific locales for understanding the atmosphere. The spatial structure of modes of variability will likely vary with height. For example, in the case of water vapour, longitudinal gradients are larger near the tropopause in the tropics than higher in the stratosphere. Measurements are required both where the amplitude of the pattern peaks and at the nodes of the patterns to quantify changes in the mode amplitude. A broad range of locations should be identified with consideration for existing infrastructure and coordination with established networks.

5.4 Environments

For trend detection, relatively simple, climatological vertical profiles of temperature and humidity are most useful. In other words, when choosing locales or environments, one should avoid complicated features that make trend determination difficult. Structures to avoid include diurnally-varying local circulation patterns (e.g., land/sea breezes, mountain/valley breezes, urban/rural circulations); seasonally varying or persistent layering of the troposphere (e.g., subsidence inversions, coastal flow incursions); intermittent features that introduce layered temperature or moisture anomalies (e.g., “atmospheric rivers”, plumes of aerosols). By selecting sites that exhibit little short-term atmospheric variability, it is more likely that robust estimates of monthly means of vertical profiles of temperature and humidity can be derived as input to trend analyses.

5.5 GRUAN and the broader GOS

For detecting possible trends in upper-air variables with statistical significance, long-term high-quality observations from GRUAN might be supported by regular soundings from the wider GUAN, which is based on weather observing sites. To this end, looking at clusters of sites will likely be a valid strategy in which GRUAN observations can serve as anchor point or provide the so-called “backbone” for the operational meteorological sites.

Other important communities to be contacted to make best use of combined observations are:

- NDACC,
- the SPARC Temperature Trends group,
- the SPARC Gravity Waves group,
- the SPARC CCM Validation Initiative,
- the GEWEX GDAP project,
- lead authors of atmospheric chapters in recent IPCC Assessment Reports, and
- authors of the WMO/UNEP International Scientific Assessments of Ozone Depletion.

5.6 Geographical coverage

Future changes in climate will occur with respect to mean state, variability and extremes. The magnitude of these changes will be different over different regions of the globe. The processes associated with polar amplification (Serreze and Barry, 2011) are expected to lead to larger changes in climate over the Arctic than over other regions. Given that the number of GRUAN sites is envisaged to be on the order of 35 to 40, measurements at these sites alone will not be sufficient to fully capture all trends and possible changes in variability around the globe. However, there are key climate regimes such as those detailed in Section 5.2 that should be monitored. Different strategies are required depending on the desired outcome. One strategy may be to locate GRUAN sites where geophysical variability is minimal since this would presumably (but see further below) allow the earliest detection of a statistically significant signal in the mean state. Alternatively, it may be preferable to locate sites such that the total financial expense in detecting an expected signal is minimized, e.g., in locations where flying significantly cheaper instruments is possible, likely with larger measurement random uncertainties, more frequently, and where the conditions at the site are such that this trade-off does not compromise the trend detection. Another consideration is whether there are changes in inter-annual variability. Siting may therefore need to consider regions that are strongly impacted by large-scale geophysical oscillations. It may also be beneficial to locate some sites near the edges of climatic zones to identify potential changes in the latitudinal extent of zonally averaged climatic regimes. Finally there may be a need to monitor changes with special significance for the biosphere, e.g., changes in climate patterns that may affect sensitive ecosystems of limited spatial extent.

In addition to the considerations presented in Section 5.4, the climate change detection and attribution community would also value locales that sample the interior and coasts of the continents, and ideally one site would be located in each ocean basin for each 30° latitude zone. For climate monitoring over the ocean and for validating space-based measurements, island sites are attractive. However, care must be taken as to whether the island is representative of the surrounding ocean. Island heating and local climate due to topography may compromise the representativeness of measurements from such a location.

To approach this issue systematically, this report has considered where GRUAN sites might be located to best track changes in temperature, water vapour and ozone, and to track changes in the modes of variability of interest. For modes of variability, consideration needs to be given as to whether sites should be in the centre of a climate zone, on the leading edge of a climate zone (where larger changes may be expected), or are located to detect maxima in extremes for a particular large-scale mode of variability.

5.6.1 Detecting trends in upper-air temperatures

Trend detection involves finding a systematic change that is large relative to natural variability and measurement uncertainty. It is important to understand the statistical significance of trends and to understand the source of uncertainty in any trend calculation. For trend detection, sites should be selected based on the magnitude of the expected trend, the natural variability, and the autocorrelation in the data. Kreher et al. (2014) show that if the random error in each temperature measurement used to calculate the monthly means that form the basis for the trend determination is less than 2 K, this source of uncertainty in the monthly mean has little impact on the number of years required to detect projected trends in upper air temperatures. Similarly, it is only for sampling regimens of every 4 days, or less frequently, that sampling frequency affects the number of years required to detect the projected trend (Seidel and Free, 2006). The biggest effect on the time required to detect the projected trend is the natural variability in the time series (the noise) and the auto-correlation (Tiao et al., 1990) in the data.

Kreher et al. (2014) also show how estimates of natural variability and autocorrelation in merged Microwave Sounding Unit (MSU) data and Advanced Microwave Sounding Unit (AMSU) data (Mears and Wentz, 2008), together with projections of expected future changes in upper air temperatures from chemistry-climate models (CCMs), can be used to identify those regions of the globe where the number of years expected to detect the simulated temperature trend minimizes. Based on the global map of the number of years of measurements required to detect the CCM simulated trend in temperature, they discuss one objective strategy (but certainly not the only strategy) that can be formulated on where best to locate sites to detect those temperature trends. Sites from the ARM, GAW, GUAN, NDACC, SHADOZ and WOUDC networks were considered.

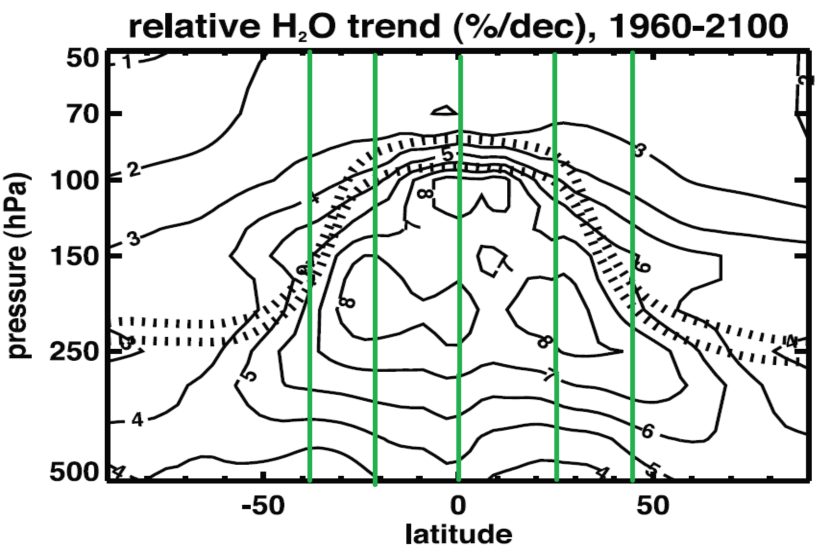

Figure 2: *Latitudinal cross-section of expected trends in H_2O from 1960-2100. The dotted line denotes the tropopause with the lower line corresponding to the reference period (1960 - 1980) and the upper line corresponding to the year 2100. Green lines: Suitable latitudes to observe these expected trends. Adapted from Gettelman et al., 2010.*

The results indicate that the GUAN site at Guam is the optimal location to detect expected future changes in temperature trends in the middle troposphere. Additional sites could then be selected with the requirement that sites are at least 6000 km apart and with a preference for sites in regions where the time to detect expected trends is minimal. Similar analyses of merged MSU channel 4 and AMSU channel 9 temperatures, indicative of the lower stratosphere (weighting functions peaking at ~17.5 km), indicate that sites around 30°N and 30°S are optimally located to detect expected trends in temperature in this region of the atmosphere.

5.6.2 Detecting trends in water vapour

With increasing temperature, the moisture holding capacity of the atmosphere increases approximately according to the Clausius-Clapeyron equation at a rate of about 7%/K; there are, however, many caveats associated with such a first order estimate of changes in atmospheric water vapour. It has been shown, at least over the ocean, that given known uncertainties, an increase of ~7%/K cannot be refuted based on observational data (Trenberth et al., 2005; Mears et al., 2007). In turn, the increase in water vapour leads to an even higher temperature. This water vapour feedback is dominated by upper tropospheric humidity in the tropics (Held and Soden, 2000). Looking at past and expected future water vapour trends in the upper troposphere (Figure 2) preferable latitude bands can be identified for observing the spatial structure of changes in upper tropospheric humidity – sites close to the equator are ideally suited to detect the expected trend local maximum in the tropical upper troposphere just below ~100 hPa, while sites between 20-25°N/S are well suited to detecting the expected trend local maxima at ~200 hPa. Sites at around 40°N/S are needed to detect

