WORLD METEOROLOGICAL ORGANIZATION
GLOBAL ATMOSPHERE WATCH
(A system for environmental pollution monitoring and research)

GLOBAL ATMOSPHERE WATCH GUIDE
NOTE

The designations employed and the presentation of material in this document/publication do not imply the expression of any opinion whatsoever on the part of the Secretariat of the World Meteorological Organization concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries.

This report has been compiled from information furnished to the WMO Secretariat. It is not an official WMO publication and its distribution in this form does not imply endorsement by the Organization of the ideas expressed.
GLOBAL ATMOSPHERE WATCH GUIDE

A contribution to the Global Environment Monitoring System (GEMS)

WMO/TD-NO. 553
PREFACE

The primary purpose of the WMO Global Atmosphere Watch (GAW), the backbone of which is a network of long-term monitoring stations operated by WMO Members, is to provide reliable, systematic observations from which definitive information can be derived on the changing chemical composition of the atmosphere and related physical characteristics. Such information will aid in understanding both the environmental and climate impacts of these changes and the need for regulatory controls, so that the adverse environmental trends such as global warming, depletion of the ozone layer and acid rain can be reduced or avoided.

This GAW Guide was prepared to give overviews of individual GAW programme measurements. Among other topics, it reveals the importance of the measurement of a given variable; the siting requirements; the current measurement techniques and application of results; as well as the projected cost of equipment, personnel, and training. It also lists as contact persons the specialists who authored the respective chapters and who could provide additional information and advice. The Guide, we believe, will be especially useful for users who intend to upgrade an existing monitoring station or to establish a new station to meet the GAW requirements for global or regional observations. In the future, the Guide will periodically be updated and expanded as necessary.

I wish to convey my sincere appreciation and gratitude to the Executive Council Panel of Experts/Commission for Atmospheric Sciences Working Group on Environmental Pollution and Atmospheric Chemistry for initiating the preparation of this Guide, to all specialists for drafting and reviewing the various chapters, and to the CIMO Rapporteur on Instruments and Methods of Environmental Pollution Measurements for preparing this publication.

(G.O.P. Obasi)
Secretary-General
1. INTRODUCTION

The WMO's Global Atmosphere Watch (GAW) integrates many monitoring and research activities involving the measurement of the chemical and physical properties of the atmosphere. GAW serves as an early warning system to detect further changes in atmospheric concentrations of greenhouse gases, and changes in the ozone layer and in the long-range transport of pollutants, including acidity and toxicity of rain as well as atmospheric burden of aerosols. This new system, approved in June 1989 by the WMO Executive Council, will strengthen and coordinate the WMO environmental data-gathering programme that began in the 1950's. The system will include the Global Ozone Observing System (GO2OS), the Background Air Pollution Monitoring Network (BAPMoN), and other smaller measurement networks. The GAW will provide framework design, standards, intercalibrations, and data collection systems for global monitoring and data evaluation.

Specifically, the GAW measurement programme includes:

- Greenhouse gases - carbon dioxide, the chlorofluorocarbons, methane, nitrous oxide, tropospheric ozone;
- Ozone - surface, total column, vertical profile and precursor gases, using ground-based instruments and satellites;
- Radiation and optical depth or transparency of the atmosphere, including turbidity, solar radiation, UV-B, visibility, total and vertical distribution of aerosols and water vapour;
- Chemical composition of rain and snow;
- Reactive gases such as sulphur dioxide and the reduced sulphur species, nitrogen oxides and the reduced nitrogen species, carbon dioxide;
- Particle concentration and composition characteristics;
- Radionuclides including krypton- 85, radon, tritium and the isotopic composition of selected substances.

The quality control and quality assurance (QA/QC) of the above measurements must be an integral part of the Global Atmosphere Watch Programme. Through a series of expert meetings, a QA programme for GAW is presently being defined and formulated. A series of three GAW reports describe this process (GAW Report No. 80, and two others in preparation). A new organization within the GAW system has been recommended: Quality Assurance/Science Activity Centres (QA/SAC). These centres will play the leading role in defining - together with the scientific community - data quality objectives (DQO's) and QA standards for the GAW measurements. They will also coordinate the required training associated with the GAW measurements. One QA/SAC is being set up in Germany for Europe and Africa. Others will be established in the Americas and Asia. It is planned for the next edition of the GAW Guide that the QA activities will be fully integrated into the two page description of the measurements.

The following Guide provides short overviews of selected GAW measurement programmes and was compiled to provide a quick reference source for administrators and scientists requiring information on a given programme.
2. GASES

2.1. Greenhouse Gases

2.1.1. Carbon Dioxide

**Importance**

Carbon Dioxide (CO$_2$) is one of the most common and important trace gases in the earth-ocean-atmosphere system. It has both natural and industrial sources. Within the natural carbon cycle, CO$_2$ plays a key role in a number of biological processes. Because fuels contain carbon, the burning of coal, oil, and wood thus injects CO$_2$ into the atmosphere and so has been the cause of the continuous increase in atmospheric concentration over the last several decades. Because of CO$_2$’s role as one of the more important greenhouse gases, scientists have attempted to understand its potential impact on climate and global change.

**Siting Requirements**

CO$_2$ has been one of the required measurements made at global sites under the GAW programme. The purpose was to monitor the rising atmospheric concentration so as to evaluate its role in the carbon cycle and its potential as a greenhouse gas. Because of its long residence in the atmosphere (6 years), a background level can be readily determined and has been documented at such sites as Mauna Loa, Hawaii; Cape Grim, Australia; and other global sites. At regional sites, where a number of sources and sinks (mainly vegetation) are present, it is more difficult to find a clear global signal. However, these sites are useful in quantifying the process by which the gas is exchanged in the environment.

**Methods of Measurement and Sampling Frequency**

At present, all background atmospheric CO$_2$ concentration measurements are made with Non-Dispersive Infra-Red (NDIR) gas analysers. Though these instruments are designed for industrial use, with special care, such as the use of reference gases, most types can achieve the required precision (±0.1 ppm). Basically, an infra-red source provides a beam of radiation that passes through a reference and through a sampling measuring cell. The relative intensity of radiation transmitted through the two cells is a measure of the CO$_2$ concentration difference between the gases contained in the two cells. During normal operation, comparison gases of constant but not necessarily precisely known concentration are flushed through the reference cell. Alternately, the sample gas, whose CO$_2$ concentration is to be determined, is passed through the cell. The CO$_2$ concentration of the sample is determined from the relative analyser output between the sample gas and the reference gases.

To obtain global intercomparability of background CO$_2$ measurements, a calibration system has been developed by using a three-level reference gas system. This consists of primary, secondary, and working reference gases. The exchange of reference gases between the different national programmes and a central calibration laboratory (Scripps Institution of Oceanography) is described in a number of WMO and journal publications.

The IR analysis gives a constant trace of the ambient CO$_2$ concentration interspersed with calibration gas measurements at a set interval. At least once a week, a calibration test is made using the secondary standards.

An alternate method of CO$_2$ measurement which is generally applicable to many other trace gases is collecting air in specially designed glass/stainless steel flasks. These flasks are returned to a central laboratory where CO$_2$ is determined by NDIR. This method has become a standard technique employed by a number of countries.

**Data Reduction**

NDIR measurements are generally recorded on an electronic data system using chart recorders as a backup. To separate periods of local disturbances from background conditions, data selection based on conditions unique to each observatory is made. These edited data form the set that is then corrected for calibration adjustments provided by the central calibration laboratory.
Archiving Procedures

Besides the national data archives, some of the CO₂ data have been deposited at the Collaboration Centre on Background Air Pollution Data in the United States. The WMO has produced the data in hard copy reports in the Environmental Pollution Monitoring and Research Series. Since 1990, the WMO World Data Centre for Greenhouse Gases, operated by the Japan Meteorological Agency in Tokyo, has managed the CO₂ data archive.

Application of Results

The CO₂ data set have been used extensively by the scientific community to investigate a number of aspects of the carbon cycle such as exchange between the atmosphere and the ocean or impacts on the biota and to predict the long-range climate effects of increasing CO₂ concentrations.

Equipment and Infrastructure Cost (US$)

CO₂ In-Situ Analyser - Remote Baseline Station

- Analyser - $18,000 (one-time cost)
- Calibration gases - $16,000 (one-time cost)
- Total start-up cost - $37,000
- Various annual costs to maintain system, new calibration gases, etc.

CO₂ Flask Sampling at Remote Sites

- Flasks and sampler for one site - $11,000
- Central Processing and Calibration Facility - $63,000

Personnel Requirements and Training

Personnel:
- NDIR operator at baseline - 8 man-months per year
- Central Laboratory - 18 man-months per year

Training:
- NDIR operator for baseline location or Central Laboratory - 1 month
- Flask sampling - 2 days

References

WMO 1990: Carbon Dioxide: WMO Monitoring and Research, Fact Sheet No. 6.

WMO 1991: Provisional Daily Atmospheric Carbon Dioxide Concentrations as Measured at BAPMoN Sites for the Year 1990, Environmental Pollution Monitoring and Research Programme Report No. 75, 148 pp. (Earlier CO₂ data publications are available from the WMO.)

WMO 1992: Report of the WMO Meeting of Experts on Carbon Dioxide Concentration and Isotopic Measurement Techniques, GAW Report No. 77, 71 pp. (Earlier CO₂ meeting reports are available from the WMO.)

Contact:
- Dr. G.I. Pearman
  CSIRO, Div. of Atmospheric Research
  Mordialloc, Vic., 3195
  AUSTRALIA
2.1.2. Total Ozone

Importance

During the last two decades, understanding man’s impact on atmospheric ozone through releases of chlorofluorocarbons and other trace gases has been considered one of the major environmental issues. To date, the most important consequence of the increased presence of these gases in the atmosphere, has been the steady decrease of stratospheric ozone, especially over the Antarctic, i.e. the creation of the so-called ozone hole. Ozone in the higher atmosphere is an important absorber of UV radiation which if on the increase on the ground could have an impact on biological systems on Earth. Because of these impacts, the Montreal Protocol has been negotiated to reduce gases such as CFC’s and halons that cause destruction of ozone in the stratosphere.

Total ozone is defined as being equal to the depth of ozone in a vertical column with a base of 1 cm² at standard temperature and pressure and is expressed in units of pressure. The global average value is about 300 m atm cm, commonly called Dobson units (1 DU is equivalent to a depth of 0.01mm). Typical values range from 230 to 500 DU. The ozone is unevenly distributed in a vertical plane with about 90% of the total being in the stratosphere, where ozone reaches a maximum.

Siting Requirements

Total ozone started to be measured at a few sites in the late twenties and early thirties. Since the mid 1950’s, the systematic monitoring at more than a hundred stations has been carried out by the WMO Global Ozone Observing System (GOOS). Major factors in site selection are the ability to have a clear cloud-free view of the sun for most of the year, and protective housing for the instrument in order to reduce large temperature fluctuations when viewing the sun.

Methods of Measurement

Three types of instruments are currently used for ground-based measurement of total ozone. All of them use the principle of different absorption by ozone of the UV at 300-460 nm band.

Dobson Spectrophotometer. Developed in the early twenties by Dobson, this instrument has been the backbone of the total ozone measuring network. The instrument is a basic UV double monochromator spectrophotometer which compares the UV intensity at a few pairs of wavelengths. One wavelength absorbs ozone strongly, and the other only slightly, chosen from the 355- to 454-nm range. From this the total column ozone is calculated.

Filter Ozonometer (M-134). This filter instrument is based on the same principle as the Dobson spectrophotometer in using differential absorption of UV radiation. It has been used extensively in the countries of the former Soviet Union for the last 30 years.

Brewer Grating Spectrophotometer. This instrument has one diffraction grating and five slits corresponding to five wavelengths in the 306- to 320-nm spectral band. The instrument continuously tracks the sun during the day. Since the mid 1980’s, a number of these instruments have been placed around the world to supplement the Dobson network.

All instruments use the absorption of UV light as a detection method.

Data Reduction

Generally, 3-5 measurements of total ozone are made at each station on a daily basis. International protocol requires that one report of the total ozone measured each day by each station, with coded information indicating wavelength and observation conditions, be sent to the WMO World Ozone Data Centre (Toronto), on a monthly basis. For reduction of the values obtained at cloudy or clear zenith sky to their corresponding direct sun values each station prepares their own diagrammes.

Archiving Procedures

All total ozone data are submitted and available from the WMO World Ozone Data Centre operated by the Atmospheric Environment Service in Toronto, Canada.
Application of the Results

The total ozone data have played a critical role in documenting the major changes in the ozone layer going back several decades. It has also been used as ground truth for satellite measurements of total ozone.

