# WORLD METEOROLOGICAL ORGANIZATION
# GLOBAL ATMOSPHERE WATCH

**No. 166**

# Joint WMO-GAW/ACCENT Workshop
# on
# The Global Tropospheric Carbon Monoxide Observations System, Quality Assurance and Applications

**(EMPA, Dübendorf, Switzerland, 24 – 26 October 2005)**

**2006**

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**Editor: Jörg Klausen**

**WMO TD No. 1335**

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## 1. OPENING OF THE MEETING

Thirty-six scientists from 10 countries (see Annex A) met at the Swiss Federal Laboratories for Materials Testing and Research (EMPA) in Dübendorf (Switzerland) from 24-26 October 2005 to discuss the global carbon monoxide observations system, quality assurance and applications in the context of the World Meteorological Organization's (WMO) Global Atmosphere Watch (GAW) programme. The meeting was co-sponsored by the European Commission's ACCENT Network of Excellence and WMO-GAW.

The meeting was opened by Dr Peter Hofer, Board of Directors of EMPA, who welcomed participants on behalf of the host institution and expressed EMPA's support of the meeting. He highlighted EMPA's contribution to GAW and gave an overview of EMPA's research activities ranging from materials to environmental sciences. Dr Geir Braathen, Senior Officer at WMO, welcomed participants on behalf of the sponsoring agencies and presented an overview of the status of and challenges faced by GAW, the Network for the Detection of Stratospheric Change (NDSC), recently renamed to Network for the Detection of Atmospheric Composition Change (NDACC), and the Integrated Global Atmospheric Chemistry Observations (IGACO) strategy. Dr Jörg Klausen, representing the workshop science programme and organizing committee, explained that the workshop should try to bridge the gap between the various communities involved in ground-based in-site, aircraft and satellite observations, and expressed his hope that concrete recommendations would be developed by the working groups that would help GAW and other programmes to embrace the spirit of IGACO.

## 2. PURPOSE OF THE WORKSHOP

The objectives were to review the traceability, uncertainty and use of long-term in-situ and remote-sensing CO observations and to offer guidance for the future Integrated Global Atmospheric Chemistry Observations (IGACO) system involving WMO-GAW, NDACC, as well as systematic aircraft and satellite measurements. In oral and poster presentations, as well as working groups, the workshop addressed a number of key questions:

- What is the current state of the long-term global CO measurement system (surface-based, aircraft, satellite)?
- What analytical methods are suitable/being employed?
- What is the uncertainty of current CO data?
- How can CO instrumentation best be calibrated and traceability chains to the WMO-GAW World Reference scale maintained?
- How can CO observations of all types be optimally integrated using atmospheric models?
- To what extent can satellite data and ground-based in-situ or total column CO measurements complement each other?
- How are atmospheric CO observations archived and made available to users?
- What are the applications of integrated CO observations on a local, regional, hemispheric and global scale?

## 3. WORKSHOP PROGRAMME

The Workshop programme (Annex B) consisted of oral and poster presentations organized in four sessions that covered user requirements; quality assurance of ground-based measurements and the WMO CO reference scale; aircraft and ground-based remote-sensing, as well as reconstructions; and satellite-based remote sensing. All the presentations are available on the internet at www.EMPA.ch/co-workshop.

In addition to oral and poster presentations, the workshop featured 4 working groups. These were given a total of about 5 hours over the course of the two-and-a-half day meeting to discuss a given topic. The working groups were guided by a number of questions. The outcome of each working group was presented and discussed in plenary. The reports presented here were open to review by the working group members for about 6 weeks. The topics and the questions to guide the working groups were as follows:

***Global CO Cycle***

- Do we understand the global CO cycle sufficiently? What are the major gaps in our understanding? What needs to be done to improve our understanding?
- Has the global CO cycle changed? How?
- How are CO observations important to research on ozone depletion, climate-chemistry interactions, air quality/LRTAP studies and understanding atmospheric oxidizing potential?

***The Global Observing System (IGACO CO)***

- Who are key contributors performing long-term CO measurements (in situ, remote sensing)? What do we have for a global network? Update IGACO Figure 4.4 (see GAW website for report)
- How can the global coverage of CO measurements be improved? Identify gaps and suggest ways to fill them including suitable methods. To what extent can satellite, aircraft and total column observations complement ground-based in-situ CO measurements?
- How can the different CO measurements be integrated in ways useful to researchers and what is the role of GAW? What do we mean by 'integration'?
- Is a real-time tropospheric CO product desirable? How could it be achieved? Identify the need and feasibility for real-time delivery of CO for assimilation in models and recommend ways to implement including the role of GAW.

***Calibration / Validation and CO Scale***

- How is the GAW CO world standard defined and what is its status?
- Can the stability of the current scale be guaranteed? What is required to that effect?
- To what extent can high concentration cylinders solve some of the recognized problems of the current CO scale?
- How can the GAW CO scale be applied to in-situ as well as remote-sensing instrumentation? What are the resulting calibration uncertainties?
- What are the traceability chains at individual monitoring sites / national networks?
- Are there issues common to $H_2$ (hydrogen) and CO measurements? Is a common Central Calibration Lab (CCL) for CO and $H_2$ feasible / desirable?
- How can the GAW CO scale be transferred to regional/national networks?
- What is current practice for quality-assuring CO measurements in national networks and is this adequate for GAW purposes?
- Is the current data quality achieved by ground-based in-situ, flask, ground-based remote-sensing, aircraft, and satellite instruments sufficiently well documented?
- What limits the achievable data quality?
- What is the uncertainty of current CO data?

***Data Quality, Data Management and Integration***

- What data are available and from where?
- Are the available data up-to-date?
- What are the factors limiting data submission / data use?
- What is the role of the World Data Centre for Greenhouse Gases? If it needs to be improved, in what way / direction?
- What are the metadata required for CO data? How does this differ from current practice?
- Are the publicly available data sufficiently well documented? How can they be traced to the global standard? What is needed to produce a harmonized global CO data set?
- What are the traceability chains at individual monitoring sites / national networks?
- What is the uncertainty of current CO data?
- Is a harmonized data quality flagging system desirable? Could the CMDL system be adopted by GAW?

- Should the ‘data level’ terminology be adopted by GAW? What are these levels in the context of GAW?

## 4. WORKING GROUP REPORTS

### 4.1 Global CO Cycle

Chair: Geir O. Braathen
Rapporteur: Geir O. Braathen
Members: Carl Brenninkmeijer
Justus Notholt
Curtis Rinsland

#### *4.1.1 Current Status*

Firn air data [*Assonov, et al.*, 2005] show an increase in CO in the southern hemisphere for the 20th century. Ice core data show however that CO may have been higher in the southern hemisphere in the past, due to more intensive biomass burning [*Ferretti, et al.*, 2005]. Thus the history of CO is vaguely known and levels were variable. Because the photochemical oxidation of $CH_4$ is an important source of CO (in particular in the southern hemisphere), the doubling of $CH_4$ has lead to a doubling of CO from this source. This part of the CO cycle is perhaps best known. Recently, the increase in $CH_4$ has lost momentum, but the implications for CO are still uncertain. Globally averaged CO has increased during the industrial revolution, but a levelling off over the recent decades has been postulated, likely due to more efficient combustion and use of catalysts. Global energy demand is still rising, though, more or less in proportion for all major energy types [*BP*, 2005]. To what degree past increases of CO have been driven by intensified forest fire is still being discussed. During the last few decades, atmospheric levels of CO appear to have decreased [*Novelli, et al.*, 2003]. Several stations in the Northern Hemisphere (such as Jungfraujoch in the Swiss Alps, Barrow in the Arctic, and Mauna Loa in Hawaii) report a slight decrease in both in-situ and column CO over the last 20 years. However, inter-annual variability in the Northern Hemisphere is quite high, and this is linked to variations in the frequency of extensive forest fires. Due to drought, certain years are more susceptible to forest fires than others.

