# WORLD METEOROLOGICAL ORGANIZATION
# GLOBAL ATMOSPHERE WATCH

**No. 101**

# REPORT OF THE WMO WORKSHOP ON THE MEASUREMENT OF ATMOSPHERIC OPTICAL DEPTH AND TURBIDITY

**(Silver Spring, USA, 6 – 10 December 1993)**

**WMO TD No. 659**

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## EXECUTIVE SUMMARY

It is widely acknowledged that the measurement of atmospheric turbidity as under the Background Air Pollution Monitoring Programme of the World Meteorological Organization has been far from perfect. In fact, the perceived flaws in the programme and noise in the accumulated data set generated a detailed review of the entire BAPMoN turbidity data acquisition and reduction operation (GAW Report No. 94). The report of the expert committee made a number of specific recommendations for the improvement of the programme under WMO's Global Atmosphere Watch (GAW) System.

Following completion of the expert panel report, a larger international meeting of experts was called by the Air Resources Laboratory of NOAA, on behalf of WMO, to review the conclusions drawn by the expert panel, and to refine the recommendations that were made and tailor them to the new GAW activities that are now planned. The meeting was held on 6-10 December, 1993, at Silver Spring, Maryland, USA. The present report summarizes this meeting, and presents a number of conclusions reached by the working groups that were arranged.

A number of central observations were made by the group. Among the most important are the following:

(a) In as much as the GAW is organized into tiers of stations, with a small array of advanced GLOBAL OBSERVATORIES supporting a larger assembly of less advanced REGIONAL STATIONS, it was tacitly understood that measurements at regional stations will evolve as a body of the measurements of aerosol optical depth at the GLOBAL OBSERVATORIES in the trial phase;

(b) Ongoing sunphotometry programmes having a demonstrated instrument stability of 2% over an interval of one year should be encouraged to continue their existing measurement programmes;

(c) A new standardized data reduction and analysis method is recommended, such that raw data can be re-analyzed in the future as understanding improves;

(d) A high altitude site is recommended for comparison of instruments, for sunphotometer calibrations by extrapolation, and for testing new methods for determining optical depth.

The deliberations of the working groups and their specific suggestions lead to the following major recommendations:

(a) Hand-held sunphotometers as currently prescribed by WMO for its BAPMoN network are inadequate for contemporary needs;

(b) New instrumentation descriptions, operational procedures and standards for sunphotometry are required for the GAW network. These new instruments, their operation, and their calibration procedures should be tested thoroughly during a trial phase at the GAW GLOBAL OBSERVATORIES. Moreover, a comparison programme should be established in order to assess the suitability of new ways for determining aerosol optical depth;

(c) There are several alternative methods for deriving information related to atmospheric turbidity, none of which is yet mature enough to warrant routine use at regional stations. A multi-faceted programme is recommended. Third, relevant quality control procedures must be developed and implemented in collaboration with the new GAW Quality Assurance/Science Activity Centres that are now being set up;

(d) A World Optical Depth Research and Calibration Centre (WORCC) should be established to provide:

   (i) accurate radiometric references and transfer standards for sunphotometry (as for the case for the World Radiometric Reference);

   (ii) development and testing of new instrumentation and methods;

   (iii) implementation of a trial phase at the GAW GLOBAL OBSERVATORIES; and

   (iv) development of relevant quality control procedures, in cooperation with the new GAW Quality Assurance/Science Activity Centres that are now being set up.

The World Radiation centre in Davos, Switzerland, has agreed to perform this important service.

(e) WMO (GAW) should establish a group of experts with the following charter:

   (i) assist the WORCC in defining its tasks;

   (ii) establish in cooperation with the WORCC the specifications for new sunphometers and standard references; and

   (iii) define the objectives of comparison experiments and the implementation of the trial phase.

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## 1. INTRODUCTION

A World Meteorological Organization (WMO) Meeting of Experts to Assess the GAW Measurements and Climate-Related Data of Aerosol Optical Depth/Turbidity convened on 7 December 1993 at the Air Resources Laboratory (ARL) of the U.S. National Oceanic and Atmospheric Administration (NOAA) in Silver Spring, Maryland. The meeting was convened at the request of the WMO, as a step in a process intended to result in an improved measurement protocol for use at sites of the Global Atmosphere Watch (GAW). The need for such improvement is widely recognized. The specific purposes of this meeting related to the demand for aerosol optical depth data of greater quality than had been derived from the long-running BAPMoN network.

The present meeting followed an earlier preparation of a detailed report on the BAPMoN turbidity operation, generated in response to awareness that the WMO BAPMoN/GAW atmospheric turbidity programme has been operating under difficulties and that the data set is extremely noisy. This earlier report was prepared by a small team of experts assembled in 1990; it also contained recommendations to the WMO on how GAW might proceed (GAW Report No. 94). The present meeting was called by the WMO/GAW in order to review this report and to draw up plans for the future. A portion of the planned four-day meeting included a Workshop on the Measurement of Atmospheric Optical Depth and Turbidity, which included Plenary and Working Group sessions. Three ad hoc Working Groups were defined at the start of the Workshop. This report includes the minutes of this meeting and reports submitted by the three Working Groups.

> In particular, an objective assessment and review was needed of the contents and recommendations of the 29 October 1993 GAW Report No. 94 entitled `Report of the Measurements of Atmospheric Turbidity in BAPMoN'. The report had previously been provided to each participant for review prior to the meeting.

Specific advice was needed on how to ensure the highest possible data quality of the WMO optical depth programme. To this end, an independent examination of several aspects of possible new aerosol optical depth programmes was needed.

Thus, the present meeting was called to review the contents of GAW No. 94, and to draw up a plan for the future, considering:

(a) what aerosol-related radiative measurements are required;

(b) what measurements are practical for unsophisticated regional sites and for the significantly more advanced global observatories;

(c) how the new Quality Assurance/Science Advisory Centres will interact with the new aerosol optical depth programme (including interactions with data acquisition and archiving functions); and

(d) how to arrange implementation of the new programme.

Annexes to this report include the Agenda and a List of Participants. A third annex reproduces the Executive Summary of GAW Report No. 94. A final annex presents a summation of the current state of the art of rotating shadow-band technology.

## 2. MEETING SUMMARY

Dr Douglas Whelpdale was elected to Chair the meeting.

The meeting commenced with presentations to provide participants with a basic understanding of the philosophies and operational constraints of the GAW. To this end, Dr John Miller of the WMO's Environmental Division welcomed the participants on behalf of the Secretary-General, Prof. G.O.P. Obasi, and summarized the goals, components, and infrastructure of the GAW programme. In essence, GAW is a tiered array of stations, with a small number of global observatories making research-grade measurements of a wide variety of atmospheric properties, and with a larger number of less sophisticated regional observing stations making simpler measurements. The measurement objectives of GAW are largely related to questions of global air quality and climate, with emphasis on greenhouse gases, ozone, radiation and optical depth, and chemical and physical properties of aerosols. GAW operates with an infrastructure that includes calibration centres, World Data Centres, and Quality Assurance Centres. At the time of the present meeting, only one Quality Assurance Centre is operational -- the European Centre intended to service GAW stations in Europe and Africa. Subsequent to this meeting, a second Quality Assurance Centre has been set up, in the United States and intended to service GAW stations in the Americas. Dr Volker Mohnen, present at this meeting, represented the European Quality Assurance/Science Activity Centre of GAW. A third centre has been established in Japan for Asia and the Pacific.