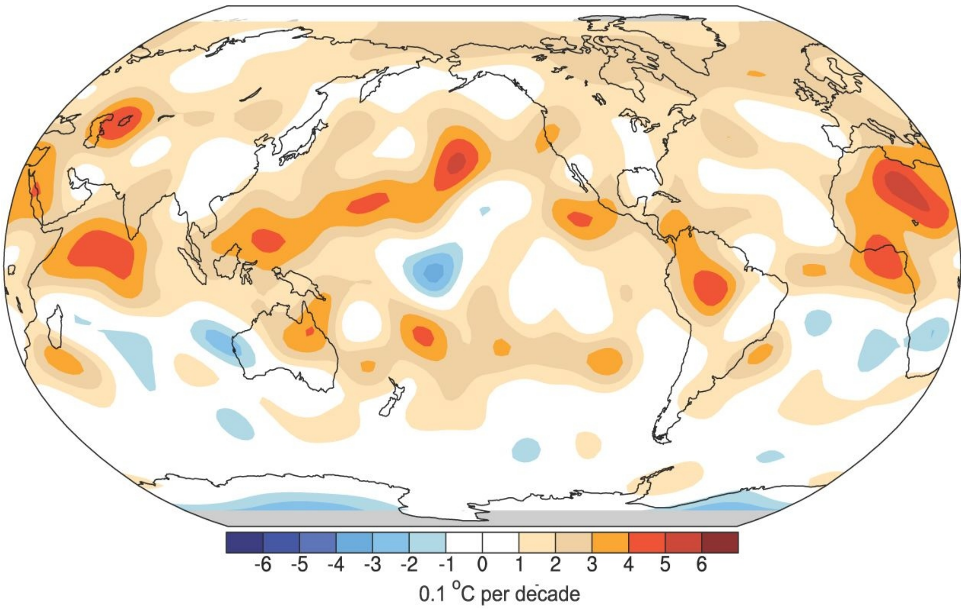

Figure 3: *The radiative signature of upper-tropospheric moistening from 1982 to 2004. Data are from the RSS T2 and HIRS T12 (Soden et al., 2005). The map is smoothed to spectral truncation T31 resolution. Figure 3.21 from the IPCC 4th assessment report.*

whether the region of steep meridional gradients in water vapour trends is shrinking equatorward or expanding poleward. Besides this rough identification of preferable latitude bands, trends in upper tropospheric moisture were not considered sufficiently robust to guide the placement of GRUAN sites. Observed trends are regionally heterogeneous (Figure 3) such that specific regions of large trends are unlikely to be robust features of the spatial pattern of trends.

5.6.3 Detecting trends in stratospheric ozone

As was done for upper atmosphere temperature trends, Kreher et al. (2014) demonstrate a similar technique for objectively selecting optimal locations for detecting expected future trends in total column ozone. Expected ozone trends for the period 2010 to 2100 were obtained from 21 CCM simulations of total column ozone changes over this period. Monthly mean total column ozone data spanning the period November 1978 to August 2012 were then analysed for the standard deviation of the monthly means and the first order autocorrelation coefficient. Month-to-month variability in the data minimizes in the tropics and maximizes over high latitudes, particularly over Siberia. This would suggest that the tropics is ideally suited to long-term total column ozone trend detection. However, the auto-correlation in the total column ozone also maximizes in the tropics. For much of the tropics, because expected trends in total column ozone are so small, the time to detect trends exceeds 175 years. As was done with temperature trends, sites can then be selected based on finding locales of minimum time to detect expected trends. While sites in the middle to sub-polar latitudes are attractive in this regard, tropical locales are also important since CCMs project decreases in tropical lower stratospheric ozone during the latter half of the 21st century.

5.6.4 Geographical coverage for capturing effects of aerosols and clouds on climate

Aerosol optical depth (AOD) is highly variable in space and time (Remer et al., 2008). It is therefore likely to be necessary to have a larger number of GRUAN sites that are capable of making aerosol measurements, but where those measurements are not necessarily made on a routine basis. Alternatively, measurements made at a few GRUAN sites could act as sources of high quality reference measurements for space-based measurements of AOD that capture the full temporal and spatial pattern of AOD variability. In addition, measurements could be made in response to specific events (e.g., volcanic eruptions), specific needs of researchers engaged in understanding aerosol processes in the atmosphere, or during seasons when aerosol effects on climate or atmospheric chemistry (e.g., during biomass burning seasons) maximize. The key requirement is for the network to be responsive to the needs of users when making aerosol measurements. Locations for GRUAN sites measuring aerosols should be selected based on where both direct and indirect aerosol effects on climate are considered important.

Aerosol and cloud effects are considered the largest source of uncertainty in current weather and climate models (Rosenfield et al., 2014). For example, recent research has shown that indirect aerosol effects (aerosols act as cloud condensation nuclei and therefore can act to increase the albedo, coverage and longevity of clouds) on surface short-wave radiation fluxes in the North Atlantic are potentially the primary driver of decadal changes in North Atlantic sea-surface temperatures (Booth et al., 2012).

In general, the albedo of warm clouds is primarily a function of the Liquid Water Path (LWP), modulated by a significant dependency on Cloud Droplet Number Concentration (CDNC). Following Slingo (1989), the sensitivity of the warm cloud albedo to CDNC peaks at LWP values around 60-90 g/m^2. For monitoring the aerosol indirect effect it is, therefore, important to measure within the stratocumulus regions off the west coasts of the continents. It is further important that the altitude of the site is below typical stratocumulus cloud base heights.

GRUAN sites measuring vertically resolved profiles of aerosol parameters and surface radiation fluxes in Newfoundland, Nova Scotia and Cape Verde would be capable of monitoring long-term changes in this climate forcing (see Figure 3 of Booth et al. (2012) – not shown here). In view of existing sites, only Santa Cruz (contributing to the World Ozone and Ultraviolet Radiation Data Centre, WOUDC) on the Canary Islands meets these criteria. In the spatial vicinity to the stratocumulus regions are also Wide Awake Field (GUAN) in the South Atlantic and Isla de Pascua

(GUAN) in the South Pacific.

5.6.5 Detecting trends in upwardly propagating gravity wave energy

Gravity waves play an important role in transporting energy and momentum in the atmosphere, contributing to turbulence and mixing, and influencing the thermal structure of the middle atmosphere (Fritts and Alexander, 2003). The spatial scales associated with gravity wave generation, propagation and wave characteristics are much smaller than the scales resolved by current climate models. Gravity wave processes, therefore, need to be parameterized in global climate models. These parameterizations are uncertain because of limited knowledge of the gravity wave spectrum, its behaviour with altitude, the variability imposed by sources and variable mean and low-frequency motions, the global climatology of gravity waves and their effects, and the processes and interactions that constrain wave amplitudes. High vertical resolution radiosonde data from GRUAN can provide much needed data to address these knowledge gaps. Optimal locations for GRUAN sites should be cognizant of the needs of the modelling community, e.g., sources of gravity wave fluxes resulting from small islands in the sub-Antarctic (around 60°S) remain a source of uncertainty for modelled gravity wave fluxes (McLandress et al., 2012).

The global distribution of gravity wave activity in the lower stratosphere shows significant spatial and seasonal variability (see, e.g., Figure 7 of Ratnam et al., 2004) such that it makes little sense to propose locations for GRUAN sites based on maps of gravity wave activity. However, since convection is a key source of gravity waves, maps showing where convective activity maximizes may provide guidance on where GRUAN sites could be located to optimally observe gravity wave activity. Typically, this would be over continental equatorial regions (Zipser et al., 2006). Easterly waves have a strong impact on tropical cyclogenesis, and are frequently observed in northern hemisphere summer over West Africa, the tropical Atlantic, and the East Pacific (Thorncroft and Hodges, 2001). In their Figures 5b and 6b the genesis density is shown – a result of climatological tracking at 600 and 850 hPa. Regional maxima are found at approximately 10°-15°N off the coast of West Africa. These easterly waves may have an influence on tropical storms in the Atlantic (Thorncroft and Hodges, 2001). Bennartz and Schröder (2012) analysed mesoscale convective systems using the homogenized Meteosat radiance archive and found that the systems leave the African continent in a relatively small zonal band around 10°N. A site slightly north of these regions is Dakar (GUAN). Another regional maximum in easterly waves extends from the northern coast of South America over Panama and Costa Rica into the Pacific (Thorncroft and Hodges, 2001). Located close to the core of this area are Juan Santamaria Airport (a GUAN site) and David City (a site providing data to the WOUDC).

5.6.6 Detecting changes in modes of variability

The El Niño Southern Oscillation (ENSO) refers to the effects of an equatorial zone of sea surface temperatures (SSTs) which are anomalously warm or cold for periods of up to 4-7 years. The SST anomaly first develops off the western coast of South America and causes anomalies in weather patterns across the tropics and subtropics. The 'Southern Oscillation' refers to variations in surface temperatures in the tropical eastern Pacific (warming and cooling known as El Niño and La Niña, respectively) and in surface pressure in the tropical western Pacific. The warm SST phase (El Niño) accompanies high surface pressure in the western Pacific, while the cold phase (La Niña) accompanies low surface pressure in the western Pacific. ENSO extremes cause extreme weather (such as floods and droughts) in many regions of the world. Based on the El Niño pattern shown in Figure 4, the two Tropical Pacific sites within opposite ENSO regimes would be desirable (i.e., Manus Island and San Cristobal) as well as Rarotonga in the South Pacific, shown with green dots in Figure 4.

