WORLD METEOROLOGICAL ORGANIZATION

WMO INTEGRATED GLOBAL OBSERVING SYSTEM (WIGOS)

GRUAN-GSICS-GNSSRO WIGOS Workshop on Upper-Air Observing System Integration and Application

Geneva, 6-8 May 2014

Final Report

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GRUAN-GSICS-GNSSRO WIGOS Workshop on Upper-Air Observing System Integration and Application

Report

1. INTRODUCTION

1.1 PURPOSE

The workshop was held from 6 to 8 May 2014 at the World Meteorological Organization (WMO) headquarters in Geneva, Switzerland, comprising 20 participants, with the purpose of exploring how the benefits of high-quality observations of the upper atmosphere using ground-based upper-air soundings from the GCOS Reference Upper-Air Network (GRUAN), satellite-based infrared measurements (intercalibrated within the Global Space-based Inter-Calibration System (GSICS)), and Global Navigation Satellite Systems for Radio Occultation (GNSS-RO)-based refractive index measurements, can be fully realized, for weather and climate applications.

The group discussed the interaction of the observing system activities in GRUAN, GSICS and GNSS-RO and made recommendations to improve their interoperability and joint data utilization to meet the requirements of users in climate and numerical weather prediction (NWP).

As such, the workshop represented a case study in support of objectives of the WMO Integrated Global Observing System (WIGOS) and addressed the action in the WIGOS implementation plan to "develop guidance for the process of sharing, between component observing systems, operational experiences, sharing of expertise and a guidance for resourcing joint activities"" (Action 4.1.2).

Following a request to clarify the scope of the workshop, the organizing committee stressed before the meeting that the workshop was dedicated to discussing GRUAN, sounders/GSICS, and GNSSRO (hereafter the "3G"s), their interaction, interoperability and data utilization, and what contribution these systems could make to meet the requirements of users in NWP and climate, in the context of the wider global observing system. They emphasized that the workshop was not about designing or optimizing the upper-air global observing system as a whole.

1.2 WORKSHOP GOALS

1. Identify measures to better connect the GRUAN with the satellite community

    The idea for the workshop had its origins in the GRUAN community, which recognizes the need for better coordination and collaboration with the meteorological satellite community; in response, GSICS groups have discussed GRUAN matters and emphasized (i) that GRUAN may benefit from the highly stable reference IR sounders used in GSICS, and (ii) that GRUAN could be particularly valuable as a reference anchor for satellite instruments operating in the microwave range (MW) where an on-orbit reference is not available.

2. Compare methods of estimating measurement uncertainty (including systematic errors), calibration/validation and collocation

Data from all "3G"s have associated uncertainties, which are relevant in the calibration and validation of other instruments; the uncertainty that accrues due to collocation mismatch of measurements in space and time is a particularly important aspect of caibration/validation and joint data exploitation in general.

3. Provide guidance on how the various upper-air observing systems and datasets can better serve meteorological and climate applications

   More integrated data utilization from all "3G"s is important to improve their relevance to weather and climate user communities, and to demonstrate the added value of synergetic use.

4. Develop recommendations for future observing system design

   The workshop discussed integration and application of the "3G"s in the context of the wider global upper-air observing system.

1.3 PARTICIPATION

The workshop invitation was extended to representatives from: the Working Group on GRUAN and its Task Team on Ancillary Measurements, the GRUAN Lead Centre, GRUAN sites, the GSICS Research Working Group, the Coordination Group for Meteorological Satellites (CGMS)-WMO International Radio Occultation Working Group, the Global Climate Observing System (GCOS), the Network for the Detection of Atmospheric Composition Change (NDACC), World Climate Research Programme (WCRP) SPARC (Stratosphere-troposphere Processes And their Role in Climate), WMO representatives (WMO Integrated Global Observing System (WIGOS) Project Office, Commission for Basic Systems (CBS)), calibration/validation experts from ESA and EUMETSAT, WMO Members (Australia, Brazil, China, Japan, South Africa, USA) and selected users of upper-air observations.

The workshop organizing committee was composed of: Greg Bodeker, Stephan Bojinski, Bojan Bojkov, Xavier Calbet, John Dykema, John Eyre, Tony Mannucci, Peter Thorne, and Holger Vömel.

1.4 PRE-WORKSHOP CONSIDERATIONS

In planning the workshop, the following science themes were considered:

- What is the value in the use of GRUAN measurements and associated uncertainties for space-based retrieval and sensor and associated radiative transfer model validation and development, with a focus on the GSICS reference satellite instruments IASI and AIRS?
- What could be the use of GRUAN measurements in comparison with GNSS-RO-based atmospheric profiles?
- What are similarities and differences in how data from GRUAN, satellite hyperspectral sounders, and GNSS-RO sensors are used in weather and climate applications?

- What are measurement scheduling options within GRUAN to best meet the needs of the space-based measurements and products community? What is the impact of space-time collocation? Where and when does this matter? Scheduling and respective impacts for (1) intensive cal/val and versus (2) sustained cal/val as part of a constellation of cal/val capabilities. Answering these questions should build on material developed through the 2012 GRUAN workshop on network expansion criteria[1]
- What is the utility of data in their native geophysical format compared to sets of calculated and observed radiance equivalents?
- How do we integrate and use uncertainties at the native measurement resolution in GRUAN to compare to satellite measurements (IR sounders, GNSS-RO)? It is not just the best guess value that needs interpolating but also the uncertainties, many of which may exhibit spatio-temporal correlation structures.
- What guidance for GRUAN/satellite operations can be generated from the lessons learned?

In addition, the following operational aspects were considered:

- What timeliness constraints apply to satellite applications of GRUAN data?
- What data formats make sense?
- How should collocation data be provided (database management) such that they are easy to use?
- How can sustained collaboration between the "3G" communities be ensured?

1.5 INTRODUCTORY COMMENTS

L. P. Riishojgaard (WIGOS Project Manager) welcomed participants on behalf of WMO. He stressed the importance of high quality temperature and humidity profiles to numerous weather and climate-related application areas. WMO through the WIGOS project is interested in integrating satellite and in-situ measurements. Finding the optimum mix of capabilities to derive best value is a challenge.

S. Bojinski (WMO Space Programme) outlined the origins of the workshop and its main objectives. He outlined how the idea originated from the GRUAN community. As the workshop concept was developed, it became clearer that the interface and synergies between the "3G"s required detailed investigation. He outlined how the workshop was intended to be discursive and for discussing how integration and interoperability can be achieved. The agenda (see Appendix B) was structured to provide necessary context (WMO, "3G"s, application areas) under items 3, 4, and 5, and then to allow for meaningful thematic discussion in item 6. He indicated that the meeting format was somewhat experimental, and, if successful, may help WMO in advancing WIGOS more broadly.

Co-Chairs P. Thorne (NERSC), T. Hewison (EUMETSAT), and T. Mannucci (NASA JPL) provided opening remarks. T. Hewison outlined the numerous ways that data comparisons can be undertaken in profile or radiance space and how each contains substantial uncertainty and ambiguity. T. Mannucci stressed that the workshop was a tremendous opportunity to benefit from each other's expertise and practices. P. Thorne noted the value of the workshop for discussing the existing high-quality measurement and intercomparison activities, with an objective to get better use of traceable measurements, better intercomparison of these measurements, and better uptake of these measurements in applications.

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[1] GRUAN Report 3: Outcomes of the GRUAN Expansion Workshop. Rev 1.0 (6 Jan 2014); ftp://ftp.bodekerscientific.com/GRUAN/GRUANReport_NetworkExpansionWorkshop_V16.pdf (uid: outgoing; pwd: outgoing)

2. PERSONAL POSITION STATEMENTS

Participants and invitees (see Appendix C) were encouraged to submit personal position statements in writing in advance of the workshop, and to introduce these early on in the agenda under item 2 (Appendix A provides a summary of the submitted material).

G. Bodeker expected guidance and clear actions on what GRUAN should do differently to serve the objectives of the various observation and application communities.

A. Dall'Antonio expected insight on how the Brazilian Meteorological Service (INMET) could benefit from ground-based and satellite observations, and how within operational constraints this service could also contribute to these observing systems. More training was required to raise awareness and attract interest.

T. Hewison raised the question of how to establish a common framework for establishing biases and uncertainties in the various satellite datasets, and how to ultimately achieve on-orbit SI-traceable measurements.

J. Eyre pointed out his background in satellite sounding in IR and MW, and radio-occultation; and in the areas of assimilating these data into numerical weather prediction systems. He disagreed with the view that the success of GRUAN should be judged by its role in "serving the satellite community", but rather was of the opinion that GRUAN should be judged by how well it contributes to WIGOS and supports application areas in the coming ten years.

A. Simmons stressed that GRUAN's success could not be judged after only ten years since it was a climate reference network, and that traceability of climate observations was important but should not be seen as an end in itself. He queried whether the case for CLARREO was as strong today as it used to be, given that (i) data from the current generation of hyperspectral infrared (IR) sounders had been shown to be highly stable, (ii) the availability of good-quality data from GNSS-RO, and (iii) the establishment of a reference upper-air network.

T. Reale would like to see a broadening of the interactions between communities; he runs a set of systems managing collocations of satellite data and upper-air soundings (GRUAN and others).

X. Calbet saw three communities that should be better integrated: sounding, NWP, and radiative transfer. He expanded on the characterization of systematic biases and the different sources. A white paper was under development on collocating satellite and ground-based profile measurements.

B. Bojkov questioned the representativeness of different data sources used for calibration and validation. Traceability could be important for understanding the deficiencies of past observing systems. He stressed the importance of accessibility of GRUAN and other meteorological data. GRUAN should continue to serve as a good example to other atmospheric composition networks (on ozone, air quality) in adhering to standards. Where needed, collaboration with the Committee on Earth Observation Satellites (CEOS) Working Group on Calibration and Validation should be sought, and the documentation principles of QA4EO (Quality Assurance Framework for Earth Observation) be followed.

G. Kirchengast expected ideas for better cross-community cooperation among the "3G"s, and for overcoming the path dependency of existing practices. He elaborated on the trade-off between maintaining current observing systems operations, and changes to these systems as a result of innovation. He advocated full exploitation of radiometric information in time and space using the "3G"s. He also pointed out the value of other measurement techniques (e.g., differential absorption spectroscopy) to fully characterize individual elements of the radiative transfer equation which are largely unexplored to date.

A. von Engeln aimed to better coordinate the GNSS-RO community with GRUAN and GSICS, and better use of RO data from research satellites.

S. Healy asserted that data assimilation techniques would be fundamental for integrating the various observation data streams; he expected that GNSS-RO would have an increasingly important role for the various applications over the next 10 years.

T. Mannucci noted the value of comparing independent measurements for advancing science. Having anchors (reference points) to measurements was very important, as well as common terminology, for example for characterizing errors.

H. Vömel recalled the emphasis of GRUAN on climate, although other applications are important; weather has been the driver for upper-air sounding, and will continue to be. However, changing practices at GRUAN sites such as Lindenberg should enable building climate records. Achieving common terminology in describing uncertainties is very important, since these provide a means to compare data.

M. de Mazière (associated with the Network for the Detection of Atmospheric Composition Change (NDACC) and the Total Carbon Column Observations Network (TCCON)) noted redundancies among the different networks and identified issues of sustainability in maintaining key networks. She advocated more cost-effective observing systems: the data generated should serve the needs of as many application communities as possible. Data access was also an issue compounded by the proliferation of online portals.

J. Dykema was interested in how the principles of error characterization and other best practices could be applied across the various systems.

A. Mikalsen described the role of the GCOS programme and its recent review of designated GCOS baseline observing networks[2], aiming at an improved global atmospheric observing system for climate.

L. P. Riishojgaard noted that WIGOS was aiming at a design exercise to make the global observing system more cost-efficient in light of a resource-constrained environment.

S. Bojinski identified all parts of the value chain of observations as possible areas of better cooperation among the various “3G” communities.

P. Thorne stressed the need for (i) being forward-looking as a community, (ii) achieving a multi-point observing system that is more resilient to failures in any one sub-system, (iii) much better addressing a broad range of user needs, (iv) providing full documentation, (v) training the next generation of scientists, (vi) a realistic approach in light of resource limitations.

In the subsequent discussion, participants raised the following points (these did not necessarily represent a consensus view) :

[2] The full report from the Workshop on the Review of the GCOS Surface Network (GSN), GCOS Upper-Air Network (GUAN) and related atmospheric networks is available under: http://www.wmo.int/pages/prog/gcos/Publications/gcos-182.pdf

- GRUAN may need 5-10 year milestones to be appealing to funders, and needs to show its value now, not only in 30 years' time;

- NOAA NESDIS are considering changes in its operational sounding validation protocol, by using GRUAN data uncertainty estimates for characterizing retrieved product performance;

- To allow for intercomparison and independent verification of data, a resilient observing system must include some duplicative measurements. It was noted that using the term 'redundant' for such measurements was counterproductive as it sends a wrong message to funders and users who may interpret the term as meaning 'superfluous' and 'of no additional value';

- Regarding the funding for global observing systems within WIGOS, participants raised the view that by demonstrating the value of observing systems for the generation of climate services, there is a good chance for identifying new or additional funding sources for maintaining and developing such systems. Furthermore, a better balance in budgets was needed between space and in-situ components of the Global Observing System, citing the European Copernicus programmes as an example;

- Related to the balance of funding observing systems vis-à-vis funding systems that turn observations into products, an example from ECMWF was cited: improvements in forecasting over the past 30 years were roughly 60% due to improving the assimilation system (arguably more from the evolution of software than hardware), and 40% from the improved observing system.

3. WMO OBSERVING SYSTEM PLANNING

This section describes the status of observing system coordination, design and planning within WMO and the Global Climate Observing System Programme (GCOS), co-sponsored by WMO, the Intergovernmental Oceanographic Commission (IOC) of the United Nations Educational, Scientific and Cultural Organization (UNESCO), the United Nations Environment Programme (UNEP), and the International Council for Science (ICSU).

3.1 STATUS OF WIGOS IMPLEMENTATION

L. P. Riishojgaard, WIGOS Project Manager, introduced WIGOS. WIGOS is an integrated, comprehensive, and coordinated system which is comprised of the current WMO global observing systems, in particular of the *in situ* and space-based components of the Global Observing System (GOS), the Global Atmosphere Watch (GAW), the Global Cryosphere Watch (GCW), and the World Hydrological Cycle Observing System (WHYCOS).

WIGOS is a strategic priority area of WMO and, together with the WMO Information System (WIS), a WMO contribution to the Global Earth Observation System of Systems (GEOSS).

WIGOS has been conceived recognizing that the mandate of NMSs is much broader now than it was when the WWW (World Weather Watch) GOS were created fifty years ago. Their mandates now encompass applications other than weather prediction, such as climate and air-quality monitoring. He mentioned several shortcomings in the current observing system that should be addressed (such as: observing systems not being stable or sustainable; design and planning not being well coordinated; observing standards not being respected; lack of qualified staff).

Strengthening the interaction between research and operational observing communities will be important for sustaining and evolving observing systems and practices in support of WIGOS in line with new science and technology outcomes.

WIGOS provides a new framework for coordinating and evolving WMO observing systems, including the contributions of WMO to co-sponsored observing systems. This framework aims at advancing:

- Design, planning and optimized evolution of WIGOS component observing systems (including space-based observing systems)
- Observing system operation and maintenance
- Quality management
- Standardization, system interoperability and data compatibility
- Integration of governance and management functions
- Data discovery, delivery and archival (through the WIS)

"Implementation" in WIGOS terms means defining the basis of manuals and technical regulations that should eventually be followed by WMO Members. Many elements follow later, such as technical guidance and actual implementation by countries. WIGOS provides guidance for global, regional and national-scale activities, with the objective of avoiding redundancy and optimizing the overall observing system.