With an atmospheric life-time of weeks to months, CO is an important tracer for biomass burning and combustion processes in general. Satellite data have shown that CO from biomass burning can be traced over continental scale distances half-way around the globe. Moreover, the largest forest fires (e.g., in 1998, 2002, and 2003) disturbed atmospheric CO background levels in the entire Northern Hemisphere.

CO also has a major effect on atmospheric chemistry through removal of OH. Less CO will, for many regions, lead to more OH that will remove more $CH_4$ and other reduced compounds. Years of extensive and intensive forest fires in the northern hemisphere show an increased CO burden. This may have had an effect on the growth rate of $CH_4$, via the complex coupling via OH, in which NOx plays an important role. Overall, the sources and sinks of CO are believed to have remained the same. Tropical biomass burning is the major source of CO in the Southern Hemisphere. In the Northern Hemisphere, emissions from transport and industry play a much larger role as sources of CO. During the last decade or so, along with industrial productivity in Asia as well as measures on cleansing vehicle exhausts, source regions in the Northern hemisphere have shifted from US/Europe to Asia.

Climate change, possibly causing droughts, may cause more variability in CO through an intensification of episodic biomass burning.

### 4.1.2 *Identification of Gaps*

There are large discrepancies in the estimates of CO source strengths. The IPCC Third Assessment Report estimates that the annual input of CO is 2800 Tg. Of this, 1550 Tg is emitted directly as CO, 800 Tg is formed through oxidation of methane and 270 Tg comes from oxidation of isoprene.

The distribution and concentrations of OH may have changed, but our knowledge is quite limited. It is desirable to observe CO together with other components, such as $O_3$, NOx, $CH_4$, VOCs to understand what is producing the changes.

The source strength of sub-surface coal fires in China and elsewhere is poorly understood, but potentially significant. Also emissions of CO from peat fires (like the 1997-1998 Indonesian fires) that usually follow strong crown forest fires seem to be significantly underestimated. They are hard to quantify, but important.

Episodes as in 1998, 2002 of high CO concentrations in the Asian tropical region are not sufficiently understood, although progress has been made, e.g., establishing a link between CO and ENSO [*Novelli, et al.*, 2003; *Spichtinger, et al.*, 2004].

In addition, many of the old questions about the CO cycle have still not been answered, as the budget is still beset with large uncertainties. CO is a major player in the global oxidative cycle, yet its budget is not well constrained. Of extreme difficulty is the quantification of CO from isoprene oxidation, as the amount of isoprene emitted annually is difficult to quantify.

There is a large number of stations (some of which are regional GAW stations) that are equipped with less sophisticated (or calibrated) CO monitoring equipment. These measurements are currently poorly exploited, in part because they are not easily accessible and the quality of these observations is not well assessed. There is a need for identification, inter-calibration and improved accessibility of these observations. Much of what we know is based on the NOAA/GMD Carbon Cycle network, and less well organized/harmonized measurements at other sites.

### 4.1.3 *Addressing the Gaps*

The uncertainty in the CO source strengths could be reduced by assessing emission ratios ($CO/CO_2$, $CO/CH_4$, CO/HCN etc.) from all existing earlier campaigns. Furthermore, a better link between fire counts and CO emissions would prove useful, as satellite observations of fires —at least visible fires (peat fires are invisible)— are relatively easy and now routinely available. CO concentrations near the surface are still difficult to estimate from satellites, see below). Although very unevenly distributed globally, the large number of CO monitoring sites operated primarily for compliance monitoring could potentially provide very valuable observations to improve source strengths estimates. This is however conditional on improved inter-calibration and accessibility of these observations.

In order to improve the global coverage on the ground, there is a need for more stations, especially in Africa, South America, China, and India. The majority of these stations should do flask sampling. A few stations with adequate infrastructure and sufficient resident knowledge are required to complete the ground-based remote sensing network. These stations could possibly take over unused instruments from developed countries. The scientific objectives call for medium resolution FT-IR instruments with spectral resolution of 0.01 $cm^{-1}$. At least one FT-IR instrument should be deployed in China at a high altitude site, such as Mt. Waliguan, in order to corroborate the few existing free tropospheric background measurements at, e.g., Jungfraujoch and Zugspitze. In addition, FT-IR measurements at a low-altitude site on the great Chinese plane, i.e. west of Shanhai Pass (Qinhuangdao) would be extremely useful to validate satellite observations and to monitor the anthropogenic CO emission in China. Other instruments for near infrared and visible measurements should in time be added to complement the capability of the FT-IR and provide complementary simultaneous measurements.

Current satellite missions are limited in their ability to provide a global picture of CO. MOPITT does not see the surface and SCIAMACHY has reduced sensitivity over the ocean. A sensor combining the capabilities of existing sensors (i.e. probing the 2.3 and the 4.7 μm bands) and improving on the temporal coverage (i.e. geostationary) is needed. True global coverage can, however, not be achieved with geostationary satellites alone, because of their limitations in the polar region. Therefore, the continuation of LEO missions is needed. Satellite missions are typically designed for 4-6 years involving 5-10 years of development before launch. Smaller, low-cost, focussed satellite missions that can be developed and deployed in a shorter time are needed to provide continuity and to be able to react to changes in requirements more quickly.

The planetary boundary layer (PBL) is the atmospheric layer atop the primary emission sources and is the lowest, yet most polluted layer of the troposphere. Satellites up to now find it difficult to probe into the PBL, a fact that severely limits the usefulness of current satellite observations in assessing the vertical distribution of CO. There is a need for more and continuing aircraft observations, making use both of the commercial fleet to cover regional and inter-continental scales, as well as dedicated smaller aircraft to probe the vertical distribution over smaller scales.

In analogy to the well-established ozone soundings, there is also a need for light-weight, low cost CO sensors for routine deployment on balloons in order to obtain vertical profiles from the ground to the upper troposphere.

Measuring the stable isotopes of CO ($^{13}CO$, $C^{18}O$) has become an order of magnitude easier (cheaper) than before thanks to continuous flow isotope ratio mass spectrometry. This should be considered for flask samples from the GAW network. Measurements of unstable isotopes of CO ($^{14}CO$) have been more or less suspended (to our knowledge, only John Mak, University of Stony Brook, and NIWA, New Zealand are active here), because of lack of funding and because these measurements were considered unimportant. However, they should be continued because they provide the best diagnostic for linking CO and OH. As there are few tracers for OH, $^{14}CO$ may be important [*Lelieveld, et al.*, 2006].

In summary, the in-situ direct measurements and flask sampling should be extended and harmonized under GAW. With the use of civil aircraft (CARIBIC, MOZAIC, JAL), more detailed information about the global distribution is becoming available. The CO budget at 10-12 km altitude is becoming better known.  Thus, these two systems of observation should be promoted. The measurement of CO together with other species is important for better understanding of its budget. Vertical information is scant, and representative sites should have surface based remote sensing equipment. This will also help to verify CO values calculated on the basis of spectral information from satellites. Together with an increasing number of $CO_2$ measurements using small aircraft (e.g. Carbon America), additional CO data will become available.