Equipment and Infrastructure Costs (US$)

Dobson spectrophotometer - approx. $80,000
Brewer spectrophotometer - approx. $90,000

Personnel Requirements and Training

Personnel: Operator - 1 hour per day
Training: Dobson/Brewer for baseline observations - 2 weeks

References


Contact: Dr. Rumen D. Bojkov (Dobson)
Dr. James Kerr (Brewer)
Atmospheric Environment Service
4905 Dufferin Street
Downsview, M4H 5T4
Canada
2.1.3. Tropospheric Ozone

Importance

Tropospheric ozone plays a key role in the chemical cycling of gases in the atmosphere. Through the production of oxygen atoms and eventually the hydroxyl radical, the oxidative properties of, and removal mechanisms in, the troposphere are modulated by ozone. In the troposphere, ozone is a greenhouse gas with the potential to change under the influence of human activities. Although ozone is not a primary pollutant (emitted directly by human activity), it is produced through the action of sunlight on precursors such as nitrogen oxides and hydrocarbons. The global influence of such anthropogenically produced ozone on the budget of ozone is a primary focus of current research. A true picture of ozone behaviour in the troposphere requires measurements of the vertical profile. Because of their expense, profiles are relatively infrequent and near-surface measurements are used to develop a time history of ozone changes.

Siting Requirements

Because ozone is a reactive gas, measurements in a number of locations are required to define the spatial and temporal variations. Close to human activities, whether industrial or biomass burning related, the distribution is dominated by the effects of such activities. At sites more remote from these primarily continental influences, measurements may be representative of broad geographic regions.

The elevation of the site may be an important factor in determining the type of measurement obtained. At stations located on mountain slopes, at least a portion of the measurement time should be representative of the free troposphere at the elevation of the site. At boundary layer sites in marine environments, photochemical losses may dominate the distribution.

Methods of Measurement and Sampling Frequency

Several methods of in-situ ozone measurement have been used to gather longer-term ozone records, including wet chemistry, chemiluminescence, and ultraviolet photometry. The latter method is now generally regarded as the preferred method because of its absolute accuracy, stability, freedom from interferences, and ease of operation. UV-photometry-based ozone monitors are readily available from several commercial manufacturers. The basic principle of these instruments is the measurement of the attenuation of a beam of UV light at about 254 nm due to the presence of ozone in a flowing air sample. In practice, the instruments measure the relative attenuation between an air sample in which only the ozone is removed and one in which ozone is present. With a knowledge of the sample path length and the absorption coefficient of ozone at 254 nm, the ozone concentration is determined.

In principle, this method is an absolute one but instrument defects or degradation in components, such as the catalyst used to destroy ozone in the reference portion of the measurement cycle, may affect the accuracy. Since ozone sources such as an ozone generator are less stable than the ozone monitors, they do not make good standards. Periodic intercalibration between an instrument maintained as a network standard and the station instrument provides one means of ensuring an instrument’s calibration level and making adjustments for station instrument changes. The network standard should be linked to a recognized international standard. At this time, no such standard has been designated, though several programmes are linked to the reference ozone photometer maintained at the U.S. National Institute of Standards and Technology.

Measurements using a UV ozone monitor are continuous in nature (every 10-25 s). On a daily to weekly schedule, the instrument samples air with ozone removed to determine the zero level of the instrument. At this time, a span concentration can also be sampled to check the operation of the instrument. Such span samples are not usually accurate enough to calibrate the instrument but may indicate abnormal instrument performance.

Data Reduction

Most of the ozone monitors are capable of producing both digital and analog outputs which readily allow recording on personal-computer-based data systems or chart recorders. Such data usually require some screening to ensure proper instrument performance and to apply necessary calibration adjustments. If ozone amount is to be expressed as mixing ratio, the raw measurement should be corrected to STP conditions, requiring a measure of the temperature and pressure of the sample. Many analysers include
these measurements and do the calculation automatically. Otherwise these corrections can be applied from available temperature and pressure information at the time of screening and application of calibration information. For most research efforts, the data are put into hourly average form.

Archiving Procedures

The WMO World Ozone Data Centre (WODC) at the Atmospheric Environment Service in Toronto, Canada, publishes daily mean, maximum, and minimum ozone partial pressures from locations providing data representative of background or regional conditions. Presently, most of the data sets are, however, available only through the investigator responsible for the measurements.

Application of Results

The primary purpose of surface-based tropospheric ozone measurements is to develop a basic climatology of tropospheric ozone behaviour and as tests for model calculations of the chemistry and transport in the remote atmosphere. Data at regional stations can be used to help evaluate the impact of higher ozone concentrations on the regional environment. A few time series of longer duration have been analysed to investigate possible anthropogenic influences on the oxidative state of the atmosphere and the possible climatic impacts of ozone increases on greenhouse warming of the atmosphere.

Equipment and Infrastructure Cost (US$)

UV Ozone Monitor

Monitor with data system - $10,000 (one-time cost)
Network standard (optional) - $10,000 (one-time cost)
Various annual costs including intercomparison with standard

Personnel Requirements and Training

Personnel: Station operator - 0.5-1.0 man-months per year
Training: Operator for station instrument - 3 to 5 days

References


Contact:
Dr. Dieter Kley
Forschungszentrum Juelich
P.O. Box 1913
Juelich W-5170
GERMANY
2.1.4. Chlorofluorocarbons

**Importance**

Chlorofluorocarbons (CFC's), which include CFC 11 (CFCl3) and CFC 12 (CF2Cl2), are a family of compounds which do not naturally exist in the environment. Since manufacture began in the 1930's, CFC's have been used as refrigerant gases, as solvents in industrial applications and dry cleaning, and as propellant in aerosol cans. Because they are resistant to destruction in the troposphere and because production has accelerated over time, CFC's have been increasing in the lower atmosphere at about 4% per year (CFC 11 and CFC 12 only).

These gases have two important environmental effects: (1) CFC's contribute to the greenhouse effect, and (2) as a source of chlorine in the stratosphere, CFC's lead to the destruction of ozone as observed particularly over the Antarctic continent.

**Siting Requirements**

CFC's have been measured on a routine basis at GAW global stations. Because of their long residence time, a background level can be readily obtained in the remote troposphere. At regional stations, however, local sources may interfere with obtaining a representative background signal.

**Methods of Measurement and Sampling Frequency**

The standard technique to measure CFC's is to pass a whole-air sample through a dryer, after which it is injected into a gas chromatograph. Electron capture detectors (ECD) are used to detect the different gases. Calibration gas measurements are interspersed with air sample measurements to obtain absolute concentration.

An alternative to on-site determination is collecting samples in clean, stainless steel flasks and returning them to a central laboratory for analysis.

**Data Reduction**

Chromatograms are recorded by an integrator or computer which determines peak heights and areas. Mixing ratios for the samples are determined relative to the standard. The data are scanned for periods when the instrument was not operating optimally and for periods when their levels do not reflect background conditions.

**Archiving Procedures**

CFC data are archived at the WMO World Data Centre for Greenhouse Gases, operated by the Japan Meteorological Agency in Tokyo.

**Application of Results**

Data obtained from the CFC monitoring programmes are used both in climate models and in models describing the global ozone depletion problem. Also, validation of release data, source and sink estimations, and lifetime calculations depend on CFC measurements.

**Equipment Infrastructure and Cost (US$)**

**In-Situ CFC Analytical System**

Total start-up - $25,000 (includes 1 year of operation)

**CFC Flask Sampling at Remote Site**

Flasks and sampling - $6,000
Central Laboratory - $25,000
Personnel Requirements and Training

Personnel:  
In-situ system - 5 hours per week (weekly maintenance)  
- 2 weeks per year (yearly overhaul)  
Central Laboratory - 1 full-time staff

Training:  
GC operator - 3 months  
Sample taker - 2 days

References


Contact:  
Dr. Paul J. Fraser  
CSIRO, Division of Atmospheric Research  
Aspendale, Vic 3195  
AUSTRALIA
2.1.5. Nitrous Oxide

Importance

Nitrous oxide (N$_2$O) is a gas that has both natural and anthropogenic sources and contributes about 6% to the enhanced greenhouse effect. It is increasing at the rate of 0.7 ppb per year. Sources include the oceans, fossil fuel, biomass burning, and agricultural fertilizers. Nitrous oxide is inert in the troposphere, and its major sink is its photochemical transformation in the stratosphere.

Siting Requirements

Because of its long atmospheric lifetime (150 years), background levels of nitrous oxide can be determined at GAW global stations. Local sources at regional stations might interfere with the concentrations measured at such sites.

Methods of Measurement and Sampling Frequency

As with several trace gases, an electron capture gas chromatograph is used to separate N$_2$O. Concentrations are determined by interpreting the measurements with calibration gases of known N$_2$O concentration.

Flask sampling of nitrous oxide is an alternative method of monitoring concentrations. Flasks would be returned to a central laboratory for analysis.

Data Reduction

Chromatograms are recorded by an integrator or computer which determines peak heights and areas. Mixing ratios for the samples are determined relative to the standard. The data are scanned for periods when the instrument was not operating optimally and for periods when their levels do not reflect background conditions.

Archiving Procedures

N$_2$O data are archived at the WMO World Data Centre for Greenhouse Gases, operated by the Japan Meteorological Agency in Tokyo.

Application of Results

N$_2$O concentration trends are used in climate models and in describing the nitrogen cycle in the atmosphere.

Equipment and Infrastructure Cost (US$)

On-site N$_2$O Analytical System

Total start-up - $25,000 (1 year of operation)

CFC Flask Sampling at Remote Site

- Flasks and sampling - $6,000
- Central Laboratory - $25,000

Personnel Requirements and Training

Personnel: In-situ system - 5 hours per week (weekly maintenance)
- 2 weeks per year (yearly overhaul)

Training: GC operator - 3 months
Sample taker - 2 days
References


Contact: Dr. James Butler
Dr. J.W. Elkins
CMDL/NOAA
325 Broadway
Boulder, CO 80303
USA
2.1.6. Methane

Importance

Methane (CH\textsubscript{4}) is the most abundant hydrocarbon in the atmosphere. Its tropospheric chemistry affects OH and CO concentrations. In the stratosphere, oxidation of methane by OH is a major source of water vapour, and its reaction with Cl atoms is a termination step in the chlorine-catalyzed destruction of ozone. A strong IR absorption band at 7.66 μm, where CO\textsubscript{2} and H\textsubscript{2}O absorb weakly, makes methane an effective greenhouse gas. Finally, the reasons behind an approximately 0.8% per year increase in the atmosphere are still largely unknown.

Siting Requirements

The distribution of methane in the remote tropospheric boundary layer, particularly in the southern hemisphere, is fairly well established. There are regions with strong sources of methane that are poorly described. These include mid-latitude population centres in the northern hemisphere, agricultural regions in South and Southeast Asia, and the regions of the Soviet Arctic where methane hydrate destabilization may be occurring. These measurements, combined with suitable transport models, can be used to constrain regional sources of methane.

Methods of Measurement and Sampling Frequency

Most measurements of atmospheric methane are made by gas chromatography with flame ionization detection (FID). The gas chromatograph systems are very reliable and technically less difficult to operate and maintain than other methods. Typically, methane is separated from other components of an air sample with a molecular sieve column (5A or 13X) at constant temperature. The FID has a detection limit for methane <20 ppbv. Measurements are made relative to a standard.

Standards composed of air with stable, well-characterized methane mixing ratios are critical to a measurement programmes. As standards are depleted, it is necessary to propagate the measurement scale to new working standards. The intercalibration of different methane calibration scales remains an open question.

Several sample introduction schemes are possible. A central processing facility for flask samples should have an automated manifold for alternate flask sample and standard introduction to the analytical system, but it can be done manually. For a field instrument, an automated stream selection valve is used to select between standards and samples.

An alternative measurement technique is to use a tunable diode laser to determine methane mixing ratios by IR absorption. This methane is expensive to set up and maintain, and it requires a high degree of technical skill to operate.

Data Reduction

Chromatograms are recorded by an integrator which determines peak heights and areas, and chromatographic data are stored on a floppy disk. Mixing ratios for samples are determined relative to the standard. There are two main steps in quality control. Data editing is used to flag measurements made when the analytical system was operating less than optimally. Data selection is used to flag data which are not representative of background conditions, for instance when the wind is not from a defined “clean air” sector. At no time are data removed from the record. The edited and selected data are sometimes corrected for adjustments in the calibration values.

Archiving Procedures

Methane data are archived with the Carbon Dioxide Information and Analysis Centre in Oak Ridge, USA, and since 1990, with the WMO World Data Centre for Greenhouse Gases, operated by the Japan Meteorological Agency in Tokyo.

Application of Results

Data obtained by methane monitoring programmes are used to constrain aspects of the global methane
budget such as atmospheric burden, total annual source, and, in combination with models of atmospheric chemistry and transport, distributions of sources and sinks.