WIGOS is not replacing or taking over existing observing systems, which will continue to be 'owned' and operated by a diverse array of organizations and programmes, nationally as well as internationally.

Currently three tasks are a priority for WIGOS: (i) developing regulatory material (currently under review, deadline 10 July 2014), (ii) developing metadata standards, and (iii) defining quality management practices. The WIGOS Information Resource will provide an overview of WIGOS-related material and the Rolling Review of Requirements, supported by the OSCAR database[3] .

S. Bojinski asked to what extent WIGOS could help coordinate NMS and non-NMS contributions at the WMO level. It was clarified that WIGOS cares about all observations. The example of the WMO Aircraft Meteorological DAta Relay (AMDAR) programme was given as a case in point, where airline companies collaborate with NMSs and data relay providers in operating an aircraft-based global observing system.

3.2 VISION FOR THE GOS IN 2025 AND ROLLING REVIEW OF REQUIREMENTS

J. Eyre, chair of the WMO Commission for Basic Systems (CBS) Inter-Programme Expert Team on Observing System Design and Evolution (IPET-OSDE) outlined the rationale behind the Rolling Review of Requirements (RRR) process and how input was captured on a rolling basis responding to evolving capabilities and user requirements. The collection of user requirements and system capabilities in the Observing Systems Capability Analysis and Review tool (OSCAR) allowed for application-specific gap analyses ("statements of guidance") which provide valuable input to the further evolution of the observing system. Different application areas have had differing extents of input to the RRR, with focal points for NWP and climate (through GCOS) having been the most active.

[3] http://www.wmo.int/pages/prog/www/wigos/wir/oscar.html

The Vision for the GOS in 2025[4] provides high-level guidance on the desirable evolution of the GOS in response to WMO application areas. The Vision makes reference to IR hyperspectral sounders, microwave sounders, a radio-occultation constellation, and GRUAN. It also makes statements about consistency and homogeneity of measurements and their traceability to standards, and about integration.

The Vision has been defined as challenging but achievable. The Implementation Plan for the Evolution of the Global Observing System[5] provides a detailed roadmap for achieving the Vision.

Integration in this context means (i) activating communities engaged in weather forecasting, climate monitoring, oceanography and others, (ii) more consistent analysis of requirements, (iii) sharing observational infrastructure, platforms and sensors, and (iv) coordinating observing systems, in a cost-effective manner.

CBS had also contributed to the development of developing observing system network design principles, which include design through a tiered approach "through which information from reference observations of high quality can be transferred to and used to improve the quality and utility of other observations". This is consistent with the approach taken by GRUAN vis-à-vis the GUAN and the comprehensive upper-air network. J. Eyre requested that the GRUAN community provide feedback on a draft set of WMO observing system design principles.

According to J. Eyre, integration means increasing both number and strength of links between observational datasets and direct users of observations. Integration does not mean the generation of integrated datasets: he argued that many users and especially NWP users would seek single-source ("clean") high-quality datasets rather than integrated observation datasets based on several observation systems. Collaboration among the observing systems (Fig. 1, left-hand boxes) was justifiable to guarantee the quality of each system and characterize their uncertainties (such as in the case of GSICS).

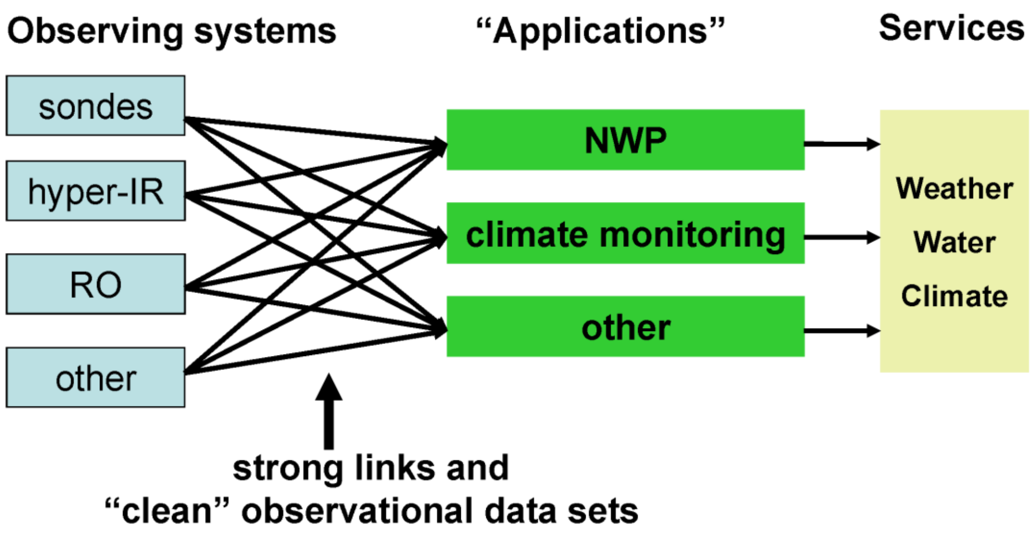

Fig. 1: "Integration" in the sense of the WMO Vision for the GOS in 2025 means strong links between observing systems and application communities. (Source: J. Eyre)

[4] http://www.wmo.int/pages/prog/www/OSY/gos-vision.html
[5] WMO Technical Report No. 2013-4: Implementation Plan for the Evolution of Global Observing Systems (EGOS-IP), http://www.wmo.int/pages/prog/www/OSY/Publications/EGOS-IP-2025/EGOS-IP-2025-en.pdf

There was general consensus that observing systems should be maintained and quality-controlled independently from each other, and that cross-linkage should only serve to improve the characterization and performance of any one of the systems (e.g., in the case of GSICS). The importance of data assimilation systems of the NWP community in supporting consistency checks of observations and to provide feedback was recognized.

3.3 REPORT FROM THE GCOS AOPC NETWORK WORKSHOP

A. Mikalsen introduced the GCOS programme and described the concept of reference, baseline and comprehensive networks, as well as the recognition of GRUAN in the GCOS Implementation Plan. The Plan stated that "a network of about 30 sites is proposed to permit systematic observation in all climatic zones". The development of GRUAN regulatory material had been designated as a pilot activity in WIGOS. She described the concept of reference, baseline and comprehensive networks.

She recalled the minimum requirements of the GCOS Upper-Air Network (GUAN) and the GCOS Surface Network (GSN). She then presented the outcome of an April 2014 workshop to review designated GCOS baseline observing networks[6] in light of changing requirements. This workshop discussed design, scientific principles, performance and use of data from the GSN and GUAN, and their roles in relation to the comprehensive surface and upper-air networks.

The network workshop agreed that GUAN should be continued but with modified focus: not primarily aiming for even global coverage but also for higher data quality. Recommendations from the workshop include that certification based on meeting the minimum requirements is needed, and that GUAN sites in the future "shall" be actively monitored by a central monitoring and archiving facility to follow quality and scheduling standards. Furthermore, ideas for further cross-fertilization of GUAN and GRUAN were presented at the workshop: the wider upper-air network could benefit from the reference observations of GRUAN and from GRUAN best practice, such as manufacturer-independent ground-checks, managed instrument change, redundant observation and intercomparison activities, as well as capacity building and training.

4. APPLICATIONS OF UPPER-AIR OBSERVATIONS

4.1 CLIMATE MONITORING

P. Thorne summarized key findings from the IPCC AR5 regarding upper-air temperature and humidity trends. Regarding water vapour, AR5 key findings are that:

- Because of large measurement uncertainty and relatively short data records, confidence in stratospheric water vapour trends is low.
- Near-global satellite measurements of stratospheric water vapour show substantial variability but small net changes for 1992–2011.
- It is very likely that near-surface and tropospheric specific humidity have increased globally since the 1970s.
- Radiosonde, Global Positioning System (GPS) and satellite observations of tropospheric water vapour indicate very likely increases at near global scales since the 1970s occurring at a rate that is generally consistent with the Clausius-Clapeyron relation (about 7% per degree Celsius) and the observed increase in atmospheric temperature.

[6] The full report from the Workshop on the Review of the GCOS Surface Network (GSN), GCOS Upper-Air Network (GUAN) and related atmospheric networks is available under: http://www.wmo.int/pages/prog/gcos/Publications/gcos-182.pdf

- Significant trends in tropospheric relative humidity at large spatial scales have not been observed."

He described the challenges associated with maintaining homogeneous long-term time series of temperature and water vapour in the context of changes in radiosonde systems and orbital drifting of microwave sounders.
GNSS-RO records show promise although they are currently too short to derive multi-decadal trends. While there are some issues with comparison methods of GNSS-RO data series, their low structural uncertainty is, and will be, of value; it may take some years for the dataset to be useful for climate monitoring.

He recognized that climate monitoring includes not only analysis of decadal records, but also the monitoring of climate variability and extremes on shorter time scales, such as seasons to years. Multi-decadal trends are uncertain depending on the datasets used, both on global and regional scales. The spread in results often does not reduce with time.

In summary, he stressed the need for a robust long-term observing system that consists of multi-point redundant traceable / comparable measurement systems, building on GRUAN, GSICS, GNSS-RO, and also on other high-quality measurement systems (such as NDACC, TCCON, a potential future CLARREO mission). Currently, the longest GRUAN time series is from Lindenberg at 6 years.

4.2 CLIMATE PROCESS STUDIES

J. Dykema presented results from a poll of the World Climate Research Programme (WCRP) Stratosphere-troposphere Processes And their Role in Climate (SPARC) community on their use of upper-air observations. The poll enquired on the use of satellites, ground-based profile and remote sensing systems (including the "3G"s) and reanalyses for inferring variability in upper-air temperature and water vapour, and on the use of global vs regional and short vs long-term datasets. The poll also ascertained perceived deficiencies in observing systems and datasets, as well as future needs over three and ten year time horizons. Responses to the poll were provided by the leads of the Temperature trends, Water vapour trends, Predictability, Solar variability, Ozone, Dynamical variability, Reanalysis, and Gravity Waves SPARC activities.

In summary, the poll revealed that:

- Reanalysis is critical to multiple themes, and ways to improve reanalyses should be further explored;
- A follow-on mission for limb-sounding of the stratosphere is essential (there are concepts for a compact microwave limb sounder);
- Continuity of sensors over the long term is essential for many process studies, and challenges are recognized;
- Better coordination among ground-based networks is needed (e.g., between GRUAN and NDACC; Establishing multi-satellite-mission ground segment infrastructures would help address this);
- Ground-based sensors can be used to safeguard the continuity of records (e.g., if satellite missions are discontinued).

Some discussion ensued on how to support reanalysis, e.g. how do reanalysis winds errors propagate into process studies, and how to evaluate data quality impacts on reanalysis. Challenges were noted in constructing climate data records from multiple sources, such as from the Stratospheric Sounding Unit (SSU) and Advanced Microwave Sounding Unit (AMSU) instruments.

4.3 NUMERICAL WEATHER PREDICTION

J. Eyre described the principles of data assimilation for NWP, and the role of reference observations. The "background" is not "a" model, but the synthesis of all observations previously assimilated, tied together in a physical model framework. At every assimilation step, roughly 80% of the information content comes from the background, and 20% from new observations. A wide range of observation types is useful for NWP. In the variational assimilation scheme, the FSO (forecast sensitivity to observations) metric can be used to assess the relative impact of individual observations on reducing forecast error.

He explained the importance for data assimilation of assessing and correcting for systematic biases in the observations, observation operator, and background. He used a comparison of Infrared Atmospheric Sounding Interferometer (IASI) data with NWP model output as an example. Some observations should not be bias-corrected and used as independent anchors, for verification and correction of drifts in the model. The Met Office only performs comparisons of observations via the medium of a NWP model; it stopped direct comparisons of observations in the early 2000s mainly because of the high noise level due to relatively small numbers of collocation samples.

He also suggested that, in addition to anchor observations, some observations could be reserved as "references". These would be anchor observations that can be traced to standards and that are of high quality and well-characterized (such as the data generated in GRUAN). He noted that even if the best GRUAN data were not available in near-real time, the profiles could be usefully compared with statistics of assimilated near-real time radiosondes from GRUAN and other stations.

4.4 REANALYSIS

A. Simmons described the use of upper-air data and the roles of GNSS-RO, GSICS and GRUAN in reanalysis. He illustrated the beneficial impact of assimilating GNSS-RO data in reanalysis, and the continuing importance of radiosonde observation of the stratosphere. He showed comparisons of the ERA-Interim, JRA-55 and MERRA reanalyses (for mean temperature at various pressure levels, and winds). He discussed aspects of bias adjustment of both satellite and radiosonde data, and added remarks on the role of GRUAN in this regard. He noted that not many high-quality reference profiles (through GRUAN) are needed to be useful, for example for evaluating the background forecast for stratospheric pressure levels.

On fundamental climate data records, he noted that correcting shifts occurring in a time series involving several instruments, as usually done in reprocessing such records, was not desirable from a reanalysis point of view if the corrections depended on the atmospheric state. He asserted that the common definition[7] of "Fundamental Climate Data Record (FCDR)" was not useful to reanalysis. A reanalysis centre would require another form of "fundamental" data record, namely sensor data records from individual instruments and their calibration coefficients (provided inter alia through GSICS) and metadata.

GRUAN would be important to reanalyses in (i) estimating biases in temperature and humidity for the current comprehensive radiosonde network, (ii) providing data for sustained cal/val of space-based upper-air observations (including bias estimates), (iii) local evaluation

[7] National Research Council (2004): Climate Data Records from Environmental Satellites, The National Academies Press, Washington D.C., USA, 150p;
GCOS (2011): Systematic Observation Requirements for Satellite-based Data Products for Climate (2011 Update), December 2011, GCOS-154, http://www.wmo.int/pages/prog/gcos/Publications/gcos-154.pdf

of reanalysis performance for recent years for which GRUAN data are available, and (iv) generally raising the standard of radiosonde observation practices, for example, in GUAN.

Studies may be needed to identify reanalysis-based requirements for GRUAN-type observations (geographic location etc.) – such stations would probably be most needed in the tropics.

5. OBSERVING SYSTEMS: PRINCIPLES, PRACTICES, UNCERTAINTIES, CAL/VAL, PLANS

This item covered measurement principles and practices in GRUAN, GSICS, and GNSS-RO, including the characterization of uncertainty (errors), and the use of these systems in calibrating and validating other instrument data. Plans for the future, e.g., on expanding GRUAN or on enhanced satellite capabilities, were also introduced.

5.1 GRUAN

G. Bodeker described the GRUAN status and principles (uncertainty characterization, traceability, minimum site requirements). 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.

A GRUAN reference observation is defined as (i) traceable to an SI unit or an accepted standard, (ii) providing a comprehensive uncertainty analysis, (iii) maintaining all raw data, (iv) including a complete metadata description, (v) being documented in accessible literature, (vi) being validated (e.g. by intercomparison or through redundant observations). Detailed information on GRUAN is available at http://www.gruan.org.

He also presented results from the 2012 workshop on the development of Network Expansion Criteria from the perspective of four data user communities: climate change detection and attribution, numerical weather prediction, satellite calibration/validation, and atmospheric process studies. These included recommendations on observed variables at sites, geographic location of sites, site environment, measurement conditions and sampling.

He addressed the question of length of time series required to detect a climate trend at a significant confidence level; this depends on noise characteristics, trend magnitude of the phenomenon, and geophysical variability. In conclusion, the need for coordinating GRUAN with the satellite communities was stressed, and for GRUAN bringing added value to its various user communities.

The question was raised on the metadata provided with GRUAN radiosonde profiles.