Altogether; improved and increased observations in conjunction with better emission databases, and modelling will allow us in future to better quantify the budget of CO. It is estimated that at least 15 years of good measurements are needed.

### 4.2 The Global Observing System (IGACO CO)

| | |
|---|---|
| Chair: | Philippe Nédelec |
| Rapporteur: | Harald Flentje |
| Members: | Jgor Arduini |
| | Leonard Barrie |
| | James R. Drummond |
| | David P. Edwards |
| | Jörg Klausen |

Michael Buchwitz

Martin Steinbacher

Leonid Yurganov

***Preamble***

"The Integrated Global Atmospheric Chemistry Observations (IGACO) as part of the Integrated Global Observing Strategy (IGOS) links research, long-term monitoring and operational programmes, bringing together producers and users of global observations to identify products needed and gaps. It aims primarily to integrate satellite, airborne and in-situ observation systems." (from IGACO report, 2004, [*IGACO Theme Team*, 2004])

### *4.2.1 Current Status*

Presently, the key-contributors of long-term CO measurements to the global network can be grouped in three categories:

- Surface based:
  - In-situ/profile – GAW and co-operating agencies, *e.g.*, NOAA/ERSL-GMD or EMEP,
  - Column/profile – FT-IR observations as from NDACC
- Aircraft based:
  - MOZAIC, CARIBIC, JAL, NOAA/GMD
- Satellite based:
  - MOPITT (2000-2010), SCIAMACHY (2002-2010), TES (2004-2009), IASI (2006+), CRIS (2008?), AIRS (2002-2007), each listed with their expected lifetime in parentheses. Most satellite instruments measure radiances at 4.7 µm, providing 1-2 pieces of information on the profile in the troposphere. These profiles are weighted towards the middle and upper troposphere with limited information from the planetary boundary layer (PBL). SCIAMACHY measures CO in the 2.3 µm region, providing a single piece of information with nearly equal sensitivity in nadir mode to all altitudes including the PBL, but no information on the profile.
  - The 4.7 µm and 2.3 µm spectral regions provide complementary information but currently no instrument is in orbit that measures simultaneously in both spectral regions. The tropospheric column can only be retrieved by combining the SCIAMACHY nadir (total column) and limb (stratospheric profiles) information.

### *4.2.2 Identification of Gaps*

An urgent need for more vertical CO information is identified, particularly covering the lower troposphere.

Globally, the spatial coverage is very heterogeneous, with the densest networks of in-situ ground-based monitoring in the northern mid-latitudes. Currently, many of the observations made for air-quality compliance monitoring are not recognised because of the unknown quality. Also, many of these data sets are not readily accessible.

The required temporal coverage depends on the application of the data and ranges from monthly for global re-analyses to hourly for future regional chemical weather forecasting.

The various data sources (as far as they exist to date) are largely disconnected. A more uniform approach is needed to harmonize and integrate available data, which is also a pre-requisite to identifying further gaps in our observation capabilities.

### *4.2.3 Addressing the Gaps*

Vertical information can be obtained in-situ by aircraft or (potentially) balloons, or remotely by ground-based or space-borne sensors. Therefore aircraft observations, additional satellite instruments with vertical profiling capability in the (lower) troposphere, and more FT-IR measurements of vertical profiles are required and should be provided on a timely (near real-time) basis.

Satellite data are still uncertain for several reasons (uneven vertical sensitivity, insufficient reflection from the ocean, weak spectral lines, water vapour absorption, etc.). This uncertainty and a necessity to maintain consistency between successive space-borne sensors call for dedicated ground-based sites for satellite validation. A prototype for these would be the NDACC FT-IR stations with simultaneous in-situ measurements (e.g., Mauna-Loa or Jungfraujoch). Also rugged, remotely operated (unattended) FT-IR instruments should be installed in source areas (China, Africa, Siberia, Amazon, etc.).

The spatial coverage can be improved by adding regionally representative sites, e.g. operated by environmental agencies, in gaps of the global CO network. There are also several observatories equipped by FT-IR instruments within the NDACC network, operated in remote areas representing background conditions. It is highly desirable to add tropospheric gases (including CO) to the priority list of the NDACC products.

The required temporal coverage depends on the specific application. While for offline evaluations and reanalyses monthly data is often sufficient, next generation atmospheric composition/weather operational models need to assimilate few-hourly CO data as near to 'real time' as possible in order to provide chemical weather forecasts on regional scales. To evaluate photochemistry and atmospheric oxidising capacity (OH reactions) in chemical transport models the sampling of the diurnal cycle (*i.e.*, at least twice daily) would be desirable. Geostationary CO measurements would add better horizontal resolution for chemical weather forecasts, regional air quality (RAQ) modelling, monitoring and regulation. Complementary low earth orbit (LEO) CO observations provide the global coverage necessary for global studies. Both geostationary and LEO satellite instruments should incorporate both the 4.7 μm and 2.3 μm spectral regions in order to maximise the vertical information available.

Integration of observations means establishing a complete, internally consistent data flow into interlinked commonly accessible data bases. This will involve an iterative network-organising approach and is by no means straightforward. The data policy within the different networks is specified by individual data protocols, and so the guidelines for data delivery (e.g. delay, format) and -usage are different. At first, all delivered data products must include a characterisation and specified uncertainties. Absolute scales for CO must be linked to the GAW world reference standard maintained by NOAA. It seems necessary to integrate different types of data separately because e.g. satellite CO column data have different characteristics (averaging kernels) than ground in-situ observations and thus needs other ancillary information in order to allow for inter-comparison and integration. The physical units for CO have to be standardised in the data bases. Discrepancies/ambiguities must not occur between data sets at different data centres. In order to achieve a higher degree of harmonisation for each component of the measurement system for CO, adequate efforts/resources are required for characterisation, quality assurance/specification and the product itself.

The role of GAW could be to establish an integrated effort to address the use of observations of CO, ozone, ozone precursors and PM in air quality and long range transport studies as envisaged in the IGACO activities.

The working term '(near) real time' data delivery must be defined according to requirements of operational assimilation systems and typically describes a delay between observation and reporting of a few hours and generally less than half-a-day. The main motivation for a (near) real time CO observation delivery are next generation forecast models which aim at regional air quality forecasts with equally high temporal and spatial resolution.

Satellite CO products are not available in real time at the moment. This is also the case for most other data except from short field campaigns and part of environmental agencies' networks. In order to achieve (near) real time delivery of existing instrumental data usable for the forecast agency (*e.g.*, via GTS), we need rugged equipment, more automated data delivery and support for data generators to do this.

### 4.3 Calibration / Validation and CO Scale

Chair: Doug Worthy

Rapporteur: Christoph Zellweger

Members: Stefan Gilge

Armin Jordan

Paul C. Novelli

Glen Sachse

Peter G. Simmonds

The working group focused on the calibration and validation of carbon monoxide measurements at GAW stations. Some of the problems related to calibration and validation issues were already recognised and summarised as recommendations in the Addendum to the Strategic Plan of the Global Atmosphere Watch Programme (2001 – 2007) [*WMO*, 2004], namely:

- To improve the internal consistency of the current NOAA/GMD CO scale, to adopt a harmonized CO scale for all GAW activities and to promote its use.

- To issue a Scientific Advisory Group for Reactive Gases (SAG RG) guidance document on CO measurements containing data quality objectives (DQOs) and standard operating procedures (SOPs) for continuous measurements including calibration and quality assurance and covering various measurement techniques.