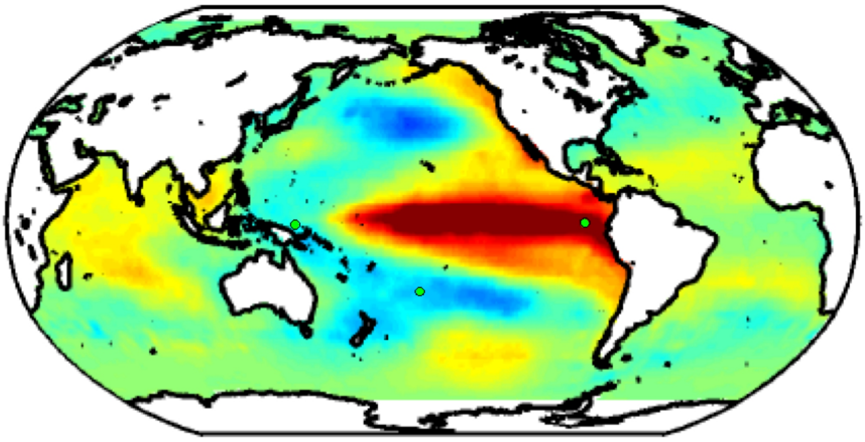

Figure 4: *The El Niño pattern in sea-surface temperatures. See http://www.nc-climate.ncsu.edu/climate/patterns/ENSO.html*

Recent research suggests that the width of the tropical belt may have increased by several degrees in latitude over the past several decades (Seidel et al., 2010, Davis and Rosenlof, 2012). Because such a change could be indicative of changes in the precipitation pattern in vulnerable regions of the subtropics (Lu et al., 2009), there is strong interest in monitoring future changes in the width of the tropics. However, this motivation does not provide a robust basis upon which to base the selection of GRUAN stations because (1) different atmospheric parameters mark the "edge" of the tropical belt at different latitudes, and (2) the latitude of the tropical edge is not the same at all longitudes. Therefore, identifying a suitable location for monitoring changes in edge position is not possible. Trends in upper-air ECVs close to the boundaries of the tropical region might better be interpreted in the context of expansion of the tropics, such that the proportion of sampling of different regimes changes, rather than a secular change in the variable above the site.

To study the SAM it would be desirable to have sites that span the maxima of the pattern, and the node of the pattern, as indicated by the three green dots in Figure 5. The longitudinal location of these sites is notional; future changes in the mode could well have maxima and minima at quite

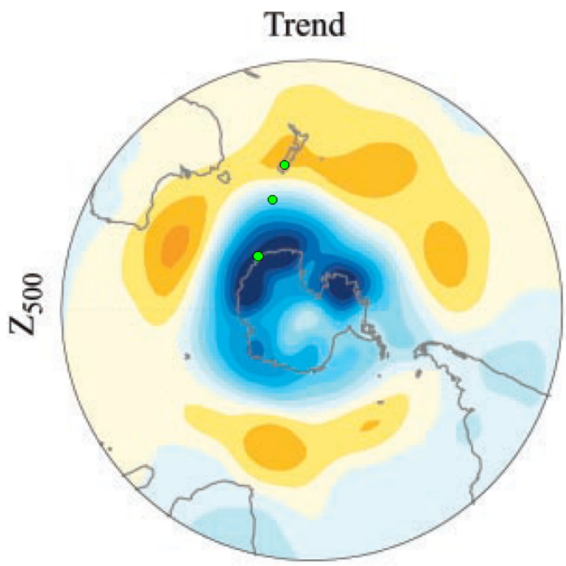

Figure 5: *22-year (1979-2000) linear trends in 500 hPa geopotential height for December-May. Shading is drawn at 10 m per 30 years for 500 hPa height (Fig. 3 of Thompson and Solomon, 2002).*

different longitudes. The priority is to have one site close to the latitude of the minimum of the mode, i.e., ~70°S, one site close to the null point of the node (to detect whether the mode as a whole is moving meridionally), i.e., ~55°S, and one site at the maximum of the mode, i.e., ~45°S.

For studying the QBO and the tropical upwelling portion of the Brewer-Dobson circulation, profile measurements are needed in the tropics, e.g., at two sites located within 10°N and 10°S of the equator and spaced ~180° apart in longitude. The GUAN site at Singapore would be particularly valuable as it is located very close to the equator and has a long history of radiosonde measurements of equatorial winds which have been used to quantify the QBO.

Measurements of ozone, water vapour and temperature made at tropical GRUAN sites will provide indirect indicators of changes in the strength of the lower branch of the Brewer-Dobson circulation (Birner and Boenisch, 2011). However, tracking changes in the strength of the Brewer-Dobson circulation is best addressed with trace gas analysis and is currently being covered by the Network for the Detection of Atmospheric Composition Change (NDACC). GRUAN will coordinate with NDACC on all issues of common interest. However, even NDACC has acknowledged a severe lack of quality measurements in the tropics.

5.7 Recommendations

The GRUAN community needs to conduct analyses for any planned GRUAN site to define the required random uncertainty on the measurements, the measurement regimen, and the time that it is likely to take to detect expected trends. It is also necessary to perform targeted sensitivity analyses to identify the most favourable locations to observe trends.

All else being equal, the following criteria should be used to identify sites best suited to satisfying climate monitoring needs:

- Sites with in-house scientific expertise in analysing and understanding long-term climate data records. On-going oversight of measurements by scientists with an appreciation of their eventual importance helps identify possible problems early, before the observational record is damaged.
- Explicit statements of long-term commitment to supporting both the observations programme and the on-going analysis of observations. This might be evidenced by appreciation of the historical contributions of a site and the desire to maintain that prominence. It is acknowledged that commitment to long-term support is difficult to obtain and yet such long-term commitment is essential to GRUAN’s success as a network providing measurements for long-term trend detection.
- History of high quality past measurements, upon which to build an even longer-term record into the future. To the extent that GRUAN ensures the viability of “legacy” sites, the ability to monitor climate over longer time periods is improved.
- Strong commitment to the GRUAN concept of management of change, and willingness to perform extra observations and analyses to fully characterize the impacts of all changes in instrumentation and observing methods.
- Relatively simple, climatological vertical profiles of temperature and humidity, to avoid complicated features that make trend determination difficult.

6 Satellite community specific needs

6.1 Introduction

The primary source of information for calibrating satellite-based instruments is laboratory information obtained by the agency developing the instrument prior to launch. It is essential, however, to validate this laboratory-based calibration 'in the field'. This validation of the initial calibration can sometimes then be used to improve the initial calibration. In this context, independent, high quality, fully characterized measurements of the atmosphere, such as those provided at GRUAN sites, are useful for:

i) Validating the calibration of satellite sensors or directly calibrating satellite sensors.

ii) Validating data products derived from measurements by satellite-based instruments, and

iii) Constraining retrieval algorithms for satellite-based measurements.

Comparisons of satellite-based measurements of atmospheric temperature and water vapour profiles, which are key variables for weather forecasting, climate research and monitoring, and which are also used in the simultaneous retrieval of other atmospheric constituents such as ozone, with coincident measurements at GRUAN sites will better quantify satellite algorithm errors and the associated uncertainties of measurements, for example due to the spatio-temporal variability of the atmosphere. Such inter-comparisons can also be used to apply adjustments to the retrieval system that is operated for the satellite instrument. Many uncertainties affect the retrieval system, such as assumptions made in the radiative transfer models used and uncertainties in the underlying spectroscopic model.

The fundamental GRUAN concept of error characterization, best-achievable accuracy and traceability, provides particular value in using GRUAN profiles for satellite calibration and validation. This is complementary to existing baseline networks such as GUAN and the Baseline Surface Radiation Network (BSRN), and research networks such as NDACC. Data from GRUAN and other observation networks could be used to create a Site Atmospheric State Best Estimate (SASBE) at the satellite overpass times (Tobin et al., 2006). The resulting validation data set would be an ensemble of temperature and water vapour profiles created from radiosondes launched at the approximate satellite overpass times, interpolated to the exact overpass time using time-continuous ground-based profiles.

Furthermore, interaction with the Global Space-based Inter-Calibration System (GSICS) would be beneficial for satellite calibration and validation efforts, as well as for GRUAN.

The discussion in this report focuses primarily on calibration and validation aspects of space-based instruments that provide critical information on priority 1 variables in GRUAN, namely infrared hyper-spectral sounders, and the GPS radio-occultation constellation. Other sensor types, such as passive microwave sounders, have a lower vertical resolution than the instruments mentioned above and, therefore, their needs should be covered implicitly.

GSICS aims to ensure global interoperability and consistency among space-based observations for climate monitoring, weather forecasting, and environmental applications. This is achieved by comparing observations from one satellite to a reference observation made from another satellite and deriving corrections to adjust its operationally-supplied calibration to be consistent with the reference. In the current inter-calibration framework of GSICS, another satellite instrument is selected by the community as the calibration reference for each spectral band, based on its availability, suitability, stability and radiometric consistency with other state-of-the-art sensors. This is a relative reference and assures comparability but not absolute traceability. While this system does not rely on external data, GRUAN observations offer a valuable dataset for independent validation of the reference instruments' (i.e., currently IASI and AIRS) stability as well as, potentially, their absolute characterization. This can be achieved by routinely comparing observed satellite radiances with those calculated using radiative transfer models applied to GRUAN provided profiles of atmospheric state variables and species concentrations. The same process may also be considered as a validation of the GRUAN observations, using the reference satellite observations as a transfer standard between GRUAN sites.

6.2 Site Attributes

For satellite calibration and validation, the quality of GRUAN measurements is more important than the quantity.

Temporal and spatial co-location is critical for the calibration and validation of satellite observations. A simple way to currently meet this need at GRUAN sites is to launch radiosondes at satellite overpass times (for example, five minutes before the overpass time). It is also critical that these atmospheric measurements are made under clear-sky conditions since the calculation of clear-sky radiances using a radiative transfer model is considerably simpler than calculating realistic cloudy-sky radiance fields.