ACTION G-1: GRUAN Lead Centre to inform the WMO IPET-OSDE (chair: J. Eyre) and the Task Team on WIGOS Metadata (WMO contact: Luis Nunes lfnunes@wmo.int) about the specifics of metadata for radiosondes.
Who: GRUAN Lead Centre
By when: 31 August 2014

5.2 HYPERSPECTRAL SOUNDING AND GSICS

T. Reale presented a summary of current on-orbit hyperspectral instruments (AIRS, IASI, CrIS). He highlighted how only subsets of these data are being utilized by most users. These data are routinely used and monitored by NOAA STAR. Monitoring can highlight issues and generally show very good instrument characterization and performance of the current hyperspectral IR sounders. He showed examples of the use of radiances in NWP, and of retrieval products (e.g., a temperature product to show the polar vortex anomaly of early 2014; trace gas products). Soundings are regularly stored and collocated with GRUAN data in the NOAA Products Validation System (NPROVS). The ensuing comparison can say something about whether the measures are truly matching specifications.

On the question of the users of the retrieved products, T. Reale stated these were mainly NOAA-internal users (for example for understanding of tropical cyclone tracks). Furthermore, the atmospheric chemistry community uses retrieved profiles of temperature as first guesses, and retrieved trace gas products.

T. Hewison introduced motivation and principles of GSICS ("to compare, monitor, correct level1 satellite data, and deliver to users"). GSICS products include bias monitoring, and applying a correction function. GSICS corrections can be derived systematically and are based on empirical comparisons. The diagnosis of the biases' root causes involves human analysis and forms the basis of guidelines and recommendations. He also expanded on the current status of GSICS products, including those under development. Users of GSICS are satellite operators and the satellite application community (operational NWP, reanalysis, users interested in consistently-calibrated satellite records, SCOPE-CM) More on GSICS is available at http://gsics.wmo.int

GSICS links individual satellite observing systems and provides some form of integration at this level, in order to better serve applications. In the MW spectrum, additional reference data (from e.g. GRUAN) may be useful since there is no obvious on-orbit reference instrument.

The success of GSICS has been due to it being very focused and practical, identifying the inter-calibration of the IR channels of geostationary imagers using hyperspectral sounders as references. Rapid consensus on a method allowed development of the infrastructure used to deliver GSICS products to users.

5.3 GNSS-RO

T. Mannucci gave a talk including on behalf of G. Kirchengast, S. Healy, and A. von Engeln. He explained the basics of using signal delay induced by atmospheric density variation used in GNSS-RO. Operating in L band, the signals are insensitive to precipitation and aerosol, and the measure is excess phase path as a function of time, from which bending angles and subsequently atmospheric parameters can be calculated. Since the time reference is highly stable, the system is "self-calibrating" and self-consistent, although SI traceability has not yet been rigorously demonstrated. Vertical resolution is particularly useful in the 8-25 km altitude range. Several Essential Climate Variable (ECV) requirements for T/q can be met using the GNSS-RO technique (using multiple profiles), others need confirmation. Structural uncertainties in datasets are due to different assumptions in retrieval processing, and differences in climate records derived from the same level 0 (raw) data.

Structural trends appear to be stable over time (using the same raw data and obtain different retrievals), for example when looking at CHAMP retrievals obtained from the different processing centres.

The impact of GNSSRO data in NWP modelling frameworks has been demonstrated (through analysing biases vs radiosondes) for example in the southern hemisphere, and in ECMWF data assimilation diagnostics.

COSMIC-2/FORMOSAT-7 is a 6-satellite follow-on to COSMIC that will help cover equatorial regions, but another 6 satellites are required for global coverage. The future of this constellation is uncertain.

RO data are available from 2001 onwards, with high volumes available since 2006. Their value for climate applications under investigation (within the ROTrends activity).

Some NWP centres are currently assimilating COSMIC data down to the surface, which gives some confidence in a reasonable treatment of water vapour in the assimilation of bending angle.

5.4 RADIATIVE TRANSFER

M. Matricardi (ECMWF) gave a remote presentation about radiative transfer models and their contribution to the observation-error covariance matrix, in the presence of the low-noise sounders AIRS, IASI, and CrIS. The exploitation of satellite radiance data for NWP requires the use of an accurate and fast radiative transfer (RT) model to simulate radiances from an input atmospheric profile. The 4D-Var assimilation scheme used at ECMWF involves the definition of the observation-error covariance matrix which is used to specify errors associated with radiance data. The observation error covariance matrix contains the instrumental-error covariance matrix and the RT-model-error covariance matrix.

The low noise level of the IASI, AIRS, and CrIS instruments makes RT errors an important contribution to the definition of the observation-error covariance matrix and consequently these errors must be properly evaluated and their origin fully understood. Two kinds of errors dominate in fast RT models: those due to parameterization used for atmospheric transmittances, and those associated with the spectroscopy underlying the line-by-line model upon which fast RT models are generally based. The latter tend to be dominated by poor knowledge of line shapes, positions, and intensities of the spectroscopy, with particular attention to spectral line shape of H2O and CO2 for which optical depth reaches high values.

Regarding H2O line shapes, the main difficulty lies in achieving sufficiently accurate measurements of H2O amounts in atmosphere and laboratory; the lack of basic understanding in nature of the water vapour continuum is generally overcome by using a semi-empirical model for parameterization. Regarding CO2, the effects of line mixing are included in line-by-line algorithms.

He showed some results of assessing the capabilities and limitations of current line-by-line models. For comparisons, the atmospheric state can be specified using satellite radiances or in-situ data (GRUAN could have role here), or NWP model output. Some features of the latest line-by-line RT model (LBLRTM; v12.3) include updates of line parameters, the introduction of CH4 and changes to CO2 spectra. Mean differences in LBLRTM from earlier versions can be up to 0.5K.

L. Strow made a (remote) intervention on this topic, stating that he used radiosonde profiles for comparison with AIRS 10 years ago, but since then RT calculations had improved based on improved spectroscopy (HITRAN database),. He noted that direct comparisons of satellite with GRUAN would not be easy since only relatively few collocation events (satellite overpasses and GRUAN soundings) were available for doing good statistics.. He argued that since the current hyperspectral sounders are instruments able to detect tenths of percent changes in water vapour, it may be difficult to get value out of GRUAN in this regard.

5.5 ADDITIONAL COMMENTS

M. de Mazière noted that the need for traceable measurement may differ depending on the application; it made a difference whether a measurement was traceable (i.e. that there was an unbroken calibration chain to a reference source) or whether it was SI traceable which involved more complexity and effort. She also raised the question how to effectively archive information on traceability, and emphasized the need for consistent terminology in expressing uncertainty and error. Within WIGOS, she noted that guiding observing system implementation nationally would have to be accompanied by a regional perspective. As for expanding GRUAN, she advised to take stock of achievements and gaps in the current network before growing the network.

6. DISCUSSION TOPICS

All discussions were held in plenary given the size of the group and the cross-cutting interest of participants. The co-chairs stressed that any identified actions should involve at least two of the "3G"s ("ACTION 3G-x). However, some actions and recommendations were identified that apply to only one of the "G"s ("ACTION G-x").

6.1 APPLICATIONS AND REQUIRED DATASET GENERATION

G. Bodeker facilitated the discussion around this topic in suggesting that participants should consider applications (NWP, climate and others) that would benefit from coordinated action, possibly dataset generation, between at least two of the "3G"s. Then, details of such actions should be formulated in a SMART way (Specific, Measurable, Achievable, Relevant, Time-bound).

The Observations for Climate Model Intercomparison (obs4MIPs) activity[8], driven by the need of the climate modelling community for gridded, well-documented observation-based climate datasets under WCRP auspices, may have an interest in a GNSS-RO-based or a combined "2G/3G" dataset. Datasets available in obs4MIPs adhere to the CF metadata standard and the netCDF file format.

ACTION 3G-1: Explore with the climate modelling community (obs4MIPs managers, e.g. Robert Ferraro) their interest in a RO-based or combined "2/3G" dataset.
Who: T. Mannucci
By when: 31 Aug 2014

S. Healy highlighted how a single GNSS-RO climatological dataset may be used for model validation of climatologies and variability (based on zonal means; monthly means). He highlighted how RO and GRUAN are key to defining the tropopause region at vertical resolution sufficient to discern e.g., tropospheric warming from stratospheric cooling and complex tropopause cases (overfolding multiple tropopauses). Such comparisons would be useful even for few locations; in cases, reprocessing and analysis of past limb sounder datasets (MIPAS) would also be useful. He also highlighted how this data may also be useful for diagnosing the planetary boundary layer.

ACTION G-2: Bring up at ROM SAF (GNSS-RO) workshop interest in a potential RO-community-based climatological dataset for model validation and variability studies by the broader climate community.
Who: S. Healy, G. Kirchengast, A. von Engeln
By when: 30 Jun 2014

[8] https://www.earthsystemcog.org/projects/obs4mips/

ACTION 3G-2: Look into tropopause and planetary boundary layer comparisons between GRUAN and GNSS-RO datasets. Bring up this idea at the upcoming ROM SAF (GNSS-RO) workshop and report back on interest, and potential participants, with timeline.
Who: S. Healy
By when: 30 Jun 2014

J. Eyre raised that the observational datasets (O-B) underlying a reanalysis were under-used, although these datasets provided a good reference for comparisons. O-B datasets are used as part of the current ERA-CLIM2 project and made available publicly for non-commercial use.

The group recommended to explore planned and potential activities for exploiting (O-B) statistics from the ECMWF Reanalyses, including GNSS-RO and radiosondes, to improve characterisation of observation uncertainties. This is an existing action on the Working Group GRUAN[9].

P. Thorne noted that the "3Gs" could be serving as a monitoring tool for the performance of the remaining radiosonde network, especially GUAN. Since WMO through WIGOS are planning to establish an observation monitoring function, the "3G"s could clearly contribute to this and the envisaged GUAN monitoring centre. NOAA are undertaking some of this monitoring within their NPROVS system capabilities.

Some "3G" datasets should also be created for independent validation, e.g., of satellite instruments, or of radiative transfer models (spectroscopy). The latter should focus on the water vapour continuum, although substantial challenges are recognized in achieving the required accuracy of reference measurements. Such activities should be coordinated as appropriate with the International TOVS Working Group (ITWG) sub-group on Radiative transfer and surface property modelling, and the CEOS Working Group on Calibration/Validation (WGCV).

RECOMMENDATION 3G-3: Investigate the value of GRUAN and GNSS-RO profiles for studying uncertainties of radiative transfer models and spectroscopic databases. Consider working with the ITWG and CEOS WGCV (K. Thome) as appropriate.
Potential contributors: X. Calbet, M. Matricardi, G. Kirchengast, J. Fischer, N. Jacquinet

H. Vömel suggested to better constrain long-term upper-air climate datasets using the "3G"s and have the "3G"s help in change management of individual observing systems (e.g., when transitioning in GRUAN from one radiosonde type to another). Sounders and GNSS-RO could then help as a "travelling standard" for GRUAN, for example.

A discussion followed on benefits of generating a merged best estimate of the profiles at GRUAN sites (such as Site Atmospheric State Best Estimates (SASBEs)), supplemented with GNSS-RO profiles, with associated consistent uncertainties. Although many application areas may not use the merged product, many could benefit from the improved understanding of the uncertainty of each data source. The group agreed that application areas could be consulted for such an activity, e.g. through a user survey.

The group then discussed in detail how to better characterize microwave sounders using the "3G"s:

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[9] GCOS (2014): Report of the sixth GCOS Reference Upper-Air Network (GRUAN) Implementation-Coordination Meeting (GRUAN ICM-6), April 2014, http://www.wmo.int/pages/prog/gcos/Publications/gcos-180.pdf

General remarks:
Satellite-based microwave profilers could be substantially better characterised through collaboration with the 3Gs. Microwave data are of high value to NWP and climate but to date GSICS has only considered including MW instruments mainly by SNO. GRUAN and GNSS-RO could help in validating SNO-based FCDRs of MW sounders at lower latitudes by comparisons with forward-modelled GRUAN and GNSS-RO composite profiles. This would be valuable even if done at a few locations only.

It was also noted that inter-comparisons of microwave sounders can also be done by double differencing using NWP model output.

Microwave sounders - specific to merging MSU/AMSU datasets:
G. Bodeker highlighted how a MSU/AMSU merge could be characterized by GNSS-RO. If different segments of the atmosphere are analysed through time then understanding of how the differing integral matters is needed.

Climate monitoring is another application where GNSS-RO (and GRUAN) can provide value, e.g. in providing independent comparison to MSU time series and not just at the times of overlap but all along the time series. Even subtle changes to radiances result in a different location in the profile where the radiance originates. This affects the detection of vertical gradients in pressure, temperature and relative humidity (PTU) due to climate change. This could be shown by looking at the MSU2/AMSU5 MSU4/AMSU9 series using GNSS-RO (and possibly GRUAN) as a demonstrator, and include the GSICS microwave SNOs.

Microwave and IR:
An anchor observation is needed for radiative bias correction for stratospheric channels of AMSU and SSU/3. It was queried whether the high channels on the IR sounders can be used for this purpose? This would generally require a combination of microwave and infrared instruments, to generate pseudo channels with the same weighting functions. This is not something currently being addressed by GSICS.

J. Dykema suggested the use of GRUAN, GNSS-RO, and RTM combined to validate radiances from microwave sounders (and GSICS products derived from them), and to investigate potential biases. In doing so, site estimates over a couple of ARM sites could be established.

ACTION 3G-4: GRUAN and GNSSRO should engage with the GSICS Microwave sub-group to define an activity on inter-comparison of MW instruments especially in areas with no SNOs to test for latitude and day /night dependencies.
Who: T. Hewison, J. Dykema, T. Reale
By when: 31 Dec 2014

6.2 MEASUREMENT UNCERTAINTY ESTIMATION AND TERMINOLOGY

H. Vömel facilitated the discussion around this topic. He advocated the use of common terminology to describe geophysical parameters (e.g., “relative humidity”), to express measurement uncertainty, and to have traceability in processing and operating practices.

The discussion was structured around five topics:
1. expression of uncertainty for each of the “3G”s;
2. traceability practices;
3. minimizing uncertainty;
4. change management;

5. other principles and practices that the "G"s could adopt.

1. Uncertainty expresses the level of confidence in an observation

A GRUAN requirement is to specify the uncertainty for every data point. Is this common practice for satellite data, and if so, in what form and terminology is it expressed and documented?

T. Hewison explained the approach adopted in current GSICS products, which follow the Guide for the Uncertainty in Measurement (GUM; as recommended by QA4EO). GSICS products include random components dynamically estimated from the statistics used to generate the products. These are supplemented by a document containing a full error analysis by considering all processes that can introduce random and systematic components of the uncertainty based on case studies. Users can combine these as appropriate to their particular application.

G. Kirchengast explained that no explicit uncertainties are provided in GNSS-RO profile data files. Random, systematic and sampling errors are being identified. Uncertainty modelling is being published. It is planned to replace the currently empirically-estimated uncertainties by estimated systematic uncertainty and operator-specific uncertainties by 2016, using the GUM as reference.

J. Eyre noted that random errors in satellite observations are mostly due to radiometric noise and, to a lesser extent, due to spectral response function variations. There are errors introduced in forward modelling (systematic in the case of spectroscopic uncertainty), and representativeness errors due to sampling and collocation mismatches - both horizontally and vertically (can be dominant for water vapour); there are random and systematic contributions to this error. Systematic errors that vary rapidly in time (e.g., calibration errors around an orbit) are particularly hard to characterize.