- To recommend a procedure detailing how to apply (a corrected) scale to existing data and how to document such corrections.

It was recognised by the working group that some progress was made but that these issues were still not fully resolved.

#### *4.3.1 Current Status*

NOAA/ESRL-GMD is the designated Central Calibration Laboratory (CCL) for carbon monoxide in the GAW programme. In this function NOAA/ ESRL-GMD provides CO standards with concentrations at ambient levels. Currently two scale versions (WMO-88 and WMO-2000) exist, both based on a set of gravimetric standards that were propagated to primary and working standards. Details about the scale and its revision in 2000 can be found in [*Novelli, et al.*, 2003]. Conversion of the WMO-88 to WMO-2000 scale is not linear and has not yet been published. It was agreed that it is the responsibility of the CCL to maintain the scale and to provide updates to users.

Drift was identified as one of the limiting factors concerning scale stability. Furthermore, instrument limitations made the scale difficult to maintain. Newer measurement techniques such as VUV-Fluorescence significantly improved the capabilities for accurate and precise CO measurements. In combination with accurate and precise dilution systems, CO standards at higher mixing ratios (ppm level) could be used to monitor the stability of ppb standards.

The designated World Calibration Centre (WCC) for CO is hosted at EMPA (WCC-EMPA), however, no Regional Calibration Centres are recognized by GAW at this point. WCC-EMPA has conducted 21 CO audits at 14 global stations between 1997 and 2005. Audit results show that traceability is not completely ensured for in-situ measurements even at global sites. Data quality is highly variable and deviations of up to 10% are often found. The main reasons for this are

- the use of different scales,
- drift of standard gases,
- insufficient characterisation of non-linear instrument response

Different scales are still in use because the accuracy and internal consistency of the scales have not yet been fully established. Recent inter-comparisons between NOAA/ESRL-GMD and WCC-EMPA showed that the WMO-2000 CO scale still reveals small inconsistencies especially at low concentrations (below 200 ppb).

Beside the NOAA/ESRL-GMD carbon monoxide scale, other scales are in use, e.g. the CSIRO (Aspendale, Australia). Furthermore gravimetric standards of National Metrological Institutes (e.g. NIST, NMI, NPL) are widely used to calibrate CO instruments especially in national networks. Information about scale comparability is not yet published.

#### *4.3.2 Identification of Gaps*

For in-situ CO measurements, several different measurement techniques are currently used. The most commonly used techniques are NDIR, GC/HgO, GC/FID and VUV-fluorescence. Some of these techniques exhibit non-linear response functions, and these require multi-point calibration procedures involving a series of standards. The quality of these observations could also be improved if standard operating procedures (SOPs) were more widely available for all of the various instruments and techniques in use.

It was recognised by NOAA/ESRL-GMD that small corrections of the WMO-2000 might be needed to improve its internal consistency and that regular preparation of gravimetric standards is important to ensure continuity and the stability of the NOAA/ESRL-GMD CO scale.

It was further recognized that the traceability of a large number of Regional GAW monitoring stations is unknown and that full traceability is not completely ensured for in-situ measurements even at global sites. Considering the gaps in global coverage, these observations are potentially extremely valuable and should be exploited.

To date, there is no formal link between ground-based in-situ and vertical profile or total column (ground-based remote and space-borne) measurements, and consistency of these various data sources has not been demonstrated. Consequently, these measurements are not all traceable to the WMO-GAW reference scale.

#### *4.3.3 Addressing the Gaps*

Currently the SAG RG is working on a guidance document which should cover instrument specific issues and address some of the above gaps. It was agreed that such a document should also contain information on typical instrument set-ups including a comprehensive description of calibration procedures.

The frequency of the preparation of gravimetric standards should be increased to a biannual interval to determine long term drift of the scale. Furthermore the CCL should improve its capability of making accurate dilutions as a second means of assuring the stability of the WMO-GAW scale. Regular inter-comparisons with other standards (e.g. NIST, NMI, NPL) would further strengthen the NOAA/GMD CO scale.

Standard drift remains a serious issue for CO measurements and recalibration of laboratory standards is strongly suggested on a biannual basis.

The idea of having a common CCL for carbon monoxide and hydrogen was also discussed. It was agreed that the only link between the two components is a common measurement technique (GC/HgO). However, stability issues are for the two species considerably different, and a common CCL seems not too feasible at the present stage.

Within the GAW programme, regular inter-comparisons or calibrations by designated calibration centres (with global or regional scope) are necessary to ensure traceability, and the use of calibration gases obtained directly from the CCL is strongly recommended.

To ensure traceability of GAW measurements, each station of the programme should obtain an adequate number of standards directly from the CCL. If this is not possible, a direct link to the CCL must be established. The number of standards needed depends on the measurement technique. Furthermore, regular audits by the responsible calibration centres are needed as an independent check of the measurements on-site.

It should further be explored if regional round robins could help to establish a link to the CCL or a Global GAW station.

For many stations, a dynamic dilution system may be an alternative (or additional) means of calibrating their instruments, in particular in cases, where non-linear instrument response may be an issue. WCC-EMPA should take the lead in establishing the practicality of such an approach and in assessing the resulting uncertainties for the ambient CO measurements.

Due to the small number of analytical labs involved, traceability and internal consistency of flask data is generally better in comparison to in-situ data. For example, extensive inter-comparisons are continuously being made between the NOAA/ESRL-GMD and CSIRO flask networks [*Masarie, et al.*, 2001]. Despite better internal consistency, drift issues are still not completely resolved.

Traceability of vertical column (ground based remote sensing and satellite) measurements to the reference scale used for ground based (in-situ and flask) measurements is currently difficult to establish for reasons of methodology, and because uncertainties of total column satellite measurements are significantly higher.

It was also recognised that the quality of in-situ data is highly variable and often unknown. The reasons for this were mainly found in the scale and calibration issues discussed above. Consequently, the following recommendations are made:

Measurements need to be better documented. This is of crucial importance when corrections of acquired data is needed e.g. as a consequence of a scale revision.

Stations should follow the guidance document for carbon monoxide that is currently in preparation by the SAG RG. This is especially important for the calibration procedures of the non-linear measurement techniques, which require a full characterisation of the response function over the entire measurement range.

Frequent inter-comparisons and audits are necessary and have been shown to improve data quality.

Additional information about data quality should be available directly at the data centre (WDCGG).

### 4.4 Data Quality, Data Management and Integration

Chair: Gabrielle Pétron

Rapporteur: Stephan Henne

Members: Brigitte Buchmann
Emmanuel Mahieu
Jörg Klausen
Isabell Kramer
Ludwig Ries

Valérie Thouret

Kazuhiro Tsuboi

### *4.4.1 Current Status*

Quality assurance and data management of CO measurements in the complex atmospheric system is of particular importance for the use of these measurements in applications like trend analysis and validation of global atmospheric chemistry models and emission inventories.

A number of different in-situ and ground based remote sensing networks and projects contribute to the global picture of CO mixing ratios in the atmosphere. Of these measurement programmes, several are part of WMO-GAW and submit CO data directly to the GAW Word Data Centre for Greenhouse Gases (WDCGG, http://gaw.kishou.go.jp/wdcgg.html) in Japan. The main contributors to the WDCGG are the flask sampling networks run by NOAA/ERSL-GMD and CSIRO/GASLAB that both part of GAW. In addition, continuous CO measurements are performed at 38 GAW sites. Of these, only 15 have submitted data to the WDCGG so far.