The recommendation from the International TOVS Working Group at the 18th International TOVS Study Conference was to have GRUAN radiosonde launches ~4 times per month co-located with overpasses of Metop, Aqua and NPP. GRUAN sites should aim to accommodate such overpass-targeted measurements but, if this is not practically possible (e.g., for cost reasons), it would be beneficial to have a few GRUAN sites located in places where satellite overpass times coincide with regular GRUAN radiosonde launch times.

Furthermore, it would be important to prevent changes in the composition, or standard operating procedures, of ground-based observations while the satellites they are providing a validation for are changing.

To optimize the use of GRUAN observations for satellite calibration and validation, the following requirements should be fulfilled:

1. To the extent possible, atmospheric profile measurements should be made so as to coincide in space and time with the satellite overpasses. The space-borne instrument field of view should contain the location of the observatory. If the ground-based measurements consist of radiosonde launches, a procedure that has previously shown its value (Calbet et al. 2011) is to launch one radiosonde around one hour before the overpass time and another about five minutes before the overpass time. If only one radiosonde launch is envisaged for a particular overpass, it should be launched around five minutes before the satellite overpass. However, the subject of how many radiosonde launches, or when to launch them, to optimize their efficiency, is a subject that needs further study.
2. Atmospheric temperature profile measurements with a random uncertainty of less than 0.2 K are required.
3. Atmospheric water vapour profile measurements with an uncertainty similar to Cryogenic Frost point Hygrometer (CFH), i.e., less than 0.5% to 5% in absolute terms of relative humidity in the troposphere and between 0.5% and 0.02% in the stratosphere are required. It is important to measure adequately all levels of the atmosphere, including those in the boundary layer and close to the surface, which are the most relevant for weather forecasting.
4. Atmospheric ozone profiles are needed if the ozone sensitive part of the spectrum needs to be verified.

6.3 Environments

To minimize the uncertainties introduced by radiative transfer modelling in the presence of clouds, it is better to make ground-based co-located measurements with most satellite instruments under clear-sky conditions. Sites with suitable clear-sky conditions should therefore be favoured.

To alleviate the requirement to determine the surface emissivity, it is desirable to perform the measurements in areas of uniform surface properties. Island-based measurements would be desirable to manage sea-surface emissivities, which in principle are easier to model - particularly for microwave instruments, but could potentially be more difficult to measure. On the other hand, measurements over land with large areas of uniformity would also be desirable, such as over forests, homogeneous deserts, etc.

A key issue for GRUAN that requires further research is that representativeness errors ("What spatial region does a site represent?") can be highly variable.

6.4 Geographical coverage

For satellite applications, it is preferable to have high quality and well-maintained sites rather than a large number of sites. The complete range of the global atmospheric variability should be covered by having sites in the archetypal climate regions (polar, mid-latitude, subtropical and tropical), possibly in both hemispheres.

Geostationary satellites. Geostationary satellites routinely scan the Earth's disk at intervals from 5 minutes to 1 hour, and so identifying collocated observations at GRUAN sites can be easily achieved. However, for many applications, it is advantageous to restrict comparisons to observations with lower incidence angles – say, within 30° latitude/longitude of the sub-satellite point. This suggests the need for GRUAN sites within the field of view of the key geostationary satellites (Knapp et al., 2011).

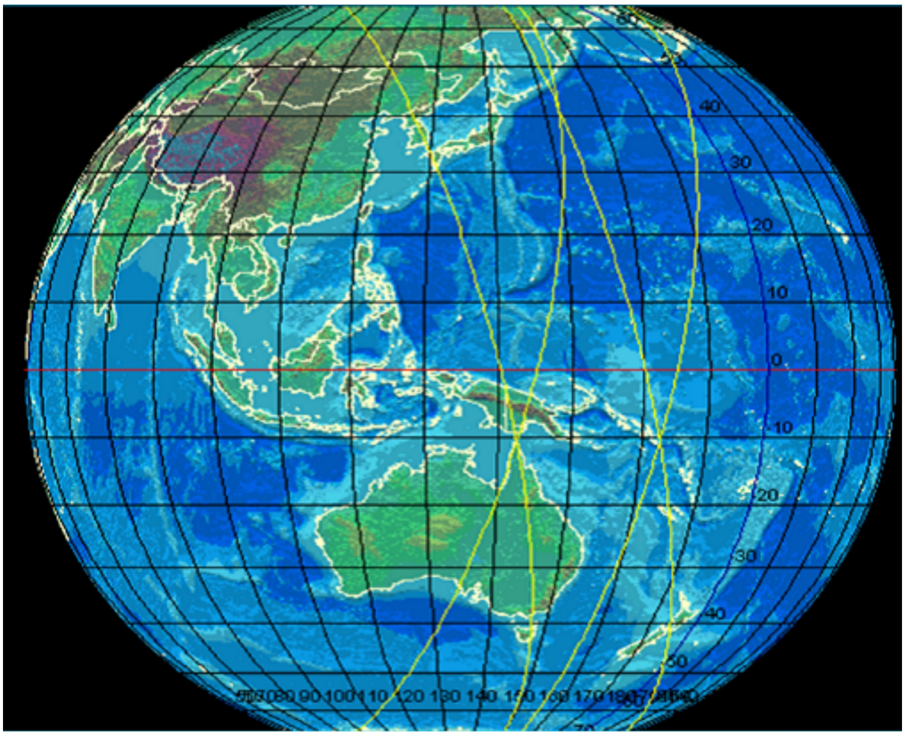

Figure 6: *Example for the ascending and descending nodes of Metop-A that occur near the 00Z and 12Z radiosonde launch times.*

Sun-synchronous polar-orbiting satellites. Unless radiosonde launch times are flexible, to minimize additional expenditure, it is proposed that GRUAN sites tasked specifically with validating sun-synchronous satellites are established in locations where the synoptic launch times of radiosondes (00Z and 12Z) coincide with the overpass times of the satellite instruments. In polar areas, there are many overpasses every day and a single GRUAN site could fall within the swath of instruments on multiple satellites. However, sites near the equator would also need to be established which can be seen by both the ascending and descending nodes of polar-orbiting satellites. To support calibration, it is important that a wide range of scene temperatures is covered because the calibration can be affected by non-linearities in the response of the instrument. An example of the swath of IASI on the ascending and descending nodes of Metop-A is shown in Figure 6, which occurs near the 00Z and 12Z radiosonde launch times.

6.5 Scientific basis

Due to their high spectral resolution, space-based infrared hyper-spectral instruments present the most demanding calibration and validation requirements for temperature and humidity profiles. These instruments typically measure Earth views in a spectral range from 600 to 3000 cm^{-1} wave numbers with a spectral sampling of about 0.25 cm^{-1}. From these measurements it is possible to accurately retrieve atmospheric profiles of temperature and water vapour. There are two ways to calibrate and validate these measurements, viz.:

1. Working in radiance space (level 1; L1), comparing the satellite-based measurements of radiances with radiances calculated using a radiative transfer model that takes measured reference profiles at GRUAN sites as input.
2. Working in atmospheric state space (level 2; L2), comparing the GRUAN profile measurements with the satellite-based retrievals.

These two methods are complementary with the latter requiring additional input, and therefore additional sources of uncertainty, such as the *a priori* information used in various retrieval algorithms. Level 1 calibration/validation is a more fundamental comparison since, if the radiances do not match, it is unlikely that the retrieved products will be valid. Therefore, it is preferable to conduct the calibration/validation in radiance space.

Validation of hyper-spectral, passive microwave radiometers or radio occultation retrievals can be done by comparing them with other reference co-located measurements. Equivalently, radiances can be validated by calculating the radiances or bending angles at the top of the atmosphere with a radiative transfer model taking as an input the reference profile measurements. Ideally, this validation should be more than just plain monitoring. It should be possible to derive, from the validation exercise, potential systematic errors in the retrievals or the reference measurements, or any other issues that could arise in the complete intercomparison system[5]. For this to be possible, the reference measurements have to be roughly an order of magnitude better constrained (less uncertain) than the retrieved profiles or the equivalent radiances.

6.5.1 Proposing future research activities

Although significant progress has been made in previous years in the ground-based and satellite measurement co-location problem, there are still many problems which need to be solved, for example:

- It appears that satisfactory co-location can be achieved with the so-called Tobin

5 We understand as a “system” in the definition of “calibration” both, the satellite sensor (i.e., its “response” is a physical radiance (Level 1)), as well as the retrieval system (i.e., its “response” is the parameter profile (Level 2)).

interpolation (Tobin et al., 2006) by launching two radiosondes around 60 and 5 minutes before the satellite's overpass time. In addition, a high quality water vapour profile measurement e.g. such as that from a CFH sonde is essential (Calbet et al., 2011). There may be possibilities to augment these requirements. For example, by launching a single radiosonde and extending the temporal applicability of those sonde data using a redundant measurement system such as a co-located lidar or microwave radiometer. It also needs to be determined whether a CFH-quality water vapour profile is necessary for input to the radiative transfer model being used for the calibration/validation or whether a standard humidity profile as measured by an operational (e.g. RS92) radiosonde, but bias corrected, would be sufficient.

- When no measurement of the surface emissivity is available, alternatives, e.g., an emissivity derived from an atlas (Borbas et al., 2007) needs to be explored.
- Similarly, if skin temperature is not measured from the ground, alternatives need to be explored.
- When the reference profiles required as input to the radiative transfer model do not extend to the uppermost atmospheric levels, the use of supplementary data, such as those from reanalyses, needs to be investigated.
- The representativeness error when using a point source measurement from a site to represent a larger area, as sampled by a satellite instrument, needs to be estimated.
- The contributions from all the terms in the error budget of the comparison of the retrieved and reference temperature and humidity profiles (background, radiometric noise, forward model errors, representativeness, radiosonde errors) need to be estimated.
- The utility of GRUAN reference measurements for better understanding the biases in satellite climate data records needs to be demonstrated.