**Equipment Infrastructure and Cost (US$)**

In-Situ Methane Analytical System

- Gas chromatograph - $14,000 (one-time cost)
- Data acquisition - $5,000 (one-time cost)
- Plumbing hardware - $4,000 (one-time cost)
- Gases and miscellaneous - $9,000 (annual cost)
- Standards - $2,000 (annual cost)
- Total start-up - $34,000 (includes 1 year of operation)

Methane Flask Sampling at Remote Site

- Flasks and sampling - $6,000 (per site)
- Central Laboratory - $50,000 (start-up; 1 year of operation)

**Personnel Requirements and Training**

Personnel:  
- In-situ system - 5 hours per week (weekly maintenance)
- 2 weeks per year (yearly overhaul)

- Central Laboratory - 1 full-time staff; minimum requirement depends on number of sites and sampling frequency

Training:  
- GC operator - 3 months
- Sample taker - 2 days

**References**


**Contact:**  
Dr. E.J. Dlugokencky  
NOAA/CMDL, R/E/CG1  
325 Broadway  
Boulder, CO 80303  
USA
2.2. Reactive Gases

2.2.1. Carbon Monoxide

Importance

In the nonurban troposphere, carbon monoxide (CO) is often the primary sink for hydroxyl radical (OH) and therefore is an intimate component in the series of photochemical reactions which ultimately oxidize reduced carbon, nitrogen, and sulphur trace gases. Although CO itself is not a significant contributor to the greenhouse effect, its effect on the concentrations of other greenhouse gases can be considerable due to its influence on the OH radical.

Siting Requirements

The atmospheric lifetime of CO is intermediate and varies from several weeks to months depending on the OH concentrations. As a result, there are relatively large differences in the mixing ratios on regional scales. The levels range from a high of approximately 200 ppb (parts per billion) in the Northern Hemisphere winter to a low of 40 ppb to 55 ppb during the austral summer. There can also be a considerable variation in the mixing ratio between continental and oceanic areas. Estimates of the rate of CO increase vary widely: from 6% per year (best estimate, 1-2%) in the Northern Hemisphere to no significant change in the Southern Hemisphere. The absolute concentrations as well as the rate of change are still uncertain. Measurements at the established clean air background sites will help to establish the growth rates, but additional data at regional sites, located closer to major source regions (industry and transportation, biomass burning), will be necessary to put better observational constraints on postulated global budgets.

Methods of Measurement and Sampling Frequency

Most measurements are made by gas chromatography with either a flame ionization (FID) detector or a mercuric oxide reduction detector. Two columns can be used in series, first silica gel for the removal of impurities, followed by the separation column of molecular sieve 5A. For the FID, CO is first catalytically converted to CH₄. In this case, the same GC can be used to measure both CH₄ and CO (and many other hydrocarbons), but the most precise results for CO are obtained when the instrument is optimized for the detection of CO. In the HgO reduction detector, CO reacts with hot HgO, releasing Hg vapour, which is detected by UV absorption. Molecular hydrogen is also detected in this setup.

Reference standards consisting of dried air with carefully determined CO mixing ratios are essential to any programme of regional CO measurements. Currently, caution must be used when comparing previously obtained data sets from various laboratories to evaluate either geographical or temporal CO trends. This is primarily due to differences in CO standard scales presently in use, which may vary by as much as 30% among one another.

There is a very significant problem of contamination associated with the measurement of CO in flask samples. CO will increase or decrease in many types of containers in a matter of weeks or even days. The introduction of samples to the GC is identical to that for CH₄, usually alternating samples and standards.

Tunable diode laser spectroscopy has been used successfully to measure ambient CO by infrared absorption. Drawbacks of this method are that the start-up costs are much higher than for a GC, and that a high degree of technical skill is required to maintain the instruments. Another technique has used solar absorption spectra to obtain total column abundances over a period of several decades.

Data Reduction

Chromatograms are recorded by an integrator, and peak heights and areas and other chromatographic information are stored on disks. All mixing ratios are determined relative to the standard. First the data are edited for instrumental malfunctions, and then several criteria (depending on the site) are used to select data that are considered to represent "background" air, representative of the mixing ratio over a large area. No data are removed from the record; they are only "flagged".
Archiving Procedures

Both flask data and data from field instruments are archived at the WMO World Data Centre for Greenhouse Gases, operated by the Japan Meteorological Agency in Tokyo.

Application of Results

The CO data are used to increase our understanding of changes in the oxidation processes that are occurring in the atmosphere. The observations will also put constraints on hypothesized global budgets of CO, that include estimates of all major sources and sinks.

Equipment and Infrastructure Costs (US$)

Field Instrument - Remote Baseline Station

- Gas chromatograph - $15,000
- Data acquisition - $5,000
- Gas handling - $3,000
- Total start-up costs - $23,000
- Reference standard gases - $5,000 per year
- Supplies and maintenance - $8,000 per year

Flask Sampling at Remote Sites

- Flasks and sampler - $6,000 per site
- Logistics - $5,000 per year, per site

Central Laboratory - $50,000 (start-up, 1 year)

Personnel Requirements and Training

Personnel: Central Laboratory - 1 full-time person, depending on number of sites and sampling frequency
Field instrument - 1 man-month per year
Collection of flask samples - 1 to 2 hours per week

Training: GC operator - 3 months
Sampler taker - 1 day

References


Contact: Dr. P.C. Novelli
NOAA/CMDL, R/E/CG1
325 Broadway
Boulder, CO 80303
USA
2.2.2. Sulphur Dioxide (SO\textsubscript{2})

Importance

The concentration of sulphur dioxide in remote areas is about .05 ppbv. In urban areas, concentrations may rise to greater than 10 ppbv. Power plant plumes and volcanic emissions may emit concentrations as high as 1,000 ppbv. SO\textsubscript{2} is a greenhouse gas because it is an infrared absorber. But, because of its low concentration relative to other greenhouse gases it is a less significant greenhouse gas.

Sulphur dioxide is a climatically active trace species, because atmospheric SO\textsubscript{2} reacts photochemically (homogeneous conversion) and on airborne particles (heterogeneous conversion) to produce sulphates. Atmospheric sulphate particles are active cloud condensation nuclei. An increase in the number of cloud condensation nuclei on a global scale may increase cloud albedo. An enhancement in atmospheric sulphate particles in the stratosphere may increase short-wave reflection to space.

Sulphur dioxide also plays a significant role in producing acid deposition. It forms sulphate particles. These particles return to the Earth’s surface via dry or wet deposition processes. Both processes transfer excess acidity to their deposition sites. This acidity may damage sensitive ecosystems.

Siting Requirements

SO\textsubscript{2} has not been routinely monitored at baseline observing stations. It has a lifetime of hours to days. The sources for SO\textsubscript{2} in the atmosphere include the sea, volcanic activity, anthropogenic emissions, and biomass decay processes. Measurements to monitor the background concentration of SO\textsubscript{2} should be made far away from sources. On the other hand, SO\textsubscript{2} is a standard measurement at a number of regional stations. Careful placement of the SO\textsubscript{2} monitoring lines should be considered in order to reduce air from local sources of contamination, such as the buildings, internal combustion engines, or power generators. SO\textsubscript{2} is a reactive gas. It may stick to intake lines or oxidize within water drops condensed in the lines. Thus, intake lines should be made of inert material (Teflon, stainless steel) and be as short as possible.

Methods of Measurement and Sampling Frequency

SO\textsubscript{2} concentrations can be measured continuously using either a pulsed-fluorescence analyser or a flame-photometric device. The response time of the pulsed-fluorescence sensor is slower, but its ease of calibration, dependability, accuracy, and SO\textsubscript{2} specificity make it preferable. More sensitive gas chromatographic techniques are available. They require significant technical expertise and regular attention. SO\textsubscript{2} concentrations also can be measured using filter media. This method yields a potentially more accurate result. It is an integrative technique, requires frequent attention, and filter analysis costs are high.

Since SO\textsubscript{2} has a short atmospheric lifetime, understanding the sulphur cycle requires knowledge of the source and sink terms. This is best accomplished with sampling frequencies of less than 1 hour. Therefore, the best technique for long-term monitoring of SO\textsubscript{2} may be a combination of the pulsed-fluorescence analyser and filter sampling. Filter samples would be exposed at intervals, but often enough to act as a quality control for the continuous analyser.

Data Reduction

Continuous SO\textsubscript{2} samplers produce an analog voltage output. The voltage bears a linear relationship to SO\textsubscript{2} concentration. The voltage to concentration algorithm is found via periodically challenging the monitor with known concentrations of SO\textsubscript{2}. The zero value of the continuous monitor drifts with time, in response to changing pressure, temperature, and humidity conditions. Data reduction consists of applying appropriate zero values and appropriate voltage to concentration conversion equations as functions of time.

Filter pack sampling systems produce filters exposed to a volume of ambient air. The volume of ambient air drawn through a filter is determined by integrating the measured flow rate through the filter. Each exposed filter must undergo a flushing process that dissolves the filter and leaves a sample residue. Ion chromatography determines the amount of sulphur in this residue. The difference between this sulphur content and that before exposure (blank value) is the exposure total. The exposure total divided by the volume of ambient air drawn through the filter yields the SO\textsubscript{2} concentration.
Archiving Procedures

Sulphur dioxide has not been monitored regularly, except as a part of acid deposition studies. The data appear as average SO₂ concentration (ppbv) at selected time intervals. They can be tabulated in report form or stored in a computer-compatible form at an appropriate data centre. The reporting of an average concentration at 10-minute intervals (continuous analyser) or 1-day intervals (filter system) is appropriate and feasible. The SO₂ measurements for GAW stations will be archived at the WMO World Data Centre for Greenhouse Gases, operated by the Japan Meteorological Agency in Tokyo.

Application of Results

Average SO₂ concentrations at remote sites may be coupled with emission inventories, sulphate conversion rates, and deposition rates to refine our knowledge of the atmospheric sulphur cycle. These refined assessments may be used to predict regions where atmospheric sulphur concentrations will rise. The consequences of rising regional atmospheric sulphur concentrations may be increased acid deposition or the enhancement of cloud albedo.

Equipment and Infrastructure Cost (US$)

SO₂ In-Situ Sampler

- Analyser - $15,000 (one-time cost)
- Calibrator system - $8,000 (one-time cost)
- Calibration gases - $1,000 (one-time cost)
- Total start-up cost - $24,000
- Variable annual costs to maintain system, calibration gases, etc.

SO₂ Filter-Pack Sampler

- Filter sampler - $10,000 (one-time cost)
- Total start-up cost - $10,000
- Filter analysis - 100 per sample, 1 sample per day
- Filter blank anal. - 100 per sample, 0.5 sample per day
- Variable annual costs to maintain system

Personnel Requirements and Training

Personnel: Chemist to install and calibrate system at site - 2 weeks
- Technician to check system, change calibration gases, and change filter media - 3 man-months per year
- Analyst to apply calibration corrections, provide quality control, and archive collected data - 2 man-months per year

Training: Technician - 2 weeks

References


Contact:
- Jan Schaug
  Norwegian Institute for Air Research
  P.O. Box 64
  N-2001 LILLESTROM
  Norway
2.2.3. Nitrogen Oxides

Importance

Nitrogen oxides form a large family of trace gases that are ubiquitous in the Earth’s troposphere. Their origin is from both anthropogenic (combustion) and natural (biomass burning, lightning, soil microbial activity) processes; transport from the stratosphere is also thought to be a source. Nitrogen oxides play a crucial role in determining the ozone concentration in the air; they can also contribute to acid precipitation. Although the need for knowledge of the abundance of these compounds is unquestioned even at the pptv level (1 pptv = 1 in 10^{12} molecules), very little observational data outside urbanized areas are presently available due to the unavailability of equipment necessary to determine such low concentrations. The more important compounds are NO, NO_2 (the sum of these two compounds is often indicated as NO_x), HNO_3, aerosol nitrate, and peroxy-acetyl-nitrate (PAN). NO and NO_2 are the initial compounds produced, while the other are the product of chemical conversions in the atmosphere from the former.

Nitrous oxide (N_2O) is a special case; its chemistry is very different from all other nitrogen oxides in that it is essentially inert in the troposphere. It is discussed separately as part of the greenhouse gases (Section 2.1.).

Siting Requirements

Nitrogen oxides have not been routinely measured at baseline sites, since no acceptable methods existed. Conversions between the different compounds are generally rapid, and the unambiguous data for nitrogen oxides would be the sum of all compounds (excluding N_2O), which is often denoted as "NO_x". Since anthropogenic activities constitute a large source of nitrogen oxides, any true global signal (if it exists) can be observed only at very remote locations.

Siting requirements are dependent on the type of information that is sought. Since the chemistry of nitrogen oxides is quite rapid, a dense network is required for any true description of its overall variability. Obvious precautions related to human interference with the measurements have to be taken into account. Since the levels are so low, even at less remote locations, great care has to be taken to minimize potential contamination from any form of motorized transportation, which is a principal source of NO_x.

Methods of Measurements

NO, NO_2: Reliable measurements of these compounds at background levels have only been possible with instruments that are based on chemiluminescence of NO (with ozone) or NO_2 (with luminol solution). The other compound (NO_2 or NO, respectively) is then measured by converting it into the principal luminescing compound. Unfortunately, the first method (NO luminescence) has only been possible with carefully designed special equipment, while the other method so far has not been successful, largely due to technical and interference problems. A further major problem is to ascertain that the conversion of NO_2 into NO, or vice versa, is unique.

PAN: A few long-time records on PAN have been collected, based on automated gas chromatography, equipped with electron capture detection. The major problem with PAN measurements is the method, and reliability of calibration. Standards have to be made in the laboratory and have to be carefully calibrated, which is usually done by infrared spectroscopy or ion chromatography. These standards have a relatively short lifetime, and frequent calibration is therefore impractical for long-time monitoring.