Other programmes host their data in independent data centres. These include in particular the Network for the Detection of Atmospheric Composition Change (NDACC, http://www.ndacc.org/), and Measurement of Ozone and water vapour by Airbus In-service aircraft / Integration of routine Aircraft measurements into a Global Observing System (MOZAIC/IAGOS, http://www.aero.obs-mip.fr/mozaic/). Both programmes are associated with the GAW project or will be associated in the near future.

Furthermore, satellite retrieval of CO columns is performed by a number of satellites in operation (e.g. MOPITT, SCIAMACHY, AIRS, TES). Further details on the various measurement programmes can be found in the IGACO theme report [*IGACO Theme Team*, 2004].

Quality assurance is done in many different ways by different data collectors and networks. Different measurement techniques and instrumentation ask for individual treatment of data quality assurance. Different CO scales have been used in the past and measurements are often not linked adequately to these scales.

Again, the data management by different centres is done in various ways and data are stored in various formats. Of the data sources mentioned above, access to the WDCGG and NDACC is public, while access to MOZAIC data requires the submission of a data request. All data are free of charge for non-commercial use.

### *4.4.2 Identification of Gaps*

Since quality assurance is done in various ways, no common data flagging definition exists within the GAW CO programme. Individual data providers submit their data flags to the WDCGG, however, no harmonization is done at the data centres and submission of flags is not required. Other data centres do not store flagging information at all (NDACC, MOZAIC). Data flags provide important ancillary information about instrument performance, and are also a convenient way of describing the representativeness of a data point.

A data point is only useful for interpretation by the data user if the data collector provides an uncertainty estimate with it. Within the WMO-GAW in-situ CO measurement programme, no general concept exists yet of how to assign a meaningful and commonly used uncertainty to the measurements. Furthermore, for data submission to the WDCGG, the data collector is not required to submit uncertainties. In the NDACC and MOZAIC data bases, the data user is given a typical uncertainty, but no estimate for individual measurements is given. For data assimilation purposes in chemical model systems, however, an uncertainty estimate for individual data points would help to improve the assimilation quality. In addition, the information on the applied CO scale is often missing or incomplete at the WDCGG. As a consequence, the various data series might be biased relative to each other.

Besides the different physical locations of the individual data centres, CO data is often reported in different units, so that ancillary data are needed for conversion. However, this ancillary information is not always available. Furthermore, data are often submitted with an unnecessary delay that ranges from one year to more than three years. Within GAW, no central evaluation of commitments to the project exists. Data submission is often hindered by insufficient man power and the urge to finish all kind of data analysis before data submission.

#### *4.4.3 Addressing the Gaps*

In order to improve harmonized quality assurance within the GAW in-situ CO network, an annual station activity report, to be submitted to the GAW Secretariat by the data collectors, is suggested. The GAW Scientific Advisory Group for Reactive Gases (SAG/RG) should provide templates for different CO measurement techniques. These templates could be included in the SAG RG 'Guidance Document on Carbon Monoxide' that is currently in preparation. The annual reports should include a general description of the measurements and the data quality assurance programmes at the site. Any internal audits that were performed at individual stations should be reported together with the traceability of the CO measurements. It is suggested to make these annual reports publicly available at the WDCGG. The GAW Secretariat would be responsible for assuring submission and publication of these reports within a reasonable period.

NOAA/ERSL-GMD applies a standardized flagging system to their flask sampling network. The SAG RG is requested to consider if this flagging scheme is applicable to all GAW in-situ CO measurements. Not only a performance flag, but also a classification flag of the sampled air mass would be useful for the data user, for example to distinguish between free tropospheric air masses and boundary layer influenced air masses. A minimum list of standardized flags should be provided, depending on the measurement technique. Data collectors should be required to submit these flags together with any CO data as well as estimates of the measurement uncertainties. A harmonized definition of uncertainty has to be found by the SAG RG.

Integrated data acquisition systems, that allow one to perform certain quality checks automatically and to enter metadata in real time, could be used to harmonize procedures between different stations and increase acquisition reliability.

In order to harmonize the units of reported CO data, it is suggested to present CO data as mixing ratios (ppb) for in-situ and retrieved profile measurements, and as number concentrations (molecules $cm^{-2}$) for column data. The submission of ancillary data is still encouraged, in order to enable unit conversion for different purposes. The units of current data items at the data centres should be re-evaluated and harmonized.

Certain international standards for data storage have been defined by ISO [*ISO*, 2003]. These should be followed whenever new data formats are established or to revise existing data formats. Again, the submission and storage of essential metadata has to be defined and required by the data submitter.

The data centres should be able to perform consistency checks of submitted data. Data should be rejected if certain criteria, that have to be defined, are not met. The WDCGG is asked to evaluate its capacity to accept other spreadsheet data formats for data submission, in order to reduce the work load of the data providers.

At the moment it seems to be too demanding to integrate the different global CO databases into one comprehensive database, both because of funding and additional work load. However, it is recommended that the data centres provide an up to date, complete detailed list of other available CO data sources in a way that the data user can easily access data from different databases.

### *4.4.4 Conclusions*

Though often too little attention is paid to data quality assurance, only improved harmonization of quality assurance, data management and further integration of various data sources will assure enhanced use of the measured CO data. The knowledge of the measurement uncertainty is crucial for the application of CO data in trend analysis, model evaluation, data assimilation, and inverse modelling.

## 4.5 References


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# 5. WORKSHOP RECOMMENDATIONS

The numerous results produced by the working groups were first reviewed during the last day of the meeting. They were then refined and grouped, and were open for review by all participants for a period of about 3 months after the meeting. In summary, the recommendations are as follows (responsible bodies are given in parentheses):

### Design and Implementation of Observing System

1. FT-IR systems, sampling the whole atmosphere, should be deployed to fill gaps in areas with increasing emissions in the global network (e.g. China).

   (WMO-GAW Secretariat, in collaboration with NDACC)

2. The global coverage of the surface in situ CO observation system should be improved by either establishing more flask sampling sites or continuous in situ monitoring sites. This is necessary to adequately take into account the large differences in strength and spatial variability of emission sources.

   (WMO-GAW Secretariat, in collaboration with NOAA, CSIRO)

3. Flask sampling programmes should be extended to all GAW continuous monitoring sites to ensure comparability of global observations.

   (GAW Stations, in collaboration with NOAA, CSIRO)

4. The global scale monitoring using passenger aircraft as carried out by scientists in Japan (the JAL Project) and Europe (CARIBIC and MOZAIC) should be more strongly supported. These "flying GAW stations" are a new, powerful component in the total observing system.

(WMO-GAW Secretariat)

5. (WMO-GAW Secretariat) Future satellite missions should deploy a mix of geostationary satellites (GEOS) and low earth orbiting satellites (LEOS), both equipped with the 2.4 and 4.7 μm channels, recognizing that GEOS are needed to address issues of regional air quality and compliance monitoring, and LEOS are needed to complement the limited polar coverage of GEOS and to study the long range transport of pollutants.

(NASA, ESA, in collaboration with WMO-GAW Secretariat)

6. Column CO and vertical CO profiles should be included in the list of priority parameters for the Network for the Detection of Atmospheric Composition Change (NDACC).

(NDACC)

7. Measurement of stable isotopes of CO ($^{13}CO$, $C^{18}O$) should be considered for flask samples from the GAW network. Measurements of unstable isotopes of CO ($^{14}CO$) should be continued and intensified, because they provide the best diagnostic for linking CO and OH.