Due to their high temporal sampling rate, ground-based remote sensing instruments are more likely able to provide measurements coincident with satellite overpasses than would be available from radiosondes. Robust techniques to interpolate such ground-based remote sensing measurements to the exact time and location of the satellite overpass would be beneficial (i.e., Löhnert et al., 2007).

6.6 Recommendations

Ground-based measurements are most likely to be useful for satellite calibration and validation if the following recommendations are adhered to:

1. Take measurements under clear-sky conditions. This should be especially the case if each measurement has a high cost associated with it (e.g., CFH sondes).
2. Make measurements over uniform surface conditions, which could be the ocean (i.e., from island sites) or over a uniform and flat land surface (i.e., forest sites). In the former case, the location of the GRUAN site should preferably be most of the time on the windward side of the island, so as to avoid any orographic effects on the measurements such that it can be representative of a satellite observation over the ocean. In the latter case, it would be desirable to also measure the surface emissivity using a downward looking spectrometer.
3. Make measurements over regions where very few observations are available for satellite calibration and validation and where the satellite has difficulty, such as the polar regions and tropical rainforest. Such GRUAN sites would help to improve future satellite retrievals and

potential new satellite missions targeted for these regions.

4. Since satellites measurements are global or near global, it is desirable to cover as many climate regimes and regions of the world as possible: in particular, polar, mid-latitude, sub-tropical and tropical.
5. Use GRUAN experience, best practices and high-quality atmospheric profile data to augment the value of measurements from neighbouring operational sites, such as non-GRUAN sites in GUAN, BSRN, etc.

7 Atmospheric process studies community specific needs

7.1 Introduction

GRUAN core measurements of temperature and water vapour, particularly when conducted within a fully implemented network of sites and augmented by ancillary high-quality measurements performed within other existing networks, will provide unique opportunities to address a number of atmospheric process issues. Seen as most important by workshop participants were:

Long-term measurements of tropopause temperature and upper troposphere/lower stratosphere (UTLS) water vapour. High quality measurements of water vapour and temperature in the UTLS are critically needed to determine long-term trends, evaluate climate sensitivity to future changes in atmospheric composition, validate global climate models, and assess the performance of clear-sky radiative transfer models (Clough et al., 1992). They would also provide a means to quantify the processes associated with air-mass dehydration in the tropical tropopause layer and to determine how the contributions of these processes will evolve in a changing climate.

Aerosol/water vapour/radiation interactions. Studying the hygroscopic growth of aerosols is challenging due to the variety and complexity of the aerosol population to be investigated. This is further complicated by mixing process involving different aerosol types. However, several studies have already proven the importance of aerosol hygroscopic growth on radiative balance in the atmosphere. Nevertheless, the existing parameterizations are still insufficient to accurately determine the forcing type (positive or negative). Hence, we need to understand the effects of various types of aerosols (dust, sea salt, black carbon, industrial, etc.) on other changes in atmospheric composition, circulation, and radiative balance. Such studies would relate not only to long-term changes but also to the investigation of the effects of short aerosol/water vapour injections. Dust aerosols, in particular, play a direct role in modulating the Earth's atmospheric energy balance, thereby impacting regional climate patterns such as changes in precipitation and the evolution of the hydrological cycle. For example, current analysis suggests contradictory effects of aerosols and GHGs on monsoon-related rainfall over India (Chung and Ramanathan, 2006). Aerosols alone have been shown to decrease temperature over portions of the Indian Ocean and thus reduce monsoon activity and related rainfall. However, increasing temperatures due to increasing concentrations of GHGs in the atmosphere might increase land-ocean temperature contrasts and hence strengthen the monsoon circulation and precipitation. Lau et al. (2006) recently proposed that an "elevated heat pump" effect that could provide a diabatic heating source that leads to additional heating in the upper and middle atmosphere as well as to a strengthening of the monsoon and to additional rainfall. The near-source impacts on cloud generation and hydrologic cycles are relatively unknown. In addition, recent studies indicate an upper troposphere brown/black carbon layer over much of the tropical South Asia (Lawrence, 2011) spreading west over parts of Africa, the Middle East, and the Mediterranean (Vernier et al., 2011). Model calculations do not include this feature and indicate problems with the convective transport parameterizations in the tropics (Feng and Kotamarthi, 2011). Thus, there is much interest in measuring the changes in heating rates and water vapour profiles over the tropics, and in monitoring tropical trends in these profiles and, in particular, over the Indian Ocean.

Water vapour/cloud interactions. Understanding water vapour and cloud feedback mechanisms is crucial to improving the performance of AOGCMs and could help to validate recent studies and hypotheses over the long term. Despite its importance to the sensitivity and variability of climate, a comprehensive picture of the impact of water vapour feedbacks on both externally forced and internally generated climate variations is lacking. Marine stratocumulus processes are perhaps the least understood and least well simulated in AOGCMs but may be the most important in terms of determining future climate behaviour. However, these are by no means the only cloud process/interactions whose understanding would benefit from GRUAN observations.

Intra-seasonal variations in the deep tropics. Of most interest is the Madden-Julian oscillation (MJO). This is a dominant propagating intra-seasonal (60-90 day) oscillation that strongly affects energy, moisture and clouds in the tropical troposphere and tropopause region (Zhou and Holton, 2002), and so should be well captured by GRUAN observations.

7.2 Climate regimes

One or more sites enabling measurements near the region of the tropical cold point tropopause would be very beneficial. Given the annual impact of the Asian anticyclone on UTLS water vapour abundances (e.g., Gettelman et al., 2004; Wright et al., 2011), it would be desirable to have at least one site each within the convective source and outflow regions.

Sampling the divergent circulations over the tropical warm pool is vital to our understanding of the climate system because these circulations drive weather patterns around the globe.

GRUAN expansion to sites where high quality aerosol measurements are already conducted would facilitate the investigation of these interactions, which are crucial for both weather and climate modelling. This might be accomplished on a global scale with a network covering most of the climate regions and could strongly contribute to reducing a gap in current modelling as well as to gaining a better insight into the attribution of climate change to natural or anthropogenic sources. With an appropriate suite of GRUAN and other network sites, aerosol-water vapour-radiation interactions could also be investigated by following the growth of aerosol particles along their path, starting from a point nearest to the source region. In this way, particle growth can be correlated with the radiative impact and its modification along the path.

It is important to sample regimes characterized by distinctly different cloud properties and cloud formation processes. Hence, a mix of polar, mid-latitude, sub-tropical, and tropical sites (including maritime and continental locations) would be ideal. Measurements from these sites would produce the long-term statistical data sets that are especially important to the modelling community.

The breakout group considered two categories of sites:

a) anchor sites at locales with fairly stable climates and

b) sites in locales whose climate is changing rapidly.

The anchor sites are expected to provide data needed to improve and validate the representation of important atmospheric processes in climate models. Measurements at sites located in locales with rapidly changing climate would provide insight into regionally important processes that are affected significantly by climate change.

7.3 Site Attributes

Investigations of atmospheric processes require a long-term commitment to obtaining high quality observations via a globally distributed network of sites and could benefit appreciably from measurements of water vapour, temperature, ozone, and aerosols conducted by other networks (e.g., SHADOZ, NDACC, BSRN, EARLINET, AERONET, etc.). Thus, strong consideration should be given to the selection of some sites from these complementary networks for GRUAN expansion. Instrumentation would include sondes, microwave radiometers, lidars and other ground-based instruments capable of providing height-resolved measurements over these ranges of altitudes. Priority should be given to sites that enable the required vertical extent of the measurements.

The IPCC Fourth Assessment Report (AR4) identifies cirrus and mixed phase cloud properties as key atmospheric variables whose impacts on radiative balance in the Earth's atmosphere have a high degree of uncertainty. The phase mixture and microphysical structure of such clouds have a large impact on atmospheric radiation and the hydrological cycle. The measurement of cloud phase and boundaries, ice properties, liquid water path, water vapour content, and optical depth are needed. However, there are still a number of cirrus and mixed-phase cloud properties that are not well characterized using current ground-based instruments and methods. These gaps in our observational capabilities often confound our understanding of important cirrus and mixed-phase cloud processes and continue to hinder cloud and atmosphere modelling efforts.

GRUAN could add significantly to developing improved understanding of cloud impacts by conducting its core measurements at sites where the aforementioned cloud measurements are conducted in different climate regimes, thereby contributing to the improvement of algorithms for the estimation of relevant parameters.

Advanced remote sensing instrumentation will undoubtedly be required to capture the aerosol-water vapour interactions preferably located in a less dynamically complex climate regime such as the northern equatorial Atlantic (Koren et al., 2010).

7.4 Environments

Sites where different types of aerosols are dominant in the free troposphere would be desirable (e.g., outflow regions from large sources of mineral dust, biomass burning aerosols, and anthropogenic aerosols). Some remote mountain top sites are also recommended for network inclusion, as well as remote island sites (far from urban pollution) for investigating interactions out of the boundary layer, where humidity is controlled by strong coupling with the surface.

7.5 Geographical coverage

There are several tropical environments that would enrich GRUAN and meet requirements for different dynamical regimes, surfaces, and geographical coverage. Both tropical and subtropical, northern and southern hemisphere sites should be included.

The importance of heterogeneous ice nucleation in polar stratospheric cloud formation was recently recognized (Pitts et al., 2011). This calls for accurate observations of water vapour, temperature and cloud particles in the polar stratosphere.