Dr Bruce Forgan gave an overview of aerosol optical depth measurements, emphasizing their importance in the current debate concerning possible anthropogenic influences on climate change. His presentation included discussion of attenuation and extinction, precision and accuracy, derivation of aerosol optical depth, the use of narrow- and versus broad-band sensors for deriving extinction as a function of wavelength, methods for deriving aerosol/cloud optical depth/turbidity using narrow and broad-band radiometers, and a variety of methods for calibrating single-wavelength sun photometers.

Each participant provided a short presentation on specific areas of interest. The following gave short prepared presentations: Dr Lee Harrison, Mr. Bob Cushman, Dr John DeLuisi, Dr Volker Mohnen, Mr. Bruce Hicks, Dr Adarsh Deepak, Dr Brent Holben, Dr Bruce McArthur, Dr Julian Wilson, Dr Rudolf Husar, Dr Elena Rusina, Dr Joe Michalsky, Dr Claus Frohlich, and Dr Bruce Forgan.

Dr John DeLuisi described the WMO's World Climate Research Programme Baseline Surface Radiation Network (BSRN), including locations of existing, planned, and prospective sites. Although turbidity measurements will be made at these sites, a standard procedure has not yet been adopted. Dr Deluisi also presented information on the USDA's new ultraviolet monitoring network which will include seven-wavelength rotating shadowband radiometers.

Dr Volker Mohnen discussed the quality assurance goals of GAW. He stressed the importance of training, and explained that quality control would be conducted through the use of Standard Operating Procedures (SOP). Calibration, for example, would be translated into an SOP based on input from the scientific community.

Mr. Bruce Hicks summarized the way in which the various radiation measurement arrays operated by NOAA in the United States were being integrated under a single organizational umbrella - the Integrated Surface Irradiance Study (ISIS). Within ISIS, it is proposed to operate rotating shadowband radiometers in order to obtain precise information on small trends in the ratio of diffuse to direct solar radiation. Information of this kind can reveal variations in turbidity that would otherwise require highly intensive and/or advanced sunphotometry measurements.

Dr Brent Holben described a low cost automatic sun photometer system developed by NASA/GSFC which may be remotely deployed and accessed via the Data Collection Platforms aboard geosynchronous weather satellites such as GOES or GMS. His presentation included a description of the instrument, measurement protocol, current and planned networks, maintenance, calibration, and costs. Measurements include ozone, aerosol optical thickness, precipitable water, and sky radiance.

Dr Ellsworth Dutton discussed sun photometer records of aerosol optical depth measurements between 1982 and 1993, for sites operated by the NOAA Climate Monitoring and Diagnostics Laboratory.

## 3. THE WMO BAPMoN REPORT ON TURBIDITY

A discussion of the WMO Background Air Pollution Monitoring Network (BAPMoN) report on turbidity was led by Dr Bruce Forgan. For completeness of the present document, the executive summary of this report is reproduced here, as Annex C. Preparation of this report commenced in February 1989, and was conducted by a panel of four members - John DeLuisi, Bruce Forgan (Chair), Bruce Hicks, and Elena Rusina. John DeLuisi had responsibility for evaluating the U.S. stations; Bruce Forgan, the data archive integrity and instruments; Bruce Hicks, the statistical trend analysis; and Elena Rusina, comparative analysis and pyrheliometry. The major findings of the report were summarized, and problems with the existing data set were presented.

Following a brisk discussion of the report, workshop members unanimously agreed that the panel should be commended for its frank and honest assessment of the BAPMoN turbidity measurement programme. It was also agreed that following further technical editing, the report should be submitted to WMO for review and publication. Among the items requiring attention was the use in the report of terminology referring to "calculated" and "observed" aerosol optical depth. The authors of the draft report undertook to make appropriate editorial corrections, to eliminate such causes of confusion from the text.

> In essence, two measures of the aerosol optical depth are identified with the BAPMoN observation programme. One, the `observed optical depth' is that value calculated by the individual station observer using a station algorithm based on local time and station pressure. The other, the `calculated optical depth' is that value calculated with the World Data Centre algorithm based on time and station altitude. The final report will distinguish clearly between these different quantifications.

Following such editorial attention, the report was submitted to the WMO through its EC Panel. The unanimous opinion of the participants was that the tone of the report should be as positive as possible, since any undue negativism might overshadow the undoubted contributions of the BAPMoN turbidity measurement programme. For example, it was noted that the report generated a number of important "lessons learned" that would contribute significantly to the success of GAW including the necessity for improved training and certification of observers, calibration protocols, standardized algorithms, and an aggressive quality assurance programme. It was the considered opinion of the group as a whole, that the final editing should place a greater emphasis on these aspects of BAPMoN.

A strawman list of goals for the GAW measurement programme was presented and discussed; after minor modification, these were adopted by the group for consideration by Working Groups that were then set up. These four goals related to the needs for:

(a) Standardization, i.e., the observing and reporting of optical depth measurements in a systematic and reliable manner;

(b) Trend detection, i.e., determination of climatic, long-term changes;

(c) Model evaluation/diagnostics, i.e., the use of GAW measurements for the purpose of evaluating and verifying numerical models; and

(d) Satellite ground truth, i.e., provision of high quality surface observations for calibrating and verifying satellite determined optical depth estimates.

Discussion related to these goals focused on variations of sunphotometry. The techniques employed in the use of sunphotometers are well known; a considerable part of the meeting explored recent developments in the methodologies of sunphometry, as will be evident in the text that follows.

Alternative methods have been developed over the last decade, including rotating shadow band radiometers and aureole radiometers. Both types of instrumentation are designed for automatic data collection, but neither is as yet sufficiently well developed to permit a strong unqualified endorsement as to the optimal configuration for use in an array such as GAW.

## 4. WORKING GROUP DISCUSSIONS - SUNPHOTOMETRY

An open discussion on the focus of proposed working groups resulted. As initially proposed, working groups were intended to address the distinct and different requirements for observations at Global and Regional sites, with the intent to differentiate between the more sophisticated sunphotometry methodologies suited for use at research observatories and the simpler, automated techniques that are more suited for employment at regional GAW sites. The meeting preferred, however, to focus the attention of working groups only on the sunphotometry aspects of the problem, and the working group structure was redefined to address related instrumentation, data flow, and quality assurance. Discussion began with questions on what the measurement objectives should be. It was agreed that an *ad hoc* committee consisting of Bruce Forgan, Lee Harrison, and Claus Frohlich would assemble these objectives - specifically for spectral optical depth, phase function, and spectral single scattering albedo.