(SAG RG)

***Instrument Development***

8. A light-weight CO sensor for regular deployment on air-borne platforms should be developed to improve the availability of profile information, necessary both for satellite and model validation as well as transport studies.

(All)

***Traceability, Standards***

9. The WMO-GAW Central Calibration Laboratory (CCL) for CO (NOAA-GMD) should prepare gravimetric standards (primaries) on a biannual basis to be able to determine the long-term stability of the world reference scale.

(NOAA-GMD)

10. The WMO-GAW CCL for CO (NOAA-GMD) should improve its capability of making accurate dilutions as a second means of assuring the stability of the WMO-GAW scale.

(NOAA-GMD)

11. The WMO-GAW World Calibration Centre for Carbon Monoxide (WCC-EMPA) and the CCL should work together to conduct yearly inter-comparisons to improve the traceability of the WCC to the GAW world reference standard and as a third means of assuring the stability of the WMO-GAW scale.

(NOAA-GMD, EMPA)

12. WCC-EMPA should take the lead in testing a dynamic dilution system as an alternative (or additional) means for stations of calibrating their instruments, in particular in cases, where non-linear instrument response may be an issue.

(EMPA)

13. All stations participating in the GAW programme should establish a direct link to the CCL, preferably by obtaining an adequate number of standards directly from the CCL. In particular, GAW Global stations are encouraged to get actively involved in supporting the calibration of regional stations in their area, including existing GAW Regional stations, as well as stations operated by EPAs (Environmental Protection Agencies or other national air quality agencies) and other programmes

(NOAA-GMD, GAW Stations)

*Data Documentation, Data Management*

14. Stations should be encouraged to deliver data in near-real time (NRT) to the forecasting community, recognizing however that the onus is on the forecasting community to better specify their needs and requirements.

(ECMWF, GEMS, in collaboration with GAW stations)

15. Time-stamped versions of data should be maintained in major data archives and duplication of data avoided.

(WDCGG, NDACC, MOZAIC)

16. All data archiving should include the appropriate metadata that are necessary to integrate different datasets for specific applications.

(WDCGG, NDACC, MOZAIC)

17. The GAW Scientific Advisory Group on Reactive Gases (SAG RG) sub-group on CO should develop data quality objectives (DQOs) for CO, considering the different levels of CO encountered at remote and more regional sites, taking into account different applications of the data obtained.

(SAG RG)

18. The SAG RG sub-group on CO is requested to complete the Guidance Document on CO Measurements, being specific enough and offer examples of the various measurement techniques/analytical set-ups to allow operation/documentation such that known data quality can be assured.

(SAG RG)

19. All stations should improve their quality assurance protocols according to the SAG RG sub-group on CO Guidance Document, particularly regarding the documentation of their measurement process and QA procedures.

(GAW Stations)

20. The World Data Centre for Greenhouse Gases (WDCGG) should work with the managers of the other GAW World Data Centres and the GAW Station Information System (GAWSIS) to improve documentation of the quality of the archived data.

(WDCGG, WDCs, GAWSIS)

21. WDCGG should only accept and distribute data that include appropriate uncertainty estimates, data quality flags, and information on the link to the WMO world reference scale maintained by NOAA (including the version used).

(WDCGG, data providers)

22. The GAWSIS manager and the WMO-GAW Secretariat should intensify their interactions with the stations towards updating the information about CO measurements available in GAWSIS.

(GAWSIS, GAW Secretariat)

23. The WMO-GAW Secretariat should explore the possibility and added value of requesting all GAW-coordinated programmes/stations to submit a formalised yearly activity report by March of the following year, recognizing that GAWSIS already offers similar possibilities.

(GAW Secretariat, GAWSIS)

## 6. CLOSING OF THE MEETING

The participants expressed their great satisfaction with the conduct and outcome of the Workshop. They enjoyed the excellent local arrangements, an interesting guided tour around the beautiful City of Zurich, and a memorable conference dinner in a traditional guild hall.

The Workshop was declared closed at 12:30 noon, 27 October 2005.

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## Joint WMO-GAW/ACCENT Workshop on the Global Tropospheric Carbon Monoxide Observations System, Quality Assurance and Applications (24 – 26 October 2005, EMPA Dübendorf, Switzerland)

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**ANNEX B**

## Joint WMO-GAW/ACCENT Workshop on the Global Tropospheric Carbon Monoxide Observations System, Quality Assurance and Applications (24 – 26 October 2005, EMPA Dübendorf, Switzerland)

### WORKSHOP PROGRAMME

***Monday, October 24, 2005***

| | |
|---|---|
| 8:30 | Registration |
| 9:00 | Opening |
| **Session 1** | **User Requirements (chair: Stefan Reimann)** |
| 9:30 – 9:50 | *Len Barrie*, Current gaps in GAW and an Integrated Global Atmospheric Chemistry Observations (IGACO) system for CO. |
| 9:50 – 10:10 | *John van Aardenne*, The need for high-quality CO data to improve emission estimates. |
| 10:10 – 10:30 | *Harald Flentje*, Applications of CO observations in the development of next generation forecast models (e.g. the EC GEMS project requirements) |
| 10:30 – 10:50 | *Gabrielle Pétron*, The need for high-quality CO data in Chemical Transport Models and Data Assimilation. |
| 10:50 – 11:20 | Coffee break |
| **Session 2** | **Quality Assurance of Ground-Based Measurements and the WMO-GAW World Reference CO Scale (chair: Maria Makarova)** |
| 11:20 – 11:40 | *Jörg Klausen*, Status of the GAW CO Network. |
| 11:40 – 12:00 | *Paul Novelli*, History and status of the CMDL CO scale. |
| 12:00 – 12:20 | *Paul Steele**, CO measurement issues encountered by CSIRO. (**Material will be presented)* |
| 12:20 – 12:40 | *Peter Simmonds*, Calibration and traceability of AGAGE measurements. |
| 12:40 – 13:00 | *Christoph Zellweger*, CO audits at GAW Global observatories and implications for data quality. |
| 13:00 – 14:00 | Lunch break |
| 14:00 – 15:30 | **Working Groups** |
| 15:30 – 16:00 | Coffee break & **Posters** |
| 16:00 – 16:30 | **Working Groups** |
| 16:30 – 17:00 | Presentation of WG results and discussion |
| 17:00 | Adjourn |