The proposed extension to 30-40 GRUAN sites covering a wide range of latitudes with an emphasis on the tropics would be desirable.

A relatively even distribution of sites around the globe would likely be needed. Indian monsoon and atmospheric brown cloud studies would require regular high quality soundings from selected locales over the Indian Ocean, South-East Asia and mainland India (perhaps 3-6 sites).

Another ideal natural environment for studying the interactions of dust, sea salt, or biomass aerosols is the Mediterranean basin, with at least four sites located along a transect from Central Europe to North-West Africa established according to atmospheric circulation in the basin. The Mediterranean region features a nearly closed sea surrounded by urbanized littorals and mountains from which numerous rivers originate. This results in many interactions and feedbacks among oceanic, atmospheric, and hydrological processes as well as anthropogenic activities. Similar natural environments in other climate regions for the study of different aerosol types might be identified and established accordingly.

Stratocumulus process studies would argue for coastal stations or remote island stations within the sub-tropics where such features are climatologically prevalent. More generally, some sites for each type of dominant cloud regimen globally would be advantageous. The DOE/ARM planned site at the Azores, and the sounding site at Cape Verde, could contribute to a long-term study of cloud-water vapour-aerosol processes. A study at mid-latitudes over a network of four sites performed by 'Cloudnet' (Illingworth et al., 2007) has yielded results showing that mesoscale models have a considerable problem associated with poor representation of the phase of midlevel clouds. GRUAN measurements at a polar site already equipped with cloud observation capabilities would assist in understanding PSC formation processes.

Long-term measurements of temperature, moisture, and winds near the equator are essential for improving our understanding of the MJO.

7.5.1 Specific recommendations for site locations

1. **Azores.** The Azores Islands are ideally situated to study low stratiform cloud systems over the subtropical oceans, which are poorly represented in climate models and cause major uncertainties in projections of climate change.
2. **Greenland.** Greenland, the world's second largest ice sheet, is starting to melt and the melting appears to be accelerating. Long-term measurements would provide insights into changes in cloud properties, surface reflectivity, and the atmospheric radiation budget that may result from melting and shrinking of the ice sheet.
3. **South Asia.** The Indian southwest monsoon covers an area about one-seventh of the Earth's surface, and its intra-seasonal variability is not well simulated in climate models. The high concentration of aerosols and direct impacts on the clouds and radiation feedbacks in this region provides a unique opportunity to generate data sets to predict changes taking place in the monsoon system.
4. **Amazon Rainforest.** The Amazon rainforest, the world's largest, is an ideal site to study deep tropical convective clouds over land, which have profound effects on global circulation and yet are poorly simulated in climate models. Satellite measurements of total column water vapour show large scatter over continental tropical rainforests.
5. **Middle Latitude Storm Tracks in the Southern Ocean.** The oceanic storm tracks of both hemispheres are poorly simulated in climate models. The Southern Ocean offers the advantage of pristine, unpolluted clouds in greater variety than the oceans of the northern hemisphere.

7.6 Scientific basis

Climate change is, for the large part, governed by atmospheric processes, in particular the interactions between radiation and atmospheric components (e.g., clouds, aerosols, precipitation, and GHGs). On a global basis, such interactions can have significant climate and weather effects. However, this influence is still poorly understood.

On a specific regional perspective, changes in the strength of monsoon circulations over the Indian Ocean and South Asia could be studied. The interactions between black carbon, dust, pollution and warming as it impacts the thermodynamics of the region is expected to be a significant factor (Allen et al., 2012).

Aerosol-cloud interactions have been shown to contribute to deep convection and thus to anvil modification, which plays a significant role in the top-of-atmosphere radiation balance important for climate (Koren et al., 2010). This is an issue with major economic and societal implications for many populated parts of the world.

Upper tropospheric water vapour (especially in the tropics) has a particularly large impact on radiative balance in the Earth’s atmosphere and acts as a powerful amplifier of the climate response to radiative forcing (Bony et al., 2006; Solomon et al., 2010). The growth in upper tropospheric water vapour expected from continued increases in other GHGs will exert a positive feedback and amplify the warming (Soden and Held, 2006). Climate models predict that the warming effect caused by a doubling of CO_2 is amplified by a factor of two due to water vapour. This feedback is, however, overestimated if upper tropospheric water vapour increases are assumed to occur under conditions of constant relative humidity. Rather, as upper tropospheric temperatures increase, relative humidity is predicted to decrease (Minschwaner and Dessler, 2004). This increases the value of GRUAN measurements of temperature, moisture profiles, derived lapse rate and clouds for narrowing uncertainties in climate sensitivity.

The long-term net increase in lower stratospheric water vapour documented in IPCC AR4 has a positive climate feedback with radiative forcing ranging from 0.07 to 0.12 W/m^2 (Solomon et al., 2010). However, the level of uncertainty in these estimates is very high, highlighting the need for a global network of high-quality lower stratospheric water vapour measurements (Fueglistaler and Haynes, 2005). Since the amount of water vapour entering the stratosphere largely depends on tropical cold point tropopause temperatures (e.g., Randel et al., 2004), accurate temperature measurements in the tropical UTLS are also essential. UTLS temperature records in the tropics suffer from a multitude of problems, making it difficult to determine long-term trends in cold point temperatures. The trends that have been determined from such records (e.g., Zhou et al., 2001), along with the documented growth in stratospheric methane oxidation, cannot fully explain the long-term stratospheric water vapour increase over Boulder, Colorado (Hurst et al., 2011).

Stable, long-term measurement records of UTLS water vapour and temperature would permit in-depth studies of the processes that contribute to air mass dehydration in the tropical tropopause region. Numerous dynamical and physical mechanisms have been proposed that moisten the lower stratosphere in the absence of tropical tropopause warming. These alternatives to the standard dehydration process (i.e., by the Brewer-Dobson circulation) include increased deep convective activity (e.g., Nielsen et al., 2011), enhanced aerosol loadings in the tropical UT (Sherwood, 2002), and tropical widening (Zhou et al., 2001; Rosenlof, 2002). A reasonably dense network of high quality measurements of temperature and water vapour would greatly assist in assessing these alternative mechanisms as contributors to the observed changes in UTLS water vapour.

Critical questions about ozone (as a tracer for transport between the troposphere and stratosphere), temperature, and water vapour are closely linked. In addition to being high priorities for science, they call for the high standards GRUAN seeks to achieve. One can envision some of the stations in SHADOZ and NDACC contributing in an official capacity to GRUAN in a way that is mutually beneficial.

The MJO is the dominant mode of intra-seasonal variability in the tropics, and its impacts extend around the globe (Matthews et al., 2004). Our understanding of MJO dynamics is severely constrained by the lack of observations over the Indian Ocean (Schott and McCreary, 2001) where its convection initiates. The MJO’s vertical structure also evolves as it propagates from the Indian Ocean to the Western Pacific (Kiladis et al., 2005). An improved sounding network over the tropical warm pool will uncover the nature of this evolution. Current climate models struggle to simulate the MJO (Kim et al., 2009). Hence, these observations will be central to verifying and improving the overall model performance.

8 Numerical weather prediction community specific needs

8.1 Introduction

Global NWP systems are used to produce short range and medium range weather forecasts (out to 15 days) of the state of the atmosphere from the troposphere to the mesosphere, with a horizontal resolution of typically 15 to 50 km and a vertical resolution of 10 to 30 m near the surface increasing to 500 to 1000 m in the stratosphere. There is a strong interest in using NWP system output to predict the risk of extreme or severe and damaging weather events. Global NWP systems are further used to provide boundary conditions for regional NWP systems. NWP systems also provide underpinning components of reanalysis systems which are more suited to climate applications.

The quality of an NWP model forecast is largely determined by the accuracy of the estimate of the atmospheric state at the beginning of the model simulation, i.e., NWP is an ‘initial value problem’ (Palmer, 1999). Observations from surface-based, airborne and space-based platforms are all used to help define this initial state. The observational requirements for global NWP are based on the need to provide an accurate analysis of the complete atmospheric state and the Earth’s surface at regular intervals (typically every 6 hours but increasingly at 3- or even 1-hour intervals).

The key atmospheric model variables for which observations are needed for NWP are: three dimensional fields of wind, temperature and humidity, and the two dimensional field of surface pressure. Also important are surface boundary variables, particularly sea-surface temperature, soil moisture and vegetation, ice and snow cover. Of increasing importance in NWP systems are observations of cloud and precipitation.

Using data assimilation, new observations are used to update and improve an initial estimate of the atmospheric and surface states provided by an earlier short-range forecast. Modern data assimilation systems are able to make effective use of both synoptic and asynoptic observations. Observations are most easily used when they are direct measurements of the model variables (e.g., temperature, wind), but the concept of observation operators has facilitated the effective use of indirect measurements (e.g., satellite radiances, which are linked in a complex but known way to the model fields of, e.g., temperature and humidity). The use of 4D-var data assimilation methods has facilitated the extraction of dynamical information from time series of observations and from frequent (e.g., hourly) and asynoptic data.

The highest benefit in NWP is derived from observations available in near-real-time; NWP centres derive more benefit from observational data, particularly continuously generated asynoptic data (e.g., polar orbiting satellite data), the earlier they are received, with a goal of less than 30 minutes delay for observations of geophysical quantities that vary rapidly in time. However, most centres can derive some benefit from data that is up to 6 hours old (see, e.g., Thépaut and Andersson, 2010).