The following Working Groups, topics, chairs, and rapporteurs were identified:

Working Group I - Instrumentation
Chairman - B. Forgan — Rapporteur - L. Harrison

Working Group II - Data flow and analysis
Chairman - R. Husar — Rapporteur - B. McArthur

Working Group III - Quality assurance of aerosol optical depth data
Chairman - V. Mohnen — Rapporteur - B. Cushman

### 4.1 Working Group I Report - Instrumentation

***Participants:***

Drs. A. Deepak, E. Dutton, T. Eck, B. Forgan, C. Frohlich,
L. Harrison, B. Holben, Y. Kaufman

***Introduction:***

The group reviewed and endorsed, in general, the conclusions and recommendations of the review circulated in advance of the present meeting. Considering the expertise available at the present meeting, and the time limitations under which conclusions were desired, the group decided to focus its attention on the steps that should be taken in order to implement a high-quality aerosol optical depth monitoring programme at the global observatories operated by GAW. **It was tacitly understood that measurements at regional stations would commence as a body of related experience grew out of this activity.**

***Spectral measurements of optical depth:***

The group endorsed the recommendation of the Committee for Instrument Methods and Observations (CIMO) that no further hand-held photometers be distributed.

It was concluded that future network operations of GAW should be such that automated instrumentation should take and record measurements of the direct-normal spectral irradiance (with an appropriately narrow field-of-view) at rates of at least once per minute.

The group concluded that it is now practical to make spectral measurements of optical depth at relevant passbands between 350 nm and 1000 nm chosen to distinguish aerosol and trace-gas contributions to extinction with an accuracy of 0.02 (2 SIGMA) for the determination of aerosol optical depths (in passbands dominated by Rayleigh and aerosol extinction). It was further concluded that it should soon be practical to achieve accuracies to 0.005 optical depths, and to extend spectral measurements into "window" passbands farther in the infrared.

For the purpose of observing the smallest climatologically significant trends in aerosol burden, long-term stabilities of 0.001 optical depth units will be needed. This was deemed to be beyond the likely performance of current state-of-the-art instruments. Consequently new instrumental methods and/or technologies would be needed to meet this goal.

Notwithstanding the comments above, the group concluded that the measurement programmes that have demonstrated stability sufficient to attain aerosol optical depth accuracies of 0.02, but are made with existing hand-held photometers, should continue.

***Pyrheliometric direct total irradiance measurements:***

The group agreed that such measurements are useful for long-term trend detection and investigation of large episodic events, provided that instrument stability of 0.5% can be maintained over intervals of one to two years. The group recommended strongly that sites with existing instruments meeting this criterion should continue such measurements.

***The measurement of sky-radiance distribution for inferring aerosol phase functions and size distributions:***

The group had a spirited discussion on this subject. The consensus was that such instruments/methods are not yet sufficiently mature to justify a recommendation for deployment within GAW at this time, but have promise. Further investigations of the limits of accuracy of the coupled instrument/inversion system are warranted.

***Specific operational recommendations:***

Further deliberations of the group led to the recommendation that existing turbidity stations that continue to report should change their data collection and reporting strategies to implement the following:

(a) At least five observations per day should be made, including an observation at local solar noon and four other observations made at fixed airmasses appropriate to the site (e.g., 2.2 and 3.5).

(b) Once per month (if possible) 12 observations in the morning or afternoon should be made, taken within the range 2 to 5.5 airmasses, to permit a Langley regression.

***Updated recommendations concerning sunphotometry:***

On the basis of its collective experience, the present working group expressed the desire to supplement the recommendations contained in WMO Environmental Pollution and Research Programme Report # 43, *Recent Progress in Sunphotometry*, Izana, April 1984 and the recommendations in section 1 above as follows:

(a) Time accuracy of 1 second shall be maintained and reported.

(b) All observations shall be recorded and reported in Universal Time Coordinated (UTC).

(c) Instruments shall exhibit repeatability of 1/2000 of the irradiance expected at unit airmass.

(d) Resolution and repeatability of the data system shall be 1/5000 of the signal expected at unit airmass.

(e) The following changes to the tolerances of passband accuracy are suggested for the passbands described in Report #43.

| Passband Centre Wavelength (nm) | Full Width At Half Maximum* (nm) | Error in Passband Centroid (nm) |
|---|---|---|
| 368 | 5 | 1 |
| 412 | 10 * | 2.5 |
| 450 | 10 | 2.5 |
| 500 | 10 | 2.5 |
| 610 | 10 * | 2.5 |
| 675 | 10 | 2.5 |
| 719 | 10 * | 2.5 |
| 778 | 5 | 1 |
| 817 | 5 | 1 |
| 862 | 10 * | 1 |
| 946 | 10 * | 1 |
| 1024 | 5 * | 1 |

* FWHM is not a complete specification of filter passband response. Out-of-Band (OOB) rejection shall be adequate for the intended purpose, and extended "tails" of the passband are particularly important to avoid for the channels marked with a *.

Passbands shall be determined for the overall response of the filter and detector.

The group recommended adoption of the following specific wavelengths (in nm)

368 (or 380), 500, 862 (or 778) - to measure aerosol turbidity

612, 675 - for ozone corrections

940 - for water vapour

It should be a goal of GAW to arrange measurement of the turbidity wavelengths at GAW sites. The remaining channels are strongly encouraged, particularly if collocated measures of column ozone or water vapour are not available.

***Calibrations and comparisons:***

In recent years, the National Physical Laboratory, Teddington, Great Britain, has developed a method for calibrating filter radiometers with an absolute accuracy of better than ± 0.2% in the wavelength range of interest to sunphotometry. This method has been taken up by other Metrology Institutes and is presently being implemented at the World Radiation Centre in Davos, Switzerland. Such a characterization of sunphotometers can guarantee the requested accuracy of optical depth measurements over long periods of time by relating the extraterrestrial values (determined by extrapolations, direct measurements from balloons, rockets, or satellites, or combinations of these) accurately to the absolute scale of spectral irradiance.

Improvement of in-situ calibration and intercomparison methodologies is needed. For this, a high-altitude site should be selected for a long-term comparison of instruments and testing methods for the extrapolation to the extra-terrestrial signal. This experiment will determine the minimum achievable uncertainty for atmosphere-based calibrations and will provide information for the rational optimization of instruments and algorithms to do so. It should be noted that direct measurements from high altitude balloons, sounding rockets, and satellites can also support the determination of the extra-terrestrial signal. Results of such experiments should be taken into account in assessing the accuracy of optical depth determination.

A necessary part of such intercomparison/calibration experiment(s) will be the measurement of ancillary properties needed to assist the interpretation of the data, including sky radiance (solar aureole), and if possible vertical profiles of aerosols, ozone, and water vapour. During these comparisons, new methods and instrumentation should also be tested. It seems, for example, that the advanced shadow band instruments presently being developed may well prove adequate for operation at regional sites of the GAW for determining aerosol optical depth and the properties of aerosols.

The WMO should be encouraged to promote the establishment of a specialist laboratory for the characterization and calibration of sunphotometers. The necessary expertise and logistical elements exist at the World Radiation Centre (Davos), and the working group suggested that this would represent an excellent contribution by Switzerland to GAW.

***Communications:***

To encourage further dissemination of sun photometer information and enhance collaboration, a bulletin board or mail box on the Internet should be established. This service could be used to disseminate reports, studies and data as well as having the potential for expanding the distribution range of information associated with the leading edge of sun photometer measurements.