2. Traceability: How should it be defined, how far can it be taken, what would be the benefits?

Regarding the meaning of traceability (SI-traceable? Unbroken chain?), the WMO CIMO Guide[10] states:

"Traceability: A property of the result of a measurement or the value of a standard whereby it can be related to stated references, usually national or international standards, through an unbroken chain of comparisons all having stated uncertainties.

Metrological traceability: A property of a measurement result whereby the result can be related to a reference through a documented unbroken chain of calibrations, each contributing to the measurement uncertainty."

Hence SI-traceability is an add-on, but not a requirement according to the WMO CIMO Guide. Regarding microwave imager measurements, this is confirmed by findings from a WMO-BIPM 2010 workshop[11]:

"Given the challenges of 'whole dish calibration on-orbit', the group cannot see a near-term path to fully SI traceable observations from microwave imagers, either at the Brightness Temperature or Environmental Data Product levels. In addition, the radiometric uncertainties achievable using current standards in National Metrology Institutes (NMIs) in-lab are at the

[10] http://library.wmo.int/pmb_ged/wmo_8_en-2012.pdf
[11] http://www.bipm.org/utils/common/pdf/rapportBIPM/2010/08.pdf

same level as required from satellite sensors on-orbit. … strong support for reference in-situ observations e.g. sondes, buoys, for example the GRUAN network."

S. Bojinski and B. Bojkov stressed that traceability should be pursued as a principle within reason, i.e., fit for purpose, and not as an end in itself.

B. Bojkov described the resources to support cal/val for ESA current and past missions, with the goal to provide an uncertainty estimate for each sensor and algorithm (including correlation structure where possible). Independent, high-quality and well-characterized datasets are needed for this purpose. Funding for ground-based campaigns is required for a range of sensors. New approaches to building measurement networks are being explored (e.g., portable radiometers on ships, spectral radiometers). The next generation of scientists needs to be entrained in these activities. The potential value of the Google Loon project for calibration was mentioned.

S. Healy stressed that assimilation systems require error covariance matrices in observation space (such as radiances, bending angles). Participants emphasized the value of providing uncertainty estimates along with the datasets themselves.

J. Eyre noted that the most stringent test for uncertainty often came from the application communities, or from campaigns and laboratory measurements. Validation of observations should be done against requirements, but also against expected error models.

P. Thorne noted two goals: generate consistent uncertainties in each of the "3G"s; undertake a range of comparisons in (radiance, pTu, bending angle)-space. This would require characterisation of the "sigma term" (representativeness errors), and also require incorporating information on correlated and partially correlated uncertainty terms, which need to be provided with the uncertainty estimate.

S. Healy offered to provide software to convert pTu data and propagate uncertainties into bending angle space.

A. von Engeln said that the GNSS-RO community had reviewed potential sources of uncertainty in the processing of GNSS-RO bending angle observations and retrievals derived from them. These can vary slightly from one bending angle observation to another, but the uncertainties in the retrieved profiles are non-linearly related to the bending angle uncertainties. This has not been a focus so far since GNSS-RO has been considered as being very accurate.

ACTION G-3: Raise awareness within the GNSS-RO community to make uncertainty calculations publicly reviewable, including identifying where background information comes into processing, where traceability chain may be broken.
Who: G. Kirchengast, A. von Engeln
By when: 30 April 2015

A. Dall'Antonia noted that the expression and analysis of uncertainty in upper-air observations could be addressed as a training subject for NMSs, and that best practices should be developed.

The UK National Physical Laboratory have obtained EU funding to provide a training course on Uncertainties for Earth Observation. The first of these will run in early July 2014, but is already fully booked. Interested parties are encouraged to register for future courses, which may ensure NPL can receive further funding.

X. Calbet said that IASI was characterised on-ground pre-launch. Manufacturers provide an observation error covariance matrix for radiances (level 1). These are checked in orbit by monitoring radiometric noise. Retrievals are monitored against a reference measurement (currently ECMWF profiles). Biases are adjusted to ensure consistent match.

GRUAN provides estimates of random uncertainties and residual uncertainty after removal of systematic biases at one-second vertical resolution, together with uncertainty due to the smoothing and time-lag.

S. Bojinski noted that within the ESA Climate Change Initiative[12], an overview of current practices, and recommendations were developed on the expression of uncertainty in Earth observation climate data records.

ACTION 3G-5: Compile current best practices in using uncertainty terminology in the "3G" and NWP communities, taking into account e.g. definitions in the GUM and VIM (Guide to the Expression of Uncertainty in Measurement; International Vocabulary of Metrology[13])
Who: G. Bodeker, with input from H. Vömel, T. Hewison, S. Bojinski
By when: 31 Aug 2014

3. How can one system help the other minimize their uncertainty? Verify their operating procedures?

Comparative studies among the "3G"s would be needed.

4. How can one system help the other do change management? (New satellite instruments, new radiosondes)

J. Eyre remarked that change management was generally now very good for most satellite operators, who give several weeks' notice of foreseen changes.

The "3G"s jointly can be particularly effective in helping monitor changes in any one G, since only one system typically changes at a time.

5. Are you able to promote principles we agree on here within your community that is not present here?

The WMO RRR states uncertainties that represent one standard deviation (1-σ) whereas CIMO requires that uncertainties be stated as 2-σ..H. Vömel added there was no consistent use of confidence intervals when expressing errors (1-σ vs 2-σ). Application communities also tend to use 1-σ.

ACTION G-4: Raise the issue of the diverging use in different communities of expressing uncertainty (1-σ vs 2-σ) with CIMO.
Who: CIMO representative on WG GRUAN, with G. Bodeker to ensure follow-up.
By when: 30 September 2014

12 http://www.esa-sst-cci.org/sites/default/files/Documents/public/SST_cci%20UCR%20Issue%203%20(2013%2012%2004).pdf
13 http://www.bipm.org/en/publications/guides/

6.3 OBSERVING SYSTEM COORDINATION AND COLLOCATION

X. Calbet facilitated the discussion of this topic. He suggested considering a methodology for assessing collocation errors vs observation errors, within time intervals of 30-60 minutes, and spatial intervals of 50-100 km. Work by B. Sun, N. Pougatchev should be used. The sensitivity of the number of samples required vs the standard error should be enquired. He noted that IASI-based collocations are being analyzed over the ARM Manus Island site using GRUAN processed radiosonde profiles.

B. Knutsen has analysed the collocation criteria and uncertainties from radiosonde comparisons. Systematic biases can be introduced when using relaxed time collocation windows to compare sun-synchronous satellite instruments with radiosondes (or anything else). This should be analysed.

The discussion highlighted the need for interpolation, which is likely best done by an NWP model, which can be used as a transfer standard for collocation using double differencing; the only caveat is possible systematic errors introduced by the model, such as diurnal effects.

ACTION 3G-6: Investigate providing “3G” community with a regular field (PTU) of NWP model data in the (4D) vicinity of all GRUAN stations.
Who: S. Healy, with input from X. Calbet, T. Reale, G. Kirchengast
By when: 31 Dec 2014

It was suggested that the first step in addressing many aspects of the collocation problem is to collect as much data as possible around the collocations, which can later be analysed. This approach is currently being adopted by the NOAA-STAR Product Validation System (NPROVS).

Evaluating uncertainty in collocations can be done statistically, by analysing large collections of collocations - or on a case-study basis, including analysis of NWP model fields to estimate the variability in the vicinity of the collocation - or by comparing adjacent observation (e.g. radiosondes separated by one hour). When taking dedicated launches in support of polar orbiter sensor characterisation, schedules should allow for a reasonable chance of a nearby GNSS-RO measurement.

Because the GNSS-RO GRAS instrument, AMSU and IASI are all operated on Metop satellites, there are many occultations that could be roughly collocated; however their respective viewing geometry results in not very close collocations.

ACTION G-5: Consider viability of processing GRAS temperature profile retrievals from ROMSAF (S. Healy) into NPROVS / NPROVS+.
Who: T. Reale
By when: 31 Aug 2014

G. Kirchengast noted that TLE + SGP4 could propagate orbits out to 2 weeks to predict occultations within a 100x100km box and 15min accuracy, plus the likelihood of getting a usable observation from each occultation.

ACTION 3G-7: Investigate ability to predict probability of RO observations days to weeks in advance to inform targeted dedicated launches in support of polar orbiter characterisation by radiosondes at GRUAN sites. Report results to T. Reale.
Who: A. von Engeln and G. Kirchengast
By when: 30 Sep 2014

ACTION 3G-8: Investigate feasibility of generating database of collocations between GRAS and sounders on Metop - perhaps through Visiting Scientist.
Who: A. von Engeln
By when: 30 Sep 2014

ACTION 3G-9: Coordinate an inter-comparison of methods to estimate collocation (representation) uncertainties (include double-differencing as a method), based on the analysis of:

- NWP fields to determine uncertainties
    - in hyperspectral IR sounders (S. Healy to provide fields, X. Calbet to analyse)
    - in GNSS-RO vs GRUAN, accounting for trajectories and resolution kernels (G. Kirchengast)
- Geostationary imager radiances (T. Hewison/GSICS)
- CrIS/AIRS/IASI-Radiosonde collocation statistics (X. Calbet, T. Reale)
- GNSS-RO (G. Bodeker)
- Site-atmospheric-state best estimates (J. Dykema)
- GRUAN radiosonde (H. Vömel)

in geophysical variable space, bending angle, and radiance-space for Manus, SGP, Lindenberg, since July 2013.
Who: X. Calbet
By when: 30 Sep 2014 (Plan); 31 Mar 2015 (First results); Sep 2015 (Share dataset for training etc.)

S. Bojinski noted that a subset of the generated collocation dataset could be instructive for training and education purposes.

ACTION 3G-10: Investigate feasibility of issuing this study scoped in Action 3G-9 as training dataset.
Who: T. Reale, with support from X. Calbet
By when: 31 Mar 2015.

Comparisons of radiosondes with IR sounders usually focus on clear sky situations. However, residual cloud introduces a cold-tail in the distribution of radiance differences. This can be overcome by using the mode of the distribution, instead of the mean. Comparison methodology could be developed for microwave first, as this problem is easier to tackle (no sensitivity to clouds).

There was some debate on the value of dedicated radiosonde launches, near satellite overpass times. The group recognised the prime benefit of these launches is to better characterise the retrieved (level 2) products (and their uncertainties - particularly the systematic components) and for climate users. The radiances can be well monitored through routine comparisons with NWP models - at least for microwave and infrared sounders.
It was argued that the added value of dedicated launches should be demonstrated through studies, such as suggested above.

ACTION 3G-11: Scope a study (using RO, GRUAN and NWP) to investigate systematic differences from background of all types of radiosondes over a limited area. This may be becoming a limiting factor in the use of these data in NWP in areas with high density of upper-air data (over Europe, N America). Funding could be available via the ROMSAF visiting scientist.
Who: J. Eyre and S. Healy
By when: 31 Dec 2014

On the matter of collocation databases, T. Reale clarified that the NOAA-STAR database contained all the IR sounder fields of view within 500km of each GRUAN site - both the "calibrated radiances" and the cloud-cleared radiances will be available. The single closest field of regard defines the centre of the area.

CFH launches at GRUAN sites are infrequent but provide a full WV column up to balloon burst level. It was identified that more CFH launches may be needed to continue to provide stratospheric humidity information in anticipation of the forthcoming loss of MLS.

ACTION 3G-12: Contact L. Strow to investigate the potential opportunity of using CFH measurements in the stratosphere, to inform understanding of the spectroscopy of the IR channels sensitive to stratospheric water vapour, by comparing CFH sonde profiles (loosely) collocated with IASI overpasses.
Who: X. Calbet
By: 1 Sep 2014

6.4 PARTICIPATION AND OUTREACH

S. Bojinski facilitated the discussion of this topic, aiming at better awareness and broader participation of WMO Members in operating and using the "3G"s. The value of high-quality upper-air observations for weather and climate applications should be better communicated and understood, including the critical importance of providing uncertainty estimates with the data. In addition, benefits of the "3G"s and their synergy to the wider global upper-air observing system should be highlighted.

He structured the discussion along six items:

1. Are there sufficient fora for interaction?

The existing "3G" coordination mechanisms should be used for interaction among the "3G"s. A follow-up "3G"-type workshop should be contingent on results achieved, and focus on discussing these results at a scientific and technical level.

ACTION 3G-13: Explore possibility to have a cross-representation of each of the "G"s in the coordination mechanisms of the other "2G"s
Who: Meeting chairs (P. Thorne, T. Hewison, T. Mannucci)
By when: 31 Aug 2014

2. Are R&D agencies and the CEOS WGCV sufficiently connected to the "3G"s?

There are good links of GRUAN, GSICS and GNSS-RO to R&D agencies. An Action regarding collaboration with CEOS WGCV has been noted.

3. Training and capacity development

Determination, expression, and application of uncertainty information was identified as a major topic for training and capacity development. Such training would have to be application-specific. Material may be available through the NPL training workshop, and the "collocation dataset" detailed in the previous section.

Assistance is generally required in improving the overall observing system run by each country. These should be considered national contributions to the global commons. The example of Brazil showed that the benefit of GRUAN to NWP and climate research would have to be demonstrated. However, the direct benefit of GRUAN data on NWP is likely to be marginal; engaging more countries in the GRUAN enterprise must be framed in a different way: it means that these countries, if hosting a GRUAN site, are co-owners of a global effort, make the overall observing system more robust, and build capacity of their personnel in science and operations of observing systems. Monitoring and understanding climate change should be used as a key driver for operating GRUAN.

4. Countries of particular importance

Australia, China, Japan, South Africa, Brazil, and Indonesia were all targeted to participate in the workshop. These countries are very important contributors to the GOS including in tropical and sub-tropical regions, and they participate (Japan, China, Australia) or could participate in GRUAN. In terms of GNSS-RO missions, contributions are made by India, Brazil, Argentina, China, Russia, and Australia. In GSICS, China, Japan, and India are now active members, in addition to partners from Europe and North America.

5. Outreach to application communities

This should be done through user-friendly access and documentation of “3G” datasets, including uncertainties. Each “3G” should have even stronger links to the applications communities.

It was suggested to have the list of Actions from the workshop vetted by applications communities, and prioritized.

Participants noted that GRUAN radiosondes are not expected to make a significant improvement in NWP directly through assimilation. However, GRUAN should improve NWP through improving the overall quality of the radiosonde network. GRUAN needs to continue to interact with CIMO and participate in radiosonde intercomparisons. GRUAN also needs to interact with analysis centres to point out what are the recurring issues in radiosonde operations. There is currently no clear path how GRUAN can support activities to address operational issues in the overall radiosonde network.

6. Means of outreach:

Publication of the workshop report as a WMO WIGOS publication; a meeting summary should be featured in the WMO bulletin, and in the GSICS quarterly newsletter. The recommended Actions should be discussed in the respective “3G” coordination mechanisms. In WIGOS guidance material, provisions should be made to facilitate the coordination of different observation (and application) communities, such as through the present workshop. A draft WIGOS manual was noted to be available and open for comments by the “3G” communities.

ACTION G-6: WIGOS Project Office to invite the GRUAN community to comment on the draft WIGOS manual
Who: WMO WIGOS Project Office
By when: 31 May 2014, with response by 30 Jun 2014

ACTION G-7: Publish a short meeting summary in the GSICS quarterly newsletter
Who: T. Hewison, S. Bojinski
By when: 31 Aug 2014

A GRUAN side event planned during the 2015 World Meteorological Congress could also have a presentation on collaboration with the satellite community.