HNO_3, aerosol nitrate: These compounds are amenable to monitoring with filters. A standard procedure would require a train of filters in series, with the first filter a Teflon filter to capture aerosols, including aerosol nitrate, followed by a nylon, or base-impregnated, filter to capture acid gases including HNO_3. These filters are routinely exposed for periods of at least 24 hours, by sucking air at a flow rate of several litres per minute. The filters are then transported to a laboratory, extracted, and analysed for nitrate ions by ion chromatography. To derive the amount of air that is sampled, the pumping flow rate has to be continually measured.

NO_x: The sum of all nitrogen oxides is measured by converting them all to either NO or NO_2 and measuring these compounds as described earlier. This conversion is obtained by flowing air through a gold-coated converter tube kept at ca. 300 °C, together with a small amount of either pure carbon
monoxide or hydrogen gas. Alternatively, a molybdenum tube at similar high temperatures can be used, although its efficiency for total conversion is somewhat controversial.

**Data Reduction**

All instrumental methods require an electronic data system; the use of a chart recorder as a backup is highly recommended. Flow rates for filter sampling procedures need similar data storage. In the laboratory these records have to be carefully screened for any periods of time that the data are invalid due to human interference (usually any visit of an operator to the monitoring site influences the data); periods that calibrations were performed have to be removed from the record as well. Normally, the raw field data are corrected for calibration data in the laboratory, to yield a final data set.

**Archiving Procedures**

It is common procedure to archive all raw field data, in addition to a final data set that is reduced to a longer averaging period. The averaging period depends on the anticipated use of the data and varies from 5-10 minutes to daily or monthly averages. The nitrogen oxides measured at GAW stations are archived at the WMO World Data Centre for Greenhouse Gases, operated by the Japan Meteorological Agency in Tokyo.

**Application of Results**

In view of the importance of these data for understanding global tropospheric ozone patterns, the scientific community is desperate for such data and as yet has had little success in seeing them actually being collected by any major global network.

**Equipment and Infrastructure Cost (US$)**

**NO, NO₂:**

- Analyser (NO₂ photolytic converter, O₃ chemiluminescence) - $50,000
  - (NO CrO₃ converter, luminol chemiluminescence) - $20,000
- Calibration system (NO₂ permeation) - $15,000
- NO calibration gas, each - $1,000
- Data system (data logger, computer, chart recorder) - $12,000

**PAN:**

- Gas chromatograph with electron capture detector - $20,000
- Data system (integrator, logger, computer, chart recorder) - $15,000
- Calibration system (to be "home-built") - $10,000
- Central Laboratory arrangement to prepare standards. Needs access to FTIR, HPLC, or ion chromatography equipment for absolute standardization

**HNO₃, aerosol nitrate:**

- Filter sampling system (filter packs, pump, flowmeters, loggers) - $20,000
- Needs Central Laboratory to prepare and analyse filters.
- Costs exclusive initial laboratory setup, per annum - $50,000

**NO₃⁻:**

- Analyser ("NO₃-box") - $20,000
- Hardware to modify analyser for NO₃ measurements - $25,000
- Data system (data logger, computer, chart recorder) - $12,000
- Calibration system (NO₃, HNO₃ permeation) - $15,000
- Needs specialized contractor to modify equipment - $50,000 (?)

All systems have various annual costs to maintain the system, special supplies, etc.
Personnel Requirements and Training

None of these measurements can be done on a routine basis, with the possible exception of the filter sampling for HNO₃ and aerosol nitrate. In practice, each measurement system requires a full-time PhD person to keep it running. Site operators can be trained in a short time span, but realistically they can only be expected to perform the filter-pack sampling.

References


Contact:  Dr. Jan Bottenheim
           Atmospheric Environment Service
           4905 Dufferin Street
           Downsview, Ontario
           CANADA  M3H 5T4
2.2.4. Oxygen

Importance

Molecular oxygen (O₂) is the second most abundant (almost 21%) gas in the atmosphere. Its variations are very small compared to its abundance, and they are directly coupled to CO₂ and the carbon cycle. The burning of fossil fuels and biomass consumes O₂, while photosynthesis results in the production of O₂. Other influences on the atmospheric O₂ abundance, such as the burial and oxidation of sedimentary rocks, are minor compared to the coupling with carbon. Oxygen is not very soluble in water, so that very precise measurements of changes in the atmospheric O₂ mixing ratio can give us the sum of all fossil fuel combustion and all terrestrial biomass changes. Also, because of its low solubility, the seasonal cycle of atmospheric O₂ is expected to contain a relatively large component caused by marine ecosystem seasonal productivity. This is in contrast to the seasonal cycle of carbon dioxide (CO₂), which is caused almost exclusively by the productivity of terrestrial plants.

Siting Requirements

A number of baseline observatories in both hemispheres, preferably those where CO₂ is also being measured, should suffice to measure the long-term temporal trend, the seasonal cycle, and the large-scale concentration gradient from the Arctic to Antarctica.

Methods of Measurement and Sampling Frequency

The difficulty is that the small concentration signals of interest lie on top of the enormous amount of oxygen present in the atmosphere. Consequently, the handling of the samples requires extreme care, and the precision requirements for the analytical instrumentation are severe. Several quite different methods have been and are being used to measure O₂. Other approaches are theoretically possible but have so far not been pursued for this purpose. The interferences are not the same for the various methods. At this time, no method has been developed to the point where it would be suitable for field operation. All air samples thus far have been collected in flasks (weekly) and have been measured in the laboratory. The techniques to make precise measurements of atmospheric O₂ are still under development.

Because O₂ is paramagnetic in the ground state, a magnetic field will produce a force on the molecules. This can be measured by a sensitive force balance. As another option, an alternating magnetic field can be employed to generate a modulation of the gas pressure, which can be measured in different ways, for instance with a microflow sensor.

In the ultraviolet region of the electromagnetic spectrum the index of refraction of oxygen is influenced by nearby absorption resonances. One method consists of measuring extremely small changes in the index of refraction of air in the UV relative to changes in the visible part of the spectrum. The magnitude of the relative changes depends on the O₂ concentration. This method is employed in a very sensitive Jamin interferometer.

A mass spectrometer can be employed to measure ion current ratios at the masses 28, 29, 32, 33, 34, or some combination thereof, either directly or in an isotope dilution mode after an isotopically spiked sample has been mixed with the sample. A modern mass spectrometer capable of the highest precision is required.

Chemical conversion of O₂ to some other compound that can be more easily measured has been attempted, but the precision appears to have been generally less than the interferometric or the mass spectrometric methods. The same is true of a Raman scattering method that measures the ratio of O₂ and N₂ directly in the gas phase.

Data Reduction

It is useful to measure CO₂ in the same samples for which O₂ is being determined. In principle, this would allow for the removal of most of the signal caused by local vegetation. It is prudent, however, to apply the same criteria for the selection of background conditions to O₂ as are being applied to CO₂, which vary depending on each observatory site.
Archiving Procedures

No data have been archived thus far.

Application of Results

The new O₃ measurements are expected to lead to major advances in our understanding of the global carbon cycle. One of the most important outstanding questions is the untangling of the separate roles played by the oceans and the terrestrial biosphere in the uptake of carbon. Also, the controversy about marine productivity might be cleared up.

Equipment and Infrastructure Cost (US$)

Mass spectrometer and sample handling - $300,000
Interferometer (not commercially available) - $200,000

Flasks and sampler (weekly samples, per site) - $10,000
Flask logistics (per year) - $5,000

Standard gases
(cost for initial development, still underway) - $100,000

Personnel Requirements and Training

Personnel: Central Laboratory - 2-3 full-time people
Much development work is still necessary

Training: Flask sampling - 1 day

References


Contact: Dr. Pieter P. Tans
NOAA/CMDL, R/E/CG1
325 Broadway
Boulder, CO 80303
USA
2.3. Radioactive Gases

2.3.1. Radon

Importance

Radon is an inert gas resulting from the alpha decay of radium, with a half-life of 3.82 days. Because radon fluxes from soils are typically 100 times that from the ocean, radon is useful as a tracer for air masses which have recently passed over land. Studies at the Mauna Loa Observatory in Hawaii have identified diurnal episodes of radon transported from local sources, and long-term transport of air from distant continents. In conjunction with other measurements, radon data provide a useful tool in evaluating air transport models and in identifying baseline atmospheric conditions.

Siting Requirements

Because of its short residence time in the atmosphere and wide range of surface emanation rates, the interpretation of radon measurements is highly site-specific. Radon has been routinely measured at both continental and remote baseline sites. Long-range transport studies are best made from coastal or high-altitude sites free of local radon sources.

Methods of Measurement and Sampling Frequency

Radon-222 decays through a series of five daughter products into lead-210, which is relatively stable at a half-life of 22 years. Two of these daughter products undergo alpha decay. The daughter elements are chemically reactive and quickly form complex hydrated ions which readily attach to particles and surfaces.

In a typical radon monitoring instrument, air is drawn through a filter which removes all the ambient radioactive substances but allows the inert radon gas to pass. The radon then enters a large chamber, which allows a time delay during which its daughter elements are produced. These are collected on a second membrane filter, and their alpha activity is measured by a scintillation counter.

The response of an instrument is dependent on a number of factors such as the flow rate, chamber geometry, daughter capture efficiency, sampling interval, humidity, and counter efficiency. For example, the radon detector used at the Cape Grim Baseline Station had the detection limit of 0.05 Bqm⁻³, which is about ten times lower than typical radon-222 concentrations in oceanic air. The usual frequency of sampling is 1-2 samples per hour.

Data Reduction

Data are collected and stored by a dedicated processor and recorded on a floppy disk. The data stream includes several environmental and housekeeping parameters as well as raw counts. The data are edited and radon concentrations are calculated.

Archiving Procedures

The radon-222 data are archived at the WMO World Data Centre for Greenhouse Gases, operated by the Japan Meteorological Agency in Tokyo.

Application of Results

Radon-222 data will be used in monitoring continental airmass events, and in validating the atmospheric trajectory models, as well as in studies of local air circulation patterns.

Equipment and Infrastructure Cost

No commercial radon-measuring device is presently available. A dual-filter monitoring device may cost about US$10,000 to 15,000 to construct.
Personnel Requirements and Training

Personnel: Operation and calibration of radon monitor - 8 man-hours per month
Data reduction, archival, dissemination - 24 man-hours per month

Training: Radon monitor operations and calibration - 1 week

References


Contact: Steve Ryan
Mauna Loa Observatory
P.O. Box 275
Hilo, HI 96721
USA
2.3.2. Krypton-85

Importance

Krypton-85 (\(^{85}\text{Kr}\)) is a radioactive noble gas which decays with a half-life of 10.76 years, emitting mainly \(\beta\)-particles of mean energy 251 KeV. The main sources of \(^{85}\text{Kr}\) are the nuclear fuel reprocessing plants and various nuclear reactors. The nuclear weapons tests in 1945-1963 contributed about 5% of the total \(^{85}\text{Kr}\) in the atmosphere, whereas its natural sources can be neglected. Radioactive decay is practically the only mechanism of \(^{85}\text{Kr}\) removal from the atmosphere. The present background concentrations of \(^{85}\text{Kr}\) in the atmosphere are about 1 Bq/m\(^3\) and are doubled every 15 years. At this level, \(^{85}\text{Kr}\) is not dangerous for human beings, but the air ionization caused by \(^{85}\text{Kr}\) decay will affect the atmospheric electric properties. If \(^{85}\text{Kr}\) continues to increase, changes in such atmospheric processes and properties as atmospheric electric conductivity, ion current, the Earth's magnetic field, formation of cloud condensation nuclei and aerosols, and frequency of lightning may result and thus disturb the Earth's heat balance and precipitation patterns. These \(^{85}\text{Kr}\)-induced consequences call for \(^{85}\text{Kr}\) monitoring. In addition, because of the well-known sources and sinks of \(^{85}\text{Kr}\) and its chemical stability it is a good tracer for testing the global tropospheric transport models.

Siting Requirements

For background determination, the current baseline monitoring stations such as Mauna Loa, Cape Grim, the South Pole, or almost any other location remote from \(^{85}\text{Kr}\) sources can establish the global pattern. But if one wishes to use the emissions of \(^{85}\text{Kr}\) for transport and diffusion studies, as have been reported downwind of the Idaho Falls and Savannah River nuclear installations, then additional locations in the downwind (and for background, upwind) sectors of the source would be needed. \(^{85}\text{Kr}\) being a noble gas, the special precautions that must be applied to other gases at background stations can be disregarded; natural \(^{85}\text{Kr}\) sources or interferences are either absent or can be easily dealt with.

Methods of Measurement and Sampling Frequency

Although there are several methods for collecting krypton from the atmosphere, the most usual and practical ones are cryogenic, using a charcoal trap immersed in liquid nitrogen. Before sampling, carbon dioxide and water vapour should be removed from the air. However, the aliquot so collected must be subsequently purified in a central laboratory by additional absorption and chromatographic separation. The elimination of radon, also radioactive, is especially important. Counting of the radioactivity relative to a standard \(^{85}\text{Kr}\) sample is normally accomplished in a Geiger-Mueller tube or by a scintillation gas radiometer. To date, there have been no or few intercomparisons of standard gases and none are commercially available through national standards laboratories. Current background concentrations in the atmosphere can be measured to a precision less than several percent relative to a standard \(^{85}\text{Kr}\) gas at a competent radiochemical laboratory. Taking into account the mixing time of trace substances during the long-range transport, the frequency of \(^{85}\text{Kr}\) sampling at background stations should be once every 1-2 weeks.