### 4.2 Working Group II Report - Data Flow

***Participants:***

Drs. R. Husar, D. Matt, B. McArthur, J. Michalsky, E. Rusina, J. Wilson

***Introduction:***

The mandate of Working Group II was to provide recommendations for data flow and data archival. General data flow procedures have been developed within GAW and are reported elsewhere in the series of related WMO reports. Similarly, Working Group III (Quality Assurance) indicated that data reduction, should be accompanied by quality assurance procedures. With these two major areas of endeavour defined, the Working Group altered its original mandate to one which explored the need for rapid dispersal of data, while recognizing that much of the world lags North America and Western Europe in data technology transfer methods.

***Data paths:***

The major data flow paths CONVEY information from individual sites through a QA/Science Activity Centre to a Data Centre. Along this path quality assurance procedures should be employed and the data appropriately flagged. This general data flow may be modified when stations are part of national networks. The QA/Science Activity Centre must approve a national quality control programme or alternatively, the GAW QA programme must be included as an active element of the national procedures. The QA centre acts as a watchdog organization to ensure continued station quality, thus qualifying the autonomy of the national centres but most importantly ensuring the comparability of data derived from them. Throughout this quality assurance programme there should be an emphasis on maintaining the integrity of the raw data and a record of the characteristics and history of instruments used to obtain the measurements.

***Data reduction:***

While it is recognized that Quality Assurance procedures are made easier and the data are more uniform if standardized algorithms are used in reducing data, the overall accuracy of particular data sets may not be the highest. As in any scientific endeavour, means for reducing measurements are changing continually and researchers are encouraged to use improved methods. Therefore, there is the question of whether standardized procedures are a better means for reducing data rather than allowing individual scientists to develop and catalogue new procedures within the database. No matter what the final answer is to this question, it is essential that individual researchers be able to access zero level data (i.e. "raw," unprocessed values) as well as the products of additional reduction and analysis so they can develop and test alternate data reduction schemes. One means of resolving the problem of non-standard versus standard procedures is to produce data based on consensus of the best data reduction techniques. For the purpose of obtaining the highest precision, the Working Group recommends that standardized techniques for data reduction be developed such that values can be recalculated at every level of the computation procedure. Furthermore, these techniques should be reviewed by an expert group every 12-24 months and updated as required.

It is crucial that the QA/Science Activity Centres and the scientific community be informed of improvements so that standard procedures can be updated at the earliest possible time. Each time such changes are made and the database recalculated, some form of version number must be attached to the data. A requirement for using the data in published work will be to reference the version of the data that were used.

***Ancillary information:***

The database should contain a limited number of ancillary observations that have been made at or in the vicinity of the measurement site to aid in the analysis of the data. These extra observations may be as few as is required to adequately reduce the data and as many as the general user community feels are necessary to better utilize the data. Because exact instrument requirements have yet to be finalized (see the Working Group I (Instruments) report above), these secondary measurements cannot be accurately enumerated. A number of examples are possible however. In considering the measurement of optical depth by use of sun photometers, the temperature of the instrument (both optics and detector), atmospheric temperature and the pressure at the station are crucial if the data are to be as accurate as possible. A third variable, relative humidity, is important because of the dynamics of aerosol growth. These examples are not all-encompassing, but are given to ensure that once the primary measurement quantities are decided, equal care must be given to deciding which other measurements are to become part of the database. The Working Group recommended that a group consisting of both observers and data users develop a list of ancillary measurements.

Two important ideas were offered and will require further exploration at some other time. The first is the inclusion of all records of appropriate ancillary data sources that were collected on site or within a limited geographical area. The second is the use of electronic transfer processes and virtual databases to enhance user accessibility to the data.

The first idea involves pointers, the equivalent of flags in the QA procedure, to indicate that data, not collected for the specific purpose of data reduction or primary scientific analysis, are available at other data centres. These pointers would initially indicate the location of such data centres, but it is envisaged that as electronic transfer techniques become more commonplace that these pointers could actually be used to access the data directly. An example might be the tagging of particular records to indicate that on-site columnar ozone data were available. Initially, the tag would provide a means of alerting the data user that the data existed at the World Ozone Data Centre and how to obtain such information. It is not inconceivable with relational databases, however, that within the present decade the data user could directly access the World Ozone Data Centre through the World Turbidity Data Centre. The tagging of such records would be accomplished at both the measurement site and at the national centres depending on the "value-added" information that was available. Site operators would tag the data with respect to measurements that were made during the same time frame, while the national centres would tag the data with respect to value-added information, for example, calculated back trajectories.

The second idea, the virtual database, offers a means of reducing the physical transfer of data while increasing the ability of the Data Centre to provide preprocessed data products requiring finite storage and computing power. The goal of any world data centre is to be able to access all quality assured data and provide it to users in a form suitable for data application by the user. In the past, the World Turbidity Data Centre provided data in the form of mean monthly optical depths. While appropriate for some types of applications, this format would severely limit the use of the data for many other applications, including satellite ground truth. To overcome this problem the data must be stored in its most desegregated form. However, most users are unable to utilize data in the most basic form, raw voltages. The virtual database provides a means of satisfying both the end-user interested in aggregated quantities and the quality assurance officers and scientists who require raw data.

***The World Data Base:***

It is proposed that the World Data Centre be electronically linked to national data centres such that all raw data are maintained at the national centres where the quality control procedures are performed. World access to these data could then be via read only files through anonymous FTP directories (or equivalent). For those countries unable to provide such electronic linkages, the raw data could reside at the World Data Centre. Also archived at the World Data Centre could be data stored at the highest frequency, but in engineering units. Users would then be able to access these data via a menu driven system that would allow the user to aggregate or filter the data in either a number of predetermined formats or simple user-defined formats. These formats could range from simple aggregations as mean values for specified time intervals to very complex filtering and comparative features depending upon the information associated with the primary data records. In this manner only the information that the user desires would be provided directly. The technology is available today to produce a user-driven data centre of this nature. It is recommended that several experts in the database field be tasked with the design of such a system. A workshop, following the initial design stages of this data base should be held to elicit the ideas of those responsible for the measurement, the QA and the potential users.

Without complete knowledge of the instrumentation and the quality control procedures it is impossible to provide a definitive structure for the establishment of such a database. Nevertheless, it is crucial that this database be designed for the age of electronic data transfer, while remaining able to supply information that can satisfy the present needs of lesser developed nations.

***Rapid data access:***

The Working Group also addressed the need for rapidly accessing data, in such a way that avoids eliminating any country for lack of technological means. Presently, the World Turbidity Data Centre provides access to the data via magnetic media and hard copy summaries. The Working Group recommended that both of these activities should continue, but new electronic data transfer systems should be developed. Furthermore, GAW, through WMO, must use every means available to upgrade the ability of member nations to access data through electronic means. This should begin with those countries where Global GAW stations are located and extend to countries with regional GAW stations. It is anticipated that electronic access systems will eventually be acquired by all member countries.

***Recommendations:***

The Working Group makes the following recommendations to enhance data flow and analyses:

(a) All data of a particular type should be reduced using common algorithms.