Thus, the main goal of the NWP user community, identified here as the operational weather centres, is to improve the weather forecast. This can be done in a number of ways but the two main ones are:

1. data assimilation of the observations to improve the representation of the state of the atmosphere used to initialize the forecast model; and
2. evaluation of the performance of the model in representing the state of the atmosphere so that the impact of changes in the model can be quantified.

Data assimilation requires observations which are quality-controlled, delivered in a recognized

WMO format, and have well characterized errors. Examples are the routine radiosonde ascents of temperature, humidity and winds supplied by GUAN sites. A discussion of how data assimilation notions have improved the skill of the NWP forecast is provided in Simmons and Hollingsworth (2002).

Model evaluation requires a sufficiently long time series of observations with higher accuracy than that needed for data assimilation; generally, only a limited number of stations are needed to sample the different weather regimes, and, furthermore, the data are not needed in near-real-time. The parameters needed to evaluate the model would be profiles of the key ECVs of temperature, water vapour, winds and pressure, together with information on other ECVs such as cloud, aerosols, and radiative fluxes. The model evaluation consists of getting the correct unbiased mean profile, the correct probability distribution function, and the skill score which expresses the ability of the model to simulate the correct value of the parameter at the correct time. GRUAN sites with their increased accuracy and greater numbers of parameters with respect to GUAN sites, are well suited for model evaluation. In particular, GRUAN observations have higher spatio-temporal resolution and accuracy than can be obtained from satellite platforms. This high accuracy is accomplished by establishing metrological traceability to stated international reference standards. Such traceability is more easily achieved, and improved upon, for ground-based observations than for space-based instruments.

The GRUAN data are selected to have high quality, for example, systematic errors of the order of less than 1 K in temperature. They are additional to the data in the GUAN network, which comprise radiosondes. The primary benefit of GRUAN data for NWP is via anchoring, which takes two forms: anchoring of the model, and anchoring of other observations, in both cases by having a standard against which to evaluate the model and/or observations by, e.g., direct comparison. Even without direct anchoring of the model, there are two ways in which GRUAN data can be of benefit: (a) anchoring during development/validation of model improvements, and (b) anchoring of other observations during the assimilation process.

GRUAN data products benefit the NWP user community in three ways:

i) They play an important role in characterizing satellite data, both during the calibration-validation stage and when the instrument is on-orbit and being monitored;

ii) They provide a means of assessing biases in NWP model fields at carefully selected sites; and

iii) They provide high accuracy anchoring observations to be assimilated operationally without bias correction.

For anchoring, the operational assimilation system (point (iii) above) the GRUAN data would have to be available in near-real-time. However, less timely GRUAN data would still be valuable for other types of anchoring, e.g., characterization of satellite data. GRUAN data are thus expected to be valuable for NWP assimilation and for feedback to the data providers.

8.2 Climate regimes

In addition to the large-scale climate regimes identified in Section 5.2, observations are more important for NWP in some areas than in others; it is desirable to make more accurate analyses in areas where forecast errors grow rapidly, e.g., in baroclinic zones and in areas of intense convection. Identifying these areas, targeting observations to them, and improving the assimilation under those atmospheric conditions are areas of active research (see, e.g., Masutani et al., 2010a).

8.3 Site Attributes

There are no specific site attributes to meet the needs of the NWP user community. However, flexibility of sites to add additional observing technologies if and when these become useful/beneficial was identified as desirable. Sensitivity studies carried out by NWP centres as described in Section 8.6, might help to guide the development of new measurement technologies (such as, for example, surface infrasound measurements) to see what criteria would need to be met to be incorporated into the “standard” atmospheric measurement networks. Similarly for using the GRUAN observations for assisting in parameterization development, one might conduct an analysis to determine where the largest uncertainties in parameterization development lie (parameters and climate regime) and target the network appropriately.

8.4 Environments

The specific environments that need to be considered for additional GRUAN sites, e.g., sites on remote islands or over snow, or of modified existing GRUAN sites to meet the needs of the NWP user community, depend on the gaps in the Global Observing system (GOS) and in what NWP centres perceive to be the most important information needed to test and/or anchor the elements of the NWP system. The cost of establishing the GRUAN site (set up, maintenance, manpower) would also be a factor.

8.5 Geographical coverage

In general, conventional observations (e.g., radiosonde and aircraft measurements) have limited horizontal resolution in many areas of the globe, but have high accuracy and vertical resolution. Satellite data provide very good coverage but limited vertical resolution, and they are more difficult to interpret unambiguously and use effectively. Single in situ observations from remote areas can occasionally be vital. Furthermore, a baseline network of in situ observations is currently necessary for calibrating the use of some satellite data.

At the time of writing this report, the 15 GRUAN sites are clustered in Europe and North America with a few sites in Asia, the Tropical Western Pacific and one site in New Zealand. Large areas of the world, e.g., Africa and South America are not covered. Even over Europe and North America, coverage density is low. There is thus a need to increase the number of sites in GRUAN. Because GRUAN sites have advanced instrumentation, the difficulty of operating in isolated locations must be considered, and additions to GRUAN must be necessarily small in number.

Key considerations for geographical coverage would be based on quantification of the benefit of the additional GRUAN site (or the modified GRUAN site), and the economic cost associated with it. For example, costs are likely to depend on whether the new site is set up in the developed world or in the developing world. One approach could be to set up a GRUAN site where there is an existing atmospheric observatory, for example, a site which is part of the following networks: BSRN, NDACC or GALION. The OSSE methodology could help provide an estimate of these costs.

8.6 Scientific basis

One approach on how to expand the network to make it most beneficial for the NWP community would be to set up a number of scenarios for the augmented GRUAN in consultation with the NWP user community. These scenarios could include the option of allowing site flexibility, i.e., include the possibility of adding improved observational technologies if and when they become beneficial. These scenarios would aim to cover a number of cases of interest for NWP. Once these scenarios have been established, they could be tested using various approaches. Each of the approaches has its own strengths and weaknesses, and there is no single approach that is unequivocally superior to the others. Included in the approaches are the techniques of OSEs, OSSEs, and ensemble data assimilation impact studies. The approaches all require careful experimental design and careful interpretation of their results and so the suitability of these approaches is often the subject of debate (see Section 4.1).

In addition, FSO studies could be used to identify the most sensitive observations. There are currently no widely accepted and easily affordable techniques to demonstrate that the GRUAN data are effective anchors for satellite observations and suitable for reducing model biases, e.g., by serving as the backbone for the wider GUAN.

It is desirable to use a quantitative and objective approach to determine how to augment the current GRUAN, either by establishing complementary measurement programmes at existing sites or new sites, or by establishing new sites. Notwithstanding the reservations about their suitability, the OSSE methodology (or a variant thereof), as well as ensemble data assimilation, could potentially provide an objective and quantitative metric to test various configurations of an augmented GRUAN.

The scientific justification and basis for the design of a network to meet the needs of the NWP user community could come from applying one or more approaches to quantify the benefit of a particular network design, including the relative ranking of different designs. A further aspect of the network design that could be tested is enhancement of the observations that go into the network; this enhancement could involve providing observations at higher temporal resolution than hitherto, or adding measurements of upper air ECVs hitherto not provided by GRUAN sites, or significantly improving the accuracy of existing, or new, observations. Input from users in the NWP community would help establish what kind of network design would need to be tested. The benefit will come in two ways: (i) the added value of a particular network design compared to the current GOS (e.g., the current GRUAN); and (ii) the relative added value of a particular network design compared to other network designs. It would be desirable to quantify this added value using an objective measure.

As mentioned above, the suitability of approaches such as OSEs and OSSEs to design GRUAN is a matter of debate. However, if such an approach were to be taken, possibilities include:

- By comparison against a reduced GRUAN if using the OSE approach;
- By comparison to the “truth-proxy” (or Nature Run) if using the OSSE approach;
- By comparison of different ensemble spreads if using the ensemble data assimilation impact study approach.

Based on such an objective measure, the economic cost of a particular network design could be evaluated. The suitability of these techniques would have to be assessed in consultation with NWP centres. In particular, techniques not based on data assimilation notions may be more suitable.

The scientific justification and basis for the network design relies on the methodology of the various approaches used. For completeness, three approaches based on data assimilation notions are described below.

OSE methodology. If the candidate location for extending GRUAN is already reporting on an operational basis, e.g., as part of the GUAN, an OSE could be appropriate. In this case one could test the impact of the candidate location by removing it from the network and assessing the impact of this action by comparing the quality of the analysis and/or forecast of the control run (with all GRUAN sites, including the candidate location) and the perturbation run (in which the candidate location is excluded).

OSSE methodology. Because a network like GRUAN, which aims to be a reference quality network, may only ever have a few sites, an OSSE may need a very long duration (order months) to show a significant impact. Nevertheless, it is an approach which in principle could be used to assess additions to GRUAN, when these additions do not exist. It is thus important to understand the strengths and weaknesses of the OSSE methodology. A key outcome of this network design activity could be identifying specific targeted research to fill knowledge gaps in the OSSE methodology. Specifically, and with reference to GRUAN, the caveats of OSSEs would have to be addressed. These caveats are:

- Use of the same model for the “Truth-proxy” and the assimilation experiments. The “Truth-proxy” or Nature Run is sampled in space and time to simulate the observations (and their errors) included in the OSSE;
- Testing the fidelity of the “Truth-proxy”;
- Cost of the OSSE;
- Model dependence of OSSE results;
- Bias between models if different models are used for the “Truth-proxy” and the assimilation experiments;

Possible solutions to be considered would be:

- Use different models for the “Truth-proxy” and the assimilation experiments;
- Compare the “Truth-proxy” against well-calibrated data;
- Reduce the complexity of the OSSE;
- Use the cross-OSSE approach, in which we have two setups. Setup 1 uses model A for the “Truth-proxy” and model B for the assimilation experiments; setup 2 uses model B for the “Truth-proxy” and model A for the assimilation experiments;
- Use relatively large errors to provide upper bounds for results;
- Provide a bias assessment by comparison of the models against well-calibrated data.