Data Reduction

Data reduction presents few problems at the radiochemical laboratory. Normally, the laboratory aliquot being counted for its radioactivity after purification represents a sample of krypton, not whole air. The original amount of whole air from which it was derived is known too imperfectly to be useful. Usually there is no or negligible fractionation of isotopes among the krypton isotopes during the collection and purification; the concentration of \(^{85}\text{Kr}\) per unit volume or mass of air at a given pressure and temperature can then be calculated if the average abundance of krypton in the atmosphere, about 1.14 ppm, is used.

Archiving Procedures

To evaluate the reliability of data for application to geophysical or biological problems, a measure of the uncertainty in the reported numbers must be given. This may include other information than only the measured or estimated uncertainty. The additional information might be the values of the several counts of the sample if more than one was made, the amount of krypton gas available for counting, the background of the counter, etc. The krypton-85 data are collected at the WMO Data Centre for Greenhouse Gases, operated by the Japan Meteorological Agency in Tokyo.
Application of Results

The application of the results will be those described under Importance. In addition, many scientists will be interested in the growth of $^{85}$Kr in the atmosphere as a measure of the worldwide nuclear activity.

Equipment and Infrastructure Cost (US$)

There are no published costs and each country now performing such measurements will likely have a different estimate depending upon other uses for which the equipment is used and when the installation was made. However, the lowest cost of the equipment which could be available is:

- Field collector: 3,000
- Preparative gas chromatograph: 3,000
- Analytical chromatograph: 2,000
- Scintillation gas radiometer: 5,000
- Standard gases: 2,000
- Bottles for shipping samples: 100 each

Personnel Requirements and Training

There is no published information on this subject and the estimates below are subject to considerable uncertainty:

Personnel:
- Field technician - 2 hours per day for collection
- 1 day per month for equipment maintenance
- Central Laboratory - 1 hour per month supervision by radiochemist
- 2 full-time technicians (for about 10 samples per month)

Training:
- Field technician - 1-week training
- Central Laboratory supervisor - experienced professional radiochemist
- Central Laboratory technicians - 3-month training

References


Contact:
Dr. W. Weiss
Bundesamt fuer Strahlenschutz
Institute for Atmospheric Radioactivity
Rosa Str. 9
W-7800 Freiburg
GERMANY
3. PARTICULATE MATTER

3.1. Physical Properties

3.1.1. Direct In-Situ Measurements of Aerosol Optical Properties

Importance

Nephelometers have been used since about 1970 to measure the scattering properties of aerosol particles in the visible part of the spectrum. Aethalometers have been used to measure the absorption of particles in the atmosphere. Aerosol particles can scatter and absorb both visible and infrared radiation in the atmosphere and thus interact with the radiation budget to produce a warming or cooling depending upon their size, index of refraction, and distribution in the atmosphere. These are termed direct effects of aerosols on climate. Particles may also act as cloud condensation nuclei or ice nuclei and participate in cloud-forming processes in the atmosphere. Since clouds interact strongly with radiation processes in the atmosphere and are important in determining the albedo of the Earth, aerosol particles can indirectly affect climate. These are termed indirect effects of aerosols on climate.

The measurement of aerosol optical properties may be approached in two ways. Aerosol size distribution, chemistry, and index of refraction may be measured, and then the optical properties may be calculated. Or, the aerosol scattering and absorption may be measured directly using a nephelometer and an aethalometer.

Siting Requirements

Nephelometers and aethalometers have been used to measure aerosol optical properties at the GMCC baseline stations for many years. As with other aerosol measurements, it is important to avoid local contamination effects and to select a site generally representative of the region. For example, the Barrow site was selected to be representative of the Arctic region, and the Samoa site was selected to be representative of the clean marine boundary layer. A measurement site must be carefully chosen to minimize local contamination sources. In general, a wind climatology of a potential sampling site must be determined to ensure a long fetch from a clean direction a majority of the time.

Methods of Measurement and Sampling Frequency

Several models of nephelometers have been available for measuring the scattering properties of aerosols. The original MRI model 1550 instrument (which used a flash lamp for its light source) and the model 1560 (which used an incandescent light source) were capable of measuring aerosol scatter of about the same magnitude as the Rayleigh scatter of air molecules. For operation at a clean background site, special instruments were constructed that alternately measure ambient air and filtered air, and perform a real-time subtraction. These instruments were installed at the four U.S. baseline stations, and are capable of measuring aerosol scatter about 1% of the Rayleigh scatter of air molecules at a time resolution of 1 hour. A modern three-wavelength version of this instrument is available that is capable of measuring aerosol scatter of about 1% of the Rayleigh scatter of air molecules at a time resolution of 1 minute.

The aethalometer is an instrument that measures the attenuation of a light beam passing through a filter on which aerosol is continuously accumulating. The change of attenuation of the light beam over a given time period is a measure of the aerosol absorption averaged over that time period. An instrument is currently available that is capable of measuring the equivalent of about 1 ng m$^{-3}$ black carbon aerosol with a time resolution of about 1 hour. Although the instrument measures the aerosol light absorption, it can be characterized by oxidizing the carbon present on the filter, measuring the carbon dioxide, and inferring the total mass of elemental carbon on the filter. Care must be taken to measure the aerosol light absorption at a single wavelength; current instruments do not provide spectral discrimination.

Both the nephelometer and the aethalometer run continuously; hourly averages ordinarily provide adequate time resolution at a typical monitoring site.

Data Reduction

Nephelometer (aerosol scatter) and aethalometer (aerosol absorption) data may be recorded directly on a suitable data acquisition system. Backup data may be recorded on a strip chart recorder. To separate
periods of local contamination from background conditions, data selection must be based on conditions unique to the measurement site. The Condensation Nuclei data being recorded at the site may be used along with wind direction and speed data to edit the scattering and absorption data sets. Since the aethalometer data are very sensitive to local influences, they also may be used to help with data selection for the site.

Archiving Procedures

Aerosol scattering and absorption measurements made at a variety of locations on the Earth and by a variety of institutions do not have a common data repository at present. Data are generally available from the project leaders of the various national programmes.

Application of Results

The aerosol scattering and absorption data have been used to estimate the effects of the suspended particles on the Earth’s climate. Furthermore, by measuring both scattering and absorption, it is possible to calculate the single-scatter albedo, an important parameter in climate modelling. If the vertical distribution of these quantities is known (or assumed), it is possible to estimate the total optical depth of the atmosphere, another parameter used in climate modelling. Multiwavelength measurements of aerosol scattering (and/or optical depth) allow the estimation of aerosol size distribution, a useful parameter in climate modelling. Size distribution information also allows inferences to be drawn regarding sources, sinks, and long-range transport.

Equipment and Infrastructure Cost (US$)

Nephelometer - Remote Baseline Station

Three-wavelength instrument - $35,000
Single-wavelength instrument - $10,000
Calibration gas - $500
Various annual costs for maintenance

Aethalometer - Remote Baseline Station

Aethalometer - $10,000
Pump - $1,000
Filters and supplies - $1,000

Personnel Requirements and Training

Personnel: One observer at a baseline site - about 15 minutes, 3 times per week
Training: One observer to be trained at a central laboratory - 1 day

References


Contact: Dr. Barry A. Bodhaine
NOAA-CMDL, R/E/CG1
325 Broadway,
Boulder, CO 80303
USA
3.1.2. Stratospheric Aerosol - Lidar

**Importance**

Stratospheric aerosols can have a direct impact on climate. During periods following a significant volcanic injection, optical properties of stratospheric aerosols are important factors in the determination of the heat balance of the atmosphere. Long-term increases in the "background" stratospheric aerosols due to anthropogenic sources may also be of climatic importance.

Also, during periods of nonbackground stratospheric aerosol conditions, aerosol optical thickness and aerosol distribution data are very important. They are useful for supporting precision radiometry and various remote sensing techniques for the measurement of ozone and other stratospheric trace gases.

Stratospheric aerosol measurements using lidar have also been an important tool in the study of possible heterogenous chemistry processes within the stratosphere. Lidar measurements of stratospheric aerosols may be useful in the study of atmospheric transport processes.

**Siting Requirements**

An optimum observing site should provide frequent opportunities to make measurements under clear, dark sky conditions. However, subject to various performance penalties, it is possible to make lidar measurements under less than optimum conditions.

A broad latitudinal distribution of lidar sites is desirable. Presently, there is a lack of operational stratospheric aerosol lidar systems in the Southern Hemisphere.

**Methods of Measurement and Sampling Frequency**

A typical aerosol backscatter lidar system is composed of a laser transmitter and an optical receiver, arranged in a monostatic configuration oriented toward the zenith. The laser is generally selected to produce an intense, short-duration pulse of collimated visible monochromatic light. Typically, a high-powered Q-switched ruby or, more recently, a frequency-doubled Q-switched Nd:YAG laser is used.

The intensity of the elastic backscatter signal is measured vs. time through the telescope receiver equipped with collimating optics, a narrow bandpass filter, and an appropriate PMT detector which employs either photon counting or analog techniques. Relative intensity data of all altitude intervals are accumulated over a selected observation period. An observation may include the integration of hundreds or even hundreds of thousands of individual laser shots. Factors which influence an observation include the laser and telescope utilized, the altitude interval length and range of interest, the SNR desired, the observation conditions, and the desired integration period.

**Data Reduction**

Raw signal intensity data must be range-corrected, normalized to an assumed backscatter ratio, adjusted for molecular backscatter, and corrected for molecular and aerosol extension, using the "lidar equations" and various algorithms. Real-time or quasi-real-time data reduction is possible, but it is usually followed by a more thorough processing which utilizes the most accurate algorithms and the best input data and assumptions available.

**Archiving Procedures**

At present, there is no official central archive for stratospheric aerosol lidar data from the various international sites involved in these measurements. For example, at the Mauna Loa Observatory (MLO) in Hawaii, both raw and fully processed data, as well as intermediate data products, are archived. The semi-processed as well as final results of MLO lidar data are also archived.

**Application of Results**

Lidar stratospheric aerosol data have been used to verify satellite data for aerosol corrections of Umkehr measurements, and to detect and determine the aerosol optical thickness of various stratospheric volcanic
injections. Present and future applications will likely be directed at determining trends in the background stratospheric aerosol.

Application of stratospheric aerosol lidar data from other facilities have also included the detection and study of "polar stratospheric clouds" and the study of the "ozone hole".

**Equipment and Infrastructure Cost (US$)**

Lidar systems are usually custom designed and built. Initial costs will generally range upwards from $200,000, depending on the main application of the system; the wavelength and the number of wave-lengths desired, the altitude resolution and ranges of interest; and the SNR, accuracy, and integration period requirements. At least $10K should be set aside annually for equipment maintenance, incidental system modifications, and personnel technical exchange opportunities.

If the system is to be maintained over decades, major system upgrades should be budgeted to maintain the system serviceability and to meet changing system standards.

**Personnel Requirements and Training**

Stratospheric lidar systems have typically been in-house custom designed, fabricated, and maintained to meet each facility's special applications and constraints. To maintain and operate such a system (including data) up to reasonably current standards will take at least 1 full-time employee even at only 1 to 2 observations per week. A turn-key system could be operated on site for 1 man-day or less per observation (depending on site logistics), given ideal observing conditions.

Operator technician training could easily be accomplished in 1 week.

Equipment maintenance training for a technician already generally competent with lasers, optics and electronics could probably be accomplished in 2 weeks.

Programme and system management should probably be left to a scientist or engineer with appropriate previous experience or education.

**References**


**Contact:**

Thomas E. DeFoor  
Mauna Loa Observatory  
P.O. Box 275  
Hilo, HI 96721-0275  
USA
3.1.3. Condensation Nuclei

Importance

Aerosol particles are small solid and liquid particles suspended in the atmosphere, such as sulphate, dust, and sea salt. They range in size from about 0.001 μm (clusters of molecules) to 10 μm or larger in diameter and vary greatly in shape and chemical composition. Natural sources include biogenic sulphate, volcanos, sea salt, forest fires, and desert dust. Man-made sources include power plants, industry, automobiles, home heating, and agricultural burning. Compared to gases such as CO₂ that consist of a single molecule, aerosol distributions are complex and difficult to characterize because of their wide range of size, shape, chemical composition, and index of refraction.

Condensation nuclei (CN), also called Aitken nuclei, are defined as particles that grow into droplets under conditions of high supersaturation. The main source of condensation nuclei in the atmosphere is gas-to-particle conversion, from combustion processes, and from production of sulphate in the marine boundary layer. An additional source about which little is known is the production of particles from biogenic gases such as terpenes. A fresh combustion source produces high concentrations of very small particles. However, because of coagulation processes, an aged air mass contains particles with diameters of a few tenths of a micrometer. The background troposphere is generally filled with a sulphate aerosol having a concentration of several hundred per cubic centimetre.