(b) The "optical depth" database should include pointers to all relevant data that are obtained within the same time frame and geographic region.

(c) The database should be developed as a virtual database where the physical residence of the raw data need not be at the World Data Centre. The raw data must be readily accessible by the World Data Centre through electronic means. Where this cannot be accomplished, the raw data will reside at the World Data Centre.

The WMO through GAW and other programmes should plan for an electronically linked data acquisition, quality control and database system. This could begin in countries already operating global stations.

(d) Rapid data dissemination among researchers is encouraged for data analysis and quality control. As a first means of accomplishing this task, data and descriptive metadata from the monitoring programme should be organized and made accessible through the Internet.

(e) A Working Group should be formed to formulate details of the database system before an Experts meeting is held to finalize the database concept that will include all ancillary measurements, data levels, algorithms etc. (It is suggested that R. Husar, C. Frohlich and A. Ohmura be the working group).

(f) The World Data Centre should continue to provide at least summary data in hard copy to those countries desiring such information.

### 4.3 Working Group III Report - Quality Assurance

***Participants:***

Drs. V. Mohnen, R. Cushman, J. DeLuisi, B. Herman, A. Ignatov, with additional input from A. Deepak, J. Michalsky, E. Rusina, and J. Wilson

***Introduction:***

The primary responsibility for quality assurance in WMO-GAW rests with the Quality Assurance/Science Activity Centres. The QA/SACs are assisted in their quality-assurance efforts for aerosol optical depth measurements by a small international group of experts who will define methodologies and procedures for producing aerosol optical depth (AOD) data of known quality. This group was further subdivided into three working groups:

(i) Observational techniques
(ii) Data processing
(iii) Quality assurance

The following report was prepared by the quality assurance subgroup as a preliminary document for establishing QA/QC procedures. This effort is the first step towards the production of a Quality Assurance Project Plan (QAPjP) for network-wide measurements of aerosol optical depth and associated Standard Operation Procedures (SOP). The final QA documents will reflect the consensus of the above group.

***Instrument response:***

Aerosol optical depth is being measured in different ways and new techniques are continuously emerging. The quality assurance is to a considerable degree dependent on the technology employed (instrument characteristics and data analysis software). The following report prepared by the QA subgroup focuses on sunphotometry, which has been the backbone of WMO's turbidity network.

Essential to any subsequent quality assurance of aerosol optical depth data is quantification of the characterization of instrument response. In sunphotometry, $I_{measured}$ is expressed as

$$I_{measured} = \int_o^\infty F_o(\lambda) \times T(\lambda) \times S(\lambda) \times \Phi(\lambda)\, d\lambda \qquad (1)$$

where — $F_o$ = incident solar flux at top of atmosphere,
$T = e^{-mT(\lambda)}$ = atmospheric transmission,
S = detector response function, and
$\Phi$= filter transmission function.

The terms $F_o$ and T are independent of instrument characteristics. Quality assurance, then, requires checking the product of S x $\Phi$ as a function of $\lambda$ and time. An initial accuracy goal of 0.020 for AOD (eventually reaching 0.005) has been proposed for the GAW network.

The first two steps proposed for the GAW programme that will affect data quality are the initial quality assurance and the field operational quality assurance.

***Initial quality assurance:***

At the beginning of the GAW AOD programme, the preferred procedure is to assemble all candidate instruments at an international (e.g., high-altitude clean site) calibration facility where they will be operated concurrently for about three months. Subsequent to this, relocate the instruments at a site typical of operating conditions and evaluate and possibly modify the suggested techniques. This will:

(a) Establish the relative stability, calibration, and drift characteristics of each instrument and techniques for checking instrument stability (at all measured wavelengths)

(b) Establish the highest achievable "network" precision (actual network precision could be lower due to additional systematic and random factors)

(c) Allow evaluation/intercomparison of different analysis and calibration techniques

(d) Identify the highest performing instrument(s), in terms of drift and precision, for potential use as network transfer standards

(e) Provide an initial training opportunity (facility) for all site operators/technicians.

While quality assurance is facilitated if all instruments are of the same type (the recommendations of this working group were oriented primarily towards sunphotometers; however, no significant modifications would be necessitated by the use of other equipment), this is not a requirement provided that accuracy and precision of measurement meet the data quality objectives of GAW and are thoroughly documented. However, wavelengths (in terms of both nominal wavelength and bandwidth) should be standardized throughout the GAW network.

***Field deployment quality assurance:***

Every 3-6 months, each instrument requires a performance audit either at the calibration facility or by intercalibration with an approved transfer standard. There will be a similar requirement when a new instrument is put into service, either as a replacement or at a new site.

At every opportunity, there will be ongoing checks (e.g., Langley) to monitor instrument characteristics using network-designated software. This will identify drift in intercept indicative of changes in filter characteristics and other instrumental changes; it is essential for maintaining the achievement of quality-assurance objectives. Placing responsibility for quality assurance on the site operator is important for ensuring the quality of data from the GAW network.

Daily maintenance will be as described in the standard operating procedures.

All sites should use standard algorithms; variations from this must be documented. Original data will be furnished, to support any later re-analysis that may be required.

WMO Report No. 43, Recent Progress in Sunphotometry (1984), provides guidance relevant to the quality-assurance of data. In general, those recommendations (e.g., standard wavelengths used; calibration performed against primary reference standards; raw data sent to data centres; Langley-plot checks performed when possible; training important) are still seen as valid. The concept of circulating reference radiometers among the GAW sites for comparisons should be pursued, as recommended in WMO Report No. 43.

## 5. CONCLUSIONS AND RECOMMENDATIONS

The acceptance of new and improved instruments will require further investigation to prove their accuracy, reliability, and ruggedness.

A number of critical observations were made by the group. Among the most important are the following:

(a) In as much as the GAW is organized into tiers of stations, with a small array of advanced GLOBAL OBSERVATORIES supporting a larger assembly of less advanced REGIONAL STATIONS, it was tacitly understood that measurements at regional stations will evolve as a body of the measurements of aerosol optical depth at the GLOBAL OBSERVATORIES in the trial phase;

(b) Ongoing sunphotometry programmes having a demonstrated instrument stability of 2% over an interval of one year should be encouraged to continue their existing measurement programmes;

(c) A new standardized data reduction and analysis method is recommended, such that raw data can be re-analyzed in the future as understanding improves;

(d) A high altitude site is recommended for comparison of instruments, for sunphotometer calibrations by extrapolation, and for testing new methods for determining optical depth.

The deliberations of the working groups and their specific suggestions lead to the following major recommendations:

(a) Hand-help sunphotometers as currently prescribed by WMO for its BAPMoN network are inadequate for contemporary needs;

(b) New instrumentation descriptions, operational procedures and standards for sunphotometry are required for the GAW network. These new instruments, their operation, and their calibration procedures should be tested thoroughly during a trial phase at the GAW GLOBAL OBSERVATORIES. Moreover, a comparison programme should be established in order to assess the suitability of new ways for determining aerosol optical depth;

(c) There are several alternative methods for deriving information related to atmospheric turbidity, none of which is yet mature enough to warrant routine use at regional stations. A multi-faceted programme is recommended. Third, relevant quality control procedures must be developed and implemented in collaboration with the new GAW Quality Assurance/Science Activity Centres that are now being set up;

(d) A World Optical Depth Research and Calibration Centre (WORCC) should be established to provide:

   (i) accurate radiometric references and transfer standards for sunphotometry (as for the case for the World Radiometric Reference);

   (ii) development and testing of new instrumentation and methods;

   (iii) implementation of a trial phase at the GAW GLOBAL OBSERVATORIES; and

   (iv) development of relevant quality control procedures, in cooperation with the new GAW Quality Assurance/Science Activity Centres that are now being set up.