| *Tuesday, October 25, 2005* | |
|---|---|
| **Session 3** | **Aircraft and Ground-Based Remote-Sensing, Reconstructions (chair: Armin Jordan)** |
| 09:00 – 09:20 | *Philippe Nédélec*, Four years of regular CO measurements from the MOZAIC programme. |
| 09:30 – 09:50 | *Justus Notholt*, Atmospheric CO as measured by the NDSC network. |
| 09:50 – 10:10 | *Leonid Yurganov*, Integration of ground-based and satellite measurements for a long-term CO monitoring. |
| 10:10 – 10:30 | *Carl Brenninkmeijer*, A reconstruction of the past trend of atmospheric CO based on firn air samples from Berkner Island, Antarctica, and reflections on how well we ought to know present atmospheric CO. |
| 10:30 – 11:00 | Coffee break |
| **Session 4** | **Satellite-Based Remote-Sensing (chair: Valérie Thouret)** |
| 11:00 – 11:20 | *James Drummond*, Carbon Monoxide Measurements from Space: Past, Present and Future. |
| 11:20 – 11:40 | *Curtis Rinsland*, Space-based infrared solar occultation measurements of Carbon Monoxide: Measurements and Aura validation activities. |
| 11:40 – 12:00 | *David Edwards*, Five years of Terra/MOPITT data: A satellite perspective on the variability of carbon monoxide in the troposphere. |
| 12:00 – 12:20 | *Michael Buchwitz*, Global atmospheric measurements of carbon gases by SCIAMACHY/ENVISAT: Carbon monoxide, methane, and $CO_2$. |
| **Posters** | **Authors are requested to be present near their poster** |
| 12:20 – 13:00 | *Stefan Gilge*, Quality assurance of long-term CO measurements. |
| | *Stephan Henne*, Quality Assurance and Analysis of CO measurements at the global GAW site Mt. Kenya. |
| | *Maria Makarova*, Results of carbon monoxide total column amount measurements near St. Petersburg (Russia) |
| | *Glen Sachse,* Low-Earth-Orbit Global Mapping of Boundary Layer Carbon Monoxide |
| | *Martin Steinbacher*, CO measurements at the high-alpine global GAW site Jungfraujoch, Switzerland |
| | *Kazuhiro Tsuboi*, The JMA CO Measurement Programme at the GAW stations in Japan. |
| | *Doug Worthy*, The Canadian Baseline Carbon Monoxide Measurement Programme. |
| 13:00 – 14:00 | Lunch break |
| 14:00 – 15:30 | **Working Groups** |
| 15:30 – 16:00 | Coffee break |

| | |
|---|---|
| 16:00 | **Guided tour** (walk) of Zurich |
| 19:00 | **Workshop dinner** (sponsored) |

***Wednesday, October 26, 2005***

| | |
|---|---|
| 9:00 – 10:30 | Presentation of WG results and discussion |
| 10:30 – 11:00 | Coffee break |
| 11:00 – 12:30 | Draft recommendations, final discussion |
| 12:30 | End of workshop |

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**ANNEX C**

## WORKSHOP PRESENTATIONS

All oral presentations given during the workshop, as well as some of the poster presentations are available online for download at www.EMPA.ch/co-workshop.

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## GLOBAL ATMOSPHERE WATCH REPORT SERIES

1. Final Report of the Expert Meeting on the Operation of Integrated Monitoring Programmes, Geneva, 2 -5 September 1980.

2. Report of the Third Session of the GESAMP Working Group on the Interchange of Pollutants Between the Atmosphere and the Oceans (INTERPOLL-III), Miami, USA, 27-31 October 1980.

3. Report of the Expert Meeting on the Assessment of the Meteorological Aspects of the First Phase of EMEP, Shinfield Park, U.K., 30 March - 2 April 1981.

4. Summary Report on the Status of the WMO Background Air Pollution Monitoring Network as at April 1981.

5. Report of the WMO/UNEP/ICSU Meeting on Instruments, Standardization and Measurements Techniques for Atmospheric $CO_2$, Geneva, 8-11; September 1981.

6. Report of the Meeting of Experts on BAPMoN Station Operation, Geneva, 23–26 November 1981.

7. Fourth Analysis on Reference Precipitation Samples by the Participating World Meteorological Organization Laboratories by Robert L. Lampe and John C. Puzak, December 1981.

8. Review of the Chemical Composition of Precipitation as Measured by the WMO BAPMoN by Prof. Dr. Hans-Walter Georgii, February 1982.

9. An Assessment of BAPMoN Data Currently Available on the Concentration of $CO_2$ in the Atmosphere by M.R. Manning, February 1982.

10. Report of the Meeting of Experts on Meteorological Aspects of Long-range Transport of Pollutants, Toronto, Canada, 30 November - 4 December 1981.

11. Summary Report on the Status of the WMO Background Air Pollution Monitoring Network as at May 1982.

12. Report on the Mount Kenya Baseline Station Feasibility Study edited by Dr. Russell C. Schnell.

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32. Manual for BAPMoN Station Operators by E. Meszaros and D.M. Whelpdale. October 1985 (WMO TD No. 66).

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80. Report of the WMO Meeting of Experts on the Quality Assurance Plan for the GAW, Garmisch-Partenkirchen, Germany, 26-30 March 1992 (WMO TD No. 513).

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83. Report on the Global Precipitation Chemistry Programme of BAPMoN (WMO TD No. 526).

84. Provisional Daily Atmospheric Carbon Dioxide Concentrations as measured at GAW-BAPMoN sites for the year 1991 (WMO TD No. 543).

85. Chemical Analysis of Precipitation for GAW: Laboratory Analytical Methods and Sample Collection Standards by Dr Jaroslav Santroch (WMO TD No. 550).

86. The Global Atmosphere Watch Guide, 1993 (WMO TD No. 553).

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103. Report of the Meeting of Experts on the WMO World Data Centres, Toronto, Canada, 17 - 18 February 1995, (prepared by Edward Hare) (WMO TD No. 679).

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109. Report of an Expert Consultation on 85Kr and 222Rn: Measurements, Effects and Applications (Freiburg, Germany, 28-31 March 1995) (WMO TD No. 733).

110. Report of the WMO-NOAA Expert Meeting on GAW Data Acquisition and Archiving (Asheville, NC, USA, 4-8 November 1995) (WMO TD No. 755).

111. Report of the WMO-BMBF Workshop on VOC Establishment of a “World Calibration/Instrument Intercomparison Facility for VOC” to Serve the WMO Global Atmosphere Watch (GAW) Programme (Garmisch-Partenkirchen, Germany, 17-21 December 1995) (WMO TD No. 756).

112. Report of the WMO/STUK Intercomparison of Erythemally-Weighted Solar UV Radiometers, Spring/Summer 1995, Helsinki, Finland (WMO TD No. 781).

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114. Report of the Fifth WMO Meeting of Experts on the Quality Assurance/Science Activity Centres (QA/SACs) of the Global Atmosphere Watch, jointly held with the Second Meeting of the Coordinating Committees of IGAC-GLONET and IGAC-ACE[Ed], Garmisch-Partenkirchen, Germany, 15-19 July 1996 (WMO TD No. 787).

115. Report of the Meeting of Experts on Atmospheric Urban Pollution and the Role of NMSs (Geneva, 7-11 October 1996) (WMO TD No. 801).

116. Expert Meeting on Chemistry of Aerosols, Clouds and Atmospheric Precipitation in the Former USSR (Saint Petersburg, Russian Federation, 13-15 November 1995).

117. Report and Proceedings of the Workshop on the Assessment of EMEP Activities Concerning Heavy Metals and Persistent Organic Pollutants and their Further Development (Moscow, Russian Federation, 24-26 September 1996) (Volumes I and II) (WMO TD No. 806).

118. Report of the International Workshops on Ozone Observation in Asia and the Pacific Region (IWOAP, IWOAP-II), (IWOAP, 27 February-26 March 1996 and IWOAP-II, 20 August-18 September 1996) (WMO TD No. 827).

119. Report on BoM/NOAA/WMO International Comparison of the Dobson Spectrophotometers (Perth Airport, Perth, Australia, 3-14 February 1997), (prepared by Robert Evans and James Easson) (WMO TD No. 828).

120. WMO-UMAP Workshop on Broad-Band UV Radiometers (Garmisch-Partenkirchen, Germany, 22 to 23 April 1996) (WMO TD No. 894).

121. Report of the Eighth WMO Meeting of Experts on Carbon Dioxide Concentration and Isotopic Measurement Techniques (prepared by Thomas Conway) (Boulder, CO, 6-11 July 1995) (WMO TD No. 821).