7. SUMMARY OF ACTIONS AND RECOMMENDATIONS

Recommendations including two or more of the "3G"s

Arising from 6.1

ACTION 3G-1: Explore with climate modelling community (obs4MIPs managers, e.g. Robert Ferraro) their interest in a RO-based or combined "2/3G" dataset.
Who: T. Mannucci,
By when: 31 Aug 2014

ACTION 3G-2: Look into tropopause and planetary boundary layer comparisons between GRUAN and GNSS-RO datasets. Bring up this idea at the upcoming ROM SAF (GNSS-RO) workshop and report back on interest, and potential participants, with timeline.
Who: S. Healy
By when: 30 Jun 2014

RECOMMENDATION 3G-3: Investigate the value of GRUAN and GNSS-RO profiles for studying uncertainties of radiative transfer models and spectroscopic databases. Consider working with the ITWG and CEOS WGCV (K. Thome) as appropriate.
Potential contributors: X. Calbet, M. Matricardi, G. Kirchengast, J. Fischer, N. Jacquinet

ACTION 3G-4: GRUAN and GNSSRO should engage with the GSICS Microwave sub-group to define an activity on inter-comparison of MW instruments especially in areas with no SNOs to test for latitude and day /night dependencies
Who: T. Hewison, J. Dykema, T. Reale
By when: 31 Dec 2014

Arising from 6.2

ACTION 3G-5: Compile current best practices in using uncertainty terminology in the "3G" and NWP communities, taking into account e.g. definitions in the GUM and VIM (Guide to the Expression of Uncertainty in Measurement; International Vocabulary of Metrology[14])
Who: G. Bodeker, with input from H. Vömel, T. Hewison, S. Bojinski
By when: 31 Aug 2014

Arising from 6.3

ACTION 3G-6: Investigate providing "3G" community with a regular field (PTU) of NWP model data in the (4D) vicinity of all GRUAN stations.
Who: S. Healy, with input from X. Calbet, T. Reale, G. Kirchengast
By when: 31 Dec 2014

ACTION 3G-7: Investigate ability to predict probability of RO observations days to weeks in advance to inform targeted dedicated launches in support of polar orbiter characterisation by radiosondes at GRUAN sites. Report results to T. Reale.
Who: A. von Engeln and G. Kirchengast
By when: 30 Sep 2014

[14] http://www.bipm.org/en/publications/guides/

ACTION 3G-8: Investigate feasibility of generating database of collocations between GRAS and sounders on Metop - perhaps through Visiting Scientist.
Who: A. von Engeln
By when: 30 Sep 2014

ACTION 3G-9: Coordinate an inter-comparison of methods to estimate collocation (representation) uncertainties (include double-differencing as a method), based on the analysis of:

- NWP fields to determine uncertainties
  - in hyperspectral IR sounders (S. Healy to provide fields, X. Calbet to analyse)
  - in GNSS-RO vs GRUAN, accounting for trajectories and resolution kernels (G. Kirchengast)
- Geostationary imager radiances (T. Hewison/GSICS)
- CrIS/AIRS/IASI-Radiosonde collocation statistics (X. Calbet, T. Reale)
- GNSS-RO (G. Bodeker)
- Site-atmospheric-state best estimates (J. Dykema)
- GRUAN radiosonde (H. Vömel)

in geophysical variable space, bending angle, and radiance-space for Manus, SGP, Lindenberg, since July 2013.

Who: X. Calbet
By when: 30 Sep 2014 (Plan); 31 Mar 2015 (First results); Sep 2015 (Share dataset for training etc.)

ACTION 3G-10: Investigate feasibility of issuing the study scoped in Action 3G-9 as a training dataset.
Who: T. Reale, with support from X. Calbet
By when: 31 Mar 2015.

ACTION 3G-11: Scope a study (using RO, GRUAN and NWP) to investigate systematic differences from background of all types of radiosondes over a limited area. This is becoming a limiting factor in the use of these data in NWP in areas with high density of upper-air data (over Europe, N America). Funding could be available via the ROMSAF visiting scientist.
Who: J. Eyre and S. Healy
By when: 31 Dec 2014

ACTION 3G-12: Contact L. Strow to investigate the potential opportunity of using CFH measurements in the stratosphere, to inform understanding of the spectroscopy of the IR channels sensitive to stratospheric water vapour, by comparing CFH sonde profiles (loosely) collocated with IASI overpasses.
Who: X. Calbet
By: 1 Sep 2014

Arising from 6.4

ACTION 3G-13: Explore possibility to have a cross-representation of each of the “G”s in the coordination mechanisms of the other “2G”s
Who: Meeting chairs (P. Thorne, T. Hewison, T. Mannucci)
By when: 31 Aug 2014

Recommendations that apply to a single "G", or are of general nature

Arising from 5.1

ACTION G-1: GRUAN Lead Centre to inform the WMO IPET-OSDE (chair: J. Eyre) and the Task Team on WIGOS Metadata (WMO contact: Luis Nunes, lfnunes@wmo.int) about specifics of metadata for radiosondes.
Who: GRUAN Lead Centre
By when: 31 August 2014

Arising from 6.1

ACTION G-2: Bring up at ROM SAF (GNSS-RO) workshop interest in a potential RO-community-based climatological dataset for model validation and variability studies by the broader climate community.
Who: S. Healy, G. Kirchengast, A. von Engeln
By when: 30 Jun 2014

Arising from 6.2

ACTION G-3: Raise awareness within the GNSS-RO community to make uncertainty calculations publicly reviewable, including identifying where background information comes into processing, where traceability chain may be broken.
Who: G. Kirchengast, A. von Engeln
By when: 30 April 2015

ACTION G-4: Raise the issue of the diverging use in different communities of expressing uncertainty (1-σ vs 2-σ) with CIMO.
Who: CIMO representative on WG GRUAN, with G. Bodeker to ensure follow-up.
By when: 30 September 2014

Arising from 6.3

ACTION G-5: Consider viability of processing GRAS temperature profile retrievals from ROMSAF (S. Healy) into NPROVS / NPROVS+.
Who: T. Reale
By when: 31 Aug 2014

Arising from 6.4

ACTION G-6: WIGOS Project Office to invite the GRUAN community to comment on the draft WIGOS manual
Who: WMO WIGOS Project Office
By when: 31 May 2014, with response by 30 Jun 2014

ACTION G-7: Publish a short meeting summary in the GSICS quarterly newsletter
Who: T. Hewison, S. Bojinski
By when: 31 Aug 2014

APPENDIX A: PERSONAL POSITION STATEMENTS (SUMMARY)

Invitees were asked to complete written statements regarding the following questions

1. Name
2. Affiliation
3. What do you expect from this workshop, and in which area can you contribute to this end?
4. What is your view on the following issues:
   - 4.1 What is your vision for an optimized integrated observing system for upper-atmosphere variables?
   - 4.2 What are the main steps needed to achieve this vision?
   - 4.3 Which are the main deficiencies in the current system, including gaps in infrastructure, expertise, and training?
   - 4.4 Which practical steps could WMO and co-sponsored programmes (such as GCOS, WCRP) take to address these issues?
   - 4.5.1 How can high-quality ground-based atmospheric sounding such as by GRUAN support needs of the satellite community, now and in the future?
   - 4.6 How can the satellite community support needs of the ground-based atmospheric upper-air sounding community such as GRUAN, now and in the future?
5. What are your key recommendations regarding the workshop objectives[15]:
   - The most urgent actions that should be taken by the international community over the next 3 years (based on current resources):
   - The most urgent actions that should be taken by the international community over the next 10 years (assuming additional resources):

The following individuals provided feedback:

1. Greg Bodeker, Bodeker Scientific and WG GRUAN co-chair
2. Bojan Bojkov, European Space Agency
3. Xavier Calbet, EUMETSAT
4. John Dykema, Harvard University
5. John Eyre, UK Met Office and Chair of CBS IPET-OSDE
6. Masatomo Fujiwara (Faculty of Environmental Earth Science, Hokkaido University, Japan; member of WG GRUAN)
7. Sean Healy, ECMWF
8. Tim Hewison, EUMETSAT and Chair of GSICS Research Working Group
9. Gottfried Kirchengast, Wegener Center for Climate and Global Change, University of Graz
10. Martine de Mazière, Belgian Institute for Space Aeronomy
11. Anthony Mannucci, NASA Jet Propulsion Laboratory
12. Tony Reale, NOAA/NESDIS Center for Satellite Applications and Research (STAR)
13. Adrian Simmons, ECMWF
14. Peter Thorne, NERSC
15. Holger Vömel, DWD Meteorological Observatory Lindenberg and GRUAN Lead Centre
16. Axel von Engeln, EUMETSAT, with input from Rob Roebeling, Roger Huckle, Viju Oommen-John, EUMETSAT

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[15] Regarding: an optimized, interoperable upper-air observing system (in-situ, satellites), including issues such as: measurement uncertainty estimation, dataset generation, and data utility

Question 3. What do you expect from this workshop, and in which area can you contribute to this end?

(Bodeker) To define more specifically how GRUAN's operations and data products can, together with GNSSRO, best meet the needs of GSICS. I can contribute by bringing my knowledge of GRUAN's standards of operation to the discussion.

(Bojkov) I expect clear requirements to be formulated for GRUAN by the Space and Modelling communities. As a stakeholder, I plan to formulate my "user requirements".

(Calbet)
I would expect more collaboration between different groups interested in atmospheric assimilation, retrievals, measurements and radiative transfer modelling. A forum or a group performing work on this topic and establishing these links among different communities would be welcome.
I have experience in the comparison of radiosonde measurements with satellite radiances, in which consistency problems between these measurements readily show up. I also have a long experience within these communities to know which can be the relational issues that would be needed for this kind of interactions.

(Dykema)
This workshop is an opportunity to see how metrology (the physics of measurement) and statistical sciences (time series analysis and geospatial statistics) are being viewed and incorporated (or not) as contributors to the global observing system through GRUAN, GSICS, and GNSS/RO. My research has an emphasis in both of these areas and I intend to contribute what is applicable from my own efforts as well as what I am aware of in those fields more generally that can contribute to GRUAN/GSICS/GNSS-RO objectives.

(Eyre)

- I expect the Workshop to achieve greater clarity concerning the way in which GRUAN data can contribute to WIGOS goals and to improving the use of upper air observations in key WMO applications, in particular NWP and Climate Monitoring (including Reanalysis).
- I hope to contribute to the Workshop through my input on how this can be achieved, from the perspectives of both WMO CBS OPAG-IOS and of the operational NWP community.

(Fujiwara) I expect better understanding of the needs for GRUAN from the satellite community and from the science community. I can contribute to this end from the field observation viewpoint and from the radiosonde instrumentation viewpoint. Also, the following comments are made largely as a university teacher.

(Healy)
I would like to get a better understanding of how the future role of GNSS-RO for climate monitoring is viewed in the broader community. The meeting also provides me with an opportunity to understand the GRUAN and GSICS objectives more fully.

My background is in the assimilation of GNSS-RO measurements into NWP systems. The use and value of GNSS-RO measurements in NWP is now firmly established. See for example the recommendations from the WMO Sedona workshop, on the Impact of various observing systems (2012). GNSS-RO is important because it complements the information provided by nadir sounders. This is primarily because 1) it can be assimilated without bias correction, and 2) it has good vertical resolution. The GNSS-RO measurements have generally reduced lower/mid stratospheric temperature biases in both NWP and reanalysis systems.

As with all observation types, GNSS-RO has strengths and weaknesses, and these should be discussed. However, based on the NWP/reanalysis impact, I believe that GNSS-RO measurements will become increasingly important for climate monitoring applications as the time series lengthens. The GNSS-RO time series now extends from 2001. In this meeting, I would like a better understanding of when the GNSS-RO time series will be of sufficient duration to interest the general climate monitoring community.

This workshop provides us with the opportunity to exchange information on the different observing systems. We should be able to explore the strengths and weaknesses of each system objectively. Based on my experience assimilating the GNSS-RO data, I think I am well placed to contribute to this discussion.

(Hewison)

- To identify potential interactions between communities interested in upper air observations, and
- to scope the possible establishment of new forums in which these comparisons could take place in a routine basis.

I hope to be able to contribute to this based on my experience in establishing a system of routine comparisons of satellite observations within GSICS.

(Kirchengast)
The GRUAN, GSICS, and GNSS-RO communities (as relatively broadly represented by the experts around the Table) better informing each other, learning from each other, building better mutual understanding of the capacity (including limitations) of each of these “3G” systems plus of the collective capacity of the joint “3G” system (including more specific clarifications of complementarities and synergies); identifying and discussing past and existing barriers to amongst-”3Gs” cross-community cooperation and likewise discussing steps forward to improved cooperation in future; better understanding the current and prospective future role of the “3Gs” in the wider observing system; effective work towards the workshop objectives, “realistic” recommendations.
I can contribute most in the field of GNSS-RO and climate (but also have some relations to and understanding of the other “3G” systems, and of the wider observing system context, and climate and Earth system science context).

(Mannucci)
Improved coordination of upper-air observation between ground-based, satellite-based and GNSS radio occultation. I can contribute to coordination with GNSS RO observations.

(deMazière)
Better communication between various contributing networks and partners;
Better awareness of each other’s capabilities, experiences, needs;
Enhanced cost-efficiency through collaboration and exchange of existing expertise
My contribution: sharing expertise existing in the Network for Detection of Atmospheric Composition Change (NDACC), and to some extent in the Total Carbon Column Observing Network (TCCON), as to quality control, satellite and model validation, …and as to problems encountered on the way to optimization.

(Reale)
Clarification of overall satellite provider (i.e., NOAA) and GRUAN interaction with respect to sensor vs geophysical profile vs model (NWP, RT …) cross validation including GPSRO as an emerging reference observation (from space) for stratosphere temperature, etc. STAR currently provides a “baseline” collocation dataset compilation, archive and analytic interface

which we propose can contribute as a force multiplier to initiate/expand GRUAN satellite interactivity; referred to as NOAA Products Validation System + (NPROVS+). I anticipate learning more on specific WIGOS principles, practices, status, and seek clarification of specific Satellite / GRUAN interaction hierarchy with respect to sensors, profiles, RT models and uncertainty estimates.

(Simmons)
I do not know what to expect, given the contradictory signals that have been sent out about the workshop. A workshop on Upper-Air Observing System Integration and Application sounds very broad, and the questions you ask below are very general ones. Yet the reference to GRUAN-GSICS-GNSSRO in the title, and the limited range of observing systems presented in section 5 of the agenda makes one think otherwise. Messages issued by some members of the Organizing Committee have been confusing.

(Thorne)
Better coordination of the high quality networks / activities with an interest in aspects of metrological traceability / comparability: the “3G”s. Making sure that these are measurement and analysis programmes that can truly act as a backbone to the entire heterogeneous mix of measurement capabilities of free atmosphere and boundary layer atmospheric properties that exist and will continue to exist long into the future. I can contribute GRUAN expertise.

(Vömel)
Path forward making use of the redundant observations by satellites and radiosondes to improve the observational procedures.
Identify biases and weaknesses in the observations and take steps to either correct them or quantify and document them.
Implement the global observation system such that it will be resilient to long term political changes and tolerant to changes in the instrumentation.

(von Engeln)
- expect better exchange, closer cooperation on upper-air obs. Currently, there is limited routine interaction between e.g. radiosonde and radio occultation, or radio occultation and GSICS.
- contribute with respect to use of radio occultation data, validation, inter-comparison, NWP data use

QUESTION 4. What is your view on the following issues:

Q4.1 What is your vision for an optimized integrated observing system for upper-atmosphere variables?