Siting Requirements

Condensation nuclei measurements have been made at background monitoring stations for several decades. Any increases in anthropogenic pollution emissions could result in a change in the background concentration of condensation nuclei. A measurement site must be carefully chosen to minimize local contamination sources. In general, a wind climatology of a potential sampling site must be determined to ensure a long fetch from a clean direction a majority of the time. This is especially important for CN measurements because generators, home heating, and automobiles are prolific sources of aerosol particles. For example, the clean air facility at the South Pole station is located upwind of the camp and is exposed to winds from the clean air sampling sector 98% of the time. However, occasionally winds are calm or from the camp, and samples are contaminated by local effects.

The Barrow, Alaska, station was chosen to be representative of the Arctic region. The data record from Barrow clearly shows the well-known Arctic haze event every winter and spring. The Mauna Loa, Hawaii, station is representative of the northern subtropical midtroposphere and is subject to Asian desert dust events in the spring. The Samoa station is representative of the southern tropical marine region. The South Pole station is, of course, representative of the Antarctic region.

Methods of Measurement and Sampling Frequency

The classic method for measuring CN employs a Pollak counter, an expansion-type instrument developed in the 1950’s, that uses the attenuation of a light beam to measure the density of a cloud formed in the sample chamber. A widely used manually operated portable instrument that operates on the same principle is the Gardner CN counter. The General Electric automatic CN counter was the first automated expansion chamber instrument, and this is the instrument that produced the long CN records at the four GMCC baseline sites.

Recently, an alcohol-based continuous flow CN counter manufactured by TSI Inc. has become the instrument of choice. This instrument uses a sample flow through an alcohol saturation chamber and then through a cooling tube to produce a high supersaturation and form a cloud. The sample stream then passes through a laser beam and each droplet is counted. Since the instrument uses a single-particle counting scheme, it is sometimes called an absolute counter and requires no calibration; knowledge of the flow rate is all that is required.

Concentrations between 1 and 10,000 per cubic centimetre are easily measured. This is the instrument recommended for background CN measurements.

Data Reduction

Measurements from either the Pollak or the Gardner-type CN counter are performed and recorded
The TSI CN counter output may be recorded by an electronic recording system by using a simple pulse counter. A backup analog signal may also be recorded on a strip chart recorder. It is important to select data to determine background conditions and eliminate contaminated data. As first criteria, wind direction and speed should be checked for each data point of the record to identify periods when background air is being sampled. Furthermore, CN data can be used to develop selection criteria for other parameters being measured at the monitoring station.

Archiving Procedures

Condensation nuclei measurements made at a variety of locations on the Earth and by a variety of institutions do not have a common data repository at present. Data are generally available from the project leaders of the various national programmes.

Application of Results

The CN data have been used to describe the distribution of aerosol particles at surface locations around the globe and at various levels in the atmosphere. However, because the suspended particulate is highly variable in concentration, size distribution, and chemical composition, it is difficult to provide a general model. CN data are commonly used to screen the data sets of other parameters to identify possible periods of local contamination.

Equipment and Infrastructure Cost (US$)

- TSI CN counter (with pulse-counting electronics) - $18,550
- TSI CN counter (without pulse-counting electronics) - $6,050
- Pump - $500
- Supplies - $100
- Aerosol inlet system - $500
- Annual maintenance costs Gardner CN counter - $600

Personnel Requirements and Training

Personnel: One observer at a baseline site - about 15 minutes, 3 times per week
Training: One observer to be trained at a central laboratory - 1 day

References


Contact: Dr. Barry A. Bodhaine
NOAA-CMDL R/E/CG1
325 Broadway
Boulder, CO 80303
USA
3.1.4. Aerosol Black Carbon

**Importance**

Aerosol "black carbon" (BC) is emitted from all processes involving the combustion of carbonaceous materials. The emission factor, expressed as [grams BC] emitted per [gram C] consumed in the fuel, is highly variable and depends on the nature of the combustion process and the degree of its regulation. Advanced industrialized countries consume large amounts of fuel, but may produce less BC than less-advanced countries, either developing or industrialized. BC has a long life in the atmosphere and may be used as a tracer to indicate the transport of pollutants over long distances. Its large optical absorption may perturb the solar radiation balance, especially in the Arctic over high-albedo surfaces. Its deposition to those snow and ice surfaces may increase the absorption of radiation, leading to accelerated thawing. It may act as a condensation nucleus, and its surface may catalytically promote heterogeneous chemical reactions. It is desirable to measure BC both in the airshed of major source regions and in remote areas, to estimate emissions and export of this species.

**Siting Requirements**

The measurement site should be representative of air quality at a scale no less than regional. Combustion source activity in the immediate vicinity (e.g. diesel generators) may completely overwhelm the BC measured in remote areas, however, these events may be distinguished in the time series record, and edited from the database. Thus, vehicular or similar activity upwind of the measurement site may be tolerated if data dropouts are acceptable. BC measurements are being gradually introduced at the NOAA/CMDL monitoring sites, as well as at some other locations worldwide.

**Methods of Measurement and Sampling Frequency**

BC is normally determined by measuring the optical absorption of an aerosol deposit collected on a filter. If this sample is time-integrated and analysed afterwards, the possibility of local contamination may be severe. One minute of exhaust from a nearby vehicle may contribute as much BC to the sample as 1 day of filtering the remote atmosphere. Some of the analytical techniques suffer from substantial interferences due to the effects of optical scattering by the aerosol deposit.

The aethalometer is an instrument that measures the optical absorption continuously while sampling, and produces measurements on some convenient time base, e.g. 10 minutes to 1 hour. It requires no technician attention while operating other than to change the filter periodically (1 per day - 1 per week), a model with a self-changing filter tape is under development. At the end of each filter period, a time-integrated aerosol sample remains on the filter. The filter material is usually pure quartz fibre, which is suitable for subsequent analysis for organic carbon compounds, major ions, etc. Multiple internal reflections within the matrix of the filter render the measurement insensitive to optical scattering from the aerosol. A thermal firing technique can determine any interference due to the collection of optically absorbing mineral dust. This is usually a very small contribution, although in dusty areas it may be advisable to precede the aethalometer with a size-selective inlet to pass the small (<0.3 μm) BC particles and exclude the dust. The instrument is operated by a dedicated microcomputer that calls attention to fault conditions and that can be operated remotely by landline. Contamination events are clearly recognized as giant excursions in the data and may be edited from the final database either manually or by automatic threshold.

**Data Reduction**

The aethalometer data are normally recorded on the controlling computer’s diskette, and also printed out each measurement period at the site as a backup. The data include records of internal signal voltages as well as the calculated BC concentrations. The BC results may be scanned to eliminate contamination events, and the voltages’ stability checked to assure correct instrument operation. The BC data are then available as a time series set for the site.

**Archiving Procedures**

At present, there is no central repository of global BC measurements. The WMO has a considerable body of worldwide measurements of "smoke", but these were mostly taken in cities and thus not
representative of regional or global concentrations. It would be desirable to start such a data archive and to re-examine the "smoke" data.

**Application of Results**

The distribution of BC is an indicator of the global dispersion of anthropogenic pollutants. The black spot of aerosol on a filter collected at the South Pole is a graphic demonstration of long-range transport. Knowledge of the diminution of BC downwind of source regions can assist in the modelling of the impact of other emissions. The direct optical effects of BC may be significant in the highly polluted Arctic.

**Equipment and Infrastructure Cost (US$)**

Automatic tape-feed aethalometer - $15,000 (one-time equipment cost)

Consumable supplies - $200 per year

**Personnel Requirements and Training**

Personnel: Data validation and logistical support - 1 man-month per station-year

Training: Operator training - 1 day (assumes general technical skill)

Data validation and support training - 1 week (assumes general scientific skill)

**References**


**Contact:**

Dr. A.D.A. Hansen
Lawrence Berkeley Laboratory 70A-3363
University of California
Berkeley, CA 94720
USA
3.1.5. Ice Nuclei

Importance

The role of ice nuclei in the atmosphere is potentially very great, because of the importance of ice particles that might form on them. Perhaps most important, ice particles forming in supercooled clouds can rapidly develop into precipitation (snow, hail, or, after melting, rain). Less directly noticeable, but of great significance for climate, are the impacts ice clouds have on the radiation balance of the Earth-atmosphere system. Also, the development of ice in clouds influences the removal of trace substances from the atmosphere, thereby affecting the global cycles of those substances, as well as the fate of pollutants. In turn, changes in atmospheric aerosol numbers, or in composition, might influence ice formation in clouds. Many of these connections are not yet sufficiently well known. Ice processes in clouds are quite complex, so their study is not easily accomplished, and there are very large variabilities among different atmospheric situations. Furthermore, some ice formation in clouds can occur from ice nuclei (primary mechanism), or from interactions between hydrometers (primary mechanism), or from interactions between hydrometers (secondary mechanisms). The question of the role of ice nuclei in the atmosphere is only a subset of the questions associated with the role of ice particles in general.

Siting Requirements

So little is known about sources of ice nuclei sources and their atmospheric lifetimes that siting requirements based on scientific fact cannot be established. In the absence of such facts, the requirements for the measurement of ice nuclei would be similar to those for aerosols, because ice nuclei are a subset of the larger aerosol population. These requirements would be that measurements should generally be taken away from local aerosol sources and remote from anthropogenic gaseous emissions, especially those from larger combustion sources.

Methods of Measurement and Sampling Frequency

What makes the formation of atmospheric ice a complex phenomenon is that both the vapour and the liquid phases can exist, metastably, at temperatures colder than 0°C, and over a wide range of vapour pressures. The metastable phases -- supercooled water and supersaturated vapour -- are transformed into the stable phase, ice, following the nucleation of that stable phase. One therefore deals with the nucleation of freezing and the nucleation of deposition, depending on whether the parent phase is the liquid or vapour.

Measurements of atmospheric ice nuclei can follow one of two general approaches: (1) to attempt to recreate particular atmospheric conditions in an apparatus and observe the numbers of ice crystals that develop (simulation), or (2) to perform separate measurements for each mode of nucleation, i.e. immersion freezing, deposition, contact, and condensation freezing.

Cloud chambers are the main instruments for measuring ice nuclei through simulation of atmospheric conditions. Small chambers for use in the field produce unreliable results because of a host of environment control issues. Large chambers requiring their own buildings and infrastructures produce better results, but are limited to measurements in one region.

For immersion-freezing (drop-freezing) nucleation measurements, larger volumes of nucleant-containing water are dispersed in small drops and cooled. More-active nuclei cause freezing of the drops in which they happen to be located, while leaving other portions of the sample to be frozen at colder temperatures. Ice nucleus activity spectra can then be derived.

Deposition nucleation measurements have been most widely attempted by the filter method, whereby aerosols are sampled with high-efficiency membrane filters and are then placed into a chamber in which temperature and humidity can be independently controlled. The number of ice crystals that grow on the filter are taken as a measure of ice crystal activity in the atmosphere.

Measurements of contact-freezing nuclei have been attempted by allowing particles to contact supercooled water drops in a cooled chamber and observing the freezing of the drops.

Condensation-freezing nuclei are perhaps the most difficult to measure, because it is postulated that the measurement process has two steps. The basic idea used to measure such nuclei is to produce a flow
of air between two plates. This forms a diffusion chamber in which the surfaces are covered with uniform ice layers and are maintained at slightly different temperatures to produce a supersaturated region about midway between the two plates. Ice crystals that develop in the airstream are then counted as they exit the chamber.

None of the above methods used alone provides an accepted measurement of atmospheric ice nuclei. Therefore, frequency of measurements cannot be stated with any degree of confidence. It has been shown, though, that for periods of days to weeks, ice nucleus concentration changes of up to a factor of 100 generally represent 90% of a data set; however, sudden, hundredfold changes in ice nucleus concentrations have been observed over a period of only a few minutes.

**Data Reduction**

Each measurement technique and each instrument has its own data reduction procedures, many of them using empirical "calibrations" that have various ranges, up to factors of 10. There are no standard data reduction techniques applicable across the field.

**Archiving Procedures**

None other than publication of data.

**Application of Results**

Applications are limited because of unreliability of comparisons between instruments and techniques, no accepted ice nucleus standards, and no true understanding of the role of ice nuclei in the atmosphere.

**Equipment and Infrastructure Cost (US$)**

Because there are no reliable, accepted methods to measure atmospheric ice nuclei, cost estimates are not reliable. In the past, small cloud chambers and/or freezer systems cost in the $10-$50K range, whereas big facilities such as the Colorado State University Simulation Laboratory might cost more than $500K.

**Personnel Requirements and Training**

Undefined at present.