122. Report of Passive Samplers for Atmospheric Chemistry Measurements and their Role in GAW (prepared by Greg Carmichael) (WMO TD No. 829).

123. Report of WMO Meeting of Experts on GAW Regional Network in RA VI, Budapest, Hungary, 5 to 9 May 1997.

124. Fifth Session of the EC Panel of Experts/CAS Working Group on Environmental Pollution and Atmospheric Chemistry, (Geneva, Switzerland, 7-10 April 1997) (WMO TD No. 898)

125. Instruments to Measure Solar Ultraviolet Radiation, Part 1: Spectral Instruments (lead author G. Seckmeyer) (WMO TD No. 1066)

126. Guidelines for Site Quality Control of UV Monitoring (lead author A.R. Webb) (WMO TD No. 884).

127. Report of the WMO-WHO Meeting of Experts on Standardization of UV Indices and their Dissemination to the Public (Les Diablerets, Switzerland, 21-25 July 1997) (WMO TD No. 921).

128. The Fourth Biennial WMO Consultation on Brewer Ozone and UV Spectrophotometer Operation, Calibration and Data Reporting, (Rome, Italy, 22-25 September 1996) (WMO TD No. 918).

129. Guidelines for Atmospheric Trace Gas Data Management (Ken Masarie and Pieter Tans), 1998 (WMO TD No. 907).

130. Jülich Ozone Sonde Intercomparison Experiment (JOSIE, 5 February to 8 March 1996), (H.G.J. Smit and D. Kley) (WMO TD No. 926).

131. WMO Workshop on Regional Transboundary Smoke and Haze in Southeast Asia (Singapore, 2 to 5 June 1998) (Gregory R. Carmichael). Two volumes.

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133. Workshop on Advanced Statistical Methods and their Application to Air Quality Data Sets (Helsinki, 14-18 September 1998) (WMO TD No. 956).

134. Guide on Sampling and Analysis Techniques for Chemical Constituents and Physical Properties in Air and Precipitation as Applied at Stations of the Global Atmosphere Watch. Carbon Dioxide (WMO TD No. 980).

135. Sixth Session of the EC Panel of Experts/CAS Working Group on Environmental Pollution and Atmospheric Chemistry (Zurich, Switzerland, 8-11 March 1999) (WMO TD No.1002).

136. WMO/EMEP/UNEP Workshop on Modelling of Atmospheric Transport and Deposition of Persistent Organic Pollutants and Heavy Metals (Geneva, Switzerland, 16-19 November 1999) (Volumes I and II) (WMO TD No. 1008).

137. Report and Proceedings of the WMO RA II/RA V GAW Workshop on Urban Environment (Beijing, China, 1-4 November 1999) (WMO-TD. 1014) (Prepared by Greg Carmichael).

138. Reports on WMO International Comparisons of Dobson Spectrophotometers, Parts I – Arosa, Switzerland, 19-31 July 1999, Part II – Buenos Aires, Argentina (29 Nov. – 12 Dec. 1999 and Part III – Pretoria, South Africa (18 March – 10 April 2000) (WMO TD No. 1016).

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142. Strategy for the Implementation of the Global Atmosphere Watch Programme (2001-2007), A Contribution to the Implementation of the Long-Term Plan (WMO TD No.1077).

143. Global Atmosphere Watch Measurements Guide (WMO TD No. 1073).

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145. WMO GAW International Comparisons of Dobson Spectrophotometers at the Meteorological Observatory Hohenpeissenberg, Germany (21 May – 10 June 2000, MOHp2000-1), 23 July – 5 August 2000, MOHp2000-2), (10 – 23 June 2001, MOHp2001-1) and (8 to 21 July 2001, MOHp2001-2). Prepared by Ulf Köhler (WMO TD No. 1114).

146. Quality Assurance in monitoring solar ultraviolet radiation: the state of the art. (WMO TD No. 1180).

147. Workshop on GAW in RA VI (Europe), Riga, Latvia, 27-30 May 2002. (WMO TD No. 1206).

148. Report of the Eleventh WMO/IAEA Meeting of Experts on Carbon Dioxide Concentration and Related Tracer Measurement Techniques (Tokyo, Japan, 25-28 September 2001) (WMO TD No 1138).

149. Comparison of Total Ozone Measurements of Dobson and Brewer Spectrophotometers and Recommended Transfer Functions (prepared by J. Staehelin, J. Kerr, R. Evans and K. Vanicek) (WMO TD No. 1147).

150. Updated Guidelines for Atmospheric Trace Gas Data Management (Prepared by Ken Maserie and Pieter Tans (WMO TD No. 1149).

151. Report of the First CAS Working Group on Environmental Pollution and Atmospheric Chemistry (Geneva, Switzerland, 18-19 March 2003) (WMO TD No. 1181).

152. Current Activities of the Global Atmosphere Watch Programme (as presented at the 14th World Meteorological Congress, May 2003). (WMO TD No. 1168).

153. WMO/GAW Aerosol Measurement Procedures: Guidelines and Recommendations. (WMO TD No. 1178).

154. WMO/IMEP-15 Trace Elements in Water Laboratory Intercomparison. (WMO TD No. 1195).

155. 1st International Expert Meeting on Sources and Measurements of Natural Radionuclides Applied to Climate and Air Quality Studies (Gif sur Yvette, France, 3-5 June 2003) (WMO TD No. 1201).

156. Addendum for the Period 2005-2007 to the Strategy for the Implementation of the Global Atmosphere Watch Programme (2001-2007), GAW Report No. 142 (WMO TD No. 1209).

157. JOSIE-1998 Performance of EEC Ozone Sondes of SPC-6A and ENSCI-Z Type (Prepared by Herman G.J. Smit and Wolfgang Straeter) (WMO TD No. 1218).

158. JOSIE-2000 Jülich Ozone Sonde Intercomparison Experiment 2000. The 2000 WMO international intercomparison of operating procedures for ECC-ozone sondes at the environmental simulation facility at Jülich (Prepared by Herman G.J. Smit and Wolfgang Straeter) (WMO TD No. 1225).

159. IGOS-IGACO Report - September 2004 (WMO TD No. 1235).

160. Manual for the GAW Precipitation Chemistry Programme (Guidelines, Data Quality Objectives and Standard Operating Procedures) (WMO TD No. 1251).

161 12th WMO/IAEA Meeting of Experts on Carbon Dioxide Concentration and Related Tracers Measurement Techniques (Toronto, Canada, 15-18 September 2003).

162. WMO/GAW Experts Workshop on a Global Surface-Based Network for Long Term Observations of Column Aerosol Optical Properties, Davos, Switzerland, 8-10 March 2004 (edited by U. Baltensperger, L. Barrie and C. Wehrli) (WMO TD No. 1287).

163. World Meteorological Organization Activities in Support of the Vienna Convention on Protection of the Ozone Layer (WMO No. 974).

164. Instruments to Measure Solar Ultraviolet Radiation: Part 2: Broadband Instruments Measuring Erythemally Weighted Solar Irradiance (WMO TD No. 1289).

165. Report of the CAS Working Group on Environmental Pollution and Atmospheric Chemistry and the GAW 2005 Workshop, 14-18 March 2005, Geneva, Switzerland (WMO TD No. 1302).

166. Joint WMO-GAW/ACCENT Workshop on the Global Tropospheric Carbon Monoxide Observations System, Quality Assurance and Applications (EMPA, Dübendorf, Switzerland, 24-26 October 2005) (edited by Jörg Klausen) (WMO TD No. 1335).