(Bodeker) One in which information from all available observing systems is used optimally to produce best possible estimates of the essential climate variables of interest. ‘Optimally’ would be driven by all measurements having had any systematic biases corrected for and uncertainty estimates that are traceable to SI-traceable standards. The system would be seamless in that the assimilation system (if that’s what it would be) would know how to treat each new incoming datum given its associated metadata and measurement uncertainty characteristics. The system would be robust against the loss of any one instrument. The system would be ‘integrated’ in that there would be a hierarchy of sub-systems each with characteristics that add value e.g. some sub-systems might cover only a limited temporal or spatial region but would provide high quality data that could be used to detect and correct for systematic biases in more distributed sub-systems. Metadata associated with each datum would be easily obtained. Reprocessing of historical measurements would occur in the light of better understanding of measurement systems and clear version control would be used to manage this reprocessing and flag new improved data products to users.

(Bojkov)
Key to the integrated observing system, particularly with respect to the ground-based measurements (incl.
balloons) are:

- the definition and use of measurement “best practices” across the system
- documented characterization and traceability of the instrumental differences
- easy access to the documentation and the data
- long-term sustainability of the system
- outreach/training on measurements, calibration, data processing

(Calbet)
There are currently three different broad communities related to atmospheric measurements:

- Ground-based sounding atmospheric measurement community. This would be all groups dedicated to atmospheric measurements from the ground. Radiosonde, GRUAN or GNSS groups would be a few examples.
- Numerical Weather Prediction (NWP) and Satellite (Sat) community. This would constitute groups from the space agencies or numerical weather prediction centres. Also included here would be the fast radiative transfer model community, which is sometimes embedded in the above mentioned centres. This community performs assimilation of atmospheric measurements (NWP) or retrievals of atmospheric profiles (Sat).
- Radiative Transfer Model (RTM) community. This would be formed by groups that develop line by line RTMs and compile spectroscopy data that are fed into the line by line RTMs. This community establishes the link, via RTMs, between atmospheric profiles and satellite measurements, conceptually linking together the Sounding, ground-based and the NWP and Sat communities.

The Ground-based sounding community makes routine comparisons between different measurements systems, and particularly, different types of sondes. This has led to huge progresses in understanding the systematic errors that affect these measurements, leading in the end to high quality standard or unbiased atmospheric profiles such as the ones provided by GRUAN.

The Satellite community has the GSICS group which aims at the intercomparison of satellite radiances. This group is relatively new but is showing very promising results in terms of satellite intercalibration with the potential to obtain homogenous climate data records in the future as a result of this work.

The RTM community strives to serve the other communities with high quality spectroscopic data. They occasionally make intercomparisons of different RTMs.

There are many issues within the products provided from these communities. Radiosonde observations have traditionally had significant biases in the humidity measurements, which only relatively recently are being resolved thanks to the above mentioned radiosonde intercomparisons. RTM model radiances seem to vary significantly from one particular spectroscopy database to another one or from version to version. Satellite instruments have traditionally had biases and drifts which need to be accounted for, even though, some instruments, like the infrared hyperspectral sounders (IASI for example is taken as a reference for GSICS), seem to be quite stable.

On top of this, there are groups which bring together the products which these communities generate, such as RTMs, Sat radiances and atmospheric profiles. These are typically NWP assimilation groups or infrared hyperspectral groups, the latter to which I belong. These groups have to somehow make all these products consistent. Typical shortcut solutions applied by these groups are the use of radiance bias corrections and the inflation, one way or another, of the radiance measurement noise to account for all these deficiencies. Alternatively, one would want to identify the particular problems arising in each one of these communities making them consistent to account for and potentially solve them. A good example, within the Ground-based sounding community only is the natural evolution that has occurred after radiosonde intercomparisons were made, such as the humidity bias corrections introduced for the RS92 sondes or the invention of new generation sondes which seem to not have humidity bias problems (RS41).

More collaboration between these communities would be desirable. The effort of bringing all these products together and trying to make them consistent would potentially benefit all the communities and potentially highlight some issues that would otherwise not be detected by these communities independently. The synergistic use of the products from all three communities can potentially bring benefits to all.

(Dykema)

Realistic, well-founded uncertainty estimates for a subset of measurements that can be propagated through to uncertainty estimates for the full observing systems. Using radiative transfer to ensure consistency between uncertainty estimates for in-situ/ground-based remote sensing atmospheric profiles and satellite measurements (both passive and active).

(Eyre)

It is described by the WMO "Vision for the GOS in 2025":
http://www.wmo.int/pages/prog/www/OSY/gos-vision.html

(Fujiwara)

There will be no fixed observing system. Continuous technical development and research activity are essential for better understanding of the Earth atmosphere and of the instrument technologies. We need to keep encouraging new researchers and new students to enter this field of science.

(Healy)

The Global Observing System (GOS) must meet the future needs of climate monitoring and weather forecasting. The composition of the future GOS should reflect updated user requirements, including evaluation of where these requirements are met by established measurement techniques, and where new measurement technologies need to emerge.
The satellite component of the GOS is composed of a diverse set of observing systems, each with particular strengths, so optimizing the future GOS requires finding a reasonable balance of these distinct measurement types. The value of observations cannot be assessed in isolation, because it is related to how the observations complement the other components of the GOS. The composition of the future GOS should be based on a clear understanding of the error characteristics, information content and forecast impact of each observation type.

(Hewison)

A network of diverse observing systems, each with particular strengths and limitations, and each with well characterized biases and uncertainties to allow optimal integration.

(Kirchengast)

The "3Gs" joint system makes from below (GRUAN), from within (GNSS-RO), and from above (GSICS) an essential and unique reference observing system contribution to accurate, consistent, and long-term stable monitoring of [thermodynamic] ECVs in the atmosphere (focus troposphere and stratosphere). It's key complementary systems for enabling benchmark-quality monitoring of a full set of atmospheric ECVs [and the inter-connected TOA radiation balance] are to come from LEO-crosslink and LEO-ground active microwave and infrared-laser sounding (for GHGs and wind) and [dedicated] satellite-based passive high-accuracy GHG sounding (for within the atmosphere), and from high-accuracy SW and LW radiation monitoring (for TOA).

(Mannucci)
My vision is that the three respective communities of the workshop, GRUAN, satellite sounders and GNSS-RO, can easily share their observations with those of the other two systems, so that meaningful comparison activities can take place on a routine basis. Such comparisons will improve the utility of all three systems and serve the community.

(deMazière)
Present situation:

- The present system has grown bottom-up, driven by different communities, like the meteorological community, the air-quality community linked to the national reporting agencies, the atmospheric research community, etc – and the communication between them has not always been optimal.
- Also, it is difficult to find data when you need them, because they are dispersed, sitting at various places, sometimes hidden and/or protected.
- Different formats, data quality standards, degrees of documentation live next to each other.

Thus, to optimize the system, we need

- Common understanding of requirements as to data quality, traceability and documentation,
- harmonisation as to data quality and documentation,
- and as to data archiving and dissemination systems,
- clearly identified and limited number of data access points,
- open access data,
- elimination of too much redundancy and filling of gaps, i.e., global network design, taking into account the complementarity with the satellite component, and the means to realize it.
  (Some diversity in the observing system is needed, and also some redundancy is useful for quality verification, but this should be limited to a degree that is justifiable and sustainable; important gaps need to be closed).

(Reale)
Optimized integrated global observing system could be interpreted as a state in which respective sets of observations contribute information that are consistent with the other "like" observations such that when integrated produce an improved, traceable (uncertainty) measurement of some variable. For example on a local scale, i.e., a GRUAN site, ground observations (i.e. RAOB, Lidar, etc.) are integrated to produce a site state estimate that is perhaps better suited than any given individual platform for climate and/or weather applications, or satellite validation; in the former the satellite is included in the integration but not in the latter so each application has unique recipe. These recipes have to be demonstrated and verified at each site, a lot of work both from the scheduling and actual verification approach. The site state estimate provides an integrated observation somewhat like a GOS would provide a global state estimate, except now individual global data, i.e. from satellites (polar, emerging global GOES, etc. , replace lidar, RAOB etc.). Still have to go through the same process of validating each component of the integrated system, a lot of work! Ultimately, reference observations (i.e. GRUAN) and respective uncertainty (total uncertainty budget) serve as the pillars for monitoring/validating/tuning (homogenization …) including for the respective models (weather, climate, RT) assimilating all this stuff.

(Simmons)
What do you mean by this question? What does “integrated” mean in this context? The upper-air observing “system” should not be considered in isolation of the observations made for other parts of the climate system. Even in the narrower atmospheric context one must include surface observation. My understanding was that the “I” in WIGOS referred to a much broader type of integration than is suggested by use of the word here. This question should have been more focused on the roles of GRUAN, GSICS and GNSSRO.

(Thorne)
One which actually consists of a true system of systems capability with the highest tier to which the “3G”s and similar measurement / analysis capability belong. Where these networks and capabilities assure metrological traceability and comparability for the observing capabilities as a whole and hence provide confidence in trends for the next 50 years to properly inform decision making and provide support for emerging climate services.

(Vömel)
Observations are done with the best commercially available instrumentation. Frequent intercomparisons at selected sites are used to continuously evaluate the quality of the observations. Findings are used to correct deficiencies at these selected sites as well as at the larger network.

(von Engeln)
- it should always be a combination of satellites and local information. Radio occultation and some other satellite instruments have no bias for different locations, thus they are good at bias removal. Sondes are very good to provide high resolution data, in particular also on water vapour throughout the troposphere.
- it should be encouraged to establish super-sites that operate measurements for several certified reference networks (e.g. GRUAN, BSRN, and AERONET);
- it should be encouraged to establish certified reference networks for more atmospheric properties (e.g. for cloud properties)

Q4.2 What are the main steps needed to achieve this vision?

(Bodeker) First we need to better understand why existing state-of-the-art data assimilation systems are not achieving the goal stated above. Most often this is because:
1. The measurements being assimilated have not always been corrected for systematic biases. Often this is because a reference standard for identifying such biases is not available. So one specific step is to identify those measurement programmes which feed data assimilation systems and which are not traceable to fundamental standards and then develop a strategy to address that deficiency.
2. Not all available measurements are being assimilated. A greater effort needs to be made to ensure that data are available for reanalyses and not just for near-real-time analysis.
3. The physics in the underlying data assimilation models is always incomplete. There needs to be a far greater global effort to improve the physics in atmosphere ocean general circulation models. There are too many model users and too few model developers. There is no scientific glory in model development.
4. Not all measurements being assimilated have well-founded measurement uncertainties with the result that the assimilation system cannot appropriately assign weight to every datum.

(Bojkov) First and foremost a strong and proactive coordination by WMO. Second, clear and transparent information exchange.

(Calbet)
Achieve more collaboration between these communities via a dedicated work group (similar to GSICS for satellite radiance intercomparison) or by establishing more links between these communities (Workshops, etc.).

(Dykema)
These steps to achieve this vision are underway through independent efforts. Workshops such as the current one should provide opportunities to see what can be done to improve coordination and speed progress.

(Eyre)
The main steps are described in the WMO Implementation Plan for the Evolution of Global Observing Systems, EGOS-IP:
http://www.wmo.int/pages/prog/www/OSY/gos-vision.html#egos-ip

(Fujiwara) Interesting and stimulating science is key to attract new researchers and new students to the field of science. Unsolved questions are key for interesting and stimulating science. In the field of atmospheric (and Earth-system) science, I think that in most cases, observations give us new and big questions. Atmospheric observations need both new technologies (and good understanding of them) and detailed and in-depth data analysis. Research and education activities by considering the above key points are necessary both in developed and developing countries.

(Healy)
There is need for routine and regular sets of Observing System Experiments (OSEs) to quantify the impact of the observing systems currently used in modern NWP systems. This should include estimating how the impact scales with observation number.
Changes in the GOS should be introduced through careful gap-analysis between user requirements and what the current GOS can deliver. This can be complemented by Observing System Simulation Experiments (OSSEs) and/or Ensemble of Data Assimilation (EDA) experiments to attempt to estimate the cost-effectiveness of a new observing system.

(Hewison)
Set up routine comparisons of observing systems to characterize their relative biases and uncertainties.

(Kirchengast)
Implementation of existing plans, enriching them by more innovation, plus work forward with more cross-(sub)community spirit to better avoid suboptimal solutions that have been somewhat dominating in the past, including for the “3G” system (from non-scientific and non-technical dependencies, such as heritage path dependencies, sub-community power dependencies, single-person dependencies, etc.)

(Mannucci)
Here are the steps:
1) Documentation that explains each data set to the other communities, including its strengths and weaknesses and where the recommended data sets can be obtained.
2) Documentation that addresses how to compare the data (e.g. collocation criteria) and what the expected errors are due to collocation distances and representativeness errors. As a particular subject for GNSS RO, useful documentation is how to use atmospheric refractivity among the three systems, and how to derive water vapour from GNSS RO.

3) A database of collocations easily accessible, or generated on the fly for any time/date.
4) Funded activities to perform the comparisons, with well-defined milestones and progress reports. Joint publications jointly authored my members of each community are a worthwhile goal.

(deMazière)

- Assessment of needs, for different users/purposes
- Assessment of existing capabilities for each user/objective, including the space borne component, including redundancies, gaps and deficiencies
- Network design studies
- Harmonisation efforts
- Definition, development and maintenance of (a) global data archiving and dissemination system(s)
- Commitment for sustainable funding

(Reale)

Got to start with an inventory, a prioritized inventory of what is available, what is redundant, what is backup. How do we transition over time as the old fade and the new emerge. How are each component observation processed and at what stage is it suitable/optimal for integration. Is integration needed, do certain observations stand better on their own. Computing respective uncertainties is key. This is quite a problem on the global scale where quantifying uncertainty in remote (i.e. ocean) regions is much more difficult than say at a GRUAN site. So perhaps we can learn some things at the GRUAN sites that can have global impacts later. However, conducting measurements (i.e. RAOB, lidar, MWR…) for integration, best measurement practices, scheduling, computing uncertainty (variable from day to day) and required synchronization among ground and satellite measurements are all critical and labour intensive. True, the more global distribution the better (current less than 10 active GRUAN sites, need 20 or more …), but this exacerbates the management problem, all those sites, all those recipes. Ultimately, one can envision a stream of measurements flowing from GRUAN sites consistent with GRUAN objectives, but how does this translate to WIGOS. Achieving such a vision this on a global scale (GOES, Polar …) is quite a large undertaking, but I think starting with smaller scale GRUAN prototype provides insights and at minimum a GOS validation sanity check.

(Simmons)

Whatever the vision, many steps are needed to build on what we have today, and this workshop should not try to cover all of them. This question should have been more focused on what is needed for better integration of GRUAN, GSICS and GNSSRO activities.

(Thorne)

Integration, coordination, and development of tools realizing that the total is substantially greater than the sum of the parts – that the "3G"s need to benefit from one another on a sustained basis. This includes development of collocation and metadata tools to enable users to fully exploit the high quality atmospheric measurement capabilities which exist.

(Vömel)

Raise awareness to the fact that changes in the observing system impact our ability to interpret the data on all time and special scales. Met services and Funding agencies need to support activities to guarantee the stability of the observing system under changing instrumentation.

(von Engeln)

- better integration between satellite and local site observations, e.g. by continuous cross validation, providing co-located satellite data, providing forward modelled MW

& IR radiances for radio sonde data, continuous evaluation and if required re-processing of satellite (sonde?) data. Currently, NWP partly provides this interface.

- distribution of GRUAN is not optimal, mostly NH, mostly land masses, would be nice to add improved coverage at e.g. SH and islands
- funding is always an issue, in particular long term to build up long term record

Q4.3 Which are the main deficiencies in the current system, including gaps in infrastructure, expertise, and training?