WMO should encourage the World Radiation centre in Davos, Switzerland, to perform this important service.

(e) WMO (GAW) should establish a group of experts with the following charter:

(i) assist the WORCC in defining its tasks;

(ii) establish in cooperation with the WORCC the specifications for new sunphotometers and standard references; and

(iii) define the objectives of comparison experiments and the implementation of the trial phase.

**Acknowledgements**

The efforts of Ms Allison Elgin in making most of the arrangements for this meeting are gratefully acknowledged. Science and Technology Incorporated (of Newport News, North Carolina) prepared the first draft of this report.

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ANNEX A

**WMO Workshop on the Measurement of Atmospheric Optical Depth and Turbidity**
**Silver Spring, MD, USA, 6 - 10 December 1993**

## AGENDA

**Tuesday 7 December**

0900 Opening of the meeting (John Miller)

0910 Discussion of the agenda and selection of Chairman (John Miller)

0945 Overview of the Global Atmosphere Watch (John Miller)

1030 Break

1045 The importance of aerosol optical depth (Bruce Forgan)

1115 Brief presentations by participants concerning their interest in optical depth

1200 Lunch

1300 Continued brief presentations

1400 Presentation of the "Measurements of Atmospheric Turbidity in BAPMoN, and Looking Forward to GAW" (Forgan, Rusina, DeLuisi, and Hicks)

1500 Discussion of Report (comments, corrections, minority views, etc.)

1630 Close

**Wednesday 8 December**

0900 Summary and review of previous discussion

1000 Discussion of a strategy to make ground-based optical depth measurements for the Global Atmosphere Watch, with emphasis on:

(a) what aerosol-related radiative measurements are required, and why;

(b) what is possible (and not possible) from present day measurement systems;

(c) what is feasible for both GAW regional stations and GAW global observatories;

(d) how the strategy can be implemented;

(e) the role of the QA/SACs; and

(f) the design of a data archive.

1030 Break

1045 Continued discussion of aerosol optical depth strategy for GAW

1200 Lunch

1300 Continued discussion

1500 Discussion of writing assignments, and/or working groups

1630 Close

**Thursday 9 December**

0900 Working groups deliberations

Group I — Instrumentation
Group II — Data Flow
Group III — Quality Assurance and the data archive

1030 Break

1045 Working groups (continued)

1200 Lunch

1300 Plenary — progress reports and discussion

1400 Working groups (continued)

1630 Close

**Friday 10 December**

0900 Plenary - Working group reports and discussion

1000 Clean up

1100 Close

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ANNEX B

**WMO Workshop on the Measurement of Atmospheric Optical Depth and Turbidity**
**Silver Spring, MD, USA, 6 - 10 December 1993**

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ANNEX C

**WMO GAW Report No. 94**

**MEASUREMENTS OF ATMOSPHERIC TURBIDITY IN BAPMoN, AND LOOKING FORWARD TO GAW**

**EXECUTIVE SUMMARY**

*A review of the network measurements of aerosol optical depth conducted as part of the Background Air Pollution Monitoring Network of the World Meteorological Organization.*

An intensive examination of aerosol optical depth data generated by the sunphotometer measurement programme of the WMO Background Air Pollution Monitoring Network reveals serious flaws in both the internal consistency of data from any single station and the comparability among any specific set of station records. Data records prior to 1982, when measurements were made using the Volz sunphotometer, appear to be comparatively consistent although still of questionable value. Data from later periods are fraught with even more substantial problems of internal consistency.

Based on the investigations made of data contained in the WMO turbidity archive maintained by the US National Climatic Data Center (in Asheville, North Carolina), it is concluded that:

(a) 50% of stations reporting atmospheric turbidity produced data showing poor relationships between the observed and NCDC-calculated aerosol optical depth;

(b) in some cases, inappropriate algorithms have been used to determine the NCDC-calculated aerosol optical depth, and

(c) there are inconsistencies in reporting of data within the archive (e.g. missing data, wavelength order, QC flags).

Problems arise both for the optical depth values reported by observing stations and the values computed by NCDC from reported meter readings. A major programme involving considerable investment of time and money would be required to correct these problems. Until such a programme is completed, there can be little confidence in using NCDC-calculated aerosol optical depth data or the annually published statistics. Any rationale for use of the observed aerosol optical depth is also clouded by the blanket correction of the reported aerosol optical depth to natural logarithms.

It is concluded that the measurement techniques employed in the BAPMoN turbidity measurement programme were too advanced for routine application by non-expert personnel. However, there are sound and compelling reasons to promote a turbidity monitoring programme. In particular, the satellite community requires good quality data for verification purposes, models require data as input and to test their predictions, and in all such contexts there is a need to test the suspicion that aerosol loadings are changing with time. In spite of the acknowledged need for high-quality data, there is not yet a replacement or substitute methodology that would be suitable for widespread application in the regional site network of the new Global Atmosphere Watch of WMO. Instead, it is proposed that several candidate techniques should be explored in considerable depth to determine which of several potential approaches might best satisfy WMO/GAW goals. Such exploration might profitably occur as part of the activities of the GAW Global "Observatories," where sunphotometer measurements should continue while the new methodologies are refined and through a transition period to start at sometime yet to be determined.

*In light of the results of the investigations reported here, it is recommended that no further measurements of atmospheric optical depth be made at the regional*

*stations of the GAW, and that subphotometry measurements be made only at more advanced global observatories until a proven, simple measurement technique is accepted for incorporation into the regional network observation protocols.*

The need for turbidity data may best be satisfied by partitioning the observations into two categories ─ (a) high quality research measurements such as may be made at global GAW stations ("observatories"), and (b) simpler and more routine measurements suitable for less complicated regional stations. The latter observations need not involve sun photometry in order to serve the long-term aerosol monitoring needs.

**Specific Major Recommendations**

(a) There is little reason to continue turbidity measurements conducted under the protocols of BAPMoN.

(b) The quality control practices and algorithms used in processing BAPMoN turbidity data must be revised before further use. This revision should be undertaken in consultation with the EC Panel/CAS WG review team.

(c) Turbidity reporting mechanisms and archiving formats should be refined to allow additional quality control procedures and to incorporate data from new types of instrumentation. As above, changes should be designed in consultation with the EC Panel/CAS WG.

(d) If the demand is sufficient, then a complete re-analysis of data in the turbidity archive would be feasible, although time-consuming and expensive. This would entail examining each station's data, determining whether corrective action is possible and/or warranted, consulting with site operators on the revision of calibration coefficients, making appropriate changes to the archived record, and reporting the revised numbers.