Ensemble data assimilation impact studies methodology. This methodology is an alternative to that of the OSSE. It uses the spread of the ensemble as a proxy for the analysis and background uncertainty based on arguments of error growth. This methodology has the advantage that real existing observations are assimilated exactly as in operational practice, and do not need to be simulated artificially. It is only the future observing system under test (in this case, candidate GRUAN sites) that are generated through simulation. Furthermore, and in contrast to the OSSE methodology, there is no need to generate the Nature Run, and the problems normally associated with using the same model for creating the Nature Run and performing the OSSE (see above) are avoided.

8.7 Recommendations

The NWP user community should benefit from an augmented GRUAN which will provide high accuracy observations of various parameters, including temperature, water vapour, and pressure, as well as cloud, aerosol and radiative flux information. Such a network would be particularly useful for evaluation of NWP system performance, for anchoring NWP analyses and for evaluating other observations used in the data assimilation component of the NWP system. To assess the benefit to the NWP community of an augmented GRUAN it is recommended that the NWP user community be consulted and that various approaches be considered to quantify the benefit of scenarios for an augmented network - these approaches could be based on data assimilation notions. Approaches based on data assimilation notions could be expected to provide a scientific basis for the augmented network and quantify the economic cost of the augmented network, but the methodology to be used should be discussed with the NWP user community.

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Appendix A – Workshop Agenda

Wednesday 13 June 2012

Opening session Chair: Greg Bodeker

08:30 – 09:00	On-site sign in and set up
09:00 – 09:10	Welcome from the local organizing committee and logistics – Frank Beyrich
09:10 – 09:20	Welcome from the scientific organizing committee and statement of workshop objectives, introductions – Greg Bodeker
09:20 – 09:50	An overview of GRUAN – Holger Vömel
09:50 – 10:10	The contribution of GRUAN to GCOS - Anna Mikalsen
10:10 – 10:30	WIGOS - Coordination and Integration of Global Observing Systems – Tim Oakley
10:30 – 11:00	Tea/coffee break

Introductory presentations Chair: Holger Vömel

11:00 – 11:15	The GRUAN challenge – Greg Bodeker
11:15 – 11:45	Monitoring upper air temperature and humidity trends in the absence of GRUAN – Dian Seidel
11:45 – 12:15	Keeping the real world in mind when thinking about GRUAN expansion – Richard Thigpen
12:15 – 12:30	Discussion
12:30 – 13:30	Lunch

The satellite perspective Chair: Dian Seidel

13:30 – 14:00	Assessment of adequate quality and co-location of sondes with space borne hyperspectral infrared instruments to validate retrievals of temperature and water vapour - Xavier Calbet
14:00 – 14:30	The global space-based inter-calibration system (GSICS) and characterising collocations' temporal/spatial variability - Tim Hewison
14:30 – 15:00	Requirements on GRUAN network design and expansion criteria from CM SAF perspective - Marc Schröder
15:00 – 15:15	Discussion of session 1 presentations
15:15 – 15:45	Tea/coffee

Design and extension of networks Chair: Ruud Dirksen

15:45 – 16:15	Presentation from Betsy Weatherhead
16:15 – 16:45	Potential Contribution of Ground Based Profiling Networks in Europe - Anthony Illingworth
16:45 – 17:15	An international network of ground-based microwave radiometers for operational retrievals of atmospheric temperature, water vapour, and cloud properties - Domenico Cimini
17:15 – 17:30	Discussion of session 2 presentations
17:30 – 17:45	Summary of plans for tomorrow – Greg Bodeker

Thursday 14 June 2012

Observing system experiments and process studies Chair: Holger Vömel

08:30 – 09:00	Determining the future Global Climate Observing System (GCOS): the role of Observing System Simulation Experiments - William Lahoz
09:00 – 09:30	ARISE: Atmospheric dynamics Research InfraStructure in Europe - Philippe Keckhut
09:30 – 10:00	Particle backscatter and relative humidity measured across cirrus clouds and comparison with state-of-the-art cirrus modelling – Thomas Peter
10:00 – 10:15	Discussion of session 3 presentations
10:15 – 10:45	Tea/coffee break

Brief summaries of current status of white papers Chair: Holger Vömel

10:45 – 11:10	Monitoring changes in climate – Greg Bodeker standing in for Karen Rosenlof
11:10 – 11:35	Satellite calibration and validation - Xavier Calbert
11:35 – 12:00	Atmospheric process studies – Michael Kurylo
12:00 – 12:25	Numerical weather prediction – William Lahoz
12:25 – 12:30	Summary of afternoon assignments – Greg Bodeker
12:30 – 13:30	Lunch

Break-out writing teams

13:30 – 15:30	Writing teams work in break-out sessions to progress the development of the white papers
15:30 – 16:00	Tea/coffee break
16:00 – 18:00	Writing teams work in break-out sessions to progress the development of the white papers

Friday 15 June 2012

Break-out writing teams

08:30 – 10:00	Writing teams work in break-out sessions to progress the development of the white papers
10:00 – 10:30	Tea/coffee break

Report back on progress on white paper development in plenary Chair: Stephan Bojinksi
The focus of this session is to identify and resolve overlaps, cross-cutting issue, consistency and conformity of the style of the white papers etc. Each presentation would be 15 minutes followed by 15 minutes of discussion.

10:30 – 11:00	Monitoring changes in climate – Greg Bodeker standing in for Karen Rosenlof
11:00 – 11:30	Satellite calibration and validation - Xavier Calbert
11:30 – 12:00	Atmospheric process studies – Holger Vömel standing in for Michael Kurylo
12:00 – 12:30	Numerical weather prediction – William Lahoz
12:30 – 12:50	Summary of the way forward and review of actions
12:50 – 13:00	Closure of the workshop
13:00 – 14:00	Lunch
14:00 – 18:00	Visit to GRUAN Lead Centre at Lindenberg

Appendix B – Workshop Attendees and remote participants

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7 Participated remotely

Appendix C – Acronyms

ACC	Atmospheric Composition Constellation
AERONET	Aerosol Robotic Network
AIRS	Atmospheric Infrared Sounder
AMSU	Advanced Microwave Sounding Unit
AOD	Aerosol Optical Depth
AOGCM	Atmosphere-Ocean General Circulation Model
ARM	Atmospheric Radiation Measurement
BSRN	Baseline Surface Radiation Network
CCM	Climate Chemistry Model
CDNC	Cloud Droplet Number Concentration
CEOS	Committee on Earth Observation Satellites
CFH	Cryogenic Frost point Hygrometer
CFSR	Climate Forecasting System Reanalysis
DFS	Degrees of Freedom for Signal
DOE	Department of Energy
DWD	Deutscher Wetterdienst (Germany's National Meteorological Service)
EARLINET	European Aerosol Research Lidar Network
ECV	Essential Climate Variable
ENSO	El Niño Southern Oscillation
FCDRs	Fundamental Climate Data Records
FSO	Forecast Sensitivity to Observations
GALION	GAW Aerosol Lidar Observation Network
GAW	Global Atmosphere Watch
GCOS	Global Climate Observing System
GDAP	GEWEX Data and Assessments Panel
GEWEX	Global Energy and Water Exchanges Project
GHG	Greenhouse Gas
GOS	Global Observing System
GPS	Global Positioning System
GRUAN	GCOS Reference Upper-Air Network
GSICS	Global Space-based Inter-Calibration System
GUAN	GCOS Upper-Air Network
HCFCs	Hydrochlorofluorocarbons
IASI	Infrared Atmospheric Sounding Interferometer
IPCC	Intergovernmental Panel on Climate Change
LWP	Liquid Water Path
MJO	Madden-Julian Oscillation
MPLNET	Micro Pulse Lidar Network
MSU	Microwave Sounding Unit
NAM	Northern Annular Mode

NAO	North Atlantic Oscillation
NCEP	National Centres for Environmental Prediction
NDACC	Network for the Detection of Atmospheric Composition Change
NILU	Norwegian Institute for Air Research
NOAA	National Oceanic and Atmospheric Administration
NPP	National Polar-orbiting Partnership
NRC	National Research Council
NWP	Numerical Weather Prediction
ODS	Ozone Depleting Substances
OLR	Outgoing Longwave Radiation
OSE	Observing System Experiment
OSSE	Observing System Simulation Experiment
QBO	Quasi-biennial Oscillation
RTM	Radiative Transfer Model
SAM	Southern Annular Mode
SASBE	Site Atmospheric State Best Estimate
SHADOZ	Southern Hemisphere Additional Ozonesondes
SI	International System of Units
SPARC	Stratosphere-troposphere Processes And their Role in Climate
SRES	Special Report on Emission Scenarios
SST	Sea Surface Temperatures
TIROS	Television Infrared Observation Satellite Program
TOVS	TIROS Operational Vertical Sounder
UNEP	United Nations Environment Programme
UTLS	Upper Troposphere / Lower Stratosphere
WIGOS	WMO Integrated Global Observing System
WMO	World Meteorological Organization
WOUDC	World Ozone and Ultraviolet Radiation Data Centre