(Bodeker) The overriding deficiency is a lack of appreciation in the operational meteorological community, and perhaps also the satellite community, of the need for long-term homogeneous measurement series suitable for generating climate data records of essential climate variables. Since the emphasis is on producing data in support of numerical weather prediction, little investment is made in ensuring the long-term homogeneity of the record. I cannot think of any specific gaps in infrastructure. It is possible that the computing and data storage resources may not always be available for assimilating hyper-spectral measurements into current 4D-var data assimilation systems. It may be that current systems cannot fully assimilate hyper-spectral measurements and, if so, more emphasis needs to be placed on developing such systems.

(Bojkov)
Currently infrastructure and expertise seem to be well covered at the current GRUAN stations. Main concern, but maybe it is just an impression, is that the advanced techniques and information developed at GRUAN sites does not necessarily transfer efficiently to other networks (although most information seems to be available through the GRUAN web site). Maybe a better outreach, communication and course activity needs to be implemented. Also, interoperability and differences between techniques needs to be stressed. This is very important for validation and assimilation uses.

(Calbet)
The above mentioned technical problems within each one of the communities or the inconsistency between the products coming from these three communities.
Another issue is the lack of awareness from members of one community of the typical issues that are present in the other communities. Somehow bringing these communities together would also increase the awareness of this.

Note that the biggest issues are related to the detection and correction of systematic errors (biases) in all three communities. The synergistic collaboration of all three communities would potentially bring to the surface potential underlying undetected biases. The high quality uncertainty estimation which GRUAN provides is also very important, but only secondary to removing undesired remaining systematic errors.

Another important aspect would be to have an estimation of the co-location uncertainties of the ground based measurements with the satellite data. This can be done in a number of ways (statistical or on an individual basis) and with different input data (several ground based measurements or with NWP fields).

(Dykema)
Currently, calibration and uncertainty analysis is considered an essential activity, but the benefits to applications and end-users are diffuse and perhaps not comprehensively characterized nor effectively communicated. Overall there is probably not strong enough linkages between research, development of best practices, and evaluation of accrued benefits.

(Eyre)
The main deficiencies are summarized in the WMO RRR “Statements of Guidance”:
http://www.wmo.int/pages/prog/www/OSY/GOS-RRR.html#SOG
and Actions to address these deficiencies in EGOS-IP:
http://www.wmo.int/pages/prog/www/OSY/gos-vision.html#egos-ip

(Fujiwara)
As a researcher and a teacher in a university in a developed country in Asia, I would like to point out that we (or I) need more efforts to increase the number of people (in the atmospheric science community) who share the visions written above. In other words, there are still gaps between the research community and operational community.

Also, I think that new measurement technologies are the ones that always advance the Earth science. We need continuous communication with engineering communities in some way. WMO may have covered this aspect. University researchers also need more efforts toward this end.

(Healy)
Infrastructure: I think there is now a strong case for increasing the number of GNSS-RO observations available for NWP from the present levels to 10,000 to 20,000 per day.

(Hewison)
1. Interaction between different observing systems
2. Systematic methods of characterizing biases and uncertainties

(Kirchengast)
Exploiting the available synergies (such as also amongst the “3G” subsystems), non-scientific non-technical path dependencies that led to suboptimal balance in the integrated observing system.

(Mannucci)
GNSS RO data are not well understood by the broader community. Conversely, what should we expect when comparing GNSS-RO to GRUAN and satellite sounders? The GNSS-RO community has published research on this topic, but routine utilization is difficult. There is no standardized approach to comparisons or centralized data access.

(deMazière)
- Very inhomogeneous distribution of the research infrastructures over the globe, with redundancies on the one hand versus large gaps on the other hand.
- Lack of consistency between different networks and even inside networks
- Lack of harmonization
- Not enough care for historical data, partly because of lack of funding/interest; stations of historical importance are closed and their data are lost or not well preserved.
- Various bodies, like IPCC, and agencies, like the space agencies, need observational data, but they take them for granted. There is a lack of commitment to long-term funding: EC, ESA and member states push responsibilities towards each other; nobody wants to assume the responsibility and certainly not the costs
- Costs should be reduced. Options to achieve this: (1) automatisation; (2) cost-efficient design of the networks;
  The effort of automatisation can be done in part by SMEs thus generating jobs on the short-term and reduced costs on the longer term.

  Question: can private-public partnerships support funding problems ?

(Reale)
I will essentially pass on this question as I really am not so familiar with what is meant by the current system. I would characterize a possible main deficiency in the current system as one in which the existing and evolving global state remains to some extent misrepresented due to constraints these systems place on being responsive to the observations, or perhaps being overly responsive.

(Simmons)
This is far too general a question to be addressed by the workshop. This question should have been more focused.

(Thorne)
Different aspects are overseen by different governance structures within WMO and elsewhere, and funded by different pots, which significantly inhibits their coordination and the realization of indubitable efficiencies that could exist. In general these communities do not talk enough to each other and are not aware of what potential synergies there are.

(Vömel)
Change management is limited to an insufficient number of stations. Ongoing automation and staff reduction makes the observing system susceptible to uncontrollable changes and impact.

(von Engeln)

- improved coverage of radio sonde data (more SH, and e.g. islands)
- radio occultation observation gaps / insufficient coverage and funding issues
- we are unaware of any routine cross observation / validation or even data access sites of all the three “G”s discussed here
- for radio occultation we should work towards an international provider of GNSS orbits/clocks/NavBits data, which provides this data in (Near)-Real-Time to all missions (something akin to ECMWF, but for GNSS data). This would also benefit other GNSS observation types, e.g. ground based.

Q4.4 Which practical steps could WMO and co-sponsored programmes (such as GCOS, WCRP) take to address these issues?

(Bodeker) WMO could strongly encourage NMHSs which currently make observations primarily (or exclusively) for numerical weather prediction to take a longer term view and, with a moderate additional investment, ensure that these same observations also serve the needs of the climate monitoring community.

(Bojkov) Effective outreach, communication and training courses to make others aware of measurement “best practices”, measurement issues, interoperability issues, etc.

(Calbet) Create a dedicated work group for this task or support more links within these communities (Workshops?).

(Dykema)
Working with national agencies to develop long-term and sustained support for research programs that support broad-based participation in these efforts: from academic centers, research organizations, operational organizations, and commercial entities.

(Eyre) See reply to 4.2.

(Fujiwara) I think that GRUAN also has a very good function to connect the operational community and the research community. But, the number of people from universities is still small in the GRUAN community. WMO is a very professional organization, but is there a function within it that connects WMO with university students who major in physics, chemistry, mathematics, and other sciences? The outreach activities are probably more for the general public, and we need closer connection with university students.

(Healy)
I would hope the WMO can coordinate and support the required OSEs and OSSEs noted in 4.2.
The International Radio Occultation Working Group (IROWG) has recommended the drafting of a "GNSS-RO Continuity Plan" by CGMS, outlining how we move towards an observing system with 10,000-20,000 GNSS-RO observations per day. I think WMO should take an active role in formulating this plan.

(Hewison)
1. Establish forums for interaction between upper air observation communities.
2. Promote uncertainty training.

(Kirchengast)
Foster interaction and coordination amongst sub-communities (such as done amongst the "3G"s with this Workshop), be impartial, mediator, forum etc., and be a key institutional stakeholder of overcoming path dependencies leading to suboptimal results.

(Mannucci)
Here are the steps:
1) Create infrastructure for the respective communities to distribute information regarding recommended data sets and best practices.
2) Create collocation data sets and ways to acquire collocated data.
3) Create relevant documentation.
4) Fund research with clear milestones.

(deMazière)
- Make Member States better aware of the needs for long-term monitoring.
- Encourage commitments of Member States to support the required monitoring networks.
- Support actions for cost reduction on the long-term.
- Stimulate awareness and support training in developing countries to get them involved in the global efforts
- Coordinate between different agencies and bodies

(Reale)
It would seem that the need for data compression is a concern. There is so much data making similar observations but at varying spatial and temporal resolutions (for example, witness the COSMIC GPSRO spatial geometry). Retrieval is one form of data compression, where for example a temperature or moisture profile is deduced from the sensor data. This could at least level the playing field, but of course comes at a price, one being the apriori state required by most approaches, the other the RT model ambiguity. A question I have is whether its radiance or temperature or humidity. It's nice to reside within the comforts of the root measure, i.e. radiance, but ultimately its temperature that we want.

(Simmons)
The issues need to be narrowed down first. The breadth of the preceding questions is unhelpful.

(Thorne)

- In the short term cross-pollination of oversight groups would assure on a practical level better information sharing and likely yield improved coordination and win-win activities being identified.
- WMO should explicitly recognize that to truly realize the value of the many NMS member measurement activities requires a truly multi-point cal/val system and that it is a false dichotomy to play the “3G”s and similar measures in any sense as ‘competitors’. We need all these programs and measurements if we are to assure the long-term record continuity and understanding.
- Through the standing committee with BIPM improve metrological aspects of all measurements and analyses under the “3G”s.
- Encourage members to participate in the analysis of data from the “3G”s
- Work with satellite agencies, NWP centres and reanalyses to start to make use of metrologically traceable measures from GNSS-RO and GRUAN to provide absolute rather than relative constraints on L2 products and model biases.

(Vömel)

Recommend to member states to implement recommendations by WMO and GCOS to guarantee change management and redundant observations of old and new systems during changes in the observing system, in particular during sensor changes. Make sure the impact of sensor changes on satellite validations is documented.

(von Engeln)

- provide framework to bring communities together
- start discussions with CGMS/relevant other satellite operators, IGS, GNSS operators to work towards an international GNSS service provider
- funding of any activities is generally an issue

Q4.5 How can high-quality ground-based atmospheric sounding such as by GRUAN support needs of the satellite community, now and in the future?

(Bodeker) GRUAN can help to define what constitutes a reference measurement and how to ensure that measurements are traceable to internationally accepted measurement standards. GRUAN may even be able to provide a pathway to link a space-based calibration standard to ground-based measurement standards. GRUAN can help to define what the requirement is for an inter-calibration product to meet the needs of different user communities i.e. equate product requirements to reference requirements. GRUAN can provide a ground-based network to ensure continuity across multiple space-based inter-calibration systems. While a multi-decadal ground-based measurement programme, with regular calibration against measurement standards is possible, it is far less likely that a single space-based instrument can be operated over many decades to provide a calibration standard for all other space-based instruments. High-quality measurements, such as those from GRUAN, should also be useful for validating the radiometric stability of space-based calibration system by providing input to radiative transfer models that can be used for level 1 data quality control and validation. In this way GRUAN should also be able to establish a ground-based reference for Fundamental Climate Data Records. Where historical data are available at GRUAN sites these can be used to generate an historical climate data record which might then be useful e.g. for bringing HIRS into the GSICS fold. Together with GNSSRO, it may also be possible to use GRUAN data to ‘extend’ the coverage of a space-based calibration standard such as AIRS or IASI (and MTG-IRS in the future?) in time and space by permitting the calculation of ‘virtual’ measurements at the time and location of other satellite measurements.

(Bojkov) Key is the provision of independent, well characterized, timely, globally coherent and documented datasets (for intercomparison and validation purposes). This need will continue as long as EO satellites are in operations.

(Calbet)
The existence of high quality ground based soundings is proving useful to validate and, possibly also, calibrate Sat measurements.
An area that could be improved is to increase the geographical coverage of the GRUAN stations. Also, until we have infrared hyperspectral sounders in GEO orbit (something like 2020), it would be advisable to launch sondes at LEO infrared hyperspectral sounder overpass time (IASI is a case where there are very few collocations present and there will be even less when Manus is shut down).

(Dykema)
The first value of GRUAN to the satellite community is for product validation—well-characterized profiles of temperature, water vapour, and other key variables.
The second contribution of GRUAN is that ensembles of GRUAN measurements, processed through various techniques such as 1-D variational assimilation, site atmospheric state best estimation, optimal estimation methods, and others, will provide a foundation for improving radiative transfer models in a systematic way.
Finally, the improvement of radiative transfer models should lead to the possibility of monitoring satellite sensor calibration for spurious long-term trends.

(Eyre)
From the perspective of WMO CBS OPAG-IOS, it is not the main purpose of GRUAN to support the satellite community, but to support the Application Areas of WMO, and chiefly Numerical Weather Prediction and Climate Monitoring (including Reanalysis).

(Fujiwara) High-quality ground-based atmospheric sounding is and will continue to be the key instrument for validation of any remote sensing measurements. It is much easier to characterize the uncertainty of the measurements compared to higher-technology remote sensing measurements.

(Healy)
The GRUAN network potentially provides a useful data for satellite CAL/VAL activities. Clearly, the aim will be to demonstrate that the theoretical error models for both the satellite data and GRUAN measurements are consistent with the observed differences. However, these activities will require close collaboration between the satellite data and GRUAN experts to address some subtle questions. For example, for GNSS-RO should the GNSS-RO temperature retrievals be compared with the GRUAN radiosonde measurements? Alternatively, should the radiosondes measurements be forward modelled to quantities more routinely used in NWP and reanalysis?

(Hewison)

1. As part of WIGOS and by providing high vertical resolution atmospheric profiles for systematic validation of NWP and satellite retrievals.
2. Potentially to provide reference observations (together with RTMs) for calibration of microwave instruments.

(Kirchengast)
Act as the reference data source from below (from the point of view of the upper-air atmosphere), cover in particular the boundary layer and the troposphere as a best-calibrated and -traceable data source.

(Mannucci)

GRUAN can provide the “third vote” in comparisons between GNSS RO and traditional satellite data. The GNSS RO community is trying to establish an SI-traceable data set that will not require calibration via other data sets. However, validation/comparison of RO to other data sets is necessary. An important comparison is between RO and traditional satellite soundings. In cases of discrepancy, it is valuable to have GRUAN help to resolve and understand these discrepancies.

(deMazière)
- By providing a long-term continuous reference for subsequent satellite series, of high and constant quality
- By providing transfer standards to fill gaps between interrupted satellite series
- By providing test facilities for satellite instruments and a training ground for satellite teams

(Reale)
The main support of GRUAN to the satellite sensors in my opinion is in the validation of derived sounding products and associated RT models (not necessarily) in that order. The GSICS program offers a broad and highly successful space base program that assures the consistency of sensor calibration and performance across respective satellites. STAR ICVS provides routine near-real time monitoring and associated uncertainties for all sensors on orbit and GSICS/SNO supports this with post analysis and adjustment later. Derived sounding retrieval using near-real time processed sensor data and RT model directly demonstrates the utility of the sensor alone to measure the geophysical space. Synchronized ground measures at GRUAN offer the best opportunity to validate each of the above; even non-synchronized reference can be useful as mislocation errors can to some extent be modelled at the GRUAN site (sigma term in uncertainty equation). Ultimately, integrating uncertainty for all parameters (ground, space based sensor and retrieval, RT model, air mass dependence, etc. …) and demonstrating consistency within uncertainty estimation is a primary support component of GRUAN to satellites, both in the radiance and geophysical space.

(Simmons)
Why “such as by GRUAN”. If this is a workshop on ground-based atmospheric sounding in general, rather than GRUAN in particular, GRUAN should not appear in the title of the workshop. If GRUAN is kept in the title “such as” should at the very least be replaced by “in particular”.

GRUAN should be able to help quite directly in cal/val and the development of the radiative transfer models needed to exploit satellite data. Whether GRUAN has (or will ever have) sufficient network density and coverage to constrain radiance bias correction for use of satellite data in NWP and reanalysis is unclear to me, but I suspect not. But GRUAN should help in the longer term if it can serve to help raise the standard of radiosonde observation and other types of ground-based observation in general. When GRUAN starts to provide a critical mass of water-vapour observations for the UTLS, it may help determine the need for complementary space-based observation of the region.

(Thorne)
By providing sets of collocations within time and space windows with quantified uncertainties and traceability both at L2 and L1. To improve radiative transfer modelling by providing absolutely calibrated geophysical and chemical profile data.