(e) A scientific and technical advisory sub-group of the EC Panel/CAS WG should be appointed to oversee operations of the turbidity monitoring programme, and to coordinate with other WGs (e.g. CIMO, CAS) on issues of quality control, calibration procedures, and instrument developments.

(f) The development of techniques and instruments to improve the measurement of aerosol optical depth should be actively fostered.

(g) Sunphotometry calibration centres (regional and global) should be established, similar to those set up for solar radiation.

(h) A GAW handbook should be produced which highlights the minimum and state-of-the-art requirements for sun photometer (and alternatives, e.g. rotating shadow-band systems), including a thorough error analysis, and description of calibration and quality control procedures.

(i) An independent GAW handbook should be prepared, to highlight the minimum and state-of-the-art requirements for aerosol extinction measurements by broad band pyrheliometry, including a thorough error analysis and description of calibration and quality control procedures.

(j) A workshop is needed to consider methods and instruments to use in the next generation of turbidity measurement programme.

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ANNEX D

## ROTATING SHADOW-BAND TECHNOLOGY

Developments in sunphotometry have been paralleled by improvements in the technology and interpretation of direct and diffuse radiation measurements, simplified considerably by the evolution of a number of devices generally categorized as "rotating shadow-band radiometers." There are three such devices now in use, each with a specific purpose but each also employing an identical measurement philosophy -- as much as possible to depend on the use of a single sensor to measure different irradiance components, so as to avoid difficulties associated with sensor deterioration with time and to minimize the consequences of different sensor performance characteristics among a spatial array.

Some very practical applications of atmospheric extinction data do not require exceedingly high accuracy but rather continuing long-term precision. Relative measurements that encapsulate changes in scattering conditions can be made at small cost but with lasting benefit. Such measurements include monitoring the relative magnitude of the direct and diffuse irradiance components in an optically active portion of the solar spectrum. A single sensor that is periodically shaded by a rotating shadow band provides adequate data for many purposes of this kind. The simplest form of rotating shadow band radiometer is of this type. A single silicon cell sensor is mounted horizontally at the centre of the sphere described by a rotating band, thick enough to provide a short period of shade but narrow enough to minimize errors in the measurement of total irradiance. Broad-band data are collected automatically, usually at intervals short enough to ensure that a representative fully-shaded value is reported for each brief pass of the shadow-band.

As a first-order approximation to a measure of optical depth (to be refined as preliminary studies indicate), it is useful to quantify the variable

$$\mathcal{L} = (D/I).\cos(\zeta)$$

from indicated values of the diffuse (D) and directly incident (I) radiation detected by the horizontal sensor, where $\zeta$ is the solar zenith angle at the time of the measurement. Devices of this kind normally employ silicon cell sensors, that have diminished cosine response at low elevations. Consequently, emphasis is usually given to measurements made near local solar noon.

At an opposite extreme is a computer-controlled and multi-wavelength rotating shadow band instrument presently being deployed in some networks in the USA. In simple concept, this instrument permits quantification of the ratio of diffuse to direct radiation for specific wavelengths, so that information related to the size of scattering particles can be derived.

Instruments at intermediate levels of complexity are also now available, potentially suitable for routine use in areas lacking expert technical capabilities. At this time, there has been no side-by-side comparison of these various sensors, nor has there yet been an objective and independent assessment of their relative benefits.

It is recommended that sensors of this kind be included in field tests of alternative aerosol optical depth sensors, so as to evaluate their utility *vis-a-vis* sunphotometers. It is anticipated that sensors of the rotating shadow band configuration may well prove adequate for operation at regional sites of the GAW, and that understanding of their answers will require more intensive application of modern sunphotometry methods at a subset of sites, perhaps the GAW global observatories.

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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

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

13. Report of the Executive Committee Panel of Experts on Environmental Pollution, Fourth Session, Geneva, 27 September - 1 October 1982

14. Effects of Sulphur Compounds and Other Pollutants on Visibility by Dr. R.F. Pueschel, April 1983

15. Provisional Daily Atmospheric Carbon Dioxide Concentrations as Measured at BAPMoN Sites for the Year 1981, May 1983

16. Report of the Expert Meeting on Quality Assurance in BAPMoN, Research Triangle Park, North Carolina, USA, 17-21 January 1983

17. General Consideration and Examples of Data Evaluation and Quality Assurance Procedures Applicable to BAPMoN Precipitation Chemistry Observations by Dr. Charles Hakkarinen, July 1983

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20. Extended Abstracts of Papers to be Presented at the WMO Technical Conference on Observation and Measurement of Atmospheric Contaminants (TECOMAC), Vienna, 17-21 October 1983

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22. Report of the Fifth Session of the WMO Executive Council Panel of Experts on Environmental Pollution, Garmisch-Partenkirchen, Federal Republic of Germany, 30 April - 4 May 1984 (TD No. 10)

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24. Final Report of the Expert Meeting on the Assessment of the Meteorological Aspects of the Second Phase of EMEP, Friedrichshafen, Federal Republic of Germany, 7-10 December 1983. October 1984 (TD No. 11)

25. Summary Report on the Status of the WMO Background Air Pollution Monitoring Network as at May 1984. November 1984 (TD No. 13)

26. Sulphur and Nitrogen in Precipitation: An Attempt to Use BAPMoN and Other Data to Show Regional and Global Distribution by Dr. C.C. Wallén. April 1986 (TD No. 103)

27. Report on a Study of the Transport of Sahelian Particulate Matter Using Sunphotometer Observations by Dr. Guillaume A. d'Almeida. July 1985 (TD No. 45)

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29. Recommendations on Sunphotometer Measurements in BAPMoN Based on the Experience of a Dust Transport Study in Africa by Dr. Guillaume A. d'Almeida. September 1985 (TD No. 67)

30. Report of the Ad-hoc Consultation on Quality Assurance Procedures for Inclusion in the BAPMoN Manual, Geneva, 29-31 May 1985

31. Implications of Visibility Reduction by Man-Made Aerosols (Annex to No. 14) by R.M. Hoff and L.A. Barrie. October 1985 (TD No. 59)

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

33. Man and the Composition of the Atmosphere: BAPMoN - An international programme of national needs, responsibility and benefits by R.F. Pueschel. 1986

34. Practical Guide for Estimating Atmospheric Pollution Potential by Dr. L.E. Niemeyer. August 1986 (TD No. 134)

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36. Global Atmospheric Background Monitoring for Selected Environmental Parameters. BAPMoN Data for 1984. Volume I: Atmospheric Aerosol Optical Depth. October 1985 (TD No. 96)

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39. Report of the Third WMO Expert Meeting on Atmospheric Carbon Dioxide Measurement Techniques, Lake Arrowhead, California, USA, 4-8 November 1985. October 1986

40. Report of the Fourth Session of the CAS Working Group on Atmospheric Chemistry and Air Pollution, Helsinki, Finland, 18-22 November 1985. January 1987

41. Global Atmospheric Background Monitoring for Selected Environmental Parameters. BAPMoN Data for 1982, Volume II: Precipitation chemistry, continuous atmospheric carbon dioxide and suspended particulate matter. June 1986 (TD No. 116)