**References**


**Contact:**

Dr. Russ Schnell  
Mauna Loa Observatory, NOAA/CMDL  
PO Box 275  
Hilo, HI, 96720  
USA
3.2. Chemical Properties

**Importance**

The chemical properties of atmospheric particles can affect the environment in many ways. The toxic aerosols, e.g. Pb, As, or Se particles, can cause death and harm to humans and animals. Hygroscopic aerosols, e.g. sea salt, sulphate, and nitrate particles, are active cloud condensation nuclei which govern concentration and size distribution of cloud droplets and thus affect cloud lifetime, cloud amount, cloud albedo, and overall climate. Hydrophobic aerosols, e.g. soil dust and decayed bio-debris, can serve as ice nuclei and thus control precipitation amount. To improve our understanding of the trend and the extent of aerosol effect on global change, it is important to measure the spatial and temporal variabilities of aerosol chemical properties.

**Siting Requirements**

To detect a clear signal, the measuring sites should be representative and characterizing a region. The site should be free from any local contamination.

**Methods of Measurement and Sampling Frequency**

The most simple and direct sampling technique is to collect particles on filters. Sampling once a week for 12 hours with a flow rate of 200 L min^-1 would be sufficient. Samples can be collected on one stage for bulk analysis or on several cascade stages for size discrimination. The samples are sent to a central station for chemical analyses. The soluble portion of aerosol particles can be extracted with water and determined with an ion chromatograph for cation and anion concentrations. The insoluble particles are analysed with a neutron activation spectrometer or a proton induced x-ray energy (PIXE) instrument for elemental composition. The sampling and analytical procedures should be standardized for all samples collected at all sites.

**Data Reduction**

After completion of chemical analyses, the data sets are recorded on an electronic data processing system. Data are evaluated for assurance of quality and identification of outliers. The qualified data of monthly means and standard deviations are sent to the central archiving facility of GAW.

**Archiving Procedures**

No central archive system has been established for aerosol chemistry so far. It is a challenge to initiate a computer storage system that provides easy access to the data producers and users.

**Application of Results**

Data sets of aerosol chemistry will be very useful to scientists who investigate air quality, acid rain, cloud microphysics, cloud radiation, desertification, and overall climate change.

**Equipment and Infrastructure Cost (US$)**

Field Sample Collection

- Aerosol sampler - $2,000
- Teflon filters - $1,000
- Plastic ware, postage, etc. - $500

Laboratory Analyses (per sample)

- Ion chromatograph - $50
- Neutron activation - $80
- PIXE (optional) - $50
Personnel Requirements and Training

Personnel: On-site operator for weekly samples - 3 man-months per year
Central Laboratory analyst - depends on number of samples

Training: On-site university trained operator - 1 week (hands-on)
Central Laboratory - personnel for chemical analyses require special experience and skill;
service is included in price per sample

References


Contact: Dr. F. P. Parungo
NOAA/ERL/ARL, R/E/ARx1
325 Broadway
Boulder, CO 80303
USA
4. PRECIPITATION CHEMISTRY

Importance

Measurements of the chemistry of precipitation have been made in many parts of the world for over one hundred years. At an early stage, scientists realized that processes that produce rain and snow are important mechanisms for cleansing the atmosphere of trace substances both natural and man-made. In recent years, interest in total deposition, i.e. wet and dry, has increased because of such phenomena as the long-range transport of acidic and toxic materials. Both dry deposition and wet deposition require different measuring systems. Wet deposition, which involves all forms of precipitation, is sampled in specifically designed collectors and then analysed, according to a standard protocol for its chemical composition.

From a broader perspective, precipitation chemistry measurements provide information on the exchange of trace materials between the atmosphere and the land/oceans and hence are an important link in understanding the chemical cycles of substances as, for example, sulphur or nitrogen. The impact of changes in these cycles will have a direct influence on both climate and global change.

Siting Requirements

GAW stations collecting samples for precipitation chemistry analysis can be classified into two groups: baseline and regional, depending on their distance from natural and anthropogenic sources, their location within a given climatological/ecological region, and a number of other factors. For both station types, particular care must be taken that any form of local contamination, such as dust, be excluded to avoid cancelling the usefulness of the measurements.

Critical on-site precautions consist of placing the collector away from high structures such as buildings and trees and selecting a level, preferably grass-covered plot.

Methods of Measurement and Sampling Frequency

Precipitation chemistry monitoring can be divided into two phases: collection of the sample and laboratory analysis. When a rain or snow event takes place at a site, a special open-close collector is activated to capture the sample. The amount of rain from the national precipitation gage is also recorded. Sampling periods are either weekly or daily. From past monitoring experience, daily sampling, where the collector is checked at a given time each day, has been found to be the most scientifically useful. Under the weekly protocol, all events are composited over a 7-day period. In some networks, pH and conductivity are determined on site and biocides are added to the sample before shipping to the laboratory.

The second phase begins when the sample is received by the national laboratory or central analysing facility designated by the WMO. At these laboratories, the major ions are determined (SO₄₂⁻, Cl⁻, NH₄⁺, NO₃⁻, H⁺(pH), Ca, Mg, Na, and K). Because of their importance in certain areas, formic and acetic acids should be measured. Conductivity is also measured. A wide variety of analysis techniques are used by the different laboratories, with ion chromatography as the leading method. A considerable effort has been made by the WMO to improve the quality of the analysis by conducting over 12 laboratory intercomparisons, wherein participating national laboratories analysed a series of solutions with known concentration and reported the values to the WMO. These results were then used as a measure of the performance of the given laboratory.

Data Reduction

After completion of the laboratory analysis, the concentrations of major ions from a given sample can be evaluated. At this point, a number of quality assurance checks are performed to identify outliers which may require that a given sample be analysed a second time. When all quality checks have been made, the data are recorded in the approved WMO format and sent to the central archiving facility.

Archiving Procedures

The central archive for precipitation chemistry data is located at Environmental Protection Agency, Research Triangle Park, NC, USA. Here the data are placed in electronic storage and issued for scientific use in hard copy or on a diskette.
Application of Results

Scientists have actively used the precipitation chemistry data from the BAPMoN along with other data sets to investigate a number of environmental problems. One of the main areas has been the impact of acid rain on the environment. The data have been used in establishing trends in sulphur and nitrogen deposition and as ground truth for model calculations of pollutant transport. Further, studies of background levels of trace materials have been completed using the precipitation chemistry data. If high-quality data are taken, they can be used for a number of national and international scientific studies.

Equipment and Infrastructure Cost (US$)

Field Collection

- Open-close collector - $1,500 to $2,000
- Postage, plasticware, etc. - $300
- pH meter (optional) with buffers - $1,000
- Laboratory analysis (per sample) - $80 to $100

Personnel Requirements and Training

Personnel: Site operator - 1 man-month per year (weekly sampling)
- 3 man-months per year (daily sampling)

Training: Site operator - from 1 to 2 weeks depending on whether pH and conductivity are measured on site
Laboratory - the chemistry laboratory would be expected to provide all services, including training, to be covered through price charged per sample

References

WMO, 1989: GAW and Precipitation Chemistry Measurement Activities, Fact Sheet No. 5.


Contact: Richard Artz
NOAA - Air Resources Laboratory
1315 East West Highway
Silver Spring, MD 20910
USA
5. SOLAR RADIATION

5.1. Solar Radiation Measurements
(Direct, Total, and Diffuse)

**Importance**

Solar radiation at the Earth’s surface is the principal source of energy responsible for maintenance of the world’s climate as we now know it. Surface solar radiation also provides the possibility of man using a very small amount of that energy for controlled heating and electrical power generation. Basic principles in atmospheric science suggest that changes in the amount of solar energy received at the surface will affect atmospheric thermodynamics and hydrodynamics, although the exact mechanisms by which a given change in solar radiation will affect any particular atmospheric variable are very complicated and poorly understood. Accurate and long-term measurements of solar radiation over a large and representative portion of the globe will aid in determining energy deposition and transport mechanisms responsible for the planet’s climate and its variations. Such ground-base networks along with satellite radiation observations form a complimentary system. The surface measurements furnish ground truth, and the space observations provide global coverage and a measure of variability. Such measurements also enhance the ability to utilize efficiently and intelligently solar power for technical applications to man’s domestic and industrial needs.

**Siting Requirements**

Surface solar radiation is highly variable in time and space. Siting requirements for solar power utilization may vary from those seeking regional representativeness for climate studies. For solar power utilization the best site will be that at which the power application is to be made or from a site or set of sites near enough that measurements are representative of conditions at the prime site. For climate applications, the site must be free of sub-grid scale influences. The global climate grid scale of interest will depend on the spatial resolution of the diagnostic and analytic tools used in a particular climate study. In general, a solar radiation measurement site will be useful in climate analysis, if free of local influences such as orographic cloud effects, localized moisture or pollution sources, or obstructions to a clear upward hemispheric field-of-view of the sky. The site must provide a stable platform from which to make the observations and have access for routine, but potentially infrequent, instrument inspection and maintenance.

**Methods of Measurement and Sampling Frequency**

Several commercially available sensors are used for surface solar radiation measurements. Proven reliability, accuracy, and precision can vary widely between types of sensors. Accuracy and precision for individual sensors should be established by experienced personnel prior to and during field use. The absolute calibration of the sensors should be directly traceable to the world standard maintained by the WMO in Davos, Switzerland. Routine and frequent, approximately once per year, calibrations and/or comparisons of the field sensors are required to maintain minimum measurement accuracy. The instruments are generally passive and relatively simple electronically. Instruments for measuring total and diffuse sky radiation require fixed orientation, and those directly measuring the solar beam require a solar tracking device. The diffuse measurement also requires a movable shading device. Routine inspection of the instruments is necessary to provide orientation assurance and cleanliness of optical surfaces and apertures. Solar radiation affected by clouds can vary significantly on time scales of less than 1 second, but few sensors are capable of responding to such variations. Typically, the shortest time scales of solar radiation variability are ignored, but averages or sums compiled from 1-second samples are common. Averaging times vary from less than 1 minute to a few minutes to 1 hour. Hourly, daily, and monthly sums and averages are often used in climate analysis, whereas nearly instantaneous values are used in some engineering and scientific applications.

**Data Reduction**

Basic data reduction is trivial on modern computers. However, overall data quality control can be very complex, involving visual examination and editing of the data for inadvertent shading of the instruments and other gross errors. Also, corrections for solar zenith angle, temperature, voltage measurement calibration, and long-term instrument calibration drift may be required.
Archiving Procedures

Besides local and national archives, some data have been archived at the World Radiation Data Centre in St. Petersburg, Russian Federation.

Application of Results

Data are applied to the scientific and engineering problems discussed in previous sections.

Equipment and Infrastructure Cost (US$)

Direct Sun

Tracker - $1,500 (clock drive) to $7,500 + (computer drive)
Pyrheliometer - $2,200

Total Global

Pyranometer - $1,700

Diffuse

Pyranometer - $1,700
Shade band - $500 (semi-fixed) to $2,000 (solar tracking)

Data System

Self-calibrating, auto zero, microvolt resolution - $2,000
Misc. supplies, cables, connectors - $1,500

Calibration Facility

Absolute cavity - $8,500
Pyranometer - $1,700
Solar tracker - $1,500
Shade devic - $500
Data system - $2,000
Travel to interact with world calibration standards - $2,000 per year

Data Processing

Computer - $5,000
Peripherals - $3,000
Software - $21,000 + 500 per year
Misc. supplies - $500 per year

Personnel Requirements and Training

Personnel: Field site technician or scientist with interest in atmospheric processes - 20 minutes per day.
Calibration facility technician degreed or scientist with solar radiation experience - 1 month per year plus 2 weeks per year for each field site (Note: field site could be calibration facility)

Training: Field site - 1-2 days plus exposure to different conditions
Calibration Facility - 1 month
References


WMO Guide to Meteorological Measurements, 1971, No. 8, TP 3. (Available from WMO.)

Contact: Ellsworth Dutton
NOAA/ERL/CMDL R/E/CG1
325 Broadway
Boulder, CO 80303
USA
5.2. Ultraviolet Measurements

Importance

Ultraviolet (UV) radiation reaching the Earth’s surface is classified into two categories: UV-A (320-400 nm) and UV-B (290-320 nm). The UV-A is essentially unaffected by ozone, while UV-B changes with stratospheric ozone column amount. Both bands of radiation produce deteriorating photoreactions in biological life and numerous nonbiological materials (e.g. paints, plastics, concrete, contact lenses, runner, etc.). In general, the shorter wavelengths in the UV-B region are increasingly more active and, therefore, variations in ozone will have a strong effect on the surface environment exposure rate. Monitoring UV-B along with other factors such as aerosols, clouds, and ozone to explain variations is extremely important for defining the baseline UV conditions of a region as well as determining, quantitatively, explanations of the factors that affect the surface UV exposure rate.

Siting Requirements

Siting requirements are generally those specified for surface-based solar radiation measurements. However, if UV data are desired for validation of satellite determinations of surface UV, then requirements can become more stringent. In this case, it is not necessary to have a numerous distribution of sites. Rather, ten to twenty sites located in regions where surface properties are reasonable will suffice. The WCRP Baseline Surface Radiation Network (BSRN) procedures can serve as a guideline. Examples of regions for consideration are desert, steppe, forest, agricultural, polar, and oceanic. A few mountain sites will be useful for exploratory studies. However, mountain sites often suffer from local cloud and fog effects, and this has to be taken into account when considering which sites are best suited for exploration.