(Vömel)
The satellite community should be able to go to one network to get the best possible data and should not need to worry about how good these data are. The network data should contain that information.

(von Engeln)

- the possibility to forward model radio sondes to microwave, infrared radiances would make co-location and comparison easier
- add relevant satellite data for each station, e.g. co-located radio occultation, potentially add analysis, re-analysis data
- we noted that the sondes are not consistent for all stations, e.g. Xilin Hot, China has different radio sonde types, maybe it is not part of GRUAN, but is listed in the stations
- would be highly beneficial to have the same ground equipment at each stations, to provide further information
- we noted that GPS IWV is available for stations, are they all based on the same GPS orbits clock information?
- provide a compound product from all available site instrumentation?
- is there a database search to find co-locations in time, space?
- what information is provided for the site? Homogeneity over the site (e.g. by analysing adjacent satellite radiance observations)?
- are there actually format changes for the different sites, so can longer term data sets be read with one software (even if they were not part of GRUAN)?
- encourage operators of local observation sites (super-sites) to provide integrated retrievals of the atmospheric state (e.g. by applying the integrated profiling technique to the observations of their reference networks)

Q4.6 How can the satellite community support needs of the ground-based atmospheric upper-air sounding community such as GRUAN, now and in the future?

(Bodeker)

- Ensure that every level 2 or level 3 data value is accompanied by a robust estimate of the measurement uncertainty.
- Use some portion of the funds allocated for validation of satellite-based instruments to financially support GRUAN operations at key validation sites.
- Accurately calibrated satellite measurements can provide a travelling reference standard for GRUAN stations.

(Bojkov) By stressing the need of independent, well characterized, timely, globally coherent and documented datasets.

(Calbet)
Infrared hyperspectral sounders, IASI currently being the radiation reference for GSICS, due to its global coverage could become a reference for quality control of the GRUAN measurements. To serve this purpose, more GRUAN support coming from the Sat or NWP community would be useful, in terms of converting the GRUAN profiles into radiances via an RTM or more concrete support for GRUAN sonde launches.

(Dykema)
Having a well-calibrated space-based network with calibration/uncertainty estimation tied to independent, fundamental standards—such as GNSS/RO tied to atomic clocks—provides a check for spurious long-term trends in GRUAN measurements.

(Eyre) See reply to 4.5.

(Fujiwara) Global coverage of satellite measurements is the strength. It attracts researchers and students to the field of atmospheric science. Once they start to analyse the data to answer some specific scientific questions, they realize that ground-based in-situ measurement data are necessary to validate satellite data and thus to test their scientific hypotheses.

It may be a good idea to combine satellite measurement data and collocated ground-based data (and perhaps, data from other satellite sensors) in one file in some way, so that the data users are able to compare the two types of data very easily. There is of course technical challenge to do so because of the difference in the sampling air volume (e.g., vertical resolution/weighting function) and the difference in the vertical axis information (as the satellite measurements often need meteorological analysis data to assign the measurement to a specific pressure/geopotential-height level).

(Healy) See 4.5.

(Hewison)
By providing travelling reference observations to better characterize the biases in GRUAN measurements and, in particular, to transfer these between GRUAN sites.

(Kirchengast)
See a joint "3G" system as a valuable contribution to the wider atmospheric observing system, with GRUAN bringing its own unique contributions to the "3G" system (see previous question/answer).

(Mannucci)
Documentation and experiments that improve understanding of satellite (RO) data and how GRUAN can use these data to advantage.

(deMazière)
- Co-funding of the ground-based data that are indispensable for satellite calibration and validation
- Collaboration on common issues, such as spectroscopic uncertainties, radiative transfer tools, …
- Better communication and collaboration as to data formatting standards, data archiving and dissemination issues
- Supporting tools for data extraction collocated with ground-based data

(Reale)
The satellite community supports the needs of GRUAN by being a primary user and demonstrating value in product validation and scientific algorithm (including RT model) development; at NOAA/STAR we are well on our way to doing this. The application is primarily for validation; products, RT model and sensors in that order. There are also opportunities for tuning but the sparse global distribution makes this prohibitive. The satellite community (at STAR) places such high value on potential GRUAN reference observations that anytime a RAOB is in the air or a satellite is overhead the STAR attempts to collocate all observations from the satellite with those from the ground (RAOB, ancillary, etc.). This is referred to as NOAA Products Validation System (NPROVS+) which began operating at in July 2013. Such a dataset is a basic, efficient and a potential important first step toward a standardized international validation framework for both satellites and GRUAN, now and sustained. We may never cease to argue on how to interpret said results, what it all means, but there should not be an argument on how to compile validation datasets; save it all, save it now, baseline, automate, share!

(Simmons)

Again, why is GRUAN only a "such as" in this question? How the satellite community can support the ground-based sounding community is a wide topic and it is unclear that this can be adequately covered by the workshop as it is currently constituted. Why does GRUAN get mentioned in this and the preceding question but not GNSSRO and GSICS?

(Thorne)
By providing collocations which enable cross-validation and metrological comparability of similar measures from different sites as a key aspect of assuring their quality. By using their data and therefore providing a demonstrable application and benefits.

(Vömel)
The satellite community should explicitly fund validation activities. These activities could be either campaign based or routine activities as dedicated sites. Routine validation activities at dedicated sites should have the preference and should be given adequate support to be able to continue. These sites can supply dedicated observations to a larger number of satellite systems and thus serve a larger community.

(von Engeln)
- the sondes have bias depending on the solar angle, this has been observed in radio occultation comparisons. Thus collocated radio occultation information could be used to get a better handle on these biases.
- continuous re-assessment and, if required, re-processing of satellite data by different centres

QUESTION 5. What are your key recommendations regarding the workshop objectives:

(Dykema)
Developing a handful of well-scoped, practical, actionable items to support/carry forward the workshop's findings.

(Healy)
I would like to see a clear statement acknowledging the importance of ensuring the continuity of the GNSS-RO measurements for climate applications.

(Simmons)
My sole recommendation is that the Organizing Committee clarify the objectives.

The most urgent actions that should be taken by the international community over the next 3 years (based on current resources):

(Bodeker)

- Define more clearly to space agencies the value that GRUAN and GNSSRO bring to support calibration of satellite-based instruments with the goal of attracting additional resourcing for GRUAN and GNSSRO.
- GRUAN (and some selected GUAN) sites must be encouraged to adapt their measurement programmes to better meet the needs of the satellite community e.g. shifting radiosonde launch times to better match satellite overpass times, especially overpass times of IASI, AIRS and, in future, MTG-IRS. Tables of overpass times need to be generated and made easily available to all such sites.

(Bojkov)
1. Development of measurement best-practices (following QA4EO principles)

2. Identification of measurement (instrumental) differences (through thorough characterization)
3. Focus on outreach of techniques (measurement, calibration, processing) to non-GRUAN measurement networks and the stakeholders

(Calbet)
Establish bridges between all three communities in the form of recommendations workshops, or dedicated groups actively working on these issues. Establish a working group to determine the co-location uncertainties.

(Dykema)
Identifying some practical cross-cutting demonstration studies between GRUAN, GSICS, and GNSS/RO.

(Eyre)
- To refine and record the understanding of the primary role of GRUAN, as set out in the reply to question 3 above.
- To improve the working links between the GRUAN community and relevant applications communities (NWP, Climate Monitoring, Reanalysis).
- To undertake projects demonstrating the value of GRUAN data for the above applications.

(Fujiwara)
Have better communications within the various upper air measurement communities, and try to get an integrated view for the future of the upper air network. This workshop is a very good starting point. Do we need a survey of such communities? (I just heard about an EU FP7 project 'Quality Assurance for multi-decadal ECVs' (QA4ECV), which are making a user requirement survey to collect opinions from users of satellite-derived climate data records. It seems like there are overlaps with them.)

(Healy)
The formulation of GNSS-RO Continuity Plan, and clear support for the COSMIC-2 programme is of importance over the next 3 years.

(Hewison)
1. Establishing a forum for interactions between upper air observing communities.
2. Promoting a common framework to assess biases and uncertainties.
3. Establishing working processes, data formats, guidelines, standards and conventions to simplify collaboration, and manage users' expectations.
4. Promoting the establishment of SI-traceable observations in orbit. (This would also provide a common focus for future interactions.)

(Kirchengast)
Good summaries available already (e.g., see Hewison above); start to actually build and exploit the joint "3G" system and to get the sub-communities work together ("it's the cooperation, stupid").

(Mannucci)
1) Create a plan for improved interaction and interoperability.
2) Start exchanging data.

(deMazière)
Optimize the observing system as to cost-efficiency and harmonisation

(Reale)

- Sanction NPROVS+ as baseline component process for compiling satellite collocations with existing and pending reference observations at GRUAN to serve as a common validation dataset across the international community
- Expand current GRUAN network for improved global weather representation
- Provide inventory of critical GOS for weather and climate problem

(Thorne)

- Better coordinate the “3G” communities through better cross-pollination.
- Develop improved collocation and metadata databases and visualization capabilities between the “3G”s.
- Fully develop and document the metrological and analysis basis underlying a tiered system of systems architecture. Apply this to the totality of the GOS UA capabilities to realize the benefits and identify the gaps in capability that act to diminish their value.

(Vömel)
To maintain current resources on current high quality observations. To maintain observational staff.

(von Engeln)

- get the communities talking / interacting
- create formal link to relevant CGMS/other working groups
- make better use of research satellite data (at least for radio occultation)

The most urgent actions that should be taken by the international community over the next 10 years (assuming additional resources):

(Bodeker)

- Expand the development and use of the NPROVS+ system for validation of space-based instruments.
- Implement the routine generation of SASBEs at selected GRUAN and GUAN sites for use in the calibration/validation of space-based instruments.
- Biases in radiance data assimilation are affected by systematic biases in the radiative transfer models and so the quality of radiative transfer models needs to be improved; more emphasis needs to be placed on intercomparisons of radiative transfer models and on further development of radiative transfer models.
- Since cloudy regions are the sensitive areas for the forecast of cyclogenesis, more resources need to be committed to assimilating cloudy-sky radiances into for NWP.

(Bojkov)

1. A well planned and sustainable expansion of GRUAN to no more than a dozen sites in key climatic areas globally
2. Continued efforts focusing on “best practices” and instrumental characterization
3. Outreach and training to related networks, as well as stakeholders

(Calbet) Have a greater interest and dedicate more funding to cross-community related collaboration, groups or studies.

(Dykema)

- Developing a mobile calibration lab to travel between GRUAN sites for cross-calibration

- Developing and deploying satellite sensors with on-board calibration diagnostics to provide fundamental on-orbit physical calibrations standards for GSICS
- Detailed three-way intercalibration analysis of GSICS, GRUAN, and GNSS-RO, by season and region
- Evaluation studies to optimize sensor mix and to optimize sensor calibration hardware development efforts: probably a mix of OSSEs and less computationally-expensive but similarly designed modelling/assimilation experiments (perhaps utilizing a hierarchy of models)

(Eyre)

- To move from demonstration projects to effective use of GRUAN data in operational applications.
- To provide research findings from GRUAN which help to improve the quality of other operational observations, chiefly from GUAN and other operational upper air stations.

(Fujiwara) Try to get more students who are interested in atmospheric sciences particularly from the observation viewpoints.

(Healy) We should be aiming for 10,000 - 20,000 GNSS-RO observations per day.

(Hewison)

1. Operating SI-traceable reference measurements in orbit.
2. Implementing systematic comparisons of observing systems against these references.

(Kirchengast)
Just on “3G”: get all three systems to an adequate sustainable operation, and to an adequate “size of subsystem” (e.g., for GNSS-RO, “my” primary sub-community: long-term ensure at least 20,000 GNSS-RO measurement events per day), and to a seamlessly operating joint “3G” system.
On the wider observation system in general: the available planning documents (e.g., cited by Eyre, out to 2025) are fine, but strive to be more innovative and to avoid path dependencies, and strongly foster sub-communities’ cooperative work styles.

(Mannucci)

1) Create resources for collocating observations.
2) Simplify access to data among the diverse communities.
3) Perform comparisons among the diverse systems and initiate dialog via workshops to understand the comparisons.

(deMazière)
Consolidate the integrated observing system in a sustainable way.

(Reale)
See me after the meeting

(Thorne)

- Grow GRUAN and similar ground-based networks to be 30-40 sites and have the capability to measure all upper-air ECVs
- Operationalize the use of products arising from the “3G”s to provide better constraints on NRT operations and climate monitoring activities.
- Rationalize measurement capabilities and programmes to realize cost efficiencies and science benefits (i.e. collocate capabilities; build centres of UA measurement and analysis excellence that combine expertise in ground-based, in-situ, sub-orbital and active and passive sounder measurements).

(Vömel)
To implement procedures to utilize high quality observations to their full potential. To implement procedures and allocate funding allowing the observing system to handle system change.

(von Engeln)

- work towards implementing missions like CLARREO
- increase radio occultation coverage by promoting COSMIC-2 polar mission
- work towards the above mentioned international GNSS service provider

APPENDIX B: WORKSHOP AGENDA

	TUESDAY, 6 MAY 2014	
8:30	**REGISTRATION (SALLE C2)**	***APPROX.TIME INCL. DISCUSSION***
9:00	**1. OPENING REMARKS (WMO AND CO-CHAIRS P. THORNE, T. HEWISON, T. MANNUCCI)**	**20'**
9:20	**2. INTRODUCTORY POSITION STATEMENTS (ALL PARTICIPANTS)**	**120' (5' PER PARTICIPANT)**
11:30	**3. WMO OBSERVING SYSTEM PLANNING**	
	3.1 Status of WIGOS Implementation (L. P. Riishojgaard)	20'
	3.2 Vision for the Global Observing System in 2025 and Rolling Review of Requirements (J. Eyre)	20'
	3.3 Report from GCOS AOPC Network Workshop (A. Mikalsen)	15'
12:30	*Lunch Break*	70'
13:40	**4. APPLICATIONS OF UPPER-AIR OBSERVATIONS**	
	4.1 Climate Monitoring (P. Thorne)	20'
	4.2 Climate Process Studies (J. Dykema)	20'
	4.3 Numerical Weather Prediction (J. Eyre)	20'
	4.4 Reanalysis (A. Simmons)	20'
15:00	**5. Observing systems: principles, practices, uncertainties, cal/val, plans**	
	5.1 GRUAN (G. Bodeker)	20'
	5.2 Hyperspectral sounding; GSICS (T. Reale; T. Hewison)	20'
	5.3 GNSS-RO (T. Mannucci; G. Kirchengast; S. Healy)	20'
	5.4 Radiative transfer (TBD)	20'
16:20	*Coffee Break*	20'
16:40	**6. FORMATION OF BREAK-OUT GROUPS ALONG AREAS OF INTEGRATION AND INTEROPERABILITY**	
	6.1 Applications and required dataset generation (Facilitator : G. Bodeker)	
	6.2 Measurement uncertainty estimation and terminology (Facilitator: H. Vömel)	
	6.3 Observing system coordination and collocation (Facilitator: X. Calbet)	
	6.4 Participation and outreach (Facilitator : S. Bojinski)	
17:30	*Adjourn for Day 1*	
	WEDNESDAY, 7 MAY 2014	
9:00 - 17:00	**Work in Break-out and Plenary sessions (Rooms: C2, 7 Lake, 7 Jura)**	
19:15	*Dinner at Auberge de Savièse (http://www.aubergedesaviese.ch/)*	
	THURSDAY, 8 MAY 2014	
9:00	**7. DEVELOPMENT OF RECOMMENDATIONS**	

15:00	**Final Plenary session**	120’
17:00	*Adjourn workshop*	

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