42. Scripps reference gas calibration system for carbon dioxide-in-air standards: revision of 1985 by C.D. Keeling, P.R. Guenther and D.J. Moss. September 1986 (TD No. 125)

43. Recent progress in sunphotometry (determination of the aerosol optical depth). November 1986

44. Report of the Sixth Session of the WMO Executive Council Panel of Experts on Environmental Pollution, Geneva, 5-9 May 1986. March 1987

45. Proceedings of the International Symposium on Integrated Global Monitoring of the State of the Biosphere (Volumes I-IV), Tashkent, USSR, 14-19 October 1985. December 1986 (TD No. 151)

46. Provisional Daily Atmospheric Carbon Dioxide Concentrations as Measured at BAPMoN Sites for the Year 1984. December 1986 (TD No. 158)

47. Procedures and Methods for Integrated Global Background Monitoring of Environmental Pollution by F.Ya. Rovinsky, USSR and G.B. Wiersma, USA. August 1987 (TD No. 178)

48. Meeting on the Assessment of the Meteorological Aspects of the Third Phase of EMEP IIASA, Laxenburg, Austria, 30 March - 2 April 1987. February 1988

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51. Report of the NBS/WMO Expert Meeting on Atmospheric $CO_2$ Measurement Techniques, Gaithersburg, USA, 15-17 June 1987. December 1987

52. Global Atmospheric Background Monitoring for Selected Environmental Parameters. BAPMoN Data for 1985. Volume I: Atmospheric Aerosol Optical Depth. September 1987

53. WMO Meeting of Experts on Strategy for the Monitoring of Suspended Particulate Matter in BAPMoN - Reports and papers presented at the meeting, Xiamen, China, 13-17 October 1986. October 1988

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61. Global Atmospheric Background Monitoring for Selected Environmental Parameters. BAPMoN Data for 1987 and 1988, Volume I: Atmospheric Aerosol Optical Depth.

62. Provisional Daily Atmospheric Carbon Dioxide Concentrations as measured at BAPMoN sites for the year 1988 (TD No. 355)

63. Report of the Informal Session of the Executive Council Panel of Experts/CAS Working Group on Environmental Pollution and Atmospheric Chemistry, Sofia, Bulgaria, 26 and 28 October 1989

64. Report of the consultation to consider desirable locations and observational practices for BAPMoN stations of global importance, Bermuda Research Station, 27-30 November 1989

65. Report of the Meeting on the Assessment of the Meteorological Aspects of the Fourth Phase of EMEP, Sofia, Bulgaria, 27 and 31 October 1989

66. Summary Report on the Status of the WMO Global Atmosphere Watch Stations as at 31 December 1990 (TD No. 419)

67. Report of the Meeting of Experts on Modelling of Continental, Hemispheric and Global Range Transport, Transformation and Exchange Processes, Geneva, 5-7 November 1990

68. Global Atmospheric Background Monitoring for Selected Environmental Parameters. BAPMoN Data For 1989, Volume I: Atmospheric Aerosol Optical Depth

69. Provisional Daily Atmospheric Carbon Dioxide Concentrations as measured at Global Atmosphere Watch (GAW)-BAPMoN sites for the year 1989 (TD No. 400)

70. Report of the Second Session of EC Panel of Experts/CAS Working Group on Environmental Pollution and Atmospheric Chemistry, Santiago, Chile, 9-15 January 1991 (TD No. 633)

71. Report of the Consultation of Experts to Consider Desirable Observational Practices and Distribution of GAW Regional Stations, Halkidiki, Greece, 9-13 April 1991 (TD No. 433)

72. Integrated Background Monitoring of Environmental Pollution in Mid-Latitude Eurasia by Yu.A. Izrael and F.Ya. Rovinsky, USSR (TD No. 434)

73. Report of the Experts Meeting on Global Aerosol Data System (GADS), Hampton, Virginia, 11 to 12 September 1990 (TD No. 438)

74. Report of the Experts Meeting on Aerosol Physics and Chemistry, Hampton, Virginia, 30 to 31 May 1991 (TD No. 439)

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76. The International Global Aerosol Programme (IGAP) Plan: Overview (TD No. 445)

77. Report of the WMO Meeting of Experts on Carbon Dioxide Concentration and Isotopic Measurement Techniques, Lake Arrowhead, California, 14-19 October 1990

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79. Report of the Meeting of Experts to Consider the Aerosol Component of GAW, Boulder, 16 to 19 December 1991 (TD No. 485)

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

81. Report of the Second Meeting of Experts to Assess the Response to and Atmospheric Effects of the Kuwait Oil Fires, Geneva, Switzerland, 25-29 May 1992 (TD No. 512)

82. Global Atmospheric Background Monitoring for Selected Environmental Parameters BAPMoN Data for 1991, Volume I: Atmospheric Aerosol Optical Depth (TD No. 518)

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

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

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

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

87. Report of the Third Session of EC Panel/CAS Working Group on Environmental Pollution and Atmospheric Chemistry, Geneva, 8-11 March 1993 (TD No. 555)

88. Report of the Seventh WMO Meeting of Experts on Carbon Dioxide Concentration and Isotopic Measurement Techniques, Rome, Italy, 7 - 10 September 1993, (edited by Graeme I. Pearman and James T. Peterson) (TD No. 669)

89. 4th International Conference on $CO_2$ (Carqueiranne, France, 13-17 September 1993) (TD No. 61)

90. Global Atmospheric Background Monitoring for Selected Environmental Parameters GAW Data for 1992, Volume I: Atmospheric Aerosol Optical Depth (TD No. 562)

91. Extended Abstracts of Papers Presented at the WMO Region VI Conference on the Measurement and Modelling of Atmospheric Composition Changes Including Pollution Transport, Sofia, 4 to 8 October 1993 (TD No. 563)

92. Report of the Second WMO Meeting of Experts on the Quality Assurance/Science Activity Centres of the Global Atmosphere Watch, Garmisch-Partenkirchen, 7-11 December 1992 (TD No. 580)

93. Report of the Third WMO Meeting of Experts on the Quality Assurance/Science Activity Centres of the Global Atmosphere Watch, Garmisch-Partenkirchen, 5-9 July 1993 (TD No. 581)

94. Report on the Measurements of Atmospheric Turbidity in BAPMoN (TD No. 603)

95. Report of the WMO Meeting of Experts on UV-B Measurements, Data Quality and Standardization of UV Indices, Les Diablerets, Switzerland, 25-28 July 1994 (TD No. 625)

96. Global Atmospheric Background Monitoring for Selected Environmental Parameters WMO GAW Data for 1993, Volume I: Atmospheric Aerosol Optical Depth

97. Quality Assurance Project Plan (QAPjP) for Continuous Ground Based Ozone Measurements (TD No. 634)

98. Report of the WMO Meeting of Experts on Global Carbon Monoxide Measurements, Boulder, USA, 7-11 February 1994 (TD No. 645)

99. Status of the WMO Global Atmosphere Watch Programme as at 31 December 1993 (TD No. 636)

100. Report of the Workshop on UV-B for the Americas, Buenos Aires, Argentina, 22-26 August 1994

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