Methods of Measurement and Sampling Frequency

Methods of measuring UV are highly cost dependent. High-spectral-resolution (~1 nm) measurements made by grating or prism instruments are expensive and require greater technician involvement than low-resolution measurements made by filter photometers or by the concept of Robertson (1972). The choice of high-resolution versus low-resolution instruments for UV monitoring is a source of continual debate. This arises from the fact that the UV cutoff below ~310nm becomes increasingly steeper with decreasing wavelength, and to capture the essence of the cutoff, high-resolution is required. The other side of the debate argues that measurements in one to several broadband is sufficient for monitoring variations and trends and applies sufficiently well for validation of satellite measurements. The arguments of both sides are valid, and what seems to be a compromise is to employ both types of measurements according to whether a basic research site is desired (spectral resolution) or baseline monitoring measurements are desired (broadband). It is expected that some basic research sites will have available UV spectral radiometers. These sites should also have broadband instruments of the type used in the baseline monitoring sites so that an improved understanding of the performance, calibration, and utilization of the broadband instrument data can be established.

Sampling frequency by broadband UV instruments can range from a 6-minute average (BSRN requirements) to an hourly average depending on the capability of the recording system and application of the data. The sampling rate of high-resolution instruments will likely be dictated by special measurement applications because recording of spectra requires a large data storage capacity. It is envisioned that only a few sites will be able to maintain operation of high-spectral-resolution instruments. As a passing comment, the Canadian Brewer Spectrophotometer is capable of making spectral measurements. However, its main use is for observation of total ozone.

For both types of instruments, calibration procedures must be clearly defined and stringently followed. Otherwise, measurement noise and calibration drifts can increase the uncertainty of the data and create embarrassment. To this end, a UV measurement project must be intimately tied to a radiation laboratory that is adequately staffed with competent personnel.

Data Reduction

Data reduction with the use of electronic recording systems can usually be done on site if instrument calibrations are known and well monitored. Calibrations must be tied to a central laboratory facility that carefully monitors the performance and calibration of the field instruments. In addition, operation of the field instruments must be continually monitored as a part of the overall management of radiation
measurements. Data reduction must include all aspects (including careful documentation) of the UV measurement project, from central laboratory operations to field operations and personnel training and management. Central management of radiation measurements made at all sites is mandatory if reliable measurements are to be realized.

**Archiving Procedures**

The World Radiation Data Centre resides in St. Petersburg, Russian Federation. The centre archives solar and infrared radiation data contributed by all participating countries. UV radiation data from networks are to be archived at the radiation data centre. In addition, an additional archive could be located at Toronto, Canada, and, if data are obtained at a BSRN site, the data can be stored in the BSRN archive. This archive will parallel the World Ozone Data Centre archive because of the natural connection between UV and ozone. Each participating country will perform the final data review process at its respective radiation laboratory for quality assurance before submitting the data to an international archive. In addition, each radiation laboratory will have its own permanent archive. Because of the close similarity of the WCRP Baseline Surface Radiation Network (BSRN) measurement requirements, the same central radiation laboratory for each network should be used.

**Equipment and Infrastructure Cost (US$)**

- UV-B sensor - $5,000 (one-time cost)
- Spectral radiometer* - $100,000 (one-time cost)
- Total startup cost - $5,000 or $105,000

Various costs for maintenance and calibration apparatus

*An option is an existing Brewer spectrophotometer

Central Processing and Calibration Facility - $65,000

**Personnel Requirements and Training**

Personnel: Central Radiation Facility - 1 full-time radiation expert and 1 half-time data processor assistant

Training: For low-resolution instrument - 2 days
          For high-resolution instrument - 1 month

**References**


**Contact:**

Dr. John DeLuisi
NOAA/ERL/ARL
325 Broadway
Boulder, CO 80303
USA
6. METEOROLOGICAL PARAMETERS

6.1. GAW Station Climatology

Importance

An understanding of the climatology in the area immediately around and especially upwind of a GAW station is necessary for the interpretation of any long-term data that will be collected at the site. Any seasonalities, data extremes, and secular changes of meteorological parameters will need to be examined and put in context with the climate of the region.

Siting Requirements

The climatology, along with the topography and ecosystems of a site, must be described and understood in order to interpret the observations properly. It may be difficult to find a location that will meet all the requirements for measuring all species important to global change. Therefore, as a first step, the global change parameter(s) important for measurement and study within the region of interest should be identified, and then the best site in the region should be located where the most representative measurement of the parameter(s) can be made. If solar fluxes are important, then clear skies are a prerequisite; if CO₂ is important, then sources and sinks around and upwind of the site must be understood and quantified, etc. The climatology of the region must be of sufficient spatial and temporal homogeneity to ensure the broadest extrapolation of the results in both space and time. The influence of local factors such as local wind regimes, orographic rain bands/shadows, dust storms, or seasonal (such as slash and burn) fires must be identified and factored out of the long-term measurements if a broad extrapolation of the data is intended. The same procedure is applicable for infrequent local pollution sources, which must be identified and edited out of the data record. Similarly, sources and sinks of interest, such as swamps for methane or deserts for aerosols, must be situated upwind of the proposed site in such a way that the regional climatology will provide the best opportunity to measure its downwind effects after they have been mixed and must be representative of concentrations of the regional air mass.

Methods of Measurement and Sampling Frequency

Meteorological instrumentation for measurement of climatological parameters has been standardized around the world. A continuous and in-situ measurement programme of meteorological parameters will be necessary to complement and interpret the individual global change parameters as well as their chemical and dynamical transformations at each regional station. The measurements should be of sufficient frequency and accuracy to register the smallest variations in, and possible long-term increases of, the trace species investigated, to document changes in the Earth-atmosphere system.

In addition, all past climatological data of the site and region should be analysed and used to aid future analyses of the global change parameters measured at the station. Climatic classifications, ground cover, synoptic flow patterns, and evapotranspiration rates are some examples of complementary data sets that can be used to characterize the site and to interpret measurements.

One-time studies should be made when necessary to characterize the meteorological conditions at the site that can influence the measurements at the station. Local wind studies, seasonal boundary layer mixing depth studies, or a study of the frequency of seasonal storm tracts in the vicinity of the station are examples of such studies. Every aspect of the Earth-atmosphere should be studied and understood as much as possible in the region where GAW regional stations are set up.

Archiving Procedures

All climatological and special studies data should become part of the national climatological archives of the country in which the station is set up according to their common practice and units of measurement. Thought should also be given to setting up a climatological description format for GAW stations that would be uniform throughout the network.
Personnel Requirements and Training

Training and experience in meteorological field measurements and climatological analyses.

Contact: Bernard G. Mendonca
NOAA/CMDL, R/E/CG1
325 Broadway
Boulder, CO 80303
USA
6.2. Trajectories

Importance

One of the most important aspects of atmospheric chemistry is interpreting the measurements of different chemical species in terms of their cycles in the Earth-atmosphere system. One method, the calculation of back trajectories from the point of measurement (receptor) or from the point of emission of the material being studied (source), has been widely and successfully employed to evaluate transport of chemical substances in the atmosphere.

Typically trajectories are used to create a flow climatology, a tool that gives the statistically important atmospheric flow characteristics for a specific source or receptor, over a period of time ranging from days to years, using individual trajectories calculated for 10 days or less. Trajectories are typically grouped by compass direction, or by some other real or suspected physical or chemical trait in the chemical database being studied. New analysis techniques have been developed in the last few years to group trajectories using objective computerized techniques designed to make the construction of a trajectory climatology less labour intensive.

Siting Requirements

Using gridded meteorological input data, computer models are able to construct trajectories anywhere on the globe and at almost any height desired. The confidence one is able to place in these simulations, however, is highly dependent upon geographic location and height above the surface from which calculations commence. In very remote areas, particularly over oceans, and almost anywhere in the Southern Hemisphere, the meteorological database of rawinsonde measurements is very sparse, making the gridded fields less accurate. Mountainous regions are also difficult to simulate due to very large changes in wind flow over very short distances.

Methods of Measurement and Sampling Frequency

Several different types of trajectory models are currently in use. Practically all rely on some sort of gridded meteorological input fields constructed from either diagnostic or prognostic meteorological information. The principal difference between most of these models is in the treatment (or lack of treatment) of vertical motion. Common models work using constant height, constant pressure, or isentropic (constant potential temperature) assumptions, or using terrain-following (sigma) coordinates. A few models incorporate the vertical velocity computations included with the gridded wind information.

Computation frequency depends in large regard upon the resolution of the meteorological fields and in the nature of the transport field being addressed. Upper-air meteorological data are gathered twice daily, at 00UT and 12UT, over the entire globe; therefore, trajectories are typically computed twice daily at these times. Interpolation of the meteorological fields between the observation times is usually not warranted.

Data Reduction

There are no standardized techniques for trying to understand trajectory output. In the complete absence of good chemical or topographical data, trajectories are typically stratified by compass direction. More sophisticated sectoring schemes can be devised by either subjectively or objectively comparing the trajectories to their corresponding chemical or meteorological data, or by stratifying according to topographical information.

Archiving Procedures

Meteorological input parameters are stored in the United States by the National Climate Data Centre in Asheville, North Carolina. In Great Britain, these data are stored by the European Centre for Medium-Range Weather Forecasting in Reading. Other meteorological data repositories undoubtedly exist in other countries. No archive currently exists for computed trajectory information.

Application of Results

Air parcel trajectory information has proved very useful in the interpretation of atmospheric chemistry data. One of the main areas has been the determination of source regions of emissions in Europe and
North America for materials implicated in dry and wet acidic deposition. At remote locations, trajectory information has been used to implicate emissions from continental locations of both natural and anthropogenic materials to the local deposition and to establish natural background levels of major ions found in precipitation.

**Equipment and Infrastructure Cost (US$)**

Trajectory costs are very difficult to quantify but are typically very inexpensive. Meteorological data may be purchased from national centres at a nominal cost. Equipment required to run the models ranges from $2000 to $3000 for personal computers, to considerably greater costs for the acquisition of mainframe computers. (Typically time-share arrangements are available for mainframe equipment, often making real costs comparable with personal computer costs.) Labour charges to work up the trajectory analyses are highly dependent upon local skilled labour costs and the depth of analysis performed.

**Personnel Requirements and Training**

People attempting to perform trajectory analysis should be well versed in basic meteorology, and have substantial knowledge regarding the types and formats available for computer databases of standard meteorological data. The researcher must also have a thorough understanding of all chemical and topographical data sets used in the study. The number of personnel required is dependent upon the period and depth of study.

**References**

Draxler, R.R., 1988: Hybrid Single-Particle Lagrangian Integrated Trajectories (HY-SPLIT): Model Description, NOAA Technical Memorandum ERL ARL-166, Air Resources Laboratory, Silver Spring, MD.


**Contact:**

Mr. Richard Artz
NOAA Air Resources Laboratory
1315 East West Highway
Silver Spring, MD 20910
USA
ENVIRONMENTAL POLLUTION MONITORING AND RESEARCH PROGRAMME REPORT SERIES


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


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


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*


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


19. Forecasting of Air Pollution with Emphasis on Research in the USSR by M.E. Berlyand, August 1983

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


23. Provisional Daily Atmospheric Carbon Dioxide Concentrations as Measured at BAPMoN Sites for the Year 1982. November 1984


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


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


35. Provisional Daily Atmospheric CO₂ Concentrations as Measured at BAPMoN Sites for the Year 1983. December 1985


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


46. Provisional Daily Atmospheric Carbon Dioxide Concentrations as Measured at BAPMoN Sites for the Year 1984. December 1986


50. Provisional Daily Atmospheric Carbon Dioxide Concentrations as Measured at BAPMoN Sites for the Year 1985. December 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

55. Summary Report on the Status of the WMO Background Air Pollution Monitoring Network as at 31 December 1987


58. Provisional Daily Atmospheric Carbon Dioxide Concentrations as measured at BAPMoN sites for the years 1986 and 1987


62. Provisional Daily Atmospheric Carbon Dioxide Concentrations as measured at BAPMoN sites for the year 1988


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)


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


72. Integrated Background Monitoring of Environmental Pollution in Mid-Latitude Eurasia by Yu.A. Izrael and F.Ya. Rovinsky, USSR

73. Report of the Experts Meeting on Global Aerosol Data System (GADS) (Hampton, Virginia, 11-12 September 1990)


75. Provisional Daily Atmospheric Carbon Dioxide Concentrations as measured at Global Atmosphere Watch (GAW)-BAPMoN sites for the year 1990

76. The International Global Aerosol Programme (IGAP) Plan: Overview

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

78. Global Atmospheric Background Monitoring for Selected Environmental Parameters BAPMoN Data for 1990, Volume I: Atmospheric Aerosol Optical Depth


80. Report of the WMO Meeting of Experts on the Quality Assurance Plan for the GAW (Garmisch-Partenkirchen, Germany, 26-30 March 1992)


83. Report on the Global Precipitation Chemistry Programme of BAPMoN

84. Provisional Daily Atmospheric Carbon Dioxide Concentrations as measured at GAW-BAPMoN sites for the year 1991

85. Chemical Analysis of Precipitation for GAW: Laboratory Analytical Methods and Sample Collection Standards